coral reef ecosystem monitoring report of the mariana archipelago: 2003–2007



Coral Reef Ecosystem Division

Pacific Islands Fisheries Science Center

Coral Reef Ecosystem Monitoring Report of the Mariana Archipelago: 2003–2007

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REFERENCES

LIST OF ABBREVIATIONS

ADCP	Acoustic Doppler current profiler
AHI	Acoustic Habitat Investigator
ARMS	Autonomous reef monitoring structures
ASCII	American Standard Code for Information Interchange
AD	Anno Domino
AVHRR	Advanced very high-resolution radiometer
BLE	Bleaching
BLT	Belt transect
BP	Before Present
BPI	Bathymetric position index
BSP	Bureau of Statistics and Plans
CCMA	Coastal Monitoring and Assessment
CEDS	Comprehensive Economic Development Strategy
Chl-a	Chlorophyll-a
CNMI	Commonwealth of the Northern Mariana Islands
COTS	Crown-of-thorns seastars
CRCA	Coral Reef Conservation Act of 2000
CRCP	Coral Reef Conservation Program
CRED	Coral Reef Ecosystem Division
CREIOS	Coral Reef Ecosystem Integrated Observing System
CREWS	Coral Reef Early Warning System
CRM	Coastal Resources Management
CRTF	U.S. Coral Reef Task Force
CRW	Coral Reef Watch
CTD	Conductivity, temperature, and depth
CUC	Commonwealth Utilities Corp.
DAWR	Division of Aquatic and Wildlife Resources
DEQ	Division of Environmental Quality
DFW	Division of Fish and Wildlife
DIC	Dissolved inorganic carbon
DTC	Data transaction center
DOI	U.S. Department of the Interior
EAR	Ecological acoustic recorder
EEZ	Exclusive economic zone
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute Inc.
FLNTU	Combined fluorescence and turbidity sensor
FUN	Fungal infection
GAO	U.S. Government Accountability Office
GEPA	Guam Environmental Protection Agency
GIS	Geographic Information System
GPS	Global positioning system
GSF	Generic sensor format
GWQS	Guam water-quality standards
H_2	Significant wave height
LAS	Local action strategy
LPI	Line-point intercept
MARAMP	Mariana Archipelago Reef Assessment and Monitoring Program
MCE	Mesophotic coral ecosystems
MMT	Marine Monitoring Team
MNM	Marine National Monument
MPA	Marine protected area
MSC	Military Sealift Command

NASA	National Aeronautics and Space Administration
NAVFAC	Naval Facilities Engineering Command
NAVOCEANO	Naval Oceanographic Office
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center
NPS	National Park Service
OCS	Office of Coast Survey
ODP	Ocean data platform
OTH	Algal and cyanophyte infections and other lesions of unknown etiology
OTR	Ocean Trek Research
PCB	Polychlorinated biphenyls
PFM	Pure File Magic
PIBHMC	Pacific Islands Benthic Habitat Mapping Center
PIFSC	Pacific Islands Fisheries Science Center
PQS	Photoquadrat
PRE	Predation by COTS or corallivorous snails
PRS	Pigmentation response
QS	Quadrat
RAMP	Reef Assessment and Monitoring Program
RD	Roving diver
REA	Rapid Ecological Assessment
RMS	Root mean square
ROV	Remotely Operated Vehicle
SABER	Survey analysis and area-based editor
SAIC	Science Applications International Corporation
SBE	Sea-Bird Electronics Inc.
SD	Standard deviation
SE	Standard error of the mean
SGA	Skeletal growth anomalies
SHOALS	Scanning hydrographic operational airborne lidar survey
SPC	Secretariat of the Pacific Community
SPL	Sound pressure level
SST	Sea-surface temperature
STR	Subsurface temperature recorder
TL	Total length
TLS	Subacute tissue loss
TOAD	Towed optical assessment device
TTPI	Trust Territory of the Pacific Islands
TN	Total nitrogen
UG	University of Guam
U.S.	United States
USNS	United States Naval Ship
UV	Ultraviolet
VS	Voucher specimen
WPacFIN	Western Pacific Fisheries Information Network
WPFMC	Western Pacific Fishery Management Council
WSY	White syndrome
WTR	Wave-and-tide recorder
WWI	World War I
WWII	World War II

Three-letter island codes:

AGR	Agrihan
AGU	Aguijan
ALA	Alamagan
ANA	Anatahan
ARA	Arakane Reef
ASC	Asuncion
FDP	Farallon de Pajaros
GUA	Guam
GUG	Guguan
MAU	Maug
MAU	Maug
PAG	Pagan
PAT	Pathfinder Reef
ROT	Rotan
SAI	Saipan
SAR	Sarigan
SRR	Santa Rosa Reef
STI	Stingray Shoal
SUP	Supply Reef
TAT	Tatsumi Reef
TIN	Tinian
ZEA	Zealandia Bank

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EXECUTIVE SUMMARY

HISTORY & MISSION OF CRED

The mission of the Coral Reef Ecosystem Division is to provide high-quality, scientific information about the status of coral reef ecosystems of the U.S. Pacific islands to the public, resource managers, and policymakers on local, regional, national, and international levels.

National coral reef conservation efforts were formalized in 1998 with a presidential executive order to "preserve and protect the biodiversity, health, heritage, and social and economic value of U.S. coral reef ecosystems and the marine environment." This executive order established the U.S. Coral Reef Task Force (CRTF) and emphasized the need to undertake a comprehensive approach to research, mapping, and monitoring of all U.S. coral reef ecosystems. In 2000, the CRTF developed *The National Action Plan to Conserve Coral Reefs* (CRTF 2000), and the *Coral Reef Conservation Act of 2000* laid out a national framework to address the degradation of U.S. coral reef ecosystems and other coral reef conservation issues (Coral… 2000). The *Coral Reef Conservation Act* also led to the creation of the national Coral Reef Conservation Program under the direction of the Secretary of Commerce. This legislation requires NOAA to conduct scientific research, mitigation, and outreach activities that directly contribute to the conservation of coral reef ecosystems. NOAA, in cooperation with the CRTF, produced *A National Coral Reef Action Strategy* in 2002 with goals and objectives that included mapping, information management, research, and monitoring (NOAA 2002). In response to these mandates and with the support of NOAA's Coral Reef Conservation Program, the NOAA Pacific Islands Fisheries Science Center initiated the Pacific Reef Assessment and Monitoring Program (Pacific RAMP) in early 2000 and established the Coral Reef Ecosystem Division (CRED) in 2001.

To fulfill its mission, CRED conducts a comprehensive suite of integrated, interdisciplinary research activities, including habitat mapping, oceanographic studies, and long-term monitoring of multiple components of coral reef ecosystems in the U.S. Pacific islands (Fig. 1). CRED conducts biennial Pacific RAMP surveys in each study area to improve our understanding of ecosystem variability over climate time scales ranging from several years to decades and across broad spatial scales ranging from individual islands and atolls to entire archipelagoes and the Pacific Basin. Complementary methods are used to assess benthic community composition and abundance and diversity of invertebrates, algae, and fishes in the context of their benthic habitats and associated oceanographic and water-quality conditions. Using consistent methodologies across ~ 50 U.S. Pacific islands, atolls, and shallow banks enables unprecedented comparative analyses of coral reef ecosystems across diverse gradients of biogeography, environmental conditions, and human uses. Results from Pacific RAMP surveys significantly improve our understanding of ecosystem processes and cause-and-effect mechanisms that influence the status and resilience of coral reefs.

Pacific island communities are economically and culturally dependent on their marine resources. Accurate and up-to-date characterizations of coral reef ecosystems are necessary to develop and evaluate effective strategies for resource management. For a significant majority of the islands, atolls, and banks surveyed

TIMELINE

- **1998**
  - Executive order to protect reefs
  - U.S. Coral Reef Task Force (CRTF) is formed
- **1999**
  - CRTF creates National Action Plan to Conserve Coral Reefs
  - Coral Reef Conservation Act of 2000 (CRCA)
- **2000**
  - NOAA creates Coral Reef Conservation Program (CRCP)
  - 1st Pacific RAMP cruises
- **2001**
  - NOAA PIFSC forms Coral Reef Ecosystem Division (CRED)
- **2002**
  - NOAA & CRTF produce National Coral Reef Action Strategy
- **2003**
  - 1st CRED Mariana Archipelago RAMP (MARAMP) cruise
  - Included mapping
- **2004**
- **2005**
  - 2nd MARAMP cruise
  - Added water-quality sampling
- **2006**
- **2007**
  - 3rd MARAMP cruise
  - Included mapping
  - Added coral-disease surveys
  - Added sampling for carbonate chemistry
- **2008**
- **2009**
  - 4th MARAMP cruise
  - Improved fish surveys: increased number, added stratified random sampling design and expanded depth range to 0–30 m

*2009 data are not included in this document

through the Pacific RAMP, virtually no prior ecological surveys, bathymetric or habitat maps, or in situ oceanographic observations had been completed. Little or no information was available about what to expect in terms of habitats, biogeographic structure, oceanographic conditions, or species composition, distribution, and abundance. In almost all regards, the initial surveys of the Pacific RAMP in 2000–2003 were exploratory baseline assessments with the purpose of shaping this monitoring program. The logistical and financial challenges presented by the remoteness of the U.S. Pacific islands and the vastness of this region as a whole had a major impact on the initial scope of this program and continue to shape its evolution.

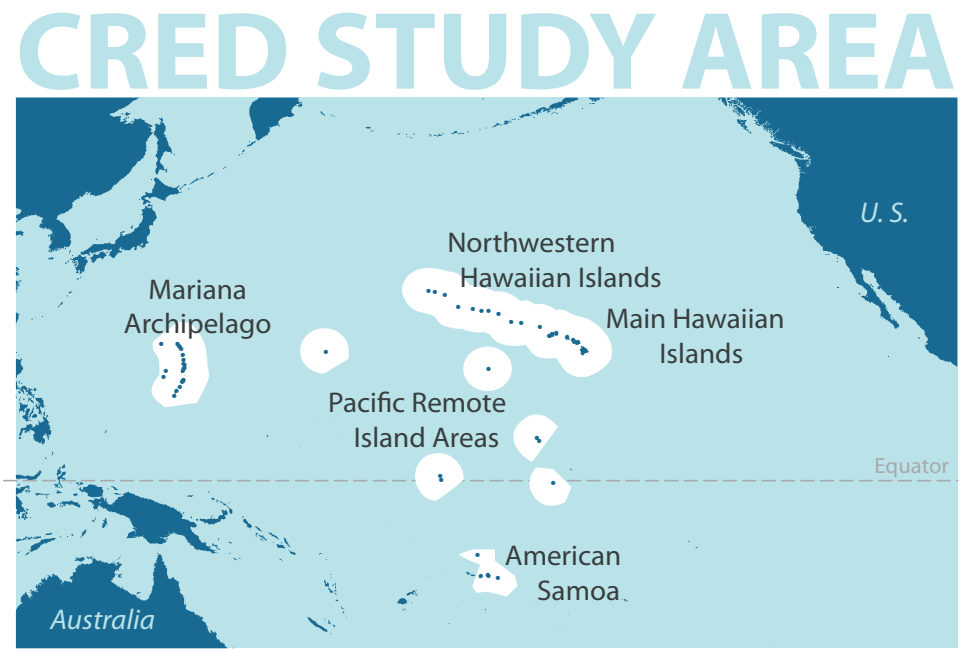


Figure 1. CRED focuses on a study area that consists of ~ 50 islands, atolls, and shallow banks in American Samoa, the Hawaiian Archipelago, the Mariana Archipelago, and the Pacific Remote Island Areas. White areas represent U.S. Exclusive Economic Zones.

With the exception of moored oceanographic and bioacoustic instruments that collect data nearly continuously, Pacific RAMP activities do not detect high-frequency (short-term) ecological fluctuations. Instead, triennial Pacific RAMP surveys are designed to examine ecological variability over a longer term of several years or decades, taking periodic "snapshots" of ecosystems when surveys are conducted. As such, many of these triennial ecosystem snapshots are needed before rigorous discussions about changes and trends become possible.

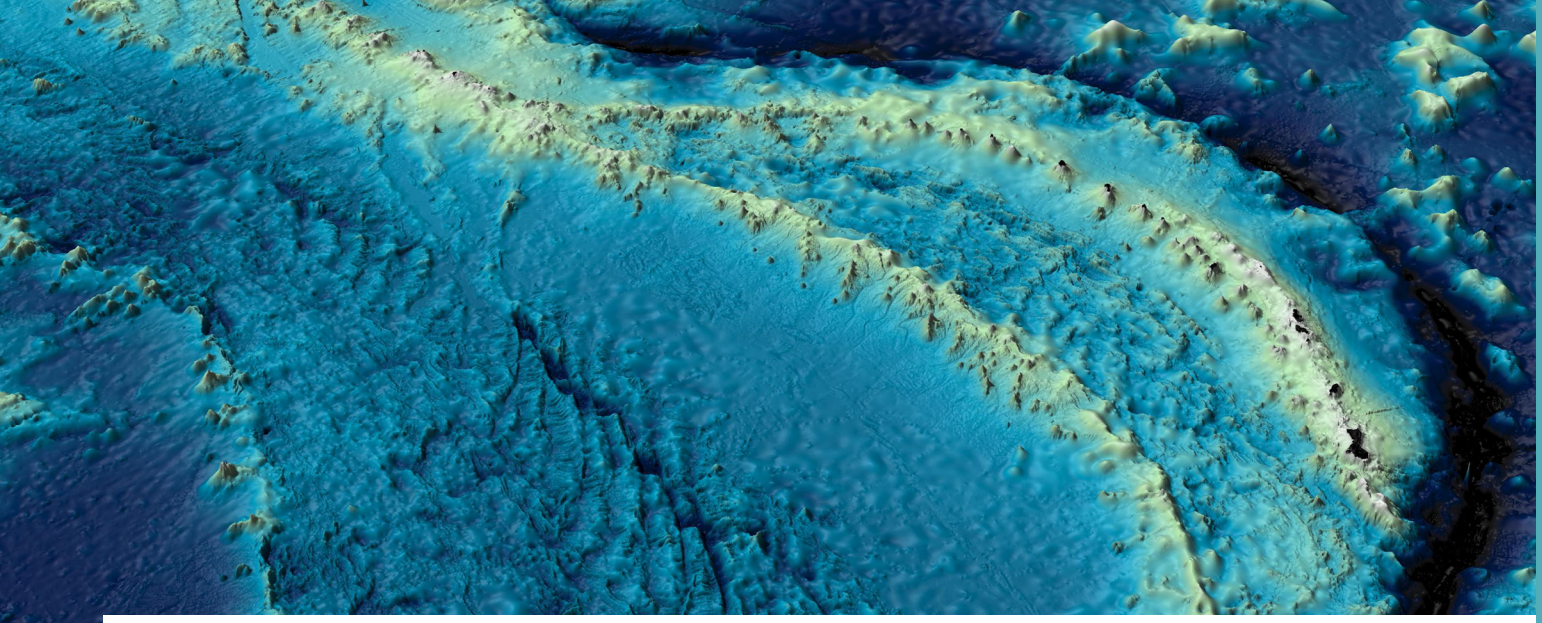
Though changes in survey protocols inherently introduce some inconsistencies in data, CRED has expanded or added some protocols in response to evolving management priorities and a continually improved understanding of factors that affect coral reef ecosystems, such as sampling carbonate chemistry to measure ocean acidification (see timeline on Page 1), and has continued to refine survey methods to better limit variability between survey staff members. CRED conducted its last Pacific RAMP cruise in the Mariana Archipelago in 2011 on the NOAA Ship *Hi`ialakai*, and more information can be found in the cruise reports for this expedition at http://www.pifsc.noaa.gov/library/hiialakai.php. The next cruise in this archipelago is scheduled for 2014.

Below: Two batfish (*Platax tiera*) near Farallon de Pajaros. *NOAA photo by Chip Young*

"...preserve and protect the biodiversity, health, heritage, and social and economic value of U.S. coral reef ecosystems and the marine environment..."

—1998 executive order





THE MARIANA ARCHIPELAGO

Above: Since 2003, CRED has mapped ~ 90% of the coral reef habitats across the Mariana Archipelago and has maintained an ongoing bathymetric data synthesis that combines CRED data with bathymetric data collected by other government and academic groups. Bathymetric and optical data are used for geologic studies, benthic habitat maps, tsunami inundation models, and nautical charts and are routinely provided to management partners in the Commonwealth of the Northern Mariana Islands and Guam to support improved implementation of ecosystem approaches to management of marine resources.

The Mariana Archipelago is 890 km long and encompasses 15 islands, located on the Mariana Arc, and numerous offshore banks. The territory of Guam includes the island of Guam and adjacent offshore banks and reefs. All other islands and offshore banks compose the Commonwealth of the Northern Mariana Islands (CNMI). The islands and reefs of the Mariana Archipelago can be divided into 3 geologic groups (Figs. 2 and 3): (1) various offshore banks and submarine volcanoes located on the West Mariana Ridge; (2) the young, volcanic northern islands on the Mariana Arc, including, from south to north, Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros; and (3) the old, southern islands located on the Mariana Arc, including Guam, Rota, Aguijan, Tinian, Saipan, and Farallon de Medinilla. The 3 northernmost islands, the Mariana Trench, and several volcanic features between the Mariana Arc and Trough were designated as the Marianas Trench Marine National Monument by presidential proclamation in January 2009.

The islands of the CNMI and Guam differ in size, population, and isolation (Table 1). Guam is the largest island in the Mariana Archipelago with a land area of 544 km². Saipan is the largest island in the CNMI with a land area of 119 km², roughly similar to the combined area of 160 km² for the 9 northern islands of the CNMI. Pagan and Agrihan (48 and 44 km²) are the largest of the northern islands, the majority of which have land areas < 10 km², very small relative to the southern islands.

The combined human population of Guam and the CNMI in 2010 was estimated at 213,241 (U.S. Bureau of the Census 2011a, 2011b), with population centers largely focused on 4 of the 6 southern islands: Guam, with an estimated population of 159,358, as well as Rota, Tinian, and Saipan. The 9 northern islands are sparsely inhabited with total populations on Agrihan, Pagan, and Anatahan fluctuating from 0 to 100 persons since

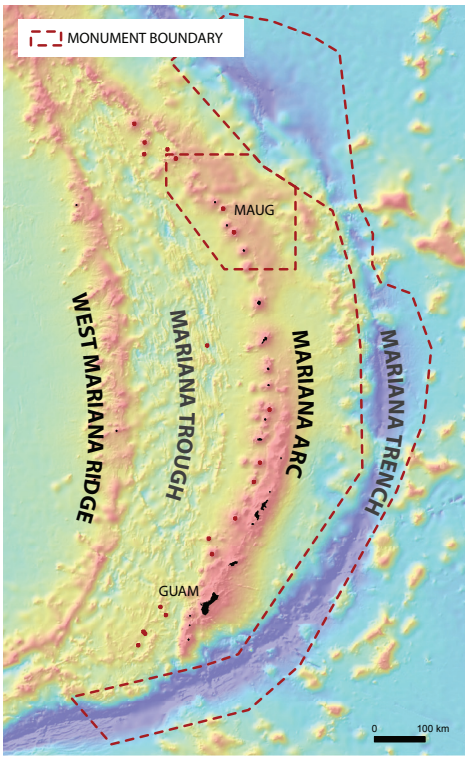


Figure 2. Topography of the Mariana Archipelago and the location of the Marianas Trench Marine National Monument. This monument consists of the Mariana Trench, the 3 northernmost islands of the Mariana Arc, and volcanic features (see red dots) between the Mariana Trough and Arc.

World War II. While land cover on the southern islands is primarily influenced by population density, land cover on the northern islands is influenced by the shape and activity of volcanoes. Beyond population density and volcanic activity, a major determinant of land cover on all the islands is the presence of feral animals introduced by previous and present human inhabitants. On almost all islands of the Mariana Archipelago, introduced feral goats, pigs, deer, and cows destroy or alter native understory vegetation—typically causing an increase in erosion and, thus, sedimentation and runoff into nearshore waters that could have significant impacts on coral reef ecosystems. Only Farallon de Pajaros is thought to have no introduced feral animals at this time (Table 1). Because of their isolated location and lack of inhabitants, the 3 islands within the Marianas Trench Marine National Monument have relatively few direct pressures from human activities.

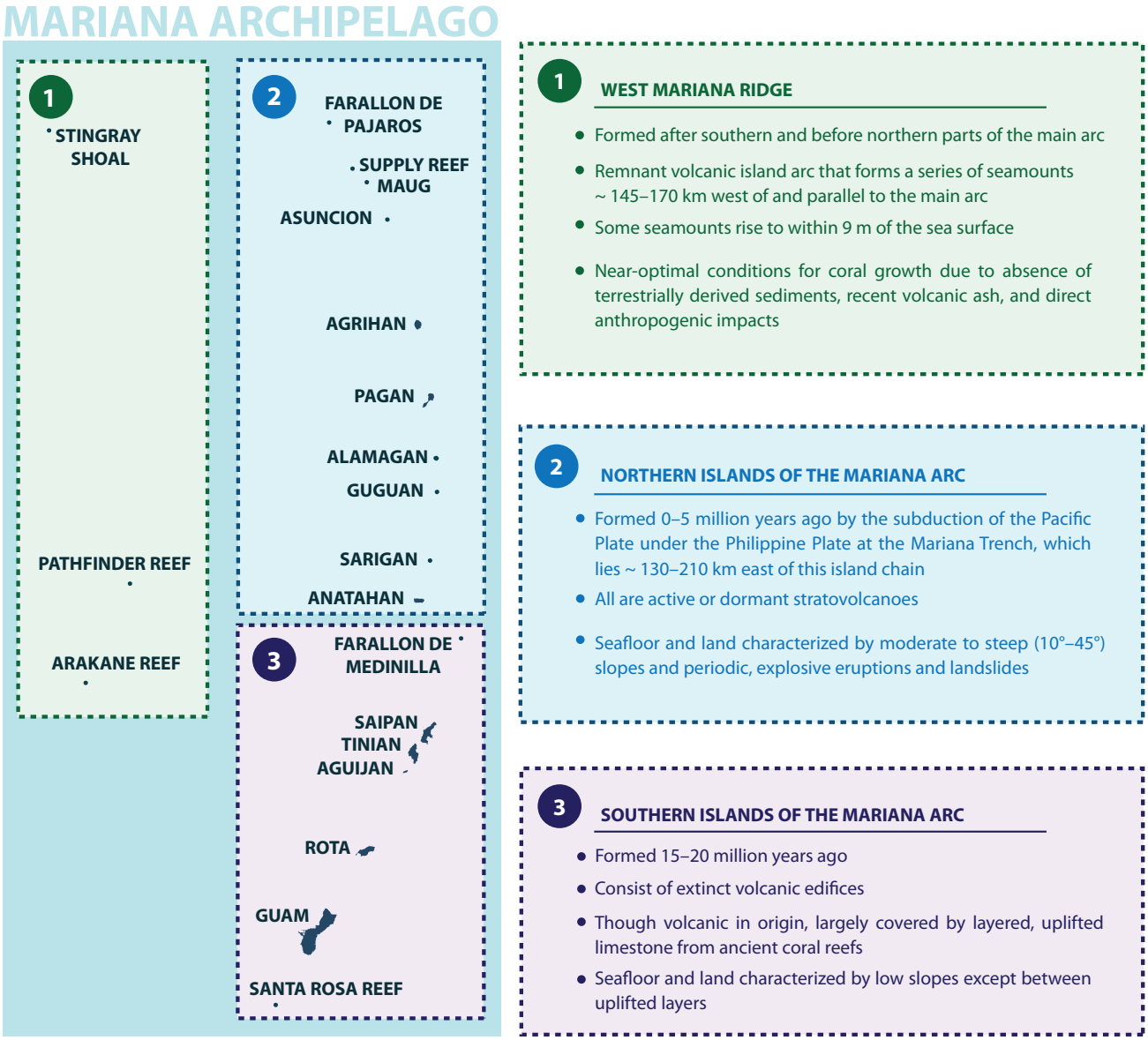
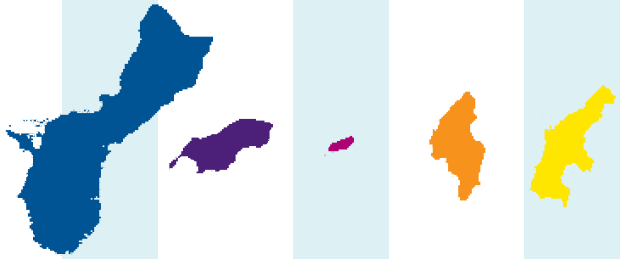


Figure 3. The islands and reefs of the Mariana Archipelago can be grouped into 3 main geologic groups, shown here with information about their characteristics.

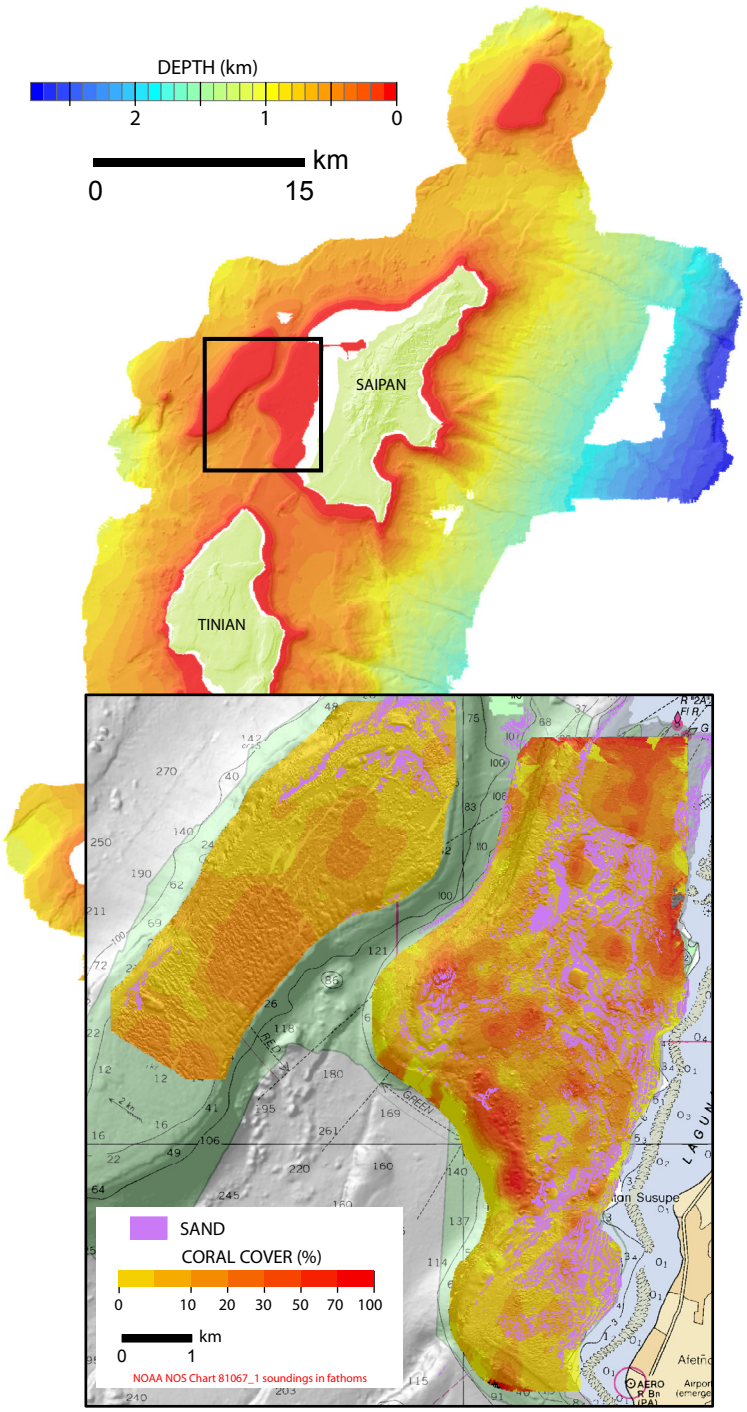
Table 1 (*opposite page*). Summary table of island parameters across the Mariana Archipelago: land area, proportion of archipelagic population, population density, year of last volcanic eruption, and animal threats. Land areas were calculated using geographic-information-system (GIS) techniques. See List of Abbreviations for island codes. Asterisk (*) indicates eraticated animals. Sources: U.S. Bureau of the Census, Smithsonian Institution, U.S. Geological Survey, CNMI Division of Fish and Wildlife, and Pacific Biodiversity Information Forum.

	SOUTHERN					NORTHERN								
ISLAND CODE	GUA	ROT	AGU	TIN	SAI	ANA	SAR	GUG	ALA	PAG	AGR	ASC	MAU	FDP
SHAPE & RELATIVE SIZE														
AREA (km^2)	544.34	85.13	7.01	101.22	118.98	33.91	4.46	4.24	12.96	47.75	44.05	7.86	2.14	2.25
SHARE OF ARCH. POPULATION (% IN 2000)	74.7	1.2	0	1.5	22.6	0	0	0	0	0	0	0	0	0
POPULATION DENSITY (PERSONS/km^2)	292.8	29.7	0	31.0	405.3	0	0	0	0	0	0	0	0	0
YEAR OF LAST ERUPTION	—	—	—	—	—	2008	—	1883	870	2010	1917	1906	—	1967
TREE SNAKES	✓	✓		✓	✓									
CATS	✓	✓		✓	✓		✓		✓					
CATTLE	✓	✓		✓	✓					✓				
GOATS	✓	✓	✓	✓	✓	✓	✓*		✓	✓	✓		✓	
PIGS	✓	✓		✓	✓	✓	✓		✓	✓	✓			
RATS	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	

MESOPHOTIC CORAL REEFS

Bathymetric and optical mapping have revealed extensive and dense coral reefs at depths > 30 m in numerous locations in the Pacific. Although few optical surveys have been carried out in such relatively deep areas in the Mariana Archipelago, those surveys that have been conducted have revealed light-dependent scleractinian (hard) corals. For example, a detailed survey carried out in 2004 at the Garapan Anchorage off Saipan revealed large expanses of corals in the mesophotic range (30–150 m) with reefs predominantly formed by *Euphyllia paraancora*, a hard coral species that was included in a recent petition to list 83 corals under the *Endangered Species Act*. The highest average live coral cover from this study was observed in the depth range of 61–70 m with cover values > 33%. These results highlight the importance of monitoring at the full range of depths (0–150 m) in which coral communities may be present. More widespread surveys at these depths could define the extent of mesophotic reefs in this archipelago.

Right: Bathymetric and optical data collected by CRED in 2003 and 2004 were used to create a coral- and sand-cover map of the Garapan Anchorage and to aid management agencies in making decisions related to a proposed expansion of this anchorage into potentially coral-rich areas.





METHODS OVERVIEW

Above: CRED diver conducting a REA survey for coral disease. *NOAA photo by Russell Moffitt*

SUMMARY OF METHODS

BIOLOGICAL	TOWED DIVER - broad surveys of benthic and fish communities
	REA - detailed view of benthic and fish community structure
	TOAD - optical validation and habitat characterization
PHYSICAL/ CHEMICAL	MOORED INSTRUMENTS - collect continuous oceanographic data
	CTD CASTS - measure conductivity, temperature, and depth
	WATER SAMPLES - measure nutrients and Chl-*a*
MAPPING	MULTIBEAM SONAR - bathymetry, habitat characterization

CRED conducted its first Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) cruise in 2003, with subsequent cruises in 2005, 2007, 2009, and 2011. Partners from Guam (Division of Aquatic and Wildlife Resources, Bureau of Statistics and Plans, Guam Environmental Protection Agency, and University of Guam) and the CNMI (Department of Environmental Quality, Department of Fish and Wildlife, and Coastal Resources Management) worked alongside CRED scientists to develop and implement a comprehensive monitoring program. Extensive biological, physical, and chemical surveys were conducted to document the conditions of and processes influencing the coral reef ecosystems around the islands of the Mariana Archipelago. Benthic habitat mapping data were collected using multibeam sonar surveys. Spatial and temporal observations of key oceanographic and water-quality parameters were collected using (1) a diverse suite of moored instruments designed for long-term observations; (2) closely spaced conductivity, temperature, and depth profiles of the vertical structure of water properties; and (3) discrete water samples for nutrient and chlorophyll-a analyses. Information on the condition, abundance, diversity, and distribution of biological communities around islands and on offshore reefs was collected using Rapid Ecological Assessment (REA), towed-diver, and towed optical assessment device (TOAD) surveys (Figs. 4 and 5). Towed-diver surveys, conducted on the forereef slopes of islands and banks loosely following the depth contour of ~ 15 m and encompassing various substrates, generate a broad overview of substrate types and associated large-fish and benthic communities. REA surveys, carried out at selected forereef locations at islands or banks at similar depths, produce more detailed, site-specific information on fishes of all sizes and community structure of hard substrate. TOAD surveys and a subset of towed-diver-survey data were used for optical validation and habitat characterization, documenting cover of live scleractinian (hard) corals, sand cover, and habitat complexity.

To compare the coral reef ecosystems across the Mariana Archipelago, CRED developed 3 composite metrics based on towed-diver visual observations from 2005 and 2007 (Fig. 6). The overall *Coral Reef Condition Index* has equally weighted benthic and fish components. The *Benthic Condition Index* was calculated using data for live coral cover, stressed-coral

cover, crustose-coralline-red-algal cover, macroalgal cover, and density of crown-of-thorns seastars (*Acanthaster planci*). The *Fish Condition Index* was calculated using data for density and biomass of large fishes (≥ 50 cm in total length). These indices were calculated at 2 scales for this report: (1) archipelagic level for comparisons among 13 islands of the CNMI and Guam and (2) island scale for comparisons among only the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan. The ranks in these condition indices, for the purposes of discussion and visual representation, are grouped as high, medium, or low. A high rank means superior condition relative to (a), in the archipelagic indices, other geographic regions in the Mariana Archipelago or (b), in the island-level indices, other survey areas in the 4 populated, southern islands. The *Archipelagic Coral Reef Condition Index* is used in the next section as a basis for comparing the ecosystems around the southern islands to the ones around the northern islands. The *Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan* is used later in the discussion of the reef conditions observed around individual southern islands.

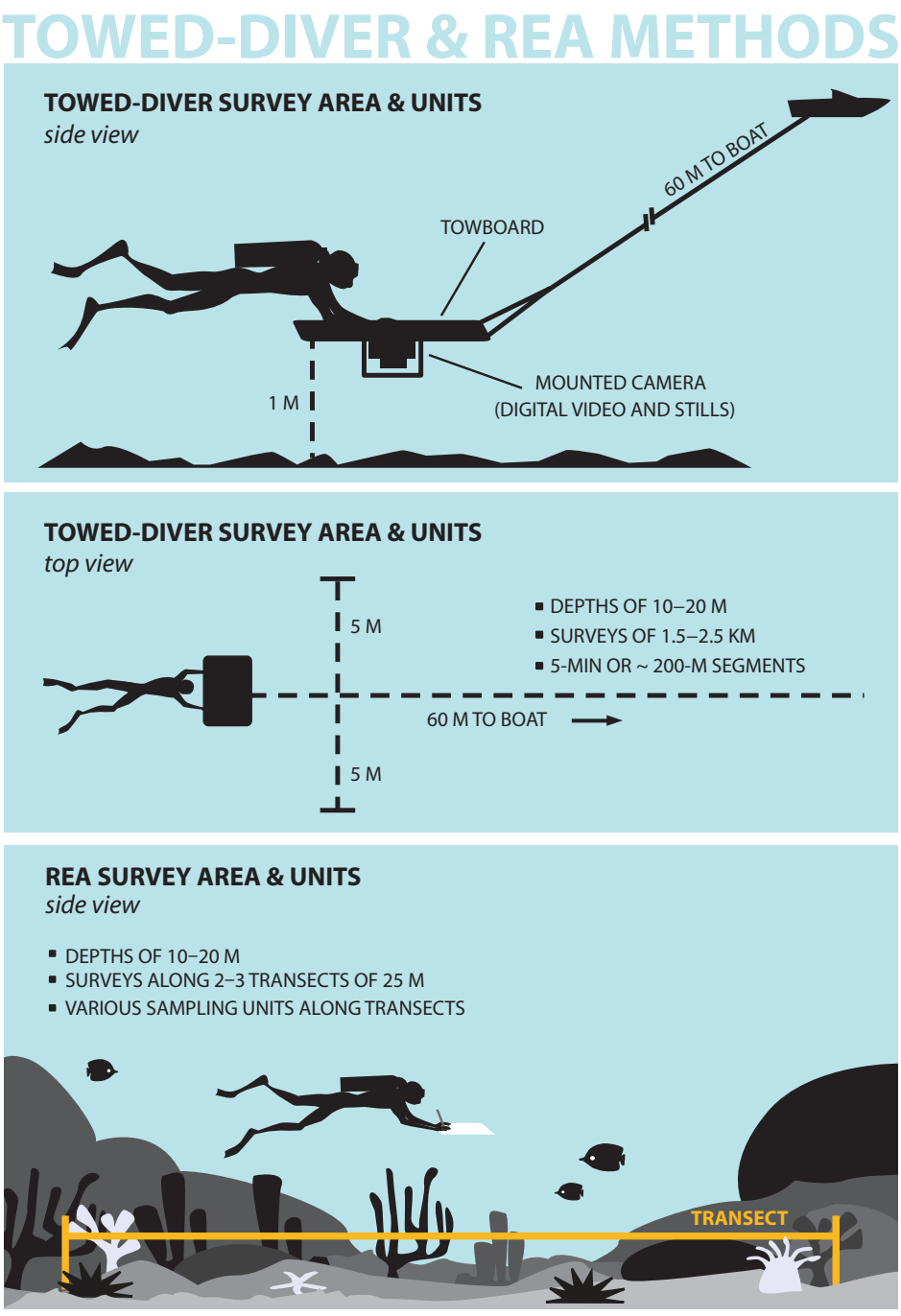


Figure 4. Schematic diagrams of (*top & middle*) 1 of 2 divers conducting a towed-diver survey, and (*bottom right*) a diver conducting a REA survey along a 25-m transect line.

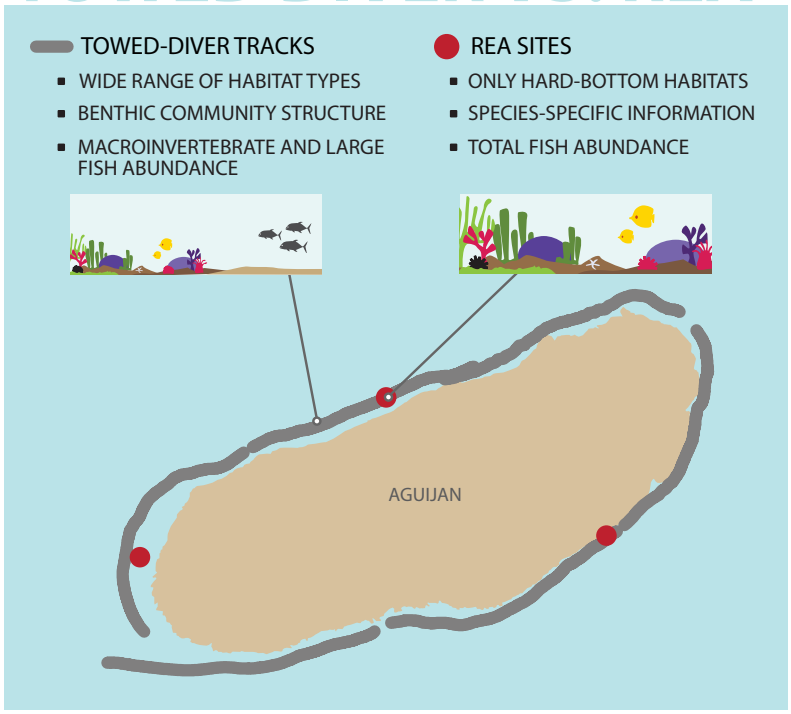


Figure 5. Diagram of the main differences between towed-diver surveys and Rapid Ecological Assessment (REA) surveys,

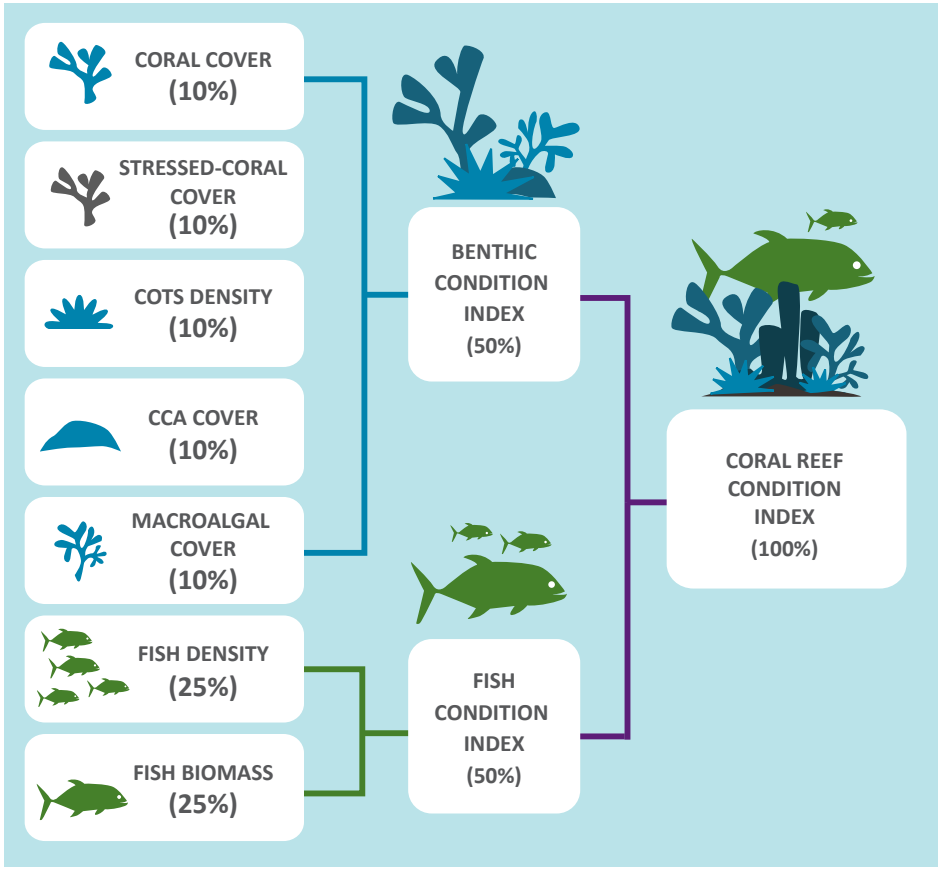
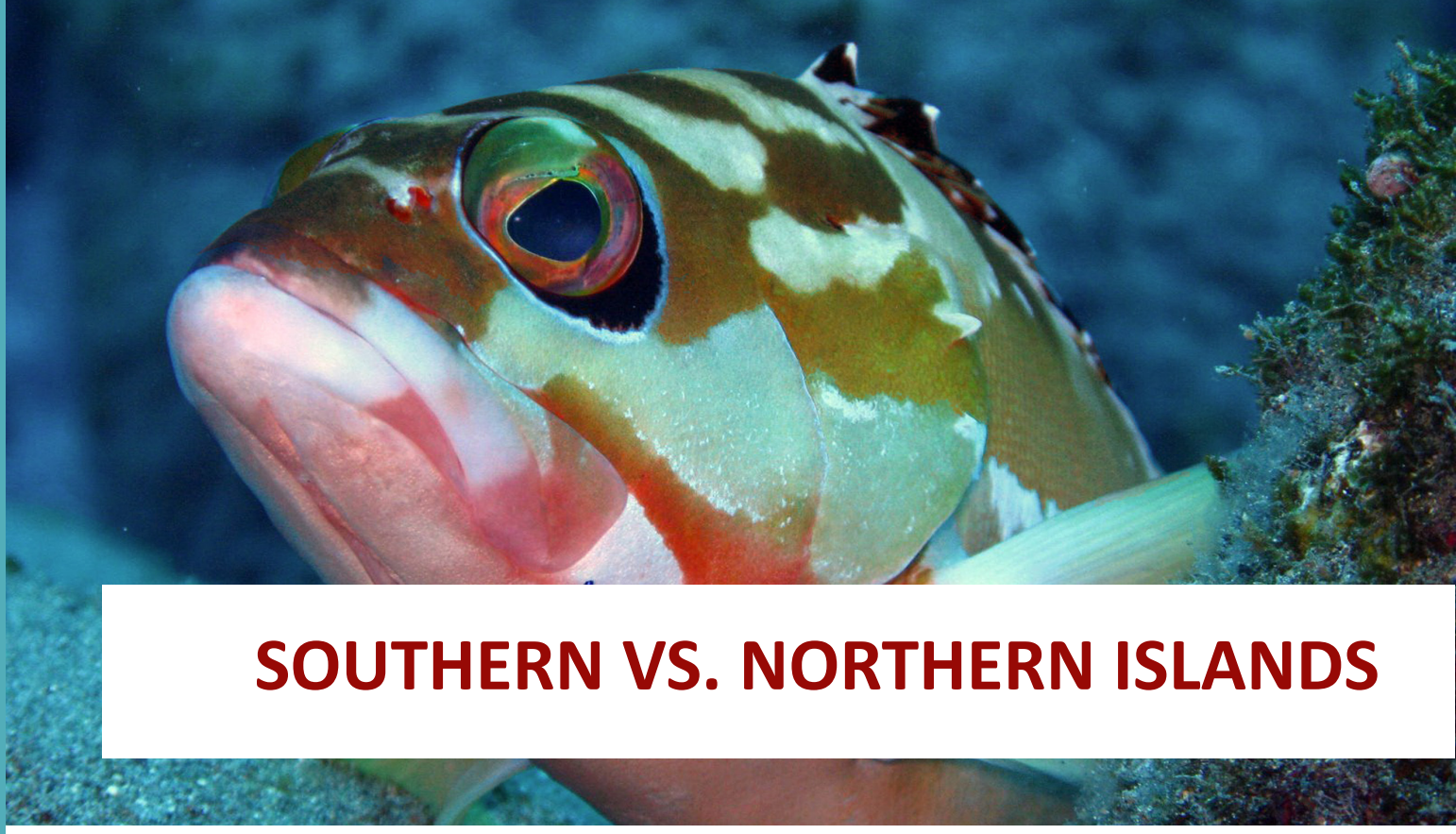


Figure 6. Conceptual diagram of the calculation of the 3 condition indices, which are based on data from towed-diver surveys conducted on forereef habitats during MARAMP cruises in 2005 and 2007. CCA stands for crustose coralline red algae and COTS for crown-of-thorns seastar.



SOUTHERN VS. NORTHERN ISLANDS

Above: A blacktip grouper (*Epinephelus fasciatus*). *NOAA photo by Chip Young*

Differences in the geologic histories of these islands, which result in large differences in land area and slope, have been identified as a major factor shaping the coral reef ecosystems of the Mariana Archipelago (Burdick et al. 2008; Houk and Van Woesik 2010; Riegl et al. 2008). The 6 southern islands are, in general, significantly larger than the northern islands and have uplifted calcium carbonate terraces with mostly low slopes (0°–10°) both onshore and offshore, resulting in a substantial amount of total potential reef area. In contrast, the 9 small, northern islands are active or dormant volcanoes with steep onshore and offshore slopes, narrow ridges, and few offshore terraces, resulting in total potential reef areas that are much smaller relative to the southern islands (Fig. 7). Other factors likely influencing coral reef conditions include the anthropogenic stressors of coastal sedimentation and pollution, fishing pressure, and land use that in the populated, southern islands are associated with increasing population, tourism, and development. In the northern, largely uninhabited islands, the frequency, duration, and magnitude of active volcanism can severely affect coral reef ecosystems.

MARAMP surveys found differences in several key oceanographic indicators between the southern and northern islands. The north–south orientation of the Mariana Archipelago results in latitudinal gradients in sea-surface temperatures (SST), wind conditions, currents, and chlorophyll-*a* (Chl-*a*) and nutrient concentrations across this archipelago. The southern islands exhibited warmer SSTs, stronger wind conditions and surface currents, lower salinities, and less productive waters (Fig. 8). Additionally, episodic volcanic eruptions, ash discharge, and landslides on the northern islands can significantly modify the quality and chemistry of surrounding coastal waters over short (days to weeks) and medium (months to years) time frames. As a result of such natural and human-induced coastal processes, the nearshore waters around the southern islands exhibited considerable spatial and temporal variability in water-quality parameters, including inorganic nitrogen and Chl-*a*, particularly around Guam.

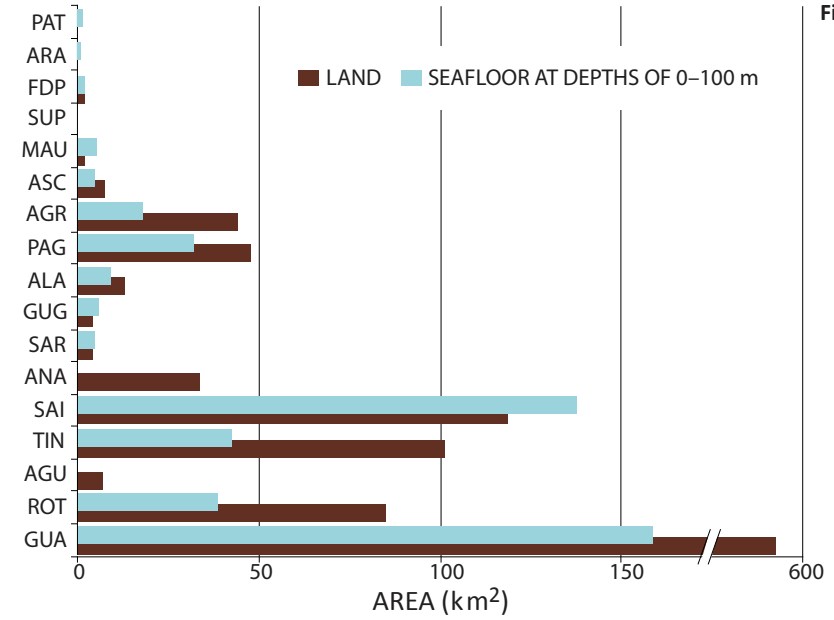


Figure 7. Land and potential reef area per island.

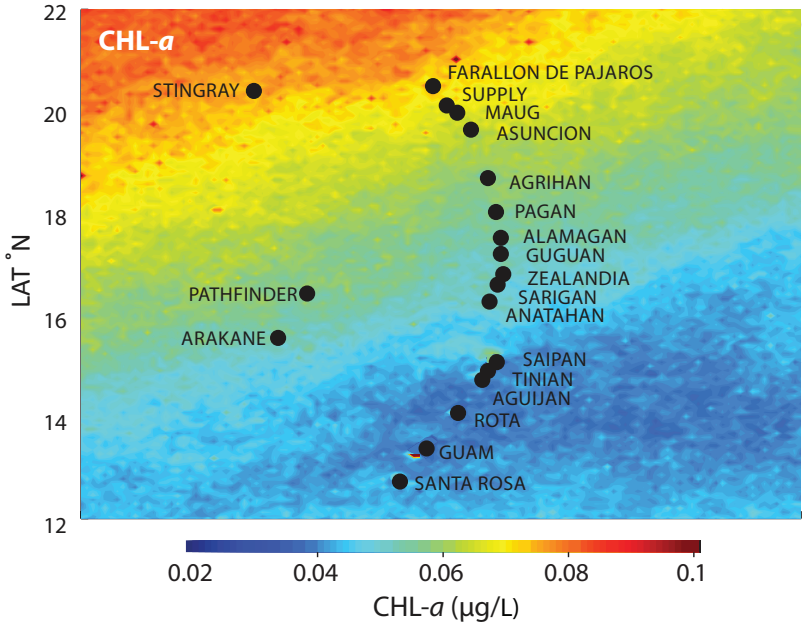


Figure 8. Latitudinal gradients of seasonal Chl-*a* concentrations in the Mariana Archipelago for January–March using National Aeronautics and Space Administration SeaWiFS imagery (12°–22° N, 140°–150° E; http://oceancolor.gsfc.nasa.gov/SeaWiFS).

BLEACHING AND STORM EVENTSTS AROUND GUAM

Corals bleach when the ocean temperature increases 1°C–2°C above the maximum monthly mean for ocean temperatures in their area. Satellite-derived sea-surface temperatures (SST) and in situ observations from subsurface temperature recorders (STRs) deployed around Guam show that water temperatures reached a maximum (29.5°C) in late August or September and a minimum (27.1°C) in February. These SST and STR data show that water temperatures around Guam in August and September 2006 surpassed the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean. David Burdick of the Guam Coastal Management Program reported field observations of bleaching occurring among numerous species at several sites around Guam to a depth of 7 m (Burdick et al. 2008). Follow-up observations in October 2006 showed that some coral species had recovered whereas others exhibited partial to full mortality (Brown 2007). MARAMP data show that estimates of coral cover were lower in 2007 than in 2005 from both towed-diver and REA surveys.

Relief from temperature increases that can cause bleaching sometimes comes from storms, since they typically mix cool, deep waters with warmer, shallow waters. The waters around Guam are dominated by trade wind swells, characterized by frequent (6–10 s), relatively small waves (2–3 m), originating from the east. Typhoons are a common occurrence around Guam and generate large (> 4 m), mid-to-long-period (10–16 s) wave events, generally from the southeast (110º) and typically between August and December. Infrequent long-period swells with moderate wave heights (2.5–3.5 m) occur from the west-southwest and are associated with distant storms. While several tropical cyclones have passed close enough to Guam to influence its weather since 2003, the only large wave event (> 4 m) observed during the period of 2003–2007 occurred during the summer of 2004 with the passages of Typhoons Tingting and Chaba. Damage from these wave events did not appear to be extensive.

Below: Partially bleached *Acropora* coral near Guam. *Photo by Dave Burdick (www.guamreeflife.com)*



BENTHIC COMPOSITION AND DIVERSITY

Based on towed-diver surveys of forereef habitats for each of the 3 MARAMP cruises in 2003, 2005, and 2007, estimates of mean macroalgal cover generally were higher and estimates of mean coral cover were lower around the southern islands than around the northern islands (Fig. 9). These differences in ecosystem conditions for the southern islands may result from differences in human impacts (for example, variation in levels of nutrient input and harvest of herbivorous fishes). It is important to note, however, that macroalgae are a normal and necessary part of reef ecosystems. The southern carbonate islands may naturally experience conditions that promote higher macroalgal growth than the growth seen in the northern, volcanic islands. Without a sufficient number of time-series observations, it is difficult to conclude that macroalgal populations are increasing or coral populations are decreasing around the southern islands, thus, underscoring the importance of the kind of long-term monitoring conducted by CRED.

Data from towed-diver surveys conducted on forereef habitats in 2005 and 2007 are integrated in the *Archipelagic Benthic Condition Index* by geographic region in the Mariana Archipelago. Based on these analyses, the benthic condition was generally better in the northern islands compared to the southern islands (Fig. 15). Ranks in this index indicate that the benthic conditions for Maug, Alamagan, Guguan, and Sarigan were superior to the conditions for other islands in the Mariana Archipelago, a result of high or increasing coral cover, low stressed-coral cover, and low densities of crown-of-thorns seastars (COTS). Index ranks for the southern islands of Saipan, Tinian, Aguijan, Rota, and Guam were low in or decreasing between 2005 and 2007, except for a few geographic regions of Tinian and Saipan and the north coast of Aguijan. The low ranks for these 5 islands in this condition index resulted from relatively high levels of stressed-coral cover and macroalgal cover and low levels of coral cover. Particularly around Rota, some of the lowest coral-cover values in the Mariana Archipelago were observed (Fig. 9). Around the southern islands, compared to the northern islands, the occurrence of bleaching and coral disease was higher and COTS densities were found more often at levels of a potential outbreak.

REA benthic surveys of hard-bottom habitats conducted in 2007 found that mean coral cover was moderate and similar around all southern islands. Conversely, around the young, sparsely inhabited or uninhabited, volcanic northern islands, coral cover was more variable, and both the highest and the lowest levels in the Mariana Archipelago were recorded there, with overall mean coral cover of 34.1% (SE 5.7) at Maug and 3.6% (SE 0.7) at Farallon de Pajaros (SE stands for standard error of the mean). Macroalgal-cover estimates from REA surveys reveal a clear spatial pattern with high algal cover in the southern islands compared to the northern islands (Fig. 9).

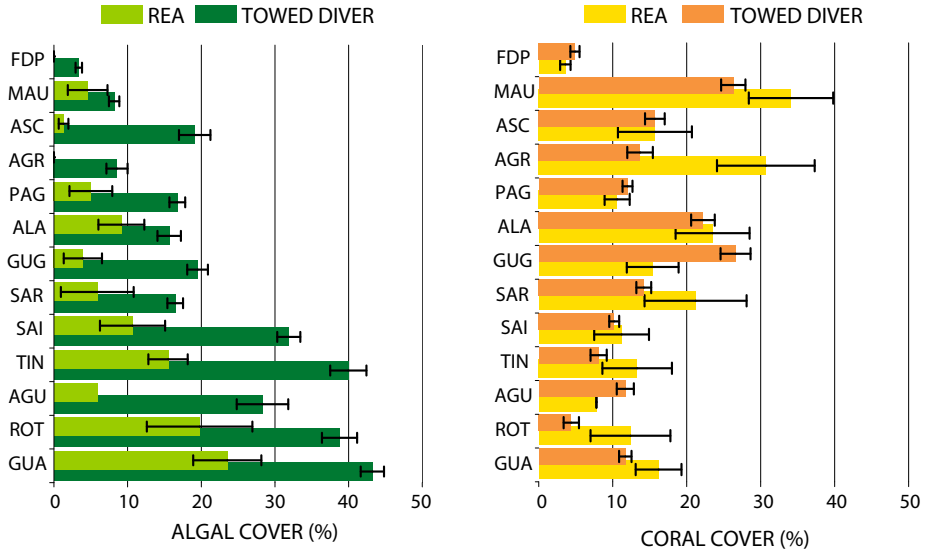


Figure 9. Comparisons of mean (left) algal cover (%) and (right) coral cover (%) from REA and towed-diver surveys of forereef habitats conducted in the Mariana Archipelago in 2007. Error bars indicate standard error (± 1 SE) of the mean.

The diversity of benthic communities, measured as mean richness of coral genera and of macroalgal genera per island, was greater in the southern islands than in the northern islands (richness was computed as the maximum number of coral genera or macroalgal genera recorded at a REA site). This difference is probably a result of the southern islands having greater potential habitat areas at shallow-water depths of < 100 m, compared to the northern islands (Fig. 7). These large areas in the southern islands support a wider range of habitat types and oceanographic conditions that result in a greater number of niche environments. The notion that the size of islands and disturbance frequency (predominantly volcanic activity) are likely predictors of taxonomic richness (Houk and Starmer 2010) is supported by data from MARAMP surveys (Tribollet and Vroom 2007). The greatest overall mean generic richness of corals for an island was recorded around Saipan (17.3 [SE

1.1]), and the highest overall mean generic richness of macoalgae was observed around Rota (13.1 [SE 0.74]) and Guam (13 [SE 0.68]). In this context, some coral and algal taxa were restricted to or particularly widespread around the southern islands, including the hard corals *Diploastrea, Plesiastrea, Alveopora,* and *Coscinaraea* and the red algae *Amansia, Crouania, Gelidiella, Haloplegma, Halymenia,* and *Predaea*. The lowest diversity was found around Farallon de Pajaros with a mean richness of 7.6 (SE 1.4) for coral genera and a mean richness of 6 (SE 0.47) for macroalgal genera. Farallon de Pajaros has a land area of a mere 2.3 km² and experienced frequent volcanic activity during the 19th century and recurrent eruptions from the 1940s to the 1960s.

CROWN-OF-THORNS SEASTAR DENSITIES

With the exception of Pagan, the northern islands had low islandwide mean densities of crown-of-thorns seastars (COTS). These corallivorous seastars oscillate in a boom-and-bust population cycle with natural fluctuations in food availability and successful recruitment events. Using a threshold of 0.15 organisms/100 m², towed-diver surveys of forereef habitats in 2005 recorded potential outbreaks at Pagan with a mean islandwide COTS density of 0.24 organisms/100 m², the greatest density value recorded for any island in the Mariana Archipelago. This high COTS density may have caused the observed decline in coral cover from 19% (SE 0.8) in 2003 to 10% (SE 0.8) in 2005. By 2007, COTS densities had decreased threefold at Pagan, and coral cover appeared to be recovering slightly with an islandwide mean of 12% (SE 0.7). At all of the southern islands, with the exception of Tinian, localized outbreaks were observed during towed-diver surveys in 2003 and 2005. By 2007, however, COTS populations declined sharply around all of these islands except Guam. There, the islandwide mean density almost doubled from 0.1 organisms/100 m² (SE 0.03) in 2005 to 0.16 organisms/100 m² (SE 0.03) in 2007, with the highest densities recorded along the south and east coasts of Guam (Fig. 10). Across the Mariana Archipelago in 2007, signs of predation by COTS or snails were observed on a total of 14 genera of hard corals, belonging to 7 families, with more than 96% of all scars found on members of the families Faviidae, Acroporidae, Poritidae, and Pocilloporidae. Of these coral genera, *Goniastrea, Porites,* and *Astreopora* hosted 60% of all cases. Interestingly, around the northern islands of Asuncion and Maug, colonies of *Goniastrea* hosted 50% of all scars islandwide, whereas colonies of *Astreopora, Porites, Pocillopora*, and *Stylophora* hosted more than 60% of cases around the inhabited Guam and Saipan.

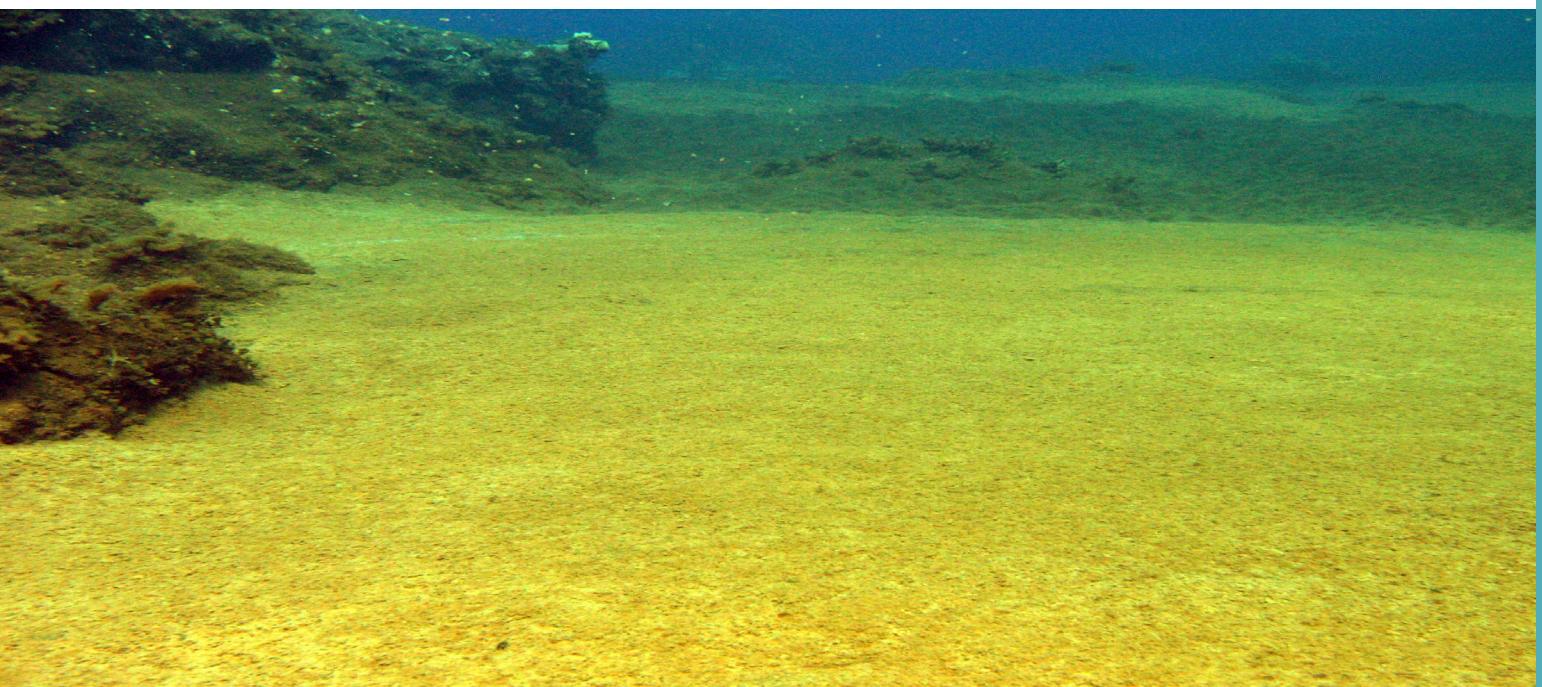


Figure 10. Densities (organisms/100 m²) of crown-of-thorns seastars (COTS) from towed-diver surveys of forereef habitats conducted around Guam in 2007.

OCEAN ACIDIFICATION AROUND MAUG

During CRED's MARAMP cruise in 2003, a hydrothermal vent system (depth of ~ 10 m and seafloor area of ~ 400 m^2) was observed within the caldera of Maug. In 2007, area-wide and near-vent water samples were collected to gain insight into the biogeochemistry of hydrothermal vents. Divers collected (1) gas bubbles for analysis of carbon dioxide (CO_2) and hydrogen sulfide concentrations; (2) water samples for dissolved inorganic carbon, total alkalinity, pH, iron, manganese, trace metals, and nutrient concentrations; and (3) water temperatures from multiple locations within and around the area of this vent system. The seafloor within this vent system was composed of boulders and sand, layered with accumulations of iron-rich, orange-tinted flocculent material. *Spatoglossum* sp. was the dominant alga within this vent system, covering every hard surface. No calcium-carbonate-producing organisms were observed within this vent system. However, a REA survey conducted only 15 m south of this vent revealed live coral cover of 67% in 2007, reaching close to 100% cover of *Porites rus* within one part of this REA site. Water temperatures were 45°C–63°C at the vent openings, 16°C–34°C above the surrounding subsurface water temperatures. Gas bubbles collected consisted of CO_2 and probably contributed to pH values of 6.07 in this vent system, much more acidic than the pH of 8.13 of surrounding waters. Calculated states of calcite and aragonite saturation of undiluted vent waters were < 1, demonstrating that these waters were highly corrosive to calcifying organisms (calcium carbonate generally dissolves in waters with saturation states of < 1). The unique temperature and pH values for this vent system clearly regulated the benthic community structure there, but they had only a very local impact on coral growth as nearby water temperatures (29°C) and pH (8.13) reflected levels typical for this region. These preliminary results provide the only known example of present day ocean acidification within a coral reef ecosystem.

Below: Vents release gas bubbles and warm water west of East Island, one of the 3 islands that make up the Maug island group. The seafloor is covered by "fluffy" orange silt. *NOAA photo by Ellen Smith*



INFORMING RESOURCE MANAGEMENT

Climate change and the anticipated expansion of the military presence on Guam are primary factors affecting coral reefs around Guam and the Commonwealth of the Northern Mariana Islands (CNMI), as outlined in the NOAA Coral Reef Conservation Program (CRCP) Management Priority Setting documents for Guam and the CNMI, along with impacts of fisheries and land-based sources of pollution, especially around populated areas.

The population of military personnel and their dependents on Guam is expected to increase 160% from 15,000 persons in 2009 to more than 39,000 by 2020—a change expected to directly affect this territory's coral reef ecosystems. Resource managers on Guam have explicitly expressed a need for baseline data, which they view as crucial to measuring the effects of the military buildup and potential mitigation activities. Continuing ecosystem monitoring, along with examination of existing data from previous CRED research activities, will provide valuable guidance for setting future priorities for coral reef management and research tied to the CRCP's National Goals and Objectives.

Since 2003, CRED has been conducting a broad range of surveys of the coral reef ecosystems around Guam, including nearshore waters adjacent to the Piti-Asan and Geus-Manell watersheds. These watersheds, which discharge into ocean areas that include the Piti Bomb Holes Marine Preserve and Achang Reef Flat Marine Preserve, along with other Pacific RAMP survey areas, such as the Tumon Bay and Pati Point Marine Preserves, have been identified as priority management sites by the CRCP and local Guam resource management agencies.

Similarly, Pacific RAMP surveys have been conducted in priority management sites and marine protected areas around the more populated areas of the CNMI, including around Saipan, the Bahia Laolao Sea Cucumber Reserve, Managaha Marine Conservation Area, Lighthouse Reef Trochus Reserve, Bird Island Marine Sanctuary, and Forbidden Island Marine Sanctuary; at Rota, the Sasanhaya Fish Reserve and Talakhaya Watershed Revegetation Area; and a marine reserve designated on the southwest coast of Tinian.

CRED will continue to monitor these and other areas through the Pacific RAMP and other collaborative opportunities. Improved techniques implemented in 2009 will yield enhanced data about nearshore fish communities, data that are important in developing stock assessments and annual catch limits for commercially important reef-fish species. In 2009, CRED performed some limited studies and established a permanent benthic Rapid Ecological Assessment site within Apra Harbor. In 2010, a PIFSC-led fisheries cruise in this archipelago focused on filling gaps in mapping data and improving studies of coral reef fishes. These projects were designed to respond to questions, interests, and information gaps presented by local scientists, managers, and fisheries groups in the CNMI and Guam.

To find out more about the information available from CRED or to make suggestions for future research and outreach activities, please contact CRED at nmfs.pic.credinfo@noaa.gov.

Below: School of breams (*Gnathodentex aureolineatus*). *Photo by Dave Burdick (www.guamreeflife.com*)



FISH BIOMASS AND DIVERSITY

The *Archipelagic Fish Condition Index*, based on towed-diver surveys, demonstrates a north–south pattern of ranks declining from high to low (Fig. 15). The highest values of biomass of large fishes (≥ 50 cm in total length), calculated as weight per unit area, in the Mariana Archipelago were observed around Farallon de Pajaros and Asuncion in 2005 and 2007. Around the southern islands, where human populations and exposure to anthropogenic stressors are greater than in the northern islands, towed-diver surveys of forereef habitats recorded generally lower levels of large-fish biomass in 2005 and 2007, compared to the northern islands, or decreasing values between these survey years. Observations from these surveys of large fishes (Fig. 11) were dominated by jacks and sharks, both piscivores (fishes that prey primarily on other fishes), with mean large-fish biomass estimates more than 4 times higher around the northern islands than around the southern islands: 0.92 kg/100 m^2 (SE 0.18) versus 0.22 kg/100 m^2 (SE 0.04). The density of sharks encountered during towed-diver surveys was nearly 10 times higher around the northern islands than around the southern islands: 174.5 individuals/km^2 versus 17.6 individuals/km^2.

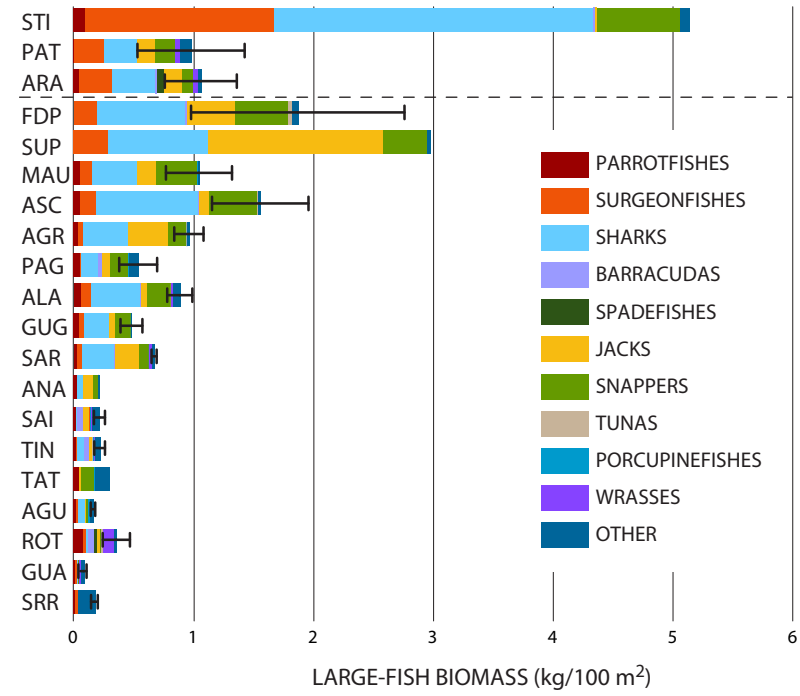


Figure 11. Estimates of islandwide mean biomass (kg/100 m^2) of large fishes (≥ 50 cm in total length) based on pooled data from the 3 MARAMP cruises in 2003, 2005, and 2007. Large-fish biomass is derived from towed-diver surveys of forereef habitats and divided into taxonomic family groups. The dotted line distinguishes the West Mariana Ridge from the Mariana Arc. Error bars indicate standard error (± 1 SE) of the mean.

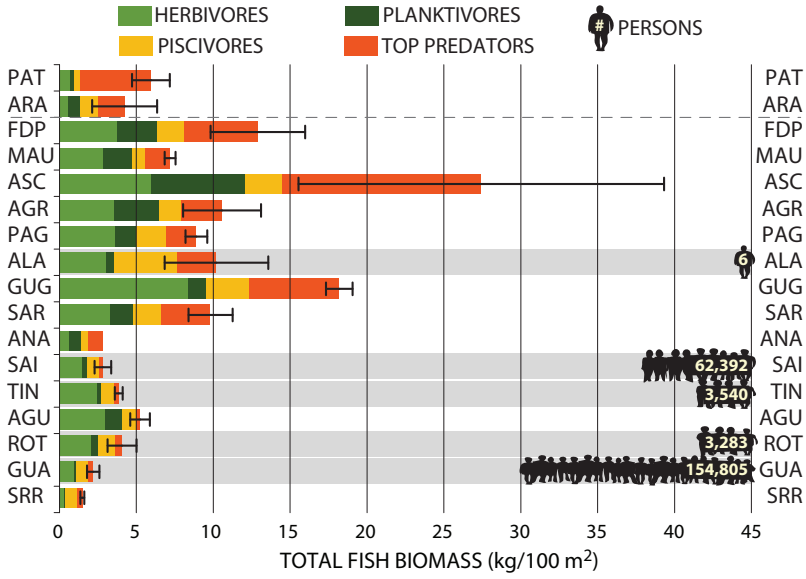


Figure 12. Estimates of (right axis) human population from the U.S. Census 2000 (not to scale) and (left axis) mean total fish biomass (kg/100 m^2). Values of total fish biomass from REA fish surveys were pooled from the 3 MARAMP cruises in 2003, 2005, and 2007 and divided into 4 trophic groups. The dotted line distinguishes the West Mariana Ridge from the Mariana Arc. Error bars indicate standard error (± 1 SE) of the mean.

Site-specific results from REA surveys that included all fishes of all sizes indicate that the overall mean total fish biomass for the 9 northern islands was more than 3 times higher than the total fish biomass for the 5 surveyed southern islands: 12 kg/100 m^2 (SE 2.37) versus 3.63 kg/100 m^2 (SE 0.53). Biomass values from REA fish surveys were higher around the northern islands for all trophic groups, but these south–north differences were greatest for piscivores (Fig. 12), for which mean total fish biomass around the northern islands with 4.04 kg/100 m^2 (SE 1.38) was more than 13 times the value recorded around the southern islands with 0.30 kg/100 m^2 (SE 0.03). Fish assemblages at the southern islands were dominated by herbivores (54% of total biomass), including surgeonfishes and parrotfishes. These patterns in total fish biomass and trophic composition are consistent with the patterns found along anthropogenic gradients in other archipelagoes in the central Pacific (Williams et al. 2008; Stevenson et al. 2007; Friedlander et al. 2008; Friedlander and DeMartini 2002).

Levels of species richness, measured as the number of fish species encountered per 100 m^2, were averaged across the 3 survey years of 2003, 2005, and 2007. Species richness was higher at all northern islands with a range of 30.6–43.6 spe-

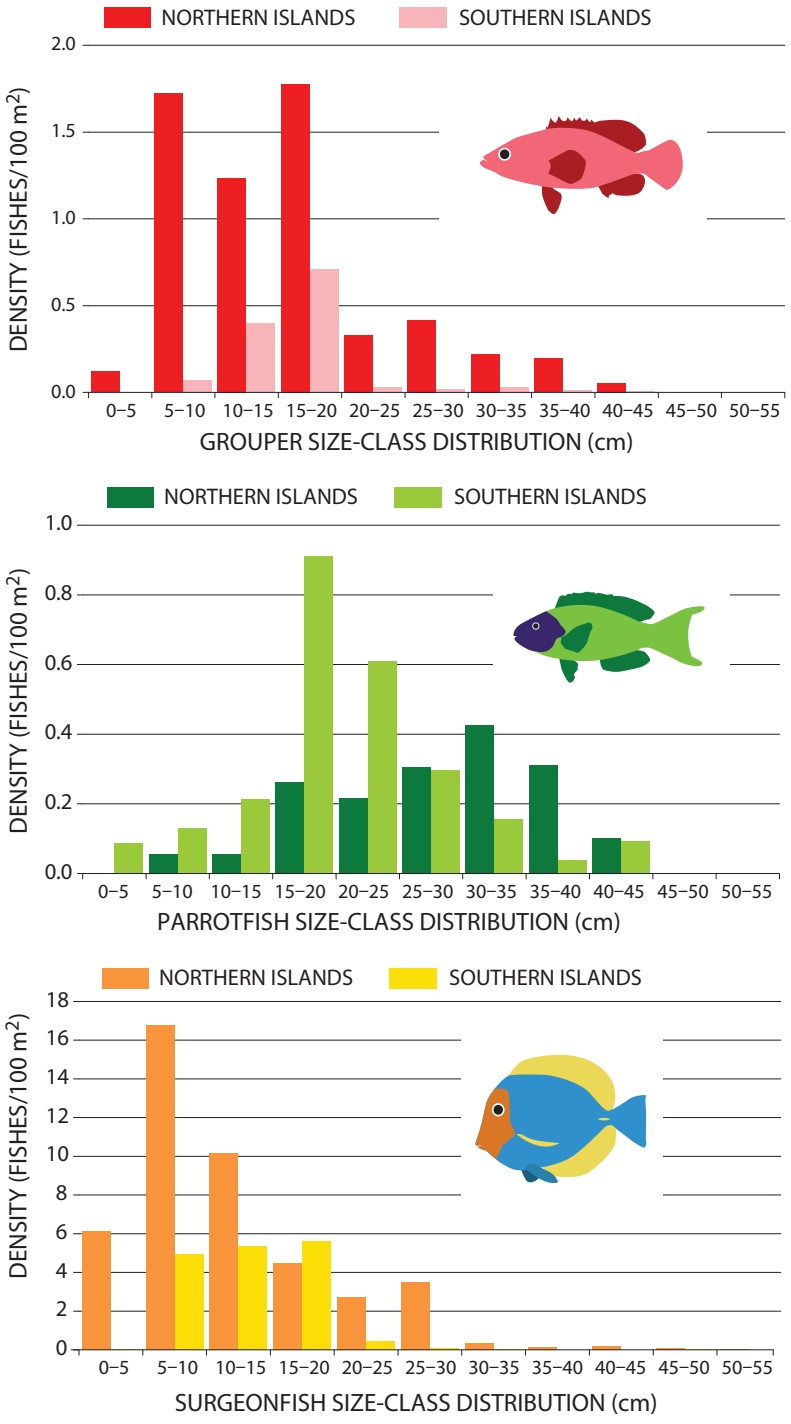


Figure 13. Size-class distribution (length in cm) for (*top*) groupers, (*middle*) parrotfishes, and (*bottom*) surgeonfishes from REA fish surveys conducted in 2007 on forereef habitats around the northern and southern islands of the Mariana Archipelago.

cies/100 m^2, except for Anatahan with 14.1 species/100 m^2, than at any of the southern islands with a range of 20.2–30 species/100 m^2. The low species richness and biomass around Anatahan was likely a consequence, at least partially, of the low visibility encountered as a result of ash and debris in the water column from volcanic eruptions in 2003 and may also reflect low sampling effort there (just 3 REA sites were surveyed there during the MARAMP cruise in 2003).

Observations of size-class distribution for 3 families of fishes from REA surveys show that densities of large size classes were higher in the northern islands of the Mariana Archipelago than in the southern islands (Fig. 13). Groupers of all size classes were more abundant in the northern islands. Large size classes (≥ 25 cm) were commonly encountered in the northern islands, but these size classes were rare in the southern islands. Parrotfishes displayed more of a bimodal distribution with large individuals more common in the northern islands and small individuals more common in the southern islands. While the surgeonfish community was dominated by small size classes, its overall size range was greater around the northern islands, where densities were higher in all but the size class of 15–20 cm.

INTEGRATED ECOSYSTEM COMPONENTS

The Archipelagic Coral Reef Condition Index provides a simple tool to compare the general conditions of coral reef ecosystems across the Mariana Archipelago. This index illustrates striking differences in the conditions of both benthic and fish communities: conditions become lower moving from the northern islands to the southern islands (Figs. 14 and 15). These spatial patterns coincide with gradients in several potential causative factors, including human population, latitude, and geologic age and structure. A comparison of the 2005 and 2007 ranks for geographic regions in the Archipelagic Coral Reef Condition Index demonstrates that the index ranks (high, medium, or low) for about two-thirds of the geographic regions in this archipelago did not change between years. The other one-third of geographic regions, then, are identified as areas of change by the shift in their index ranks between years. With continued long-term monitoring, and additional years of data beyond 2005 and 2007, changes illustrated with these condition indices will reveal ecologically relevant patterns.

This analysis of MARAMP survey data shows that our observations are in agreement with other studies that suggest higher levels of macroalgal cover, lower fish biomass, smaller fish sizes, and lower percentage of coral cover are likely to occur in association with high densities of human population and high use of resources. In addition, the overall abundance of marine debris was greater around the southern islands compared to the rest of the Mariana Archipelago, with the greatest number of sightings of derelict fishing gear and other man-made objects, such as anchors, ground tackle, mooring blocks, and metal scrap, found around Guam and Tinian.

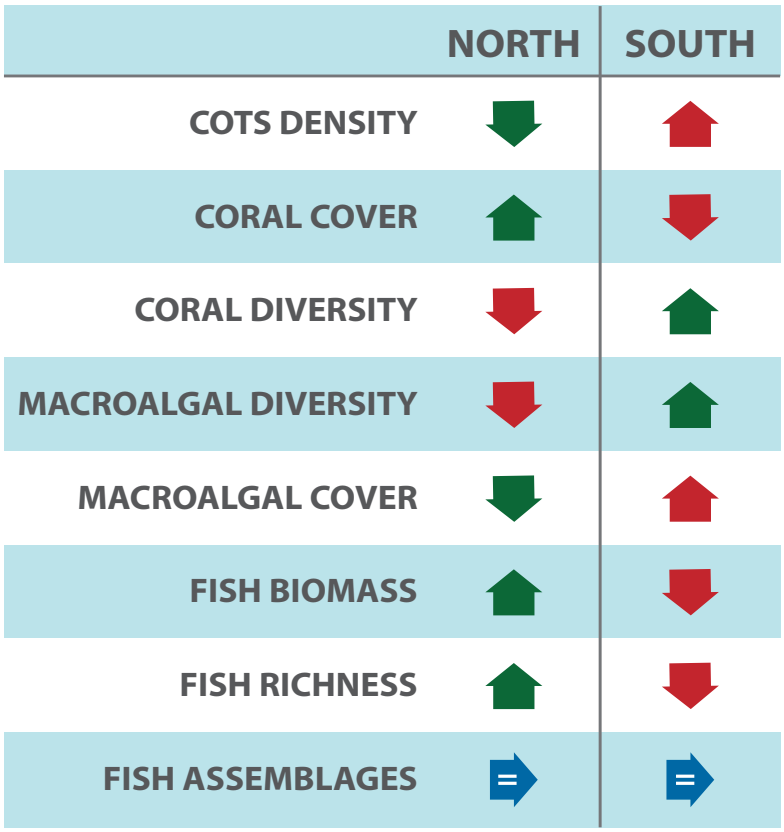


Figure 14. General comparison of parameters between the 9 northern islands and 5 southern islands. A green arrow indicates superior condition, a red arrow represents inferior condition, and the direction of an arrow shows whether a condition was higher or lower relative to the other island group. The blue arrows indicate that conditions were similar.

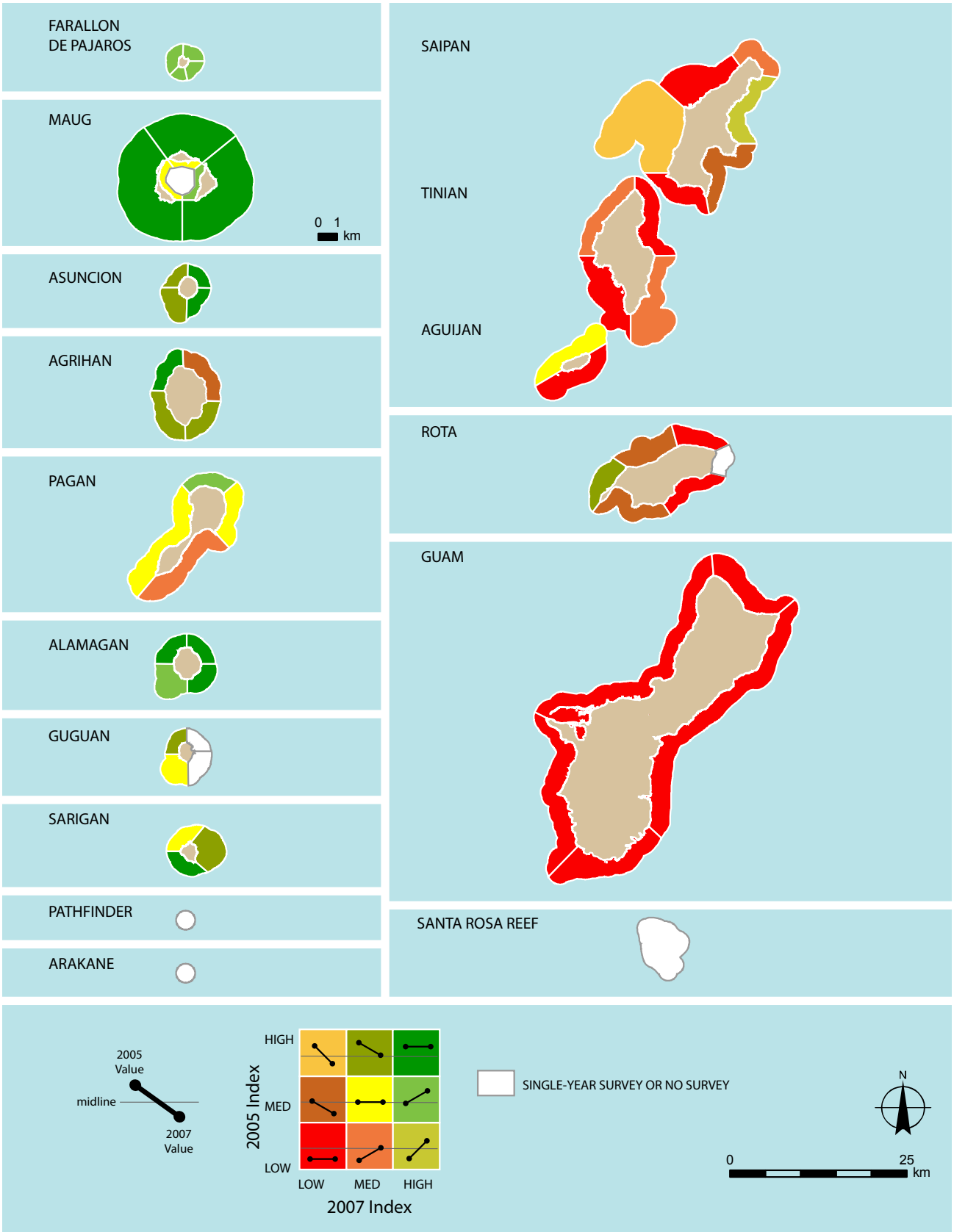
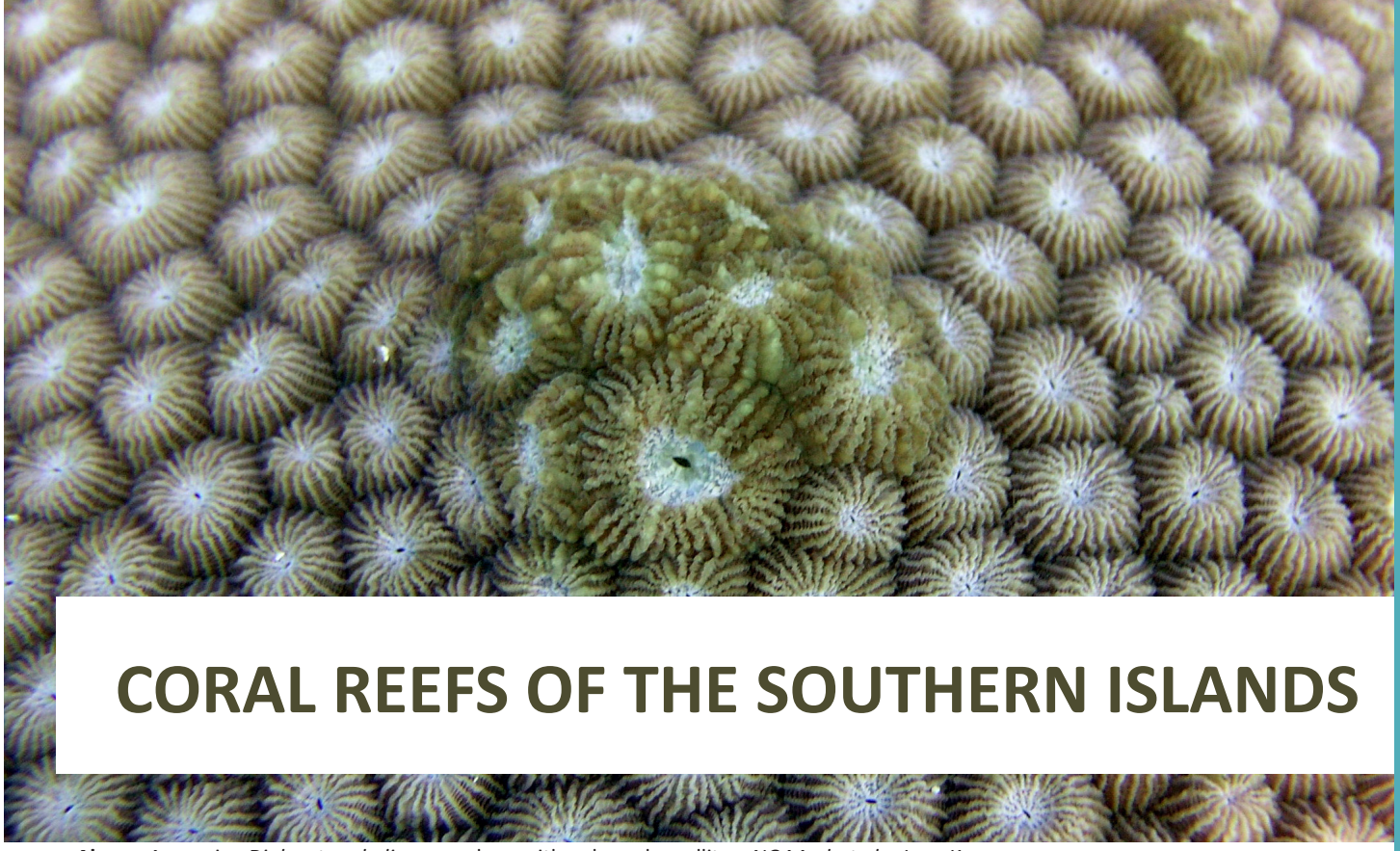


Figure 15. The Archipelagic Coral Reef Condition Index, based on towed-diver surveys conducted in 2005 and 2007, reflects the integrated condition of the benthic and fish communities for each geographic region, *relative to other regions across the Mariana Archipelago*. The regions around Maug, for example, have high index ranks for both 2005 and 2007. Thus, they are all assigned the bright-green color that corresponds to the top-right square in the legend. The position of the horizontal bar above the midline in this square also reflects that those geographic regions maintained a high rank for both 2005 (y-axis) and 2007 (x-axis).



CORAL REEFS OF THE SOUTHERN ISLANDS

Above: A massive *Diploastrea heliopora* colony with enlarged corallites. *NOAA photo by Jean Kenyon*

This section includes management-relevant analyses from observations collected in the southern islands of the Mariana Archipelago, where human populations are more concentrated and there is high interest in issues of marine resource management.

BENTHIC COMPOSITION

The southern islands and nearby reefs include Guam, Rota, Aguijan, Tinian, and Saipan as well as Santa Rosa Reef, near Guam, and Tatsumi Reef, close to Tinian. The composition of the benthos around these islands was dominated by macroalgae. Mean macroalgal cover from towed-diver surveys conducted on forereef habitats in 2005 and 2007 was 47% with islandwide mean values ranging from 31% (SE 1.2) around Saipan to 50% (SE 1.5) around Tinian. The highest macroalgal cover in the Mariana Archipelago was recorded on Santa Rosa Reef with 70.5% (SE 3.1). Mean live coral cover, from towed-diver surveys conducted during the 3 MARAMP cruises in 2003, 2005, and 2007, was 11% with values ranging between 7% (SE 0.5) around Rota and 19% (SE 0.6) around Guam. A mean coral cover of 7.7% (SE 0.2) was recorded for the 2 nearby offshore reefs, Tatsumi and Santa Rosa. Cover of crustose coralline red algae did not vary much among the southern islands, with mean cover ranging from 8% (SE 0.4) to 12.3% (SE 1.3) and the highest mean values recorded around Aguijan. At Santa Rosa Reef and Tatsumi Reef, crustose-coralline-red-algal cover was slightly lower with 4.9% (SE 1.2). Looking specifically at hard-bottom areas, results from REA surveys conducted only in 2007 show lower estimates of macroalgal cover (6%–24%) and similar values of coral cover (8%–16%) compared to islandwide estimates from towed-diver surveys encompassing all substrate types. Size-class distribution of coral colonies did not vary substantially among the southern islands in 2007.

Coral and coralline-algal diseases were observed around all 5 of the surveyed southern islands. The highest prevalence of coral disease of 1.4% (SE 0.4) was recorded at Guam, and the lowest prevalence of 0.1% (SE 0.03) was observed at Rota. Many of the cases of coral disease observed around these 5 islands disproportionately affected important reef-building taxa, including hard corals in the families Poritidae, Acroporidae, and Faviidae, as well as the carbonate-producing crustose coralline red algae. Excluding Aguijan, where only one site was surveyed, islandwide mean density of coralline-algal diseases was greatest at Tinian with 2.8 cases/100 m^2 (SE 1.5). Although prior field surveys (Starmer et al. 2008; J Goreau, pers. comm.) have identified the presence of coralline-algal disease in this region, the results from MARAMP surveys conducted in 2007 represent the first attempt to quantitatively evaluate the occurrence of these diseases across the Mariana Archipelago. In this context, patterns of coralline-algal disease indicate that some disease states were abundant and widespread and others were uncommon and rare. Of the 124 coralline-algal disease cases enumerated during MARAMP surveys in 2007, > 87% of cases corresponded to coralline lethal orange disease.

REEF FISHES

Mean large-fish biomass, estimated from towed-diver surveys conducted on forereef habitats in 2003, 2005, and 2007, was highest around Rota with 0.4 kg/100 m² (SE 0.1) and lowest around Guam with 0.1 kg/100 m² (SE 0.03). Mean total fish biomass, estimated from REA surveys conducted in 2003, 2005, and 2007, was highest around Aguijan with 5.2 kg/100 m² (SE 0.6) and Rota with 4.1 kg/100 m² (SE 0.9) and lowest around Santa Rosa Reef with 1.5 kg/100 m² (SE 0.1).

INTEGRATED OVERVIEW OF SAIPAN & GUAM

This report devotes individual chapters to Guam and 13 islands of the CNMI, discussing results from each of several interdisciplinary surveys. For the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan, this report also provides comparisons of the benthic and fish communities around each island relative to the conditions around only these 4 islands. This overview section focuses on Saipan and Guam, which have the largest human populations in this archipelago.

Despite the lower levels of live coral cover along the east coast of Saipan relative to the west coast, the general condition of the benthic communities in most survey areas around Saipan appeared above average compared to other survey areas in the 4 populated, southern islands in 2005 and 2007, based on the calculated *Benthic Condition Index for Guam, Rota, Tinian, and Saipan*. The relatively low coral cover on the east coast may reflect the natural character of the reef, including geologic, topographic, and oceanographic factors, rather than the impact of human activities. Integrating towed-diver benthic and fish data with modeled wave conditions reveals that coral cover was higher along Saipan's sheltered west coast than in other areas, but large-fish biomass was relatively constant around this island (Fig. 16).

Ranks for survey areas in the Coral Reef Condition Index for Guam, Rota, Tinian and Saipan, as well as in the associated Benthic Condition Index, varied around Guam. The survey area near the Guam National Wildlife Refuge on the northwest corner of this island had coral cover of 11%–20% (Fig. 17) and a high rank in the Benthic Condition Index in 2005, but this rank declined to medium in 2007. The large population near and frequent use of Tumon Bay on the northwest coast of Guam and the numerous associated stressors that can impact high-use areas may have resulted in deteriorating conditions of the benthic communities on the forereef off Tumon Bay: the rank for this survey area in the Benthic Condition Index changed from medium in 2005 to low in 2007. It should be pointed out that many possible land-based impacts likely take place predominantly on the shallow backreef that was not surveyed as part of the MARAMP. Within the Tumon Bay Marine Preserve, regulations prohibit various fishing activities, yet towed-diver surveys of the forereef habitats of Tumon

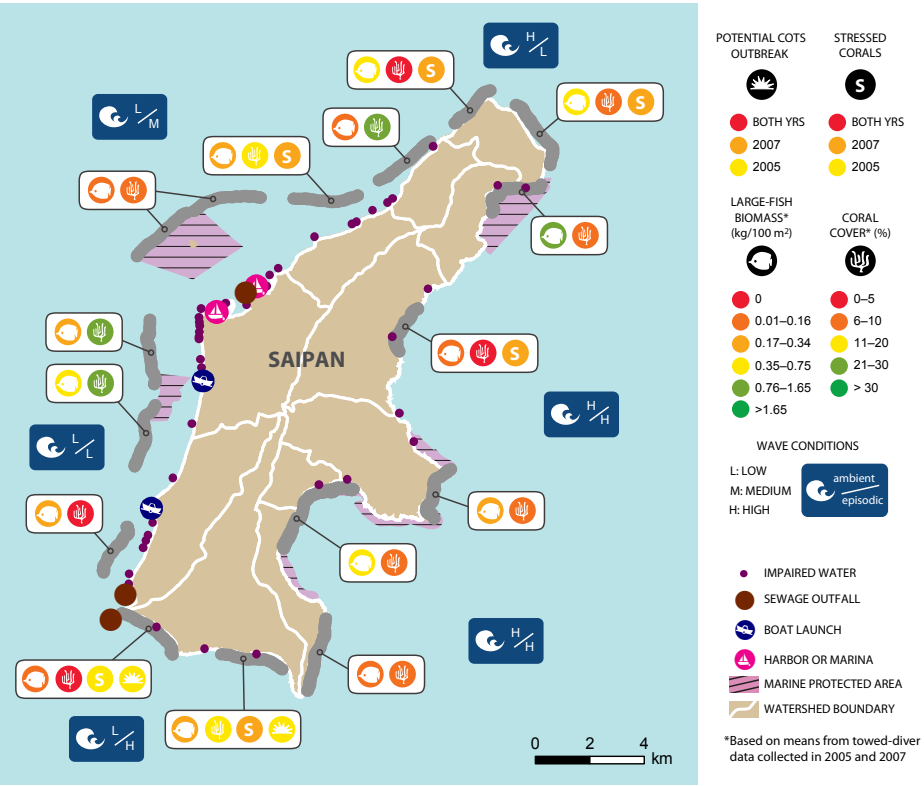


Figure 16. Integrated overview of benthic and fish communities around Saipan, illustrated with various human and natural factors that may influence their condition.

Bay recorded very low biomass of large fishes (≥ 50 cm in total length) in all 3 survey years, with generally only a few individuals recorded per survey (the low values from 2005 and 2007 are illustrated in Fig. 17). Around southwest Guam, where very low levels of coral cover (0%–5%) were observed (Fig. 17), factors exerting a potential negative influence on reef communities included poor water quality along portions of the coastline, a lack of favorable substrate for reef development, and elevated sediment input. The conditions of the reef in the Pati Point Marine Preserve, located around the northeast corner of Guam, were among the best observed around the 4 populated, southern islands. Ranks for the survey area closest to the northeastern tip of Guam were high in the Coral Reef Condition Index and Benthic Condition Index for 2005 and 2007. The highest numbers of large fishes around Guam, from towed-diver surveys conducted in 2007, were recorded in this area.

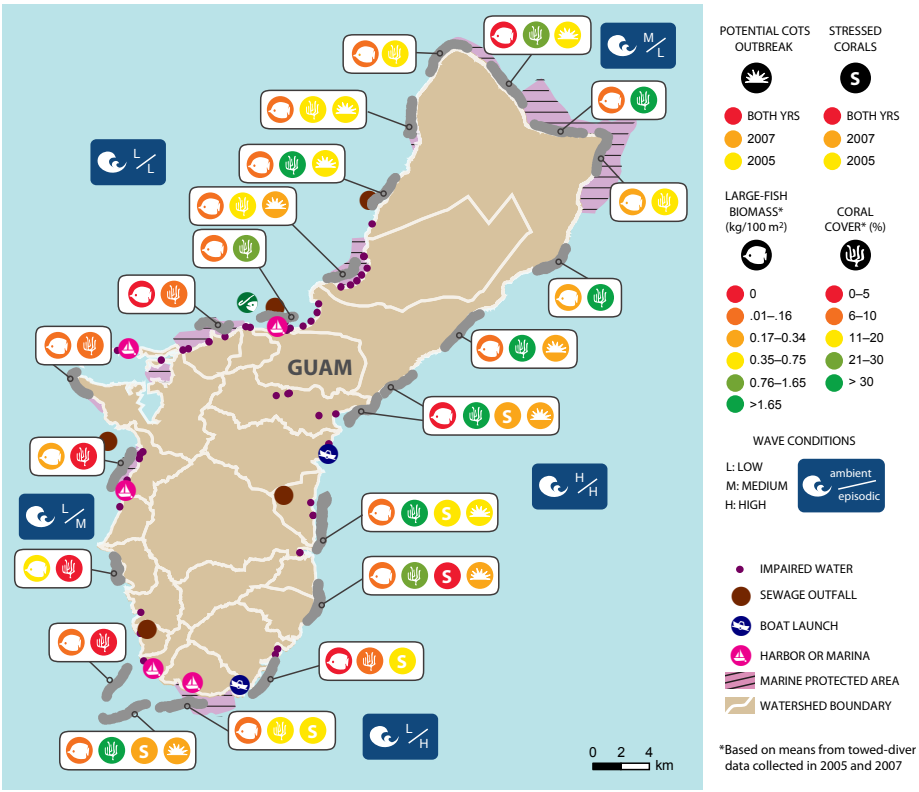
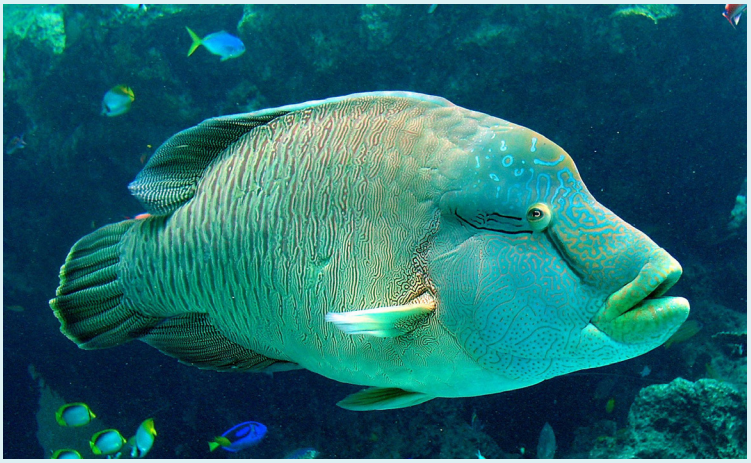


Figure 17. Integrated overview of benthic and fish communities around Guam, illustrated with various human and natural factors that may influence their condition.

SIGHTINGS OF RARE WRASSE

Although large-bodied fish species generally were encountered more frequently around the northern islands, an exception was the rare humphead wrasse (*Cheilinus undulatus*), also known as the Napoleon Wrasse. This fish species is one of the largest coral reef fishes, reaching up to 2 m and 190 kg. It occurs patchily throughout much of the Indo-Pacific region, and its life-history characteristics make it more vulnerable than most other species of coral reef fishes to overexploitation. Although this species is not common, CRED recorded 48 sightings of humphead wrasse around the southern islands, with a mean density of 10.9 individuals/km^2 (SE 7.3), but only 7 sightings around the northern islands, with 2.2 individuals/km^2 (SE 1.1), over 3 survey years. The sizes of individual fish were similar with an average length of 92.8 cm (SE 9.9) in the northern islands and 90.7 cm (SE 4.1) in the southern islands. Three of the individuals seen at the remote banks on the West Mariana Ridge were slightly larger with a mean length of 115.8 cm (SE 9.3).



Left: The humphead wrasse (*Cheilinus undulatus*) was seen more frequently around the southern islands compared to the northern islands. *NOAA photo*



REMOTE REEF AREAS

Above: Benthic composition at Arakane Reef captured during a towed-diver survey. *NOAA Photo*

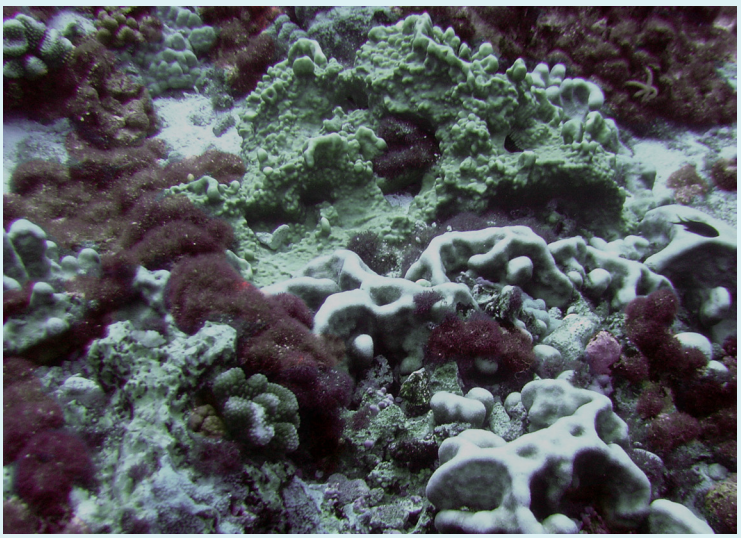
Before CRED initiated MARAMP surveys, little information was available on the benthic composition and geologic structure of the remote reefs and banks located on the West Mariana Ridge (Fig. 18). CRED conducted limited reconnaissance surveys at Arakane Reef, Pathfinder Reef, and Stingray Shoal in 2003 and at Arakane and Pathfinder Reefs in 2005. Results show, in general, that cover percentages for corals and crustose coralline red algae were fairly high (Table 2) at these 3 remote reef areas, relative to other survey areas in the Mariana Archipelago. Estimates of coral cover and large-fish biomass were higher at Stingray Shoal, with 54.9% and 5.2 kg/100 m^2, than at any other area surveyed in the Mariana Archipelago, and macroalgal cover was highest on Arakane Reef with 52.3% (Table 2).

Table 2. Overview of benthic composition and fish biomass at 3 remote, submerged reefs on the West Mariana Ridge.

	ARAKANE REEF				PATHFINDER REEF				STINGRAY SHOAL	
	2003		2005		2003		2005		2003	
	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
MACROALGAL COVER (%)	52.3	1.6	45.8	2.3	37.3	1.3	29.0	1.1	33.9	1.9
CRUSTOSE CORALLINE RED ALGAL COVER (%)	5.3	0.7	3.6	0.6	5.6	0.8	10.0	1.2	1.5	0.4
CORAL COVER (%)	24.1	1.1	11.8	1.6	24.2	0.9	24.8	1.4	54.9	2.7
STRESSED-CORAL COVER (%)	–	–	0.0	0.0	–	–	0.1	0.0	–	–
LARGE-FISH BIOMASS (kg/100 m^2)	0.8	0.5	1.4	1.1	1.4	0.4	0.5	0.1	5.2	1.1
TOTAL FISH BIOMASS (kg/100 m^2)	2.1	N/A	6.4	2.8	4.7	N/A	7.2	1.9	–	–

NEWLY MAPPED REEFS: STINGRAY SHOAL

Though there were undocumented reports from fishermen about Stingray Shoal, the best available nautical charts in 2003 indicated shallowest water depth in this area of 931 fm (1703 m), with no suggestion of a shallow-water coral reef ecosystem. Using shipboard and handheld single-beam sonars, CRED located this little-known, submerged seamount and mapped a minimum depth of only 13 m. Ensuing diver-based biological surveys found predominantly hard substrate with high-complexity habitats supporting live coral cover of 40%–100% (Fig. 18). The coral reefs of Stingray Shoal were found to support a high-density reef-fish community, with large-fish biomass levels of > 5 kg/100 m^2 almost 5 times the values observed for the northern islands and 23 times the values found around the southern islands. Reef sharks accounted for the highest proportion (50%) of large-fish biomass with the greatest contribution from the grey reef shark (*Carcharhinus amblyrhynchos*). Though biomass was high, towed-diver surveys discovered derelict fishing gear and other man-made objects, clearly indicating that these reefs had been fished.



The reef at Stingray Shoal, part of the West Mariana Ridge. *NOAA photo*

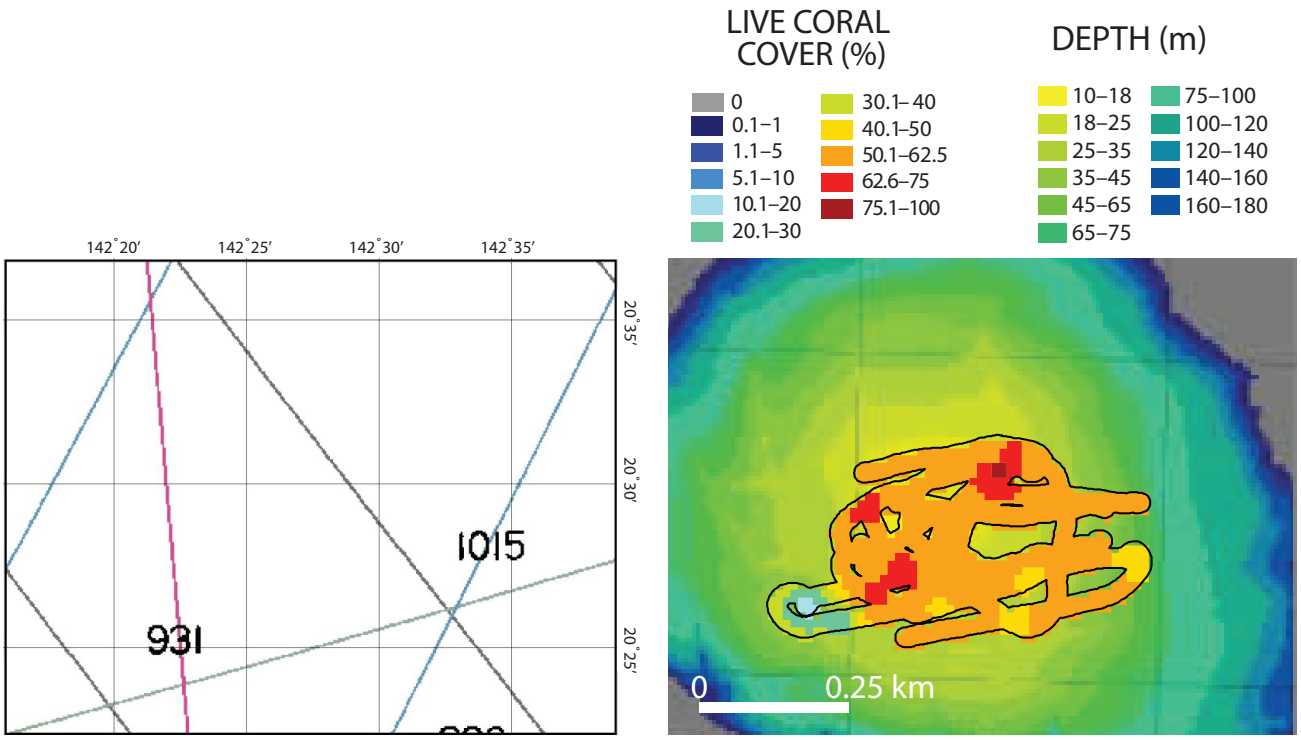


Figure 18. Information about Stingray Shoal (*left*) prior to Pacific RAMP surveys and (*right*) live-coral cover (%) from towed-diver surveys and depths (m) from sonar mapping conducted by the CRED in 2003.

1 INTRODUCTION

1.1 Mariana Archipelago

The territory of Guam and the Commonwealth of the Northern Mariana Islands (CNMI) are the westernmost territories of the United States and are part of the Mariana Archipelago (Fig. 1.1a), a chain of islands, reefs, and offshore banks located ~ 2500 km east of the Philippines and ~ 6000 km west of Hawai`i. The Mariana Archipelago is 890 km long and encompasses 15 islands and numerous offshore banks. The territory of Guam includes the island of Guam and adjacent offshore banks and reefs. All other islands and offshore banks are under the jurisdiction of the CNMI.

The Mariana Archipelago can be divided into 2 geologic groups. The old, southern islands consist of Guam, Rota, Aguijan, Tinian, Saipan, and Farallon de Medinilla, while the young, volcanic, northern islands include Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros (also called Uracas). Numerous offshore banks and submarine volcanoes are included within the U.S. exclusive economic zone (EEZ) around this archipelago. The 3 northernmost islands, the Mariana Trench, and several volcanic features between the Mariana Arc and the Mariana Trough (Fig. 1.1a) were designated as the Marianas Trench Marine National Monument by presidential proclamation in January 2009.

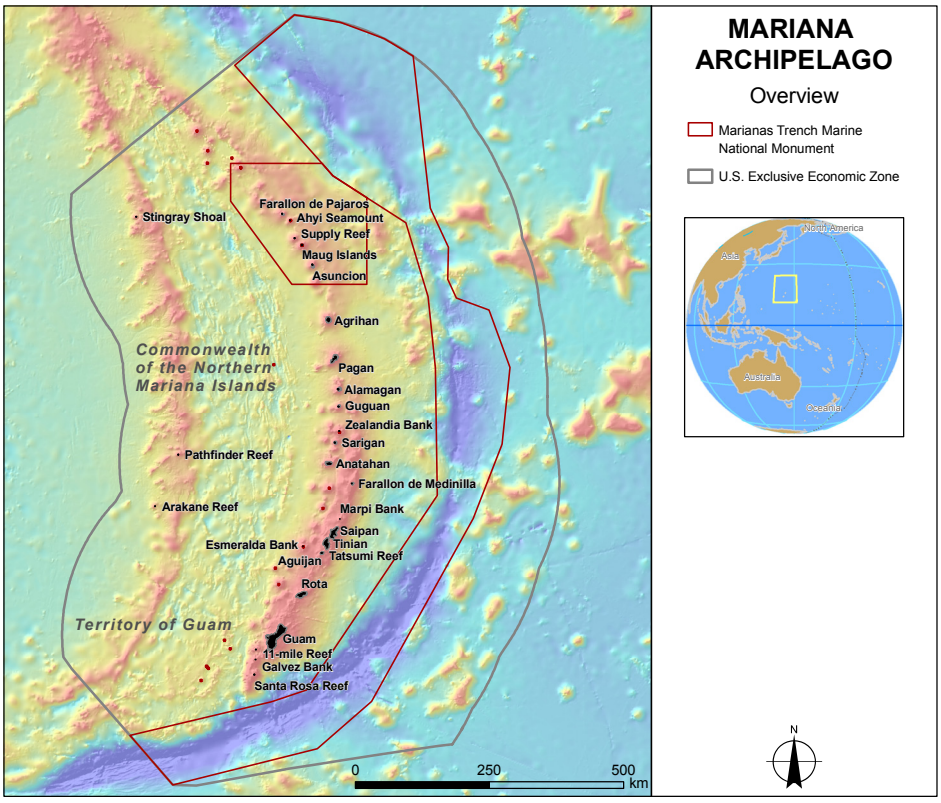


Figure 1.1a. The Mariana Archipelago includes the territory of Guam and the Commonwealth of the Northern Mariana Islands. The Marianas Trench Marine National Monument, shown above with a red outline, was created in January 2009. The grey outline indicates the boundaries of the U.S. EEZ around this archipelago.

1.1.1 History and Demographics

The known human history of the Mariana Archipelago, or Mariana Islands, began about 3500 years ago when Asians, who were the ancestors of the Chamorro people, arrived in these islands (Rogers 1995). Contact with the Western world began in 1521 when Magellan landed on Guam. The islands of the Mariana Archipelago were claimed by Spain in 1565. A century later, Spanish missionaries arrived and named these islands after Mariana of Austria, the widow of King Phillip IV of Spain (Rogers 1995). Disease and conflicts with Spain decimated the Chamorro population, which decreased from a level estimated between 24,000 and 100,000 in 1668 to only 3539 in 1710 (Rogers 1995; Underwood 1973). At the turn of the 18th century, Spain moved all of the remaining Chamorro people to Guam and Rota, and Spanish, Filipino, and Carolinian

immigrants were brought in to resettle the Mariana Islands (Rogers 1995). Subsequent Chamorro resettlements occurred in the late 1800s (Alkire 1984). The Mariana Islands remained under control by Spain until the end of the Spanish American War in 1898, when Guam was placed under the control of the United States. Subsequently, the United States established major military bases on Guam (Rogers 1995).

Germany bought all the other islands of the Mariana Archipelago from Spain in 1899 with the intent of establishing copra plantations. During this period, Germany also let contracts for collection of exotic bird feathers for the European and Japanese hat trade (Spennemann 1999a). After World War I, the League of Nations stripped Germany of all its overseas possessions and awarded Japan administrative authority over the Mariana Islands, except for U.S.-controlled Guam. Japan established sugarcane plantations and fishing operations with an influx of 40,000 immigrants mostly from Japan, the Philippines, and the Caroline Islands (U.S. Department of the Interior [DOI] 2009a). In 1941, Japan captured Guam a few days after the Dec. 7 attack on Pearl Harbor and held the rest of the Mariana Archipelago with troops or settlers on the islands of Rota, Tinian, Agrihan, Saipan, Anatahan, and Pagan (more than 30,000 Japanese resided on Saipan alone in 1945). After intense fighting in the summer of 1944, the United States recaptured Saipan in July and Tinian and Guam in August, and the remainder of the islands were turned over to the United States after the war ended. Most of the Japanese survivors who did not believe the war was over were evacuated from Anatahan in 1951, and one last survivor was found on Guam in 1972 (Trefalt 2003). In 1947, the United Nations created the Trust Territory of the Pacific Islands (TTPI), which included all the Mariana Islands except for Guam and was administered by the United States. Guam became a U.S. territory in 1950 (Rogers 1995).

The current political structures of the CNMI and Guam are different because of the nature of their relationships with the United States (commonwealth versus territory) and the time frame in which their relationships were established. For the first 4 decades of U.S. control, from 1898 to World War II (WWII), Guam was administered by the U.S. Navy with a naval officer serving as governor. After occupation by Japan during WWII and recapture by the United States, Guam became an organized, unincorporated territory when the U.S. Congress passed the *Organic Act of Guam* in 1950. The *Organic Act* gave the people of Guam U.S. citizenship, for which they had petitioned since 1902 (Rogers 1995). Administration of Guam was transferred from the U.S. Department of Defense to the DOI, Office of Insular Affairs, in 1950 (DOI 2009a). As an unincorporated territory, Guam belongs to but is not a part of the United States, and no guarantee of eventual statehood is implied. The governor of Guam was appointed by the United States until 1968 when the *Organic Act* was amended, and the first gubernatorial election was held in 1970. Federal legislation awarded Guam a delegate in the U.S. House of Representatives in 1972. This delegate can participate and vote in House committees. The *Organic Act* also transformed the existing Guam Congress into a lawmaking body, but Guam's legislation is still subject to the will of the U.S. Congress. (Howe et al. 1994) The governor and lieutenant governor of Guam are chosen jointly with a single vote applicable to both offices for 4-year terms (Governor… 2006).

The islands of the CNMI first became officially affiliated with the United States after the U.S. military won battles on them against Japan near the end of WWII and in 1947 became part of the TTPI. The United States became the administering authority of the TTPI under the terms of a trusteeship agreement. In 1975, the people of the Northern Mariana Islands voted to become the Commonwealth of the Northern Mariana Islands, and, in 1976, the U.S. Congress approved a mutually negotiated covenant to establish the CNMI in political union with and under the sovereignty of the United States. This agreement ceded control of foreign affairs to the United States but allowed the CNMI to administer its own immigration and minimum wage laws. The CNMI government adopted its own constitution in 1977, and the constitutional government took office in January 1978. The covenant was fully implemented on November 3, 1986, by presidential proclamation, which named the Northern Mariana Islands as a U.S. commonwealth and conferred U.S. citizenship on legally qualified CNMI residents. In 1990, the United Nations terminated the TTPI. The CNMI is self-governing with locally elected governor, lieutenant governor, and legislature. Like their counterparts on Guam, CNMI citizens do not vote in elections for U.S. president and vice president but may vote in Democratic and Republican presidential primary elections. The CNMI had only an appointed "resident representative" to the U.S. House until 2008, when President George W. Bush signed a bill providing for the election of a representative. The first elected representative, who has the same voting rights as other territorial delegates, went to the U.S. Congress in 2009. In 2005, the U.S. Congress passed a bill that began to "normalize" minimum wages in the CNMI to the same rate required by law in the United States, and in 2008 other legislation turned over control of CNMI immigration laws to the United States. (DOI 2009b)

The islands of the CNMI and Guam differ in size, isolation, and human population. Guam, the largest island with an area of 544 km², had an estimated population of 159,358 persons in 2010 (U.S. Bureau of the Census 2011b), and significant growth is expected as the U.S. Department of Defense plans to move between 4700 and 8000 Marines, as well as other personnel, to Guam (Parrish 2012; Hart 2012). An enviornmental impact statement completed by the U.S. Navy in 2010

estimated that the move of additional active-duty and civilian military personnel and dependents to Guam will increase the population on this island by 24,713 persons within the next decade (U.S. Department of the Navy 2010). Farallon de Medinilla and areas of Tinian and Saipan are also used for military training activities, and these and other islands of the CNMI are under consideration for expanded military use. Saipan is the largest island in the CNMI with an area of 119 km² (Fig. 1.1.1a), roughly similar to the combined area of 160 km² for the 9 northernmost islands of the CNMI.

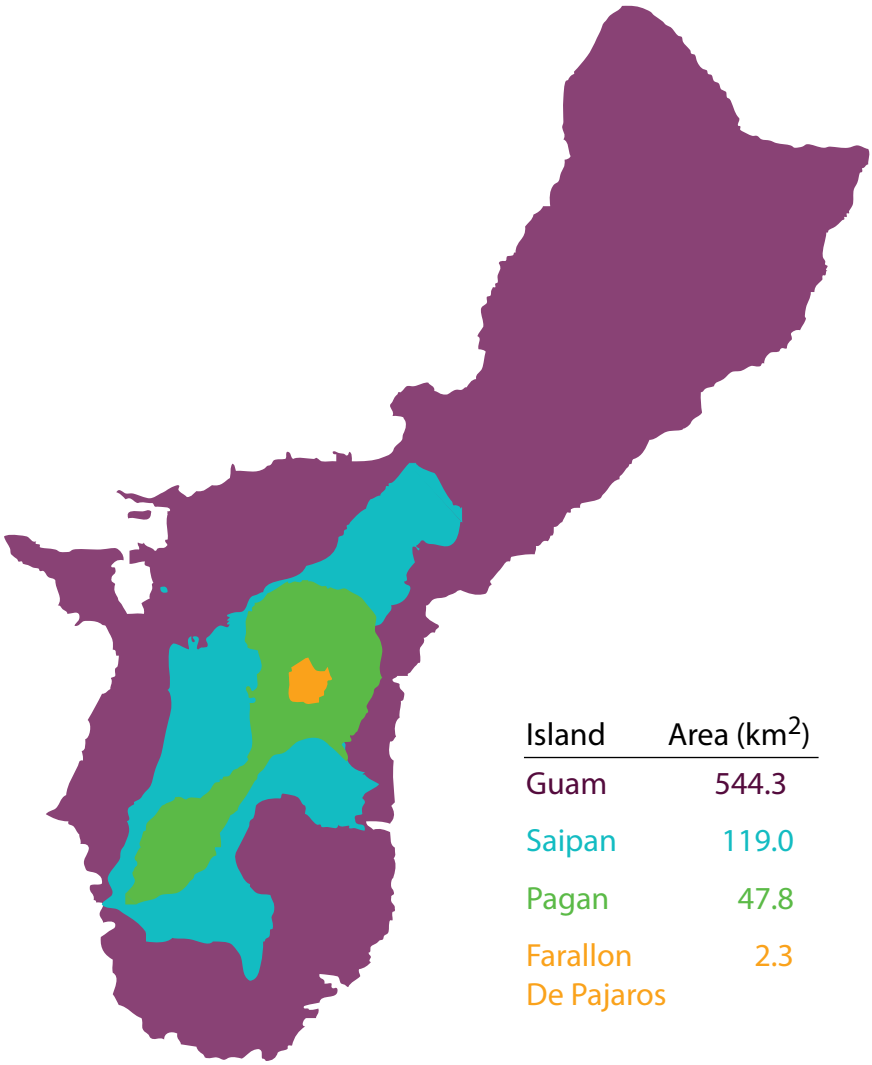


Figure 1.1.1a. The islands of the Mariana Archipelago vary widely in size. Saipan, the largest island in the CNMI, for example, is 22% of the size of the island of Guam. Among the northern volcanic islands, Pagan is the largest and Farallon de Pajaros and Maug are the smallest islands.

The combined population of Guam and the CNMI in 2010 was estimated at 213,241 (Fig. 1.1.1b; U.S. Bureau of the Census 2011a, 2011b), with population centers largely focused around 4 of the 6 old, southern islands: Guam, Rota, Tinian, and Saipan. Aguijan, located near the southern point of Tinian, has a steep, inaccessible shoreline and has remained largely uninhabited following WWII. Farallon de Medinilla is a tiny islet north of Saipan that has also remained unpopulated and primarily has been used for military operations. The U.S. Congress authorized continued military use of this islet in the *Bob Stump National Defense Authorization Act for Fiscal Year 2003* (Migratory… 2007), and live fire exercises were ongoing in 2012 (Pacific News Center 2012). All of the young, northern islands, except Farallon de Pajaros and, perhaps, Maug and Guguan, have supported human populations at some point, starting with an unknown number of native Chamorro settlements ~ 3500 years ago.

During the period of contol by Germany in 1899–1914, human populations on the Northern Mariana Islands were relatively small (Spennemann 1999a). According to U.S. Census reports, populations on these islands, excluding Saipan, Tinian, and Rota, fluctuated between 100 and 300 occupants under control by Japan and the United States from 1920 to 1980 (U.S. Bureau of the Census 1983; CNMI Department of Commerce 2002a; Office of the High Commissioner 1959). After a major volcanic eruption at Pagan in 1981, the CNMI government, which was then only recently established, evacuated all residents from the northern islands, which have remained largely uninhabited aside from small and sporadic populations at Agrihan, Pagan, Alamagan, and Anatahan.

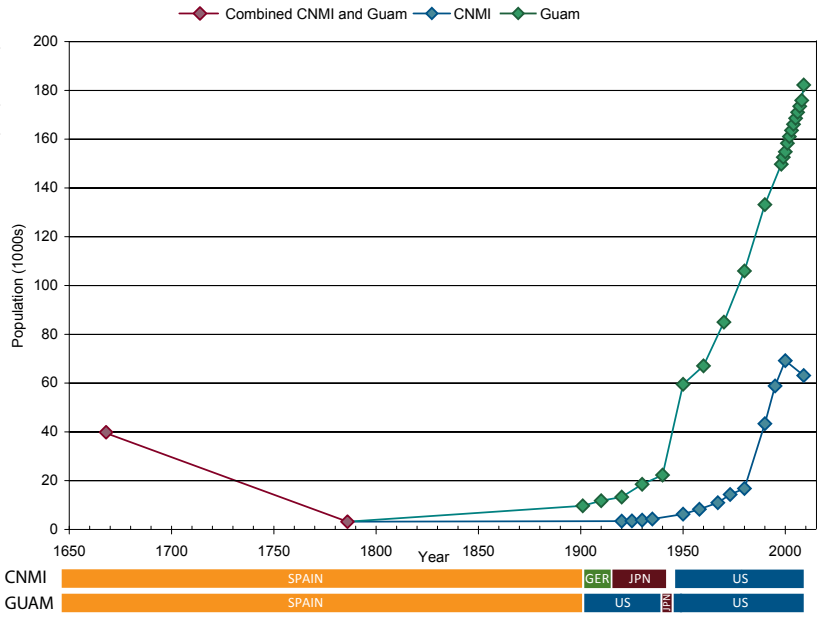


Figure 1.1.1b. Population growth of the Mariana Archipelago 1668–2009 (U.S. Bureau of the Census 1982, 1983, 1992, 2002, 2003, 2011a, 2011b; CNMI Department of Commerce 2002a; U.S. Department of Defense; Office of the High Commissioner 1959; Underwood 1973).

1.1.2 Geologic and Geographic Setting

The 6 southern islands of the Mariana Archipelago share a similar geologic structure, were formed in the late Eocene to early Miocene epochs (15–20 million years ago; Hawkins 2003), and are part of the frontal arc of the Mariana arc-trench system (Fig. 1.1.2a). Although these southern islands are volcanic in origin, they are all largely covered by uplifted limestone from ancient coral reefs. These episodically uplifted limestone terraces create planar "layer-cake" topographies

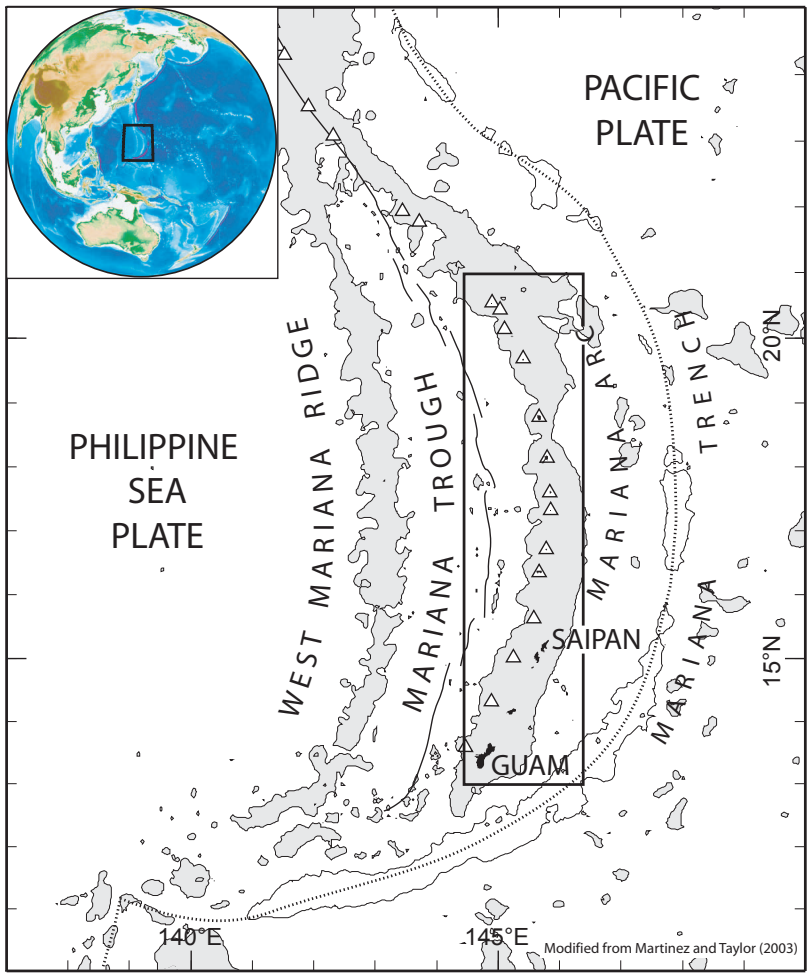


Figure 1.1.2a. Geologic setting of the Mariana region, modified from Martinez and Taylor (2003).

(Fig. 1.1.2b) with numerous above-ground and underwater caves. In comparison with the other southern islands, Guam is unique in that uplifted limestone covers its northern half, while the southern half is primarily covered by heavily eroded Eocene volcanics with no limestone cover (Fig. 1.1.2c; Riegl et al. 2008).



Figure 1.1.2b. Flat-topped Forbidden Island is an uplifted, fossil coral reef platform on the island of Saipan. *NOAA photo by Molly Timmers*



Figure 1.1.2c. Watersheds in southwestern Guam are steep-sided, with Eocene volcanic rocks and red, easily eroded laterite soils. *Photo courtesy of the Water and Environmental Research Institute of the Western Pacific and Island Research & Education Initiative*

The northernmost islands of the Mariana Archipelago are part of the Mariana Arc, where the Pacific Plate is subducted beneath the Philippine Plate at the Mariana Trench, which lies ~ 130–210 km east of this island chain. These northern islands, spanning from Anatahan to Farallon de Pajaros, are all stratovolcanoes characterized by steeply sloping surfaces and periodic, explosive eruptions. These islands are predominantly composed of hardened lava, tephra, and volcanic ash, which result from the re-melting and subsequent eruption of subducted material.

The West Mariana Ridge is a remnant volcanic island arc that forms a series of seamounts 145–170 km west of and parallel to the main island chain. The West Mariana Ridge is of intermediate age: younger than the southern part of the Mariana

Arc and older than the northern part of the Mariana Arc. Some of these seamounts rise to within 9 m of the ocean surface and were probably, at some point in time, above sea level. The absence of terrestrially derived sediments, recent volcanic ash, and infrequent direct anthropogenic impact at the West Mariana Ridge contribute to the near-optimal conditions for coral growth. Accordingly, some of the shallow structures feature well-developed reef ecosystems with lush gardens of hard corals (Fig. 1.1.2d).

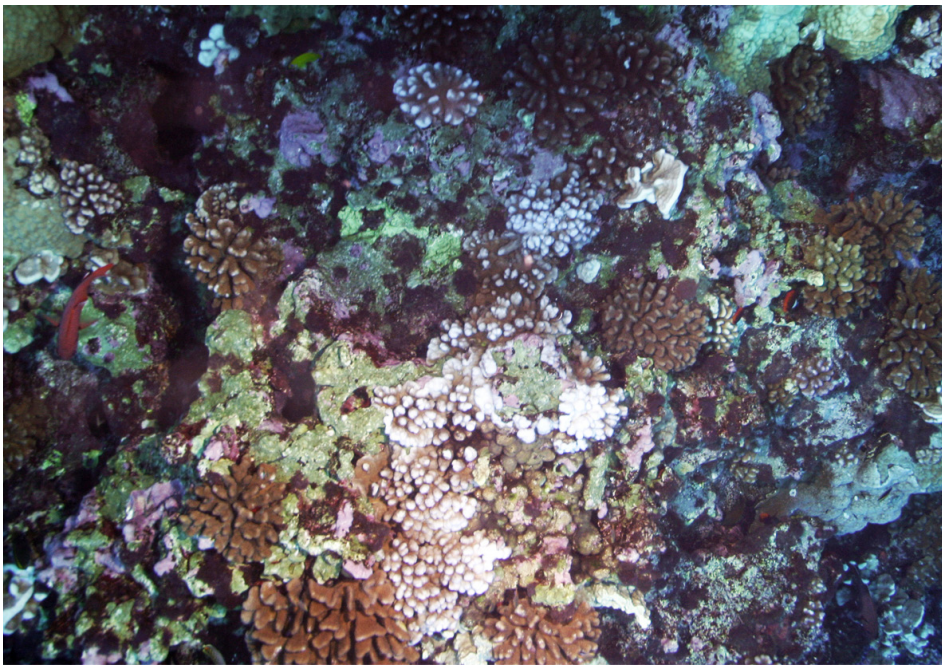


Figure 1.1.2d. Luxuriant coral growth at Stingray Shoals in the West Mariana Ridge, which is ~ 275 km west of Farallon de Pajaros. *NOAA photo*

Offshore banks and their associated habitats can be formed through 2 major types of events: (1) rapid tectonic or volcanic events, such as landslides, uplifts, or eruptions and (2) long-term changes in sea level, resulting in coral growth or erosion. For at least the past 800,000 years, global sea level has fluctuated ~ 120 m over every period of ~ 100,000 years in response to glacial-interglacial cycles. In the current interglacial period, sea level is near the peak of this 120-m oscillation (Ruddiman et al. 1989). When sea level is static for a prolonged period, the sea tends to erode terraces into land areas or form offshore platforms.

Because of their hybrid geological history, islands in the Mariana Archipelago, their immediately surrounding banks, and the banks that lie farther offshore represent a composite of these influences. In the young, volcanically active northern islands, such as Pagan, Alamagan, and Maug, some terraces and offshore formations are clearly extensions of recent onshore lava flows into offshore areas, and some of the terraces were formed during previous sea-level stands. In the old, southern islands, previous sea-level stands have formed carbonate terraces on top of volcanic structures from the Eocene to Miocene epochs, and these terraces subsequently have been exposed to sea-level change and, because of tectonic activity, have been uplifted or downthrown.

1.2 Coral Reef Management

1.2.1 National Coral Reef Management

In 1998, President Bill Clinton signed Executive Order no. 13,089 to "preserve and protect the biodiversity, health, heritage, and social and economic value of U.S. coral reef ecosystems and the marine environment" (Coral… 1999). This executive order created the U.S. Coral Reef Task Force (CRTF), with the secretaries of interior and commerce acting as co-chairs and federal agencies acting as participants. Working with state, territorial, commonwealth, and local governments, as well as nongovernmental organizations and commercial interests, this task force has 4 primary tasks:

1. Coordinate a comprehensive program to map and monitor U.S. coral reefs
2. Develop and implement research aimed at identifying the major causes and consequences of degradation to coral reef ecosystems
3. Develop, recommend, and seek or secure implementation of measures necessary to reduce and mitigate coral reef

ecosystem degradation and to restore damaged coral reefs
4. Assess the role of the United States in international trade and protection of coral reef species, and implement appropriate strategies and actions to promote conservation and sustainable use of coral reef resources worldwide

Executive Order no. 13,089 set the stage for national coral reef conservation efforts—emphasizing the need to undertake a comprehensive, rather than location-specific, program of ecosystem research, mapping, and monitoring of all U.S. coral reefs. In 2000, the CRTF developed the *National Action Plan to Conserve Coral Reefs* (National Action Plan) as the first U.S. blueprint to focus on the loss and degradation of U.S. and international coral reef ecosystems. Coral reef conservation was framed in 2 broad themes (U.S. Coral Reef Task Force 2000):

1. Understanding coral reef ecosystems
2. Reducing the adverse impacts of human activities

The National Action Plan stated, "Ultimately, our success—or failure—in conserving these highly complex and extremely fragile ecosystems will depend on a parallel approach of proactive, precautionary management measures coupled with a much more sophisticated level of understanding about their fundamental ecology and response to environmental stressors" (U.S. Coral Reef Task Force 2000). For this first theme, 4 goals were outlined:

1. Develop comprehensive maps of all U.S. reefs
2. Develop a nationally coordinated coral reef inventory, assessment, and monitoring program
3. Support strategic research focused on the determinants of coral reef health and recovery, including basic ecological processes, bleaching and disease, and best management practices for coral reefs and closely linked marine and terrestrial habitats
4. Conduct socioeconomic studies of the human dimension of successful coral reef conservation

As with Executive Order no. 13,089, the National Action Plan emphasized a nationally coordinated, comprehensive investigation of coral reef ecosystems from a mapping, research, and monitoring perspective. In the same year, the *Coral Reef Conservation Act of 2000* (CRCA; Coral… 2000), which served as the congressional response to Executive Order no. 13,089, laid out a national framework to address coal reef conservation issues. This legislation required the development of a national coral reef action strategy with goals and objectives that would include mapping, information management, research, and monitoring. The CRCA also created the national Coral Reef Conservation Program (CRCP) under the direction of the Secretary of Commerce. The CRCA requires NOAA to conduct collaborative research, mitigation, and outreach activities that directly contribute to the conservation of coral reef ecosystems. In response, NOAA performs a range of authorized activities, some of which are listed below:

1. Providing mapping, monitoring, assessment, restoration, and scientific research that benefits the understanding, sustainable use, and long-term conservation of coral reef ecosystems
2. Enhancing public awareness, education, understanding, and appreciation of coral reef ecosystems
3. Collaborating with local, regional, or international programs and partners for the cooperative conservation and management of coral reef ecosystems

NOAA, in cooperation with the CRTF, produced the *National Coral Reef Action Strategy* (National Action Strategy) in 2002 to fulfill the requirements of the CRCA and to help track the implementation of the National Action Plan. Two of the actions outlined in the National Action Strategy are listed below:

1. *Map all U.S. coral reef ecosystems* to address the threats of overfishing, habitat destruction, coastal development, and coastal pollution
2. *Assess and monitor coral reef health* to address the threats of global warming and climate change, diseases, overfishing, destructive fishing practices, habitat destruction, invasive species, coastal development, coastal pollution, sedimentation and runoff, and overuse related to tourism

As required by the CRCA, the CRCP has produced 3 "state of the reefs" reports since 2002. *The State of Coral Reef Ecosystems of the United States and the Pacific Freely Associated States: 2002* (Turgeon et al. 2002), *The State of Coral Reef Ecosystems of the United States and the Pacific Freely Associated States: 2005* (Waddell 2005), and T*he State of the Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008* (Waddell and Clarke 2008) are designed to provide overall assessments of coral reef ecosystems in U.S. jurisdictions at the time and are organized based on the primary threats, topics, and goals outlined in the National Action Strategy. The Guam and CNMI chapters in this 2008 report (Burdick et al. 2008; Starmer et al 2008) provide an overview of monitoring activities, a summary of results to date, current management activities, and overall conclusions and recommendations.

In September 2007, an external review of the CRCP was conducted to evaluate the success of this program in meeting the purposes of the CRCA and the National Action Strategy during the period of 2002–2006 and to provide recommendations for improving this program. As a result of this external review, CRCP developed a *Roadmap for the Future* report to set CRCP's direction for the period of 2010–2015 (CRCP 2008).

The primary objective of the CRCP is to address strategic coral reef management needs in a targeted, cost-effective, and efficient manner. To make the most of limited resources and to have the largest impact in reversing the general decline in coral reef health that has occurred over the past several decades, the CRCP is now narrowing the focus of its national program and shifting allocation of CRCP resources to take on-the-ground and in-the-water action. The CRCP is focusing efforts on understanding and addressing the following 3 priority threats:

- Impacts of fishing
- Impacts of land-based sources of pollution
- Impacts of climate change

The CRCP made the strategic decision to invest part of its annual operating budget in perpetuity to support long-term, integrated, multidisciplinary monitoring on a national scale and in 2010 put together a working group to develop a National Coral Reef Monitoring Plan for providing a consistent flow of information to assess and report the status and trends of environmental conditions, living reef resources, and the people and processes that interact with coral reef ecosystems. This CRCP-funded national monitoring program will provide a consistent and comprehensive analytical backdrop for other CRCP and partner activities. For the Pacific Islands Region, this plan means that a modified version of the CRED-led Pacific Reef Assessment and Monitoring Program (Pacific RAMP) will be executed on a national basis moving forward. Development of this national plan is ongoing in 2012 and implementation will occur over several monitoring cycles, but an outcome already initiated is a shift in the frequency of Pacific RAMP cruises with monitoring activities conducted on a triennial basis rather than a biennial basis.

1.2.2 Coral Reef Management in Guam

One of the first major steps in local coral reef management on Guam occurred in 1997 when more than 10% of the Guam coastline was set aside in 5 marine protected areas (MPAs) through Guam Public Law 24-21: Piti Bomb Holes Marine Preserve, Sasa Bay Marine Preserve, Tumon Bay Marine Preserve, Pati Point Marine Preserve, and Achang Reef Flat Marine Preserve. The goal of these preserves was to increase reef fish stocks. Limited take for cultural purposes was permitted in 3 of these 5 areas, full protection was first fully enforced in 2001, and regulations were strengthened with the passage of Guam Public Law 28-107 in 2006. Legislation (Guam Public Law 29-127) passed in 2008 and modifications proposed in 2009 through Bill 190-30 may open some of these no-take MPAs to fishing by indigenous people, although there is evidence of increased fish abundance in these marine preserves (Burdick et al. 2008). In addition, the U.S. Fish and Wildlife Service has established the Guam National Wildlife Refuge at Ritidian Point, and the Navy has established 2 ecological preserves at Orote and Haputo Points.

As a response to national CRCA initiatives discussed previously, between August 2002 and February 2003, the Guam Coral Reef Initiative Coordinating Committee worked to select and prioritize which main threats to local coral reefs would be the focus of local action strategy (LAS) efforts. This process significantly expanded and enhanced the network of stakeholder groups working on coral reef issues. Members of the Guam Watershed Planning Committee, a group of local, federal, and nongovernmental agencies involved primarily with watershed restoration, also became involved in LAS development, and members of the Guam Coral Reef Initiative Coordinating Committee now participate in the Watershed Planning Committee. In addition, the University of Guam Marine Laboratory and the Water and Environmental Research Institute of the Western Pacific, guided by the needs of local natural resource agencies, have shifted much of their focus toward management-driven research. The Guam Visitors Bureau and the tourism industry as a whole now are working with these natural resources agencies to market Guam's coral reefs and, in particular, Guam's marine preserves to the 1 million visitors that travel to this island each year.

During LAS development in 2002, major issues identified for the management of Guam's coral reefs included the following 4 challenges:

1. Land-based sources of pollution
2. Fisheries management
3. Lack of public awareness
4. Recreational misuse and overuse

During a CRCP workshop held in Honolulu in November 2008, land-based sources of pollution and fisheries management were again discussed as critical issues for coral reef management in Guam (CRCP 2009). The CRCP's monitoring, mapping, and assessment activities are collectively known as the Coral Reef Ecosystem Integrated Observing System (CREIOS), so this meeting was called the "Pacific CREIOS Workshop." Listed below are some of the mapping and monitoring needs that were identified by representatives from Guam management agencies:

1. Maps of Apra Harbor to assist with management efforts associated with military expansion
2. Hydrographic data for modeling of currents and water quality
3. Assistance with integrating various types of data and information

In 2006, Guam became a signatory to the Micronesian Challenge, a program initiated by the Republic of Palau that aims to effectively conserve at least 30% of nearshore marine and 20% of forest resources across Micronesia by 2020.

The Guam chapter of *State of the Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008* (Burdick et al. 2008) reports that the health and resiliency of Guam's coral reefs varies considerably, depending upon a variety of factors, including geology, human population density, level of coastal development, level and types of uses of marine resources, oceanic circulation patterns, coral predator outbreaks, and natural events such as typhoons and earthquakes. Burdick et al. 2008 also report that northern reefs are generally healthier than those in the south, where land-based pollution and runoff are more severe, and that fishes > 25 cm in length are uncommon to rare around all of Guam. Local and federal agencies and a variety of stakeholders have combined forces to promote re-vegetation efforts, outreach campaigns, enforcement within marine preserves, and development of a comprehensive monitoring strategy, and they have formed action groups such as the Island Pride Campaign and the Guardians of the Reef program. Financial and human resources, however, are still very limited and the challenges they face are likely to become more pronounced, particularly because of the planned military expansion and potential stressors associated with increased development (Burdick et al. 2008). This 2008 report cited specific issues of concern: wildland arson and resulting runoff; continuing severe depletion of reef fish species; and global climate change and resulting coral bleaching, ocean acidification, and increases in storm strength (Burdick et al. 2008).

1.2.3 Coral Reef Management in the CNMI

One of the first major steps in ecological protection in the CNMI was taken in 1985 when the islands of Guguan, Asuncion, Farallon de Pajaros, and Maug were established as nature preserves, through an amendment to the CNMI Constitution that stipulated that the "islands of Maug, Uracas, Asuncion, Guguan, and other islands specified by law shall be maintained as uninhabited places and used only for the preservation and protection of natural resources, including but not limited to bird, wildlife, and plant species" (CNMI Constitution).

A Marine Monitoring Team (MMT) was established in 1997 to foster better understanding of the condition of coral reefs and reef resources. Members of the MMT include the Division of Environmental Quality (DEQ), Division of Fish and Wildlife (DFW), Coastal Resources Management (CRM) Office, and Northern Marianas College.

The CNMI established a Marine Sanctuary Program in 1998 under which areas around Saipan, Rota, and Tinian have been protected (Starmer et al. 2005). Saipan has 3 no-take marine reserves: Managaha Marine Conservation Area, Forbidden Island Marine Conservation Area, and Bird Island Marine Sanctuary. The Sasanhaya Fish Reserve is a no-take zone for all species on the southwest coast of Rota. The CNMI in 2006 became a signatory to the Micronesian Challenge. In 2007, CNMI Public Law 15-90 created a new no-take marine reserve on the southwest coast of Tinian from Puntan Carolinas to Puntan Diapblo.

In response to the CRTF's 2002 call for LAS, the DEQ, DFW, and CRM held a series of public meetings with the CNMI Watershed Group, the MMT, and other stakeholders. The major foci of the CNMI's LAS were identified in 2002:

1. Land-based sources of pollution
2. Fisheries management
3. Recreational use
4. Increasing awareness and involvement
5. Coral reef resources management

During the CRCP "Pacific CREIOS Workshop" held in November 2008, these LAS items were reviewed and the following mapping and monitoring needs were added or clarified (CRCP 2009):

1. Bathymetric data to fill gaps in critical shallow-water areas
2. An archipelago-wide hydrographic model to investigate larval connectivity
3. Assistance with integrating various types of data and information

In January 2009, President Bush proclaimed the 3 northernmost islands of Mariana Archipelago, Farallon de Pajaros, Maug, and Asuncion, the entire Mariana Trench, and active undersea volcanic areas of particular interest as the Marianas Trench Marine National Monument (MNM). Details of the administration of this MNM will be jointly determined by the departments of Interior and Commerce, and the CNMI government will be involved as a cooperating agency (President… 2009). The governor of the CNMI appoints government representatives to be participants in the Marianas Trench MNM management council.

The CNMI chapter of *State of the Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008* (Starmer et al. 2008) reports that the capacity of the CNMI to manage its coral reef ecosystem resources has grown substantially over the past 7 years, thanks to U.S. Coral Reef Initiative funding. Critical goals are the development of justifiable performance indicators and programmatic self-sufficiency. LAS efforts have played a large part in the development of performance indicators, but the CNMI is just beginning to realize programmatic self-sufficiency through activities associated with fulfilling the Micronesian Challenge.

1.3 Ecosystem Approach to Management

Fishery and marine resource managers strive to make management decisions that will not only allow humans to sustainably interact with and use complex ecosystems but also ensure long-term ecosystem conservation and viability for future generations. To date, fishery management plans have traditionally focused on single stocks or, at most, commercially important groupings of stocks. Under these types of plans, fishery managers typically set biomass harvest or mortality rate goals with limited consideration of other stock characteristics or broader ecosystem concerns. In recent years, however, there has been a growing understanding that exploited marine resources must be considered as an integral component of a functioning ecosystem instead of as phenomena that operate independently of the broader biological community and environment.

Internationally, the need to move toward an ecosystem-based approach to fisheries management has been widely recognized, a shift that has been spearheaded by the Food and Agriculture Organization of the United Nations through the Code of Conduct for Responsible Fisheries and supported by numerous regional and national institutions as well as academia, nongovernmental organizations, and the public at large (Cury and Christensen 2005). In the United States, our understanding of marine ecosystems has been identified as a critical means to ground our ocean policy. The 2004 report of the U.S. Commission on Ocean Policy highlighted the importance of an ecosystem-based management approach and a vision for a future in which "management boundaries correspond with ecosystem regions, and policies consider interactions among all ecosystem components" (U.S. Committee on Ocean Policy 2004).

More recently, in its 2010 report, the Interagency Ocean Policy Task Force, created by President Barack Obama in June 2009, identified 9 priority objectives that the United States should pursue to implement a national ocean policy. The first of these priorities read, "Adopt ecosystem-based management as a foundational principle for the comprehensive management of the ocean, our coasts, and the Great Lakes" (Council on Environmental Quality 2010). Acknowledged as the second priority objective and closely linked with ecosystem-based management is the use of marine spatial planning, which is a comprehensive process through which compatible human uses are objectively and transparently allocated to appropriate ocean areas to sustain critical ecological, economic, and cultural services for future generations.

Executive Order no. 13,547, which was signed by President Obama on July 19, 2010, adopted those priority objectives and other recommendations of the Interagency Ocean Policy Task Force, created the National Ocean Council, and established the country's first *National Policy for the Stewardship of the Ocean, Our Coasts, and the Great Lakes* (Stewardship… 2010). "To achieve an America whose stewardship ensures that the ocean, our coasts, and the Great Lakes are healthy and resilient, safe and productive, and understood and treasured," this executive order stated, "it is the policy of the United States to…increase scientific understanding of ocean, coastal, and Great Lakes ecosystems as part of the global interconnected systems of air, land, ice, and water, including their relationships to humans and their activities."

In theory, an ecosystem-based approach to management might overcome the challenges of addressing issues that cross traditional jurisdictional boundaries (local, state, national, and international) and of continually adapting to new scientific

information and improved management tools. The Interagency Ocean Policy Task Force in its 2010 report described ecosystem-based management as an approach that "recognizes both that humans are key components of ecosystems and also that healthy ecosystems are essential to human welfare" (Council on Environmental Quality 2010). The U.S. Committee on Ocean Policy (2004) report also acknowledged that our management approach should account for the complex interrelationships between abiotic environmental factors driving oceanic, atmospheric, and terrestrial processes and their interaction with living organisms on systematic ecological levels.

While there is general agreement on the need to transition to ecosystem-based fisheries and marine resource management, vigorous debate continues at all levels on how to implement policies to accomplish this transition. Still, there is, particularly among management agencies, agreement on the need for unbiased, credible, and up-to-date scientific information that examines the status and trends of ecosystem health and increases the understanding of mechanistic functions that determine ecosystem processes.

As an example of ongoing efforts in the Pacific Islands Region, the Western Pacific Fishery Management Council (WPFMC) established in 2001 its *Coral Reef Ecosystems Fishery Management Plan*, an ecosystem-based plan that in 2002 was approved by the National Marine Fisheries Service and in 2004 received a final ruling (Fisheries… 2004), and followed up with the development of archipelagic fishery ecosystem plans for the regions in its jurisdiction. The *Fishery Ecosystem Plan for the Mariana Archipelago*, which was published in 2009 and codified in 2010 (Western… 2010; WPFMC 2001) represents the first step in an incremental and collaborative endeavor to implement ecosystem approaches to fisheries management in the Mariana Archipelago (WPFMC 2009).

Moreover, there is similar consensus on the need to translate scientific findings into useful and timely information products for policymakers, managers, educators, and the public. Resource managers and policymakers need a foundation of reliable scientific information to make informed decisions and effectively implement ecosystem-based management principles with the objective of balancing sustainable use and long-term ecosystem conservation, including conservation of biodiversity, protected species, and habitats.

1.4 Pacific Reef Assessment and Monitoring Program

1.4.1 Background and Purpose

In response to the executive and legislative mandates and policies previously outlined in this chapter (see Section 1.2: "Coral Reef Management" and Section 1.3: "Ecosystem Approach to Management"), including Executive Order no. 13,089, the National Action Plan, and the *Coral Reef Conservation Act of 2000*, the Coral Reef Ecosystem Division (CRED) of the NOAA Pacific Islands Fisheries Science Center (PIFSC) was formed in 2001 with the support of the CRCP. The mission of CRED is to lead an integrated, interdisciplinary, ecosystem-based program of research, mapping, and long-term monitoring of coral reef ecosystems of the U.S. Pacific islands to promote conservation, management, and public awareness through innovative and collaborative science of the highest integrity.

Sustainable management and long-term conservation of coral reef ecosystems of the U.S. Pacific islands require comprehensive habitat mapping and interdisciplinary ecosystem assessment and monitoring of environmental conditions, biological communities, and human-use practices. The goal of CRED is to provide high-quality, unbiased ecosystem-based data and value-added information products to resource managers and policymakers on local, regional, national, and international levels in a timely manner.

CRED leads the Pacific RAMP as a key component of these efforts, conducting comprehensive ecosystem monitoring surveys every 3 years at ~ 50 islands, atolls, and shallow banks in the Hawaiian Archipelago (main Hawaiian Islands and Northwestern Hawaiian Islands), the Mariana Archipelago (territory of Guam and the CNMI), territory of American Samoa, and the Pacific Remote Island Areas (Wake, Johnston, Palmyra, and Kingman Atolls and Howland, Baker, and Jarvis Islands). To accomplish this monitoring, CRED uses NOAA research vessels capable of supporting multidisciplinary research teams of 20–22 scientists for extended voyages lasting 2–3 months.

Pacific RAMP cruises are conducted in collaboration with colleagues and partners from other NOAA offices; federal, state, and territorial agencies; academia; industry; and nongovernmental organizations. These partnerships are essential to the effectiveness of long-term ecosystem monitoring in this region because they bring together marine scientists and managers with local, regional, national, and international experience over a broad range of scientific and management issues. They also provide much needed logistical and operational support for CRED activities.

CRED's integrated coral reef ecosystem monitoring uses a suite of complementary methods to assess corals, algae, other invertebrates, fishes, and microbes in the context of their benthic habitats and oceanographic and water-quality environments. These methods are used consistently across the Pacific Islands Region to enable comparative ecosystem analyses across diverse biogeographic, environmental, oceanographic, and socioeconomic (human use) gradients. Ecological gradients include biodiversity, endemism, geomorphology (high or low island), island landmass, and reef classification and zonation. Environmental and oceanographic gradients include temperature (based on seasonal and interannual variability or geographic location), wave energy, tropical storm frequency and intensity, current patterns, precipitation and runoff, and water quality (nutrient availability) and carbonate chemistry. Socioeconomic gradients include population density, coastal development, fishing pressure, agricultural use, and cultural practices. Having similar interdisciplinary observations of coral reef ecosystems across these complex and diverse gradients makes it possible to significantly improve our understanding of ecosystem relationships and implicate cause-and-effect mechanisms that influence the health and resilience of coral reef ecosystems.

The integrated monitoring and assessment efforts of the Pacific RAMP are part of a diverse array of research platforms, tools, and methods that CRED uses to support the CRCP's CREIOS in the U.S. Pacific islands (see Chapter 2: "Methods and Operational Background").

1.4.2 Scope of the Pacific RAMP

The Pacific RAMP encompasses comprehensive efforts to map, assess, and monitor the coral reef ecosystems of the U.S. Pacific islands. In this process, CRED provides data and information products to resource managers and policymakers on local, regional, national, and international levels. This broad scope reflects the reality that coral reef ecosystems are influenced by local, regional, and global processes and stressors.

Although local resource managers generally implement policies that influence human uses of and impacts to local resources, ecosystems are significantly influenced by processes both within and well beyond local jurisdictional boundaries. The Pacific RAMP aims to assist local and regional resource managers by providing essential information about these biogeographic and ecological processes that influence local and regional resources. As such, the Pacific RAMP is envisioned as a key component of the national backbone to provide broad-scale baseline assessments for the Pacific Islands Region. These baseline assessments are explicitly expected to be complemented by more focused, local monitoring programs within each jurisdiction, including those jurisdictions funded by CRCP-administered coral reef monitoring grants. Pacific RAMP efforts provide the ecological and oceanographic context within which local ecosystems are embedded. These extensive spatial and temporal surveys across the Pacific Islands Region support and guide local monitoring efforts by helping to identify ecological concerns and defining the appropriate questions for more specific, local-level research and monitoring.

One of the key goals of the Pacific RAMP is to provide essential observations to describe, understand, and predict ecological and environmental conditions across broad—and inherently variable—spatial and temporal scales. Although local and regional resource managers and policymakers cannot manage or directly influence these large-scale processes, it is important to recognize that they cannot effectively manage local resources without good information, knowledge, and predictions about these large-scale processes. Certainly, ecological processes and changes occur at spatial and temporal scales that are finer than the scale observed by the Pacific RAMP. Yet many of the pervasive and chronic threats facing coral reef ecosystems are taking place on global and climatic time and space scales.

The temporal scope of the Pacific RAMP, with surveys conducted initially every 2 years and now every 3 years, is designed for observing and improving our understanding of ecosystem variability over time scales ranging from many years to decades or centuries. More specifically, this program is designed to examine the potential ecological impacts of long-term threats facing coral reefs, including threats related to climate change, fishing, coastal development, and land use:

- Mass coral bleaching and increased incidence of coral diseases in response to ocean warming
- Decreased calcification rates of corals, crustose coralline algae, and other calcifying organisms in response to ocean acidification and based on changing water chemistry (increased uptake of carbon dioxide from the atmosphere)
- Restructuring of many coastal and reef communities in response to rising sea levels, changing storm tracks and intensities, and modified ocean circulation patterns
- Changes in coral reef ecosystem communities (corals, algae, invertebrates, fish) in response to the impacts of fishing
- Effects of pollution, runoff, and sedimentation on corals reefs associated with coastal development and land-use practices

Although most of these potential threats are poorly understood today, they clearly pose significant risks to coral reef ecosystems across all scales ranging from local to regional to global. Recent analyses (Kleypas et al. 2006) suggest that the combined impacts of ocean acidification and warming could potentially dwarf those of many of the traditional local stressors (fishing, coastal development, pollution, etc.) with which marine resource managers currently struggle. As these global- and climate-scale processes become better understood, the need for the long-term, broad-scale ecosystem observations (biotic and abiotic) provided by the Pacific RAMP is becoming more evident and essential.

1.4.3 Pacific RAMP in the Mariana Archipelago

Pacific island communities are economically and culturally dependent on their marine resources. Accurate and up-to-date characterizations of the coral reef ecosystems of the Mariana Archipelago are necessary to develop and evaluate effective management strategies. The ecosystem "snapshots" acquired during Pacific RAMP surveys are used to identify both spatial and temporal (short- and long-term) changes of coral reef organisms and their environment. Thus, the ecosystem-based program that CRED has developed for reef assessment and monitoring in the Mariana Archipelago will provide local, regional, and national resource managers with reliable scientific information to more effectively implement ecosystem approaches to management in the region.

As part of its Pacific-wide monitoring effort, CRED conducted its first Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) cruise in 2003, with subsequent cruises in 2005, 2007, 2009, and 2011. The next MARAMP cruise is planned for 2014. Partners from the CNMI (the DEQ, DFW, and CRM) and from Guam (the Division of Aquatic and Wildlife Resources of the Department of Agriculture, Bureau of Statistics and Plans, Guam Environmental Protection Agency, and University of Guam) worked alongside CRED scientists to plan and conduct surveys and determine and establish monitoring sites.

The value of the MARAMP effort may not have been fully realized during its earlier stages. Based on observations to date, however, scientists and managers can begin to characterize spatial patterns of variability of the reef ecosystems around Guam and the CNMI and compare them to other regions in the Pacific. The value of Pacific RAMP and MARAMP will increase steadily as observations extend in time and the ability to detect significant ecological changes and climate fluctuations advances. Over time, ecological and environmental trends may include biodiversity shifts, population shifts, sudden species die-offs, disease outbreaks or bleaching pandemics, and introductions of bioinvasive species. With continually improved observations and understanding, our ability to develop predictive models will likewise increase and, thereby, provide managers with better tools for protecting and conserving reef resources. CRED is committed to providing superior, unbiased, and integrated ecosystem observations of the coral reefs of the Mariana Archipelago, as well as of other U.S. jurisdictions in the Pacific, well into the future.

1.4.4 Limitations and Improvements of Pacific RAMP

As with any large research effort, the Pacific RAMP has numerous logistical, operational, and scientific constraints. These limitations shape the nature of the data presented within the body of this Monitoring Report and provide a matrix for future improvement and continued program development. Program limitations are discussed here to clarify the current state of CRED's Pacific RAMP, the nature of the data, and the future of this program's research.

Since the beginning of this ecosystem assessment and monitoring program, CRED has worked with partners in each jurisdiction to develop, adapt, and implement comprehensive Pacific RAMP surveys. During this program's initial years of 2000–2003, several monitoring programs were in place across the Pacific and many monitoring workshops evaluated scientific methods and approaches. Despite this activity, however, there was and still is little consensus within the scientific community on any singular investigative approach. Moreover, as CRED and the Pacific RAMP were being established, few, if any, examples existed of coral reef monitoring programs with a similar geographical scale or interdisciplinary, ecosystem-based scope. As a newly established program, CRED and affiliated partners needed to accomplish the following objectives:

- Determine, develop, test, and adapt sampling methods and protocols
- Create protocols, algorithms, and tools for data processing, quality control, and analysis
- Devise and implement a data management, integration, and dissemination infrastructure

A significant majority of the ~ 50 islands, atolls, and banks surveyed by the Pacific RAMP had virtually no prior ecological surveys, bathymetric or habitat maps, or in situ oceanographic observations. Little or no information was available about

what to expect in terms of habitats, biogeographic structure, oceanographic conditions, or species compositions, distributions, or abundances. In almost all regards, the initial surveys of the Pacific RAMP were exploratory assessments with the purpose of shaping this monitoring program. Perhaps, the logistical and financial challenges presented by the vastness and remoteness of the Pacific Islands Region, more than anything else, structured the initial scope of this program and continue to inform its evolution.

The primary role of an ecosystem-based monitoring program is to provide characterization of natural variability in environments and biological communities that in turn enables detection and understanding of anthropogenic impacts. In marine environments, specifically for dynamic coral reef ecosystems, this role presents an unusual challenge. Patterns of natural variability are quantified over broad temporal and spatial scales. Temporal scales include diurnal, seasonal, episodic (e.g., weather and storms), interannual (e.g., El Niño Southern Oscillation), decadal (e.g., Pacific Decadal Oscillation), and longer-term climate changes. Spatially, reef ecosystems vary over scales ranging from meters to thousands of kilometers. Ecological zones, such as intertidal, lagoonal, or barrier reef, and habitat types, such as reef slope, forereef, reef crest, backreef, and patch reefs, often vary as a function of prevailing or episodic oceanographic conditions (waves and currents, water quality, terrestrial inputs, etc.).

To document climate frequency oscillations, Pacific RAMP surveys have been conducted every 2 years and are now undertaken every 3 years. With the exception of oceanographic and bioacoustic moorings, which collect data nearly continuously, the Pacific RAMP cannot detect high-frequency ecological fluctuations. The triennial Pacific RAMP surveys are designed to examine ecological variability (multiyear to multidecadal) over longer terms, taking snapshots of an ecosystem at the time that surveys are conducted there. As such, many years worth of these so-called "snapshots" are needed before rigorous discussion of long-term changes become possible.

Operational and dive safety protocols limit the large majority of the biological observations to daylight hours in areas experiencing "workable" weather, sea, and current conditions. Although some Pacific RAMP survey methodologies, such as towed-diver surveys, provide a safe working environment even in harsh conditions, all survey types have safety limits. Because of these operational limitations, it is probable that many species remain spatially or behaviorally isolated from our surveys. For example, nocturnal species of fishes and invertebrates or species found preferentially in high wave energy environments cannot be effectively monitored using the existing sampling protocols.

Methodological improvements have been made over time among different Pacific RAMP cruises, introducing a degree of data variability. Such changes are necessary and common during developmental stages of long-term monitoring programs and reflect the relative infancy of the Pacific RAMP. For more information about the methodologies of the Pacific RAMP surveys and other data collection efforts conducted around the Mariana Archipelago, see Chapter 2: "Methods and Operational Background."

Rapid Ecological Assessment (REA) and towed-diver surveys are the 2 general methodologies used to assess biological communities around each of the islands and reefs surveyed around the Mariana Archipelago during Pacific RAMP cruises. However, the spatial repeatability of these methods to date is still under consideration by CRED. The biennial surveys discussed in this report, therefore, have not explicitly surveyed precisely the same reef locations but instead reflect similar reef habitats and generally targeted depth strata (for further discussion of the depth and spatial limitations of survey methodologies, see Chapter 2: "Methods and Operational Background"). Changes in survey locations could have resulted in a high degree of variability among biennial data sets, especially considering the inherent spatial heterogeneity often observed in coral reef communities. Discussion of variability is incorporated within the context of the REA and towed-diver data analyses presented in this report.

For research that relies on consistent observer objectivity and training, reducing errors and biases are obvious yet difficult challenges. Ideally, observer bias could be largely eliminated with consistent research protocols and proper training and if repeated field observations are completed in the same areas by the same scientific observers over subsequent Pacific RAMP deployments. In reality, continuity among scientific personnel and reciprocity divers from multiple institutions is hard to achieve. Still, CRED is committed to improving consistency in field methodologies and onsite data collection and to implementing comprehensive, evolving training protocols (such as cruise-calibration dives) in an effort to account for and limit interobserver variability.

In addition to refining protocols and limiting interobserver variability, some protocols have been expanded or added to Pacific RAMP surveys in response to changing management priorities and an improved understanding of factors that affect coral reef ecosystems. Regular coral disease observations were added to the Pacific RAMP coral surveys beginning in

2006. Water sampling to determine carbonate chemistry was added in 2006 to better study the nature of chemical changes, such as ocean acidification, that are occurring on reefs. Chlorophyll-*a* and nutrient analysis from water sampling was added in 2004 and 2005, respectively, to measure the effects of sedimentation, runoff, and other factors influencing reefs. To improve the statistical validity of Pacific RAMP fisheries data and to meet new mandates in the *Magnuson-Stevens Reauthorization Act of 2006* to determine annual catch limits, CRED in 2008 incorporated a random stratified design for Pacific RAMP fish surveys using a stationary-point-count method, expanded the survey domain to encompass all hard-bottom habitat at depths of 0–30 m, and began steadily increasing the number of fish surveys conducted per Pacific RAMP cruise. While these changes are necessary to support improved stock assessments, there will be inherent effects on temporal comparisons. As part of the decade-long, international Census of Marine Life and its Census of Coral Reef Ecosystems project, the use of autonomous reef monitoring structures (ARMS) has been expanded to establish a global baseline of spatial patterns and initiate long-term monitoring of temporal changes in coral reef biodiversity. Development of techniques for processing the cryptic invertebrates that are collected with ARMS is ongoing. To form a baseline of accretion rates by crustose coralline red algae and hard corals, installations of calcification acidification units (CAUs) began in 2010, and data from CAUs will enable comparisons of net calcification rates between islands and archipelagos throughout the U.S. Pacific islands and help determine possible consequences of increased ocean acidity and lowered aragonite saturation states.

The CRCP and its predecessor, the Office of Habitat Conservation of the National Marine Fisheries Service, since 2001 have provided the significant majority of the financial support for CRED and the Pacific RAMP. In addition to program management and administrative support, this funding provides for the staffing of research cruises, the purchase of equipment and instrumentation, the completion of data analyses and management, and the production of publications associated with processed data. The availability of funds drives CRED's capacity, directly influencing the level of staffing for each of its research disciplines. Staff members are often at sea for 2–5 months per year, and this time away impacts the speed of data processing and dissemination. As a result, CRED is highly dependent upon local partners for supplementing staff support of research cruises. This involvement of local partners on research cruises brings local knowledge of coral reef resources to Pacific RAMP efforts but possibly negatively affects data consistency.

Large-scale data organization, quality control, and database structure are high priorities for the CRED scientific team. Proper data management and data flow practices are vital for streamlining and organizing the huge data sets that result from CRED's research in the Pacific. Significant progress has been made, as evidenced by this Coral Reef Ecosystem Monitoring Report for the Mariana Archipelago, and funding specifically for data management and infrastructure became available in FY 2007, but the implementation of data management protocols remains a work in progress.

While keeping in mind these constraints, CRED strives to increase efficiencies and improve all aspects of its scientific program. This report represents an installment of the ongoing effort of CRED to bring resource managers and interested stakeholders the best available, ecosystem-based data to help them make informed decisions about the sustainable use and conservation of their resources.

1.5 Structure of this Monitoring Report

Designed to present large-scale spatial and temporal snapshots of the coral reef resources in the Mariana Archipelago, this report is based on data collected during CRED-led MARAMP cruises in 2003, 2005, and 2007. Methodological descriptions and resulting analyses of habitat, oceanographic, and biological data sets are presented within discipline-specific categories. Under habitat mapping and characterization, for example, this report describes multibeam bathymetry and acoustic backscatter and optical validation based on TOAD and towed-diver benthic assessments. The category of oceanographic and water-quality monitoring includes spatial hydrographic surveys and time-series observations from moored instruments. Sections on biological community monitoring cover corals, algae, coral and coralline algal disease, other macroinvertebrates, and reef fishes.

To the extent possible, available socioeconomic data and information about human activities—including history, demographics, land use and cover, economic statistics, and environmental issues—have been incorporated into this report, along with coverage of geography and geology. A summary of this material for the Mariana Archipelago is provided in this "Introduction" chapter, and socioeconomic data pertinent to a particular island are included in the "Geopolitical Introduction" section of the chapter for that island. In Chapter 3 "Archipelagic Comparisons," socioeconomic data, on topics such as population and environmental stressors, are compared among the islands of the Mariana Archipelago to better understand how these factors interact and influence surrounding coral reef ecosystems.

Each chapter provides comprehensive, interdisciplinary data analyses for each island or bank. Habitat mapping and characterization data for each island or bank are presented as multiyear composite analyses across all survey years. Oceanographic and biological monitoring data are presented mostly in a cruise-specific sequence so that temporal and spatial patterns of abundance and distribution can be explored. The main body of this report includes data collected for each island, spatial and temporal analyses of this data, and an integrated, ecosystem-based assessment of findings. The final chapter of this report examines archipelagic comparisons of integrated ecosystem observations to evaluate similarities and differences among the islands of the Mariana Archipelago on a regional scale, including the large-scale processes that influence the coral reef ecosystems around them. Using a linear additive model, 2 sets of benthic, fish, and coral reef condition indices compare (1) all islands of the Mariana Archipelago and (2) only the 4 populated, southern islands. The first set of these indices appears in Chapter 3: "Archipelagic Comparisons," and versions of the second set appear in the "Ecosystem Integration" sections of Chapters 4, 5, 7, and 8 for the islands of Guam, Rota, Tinian, and Saipan.

This document provides scientific data to assist local, territorial, and federal stakeholders with the challenges they face in the long-term management and conservation of their coral reef ecosystem resources. The information in this report serves 3 main purposes:

- Provide overall spatial and taxonomic snapshots of the coral reef resources around each of the islands in the Mariana Archipelago during each survey period
- Form foundation of knowledge about ecosystem conditions in the Mariana Archipelago for ongoing monitoring of temporal changes
- Deliver tool for stakeholders and resource managers for investigating marine areas of interest and formulating evolving management questions about how to best manage marine resources

At the conclusion of each MARAMP cruise, data collected by CRED scientists and local partners have been presented to the resource management agencies in the CNMI and Guam in the form of cruise reports. These cruise reports contain summary information—including area and types of operations; itinerary and daily activity record; cruise statistics; missions; list of scientific personnel; and types of data collected. Appendices to these cruise reports have provided descriptions of the methods used for data collection for each discipline as well as summaries of key data and the types and numbers of surveys and other activities performed by island. This Monitoring Report for the Mariana Archipelago, then, is intended to provide in-depth analyses that complement the summary data provided in these cruise reports.

2 METHODS & OPERATIONAL BACKGROUND

The use of Pacific Reef Assessment and Monitoring Program (Pacific RAMP) field collection methodologies produces an interdisciplinary series of integrated ecosystem observations of coral reefs around ~ 50 islands, atolls, and shallow-water banks of the Mariana Archipelago, American Samoa, the Hawaiian Archipelago, and the Pacific Remote Islands Marine National Monument. Pacific RAMP data collections, led by the Coral Reef Ecosystem Division (CRED) of the NOAA Pacific Islands Fisheries Science Center (PIFSC), are designed to characterize the spatial and temporal variability of the distribution, abundance, and diversity of corals, algae, other macroinvertebrates, and fishes in the context of their benthic habitats and oceanographic environments within in the scope of these surveys.

This report provides information from Pacific RAMP research cruises conducted in 2003, 2005, and 2007 in the Mariana Archipelago. To document the nature and temporal variation of the data gathered and to provide a context for how surveys were performed, the operational background of these 3 Mariana Archipelago RAMP (MARAMP) expeditions and details on the suite of assessment and monitoring methods employed during these cruises are presented in this chapter. Descriptions of data collection and processing methodologies are also supplied.

Although CRED collects most of its ecological and oceanographic observations every 2 years during Pacific RAMP research cruises, time-series observations of some key environmental conditions that influence reef processes are also made continuously by an array of moored oceanographic and bioacoustic instruments deployed and maintained as part of the NOAA Coral Reef Watch (CRW) program. These biological and environmental observations are further complemented by a suite of benthic habitat mapping products developed collaboratively by CRED and the Biogeography Branch of the NOAA Center for Coastal Monitoring and Assessment (CCMA), National Centers for Coastal Ocean Science. Collectively, CRED's Pacific RAMP, CRW, and benthic-habitat-mapping efforts are part of the NOAA Coral Reef Ecosystem Integrated Observing System (CREIOS) in the Pacific.

There are several primary objectives for these Pacific RAMP activities in the U.S. Pacific islands:

- Conduct benthic habitat mapping of reefs and submerged banks using ship- and launch-based multibeam sonars (echosounders), underwater towed-camera systems, and towed-diver surveys for characterizing the benthic environments that provide habitat and shelter for reef biota

- Conduct nearshore and offshore oceanographic and water-quality surveys and deploy a variety of surface and subsurface oceanographic and bioacoustic instruments to quantify, assess, and gain a better understanding of the overall hydrographic and bioacoustic parameters that influence reef biota

- Employ complementary and overlapping methods to assess and monitor species composition, abundance, percentage of cover, size distribution, diversity, and general health of fishes, corals, algae, and other macroinvertebrates in shallow-water (< 35 m) habitats

- Assess and monitor diseases of corals and coralline algae

- Conduct broadscale towed-diver surveys that provide a spatial assessment of the composition and condition of shallow-water benthic habitats and of the general distribution and abundance patterns of ecologically or economically important macroinvertebrates and reef fishes (> 50 cm in total length)

- Ascertain the existence of threats to the health of coral reef resources from natural or anthropogenic sources

Integrated ecosystem observations and monitoring of this scope were unprecedented in the waters of the Mariana Archipelago, which includes the territory of Guam and the Commonwealth of the Northern Mariana Islands (CNMI). As such, the initial interdisciplinary research expeditions for the Pacific RAMP were exploratory in nature, often providing the first-ever baseline assessments of reef resources in these mostly remote and uninhabited regions of the Pacific. As analyses of these initial baseline assessments have progressed, the Pacific RAMP has shifted to a long-term ecosystem monitoring phase. The suite of methods used by this program also has steadily evolved to improve the quality of the data. The comprehensive nature of this interdisciplinary research program is evident in Table 2a, which summarizes by year survey efforts in the Mariana Archipelago.

Table 2a. Survey efforts in the Mariana Archipelago summarized by year for the period of 2003–2007. Activities included benthic habitat mapping with multibeam echosounders; towed optical assessment device (TOAD) surveys; Rapid Ecological Assessment (REA) surveys; towed-diver surveys; shallow-water and deepwater conductivity, temperature, and depth (CTD) casts; water-quality sample collection, and deployment of a suite of moored oceanographic and bioacoustic instruments. Vessels included the NOAA Ships *Oscar Elton Sette* and *Hi`ialakai* and the R/V *Acoustic Habitat Investigator* (*AHI*), and in 2004 TOAD surveys were conducted from a chartered 19-m boat.

Survey Type	Survey Detail	Year				Total
		2003	2004	2005	2007	
	Vessels	OES/AHI	Charter	Hi'i	Hi'i/AHI	
Multibeam	Total Survey Area (km^2)	244.2	–	–	1,2992.0	**1,3236.2**
TOAD	Number of Surveys	110	41	–	–	**151**
	Total Length (km)	72.05	136.26	–	–	**208.31**
REA–Fish	Number of Surveys	72	–	74	66	**212**
REA–Benthic	Number of Surveys	85	–	74	67	**226**
Towed Diver	Number of Surveys	161	–	136	115	**412**
	Total Survey Area (ha)	309.9	–	267.6	262.0	**839.5**
CTD–Shallow water	Number of Casts	249	–	327	273	**849**
CTD–Deep water	Number of Casts	–	–	70	36	**106**
Water Quality	Number of Water Samples	–	–	57	69	**126**
Moored Instruments	Number Deployed	19	1	28	48	**96**
	Number Retrieved	–	1	14	28	**43**

2.1 Operational Background

As part of this Pacific-wide monitoring effort, CRED conducted its first MARAMP cruise in 2003 with subsequent cruises in 2005 and 2007. Partners from local resource management agencies—including scientists and managers from Guam's Division of Aquatic and Wildlife Resources (DAWR) and Bureau of Statistics and Plans (BSP), the Guam Environmental Protection Agency (GEPA), the University of Guam (UG), and the CNMI's Division of Fish and Wildlife (DFW), Division of Environmental Quality (DEQ), and Coastal Resources Management (CRM) Office, as well as the National Park Service (NPS) and Western Pacific Fishery Management Council (WPFMC)—worked alongside CRED scientists to determine and establish monitoring sites and plan and conduct surveys.

The following individuals from the CNMI and Guam participated in the planning or implementation of MARAMP cruises:

- **2003:** Fran Castro (DEQ), Peter Houk (DEQ), Trina Leberer (DAWR), Kate Moots (DFW), and Michael Trianni (DFW)

- **2005:** Fran Castro (DEQ), Tony Flores (DFW), Peter Houk (DEQ), John Iguel (DEQ), Andrew Kerr (UG), Edson Limes (DEQ), Nick Pioppi (UG), Valerie Brown (DAWR), Qamar Schuyler (DEQ/CRM/DFW), Michael Tenorio (DFW), Brent Tibbetts (DAWR), and Michael Trianni (DFW)

- **2007:** Valerie Brown (NOAA Fisheries Pacific Islands Regional Office, Guam), Peter Houk (DEQ), Edson Limes (DEQ), Allison Palmer (NPS Guam), Tom Schils (UG), John Starmer (CRM), and Michael Tenorio (DFW)

Planning of MARAMP cruises also included the following individuals: John Calvo (WPFMC), Erica Cochrane (CRM), Ken Cochrane (CRM), Gerry Davis (DAWR), Mike Gawel (GEPA), Jay Gutierrez (DAWR), Sylvan Igisomar (DFW), John Joyner (CRM), Becky Lizama (CRM), Evangeline Lujan (BSP), Dwayne Minton (NPS), Frank Rabauliman (DEQ), Bob Richmond (UG), Peter Schupp (UG), and Adam Turner (advisor to CNMI Office of the Governor).

These first 2 MARAMP expeditions were conducted from the NOAA Ship *Oscar Elton Sette* between August 19 and September 30, 2003, and between August 16 and October 9, 2005. The third cruise was conducted from the NOAA Ship *Hi`ialakai* between May 12 and June 9, 2007 (Fig. 2.1a). This change to a different time of year in 2007 was made to better avoid the typhoon season and, thus, lower the probability of weather disrupting a cruise. This shift to a different season led to significant differences in oceanographic and biological observations.

The *Oscar Elton Sette* and *Hi`ialakai*, as well as their officers and crews, have different capabilities and limitations. The *Oscar Elton Sette* can accommodate a complement of 20 scientists and carry and deploy multiple small boats. During the MARAMP 2003 expedition, CRED's 8-m multibeam survey launch R/V *Acoustic Habitat Investigator* (*AHI*) was transported to Saipan, launched, and recovered in Guam. The *AHI* was carried on the stern of the *Oscar Elton Sette* and deployed using this ship's crane. The use of the *Hi`ialakai* in 2007 increased the maximum complement to 22 scientists and significantly improved the ability of CRED to conduct benthic habitat mapping missions. The *Hi`ialakai* had hull-mounted shallow-water and deepwater multibeam systems and was able to carry the *AHI* in dedicated davits, which allowed for deployment of the *AHI* at sea. The *Hi`ialakai* is also equipped with diesel-powered, 8-m and 10-m small boats, a cascade nitrox compressor system, and a permanently installed diving recompression chamber.



Figure 2.1a. The NOAA Ships (*left*) *Oscar Elton Sette* and (*right*) *Hi`ialakai* were used to conduct MARAMP cruises in 2003, 2005, and 2007. *NOAA photos*

CRED has also increased its small-boat and dive-support capabilities with the addition of two 6-m boats (SAFE Boats International) and a portable cascade Nitrox compressor system. Over the MARAMP survey period of 2003–2007, support of diving operations was enhanced as the NOAA Dive Center endorsed the transition from exclusive use of decompression tables to the standard use of dive computers and began providing a portable recompression chamber aboard the *Oscar Elton Sette* during cruises that required extensive diving operations.

2.2 Benthic Habitat Mapping and Characterization

Accurate, high-resolution benthic habitat maps are essential tools for the effective conservation and management of coral reef ecosystems. CRED, through its Pacific Islands Benthic Habitat Mapping Center (PIBHMC), conducts mapping operations during dedicated mapping cruises, expeditions that combine Pacific RAMP and mapping objectives, and cruises that piggyback mapping operations with other missions. Using data collected during these cruises, a suite of thematic map products are created and made available to resource management agencies, researchers, and the general public.

Bathymetry is the study of the seafloor, and bathymetric data can be used to illustrate underwater terrain. High-resolution bathymetric data collected with multibeam echosounders serve as the primary base layer for CRED's benthic habitat mapping. The highly accurate and detailed maps generated from these data are useful for a number of management and research applications. Maps derived from these bathymetric data illustrate or highlight other seafloor characteristics, including slope, rugosity (a measure of topographic roughness), and bathymetric position index (BPI) zones (a BPI defines elevations of locations in reference to the overall seafloor).

In addition to bathymetric and derived data products, modern multibeam echosounders produce data about the intensity of returning acoustic signals (backscatter) that provide an indication of the roughness and hardness of the seafloor. Backscatter and bathymetry data, for example, were used to produce hard–soft substrate maps. Used in various combinations, depth, slope, rugosity (roughness), and backscatter intensity can yield information about seafloor characteristics relevant to specific groups of organisms, and such information can be used to identify and delineate the benthic habitats of key organisms.

Optical data are used to validate (or ground truth) interpretations of acoustically derived information. Toward this end, towed optical assessment device (TOAD) surveys and towed-diver surveys routinely produce observation data, still photographs, and video imagery of the seafloor. Optical data are also useful for discerning seabed information in very shallow waters, where logistical constraints may hinder or prevent multibeam acquisition.

2.2.1 Operational Background and Logistics

The U.S. Coral Reef Task Force (CRTF) identified mapping of all U.S. coral reef habitats as one of its highest priorities in the 2000 National Action Plan to Conserve Coral Reefs. Meanwhile, NOAA's CRCP established a goal to map all U.S. coral reef areas to assist in the conservation and management of U.S. coral reefs. In support of these goals, CRED and the CCMA Biogeography Branch have been leading efforts to produce benthic habitat maps of U.S. coral reef areas from the shoreline to moderate depths (≤ 1000 m). The Biogeography Branch has been leading collaborative efforts to develop shallow-water benthic habitat maps using aerial and satellite-based methods. Because of visibility constraints, these techniques are best suited for shallow-water habitats (depths ≤ 20 m). CRED has been leading efforts using multibeam acoustic echosounders and optical assessment technologies to extend existing shallow-water maps to moderate depths (~ 15–1000 m) where aerial- and satellite-based techniques are less suitable.

The NOAA Ships *Oscar Elton Sette* and *Hi`ialakai* were used to support mapping operations in the Mariana Archipelago on 3 expeditions conducted in 2003, 2005, and 2007, and the R/V *AHI* was deployed in 2003 and 2007 to conduct shallow-to-moderate depth habitat mapping.

A variety of operational scenarios have been developed to optimize the efficiency of mapping operations. In 2003, the R/V *AHI* was offloaded from the *Oscar Elton Sette* in Saipan and picked up later in Guam; *AHI*-based multibeam mapping operations were conducted independently at Saipan, Tinian, Rota and Guam while the *Oscar Elton Sette* worked in more remote locations. During these operations, the *AHI* also performed a reconnaissance survey of Saipan Harbor at the request of the harbormaster of the Commonwealth Port Authority. Optical-validation data were collected during nighttime hours using the TOAD camera-sled deployed from the *Oscar Elton Sette* at depths of 20–150 m and during daylight hours using launch-based towed-diver surveys at depths of 3–30 m.

In 2004, after learning about the multibeam and optical data collected by CRED in Saipan Harbor and Garapan Anchorage (where the U.S. Military Sealift Command [MSC] routinely anchors prepositioned supply ships), the U.S. Naval Facilities Engineering Command (NAVFAC) and MSC funded CRED collection of an additional 123 linear km of optical data during an independent shore-based deployment. In 2005, multibeam bathymetry and backscatter and optical data were used to analyze the substrates in the Garapan Anchorage and to produce a report for the NAVFAC and MSC (Rooney et al. 2005).

Because of shipboard staffing, funding, and limitations on the *Oscar Elton Sette*, no multibeam or TOAD operations were conducted during the MARAMP 2005 expedition. Still, routine towed-diver surveys were performed. During MARAMP 2007 cruises aboard the *Hi`ialakai*, shipboard multibeam mapping surveys were conducted primarily during nighttime hours to avoid interfering with daytime reef ecosystem monitoring and nearshore oceanographic surveys that require small-boat and diver-based operations. R/V *AHI*-based mapping operations were conducted during daylight hours to perform multibeam surveys in shallow, nearshore waters inaccessible to the *Hi`ialakai*. In addition, 10 d of time on the R/V *AHI* were dedicated to conducting surveys of the harbors of Saipan, Tinian, and Rota to International Hydrographic Organization standards in collaboration with NOAA's Office of Coast Survey and National Geodetic Survey as well as the CNMI Commonwealth Port Authority and in support of safe navigation in CNMI waters.

Operationally, both multibeam surveying and optical data collection have depth limitations. As a general rule, multibeam surveys by CRED have focused on depths of ~ 15–1000 m. This 15-m inshore limit is based on (1) safety concerns relating to increased risks of groundings or breaking waves in shallow water and (2) significant decreases in mapping efficiencies because the area that a surface vessel can map decreases proportionally to depth.

Similarly, optical data collection using ship-based TOAD surveys has been limited to depths of ~ 20–150 m, because of the depth limitations of instruments and ship safety concerns. Towed-diver surveys provide optical data to a maximum depth of 30 m. Ship- and launch-based multibeam surveying, as well as TOAD and towed-diver survey procedures, adhere strictly to NOAA safety policies applicable to ship, small-boat, and scuba-diving operations.

2.2.2 Acoustic Mapping

Equipment

The *Hi`ialakai* is equipped with a Kongsberg 300-kHz EM 3002D multibeam sonar that can map at depths of ~ 15–150 m and a Kongsberg 30-kHz EM 300 multibeam sonar that can map at depths of ~ 50–3000 m. Because the *Hi`ialakai* had standing orders that limit the minimum depth of nighttime operations to 200 m on almost all surveys, the EM300 was the only sonar used in 2007. The *AHI* is equipped with a 240-kHz Reson SeaBat 8101 ER multibeam sonar that can map at depths of ~ 10–300 m. When used in conjunction with the *Hi`ialakai*, the *AHI* can be deployed and recovered in locations far from sheltered harbors, making shallow-water surveys possible throughout remote areas of the U.S. Pacific islands (Fig. 2.2.2a).

Hand-held, single-beam echosounders were used in 2003 from small boats to survey the remote areas of Zealandia Bank, Stingray Shoal, Supply Reef, Pathfinder Reef, and 2 unnamed banks. These surveys were performed because rudimentary bathymetric data were needed to locate habitats for potential ecosystem assessments.



Figure 2.2.2a. The survey launch R/V *AHI* and NOAA Ship *Hi`ialakai* are outfitted with 3 multibeam echosounders that facilitate mapping at depths of ~ 15–3000 m. *NOAA photo*

Survey Design

The quality and geographic coverage of existing bathymetric data, as well as consultation with key resource managers and stakeholders, were used to determine mapping survey priorities. Existing nautical charts served as the primary base for the initial planning process. Prior to 2003, almost no modern shallow bathymetric data existed for the Mariana Archipelago, except for a limited amount of then-unavailable light detection and ranging, or lidar, data collected by the U.S. Navy. Most existing nautical charts were based on Japanese surveys conducted before and during World War II. In 2003, the Saipan harbormaster requested NOAA to perform a survey of Saipan Harbor because of suspected shoal soundings in the channels and hazards to navigation.

During the cruise in 2003, the R/V *AHI* mapped around Saipan and Tinian with almost complete coverage at depths from 20 to 250 m. The southern shore of Rota in the Sasanhaya Fish Preserve and the northern shore of Guam in the Pati Point Marine Preserve were mapped after consultation about priority survey areas with CNMI and Guam officials.

During the first of 2 cruises in 2007 in the southern part of the Mariana Archipelago, CRED personnel aboard the *Hi`ialakai* conducted surveys at depths > 300 m, with some deeper than 1000 m, around most of Guam, Rota, Aguijan, Tinian, and Saipan. During the second of the 2 cruises in 2007 around this archipelago's more isolated northern islands, *AHI* surveys were conducted at depths of 15–300 m around the islands of Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros as well as on Zealandia Bank and Supply Reef. Multibeam operations on the *Hi`ialakai*, including multibeam data collection at depths > 300 m during transits between islands and at Anatahan, were conducted during limited periods in daylight hours and almost continuously at night to complement and overlap the *AHI* shallow data and to fill in gaps in an overall synthesis of data sets from several organizations.

Data Acquisition

Since 2004, the R/V *AHI* and *Hi`ialakai* have been the exclusive platforms for CRED multibeam mapping missions. Real-time data acquisition and processing often occurred concurrently and involved several processing steps and software packages. For more details, see the "Documentation" section of the PIBHMC Web site at http://www.soest.hawaii.edu/pibhmc/pibhmc_documentation.htm.

Multibeam data were collected with an ISS-2000 collection module from the Science Applications International Corporation (SAIC, McLean, Va.). Sensors were interfaced to the system through a software module called a data transaction center (DTC), which was used to set sensor settings, calibration parameters, quality-control parameters, input formats, and output file formats. Each of the DTC modules stored data from its corresponding sensor in the appropriate file formats and assigned the appropriate names to each file. Most data were stored in ASCII text files, but the binary generic sensor format (GSF; Ferguson and Chayes 1995; SAIC 2008) was used specifically for multibeam data. Each unique filename was based on the sensor collecting the data, collection date, and a sequential extension.

A benefit of the ISS-2000 integrated survey system is that all sonar correctors are applied in real time during data collection. All data were displayed in real time for quality control and guidance of survey progress. Each GSF echosounder file not only stored all information necessary to provide the depth for each beam but also contained a permanent record of every action taken during data collection and processing.

Data Processing

Collected data were corrected for ship motion, navigation, sound velocity, and predicted tides, if selected. Predicted tidal correctors were applied, using data from the NOAA Center for Operational Oceanographic Products and Services, to multibeam data during collection to minimize apparent errors that may be caused by tide offsets or other system problems. Many of these corrections can be reapplied or changed, if desired, using SAIC's survey analysis and area-based editor (SABER), a compatible data processing package. To the majority of multibeam bathymetric data collected, 4 processing steps were applied:

- Application of alternate sound velocity profiles to a limited number of multibeam swath files
- Application of corrected tides (if available and needed) to some or all multibeam swath files to replace the predicted tides applied in real-time during data collection
- Visual editing of individual multibeam swath data files in GSF
- Assembly of all data in a given area within a Pure File Magic (PFM) grid and visual editing using an area-based editor

After edits were made to a PFM grid, data were downloaded back to their GSF files, where flags were set to indicate edits. These processed GSF files were used for data synthesis work at the PIBHMC and were documented with metadata; GSF files with metadata were sent to the NOAA National Geophysical Data Center on a cruise-by-cruise basis.

After grid editing was completed, a PFM grid was exported to ASCII or other grid formats, or the original GSF files were regridded and output to these formats. Standard grids were performed at 5 m, 10 m, or 60 m, depending upon the depth range and resolution required for a specific map. In general, 60-m grids are used for regional views that include deepwater

areas, while 5- and 10-m grids are used for high-resolution maps of shallow areas. GSF, ASCII, or other grid files were then transferred to other data processing and visualization packages, including ArcGIS (Environmental Systems Research Institute Inc. [ESRI], Redlands, Calif.) and the following open-source systems:

MBSystem: an open-source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars (http://www.mbari.org/data/mbsystem/).

Generic Mapping Tools: an open-source collection of tools for manipulating XY and XYZ data sets and producing gridded data in a variety of formats and visualizations in the encapsulated postscript format (http://www.soest.hawaii.edu/gmt/).

Backscatter data were collected and stored as part of standard GSF files and processed at the PIBHMC using software developed at the University of Hawai`i by the Hawai`i Mapping Research Group to process seafloor acoustic imagery files. This software has been modified to accept GSF backscatter data from the Reson 8101 ER and Kongsberg EM 300 and EM 3002D multibeam sonars. The following steps were included in backscatter data processing: file conversion, splitting, speckle and microstrip removal, angle-varying gain correction, and assignment of data to a grayscale color map. For a complete discussion of these processing steps, see the "Multibeam Backscatter Processing Overview" document on the PIBHMC Web site (http://www.soest.hawaii.edu/pibhmc/pibhmc_documentation.htm).

Several issues regarding backscatter data and processing affect the subsequent products, such as hard–soft substrate and backscatter maps. A number of different parameters contribute to backscatter intensity values, including sonar frequency and settings (e.g., power, range, and gain), operational procedures (e.g., speed and consistent survey direction), and seafloor characteristics (e.g., slope, roughness, and hardness). Thus, although backscatter intensity is a valuable tool for investigating seafloor characteristics (e.g., roughness and hardness), backscatter values reflect a combination of parameters, and distinguishing the effect of one parameter from others may not be possible.

The most important factors that have caused noticeable artifacts or differences in data sets are sonar frequency, settings, slope, and survey procedures. Sonar frequency is inversely related to wavelength, and different wavelengths penetrate and interact with substrate in different manners (e.g., low frequencies penetrate more than high frequencies). Thus, trying to merge backscatter data sets from 2 different frequencies (30 kHz and 240 kHz) is not advisable, particularly for soft substrates. The second major issue is that sonar settings, particularly on the Reson 8101 ER multibeam, were changed in some very steep nearshore areas where operators were trying to map in depths near the maximum range of that sonar. Often, the deepest Reson 8101 ER swath shows very different characteristics than shallower ones, because of erratic sonar settings or steep slopes. Therefore, for some islands, the outer swath was discarded or the backscatter data was clipped at a uniform depth to improve the quality of hard–soft maps. Finally, survey procedures also greatly influence the quality of multibeam backscatter data. The MARAMP 2003 surveys, which were some of the first done by CRED while standard survey procedures were still under development, were often performed at higher speeds than surveys in later years. Although, to optimize backscatter data quality, it is desirable to run straight lines at uniform depths, it is almost impossible to run straight-line surveys around the small, steep islands of the CNMI. Survey swaths, then, were mostly "doughnuts" with nearshore beams looking upslope and offshore beams looking downslope—not an ideal scenario for producing high-quality backscatter data.

Bathymetry and Backscatter Derivatives

Additional analyses of the bathymetric grids provide slope, rugosity, and BPI parameters that are useful for determining the character of the seafloor and associated benthic habitats (Fig. 2.2.2b):

- **Slope:** Cell values reflect the maximum rate of change (°) in elevation between neighboring cells. Slope was derived from multibeam bathymetry using the ArcGIS Spatial Analyst tool (version 9.3).

- **Rugosity:** Cell values reflect the ratio of surface area to planimetric area for the area contained within a cell's 9-cell neighborhood. They provide indices of topographic roughness and convolutedness (Jenness 2004). Distributions of fishes and other mobile organisms are often found to positively correlate with increased complexity of the seafloor. Investigations are underway to determine which of the many methods available for quantifying benthic complexity best correlate with fish distributions in Pacific coral reef ecosystems. Results using the method described in the Jenness (2002) ArcView extension are provided as a standard and well-documented interim product. ArcGIS 9.3 and the Benthic Terrain Modeler, downloadable from the NOAA Coastal Services Center (http://www.csc.noaa.gov/products/btm/), were the tools used to derive rugosity.

- **BPI:** Bathymetric position index is a second order derivative of bathymetry that evaluates differences between the elevation of a focal point and the mean elevation of the surrounding cells within a user-defined annulus or circle. A negative value represents a cell that is lower than its neighboring cells (depressions), and a positive value represents a cell that is higher than its neighboring cells (crests). The larger the numbers, the more prominent the features on the seafloor that differ greatly from surrounding areas. Flat areas or areas with a constant slope produce values near zero (Lundblad et al. 2006). ArcGIS and the Benthic Terrain Modeler were the tools used to derive BPI.

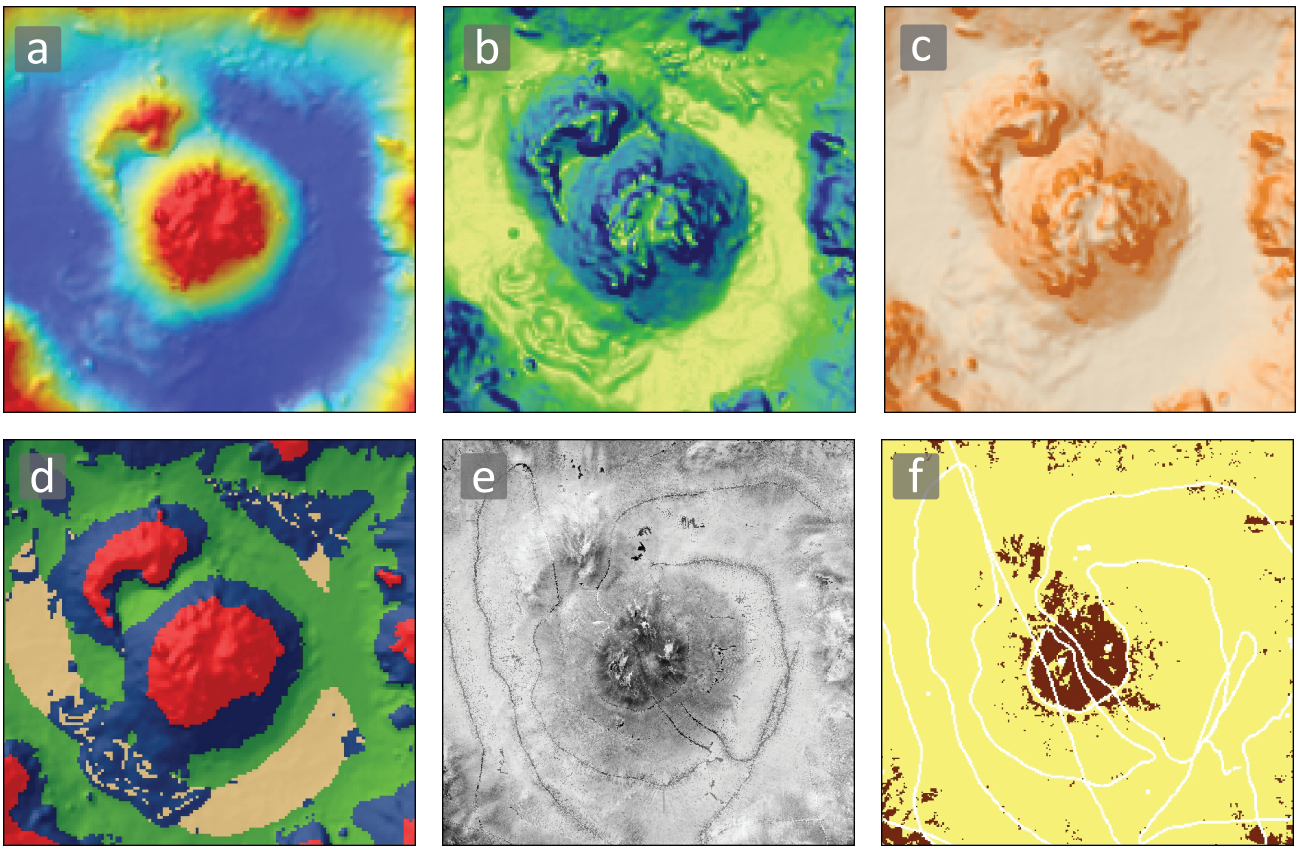


Figure 2.2.2b. Benthic habitat mapping data provide valuable information about seafloor characteristics, as seen, for example, in the above images of the caldera of Maug: (*a*) multibeam bathymetry, (*b*) slope, (*c*) rugosity, (*d*) BPI zone, (*e*) multibeam backscatter, and (*f*) hard and soft substrates.

All of the previous analyses are performed on 5- or 10-m grids of bathymetric data, clipped to 400-m or 800-m depths, respectively. These cutoff depths were chosen to ensure that grid cell size has approximately the same resolution as the average footprint of the original swath data over a range of depths.

Multibeam (bathymetry and backscatter) and optical-validation data were used to derive substrate maps in the following manner: Cell values reflect whether the seafloor is hard bottom (solid rock, boulders, and rubble) or soft bottom (sand and mud), based on an unsupervised classification run in ENVI software (version 4.3, ITT Visual Information Solutions, Boulder, Colo.). These classifications were based on backscatter, bathymetry, and acoustic derivatives. Substrate classification (hard bottom versus soft bottom) was derived from a combination of backscatter imagery and bathymetric variance and the results were then compared to optical-validation data using ENVI software, rather than first using optical data to supervise or instruct the ENVI software in a "supervised" classification process. Weiss et al. (2008) documented the development of the PIBHMC methods for unsupervised hard–soft substrate classification in a paper available on the center's Web site.

2.2.3 Combined Bathymetry Maps

For 4 islands, additional bathymetry data were available to complement the multibeam data collected by CRED, specifically providing more complete coverage in shallow areas. These bathymetry data were either collected by lidar or derived

from IKONOS satellite imagery. This section explains how these 2 types of data were acquired and how each type was combined in different ways with the multibeam data collected by CRED to create integrated bathymetry maps.

Lidar and Multibeam Data

The Naval Oceanographic Office of the U.S. Navy conducted bathymetric surveys at priority areas around the southern islands of the Mariana Archipelago between January 8 and March 20, 2001 (Naval Oceanographic Office 2004). The primary sensors used for these surveys from the shoreline to the lidar extinction depth (~ 20–40 m in these areas) were a scanning hydrographic operational airborne lidar survey (SHOALS) system on a DeHaviland Twin Otter aircraft.

Surveys were conducted in 5 primary areas:

- Guam: inner and outer Apra Harbor, Agat Bay (tide corrected)
- Guam: coastal areas specified by the U.S. Geological Survey, U.S. Fish and Wildlife Service, and U.S. Army Corp of Engineers (no tide corrections)
- Saipan: offshore and inshore anchorages and harbor
- Tinian: northern training area, southern coastline and anchorage, Tinian Harbor
- Farallon de Medinilla

In areas beyond the lidar extinction depth, bathymetric data were also collected aboard the USNS *Sumner*, using this ship's Simrad EM1002 multibeam echosounder.

For the Guam combined data set, areas too deep for lidar were surveyed using single-beam sonar. For the Tinian, Saipan, and Farallon de Medinilla combined data sets, areas too deep for lidar were surveyed using multibeam sonar.

Estimated Depths from IKONOS Satellite Imagery

Satellite remote-sensing imagery, primarily from IKONOS satellites, has been purchased by the CRCP for almost all of the U.S. Pacific islands. This imagery has been used to create benthic habitat maps using visual interpretation methods and as a visual base layer for many maps. The use of satellite remote-sensing data (e.g., IKONOS, QuickBird) to derive "estimated depths" has been a topic of research since the publication in 1978 of an early paper by David R. Lyzenga (Lyzenga 1978). A recent study supported by CRED (Hochberg et al. 2007) compared a number of different methods and demonstrated that the most accurate method was simple, empirical multiple linear regression against known depths (Lyzenga 1985). In general, derivation of estimated depths is most successful in relatively shallow water (< 20 m) and where overlapping depth data from multibeam or lidar sources are available for verification.

CRED has supported a project to derive estimated depths and perform error analyses using the Lyzenga (1985) method in areas where (1) the available IKONOS imagery is of high quality, (2) there are shallow banks (as opposed to steep flanks) where this technique might successfully be used, and (3) enough overlapping multibeam or lidar data exist to calibrate each image. In the Mariana Archipelago, acceptable estimated depths wre derived around Tinian. Other areas under investigation for estimated depth derivation include Saipan and Maug. This method allows data gaps to be filled, particularly in nearshore areas where neither multibeam nor lidar depth data are available.

Data Processing

When additional bathymetric data were available for areas where CRED was unable to obtain multibeam data, these data were combined with the multibeam data collected by CRED to produce an integrated depth grid and map. Once an integrated depth map was generated, it then was used to derive slope, rugosity, and BPI estimates.

One test of whether estimated depths accurately depict the seafloor is to evaluate adjacent rugosity values, comparing areas of estimated depths with multibeam or lidar data. If estimated depths consistently show higher rugosity than measured depths, which would indicate higher noise in estimated depths, then rugosity derived from those estimated depths should

not be used for interpretation. Also, it is not possible to derive hard–soft maps from these integrated depth maps because the hard–soft product is dependent upon the use of multibeam sonar backscatter data.

2.2.4 Optical Validation

Observations from towed-diver and TOAD surveys provide information about the seabed that is complementary to the acoustic products. Although acoustic techniques are invaluable in providing seafloor maps with high spatial coverage, acoustic signals can be influenced by factors other than the acoustic character of the seabed. Therefore, direct observations from towed-diver or TOAD surveys are an important tool for validating the seabed characteristics predicted by acoustic maps.

TOAD Surveys

CRED has used camera sleds to collect optical seafloor characterization data since 2001. The first TOAD configuration, used in the Mariana Archipelago in 2003, integrated a digital still camera, an underwater video camera, lights, a sonar altimeter, pressure transducer, and parallel scaling lasers on a Guideline Instruments Ltd. (Smith Falls, Ontario, Canada) MiniBAT 8820 tow body (Fig 2.2.3a). Typically, the TOAD is maintained at ~ 1–5 m above the seafloor but may frequently fly higher because of operational constraints. The TOAD operator entered the estimated layback distance into the MiniBAT software, which integrated the device with ship position to provide estimated positions of the tow body along survey tracks. Estimated positional accuracies using this method were on the order of 50 m. Various operational scenarios were tested, and, after several cruises, the technique of towing the TOAD at speeds of 0.5–1 kt in a drift mode was most effective and presented the least overall risk to both the tow body and shipboard personnel operating the winch, particularly over high-relief terrain.

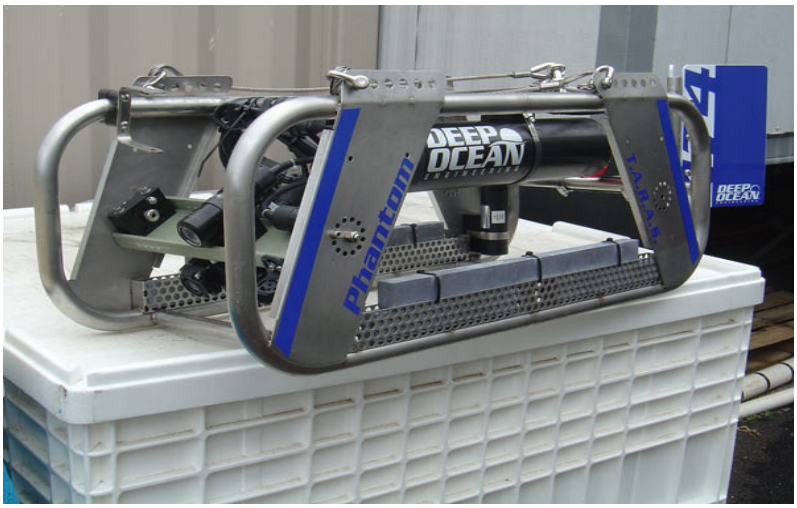


Figure 2.2.3a. TOAD configuration used in 2004 in the Mariana Archipelago to collect optical seafloor characterization data. These devices combine a digital still camera, underwater video camera, lights, and other equipment.

For the completion of the project to collect additional optical data at the Garapan Anchorage in 2004, camera sleds that could be deployed from small boats were required. Two new sleds, using a modified Phantom ROV frame were designed and built by Deep Ocean Engineering of San Leandro, Calif. These TOADs were equipped with a Deep Sea Power & Light Multi-SeaCam 2060 low-light color video camera, two 500-watt Deep Sea Power & Light model 710-0400601 underwater lights, a Tritech International PA200-20 sonar altimeter to detect the height of the camera above the seafloor, a Deep Sea Power & Light SeaLaser 100 parallel laser-pair for scaling, a compass for determining sled headings, and a depth (pressure) sensor. These camera sleds were attached to a control console via 200 m of 1.27-cm diameter umbilical cable. A video display monitor mounted on the control console was used to monitor the position of a sled relative to the seafloor. Video data were recorded to digital video cassette using a video recorder also mounted on the control console. Hypack Max (version 2.12A, Hypack Inc., Middletown, Conn.) hydrographic survey software was used to record global positioning system (GPS) data, depth, length of umbilical cable in the water, and camera-sled information (altitude, heading, etc.), which provide ship and camera-sled positions for the duration of individual TOAD surveys.

TOAD operations were conducted in 2003 around the following islands and banks: Guam, Santa Rose Reef, Galvez Bank, 11-mile Reef, Rota, Aguijan, Saipan, Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, Farallon de Pajaros, Esmeralda Bank, Zealandia Bank, Supply Reef, Arakane Reef, Pathfinder Reef, and Stingray Shoal. In 2004, an additional 123 linear km of optical data were collected in the Garapan Anchorage off Saipan.

Seafloor videography collected during TOAD deployments were analyzed using a series of 5 small, fixed circles extending in a straight horizontal line marked on a video monitor screen. The types of substrate and living cover that fell within these circles were identified at 20-m or 30-s increments along a camera's trackline. Some video frames from TOAD footage were not analyzed because of poor image quality.

Types of substrate included sand, rock, and rubble, and types of living cover included macroalgae, crustose coralline red algae, hard (scleractinian) coral, and other benthic fauna. Other biologically relevant observations were made as well. The full listing of benthic habitat classifications is shown in Table 2.2.4a. TOAD habitat classifications are incorporated in attribute tables associated with ArcView shapefiles that show the location of TOAD tracks over the seafloor. The TOAD data presented in this report are percentages of sand cover, live-hard-coral cover, and macroalgal cover.

Table 2.2.4a. Benthic habitat classifications used in analysis of video from TOAD surveys.

Zones	Classes	Zones	Classes
Depression	Narrow depression	**Slopes**	Lateral midslope depression
	Broad depression with open bottom		Open slope
	Local crest in depression		Lateral midslope crest
System	Basalt island		Steep slope
	Sea stack	**Coral (Growth) Morphology**	Massive
	Carbonate island		Platelike
	Closed atoll		Encrusting
	Open atoll		Branching
	Submerged bank/reef		Columnar
	Continental reef		Free living
Living Cover	Scleractinian corals	**Holes**	No cavities
	Non-scleractinian corals		Few small cavities
	Coralline algae		Many small cavities
	Corals or coralline algae		Few large cavities
	Macroalgae		Many large cavities
	Turf algae		Few small and large cavities
	Unclassified algae		Many small and large cavities
	Emergent vegetation		Many small and few large cavities
	Giant clams	**Substrate**	Unconsolidated (mud)
	Other Non-mobile invertebrates		Unconsolidated (sand)
Crests	Depression on crest		Hard bottom (rubble)
	Narrow crest		Hard bottom (boulder)
Flats	Local depression on flat		Hard bottom (rock)
	Broad flat		Hard bottom (man-made structure)
	Shelf		
	Local crest on flat		

Towed-diver Surveys

Data that characterizes the benthic habitats around the Mariana Archipelago in depths of 3–30 m were collected during towed-diver surveys as part of MARAMP 2003, 2005 and 2007. These benthic habitat characterizations provided background for analyses of biological data collected during towed-diver surveys and for validation (ground truthing) of habitat maps created with acoustic or satellite-derived information. A brief overview of towed-diver surveys and details on the benthic habitat categories used to make habitat characterization maps are presented in this section. The data collected during towed-diver benthic surveys are discussed fully in Section 2.4: "Reef Surveys: Corals, Algae, Macroinvertebrates, Fishes, and Substrates."

These survey methods involved towing 2 divers ~ 60 m behind a small boat, with each diver maneuvering to maintain their position ~ 1 m above the seafloor. A typical survey covered 1.5–2.5 linear km of habitat, targeted specific isobaths, and lasted 50 min. Surveys were divided into 10 segments, each 5-min and ~ 200 m in length, during which towed divers recorded visual estimates of habitat complexity and benthic substrate cover within a 10-m swath (5 m on either side of the tow line).

In addition to visual estimates of benthic cover, photographs of the benthos were taken with a downward-looking digital still camera at 15-s intervals. Also, an oblique digital video camera recorded continuous observations of the seafloor. The photos and video imagery collected during MARAMP surveys have been archived for future analyses.

Classification of habitat complexity involves a subjective assessment of topographical diversity and complexity over a large scale (~ 2000 m^2) based on 6 categories: low, medium-low, medium, medium-high, high, and very high. For example, a sandy bottom with scattered macroalgae has low habitat complexity. In contrast, a shallow reef with numerous growth forms of corals and a 3-D structure providing shelter for reef fishes of various size categories has a complexity rating medium-high to very high (see Fig. 2.4.4a in Section 2.4.4: "Benthic Habitat Complexity and Substrates" for visual examples of each complexity category).

Benthic habitat cover was estimated for 2 kinds of substrate: live hard coral and sand cover. The category of live hard coral cover included colonies or portions of colonies of live pigmented tissue. The sand cover category included unconsolidated sediment, ranging in texture and size from fine to course. Sand cover origins were both inorganic (eroded rock) and organic (eroded fragments of calcareous organisms).

Data from towed-diver observations and analysis of TOAD video footage, acquired by the very different methods described earlier, vary in terms of scale and the influence of observer subjectivity. Data also can vary spatially because towed divers and TOAD deployments survey different depth profiles. As long as these important differences are borne in mind, both sets of data provide valuable information about the nature of a seabed, and they are, therefore, presented together in habitat characterization maps that combine sand cover, habitat complexity, and live hard coral cover.

2.3 Oceanography and Water Quality

To assess the oceanographic and water-quality parameters influencing the coral reef ecosystems in the Mariana Archipelago, CRED collected and integrated 5 key data streams: (1) deepwater oceanographic surveys characterizing prevailing water properties and ocean currents around the islands and reefs in the Mariana Archipelago; (2) intensive, closely spaced, nearshore oceanographic and water-quality surveys conducted concurrently with biological surveys; (3) an array of surface and subsurface moored instruments providing continuous, high-resolution time-series observations; (4) satellite remote-sensing products providing spatial time-series observations of key oceanographic properties, such as sea-surface temperature, sea-surface height, surface winds, chlorophyll-a (Chl-a), and other derived products; and (5) numerical models, such as NOAA Wave Watch III, providing spatial and temporal estimates of various oceanographic parameters.

2.3.1 Operational Background and Survey Design

CRED has utilized a diverse suite of data collection methodologies to monitor and assess local and regional oceanographic and water-quality conditions, including in situ telemetered surface and subsurface moored instruments, shipboard and nearshore spatial hydrographic surveys performed during research cruises, and deployment of ecological acoustic recorder (EAR) instruments. Oceanographic equipment and instrument specifications are provided later in this report. Shipboard surveys in the Mariana Archipelago were conducted from NOAA research vessels, and nearshore surveys and instrument deployments and retrievals were accomplished by small boats deployed from these research vessels.

Monitoring sites were selected to characterize the prevailing climatic and oceanographic conditions by spatially and temporally quantifying key physical and biogeochemical forcing mechanisms pertinent to biological processes (e.g., temperature, salinity, turbidity, currents, wave energy, ultraviolet [UV] radiation, nutrients, Chl-*a*, dissolved oxygen, dissolved inorganic carbon) over seasonal, interannual, and decadal time scales. With this work, CRED is generating long-term time series of baseline observations of environmental conditions that influence reef ecosystems. These time series are essential for understanding and predicting the ecological impacts of global climate change and land-based sources of pollution.

2.3.2 Shipboard Surveys

Shipboard deepwater (500-m) conductivity, temperature, and depth (or pressure, CTD) casts with simultaneous water sample collection were conducted to determine prevailing water property profiles surrounding the islands in the Mariana Archipelago. These deepwater casts provide high-resolution vertical profiles of conductivity (salinity), temperature, dissolved oxygen, and Chl-*a* concentration versus depth. In addition, shipboard acoustic Doppler current profiler (ADCP) transects were conducted in deepwater regions around each island to examine the horizontal and vertical structure of the prevailing ocean currents (Lumpkin and Pazos 2005). CTD and ADCP data are critical information that aid in the assessment of offshore water mass properties and essential for contextualizing and interpreting nearshore oceanographic information.

Deepwater CTD Casts

A Sea-Bird Electronics Inc. (Bellevue, Wash.) SBE 911*plus* CTD (accuracy of 0.003 S m^{-1}, 0.001 °C, 0.015% feet of seawater) with an SBE 43 dissolved oxygen sensor (accuracy of 2% saturation) and a WET Labs (Philomath, Ore.) *ECO* FLNTU combined fluorescence and turbidity sensor (accuracy of 0.01 µg L^{-1}, 0.01 NTU) was used to collect vertical profiles of water properties from the surface to a depth of 500 m in offshore environments around each island or reef surveyed (Fig. 2.3.2a). In addition, a rosette with multiple 10-L Niskin bottles was used to collect water samples for Chl-*a* and nutrient analyses at selected depths. Data from deepwater CTD casts are presented in Chapter 3: "Archipelagic Comparisons," Section 3.3: "Oceanography and Water Quality."



Figure 2.3.2a. Shipboard deepwater CTD casts are conducted with an SBE 911*plus* profiler, which is outfitted with a rosette of Niskin water bottles for concurrent water sampling.

Shipboard ADCPs

Transects of ocean current velocity profiles were collected using shipboard ADCPs during MARAMP 2003, 2005, and 2007. During each research cruise, surveys were conducted using a hull-mounted 75-kHz Teledyne RD Instruments Inc. (Poway, Calif.) Ocean Surveyor. This system was configured with an 8-m pulse length that typically collects current profiles in 16-m depth bins over the range of ~ 25–600 m averaged into 15-min ensembles. The actual depth range depended on the density and abundance of scattering material in the water column. Additional data were generally collected continuously while vessels were underway. Although ADCP information is not presented in this report, data are served by NOAA's National Oceanographic Data Center and available for download at http://www.nodc.noaa.gov.

2.3.3 Nearshore Spatial Surveys

Closely spaced, nearshore CTD surveys were conducted throughout the shallow-water environments around each of the islands, banks, and reefs surveyed during all of the MARAMP cruises. The distance between adjacent casts ranged from 0.25 to 2.0 km, depending on the size of the area sampled with each cast typically conducted to a depth of ~ 30 m. These surveys characterize the spatial structure of the physical and chemical properties of the ocean environment influencing the living coral reef resources observed during Rapid Ecological Assessment (REA) and towed-diver surveys. To examine nearshore water quality, water samples were collected at a subset of the shallow-water CTD sites.

Shallow-water CTD Casts

Shallow-water CTD casts were conducted using an SBE 19*plus* Seacat Profiler CTD (accuracy of 0.005 S m^{-1}, 0.0002 °C, 0.1% feet of seawater), providing vertical profiles of conductivity and temperature versus depth. Beam transmission data were collected concurrently using a WET Labs C-Star transmissometer. CTD profiles were collected by hand-lowering the CTD instrument (Fig. 2.3.3a) from a small boat at a descent rate of ~ 0.5–0.75 m s^{-1} to a maximum depth of 30 m. Shallow-water CTD observations around each island are presented as vertical cross-sectional plots, which were generated using Matlab software from The MathWorks Inc., Natick, Mass. Subsets of this data representing the same oceanographic parameters at a depth of 10 m are presented to further illustrate their spatial structure around each island. Results for some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced.

Figure 2.3.3a. Shallow-water CTD casts are conducted with an SBE 19*plus*, held by Kevin Wong, for nearshore profiling of salinity, temperature, and pressure-based depth. *NOAA photo*



Seawater Laboratory Analyses

Water sampling was conducted at a subset of the shallow-water and deepwater CTD sites. During shallow-water CTD casts, water samples were collected by lowering a daisy chain (or linked series) of 1.75- and 5-L Niskin bottles, triggered with a trip weight so that separate water samples were collected at depths of ~ 1, 10, 20 and 30 m. These water samples were preserved for laboratory analyses of water quality, including levels of Chl-*a*, nitrates, nitrites, phosphates, silicates, total nitrogen, and dissolved inorganic carbon (DIC). Water samples taken for Chl-*a* analysis were processed by Paul Bienfang, PhD, of Analytical Services Inc., Honolulu. Water samples taken for analyses of nutrients and DIC were processed at the NOAA Pacific Marine Environmental Laboratory in the nutrient laboratory of Calvin Mordy, PhD, and in the carbonate chemistry laboratory of Richard Feely, PhD.

2.3.4 Surface Moorings

As key components of the NOAA CREIOS, Coral Reef Early Warning System (CREWS) and sea-surface temperature (SST) buoys were moored in shallow-water environments around many U.S. Pacific islands. The types of instruments deployed at each island or offshore bank are provided in Figure 2.3.6a. SST and CREWS buoys provide near real-time obser-

vations of oceanographic conditions influencing coral reef ecosystem processes to managers, stakeholders, and the public. These surface observations are transmitted via satellite for daily dissemination at the CRED website (http://www.pifsc.noaa.gov/cred/oceanography.php). In addition to this telemetered data, buoys store SST observations internally, and CRED downloaded this data from buoys when they were retrieved during MARAMP cruises. Data from the SST and CREWS buoys installed in the Mariana Archipelago, as well as the locations and timelines of these buoy deployments, are presented in the "Oceanography and Water Quality: Time-series Observations" sections of the relevant island chapters of this report.

Coral Reef Early Warning System Buoys

CREWS buoys telemeter in situ observations of atmospheric and oceanographic parameters influencing reef conditions (Fig. 2.3.4a). For a single location at Saipan, a series of CREWS buoys deployed between August 2003 and May 2007 provided near real-time, high-resolution SST and surface conductivity data at a depth of 1 m (SBE 37 MicroCAT recorder, accuracy of 0.0028ºC, 0.0003 S m^{-1}), air temperature (WS425 sensor, accuracy of 0.38ºC, R.M. Young Company, Traverse City, Mich.), barometric pressure (Heise DXD transducer, accuracy of 0.02% feet of seawater, Ashcroft Inc., Stratford, Conn.), wind speed and wind direction (Vaisala sensor, accuracy of 0.135 m s^{-1} in speed and 2° in direction, Helsinki, Finland), photosynthetically active radiation and 3 bands of ultraviolet radiation (305, 330, and 380 nm) measured nominally 2 m above the surface of the water and nominally 1 m below the surface.

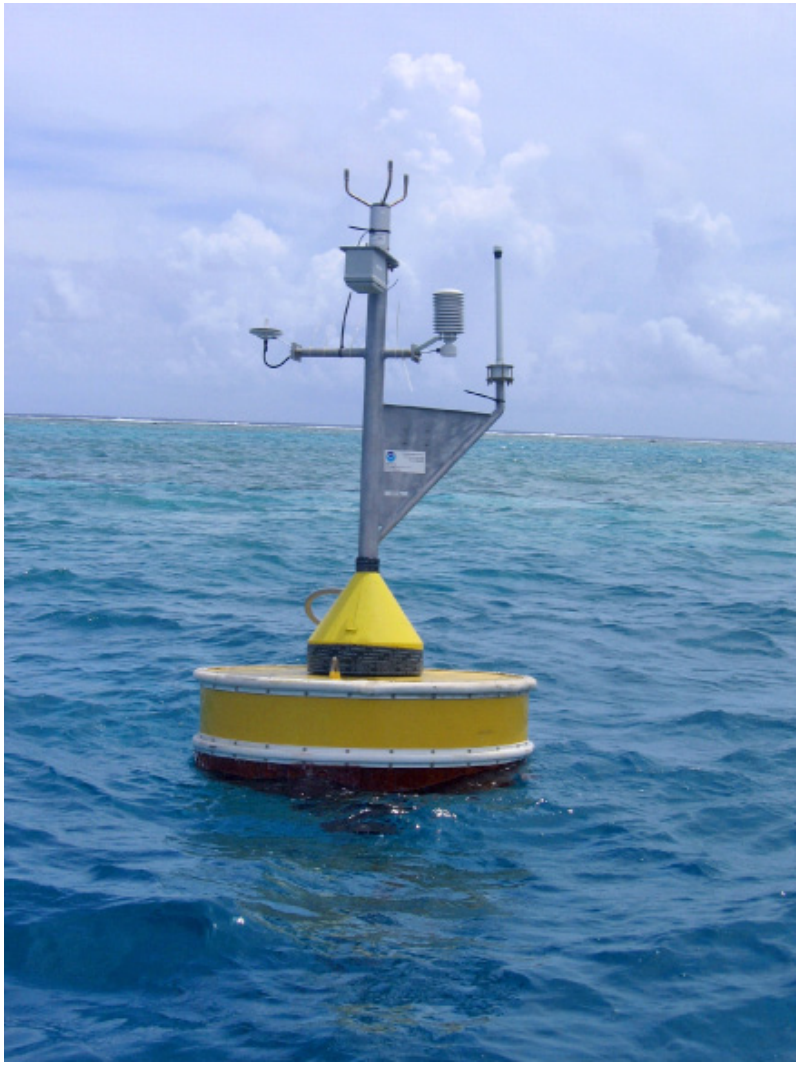


Figure 2.3.4a. Coral Reef Early Warning (CREWS) buoys relay oceanographic and meteorological data via satellite telemetry.

Sea-surface Temperature Buoys

SST buoys telemeter in situ observations of high-resolution SST in near real time. SST buoys were deployed beginning in September 2003 at Guam, Pagan, and Maug and beginning in May 2007 at Rota and Saipan. Data have been recorded internally and transmitted via satellite at 30-min intervals. There are 2 types of SST buoys: an Ocean Trek Research (Wasilla, Alaska) OTR-200 solar rechargeable buoy and a battery-powered Sound Ocean Systems Inc. (Redmond, Wash.) Model SST-001 (Figs. 2.3.4b and c).



Figure 2.3.4b. An Ocean Trek Research OTR 200 sea-surface temperature buoy at Pagan. *NOAA photo*

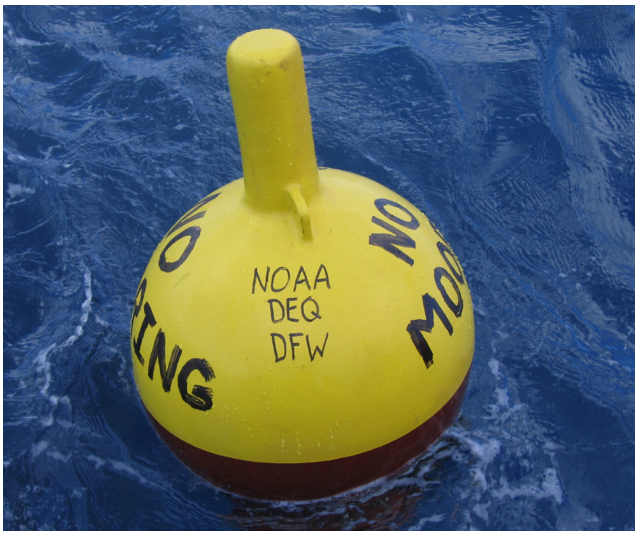


Figure 2.3.4c. A Sound Ocean Systems Inc. Model SST-001 sea-surface temperature buoy off Saipan. *NOAA photo*

2.3.5 Subsurface Moorings

Ocean data platforms (ODPs), wave-and-tide recorders (WTRs), and subsurface temperature recorders (STRs) are the types of subsurface moorings that were deployed at select locations around the Mariana Archipelago and configured to regularly record important oceanographic and ecological parameters that influence coral reef conditions. These moored instruments were recovered on a periodic basis and replaced with refurbished units to maintain a continuous time series of data at each location. Data from these STRs, as well as the locations and timelines of their deployments, are presented in the "Oceanography and Water Quality: Time-series Observations" sections of the relevant island chapters of this report. Similar information, as noted later in this section, is provided for the ODP and WTR deployments. The types of instruments deployed at each island or offshore bank are provided on a map in Figure 2.3.6a.

Ocean Data Platforms

ODPs recorded directional current profiles and wave spectra and high-resolution ocean temperature and salinity (Fig. 2.3.5a). ODPs, equipped with a 1000-kHz SonTek ADP, which is an acoustic current Doppler profiler (ADCP) from SonTek/YSI (San Diego, Calif., accuracy of 0.005 m s^{-1}, 0.1% feet of seawater) and an SBE 37 MicroCAT conductivity and temperature recorder, were deployed at Santa Rosa Reef in 20 m of water from September 2003 to September 2005 and from October 2005 to May 2007.

Current data from the ADCP were sampled for 7 min every 2 h, waves were burst sampled for 20 min every 4 h, and temperature and salinity data were sampled at 30-min intervals. Data were internally recorded and retrieved from platforms during subsequent MARAMP cruises. Data from the ODP mooring site at Santa Rosa Reef are presented in Chapter 4: "Guam and Adjacent Reefs and Banks," Section 4.10.4: "Oceanography and Water Quality."

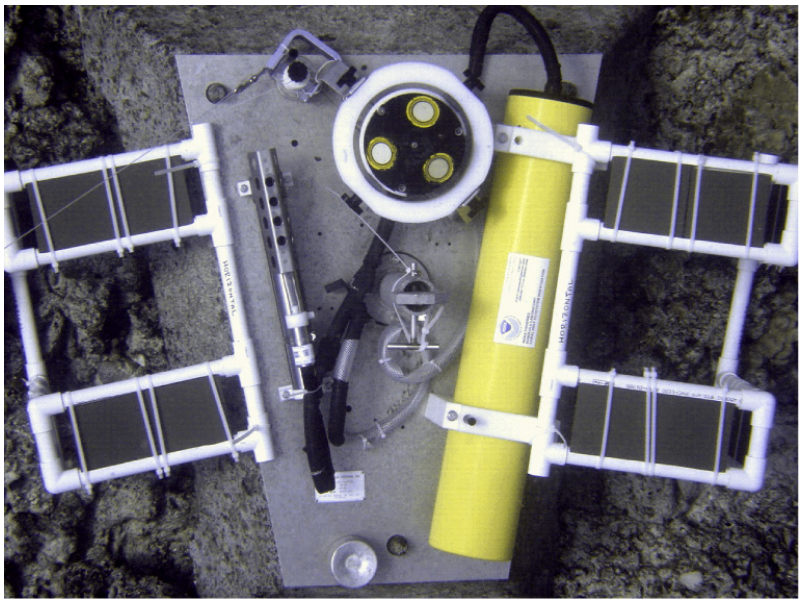


Figure 2.3.5a. Ocean data platforms (ODP) record several types of data: current profiles, wave spectra, and temperature and salinity values.

Wave-and-tide Recorders

WTRs consist of an SBE 26*plus* Seagauge wave-and-tide recorder (accuracy of 0.01% feet of seawater) that registers observations of high-resolution pressure (wave height and tides) and temperature variations. Beginning in September 2003, WTRs have been deployed at a depth of 27 m at Supply Reef and a depth of 25 m at Zealandia Bank. Data have been internally recorded with sample intervals of 15 min every 6 h. Data from the WTRs moored at Supply Reef and Zealandia Bank are presented in Chapter 18: "Reefs and Banks of the CNMI."

Subsurface Temperature Recorders

STRs consist of SBE 39 temperature recorders (accuracy of 0.002 °C) physically attached to reef structures to register observations of high-resolution temperature changes that potentially influence corals and other benthic biota. Unlike CREWS buoys, SST buoys, and satellite observations of SST, STRs record the actual temperatures at the depth to which they are deployed. These observations are particularly important during calm conditions conducive to coral bleaching. At these times, the water column is often well-stratified, meaning that many corals may not be subjected to the warm temperatures of the sea surface and, thus, are less likely to experience bleaching events. Beginning in September 2003, STRs have been deployed at depths of 2–32 m in a variety of locations and habitats throughout the coral reef ecosystems in the Mariana Archipleago, including locations around Guam and 13 islands and 2 banks of the CNMI, particularly habitats considered at high risk for coral bleaching.

2.3.6 Oceanographic Equipment Deployment in the Mariana Archipelago

Oceanographic instruments have been deployed across the Mariana Archipelago since 2003 (Fig. 2.3.6a). Data collected by these instruments—as well as the numbers, timelines, and locations of instrument deployments and retrievals—at each island or offshore bank are described in the "Oceanography and Water Quality: Time-series Observations" sections of each island chapter, in Chapter 4: "Guam and Adjacent Reefs and Banks," Section 4.10: "Reefs and Banks," and in Chapter 18: "Reefs and Banks of the CNMI."

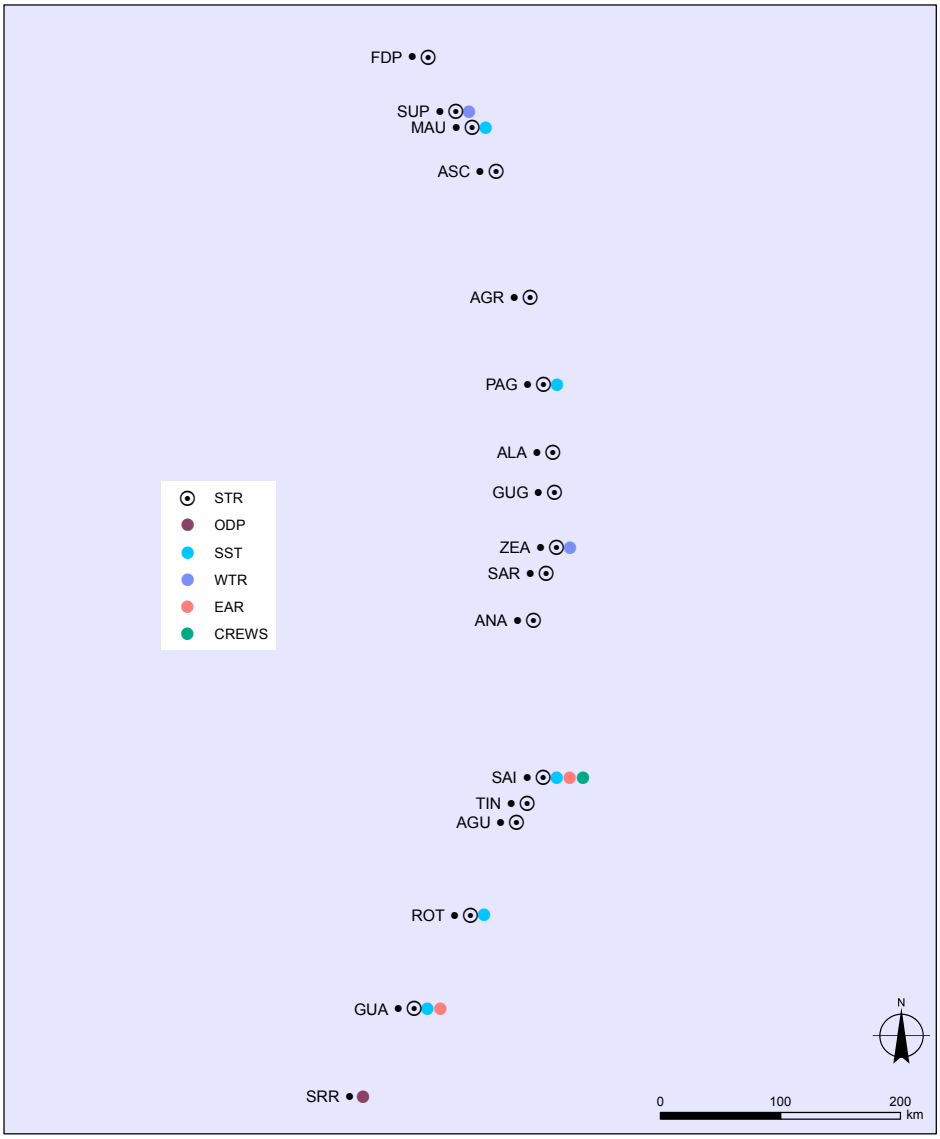


Figure 2.3.6a. Types of oceanographic and bioacoustic instruments and monitoring installation deployed at each island or bank in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Six types of moored instruments and one type of monitoring installation were deployed in this region during these survey years: autonomous reef monitoring structure (ARMS), Coral Reef Early Warning System (CREWS) buoy, ecological acoustic recorder (EAR), sea-surface temperature (SST) buoy, subsurface temperature recorder (STR), ocean data platform (ODP), and wave-and-tide recorder (WTR).

2.3.7 Satellite Remote Sensing and Ocean Modeling

Satellite Remote Sensing

All satellite-derived data products presented in this report are produced and distributed publicly by various government and private organizations. Brief summaries of data providers and any further analyses performed by CRED are outlined here:

1. NOAA advanced very high-resolution radiometer (AVHRR) Pathfinder 5.0 SST (Casey 2006)
   - http://www.nodc.noaa.gov/sog/pathfinder4km/
   - Infrared radiometer SST from NOAA polar orbiter satellites
   - grid resolution: 4 km
   - Climatology produced by the NOAA National Oceanographic Data Center (NODC) using the period of 1985–2001
   - Pathfinder 5.0 weekly data and climatology time-series plots are based on data extracted from 1° × 1° latitude-longitude boxes surrounding an area of interest
2. NASA Quick Scatterometer (QuikSCAT) SeaWinds
   - http://winds.jpl.nasa.gov/missions/quikscat/index.cfm

- Microwave scatterometer that measures near-surface wind speed and direction
- grid resolution: 0.25°
- Climatology produced by CRED and NODC for OceanEye project using the period of 2000–2003

3. NASA SeaWiFS Imager
   - http://oceancolor.gsfc.nasa.gov/SeaWiFS/
   - Measures bio-optical properties of the ocean, including a calculation of Chl-a levels
   - grid resolution: 9 km
   - Climatology produced by CRED and NODC for OceanEye project using the period of 1998–2003

Ocean Modeling: Bleaching Threshold

As early as 1997, the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) began producing Web-accessible, satellite-derived, near-real-time SST products to monitor conditions conducive to coral bleaching from thermal stress around the globe. This activity evolved into a crucial part of the CRW program in 2000, and these products can be found at http://coralreefwatch.noaa.gov/satellite/index.html. SST data is provided at a resolution of 50 × 50 km (0.5° × 0.5°).

The bleaching threshold, developed by CRW, serves as a general indicator for coral bleaching and is defined as 1°C above the maximum monthly climatological SST value for a particular geographic area. It's important to note that satellite-derived SST represents the upper few millimeters of oceanographic temperatures within the region of an island, as opposed to site- or reef-specific temperatures.

CRED generated SST and wave-height time series around the islands of the Mariana Archipelago for the period between August 2003 and June 2007. Remotely sensed data (SST climatology and weekly satellite-derived [Pathfinder] SST) and modeled significant wave height derived from NOAA Wave Watch III were overlaid with CRED in situ observations from various locations around each island or reef in the Mariana Archipelago and with indicators for each area's bleaching threshold and MARAMP cruise dates. Time-series records produced for each island from in situ and telemetered data are presented in the "Oceanography and Water Quality: Time-series Observations" sections of island chapters.

Ocean Modeling: Wave Watch III

NOAA Wave Watch III is a third-generation, full-spectral ocean wind-wave model that provides historical and near real-time open-ocean, deepwater modeled spectral wave data (height, period, and direction). Three hourly forecasts of wave conditions, up to 144 h (6 d) in advance, are generated twice daily.

Wave Watch III solves the complexities of directional waves through the spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of this equation is that properties of depth and current as well as the wave field itself vary on time and space scales that are much larger than the variation scales of a single wave. Another constraint is that the physical process parameters included in the model do not allow for assessment in conditions where waves are strongly limited in depth. These 2 basic assumptions imply that the model can generally by applied on spatial scales (grid increments) > 1–10 km and outside the surf zone (Tolman 1999, 2002; National Weather Service). For more information about Wave Watch III, go to http://polar.ncep.noaa.gov/waves/index2.shtml.

2.3.8 Monitoring of Bioacoustics

CRED monitors natural and man-made underwater ambient sounds, captured by a device known as the ecological acoustic recorder (EAR), to learn about the presence and activity of fishes, crustaceans, cetaceans (whales and dolphins), and other sound-producing marine life and about the frequency and occurrence of human activity in marine areas. EAR units have been deployed in 2 locations at Saipan, in Bahia Fanonchuluyan and near Puntan Laolao Kattan, and in 1 location at Guam northwest of Pati Point. The EAR is a digital, low-power passive acoustic system that records ambient sounds at frequencies up to 30 kHz on a programmable schedule. Equipped with a sound trigger, the EAR can also capture transient noises produced by cetaceans, passing vessels, or other acoustic events. EAR devices deployed over several months generate an amount of data far too great for manual analysis, so custom detection and classification software algorithms are used to automate the processing and analysis of data. EAR devices were deployed at Saipan (2 units) at Guam (1 unit) beginning in

May 2007. A time series of the data from the EARs installed at Saipan is provided in that island chapter. The locations and timelines of these EAR deployments are presented in the "Oceanography and Water Quality: Bioacoustic Observations" sections of the Guam and Saipan chapters.

2.4 Reef Surveys: Corals, Algae, Macroinvertebrates, Fishes, and Substrates

Information on the species composition (diversity), condition, abundance, and distribution of biological communities is vital to the effective management of coral reef resources. To provide resource managers with such information, CRED collects complementary data relating to 4 main ecological disciplines: corals, algae, other macroinvertebrates, and reef fishes (Table 2.4a). CRED acquires these integrated observations of reef-fish and benthic community structure primarily using Rapid Ecological Assessment (REA) surveys and towted-diver surveys.

During MARAMP 2003, 2005, and 2007, fine-scale REA surveys were conducted at specific reef sites (~ 300 m^2 per site), while broad-scale towed-diver surveys (~ 15,000–25,000 m^2 per survey) were performed around the islands and reefs of Guam and the CNMI. Analyses of video footage from TOAD surveys conducted during MARAMP 2003 and in 2004 provide information about benthic habitats, typically at depths of 20–150 m (see Section 2.2.4: "Optical Validation"). Overviews of REA and towed-diver surveys and descriptions of sampling design and survey methods specific to each ecological discipline are presented in the remainder of this section.

Table 2.4a. Summary of biological and benthic habitat data presented in this report from REA, towed-diver, and TOAD surveys.

Discipline	REA Surveys	Towed-diver Surveys	TOAD Surveys
Habitat Characterization	–	• Cover (%) of sand • Habitat complexity	• Cover (%) of sand
Corals	• Composition and generic richness of coral communities • Cover (%) of live scleractinian (hard) corals • Coral density (# colonies m^{-2}) • Size-class distribution of corals • Distribution and prevalence of coral disease	• Cover (%) of live hard corals • Cover (%) of stressed corals	• Cover (%) of live hard corals
Algae	• Occurrence (%) by algal genera or functional group • Cover (%) of macroalgae (both calcified and fleshy), crustose coralline red algae, and turf algae • Distribution and density of coralline-algal disease	• Cover (%) of macroalgae (in 2003, combination of macroalgae and turf algae; in 2005 and 2007 macroalgae only) • Cover (%) of crustose coralline red algae	• Cover (%) of macroalgae
Other Macroinvertebrates	• Presence of macroinvertebrate species • Species richness of macroinvertebrates	• Distribution and abundance of crown-of-thorns seastars, giant clams, sea cucumbers, and sea urchins	–
Reef Fishes	• Composition and species richness of reef-fish communities • Biomass (kg 100 m^{-2}) of reef fishes	• Species composition of large fishes • Biomass (kg 100 m^{-2}) of large fishes (> 50 cm in total length)	–
Protected Species	–	• Sighting frequency of sea turtles (# individuals km^{-1})	–
Marine Debris	–	• Direct counts of derelict fishing gear, munitions, shipwrecks, and other man-made objects	–

2.4.1 Overview of REA Surveys

REA surveys are investigations that provide data at a high quantitative level and moderate taxonomic resolution for communities of corals, algae, other macroinvertebrates, and reef fishes. During MARAMP 2003, 2005, and 2007, the majority of REA surveys were conducted along the forereef slopes of islands at depths of 10–20 m. However, additional surveyed habitats included a lagoon-type patch reef in the caldera of Maug Islands and offshore oceanic banks at Pathfinder and Santa Rosa Reefs.

The biological assessment teams used specific methodologies targeting their respective biological communities. These methodologies overlapped and complemented each other to ensure that collected data were representative of the biological state at each REA site. A timeline of methods development for each ecological discipline is shown in Tables 2.4.1a and b, and the methods used by each assessment team are discussed in the corresponding ecological discipline sections.

During REA surveys, biological assessment teams followed highly structured protocols that were repeated at each REA site (Fig. 2.4.1a). Upon arrival at a REA site, 3 teams of divers—a fish team, a coral team, and a combined algal and macroinvertebrate team—entered the water over consecutive time intervals to avoid congestion along the transect lines. The fish team was the first team to enter the water and begin surveys, followed by the coral team and then the combined algal and macroinvertebrate team. The interdisciplinary survey effort at each site took 60–80 min to complete.

Table 2.4.1a. Timeline of methods development for each of the parameters measured using REA for corals, algae, and coral and coralline-algal disease. Line-point-intercept data was collected only for Guam in 2005. Methods used during MARAMP surveys included belt transect (BLT), quadrat (QS), line-point intercept (LPI), photoquadrat (PQS), roving diver (RD), and voucher specimen (VS).

Year	Corals and Coral Disease					Algae and Algal Disease			
	Generic richness and composition	Cover (%) of live corals	Colony density (# colonies m^{-2})	Size class	Disease prevalence	Occurrence (%) of algal genera	Cover (%) of algae	Species presence	Disease density
2003	QS	—	QS	QS	—	PQS	PQS	PQS, VS, RD	—
2005	QS, BLT	LPI	QS, BLT	QS, BLT	—	PQS	PQS, LPI	PQS, VS, RD	—
2007	QS, BLT	LPI	QS, BLT	QS, BLT	BLT	PQS	PQS, LPI	PQS, VS, RD	BLT

Table 2.4.1b. Timeline of methods development for each of the parameters measured using REA surveys for macroinvertebrates and reef fishes. Methods used during MARAMP surveys included belt transect (BLT), quadrat (QS), stationary-point count (SPC), and roving diver (RD).

Year	Macroinvertebrates		Reef Fishes		
	Species presence	Species richness	Total fish biomass (all sizes)	Fish biomass (> 25 cm in total length)	Species richness
2003	BLT, RD	—	BLT	—	BLT, SPC, RD
2005	BLT, RD	BLT, RD	BLT	SPC	BLT, SPC, RD
2007	BLT, QS	—	BLT	SPC	BLT, SPC, RD

Selection of REA Survey Sites and Transect Locations

REA sites were selected in 2003 for MARAMP 2003 and, when possible, revisited during MARAMP 2005 and 2007; a few additional sites were added in 2005 and 2007. Randomization methods were not used for site selection in 2003. CRED chose REA sites in consultation with the resource management agencies of each jurisdiction, including the CNMI DFW (Mike Trianni and Kate Moots) and DEQ (Fran Castro and Peter Houk) and the Guam DAWR (Trina Leberer). The following aims were considered during REA site selection: (1) a range of survey sites representative of the benthic and reef-fish habitats around each island or reef, (2) a mixture of sites within and outside of marine protected areas, (3) a mixture of sites likely to have been affected significantly by human activities and sites likely to have little human disturbance, (4) some sites adjacent to local villages, and (5) a number of sites that could be compared to and complement previous assessment and monitoring work done by local agencies. Additionally, it is important to note that wave exposure, weather conditions, and other environmental factors, such as currents, can limit access to REA sites and affect CRED's ability to survey sites again in subsequent MARAMP survey years.

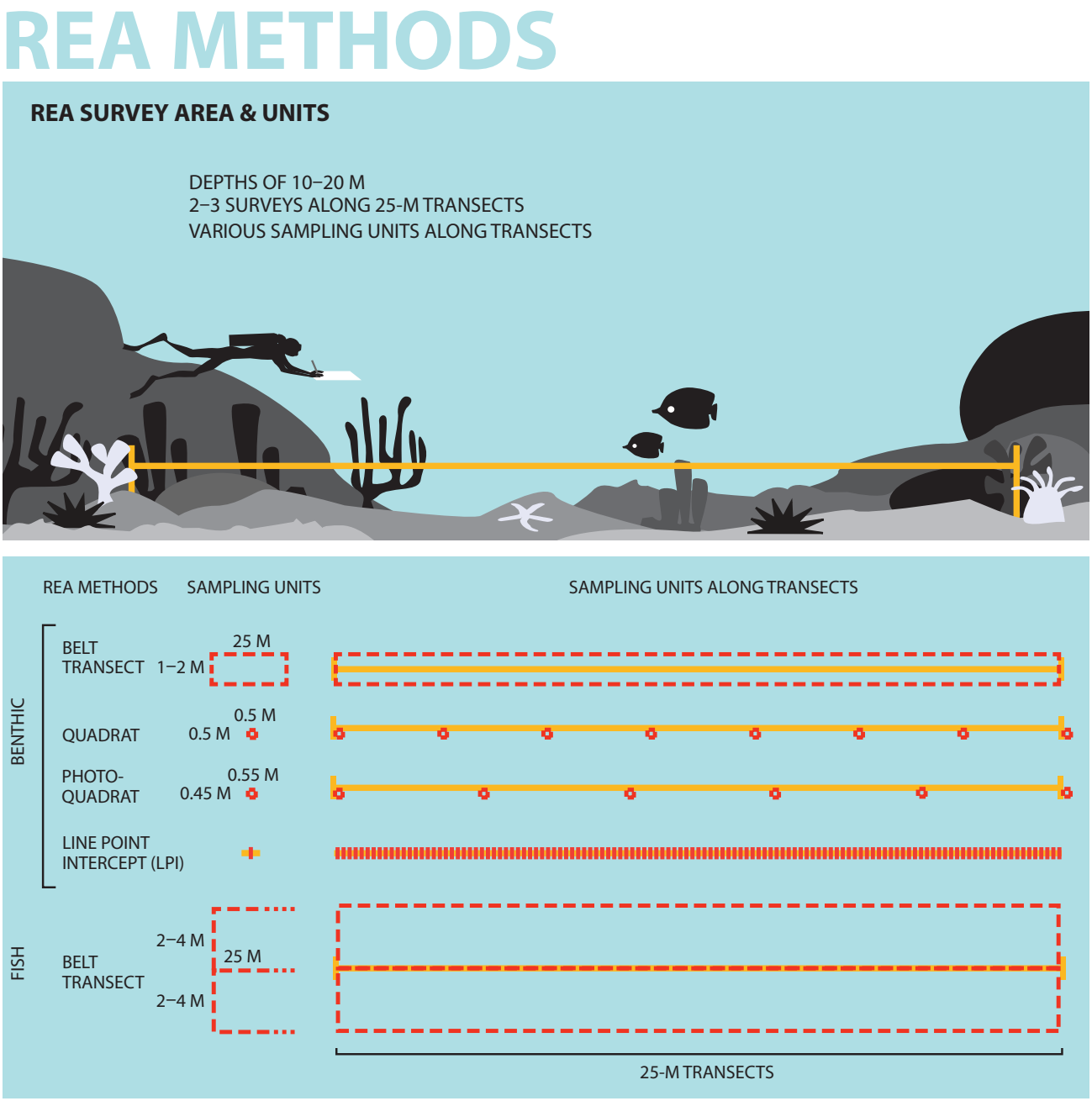


Figure 2.4.1a. Schematic diagram of survey areas and sampling designs for REA survey methods used during MARAMP 2003, 2005, and 2007.

The nonrandom nature of site selection places limits on the degree to which biotic metrics, such as percentage of cover, density, diversity, and disease prevalence of corals and coralline algae, can be extrapolated through statistical inference to the larger population around an island or bank. Because transects were not placed at the exact same location at a REA site each year and transects may not be representative of a site, interannual site comparisons need to be approached with caution. Variations in survey results between MARAMP survey years can result from transect placement and the addition of REA sites in subsequent years. However, revisiting the same REA sites each cruise does provide a basis for quantifying temporal trends in condition, which is a priority of CRED's long-term monitoring efforts.

At each REA site, 3 transect lines typically were deployed by the REA fish survey team, which was the first team to enter the water. All benthic disciplines used the first 2 transect lines and the fish survey team used all 3 transect lines as the geographical reference to guide their selection of point, area, or quadrat placement. Transects at each site were deployed (1) with a focus on hard-bottom communities, (2) along an isobath, to the extent possible, and (3) into the prevailing current. The latter was an important safety consideration that facilitated divers working against the current at the start of a dive but swimming with the current towards the end of a dive when they might be fatigued. Each discipline—corals, coral disease, algae, algal disease, other macroinvertebrates, and reef fishes—used survey protocols driven by (1) accepted methods within its discipline (Maragos et al. 2004; Houk et al. 2005; Preskitt et al. 2004; Brock 1982), (2) the number of divers available, and (3) NOAA safety guidelines (e.g., proximity to a buddy).

2.4.2 Overview of Towed-diver Surveys

Towed-diver surveys are used to characterize benthic habitats and to quantify the abundance and spatial distribution of ecologically and economically important fish, coral, algal, and macroinvertebrate taxa over an area that is much broader than the areas surveyed using REA methods. Importantly, towed-diver surveys also are able to access exposed coasts (e.g., windward-facing shores and high-swell conditions) that cannot always be surveyed using REA techniques.

During MARAMP 2003, 2005, and 2007, all towed-diver surveys were conducted along the forereef slopes of the islands of Guam and the CNMI at depths of 10–20 m. Additional surveys were completed on offshore banks only in 2003 and 2005. Towed-diver surveys were designed to cover as many habitat types (e.g., slope, lagoon, and bank) and as much of a complete revolution around each island as time allowed and to survey along a relatively constant isobath (typically 15–20 m). Around small islands, multiple circumnavigations were conducted targeting different isobath depths (e.g., 5, 15, and 25 m). Each towed-diver survey generally covered linear distances of 1.5–2.5 km.

In addition to the primary observations for each ecological discipline, towed divers were tasked with recording unusual or important sightings that included significant biological or habitat gradients, shipwrecks, unexploded ordinance or munitions, and derelict fishing gear or other types of marine debris located on the seafloor. Sightings of "species of concern," such as direct counts and size estimations of sea turtles, were also recorded during towed-diver surveys.

Towed-diver surveys were conducted by teams of 4 divers who alternated responsibilities between data gathering and boat handling. A pair of divers was towed ~ 60 m behind a small boat, a 6-m survey launch from SAFE Boats International (Port Orchard, Wash.), with 1 diver tasked with benthic data collection and 1 diver tasked with data collection on large fishes (> 50 cm in total length; Fig. 2.4.2a). Each diver made observations over a visually estimated 10-m swath (5 m out on each side of their respective tow lines, which act as transect lines). Towed at typical speeds of 0.5–1.3 m s^{-1} (1–2.5 kt), divers attempted to maintain their position ~ 1 m above the seafloor. Each survey took ~ 50 min, and 4–6 surveys were generally completed during each field day.

To georeference all data collected during towed-diver surveys, a GPS receiver located on the small boat was programmed to record longitude and latitude coordinates (waypoints) every 5 s. When towed divers were ready to begin recording data, they signaled to the coxswain, who then marked a waypoint indicating the start point of a towed-diver survey. The coxswain maintained speed and steered the small boat along a predetermined depth contour, using as guides a bathymetric chart, a singlebeam echosounder, and shoreline features (when present). "OK" signals were sent to the small boat every 5 min to inform the coxswain of the diver's status, and "mark" signals were sent to record any sites of natural or anthropogenic interest. Another coded signal was sent to the small boat to record the end-position of each survey.

The towed-diver platforms, or towboards, used by CRED were constructed of StarBoard (King Plastic Corp., North Port, Fla.) marine polymer sheets ~ 100 × 50 × 2 cm. Each towboard was outfitted with an SBE 39 temperature and pressure (depth) recorder set to record at 5-s intervals, 2 stopwatches for survey timing, an Uwatec bottom timer (Johnson Outdoors

Inc., Racine, Wis.), and a vinyl data sheet. All timing devices were set to Greenwich Mean Time and synchronized each morning using the calibrated clock on the research vessel.

Benthic towboards (Kenyon et al. 2006) were outfitted with a downward-facing Canon EOS-10D digital still camera (Canon Inc., Tokyo) in a waterproof housing attached to the underside of each towboard in a "crash-proof," stainless steel bracket. Attached to the camera housing were 2 Ikelite strobes (Ikelite Underwater Systems, Indianapolis, Ind.) and 2 waterproof lasers calibrated for an intralaser distance of 15 cm. The camera automatically and repeatedly photographed the seafloor at 15-s intervals. These benthic images have been archived as a durable record of the towed-diver-benthic-survey tracks. CRED personnel and partners are analyzing these photographs for benthic composition to the functional group level.

Fish towboards were outfitted with a forward-facing Sony DCR-PC1000 MiniDV Handycam digital video camera (Sony Corp., Tokyo) in a Gates waterproof housing (Gates Underwater Products, Poway, Calif.) and crash-proof bracket similar to the one used on benthic towboards. These forward-facing cameras were used to collect streaming video images on Mini DV. Video footage from these cameras was archived as a durable record of the towed-diver-fish-survey tracks.

Data from towed-diver surveys were collected through direct diver observations and electronic instrumentation attached to towboards. Divers recorded observations every 5 min over a survey segment length of ~ 200 m, summarizing the benthic composition and ecologically or economically important fishes and macroinvertebrates encountered throughout each survey segment. A typical 50-min towed-diver survey included a total of 10 segments, although the actual time and length of surveys occasionally varied depending on environmental conditions and diving or logistical constraints. Diver observations and accessory instrument data collection techniques specific to each ecological discipline are discussed later in this chapter.

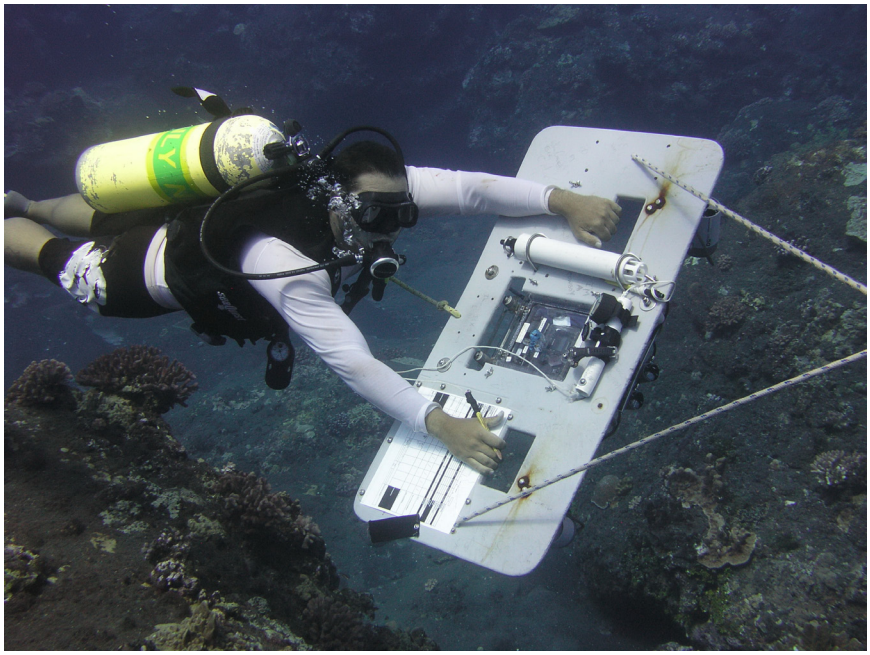


Figure 2.4.2a. Towed diver conducting a survey at Pagan. *NOAA photo Robert Schroeder*

During MARAMP 2005 and 2007, specific survey routes were preprogrammed into the small-boat GPS prior to initiating field activities, based on the towed-diver-survey tracks from MARAMP 2003. This preprogramming was done to enable as much track, target depth, and area overlap with previous years as possible.

Methods for towed-diver benthic surveys changed between MARAMP survey years to fine-tune data resolution and reduce task loading of divers (Table 2.4.2a). These changes generally were limited to 2 aspects of towed-diver-survey protocols: classification of benthic substrate categories and estimation of percentage of cover for benthic substrates. More information on variation in classification is provided in Tables 2.4.4a, 2.4.5a, and 2.4.6a.

When making temporal comparisons of results from towed-diver surveys, consider that minor fluctuations in estimates may have resulted from differences between MARAMP years in number of surveys conducted, survey depths, observer experience, and encounter rates and do are necessarily indicative of changes in the benthic or fish communities surveyed.

Table 2.4.2a. Summary of changes in the towed-diver survey method used during MARAMP 2003, 2005, and 2007.

Procedure	Description
Benthic cover estimates	Recorded to nearest percentage in 2003 and in 10 percentage bins in 2005 and 2007 (Table 2.4.3a)
Reef fish surveys	360° scan conducted during the first minute of each 5-min survey segment only in 2003
Marine debris sightings	Recorded as a direct part of method in 2003 but solely within observer comments in 2005 and 2007
Substrate Classification	**Description**
Rubble	Only rubble that was not visibly encrusted by macroalgae, calcareous algae, or corals was included in 2005 and 2007, but rubble could be encrusted in 2003 (Table 2.4.4a)
Carbonate pavement	Only recorded in 2003 (Table 2.4.4a)
Soft corals	Only recorded in 2005 and 2007 (Table 2.4.5a)
Stressed corals	Monitoring of corals that appeared stressed was improved in 2005 (Table 2.4.5a)
Recently dead corals	Only recorded in 2003 (Table 2.4.5a)
Macroalgae (both fleshy and calcified)	Turf algae was included only in 2003 (Table 2.4.6a)

2.4.3 Data Processing: REA and Towed-diver Surveys

At the end of each day of REA benthic survey operations, GPS waypoints were downloaded and quantitative data were entered into Microsoft Excel spreadsheets. These data were later transferred into a Microsoft Access database and quality controlled. Data from towed-diver datasheets were transcribed into a Microsoft Access database and quality controlled at the end of each day. The Microsoft Access database is delineated according to pre-established regions: Mariana Archipelago, main Hawaiian Islands, Northwestern Hawaiian Islands, American Samoa, and the Pacific Remote Islands Marine National Monument.

Following each day of field operations for towed-diver surveys, the GPS waypoints collected from a GPS receiver mounted on the small boat and the depth and temperature data from the SBE 39 on each of the towboard platforms were downloaded. A custom built Python script (Python Software Foundation, Wolfeboro Falls, NH) in an ArcGIS environment was used for processing these waypoints and the corresponding depth and temperature data. This data processing generated 4 standard shapefiles: GPS points, dive points, segments, and surveys. GPS points represent the raw, uncorrected, GPS waypoints, and they were used to generate the other standard shapefiles. The Python script clipped GPS points to the start and stop waypoints of a survey and imported the corresponding depth and temperature data using time stamps. Then, the script generated dive points from the clipped GPS points and repositioned them to the location of the divers based on the track, speed, and course of the boat and depth of the divers.

Two additional attributes were added to the dive points, creating a unique serial number for each 5-min segment and 50-min survey by using the date, survey, and segment numbers (e.g., the serial number, or "Dive ID," for survey 1 on May 16, 2007, is 200705161, and the serial number, or "Segment ID," for segment 5 of survey 1 is identified as 20070516105). The survey and segment shapefiles, then, were generated by lacing together each of the dive points and grouping them by either Dive ID or Segment ID. These serial numbers also were the basis for the join (or union) between the fish or benthic data and the geodatabase, allowing these data to be mapped to specific geographic locations.

Results from towed-diver benthic surveys were used to create several different types of maps: (1) habitat characterization of habitat complexity, sand cover, and cover of live scleractinian (hard) corals (see Section 2.2.4: "Optical Validation"); (2) cover of live hard corals, stressed corals, macroalgae, and crustose coralline red algae; (3) macroinvertebrate densities and distribution, and (4) biomass and distribution of large fishes (> 50 cm in total length).

Table 2.4.3a. Bin categories for estimates of benthic cover (%) used in towed-diver surveys during MARAMP 2005 and 2007.

Bin	Benthic Cover (%)	Midpoint
1	0.1–1	0.5
2	1.1–5	2.5
3	5.1–10	7.5
4	10.1–20	15
5	20.1–30	25
6	30.1–40	35
7	40.1–50	45
8	50.1–62.5	56.25
9	62.6–75	68.75
10	75.1–100	87.5

Diver observations for each 5-min survey segment were graphically projected onto ArcGIS 9.3 maps using the midpoint for each survey segment (segment length, ~ 200 m; midpoint, ~ 100 m). For estimates of benthic cover, values from MARAMP 2003 were projected as the midpoint of the percentages recorded by towed divers, while values from MARAMP 2005 and 2007 were projected as the midpoint of the binned observations (Table 2.4.3a). Macroinvertebrate values were projected as the total number of organisms observed per survey segment or as the midpoint of their binned range. Densities were calculated as the total number of macroinvertebrates observed during a survey divided by the area covered during that survey (10-m survey width multiplied by survey length and presented per 100 m^2). For habitat characterization maps only, results for all 3 MARAMP survey years are combined and interpolated (see Section 2.4.4: "Benthic Habitat Complexity and Substrates").

Within this report, summary statistics from REA and towed-diver-survey data are presented primarily as standard error of the mean (SE), since SE quantifies the precision of an estimate of a population mean, factoring in both sample size and standard deviation of the mean (SD). Because SD quantifies the variability within a set of surveys, summary statistics of depths of towed-diver surveys are presented as SD. These summary statistics are reported in the same unit of measure as their associated mean values.

2.4.4 Benthic Habitat Complexity and Substrates

Information about habitat complexity and substrate type from towed-diver surveys provides context for the analyses of biological data collected during the same towed-diver surveys. REA surveys collected data about substrate cover that give context to results from surveys at REA sites. Analyses of video footage from TOAD surveys also assists in benthic habitat characterization.

TOAD surveys were conducted during MARAMP 2003 and in 2004, and observations from analyses of video footage collected from these surveys were classified into benthic habitat categories that included substrate types, such as sand, rock, and rubble, as well as categories for living cover (for a full list of classification categories, see Section 2.2.4: "Optical Validation"). REA surveys using the line-point-intercept method in 2007 (and 2005 at Guam) collected data on a few substrate categories in addition to information on living cover. These REA surveys assigned benthic elements to 1 of 9 categories: carbonate pavement, rock, live corals (scleractinian, hydrocorals, and *Heliopora coerulea*), dead corals, crustose coralline red algae, macroalgae (both calcified and fleshy), coral rubble, sand, and other sessile invertebrates.

Data from towed-diver surveys were used to create habitat characterization maps of sand cover and habitat complexity and for optical validation of acoustic or satellite-derived information (see Section 2.2.4: "Optical Validation"), in addition to their use in producing the information about living cover presented for each ecological discipline in this report.

At 5-min intervals, benthic towed divers recorded a suite of information that included the predominant reef zone, estimates of average topographic complexity of habitats, and estimates of average percentages of cover for benthic substrate types. Reef zone categories included forereef, backreef, lagoon, bank, bank escarpment, and channel. Benthic substrate cover categories included sand, rubble, and carbonate pavement, as well as live and stressed hard corals, macroalgae (both fleshy and calcified), and crustose coralline red algae (Tables 2.4.4a, 2.4.5a, and 2.4.6a).

Estimates of habitat complexity during towed-diver surveys were subjective assessments of the benthic topographical diversity and complexity classified on a 6-level categorical scale: low, medium-low, medium, medium-high, high, and very high (Fig. 2.4.4a). For example, low habitat complexity is often associated with flat sand plains or rubble habitats; medium habitat complexity is often associated with small-to-moderate spur-and-groove, coral, or boulder habitats; and high and very high habitat complexity are often observed as high or extreme vertical relief associated with steep, spur-and-groove canyons, pinnacles, and walls.

Because of changes in methodologies regarding substrate type (Table 2.4.4a), no maps of rubble cover are presented in this report. In addition, substrate and pavement data were collected during MARAMP 2003 but not during MARAMP 2005 or 2007. Because these diver observations were limited to one year, they are not presented in this report. However, percentage of cover for hard substrate and pavement can be inferred from the sand cover maps in this report. All other benthic substrate categories used to create habitat characterization products remained the same for towed-diver surveys conducted in 2003, 2005, and 2007.

Estimates of benthic features from towed-diver surveys were plotted in ArcGIS 9.3 using the midpoint of each 5-min survey segment (Table 2.4.3a). For benthic habitat characterization maps, results from MARAMP 2003, 2005, and 2007 surveys were combined, and then an inverse distance weighting (IDW) interpolation function (ArcGIS 9.2) was applied to this combined data set. The IDW function produced a continuous plot of the salient benthic features around each island. Where towed-diver surveys from different years overlapped, this interpolation reflects the mean spatial distribution of a benthic substrate category over the time series, averaging out temporal changes in benthic cover. Where surveys from different years did not overlap, these interpolated values provide predicted spatial distribution of benthic habitats.

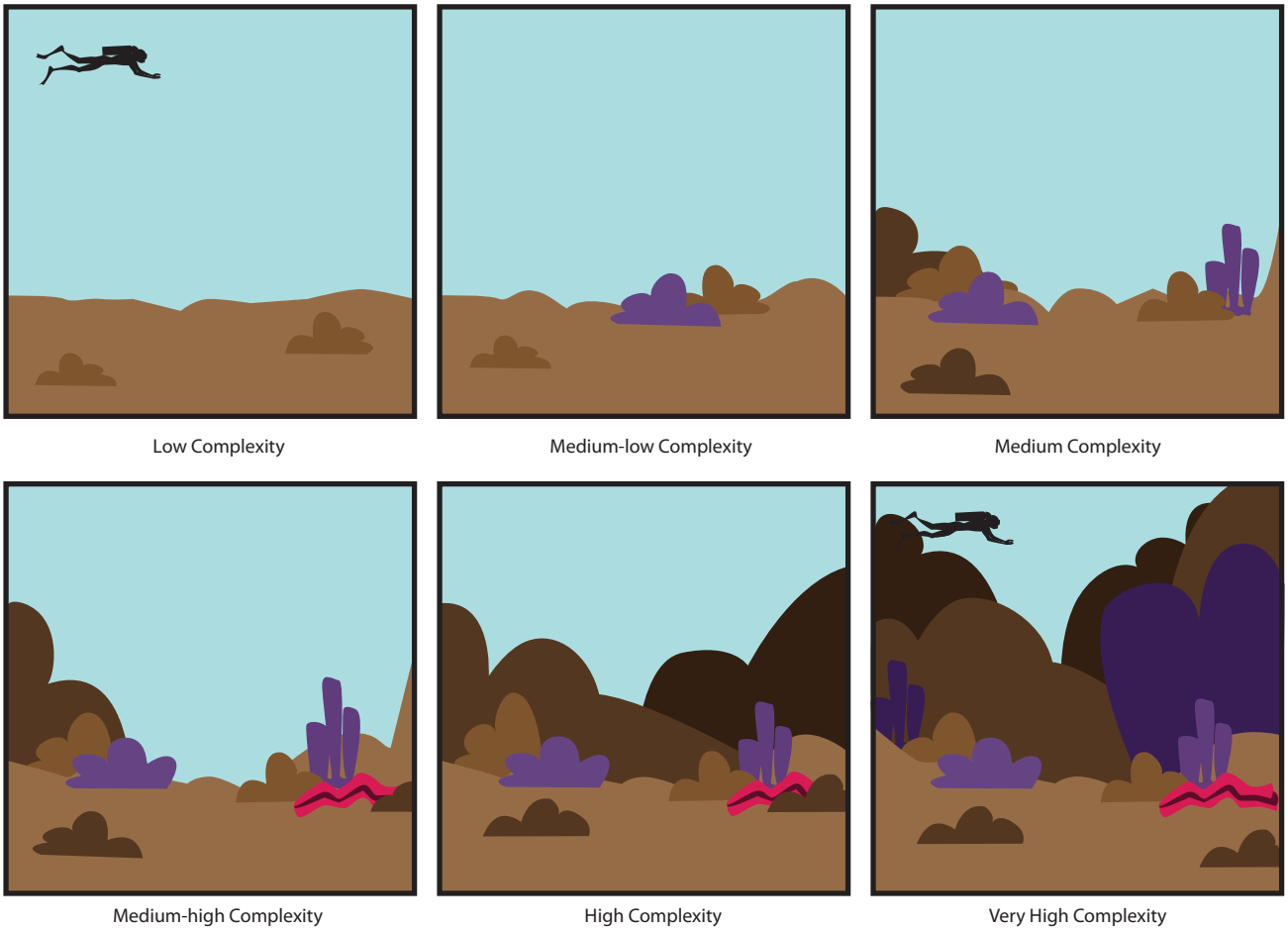


Figure 2.4.4a. Examples of the 6 categories used to classify habitat complexity: low, medium-low, medium, medium-high, high, and very high. As they regularly encounter multiple habitat types, towed divers estimate average complexity during each 5-min observation segment over a survey swath of ~ 200 x 10 m (~ 2000 m^2).

Table 2.4.4a. Descriptions of the benthic composition categories of sand, rubble, and carbonate pavement used in towed-diver surveys during MARAMP 2003, 2005, and 2007 (Kenyon et al. 2006). Data for rubble and carbonate pavement are not provided in this report. For descriptions of coral and algal categories, see Tables 2.4.5a and 2.4.6a in this chapter.

Category	Year	Description
Sand	2003 2005 2007	Unconsolidated sediment, ranging in texture and size from fine to coarse and including both inorganic (eroded rock) and organic (eroded fragments of calcareous organisms) sediments.
Rubble	2003	Unconsolidated fragments of coral skeleton or reef rock of sizes larger than sand. May be visibly encrusted by macroalgae, calcareous algae, or corals.
Rubble	2005 2007	Unconsolidated fragments of coral skeleton or reef rock of sizes larger than sand. Only rubble that was not visibly encrusted by macroalgae, calcareous algae, or corals was included.
Carbonate Pavement	2003	Consolidated substrate, typically composed of calcareous or basaltic elements, which have become cemented together by biogenic and physical processes.

2.4.5 Corals and Coral Disease

Coral communities were examined using primarily REA and towed-diver surveys during MARAMP 2003, 2005, and 2007. Towed-diver surveys were used to assess cover of live and stressed corals. Three different REA methodologies—belt transect, quadrat, and line-point intercept—were used to survey several parameters: coral cover, coral-colony density, generic richness and relative abundance, coral size-class distribution, and distribution and prevalence of coral disease.

REA surveys measured anthozoan and hydrozoan corals. Anthozoan corals are any of the Cnidarian class Anthozoa, such as the corals and sea anemones, that have radial segments and grow singly or in colonies. Hydrozoan corals are any of the Cnidarian class Hydrozoa, such as the colonial hydrocorals that secrete a calcium carbonate skeleton.

Towed-diver surveys focused on 2 types of anthozoans: corals of the order Scleractinia, also called hard or stony corals, and soft corals, which are of the order Alcyonacea. In this report, coral-cover data from towed-diver surveys is reported only for hard corals.

TOAD surveys were conducted during MARAMP 2003 and in 2004, and observations from analysis of TOAD video collected during these surveys were classified into benthic habitat categories that included hard corals (see Section 2.2.4: "Optical Validation").

During towed-diver benthic surveys, divers recorded a suite of information at 5-min intervals that included estimates of average percentages of cover for live and stressed hard corals as well as for other benthic substrate types. These estimates were recorded to the nearest percentage during MARAMP 2003 and within 10 percentage bins during MARAMP 2005 and 2007. Descriptions of benthic substrate categories for hard corals and the percentage bins used in 2005 and 2007 are provided in Tables 2.4.5a and 2.4.3a.

Because towed-diver surveys use visual estimates for coral cover, results can be subject to observer variability both within and among MARAMP survey years. While every effort is made to calibrate among observers, as well as to replicate survey-track lines among years, minor deviations in lateral position of the small boat that tows divers can result in considerable survey depth and strata disparities among survey years.

Table 2.4.5a. Descriptions of benthic composition categories related to coral cover used in towed-diver surveys during MARAMP 2003, 2005, and 2007 (Kenyon et al. 2006). Data for recently dead corals are not provided in this report. For descriptions of substrate and algal categories see Tables 2.4.4a and 2.4.6a in this chapter.

Benthic Category	Year	Description
Live Hard Corals	2003 2005 2007	All live hard corals observed in a survey swath. These observations included both stressed (see description below) and unstressed corals. Soft corals or dead corals were not included. Live corals were characterized by colonies or portions of colonies covered with living tissue. Living tissue usually appeared colored (e.g., olive green, brown, or bluish lavender) because of the presence of pigments in coral tissue or of symbiotic zooxanthellae. Stressed coral tissue could have appeared pale or completely white.
Stressed Corals	2005 2007	Live hard corals that appeared stressed or bleached as a result of loss of coloration. Signs of stress included pale-to-white coloration caused by bleaching, predation by crown-of-thorns seastars, disease, or recent coral death. Corals could be discolored, malformed, or stricken with tumors. Estimates of stressed-coral cover from MARAMP 2003 are not included in this report.
Recently Dead Corals	2003	Bare white colonies (or portions of them) that had lost living tissue and were not visibly encrusted by macroalgae or epiphytes were classified as dead coral. Lack of encrustation suggested tissue death was recent relative to encrusted portions of dead colonies. Dead coral with macroalgae growth, epiphytes, or other forms of substrate cover were classified as macroalgae (both fleshy and calcified) or other substrate category. Since, in some cases, it could have been hard to differentiate between recently dead and severely bleached corals, both were classified as stressed corals.
Soft Corals	2005 2007	All soft corals observed in a survey swath.

At each REA site, surveys were conducted by 3 dive teams, 1 of which consisted of 2 divers who performed coral and coral-disease surveys. The coral team entered the water and began to work along the first of 2 transect lines ~ 20 min after the fish team entered the water (Fig. 2.4.1a).

The REA methods employed by the coral team varied depending on the biologists conducting the surveys. For most parameters, personnel from CRED used the belt-transect method, and personnel from the CNMI DEQ used the quadrat method. Each method has intrinsic biases, in part because of the difference in areas surveyed (~ 4 m versus 50–100 m per site). The consequences of these biases are discussed in the "Coral Surveys" section of each island chapter. Only at REA sites surveyed by CRED personnel was the line-point-intercept method used to estimate percentages of live coral cover. The spatial and temporal variation of REA coral methodologies is summarized in Table 2.4.5b. Temporal comparisons of survey results are not appropriate for islands (Saipan, Aguijan, Rota, and Guam) where the belt-transect method was used during MARAMP 2007 but the quadrat method was used during previous survey years. Thus, in Chapter 3: "Archipelagic Comparisons," figures present colony-density and size-class data only from REA surveys conducted in 2007.

Results from REA surveys of coral communities were used to calculate generic richness and relative abundance, coral-colony density, size-class distributions, and percentages of cover for live hard corals for each REA site. Generic richness was computed as the maximum number of coral genera recorded within belt transects or quadrats at a site. Coral density was calculated by dividing the total number of colonies within all belt transects or quadrats at a site by the total area surveyed. Coral size-class histograms were created by calculating the relative frequencies of all hard corals in each of the 7 size classes recorded during belt-transect or quadrat surveys. Live coral cover was calculated as the average of results from line-point-intercept surveys on both transects at a site.

Coral cover from REA surveys is presented only from MARAMP 2007, the first year in which the line-point-intercept method was used in the Mariana Archipelago, with the exception of Guam, where this REA method was first used in 2005. Another REA method, the photoquadrat method, was used by the algal assessment team to survey the composition of benthic habitats at REA sites during the 3 MARAMP survey years. Analyses of benthic photographs from these surveys are underway.

Table 2.4.5b. Methods used during MARAMP 2003, 2005, and 2007 for REA coral surveys by island, year, and metric: belt transect (BLT), quadrat, and line-point intercept (LPI). Other metrics include colony density, generic richness and relative abundance, and size class. Coral cover was not assessed using these REA methods in 2003 and only assessed at Guam in 2005. One site at Tinian, TIN-04, was surveyed using the quadrat method in 2007.

Island	2003		2005		2007	
	Cover (%)	Other metrics	Cover (%)	Other metrics	Cover (%)	Other metrics
Guam	–	Quadrat	LPI	BLT	LPI	BLT
Rota	–	Quadrat	–	Quadrat	LPI	BLT
Aguijan	–	Quadrat	–	Quadrat	LPI	BLT
Tinian	–	Quadrat	–	Quadrat	LPI	BLT, Quadrat
Saipan	–	Quadrat	–	Quadrat	LPI	BLT
Anatahan	–	Quadrat	–	Quadrat	LPI	Quadrat
Sarigan	–	Quadrat	–	Quadrat	LPI	Quadrat
Guguan	–	Quadrat	–	Quadrat	LPI	Quadrat
Alamagan	–	Quadrat	–	Quadrat	LPI	Quadrat
Pagan	–	Quadrat	–	Quadrat	LPI	Quadrat
Agrihan	–	Quadrat	–	Quadrat	LPI	Quadrat
Asuncion	–	Quadrat	–	Quadrat	LPI	Quadrat
Maug	–	Quadrat	–	Quadrat	LPI	Quadrat
Farallon de Pajaros	–	Quadrat	–	Quadrat	LPI	Quadrat
Reefs and Banks	–	Quadrat	–	Quadrat	LPI	Quadrat

Belt-transect Surveys

The belt-transect method was used to quantitatively assess generic richness, colony density, and size class of coral colonies. At the beginning of each dive, the belt width was subjectively dictated by perceived colony density: a width of 1 m was used in high-density areas, while a width of 2 m was used in low-density areas. At each REA site, the coral diver

surveyed two 25-m transect lines, recording the maximum diameter of all coral colonies whose centers fell within each belt transect (total survey area = 50–100 m^2). Colonies were recorded to genus level and assigned, by visual estimation, to 1 of 7 size classes: ≤ 5 cm, 6–10 cm, 11–20 cm, 21–40 cm, 41–80 cm, 80–160 cm, and > 160 cm (this binning of coral-colony size classes was based on Mundy [1996]). Estimation of individual coral colony boundaries in the field could be complicated especially for species with life history strategies involving clonal propagation (e.g., *Acropora muricata*) or fissioning (e.g., *Porites lobata*). When estimating coral-colony boundaries, consideration was given to tissue color, interfaces (e.g., skeletal ridges) with neighboring colonies of the same species, and variations in growth forms. If determinations of individual colony boundaries could not be made on these criteria alone, conspecific areas of live tissue separated by more than 10 cm were considered to be separate colonies. All scleractinian, hydrozoan, and octocorals were included in this census.

Quadrat Surveys

The quadrat method was used to quantitatively assess generic richness, colony density, and size class of coral colonies. Along the length of a single 50-m transect line at each site, a quadrat (0.5 × 0.5 m) was haphazardly placed on hard-bottom substrate with corals for a combined total of either 15 (in 2003) or 16 (in 2005 and 2007) times per site (total survey area = 3.75 or 4 m^2 per site). Each scleractinian or hydrozoan colony whose center lay inside a quadrat was identified to species (or genus, for small colonies in which species characteristics had not yet developed), and their maximum and perpendicular diameters were measured (Houk et al. 2005). Octocorals were not included in this census, with the exception of the blue coral *Heliopora coerulea*.

Line-point-intercept Surveys

The line-point-intercept method (Hill and Wilkinson 2004) was used to assess percentage of cover for live corals and other benthic elements at REA sites surveyed at Guam during MARAMP 2005 and at all REA sites surveyed during MARAMP 2007. A coral diver swam along two 25-m transect lines recording at 50-cm intervals all benthic elements falling directly underneath the transect lines. Benthic elements were assigned to 1 of 9 benthic categories: live corals (scleractinian, hydrocorals, and *Heliopora coerulea*), dead corals, carbonate pavement, rock, crustose coralline red algae, macroalgae (both calcified and fleshy), coral rubble, sand, and other sessile invertebrates. Benthic elements were identified to the lowest taxonomic level possible. Cover of turf algae was derived from estimates of cover of dead corals, pavement, and rock.

Surveys for Coral Disease, Syndromes, and Predation

Coral diseases and syndromes, as well as predation scars from crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails, such as snails from the genus *Drupella*, were quantified using the belt-transect method at each REA site. Coral diseases were first surveyed during MARAMP 2007. In a complementary effort, during MARAMP 2005 and 2007, towed-diver surveys estimated percentages of stressed-coral cover: live hard corals that appeared stressed or bleached as a result of loss of coloration (Table 2.4.5a).

At each REA site, the occurrence of coral disease was quantitatively assessed along two 25-m transect lines, following a methodology tested and implemented at Johnston Atoll and the Northwestern Hawaiian Islands (Brainard et al. 2005; Aeby 2006). At the beginning of each dive, subjectively perceived abundance of coral disease dictated the width of the belt: 2 m at disease-rich sites or where surge, currents, or rough seas precluded expanded surveys or 6 m at all other sites to tally a suffient number of cases of low-occurring incidences. Within belt transects, all diseased coral colonies were enumerated, measured, identified to the genus level, and assigned to 1 of 6 disease state categories (Vargas-Ángel and Wheeler 2009): skeletal growth anomalies, white syndrome (acute tissue loss), subacute tissue loss, pigmentation response, fungal infections, and other impaired health conditions, including algal and cyanophyte infections, tube-worm infestations, and syndromes of unknown etiology. In assessing coral health conditions, colonies exhibiting full, partial, or spotty bleaching were also tallied, and, thus, hereafter, bleaching is treated as a disease state—an impairment of normal function (Woebser 2006). Additionally, lesions attributable to predation by crown-of-thorns seastars (COTS) or corallivorous snails were also identified, measured, and enumerated. These counts were complemented with digital photography and tissue collections for future histological examination and verification. A measure of disease severity (percentage of colony affected) was assessed on a semi-quantitative scale from 0 to 5: 1 (mild), ≤ 10%; 2 (moderate), 11%–25%; 3 (marked), 26%–50%; 4 (severe), 51%–75%; 5 (acute), > 75%. In addition, distribution of colony lesions was described following Work and Aeby (2006).

To avoid spreading diseases, when sampling corals within a disease site, fist collections of apparently unaffected (healthy) individuals were conducted first, followed by collections of portions of diseased colonies that appeared unaffected (healthy on disease), and the diseased portions (lesions) of a colony were sampled last. Also, upon return to the ship, collection tools and dive gear were rinsed in bleach solution, thoroughly rinsed with freshwater, and air dried.

Descriptions of coral disease states used during REA surveys are provided in the paragraphs that follow. For more information on coral diseases, go to the CRED website at http://www.pifsc.noaa.gov/cred/coraldiseases.php. For each REA site, overall prevalence of coral disease was computed as the percentage of diseased colonies (counts) relative to the estimated total number of colonies at that site: P_O = (total number of disease cases × 100) ÷ (colony density × total area surveyed for presence of disease).

Skeletal Growth Anomalies

Lesions characterized by changes in normal shape or form of coral colonies, unusual growths, or protuberances associated with an abnormal deposition of the skeleton. Skeletal growth anomalies are caused by changes in the coral cells that deposit the carbonate skeleton, including the following changes: (1) hyperplasia, a process resulting in an increase in the number of cells in a tissue or organ, thereby increasing the bulk of that tissue or organ, and (2) neoplasia, a pathology resulting in the formation and growth of an undifferentiated mass of cells that continues after cellular stimulus ceases (Fig. 2.4.5a[a]).

White Syndrome (Acute Tissue Loss)

White syndrome is a collective term that describes lesions characterized by acute and rapid loss of tissue, leaving behind a sharp, clean band, where tissue is completely removed from a skeleton. A progression of filamentous and turf algae generally covers an exposed skeleton. These features contrast with the wide zone of white skeleton commonly exposed following COTS predation or the scalloped or irregular tissue front produced by the corallivorous gastropod *Drupella* of the subfamily Thaidinae (Fig. 2.4.5a[b]).

Subacute Tissue Loss

Subacute tissue loss is a collective term that describes lesions resulting in slow but progressive loss of tissue. Subacute tissue loss is distinguished from white syndrome by the narrow width of the zone of recently exposed skeleton. Because a particular type of gross lesion can present multiple microscopic manifestations, coral-disease assessments and studies require biopsies for histological, microbiological, and molecular evaluation and verification (Fig. 2.4.5a[c]).

Pigmentation Response

Lesions are characterized by patches of discolored, pink, purple, and blue-to-brown swollen tissue that often occur in irregular shapes and patterns, scattered on the surface of a colony or adjacent to the sediment or algal margins of a colony. Often, but not exclusively, lesions appear to be associated with small areas of tissue loss and allopathic and parasitic interactions with filamentous algae, cyanobacteria, polychaetes, molluscs, and trematodes. However, uncomplicated lesions are also fairly common (Fig. 2.4.5a[d]).

Fungal Infections

Lesions are characterized by patchy, dark discolorations that occur in irregular patterns, bands, or scattered on a coral surface. A progression of filamentous and turf algae may generally appear on cases where infections result in tissue loss. Microscopic examination reveals extensive endolithic fungal proliferation. Upward migration of fungal hyphae into the thecal cavity is generally associated with disruption of the polyp body wall and sloughing of gastrodermis (Fig. 2.4.5a[e]).

Compromised Health States and Other Syndromes of Unknown Etiology

Coral-algae, coral-cyanobacteria, and other biotic interactions such as barnacle and tube-worm infestations may result in an impairment or inhibition of normal coral functioning (e.g., growth, calcification, or reproduction). These morphologies, together with other unidentified cases, are grouped under "other lesions" in surveys for disease prevalence and presented in maps in this report under the category of "Other Diseases" (Fig. 2.4.5a[f]).

Bleaching

This condition is characterized by a reduction in intensity, or complete absence, of coloration within living coral, due to loss of pigmentation or expulsion of endosymbiotic zooxanthellae. Patterns of bleaching can vary, with only the upper surface or lower surface of a colony affected, and can also appear patchy, mottled, or as a circular blotch, ring, or wedge. Although bleaching is considered a generalized response to stressful conditions, it is a sign of disease when it results in an

impairment or inhibition of normal coral functioning (e.g., growth, calcification, or reproduction) and colony death. Recent studies also indicate that bleaching can be caused by an intracellular bacterial pathogen of the genus *Vibrio* (Fig. 2.4.5a[g]).

Predation

Coral predators often leave scars devoid of tissue that may lead to decreased health status and increased susceptibility to algal overgrowth, invasion by other pathogens, or lower reproductive output. The pattern of tissue loss from predation often differs from tissue loss patterns from other causes. Scars characterized by wide zones of exposed coral skeleton are commonly observed following predation by COTS (Fig. 2.4.5a[h], right panel) or characterized by scalloped or irregular tissue fronts that are often produced by the corallivirous gastropod *Drupella* of the subfamily Thaidinae (Fig. 2.4.5a[h], left panel). In this report, predation is included in the values of overall prevalence shown for each REA site on coral disease maps, but predation cases are reported separately from disease prevalence in the text.

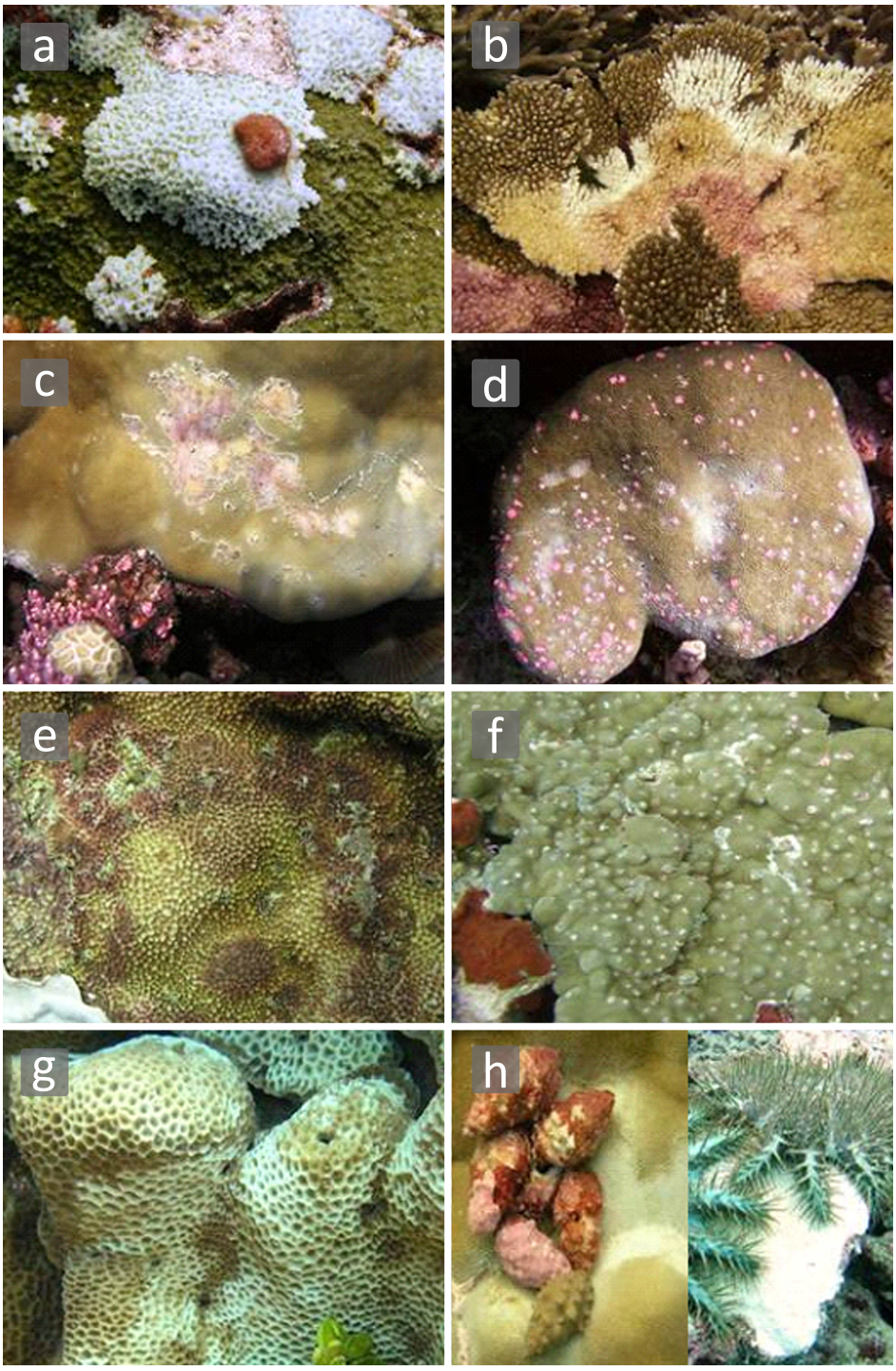


Figure 2.4.5a. Underwater photographs illustrating the field appearance of lesions affecting hard corals around Guam and the CNMI during MARAMP 2007: (*a*) skeletal growth anomalies on *Montipora* sp., (*b*) white syndrome (acute tissue loss) on *Acropora* sp., (*c*) subacute tissue loss on *Porites* sp, (*d*) pigmentation response on *Porites* sp., (*e*) fungal infection on *Pavona varians*, (*f*) "other lesions," specifically tube-worm infestation on *Porites* sp., (*g*) bleaching on *Gardineroseris planulata*, and (*h*) scars from predation by (*left*) *Drupella* snails and (*right*) COTS. *NOAA photos by Bernardo Vargas-Ángel*

2.4.6 Algae and Algal Disease

Algal communities were examined using primarily REA and towed-diver surveys during MARAMP 2003, 2005, and 2007. Cover of macroalgae (both fleshy and calcified), crustose coralline red algae, and turf algae was assessed using towed-diver surveys. Five methodologies—quadrat, photoquadrat, line-point intercept, belt transect, and voucher specimen—were used at REA sites to survey algal cover, occurrence of algal genera and functional groups, presence of algal species, and distribution and density of algal disease.

TOAD surveys were conducted during MARAMP 2003 and in 2004, and observations from analysis of TOAD video collected during these surveys were classified into benthic habitat categories that included macroalgae and crustose coralline red algae (see Section 2.2.4: "Optical Validation").

During towed-diver benthic surveys, divers recorded a suite of information at 5-min intervals that included estimates of average percentages of algal cover as well as of other benthic substrate types. These estimates were recorded to the nearest percentage during MARAMP 2003 and within 10 percentage bins during MARAMP 2005 and 2007. Descriptions of benthic substrate categories for algae and the percentage bins used in 2005 and 2007 are provided in Tables 2.4.6a and 2.4.3a.

Table 2.4.6a. Descriptions of benthic composition categories related to algal cover used in towed-diver surveys during MARAMP 2003, 2005, and 2007 (Kenyon et al. 2006). The macroalgae category included turf algae only in 2003. For descriptions of substrate and coral categories see Tables 2.4.4a and 2.4.5a in this chapter.

Benthic Category	Year	Description
Macroalgae	2003	Fleshy or frondose algae (e.g., species of *Sargassum*), heavily calcified algae (e.g., species of *Halimeda*), and turf algae.
Macroalgae	2005 2007	Fleshy or frondose algae (e.g., species of *Sargassum*) and heavily calcified algae (e.g., species of *Halimeda*). Turf algae were not included.
Crustose Coralline Red Algae	2003 2005 2007	Encrusting calcareous algal species observed within the survey swath. These encrusting algae deposit calcium carbonate as part of their structure, often giving a pinkish or lavender appearance to the encrusted substrate. In some areas these algae can also form three-dimensional spires.

At each REA site, surveys were conducted by 3 dive teams, 1 of which consisted of 2 algal biologists and 1 macroinvertebrate biologist who performed algal and macroinvertebrate surveys. About 10 min after the coral team entered the water, the combined algal and macroinvertebrate team entered the water and began to work along the first of 2 transect lines (Fig. 2.4.1a).

Algal populations at REA sites were surveyed to assess the diversity and relative abundance of algae in the Mariana Archipelago using the photoquadrat method and collection of voucher specimens. Percentages of algal cover were determined using the line-point-intercept method. The belt-transect method was used to estimate density of algal disease. The temporal variation of REA algal methodologies is summarized in Table 2.4.1a.

Observations from REA surveys of algal communities were used to calculate percentages of occurrence of algal genera and functional groups for each REA site. Percentage values of occurrence were calculated by summing the number of photoquadrats in which each algal genus or functional group was observed and dividing by 12, the total number of quadrats surveyed at a site. Percentages of occurrence were then used to create maps of algal distribution for each island or bank. In addition, algal composition results by island were calculated by summing the occurrence percentages for each algal genus or functional group and then dividing respective occurrence values by this sum.

Photoquadrat Surveys

The photoquadrat method, involving quadrats and photographic documentation, was used to examine algal communities. Quadrats were employed to assess the relative abundance of macroalgal genera and algal functional groups in the field. These estimates of abundance are considered relative because assessments for an alga observed in a quadrat, or photoquadrat, were relative to whichever other taxa were present in a photoquadrat. At each REA site, 12 photoquadrats of 0.18 m^2 (~ 16 × 23 cm) were surveyed along two 25-m transect lines. Six photoquadrats were located at randomly selected points along these transects (3 per transect), and 6 additional quadrats were placed at points 3-m perpendicular from each random point in the direction of shallower water (Preskitt et al. 2004; Vroom et al. 2005). Macroalgae were identified to genus level

in the field, whereas crustose coralline red algae, branched coralline red algae, turf algae, and cyanophytes were lumped into functional group categories. In addition, each genus or functional group found in each quadrant was assigned a rank based on its relative abundance in that quadrant (with a rank of 1 being the most abundant). All ranked data for a given MARAMP survey year were collected by the same individual, minimizing the effects of observer bias.

Photographs were taken of each 0.18-m^2 quadrat assessed during these surveys to provide a quantitative data set for later, in-depth, species-level analyses of percentages of algal cover. At each REA site, 12 photographs were taken using digital still cameras (Fig. 2.4.6a). These benthic images, along with voucher specimen collections, form a permanent record of algal communities at each REA site. Results from analyses of these benthic images to the functional group level are available from CRED.

Roving-diver Surveys

A random swim, completed after each photoquadrat survey, augmented the number of macroalgal genera enumerated in photoquadrats at each REA site. For a 5-m swath on either side of the transect line, algal divers haphazardly recorded algal taxa not encountered in photoquadrats. These data are included in the counts of macroalgal genera and functional groups provided in Chapter 3: "Archipelagic Comparisons" and in Appendix B and Appendix C but not in the presence data presented for each MARAMP survey year in the island chapters.

Line-point-intercept Surveys

The line-point-intercept method (Hill and Wilkinson 2004) was used to assess average percentage of cover of macroalgae, crustose coralline red algae, and other benthic elements at REA sites surveyed around Guam during MARAMP 2005 and at all REA sites surveyed during MARAMP 2007. For more information about these benthic composition surveys, see "Line-point-intercept Surveys" in Section 2.4.5: "Corals and Coral Disease" in this chapter.

Voucher Specimens

At each REA site, algal voucher specimens were collected from a 2-m swath on either side of the same two 25-meter transects surveyed during the photoquadrat surveys. Samples were brought back to the laboratory for qualitative species identification at the microscopic level to assemble comprehensive species lists for each site. Voucher specimens were collected at all sites, even when environmental conditions (e.g., strong currents or surge) did not allow for the completion of the quantitative photoquadrat protocol. Voucher specimens and benthic images from photoquadrat surveys form a permanent record of algal communities at each REA site.

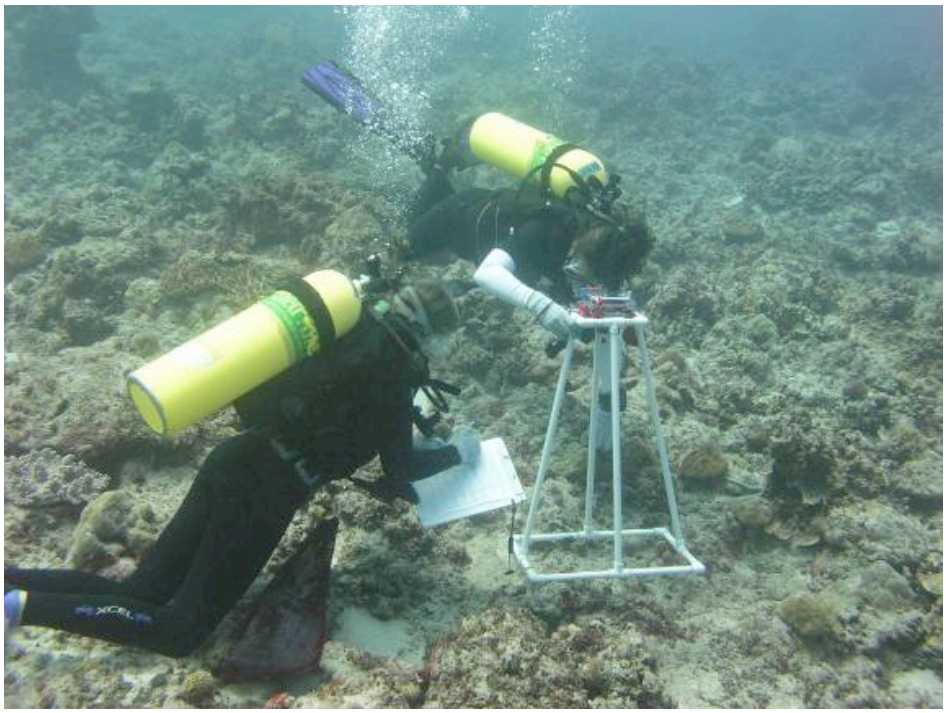


Figure 2.4.6a. An algal assessment team of 2 divers conducts photoquadrat surveys at a REA site on a reef at Guam. *NOAA photo by Jean Kenyon*

Coralline-algal Disease

Coralline-algal diseases and syndromes were quantified in tandem with surveys for coral disease using the belt-transect method at each REA site. Coralline-algal diseases were first surveyed during MARAMP 2007. These surveys were performed by 1 diver from the coral team.

At each REA site, the density of coralline-algal disease was assessed along two 25-m transect lines. At the beginning of each dive, subjectively perceived abundance of coral disease dictated the width of the belt: 2 m at disease-rich sites or where surge, currents, or rough seas precluded expanded surveys or 6 m at all other sites to tally a suffient number of cases of low-occurring incidences.Within belt transects, all afflictions to coralline algae were enumerated and classified into 3 general categories: coralline lethal orange disease, coralline white band syndrome, and coralline cyanobacterial disease. To avoid spreading diseases, when sampling within a disease site, collections of apparently unaffected (healthy) individuals were conducted first, followed by collections of portions of diseased plants that appeared unaffected (healthy on disease), and the diseased portions (lesions) of a plant were sampled last. Also, upon return to the ship, collection tools and dive gear were rinsed in bleach solution, thoroughly rinsed with freshwater, and air dried.

Descriptions of coralline-algal disease states are provided in the paragraphs that follow. For each REA site, density of coralline-algal disease was estimated, in lieu of prevalence, as the number of cases (counts) per 100 m^2 of reef area surveyed at that site: D = (total number of cases of a specific disease × 100) ÷ (total area surveyed for presence of disease).

Coralline Lethal Orange Disease

The distinguishing characteristic of coralline lethal orange disease is a band of bright orange, slimy material spreading across an algal surface, leaving behind bare skeletal carbonate remains of coralline algae. Motile rods of colonial bacteria have been detected through microscopic examination of this orange material but are yet unidentified (Littler and Littler 1995). Additionally, when this orange material has been transferred to other coralline algae, the same disease symptoms have been witnessed. Orange globules can be caught by waves and easily spread to nearby colonies.

Coralline White Band Syndrome

First discovered in the Caribbean, coralline white band syndrome was the second coralline-algal disease ever described (Ballantine et al. 2005). Lesions are characterized by white or pale yellow, irregularly shaped patches or bands spreading across the surface of coralline algae. Left behind are bare carbonate skeletal remains.

Coralline Cyanobacterial Disease

Coralline cyanobacterial disease is characterized by irregularly shaped patches or bands of slimy, fuzzy, green-to-tan cyanobacterial material spreading over algal surfaces, leaving behind bare skeletal carbonate remains; turf and filamentous algae often colonize bare coralline tallus. Lesions commonly are distinguishable by the conspicuous appearance of a cyanobacterial mat and by bright red, orange, or green discolored coralline algal tissue observable in areas where a mat has been lifted or disrupted (Vargas-Ángel 2010).

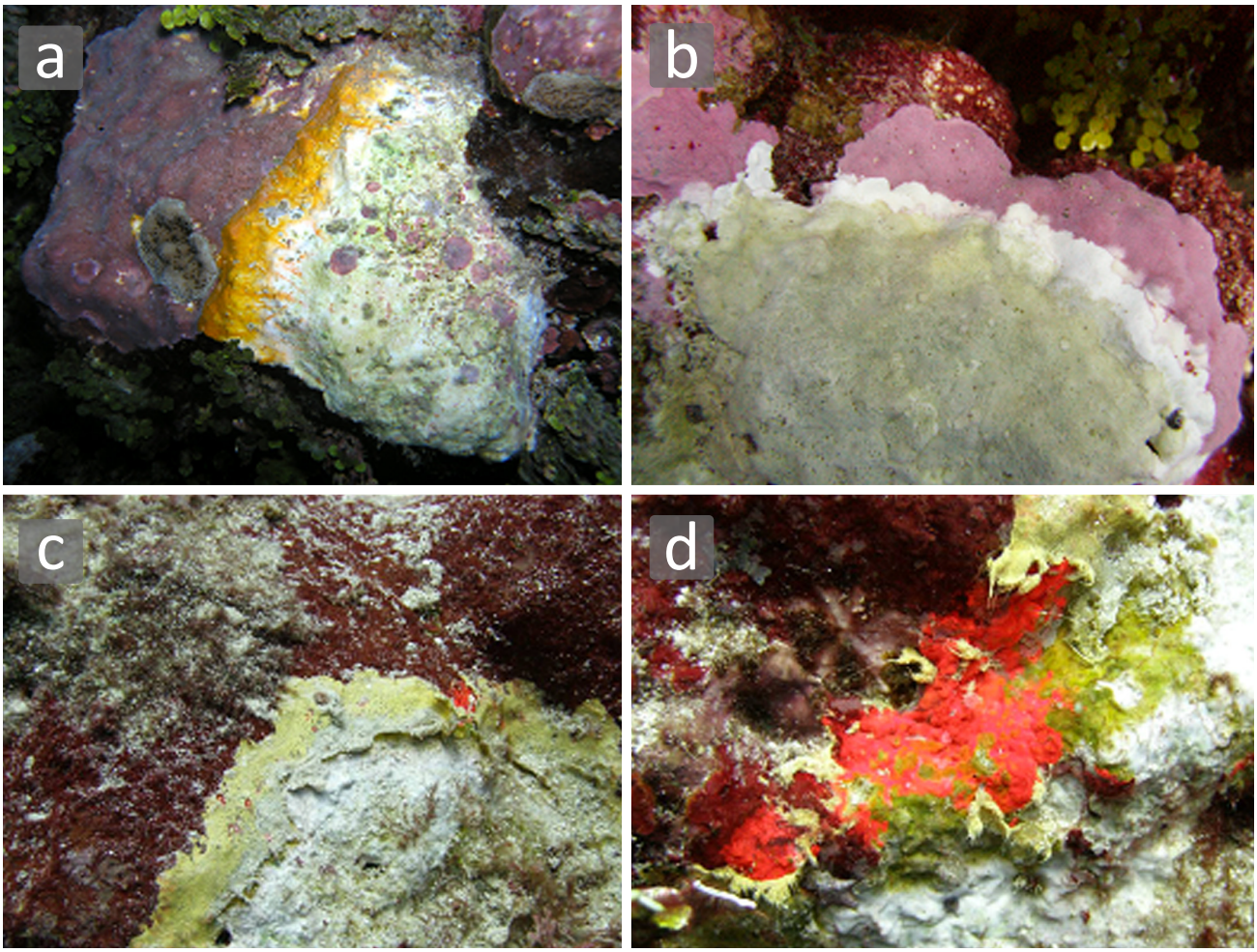


Figure 2.4.6b. Underwater photographs illustrating the field appearance of diseases affecting encrusting coralline algae around Guam and the CNMI during MARAMP 2007: (*a*) coralline lethal algal disease, (*b*) coralline white band syndrome, and coralline cyanobacterial disease, note (*c*) the green-colored cyanophyte mat overgrowing this algal surface and (*d*) the conspicuous, bight red and green color of this exposed, underlying coralline tallus. *NOAA photos by Bernardo Vargas-Ángel*

2.4.7 Benthic Macroinvertebrates

Macroinvertebrate surveys focused on targeted noncoral invertebrates that are common to the reef habitats of the Mariana Archipelago and used both REA and towed-diver methods during MARAMP 2003, 2005, and 2007. Survey results for 4 groups of ecologically and economically important macroinvertebrates—giant clams, COTS, sea cucumbers, and sea urchins—are provided in this report. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders and are harvested for food.

During towed-diver benthic surveys, divers recorded a suite of information at 5-min intervals that included counts of key conspicuous macroinvertebrates encountered within a survey swath that was 10 m wide (5 m on either side of the survey track), as well as estimates of habitat complexity and cover percentages of benthic substrate types. Macroinvertebrates, except COTS, were counted singly up to 25 and then binned as follows: 26–50, 51–100, 101–250, 251–500, 501–1000, and > 1000 organisms. COTS were counted singly up to 100 organisms, and then binned into the same higher classes. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

At each REA site, surveys were conducted by 3 dive teams, 1 of which consisted of 1 macroinvertebrate biologist and 2 algal biologists who performed macroinvertebrate and algal surveys. About 10 min after the coral team entered the water, the combined macroinvertebrate and algal team entered the water and began to work along the first of 2 or 3 transect lines (Fig. 2.4.1a).

Depending on the MARAMP survey year and region, up to 3 different REA survey methods were used to quantify diverse noncoral invertebrate communities during MARAMP 2003, 2005, and 2007: belt transect, quadrat, and roving diver (Tables 2.4.7a and 2.4.1b). Of the REA data collected, only belt-transect data is presented in this report because it was the most consistent REA survey type for all years. Belt-transect surveys were used to calculate macroinvertebrate densities for each REA site.

Note that REA methods recorded invertebrate species that are generally noncryptic (i.e., visible) and easily enumerated during the course of a single scuba dive. Therefore, these surveys documented only the noncryptic fauna of the reef habitat and should not be considered exhaustive for each site. Also, many invertebrate species are nocturnal and, thus, unlikely to be observed during MARAMP surveys, which are conducted during daylight hours.

Temporal comparisons of data from REA surveys are not presented in this report because of differences in procedures. During MARAMP 2003 and 2007, large mobile species were enumerated along transect lines. During MARMP 2005, the diver first conducted quadrat surveys, recording all species seen within 0.25-m^2 quadrats, then conducted belt-transect surveys, recording only organisms along each transect line that were not seen in the quadrat surveys done on that same transect, and, finally, conducted roving-diver surveys, recording only organisms seen on or up to 5–12.5 m on either side of each transect line. Therefore, densities from transects surveyed in 2005 may have been lower, versus densities recorded in 2003 or 2007, if the diver recorded large mobile taxa within quadrats first. In addition, invertebrate surveys were not conducted at Guam, Saipan, Tinian, Aguijan, or Rota in 2007 because of the lack of an available, experienced invertebrate diver.

Belt-transect Surveys

The belt-transect method was used to record quantitative invertebrate counts along two 25-m transects with a survey width of 2 m or three 25-m transects with a survey width of 4 m. Species searched for along these belt transects included noncryptic, mobile taxa: anemones, echinoids, holothurians, crinoids, asteroids, urchins, large gastropods, cephalopods, and large crustaceans. Tridacnid bivalves (*Tridacna* spp.) also were counted.

Quadrat Surveys

The quadrat method was used to quantify smaller, more cryptic macroinvertebrates that were sometimes overlooked or too numerous to count during belt-transect surveys. Divers enumerated organisms within a quadrat (0.25 or 1 m^2) that was either haphazardly placed or numerically aligned every 5 m along each transect line.

Roving-diver Surveys

The roving-diver method was used with the goal of observing invertebrates not seen during belt-transect surveys. During MARAMP 2003 and 2007, roving divers recorded as "present" invertebrate species observed as they haphazardly swam in the vicinity of a transect searching for species. During MARAMP 2005, roving divers swam a zigzag pattern extending 5–12.5 m to either side of both 25-m transect lines.

Survey Method and Transects	2003		2005		2007
	CNMI	Guam	CNMI	Guam	CNMI
Number of Transects (per site)	2	2	2	2	3
Belt Transect	25 × 2 m	25 × 2 m	25 × 2 m	25 × 2 m	25 × 4 m
Quadrat	–	–	0.25 m^2 (interval placement)	0.25 m^2 (interval placement)	1 m^2 (haphazard placement)
Roving Diver	haphazard swim	haphazard swim	25 × 25 m	10 × 25 m	haphazard swim

Table 2.4.7a. Number of transect lines per site and survey area per transect or quadrat for the 3 types of REA macroinvertebrate surveys conducted during MARAMP 2003, 2005, and 2007. REA macroinvertebrate surveys were not conducted around Guam, Saipan, Tinian, Aguijan, or Rota in 2007.

2.4.8 Reef Fishes

Reef fish communities were assessed using both REA and towed-diver surveys during MARAMP 2003, 2005, and 2007. Biomass and abundance per unit area of large fishes (≥ 50 cm in total length [TL]) were assessed using towed-diver surveys. During all MARAMP survey years, the same 3 complementary REA methodologies—belt transect, stationary-point count, and roving diver—were used to estimate the diversity (species richness), numeric abundance (number of fish per 100 m^2), and density (biomass in kg 100 m^{-2}) of diurnally active reef fish assemblages.

During towed-diver fish surveys, divers conducted a 360° scan during the first minute of each 5-min survey segment, recording all large fishes (≥ 50 cm in TL) within their range of visibility. During the remaining 4 min of each segment, all large fishes that appeared within a survey swath that was 10 m wide (5 m to either side of the towline) and 10 m in front of the diver were recorded. During MARAMP 2007, the 360° scan was removed from the survey method, with all 5 min of each segment used to assess large-fish populations forward of the diver and within the survey swath. This report presents data from observations recorded during the last 4 min of each segment in 2003 and 2005 and the entire 5 min of each segment in 2007.

Results from towed-diver fish surveys were used to calculate estimates of large-fish biomass, as weight per unit area, for each survey and ultimately for each island. The length of each individual fish was determined visually and each individual was assigned to predetermined size classes. Large-fish biomass was calculated for each towed-diver survey by applying the midpoint length for each size class to published length-weight relationships ($w = a \times L^b$) for individual species (Kulbicki et al. 2005). When species-specific length-weight formulas were not available, formulas available for the best comparable species (genera, body type, etc.) were used. Large-fish sightings were summed for each survey segment and used to calculate estimates of total fish biomass per survey as well as biomass by fish family.

Towed-diver fish surveys also allowed for "snapshot assessments" of very large fishes (e.g., sharks, jacks, and barracudas) and schools of various species whose range and abundance may be difficult to reliably census during fine-scaled, area-limited REA surveys. In addition, species of concern observed outside a survey swath were recorded as "present," and this data was handled separately from the quantitative towed-diver-survey data.

A forward-facing Sony DCR-PC1000 digital video camera was attached to fish towboards and used to collect streaming video images on Mini DV. To document habitats, video footage from these forward-facing cameras was archived as a durable record of the towed-diver-fish-survey track.

At each REA site, surveys were conducted by 3 dive teams, 1 of which consisted of 2–3 divers who performed fish surveys. The fish team was the first team to enter the water at each REA site. The fish team deployed the first 25-m transect line (Fig. 2.4.1a), and 2 divers began to survey along that transect while the remaining fish diver began stationary-point-count assessments in the general vicinity of that transect (if only 2 divers, then SPC surveys were not done). By the time the coral team entered the water ~ 20 min later, the fish team had deployed and begun surveys along a second 25-m transect. After completing the second transect, the fish team moved on to the third transect.

During all 3 types of REA fish surveys, fishes of all sizes were identified to the lowest taxonomic level possible, generally species, and assigned to standard bins according to their size: 1-cm bins for fishes < 5 cm in TL (0–1, 1–2, 2–3, 3–4, and 4–5 cm) and 5-cm bins for fishes > 5 m in TL (e.g., 5–10 and 10–15 cm). During belt-transect and stationary-point-count surveys, all reef-associated fishes, including those in the water column (e.g., planktivores), were counted, and coastal pelagic species (e.g., clupeids [sardines], belonids [beakfishes], and antherinids [silversides]) seen near the ocean surface were not recorded.

Results from belt-transect surveys at REA sites were used to calculate the estimates of total fish biomass provided in this report. Fish counts from belt-transect surveys were converted to biomass estimates (kg 100 m^{-2}) using length-weight relationships as explained for towed-diver surveys. Data collected from belt-transect surveys also were used to calculate values of species richness (number of species per 100 m^2) at each site. Data from stationary-point-count and roving-diver surveys are not presented in this report.

Belt-transect Surveys

Using the belt-transect method at each site, three 25-m transects lines were surveyed by a pair of divers in 2 passes. On the first (outward) pass, divers swam side-by-side recording all fishes ≥ 20 cm in TL that were observed within adjacent belts, both with widths of 4 m. Thus, the total transect width surveyed by both divers together was 8 m, and the area surveyed per outward swim was 200 m^2 (8 × 25 m). Upon completing the outward component of a survey, divers turn around and swim back down the same transect, recording all fishes < 20 cm in TL that were observed within adjacent belts with widths of 2 m (total survey area = 100 m^2). Survey dimensions were determined following methodological trials by staff from NOAA National Marine Fisheries Services before the onset of the Pacific RAMP and have been standards for CRED throughout its existence. The outward survey of large fishes took ~ 5 min to complete per transect, while the return survey of small fishes took ~ 10 min to complete per transect.

Stationary-point-count Surveys

The stationary-point-count method (Bohnsack and Bannerot 1986) was used to quantify large and mobile reef-fish species that can be difficult to survey by means of belt transects. For each stationary-point-count survey, 1 diver swam ~ 15 m away from the transect line that the other 2 divers were concurrently surveying. The diver then recorded all fishes > 25 cm in TL that passed within a visually estimated cylinder with a 20-m diameter centered on that diver's fixed position (total survey area = 314 m^2). The species and size, in 5-cm bins, were recorded for each fish. At each REA site, 4 stationary-point-count surveys were conducted, each taking ~ 5 min to complete.

Roving-diver Surveys

The roving-diver method was used to record the presence, generally to species level, of reef-fish taxa not encountered during previous surveys using the other methods. Following belt-transect and stationary-point-count surveys, as diver bottom-time permitted, the fish assessment team conducted random swim surveys throughout the area of a REA site.

2.4.9 Protected Species

As part of towed-diver surveys, divers recorded sightings of sea turtles (Cheloniidae) and other species of concern in addition to the main suite of information on fish communities and benthic composition. Sea turtles were tallied and their size estimated by towed divers whenever they were observed during a survey. Recorded sightings were not limited to the 10-m survey swath (or width) of a towed-diver-survey area. Species of concern observed outside a survey swath were recorded as "present," and these data were handled separately from the quantitative towed-diver-survey data.

Divers who had not conducted towed-diver surveys, such as divers who had conducted REA surveys, collected hydrographic data, or deployed instruments, on a daily basis reported incidental observations of species of concern. During MARAMP 2003, in addition to the regular towed-diver surveys, up to 2 towed divers performed surveys dedicated to turtle observations (Kolinski et al. 2005).

2.4.10 Marine Debris

As a secondary data set, towed-diver surveys included numeric recording of benthic anthropogenic marine debris. The secondary nature of this marine debris data set means that observations may have been omitted by a diver because of other data priorities at a given time. Therefore, data presented here can be qualified as regional underestimates. Observations of debris presented in this report are positive identifications, but absence of reports does not imply lack of debris.

Towed-diver surveys numerically tallied marine debris when sightings fell within the 10-m width of a survey swath for each 5-min survey segment. Debris items included but were not limited to the following types: (1) derelict fishing gear, (2) munitions, or unexploded ordinances, (3) shipwrecks, and (4) other man-made objects, whether of nautical or terrestrial origins. Debris sightings were recorded differently during MARAMP 2003 than during the other survey periods: sightings in 2003 were recorded as a direct part of diver observational methods, and sightings in 2005 and 2007 were recorded solely as incidental observations by the towed divers in their observer comments.

2.5 Ecosystem Integration: Coral Reef Condition Index

The *Coral Reef Condition Index* is a composite metric of biological variables that describes the relative status of coral reefs throughout the Mariana Archipelago. This integrated condition index is composed of a benthic category and a fish category, both of which contain multiple biological components (Fig. 2.5a). This approach provides a way to evaluate the condition for the fish and benthic categories individually, using the *Benthic Condition Index* and *Fish Condition Index*, as well as the overall coral reef condition for a given area. All index variables are based on observations from towed-diver surveys. The benthic category is made up of 5 components: cover of live hard corals, cover of stressed corals, cover of macroalgae, cover of crustose coralline red algae, and density of crown-of-thorns seastars (COTS). The fish category comprises 2 components: density and biomass, both of large fishes (≥ 50 cm in TL).

Analysis for the Coral Reef Condition Index was conducted at 2 spatial scales, archipelagic and island levels, using data collected during MARAMP 2005 and 2007 towed-diver surveys. Geographic regions were the unit of analysis for archipelagic comparisons. Geographic regions are delineated on map figures as 1.5-km buffers from the 100-fm isobath around each island with breaks determined by differences in coastal wave exposures and the spatial extent of MARAMP survey locations. Analysis on the island scale was performed using data from surveys around only the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan and towed-diver-survey areas as the unit. For the island-level indices, survey areas are represented on map figures by irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007 (survey tracks were often similar but not exactly the same in each survey year). For the archipelagic indices, polygons are shaped by the geographic regions. These geographic-region and survey-area polygons do not reflect the actual area surveyed but rather provide a useful, enlarged visualization of index results for data collected within geographic regions and survey areas.

Towed-diver surveys allow for a rapid and quantitative survey over a broad area (see Section 2.4: "Reef Surveys: Corals, Algae, Macroinvertebrates, Fishes, and Substrates"). The 7 index components were chosen to describe the condition of coral reef ecosystems within geographic regions and survey areas. Because of differences between years in towed-diver-survey methods, data from MARAMP 2003 surveys were not included in the Coral Reef Condition Index or its associated fish and benthic categories. In addition, data from geographic regions and survey areas where surveys were conducted in only a single year were not analyzed.

Each of the 7 components was rank-transformed from survey mean values. At the archipelagic scale, ranks were assigned to each geographic region based on mean survey segment values. At the island scale, ranks were assigned to each survey area based on mean survey values. The advantages of this method include simplicity and independence to outliers. The primary disadvantage of this method is that it loses the absolute value of information, although the ranges of component values for each year are presented to evaluate overall absolute changes.

The ranks in these condition indices are presented on maps to allow for comparisons and visual representation of spatial and temporal patterns across the Mariana Archipelago or among the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan. To create these maps, index ranks for geographic regions and survey areas were separated into tertiles categorized as "high," "medium," and "low." Temporal patterns in index tertiles provide a simplified and conservative means to track relative conditions of biological resources, such as "improving," "declining," or "unchanged."

A high rank means superior condition relative to (a), in the archipelagic indices, other geographic regions in the Mariana Archipelago or (b), in the island-level indices, other survey areas in the 4 populated, southern islands. Coral reef areas with high ranks in the Coral Reef Condition Index were characterized by relatively high values of coral cover, crustose-coralline-red-algal cover, fish density, and fish biomass as well as low values of stressed-coral cover, COTS density, and macroalgal cover. Coral reef areas with low ranks in the Coral Reef Condition Index have relatively low values of coral cover, crustose-coralline-red-algal cover, fish density, and fish biomass as well as high values of stressed-coral cover, COTS density, and macroalgal cover.

The *Archipelagic Coral Reef Condition Index* is the basis for comparing ecosystems across the Mariana Archipelago, particulary between the southern islands and the northern islands, in Chapter 3: "Archipelagic Comparisons." The *Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan* is used to compare survey areas around those individual islands and among them in the "Ecosystem Integration" sections of Chapters 4, 5, 7, and 8.

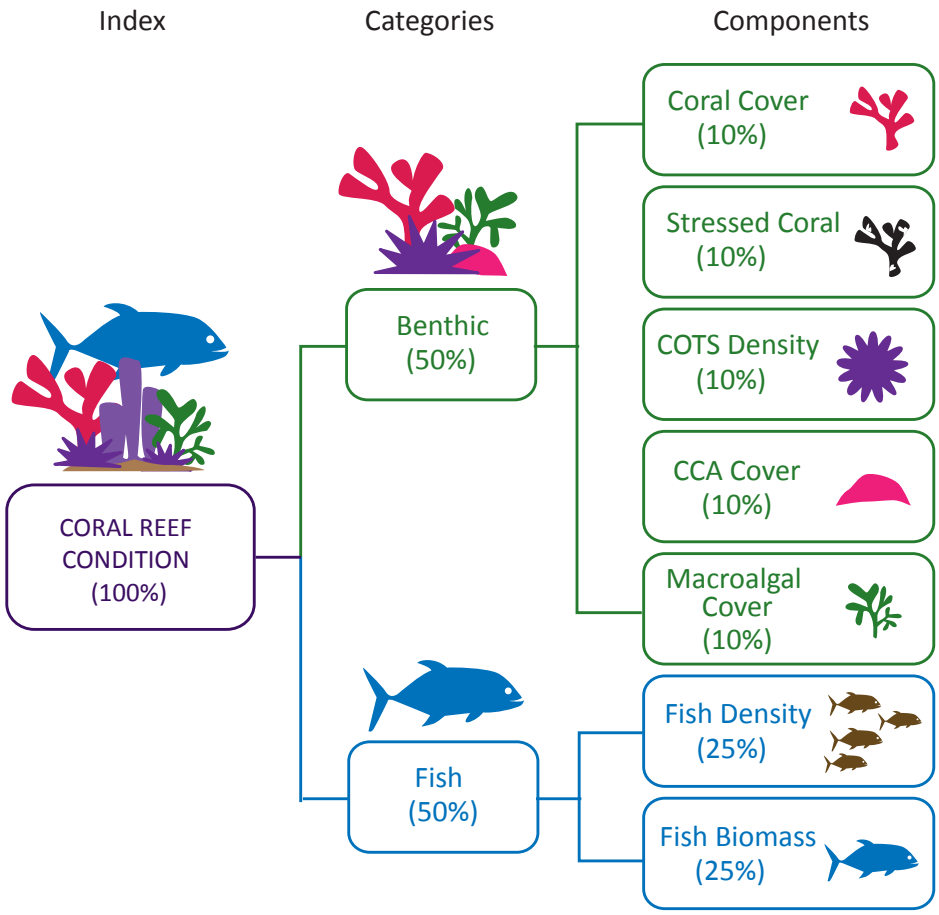


Figure 2.5a. Schematic of the categories and components of the Coral Reef Condition Index, which uses equal weights on the benthic and fish categories. Actual weights are shown in parenthesis.

Formally, the variables and components were aggregated additively with a summation of weighted and normalized components (Fig. 2.5a):

$$I_j = \sum_{i=1}^{N} w_i \, x_{ij}$$

where I_j is the composite index for j, a geographic region or survey, x_i is a variable, and w_i is the weight of the variable, x_i, with $\sum_i w_i = 1$ where $0 \le w_i \le 1$, for all $i=1,\ldots,N$ and $j=1,\ldots,M$. The Coral Reef Condition Index uses an equal average weighting method between the benthic and fish categories. Coral cover, crustose-coralline-red-algal cover, fish density, and fish biomass were rank-transformations of raw variables.

2.6 Geographic Information System Products

All map-based figures included in this report were generated with ESRI's ArcGIS 9.3 desktop Geographic Information System (GIS) software to characterize spatial variability of survey data collected primarily during MARAMP 2003, 2005, and 2007. Geographic data incorporated in maps include multibeam bathymetry and backscatter products and derivatives, TOAD survey tracks, locations of REA and towed-diver surveys, and other baseline geographic features.

These geographic data are stored and managed in an enterprise geodatabase via ESRI's ArcGIS Server 9.3 and Oracle Database 10g (Redwood Shores, Calif.). All nongeographic data (e.g., TOAD habitat classifications, physical and chemical oceanographic properties, and observations from REA and towed-diver surveys) are stored and managed in CRED's relational database management systems.

Nongeographic data were plotted in ArcGIS using 1 of 2 methods: (1) joining nongeographic data to their corresponding survey locations via a common field (e.g., towed-diver fish observations to towed-diver-survey tracks using the unique serial numbers for each survey) or (2) directly plotting the latitude and longitude of each observation or measurement (e.g., temperature from shallow-water CTD casts) using the *Add XY data* function in ArcGIS.

Data are displayed within ArcGIS using a number of different methods, depending on whether the type of geographic data is vector or raster. The vector data model uses 2-D coordinates to store and represent geographic features as points, lines, polygons, or areas (Heywood et al. 2002). The raster data model defines space as an array of equally sized cells arranged in rows and columns in which each cell contains an attribute value and location coordinates (Heywood et al. 2002; ESRI 2009).

REA survey sites (points), towed-diver-survey tracks (lines), and geographic regions (polygons) are examples of vector data. The following methods, among others, were used to display vector data in this report:

- Features: single symbol
- Categories: unique values
- Quantities: graduated colors and graduated symbols using the natural breaks (Jenks), equal interval, or manual classification methods
- Charts: pie and bar

Multibeam bathymetry and backscatter products and derivatives are examples of raster data. The following methods, among others, were used to display raster data in this report:

- Unique values
- Classification using the natural breaks (Jenks) or manual classification methods
- Stretched

3 ARCHIPELAGIC COMPARISONS

In this chapter, integrated ecosystem observations collected during Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) cruises in 2003, 2005, and 2007 are compared between islands across the Mariana Archipelago. These discussions address the following topics: geopolitical context, benthic habitat mapping and characterization, oceanography and water quality, corals and coral disease, algae and algal disease, benthic macroinvertebrates, reef fishes, species of concern, marine debris, and ecosystem-wide integration. The spatial patterns and variability of observations of coral reef ecosystems around individual islands and banks are examined on a regional scale. This broad-scale examination provides information relevant to ecosystem-based management and conservation of the coral reefs around these islands and banks at local, regional, national, and international levels. Note that many of the tables and figures in this chapter show islands from north to south and use 3-letter codes for island names; island codes are provided in the List of Abbreviations in this report.

Other chapters of this report present—on an individual island or bank basis—comprehensive and detailed spatial and temporal descriptions of the integrated coral reef ecosystem observations recorded during MARAMP 2003, 2005, and 2007. MARAMP surveys were conducted around the island of Guam and 3 adjacent offshore banks (11-mile Reef, Santa Rosa Reef, and Galvez Bank) in the territory of Guam and around 13 islands (Rota, Aguijan, Tinian, Saipan, Anatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug, and Farallon de Pajaros), 5 offshore banks (Tatsumi Reef, Esmeralda Bank, Marpi Bank, Zealandia Bank, and Supply Reef) in the Commonwealth of the Northern Mariana Islands (CNMI), and 3 remote reefs (Pathfinder Reef, Arakane Reef, and Stingray Shoal) on the West Mariana Ridge.

3.1 Geopolitical Context

This section summarizes some of the available socioeconomic and geopolitical data about Guam and the CNMI to aid analyses of coral reef ecosystems in the context of human activities that may be influencing them. Many of the anthropo-

T able 3.1a. Summary of island parameters across the Mariana Archipelago: land area, proportion of archipelagic population, population density, maximum elevation, native vegetation, vegetation cover, and animal threats (U.S. Bureau of the Census 2011a, 2011b; Siebert and Simkin 2002– ; Encyclopaedia Britannica Online; Cruz et al. 2000a, 2000b, 2000c, 2000d, 2000e; Cruz et al. 2003; Esselstyn et al. 2003; Liu and Fischer 2006a, 2006b; Mueller-Dombois and Fosberg 1998; Pacific Protected Areas Database; Martin et al. 2008; Minton 2005; National Park Service 2001, 2005; Stafford et al. 2005; Atkinson and Atkinson 2000; Burdick et al. 2008; Fritts and Leasman-Tanner 2001; Fritts and Rodda 1998; Marianas Avifauna Conservation Working Group 2008; Rodda and Savidge 2007; M Onni, CNMI Division of Fish and Wildlife, pers. comm.). Land areas were calculated using Geographic Information System (GIS) techniques.

Island	Land Area (km²)	Share of Arch. Population (% in 2000)	Population Density (persons/km²)	Maximum Elevation (m)	Year of Last Eruption	Native Vegetation	Vegetation Cover (%)	Animal Threats
FDP	2.25	0	0	360	1967	L	L	None
MAU	2.14	0	0	227	–	M	M	goat, rat
ASC	7.86	0	0	857	1906	H	M	rat
AGR	44.05	0	0	965	1917	M	H	goat, pig, rat
PAG	47.75	0	0	570	2010	L	M	cattle, goat, pig, rat
ALA	12.96	0	0	744	870	L	M	goat, cat, pig, rat
GUG	4.24	0	0	287	1883	H	M	rat
SAR	4.47	0	0	538	–	M	M	rat, eradicated: goat, cat, pig
ANA	33.91	0	0	788	2008	M?	L	goat, pig, rat
SAI	118.98	22.6	405.3	474	–	VL	M	cattle, goat, brown tree snake*, cat, pig, rat
TIN	101.22	1.5	31.0	187	–	VL	H	cattle, goat, brown tree snake*, cat, pig, rat
AGU	7.01	0	0	57	–	M	H	goat, rat
ROT	85.13	1.2	29.7	496	–	M	H	cattle, goat, brown tree snake*, cat, pig, rat
GUA	544.34	74.7	292.8	406	–	VL	M	cattle, goat, brown tree snake, cat, pig, rat

VL: very low, L: low, M: medium, H: high, VH: very high
cattle, goat, brown tree snake*, brown tree snake, cat, pig, rat
* Indicates brown tree snake sighted but not established

genic activities and effects on the coral reef ecosystems in this region are concentrated around the 4 populated, southern islands. Although a few anthropogenic issues, such as feral animals, introduced species, and fishing, affect the ecosystems of the uninhabited or sporadically populated northern islands, natural events, including storms and volcanic eruptions, presumably generate most ecological disturbances in the northern islands. Table 3.1a presents a summary of selected physical, social, and environmental attributes that have been identified in the island chapters of this report as potential sources of effects on coral reef ecosystems. Additional information regarding history and demographics, geographic and geologic settings, land use, economy, and environmental issues is discussed for each island and bank in their respective chapters and on a regional basis in Chapter 1: "Introduction."

3.1.1 History and Demographics

A native Chamorro population was established in the Mariana Archipelago as early as 3500 years ago (Rogers 1995) and declined significantly during the period of control by Spain. Estimates of the Chamorro population prior to the arrival of the first Spanish missionaries in the late 17th century range from 24,000 to 100,000, significantly higher than the 3539 Chamorro recorded in the first Spanish census in 1710 (Rogers 1995; Underwood 1973). The total human population in the Mariana Archipelago surged during and after World War II (WWII) to more than 65,000 by 1950 and has increased to more than 200,000 in recent years, although the population in the CNMI declined between the 2 most recent U.S. Decennial Cenuses (Fig. 3.1.1a; U.S. Bureau of the Census 1982, 1983, 2002, 2003, 2011a, 2011b; Office of the High Commissioner 1959). Guam and Saipan are the most densely populated islands (Table 3.1a) with 74.7% and 22.6% of the archipelagic population in 2010 and population densities of 292.8 and 405.3 persons km^{-2}, respectively (U.S. Bureau of the Census 2011a, 2011b). The 4 populated, southern islands of Guam, Rota, Tinian, and Saipan supported the entire population of the Mariana Archipelago in 2010, according to the U.S. Census 2010, although the previous U.S. Census in 2000 had an official count of 6 persons for the northern islands and sporadic, small populations of < 300 persons combined have been recorded on the northern islands of Agrihan, Pagan, Alamagan, and Anatahan since WWII (U.S. Bureau of the Census 2003, 2011a, 2011b; Cruz et al. 2000a; Siebert and Simkin 2002–; University of Hawaii 2009; Trefalt 2003).

Guam accounted for three-fourths of the estimated 2010 population for the Mariana Archipelago with 159,358 persons (U.S. Bureau of the Census 2011a, 2011b). Guam's population is expected to grow by an estimated 24,713 as the U.S. military relocates between 4700 and 8000 Marines, as well as other personnel and dependents, to the island within the next decade (U.S. Department of the Navy 2010; Parrish 2012; Hart 2012). Civilian population is also expected to increase to provide construction and other services for the military buildup (Laney 2008). Some military-related population growth is expected in the CNMI, but that increase could be offset by population declines related to other sectors of the economy. In

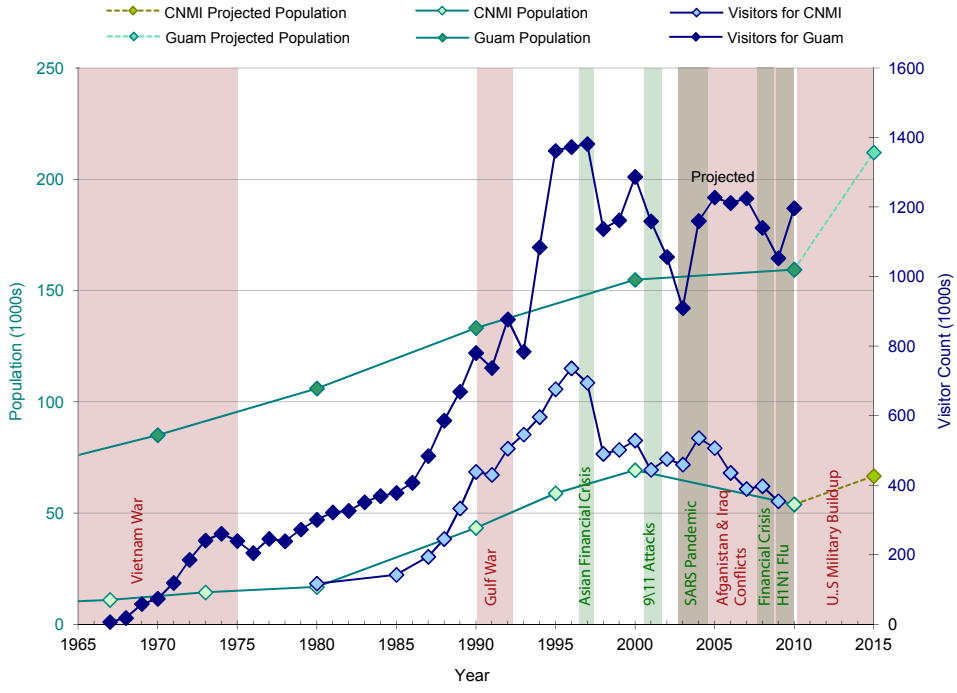


Figure 3.1.1a. Population growth (U.S. Bureau of the Census 1982, 1983, 1992, 2002, 2003, 2011a, 2011b; CNMI Department of Commerce 2002a; Secretariat of the Pacific Community 2011) and visitor count (Bank of Hawaii 1995; Lucas 1990; U.S. Department of the Interior 1996; CNMI Department of Commerce 2002b; Marianas Visitors Authority; A Cid, Guam Visitors Bureau, pers. comm.) trends on Guam and the CNMI during the period of 1965 to 2015.

the CNMI, the estimated population dropped more than 22% from 69,221 in 2000 to 53,883 in 2010 (U.S. Bureau of the Census 2003, 2011a). Legislation signed into law in 2010 may lead to the repopulation of some of the northern islands, including Sarigan, Alamagan, Pagan, and Agrihan.

3.1.2 Land Cover and Use

The major differences in land use between the southern and northern islands are primarily related to human population. In terms of land cover, WWII events in the southern islands played a significant role in determining the amount of native vegetation that remained. In recent decades, the southern islands have seen growth in military development and tourism, exacerbating land-use pressures associated with population growth and infrastructure support. In contrast, the sparsely populated, northern islands are largely removed from these development issues.

During WWII, U.S. troops captured Guam, Tinian, and Saipan from Japanese forces after fierce fighting in the summer of 1944. During and after these battles, large portions of the native limestone forests and ground cover on these 3 islands were completely destroyed. Subsequent recolonization of terrestrial flora often involved replacement with non-native plant species (Pacific Worlds & Associates 2003). Because no prolonged battles were fought on Rota or Aguijan, which Japan surrendered at the end of WWII, much more native limestone forest remains on these two islands than on Guam, Saipan, and Tinian. Estimates suggest that Rota still has land cover of more than 50% native limestone forest (Liu and Fischer 2006a).

On Saipan and Guam, 25%–50% of the land use has been classified as urban (Liu and Fischer 2006a, 2006b; see Fig. 4.1.2a in Chapter 4: "Guam and Adjacent Reefs and Banks," Section 4.1.2: "Land Use" and Fig. 8.1.3a in Chapter 8: "Saipan," Section 8.1.3: "Geography"). The land area of Saipan is only 22% of the land area of Guam, and Saipan's population density is 1.8 times greater than Guam's population density (U.S. Bureau of the Census 2002, 2003, 2008). Geographically, the human population on Guam is largely centered in the northern part of that island, while population is more evenly spread across the island of Saipan. The population density and urbanization of these 2 most heavily populated islands are also significant factors in the land cover and other environmental issues that can affect coral reefs (e.g., pollution, arson of hillside vegetation, construction, erosion, recreational overuse, excessive fishing). On Tinian and Rota, population centers are much smaller, with less associated urban development.

Beyond population density, major potential determinants in land cover include volcanic activity and the presence of feral animals introduced by previous and current human inhabitants. On the northern islands, land cover is influenced by the steepness of the stratovolcanoes and the amount, frequency, and duration of volcanic eruptions, which cause deposits of ash or lava, mass wasting, or erosion. On almost all islands of the Mariana Archipelago, introduced feral animals, including goats, pigs, deer, and cows, destroy or alter native understory vegetation—destruction that can increase erosion and runoff and can, therefore, have significant indirect effects on coral reef ecosystems. Currently, only Farallon de Pajaros is thought to have no introduced feral animals, although Guguan and Asuncion have only rats (Atkinson and Atkinson 2000; Burdick et al. 2008; Cruz et al. 2000a, 2000b, 2000c, 2000d, 2000e; Cruz et al. 2003; Esselstyn et al. 2003; Fritts and Leasman-Tanner 2001; Fritts and Rodda 1998; Martin et al. 2008; Marianas Avifauna Conservation Working Group 2008; National Park Service 2005; Pacific Protected Areas Database; Rodda and Savidge 2007).

3.1.3 Geology and Geomorphology

The differences in the geologic histories of the islands of the Mariana Archipelago have been identified together as a major factor that shapes the coral reef ecosystems surrounding these islands (Burdick et al. 2008; Houk and Van Woesik 2010; Riegl et al. 2008). The 6 southernmost islands of Guam, Rota, Aguijan, Tinian, Saipan, and Farallon de Medinilla and their adjacent banks are part of the Mariana frontal arc, consist of extinct volcanic edifices that were formed in the late Eocene to early Miocene epochs (15–20 million years ago), and are largely covered by layered, uplifted carbonate surfaces (see Figs. 1.1.2a and 1.1.2b in Chapter 1: "Introduction," Section 1.1: "Geologic and Geographic Setting"). These carbonate surfaces are flat-lying and have low slopes except between layers. Some limestone areas exhibit karst topographies, which are formed by dissolution of carbonate rocks and characterized by sinkholes, caves, and subterranean passages. Because of high limestone porosity on these southern islands, there is little surface-water retention or runoff. On these 6 islands, the underlying volcanic rocks are exposed in only a few places, except on Guam, where most of the southern half of this island consists of exposed Eocene volcanic rocks and laterite soils, which are highly susceptible to erosion, especially on the steep southwestern coast (see Fig. 4.1.2a in Chapter 4: "Guam and Adjacent Reefs and Banks," Section 4.1.2: "Land Use").

The 9 northern islands of the Mariana Archipelago are all part of the active Mariana Arc created by the subduction of the Pacific Plate under the Philippine Plate. Seven of these islands—Anatahan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, and Farallon de Pajaros—are either currently active or have been active within recorded history (Fig. 3.1.3a and Table 3.1a). Most recently, the latest recorded eruption occurred in 2010 at Pagan, which experienced a major eruption in 1981. The last recorded eruption at Anatahan ended in 2008, and this island experienced major eruptions in 2003 and 2005. Although Farallon de Pajaros has not been active since 1967, this northernmost island was known in previous centuries as the "Lighthouse of the Pacific" because of frequent eruptions. The first known eruption of a volcano in the Mariana Archipelago, based on radiocarbon dating, was of Alamagan in AD 540 (Siebert and Simkin 2002–).

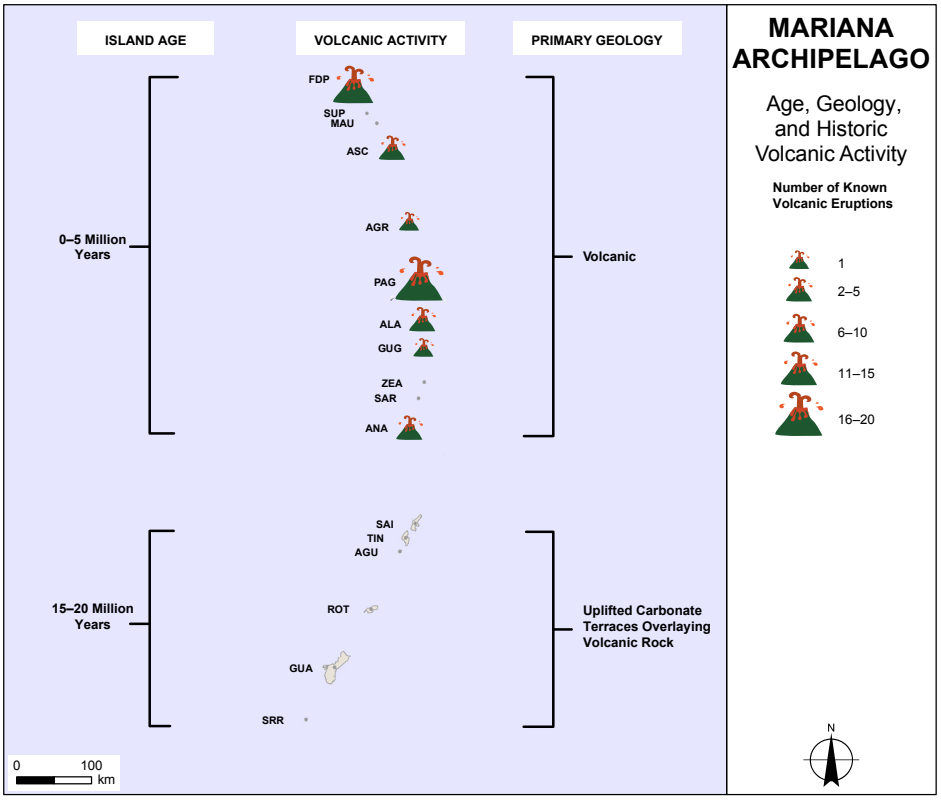


Figure 3.1.3a. Island age, primary geology, and eruptive volcanic activity in the Mariana Archipelago. Eruption information is based on historic records and radiocarbon dating back to AD 540 (Siebert and Simkin 2002–).

Two geomorphologic features potentially are important factors when considering the composition and condition of the coral reef ecosystems that surround the islands of the Mariana Archipelago: island land area and slope, both above and below the surface of the ocean. Slope is closely related to the geology and elevation of each island. The northern islands, characterized by steep profiles and periodic, explosive eruptions, are all stratovolcanoes (i.e., tall, conical volcanoes with many layers or strata of hardened lava, cinder, or volcanic ash; Fig. 3.1.3b). These volcanoes originate from the seafloor at depths of ≥ 2000 m and rise to maximum elevations ranging from 227 m (Maug) to 965 m (Agrihan) above sea level. Among the southern islands, the highest point is on the Sabana Plateau on Rota at 496 m; this high point is very near the south shore, and the steep slope in that area is subject to erosion.

The northern volcanic islands, as a group, are much steeper than the southern carbonate islands. Rota, Tinian, and Aguijan are primarily flat, step-like carbonate plateaus with steep slopes only between the different limestone layers. Southern Guam and northern Saipan have steeper slopes and more complex topography where volcanic rocks are exposed. On the northern islands, north Farallon de Pajaros, Maug, east Asuncion, north Agrihan, east Alamagan, south Sarigan, and north Anatahan have slopes in excess of 30°, and evidence of frequent landslides has been noted during biennial MARAMP surveys around these islands, especially on Farallon de Pajaros and Asuncion.

Islands range in size from a mere 2 km^2 for Maug and Farallon de Pajaros to 544 km^2 for Guam, and the total area for all 9 of the northern islands from Anatahan north to Farallon de Pajaros is only 160 km^2 (Table 3.1a).



Figure 3.1.3b. Farallon de Pajaros, a steep-sided stratovolcano with little vegetation, has had at least 15 eruptions since the first known one for this island was recorded in 1864. *NOAA photo*

3.1.4 Economy

The primary drivers of Guam's economy are tourism and the large, growing presence of the U.S. military and government. The economy of the CNMI is based primarily on tourism (Laney 2008), having lost the once-booming garment industry in Saipan. For both the CNMI and Guam, significant economic effects have resulted from fluctuations in visitor arrivals from Asia associated with global economic, political, and environmental changes, including regional recessions, the terrorist attacks on September 11, 2001, and concerns over severe acute respiratory syndrome and bird flu. The economic forecast for Guam is relatively strong because of increasing military investment and recent improvement in the tourism industry. In contrast, economic drivers in the CNMI generally are weak because visitor arrivals have decreased dramatically from their peak in 1996 and garment industry revenues essentially have disappeared.

Tourism, particularly from Asian markets, has been a major component of the economies of both the CNMI and Guam since the 1980s. Tourism suffered during the weakness of Asian economies in the 1990s. Since 2005, the decline in Japanese visitors and the related cuts in the number of direct flights from Asia to Guam or Saipan have further hurt these markets. The number of visitors arriving in the CNMI fell to 353,956 in 2009, a 52% drop from 736,117 in 1996 (CNMI Department of Commerce 2002b; Marianas Visitors Authority), while Guam's visitor arrivals decreased only slightly from a high of 1,381,513 in 1997 to 1,196,523 in 2010 (A Cid, Guam Visitors Bureau, pers. comm.). Guam in recent years has experienced increased tourism from Russia and China, both key markets for future growth (Guam Visitors Bureau). The CNMI has seen a rise in visitors from Russia but a decline in combined arrivals from China and Hong Kong each year beginning in 2007, although combined arrivals from China and Hong Kong are up dramatically from counts in 2002 (Marianas Visitors Authority). Ongoing discussions about immigration laws and their effect on tourism center on visitor eligibility for Chinese and Russian travelers under the Guam-CNMI Visa Waiver Program.

Guam has been a strategic U.S. military post in the Pacific for much of the past century. With the withdrawal of troops from the Philippines in the 1980s and the planned move of ~ 25,000 military personnel and family members, including at least 4700 Marines from Japan, to Guam in the next decade (U.S. Department of the Navy 2010; Parrish 2012; Hart 2012), Guam has become an even more important location for U.S. military operations in the western Pacific. This projected population increase and associated spending for construction, harbor, and housing projects over the next decade will be a major factor in Guam's future, economically and environmentally. In the CNMI, the U.S. Department of Defense leases 60% of Tinian for training, conducts live-fire exercises on Farallon de Medinilla, and pays for anchoring strategic "pre-positioned" ships in the Garapan Anchorage on the west side of Saipan. Use of Pagan and other northern islands for military training has been proposed. Still, the level of military spending in the CNMI is relatively low when compared to the projected $15 billion to be spent in Guam over a decade (Laney 2008).

The garment industry was a key driver of the economy on Saipan, beginning in the 1980s and peaking in 1998. As world trade opened and minimum wage requirements rose, however, Saipan's garment industry became much less competitive, and the last garment factory on Saipan closed in February 2009. In 2008, the U.S. Congress passed legislation to federalize immigration to the CNMI, which not only may have affected what remained of the garment industry but also could have considerable effect on tourism and foreign investment (U.S. Government Accountability Office [GAO] 2008).

Other sectors of the economies of Guam and the CNMI, such as fishing and agriculture, are relatively minor in their economic impacts but are culturally important. Most fishing is conducted from shore or on small vessels, primarily around the populated islands, although some vessels do fish near the northern islands. Documented local fishing issues in Guam and Saipan are discussed in the individual chapters. Agriculture is a small source of income (CNMI Department of Commerce 2008; Guam Department of Labor 2008; National Park Service 2005).

3.1.5 Environmental Issues

Many of the environmental concerns in Guam are associated with increasing population, tourism, and development. Construction of facilities for ~ 25,000 incoming military personnel and dependents is a major concern for some residents of Guam. Although the human population and tourism in the CNMI has declined in recent years, pressures from human activities still affect the coral reef ecosystems around the populated, southern islands. Military construction of piers and training facilities and ranges could potentially affect ecosystems on and around Tinian, Saipan, Pagan, and other islands in the CNMI. Tourism and associated facility construction and tourist activities, such as diving and other water sports, that can affect coral reefs are vital issues in both Guam and the CNMI, since their economies depend on tourism (Burdick et al. 2008). Fishing pressure is another concern around the southern islands of the Mariana Archipelago; fishing efforts have been stable or increased and fish catch rates have declined over the past 20 years in Guam (Burdick et al. 2008).

Coastal pollution associated with sewage outfalls, sedimentation, and runoff is a concern in most populated areas. The majority of freshwater resources on Guam and the southern, populated islands of the CNMI come from underground lenses that rest on top of saltwater lenses at or near sea level. Elevation of sea level caused by global warming possibly could affect the level of available freshwater resources (Titus 1990). In 2008, both landfills and wastewater systems on Guam were reported to be at capacity (GAO 2009). An average of 700 wildfires per year from 1979 to 2006 have been set on Guam intentionally by poachers and hunters, resulting in deforestation, land erosion, and increased sedimentation, which is one of the most significant threats to the reefs around Guam (Burdick et al. 2008).

To date, widespread mass coral bleaching and widespread coral disease have not been observed around Guam or the CNMI, although restricted outbreaks have been detected at Guam and Saipan (Burdick et al., 2008; Starmer et al. 2008). Climate change potentially could increase the frequency and severity of typhoons in one of the most active regions for tropical storms in the world; an average of 3 typhoons per year have passed within 540 km of the southern islands of the Mariana Archipelago since 1970 (Landers 2004). In addition to climate change, another factor that potentially can impact coral reef health is periodic outbreaks of crown-of-thorns seastars (COTS) that have been observed around several islands during MARAMP surveys.

In the northern, largely uninhabited islands of the CNMI, the frequency, duration, and magnitude of active volcanism can severely affect coral reef ecosystems. At Anatahan during MARAMP 2003, for example, many coral heads were observed to be covered by ashfalls. Steep slopes or absence of land cover can cause active mass wasting, landslides into the ocean, or erosion. Feral animals and a potential increase in fishing are also concerns for these northern islands.

The CNMI and Guam, as well as the federal government, have set aside a number of marine protected areas (MPAs) in recent years:

- Guam designated 5 marine preserves in 1997 with a total area of 36 km^2. Protection of these areas has been documented to improve fish stocks within these limited-take and no-take reserves (Burdick et al. 2008). Two ecological preserves were designated in 1984 with a total area of 1.68 km^2; however, legislation (Guam Public Law 29-127) that may once again open these reserves to fishing by indigenous peoples was passed in 2008.
- Sasanhaya Fish Reserve on Rota was established in 1994 and encompasses an area of 0.8 km^2. Although it is a no-take reserve, enforcement never has been implemented fully in this MPA (Starmer et al. 2008).
- Around Saipan, 3 no-take MPAs with a total area of 12.1 km^2 were designated in 2000 and 2001: Managaha Marine Conservation Area, Bird Island Marine Sanctuary, and Forbidden Island Marine Sanctuary.

- In 2008, the CNMI designated a new marine reserve for Tinian, but the exact boundaries and, thus, the total size of this MPA are yet to be defined.
- The islands of Guguan, Asuncion, Maug, and Farallon de Pajaros, with a total land area of 16.5 km^2, were set aside as protected areas in 1985 by an amendment to Article XIV of the CNMI Constitution.
- The waters and submerged lands surrounding Asuncion, Maug, and Farallon de Pajaros to a seaward boundary of 50 nmi together form the Islands Unit of the Marianas Trench Marine National Monument, which was established by presidential proclamation in 2009 and encompasses 246,608 km^2 in the Mariana Archipelago.

3.2 Benthic Habitat Mapping and Characterization

The nearshore waters of the Mariana Archipelago were surveyed by the Coral Reef Ecosystem Division (CRED) and several other NOAA and academic groups. A synthesis of the collected multibeam bathymetric data is presented in Figure 3.2a. These data were used to estimate the size and structure of potential benthic habitats available for colonization of coral reef communities around each island or bank. The high-resolution bathymetric data from all multibeam and lidar surveys, when combined with less accurate estimated depths from satellite sources (e.g., multispectral imagery and satellite altimetry from gravity readings) and the 100-fm (~ 200 m) chart boundary, allow for calculation of approximate areas of seafloor in the following depth ranges: 0–30 m (where shallow, diver surveys were conducted), 30–100 m, and 100–200 m. Figures 3.2b and c and Table 3.2a provide an overview of the absolute and relative areas of seafloor within these depth boundaries throughout the Mariana Archipelago.

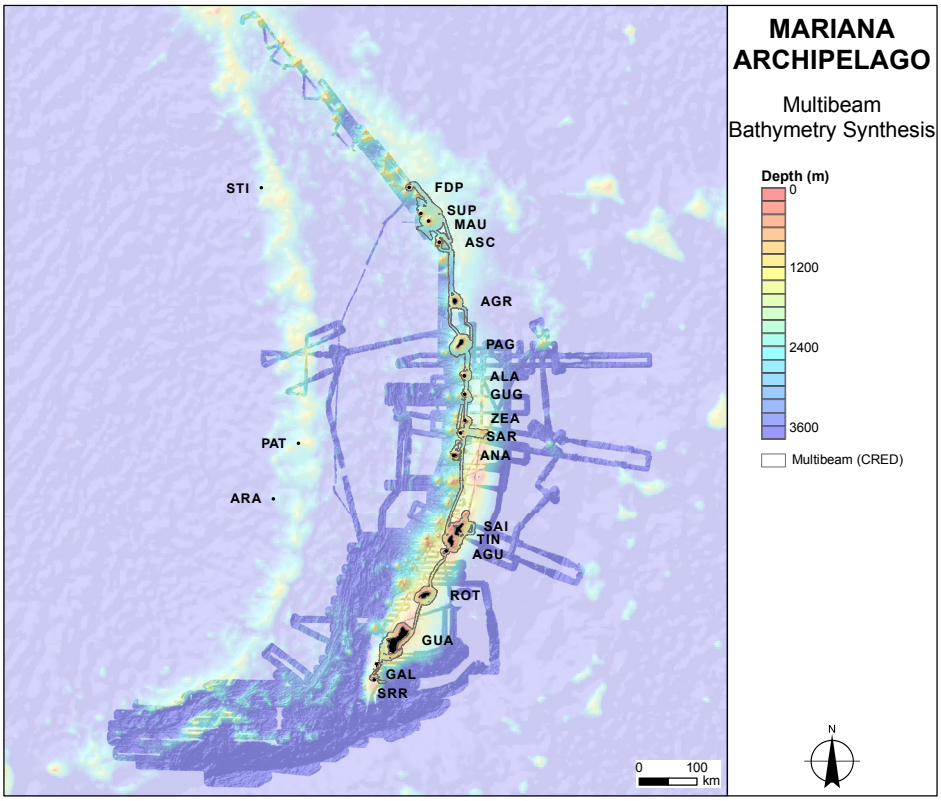


Figure 3.2a. Composite bathymetry based on various data sets available as of September 2007 for the Mariana Archipelago. The grey outline shows data collected during CRED surveys.

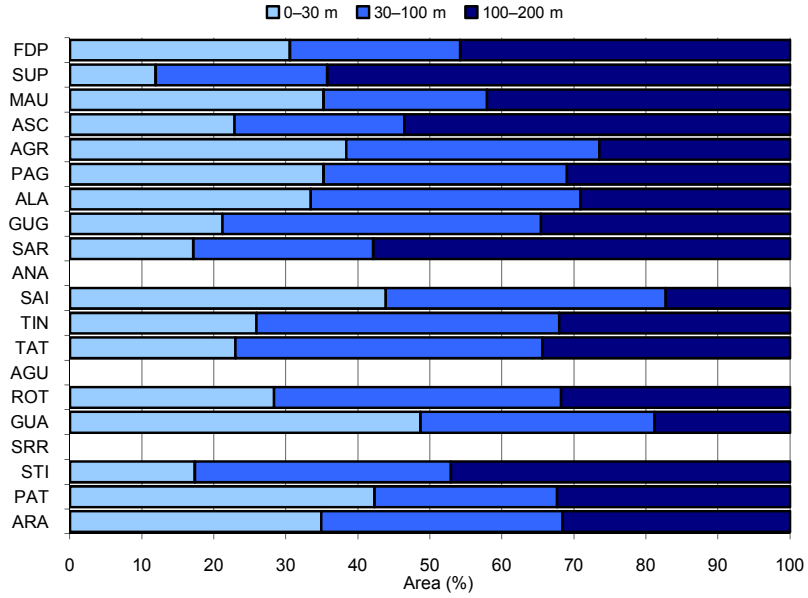


Figure 3.2b. Composition (%) of seafloor area at 3 depth ranges (0–30, 30–100, and 100–200 m) surrounding the islands and banks of the Mariana Archipelago. For seafloor areas (km²) at these depth ranges by island and bank, see Table 3.2a.

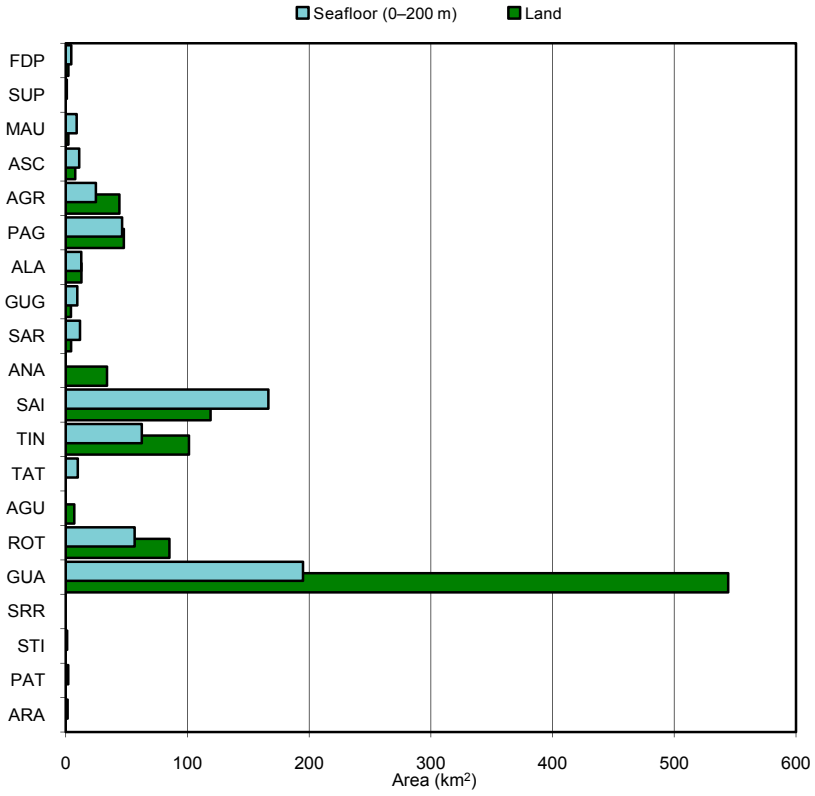


Figure 3.2c. Comparison of the land areas (km²) of the islands and banks of the Mariana Archipelago and the areas of seafloor (km²) at depths of 0–200 m surrounding these islands and banks.

The land areas of the islands in the Mariana Archipelago range from 2.14 to 544.34 km². The seafloor areas surrounding these islands at the depth range of 0–30 m vary between 1.38 and 94.85 km², and, at the depth range of 0–200 m, they vary between 4.52 and 194.99 km² (Table 3.2b). Around the northern islands, the areas of seafloor at depths of 0–100 m, or the areas of potential benthic habitat, ranged only from 2.45 to 31.93 km², reflecting the steep topography around the northern stratovolcanoes. The areas for potential benthic habitat are larger around the southern islands, particularly around Saipan, than around the northern islands. A unique and sizeable feature, Saipan's Garapan Anchorage, largely accounts for the similarity in size of the potential habitat (137.25 and 158.32 km² at depths of 0–100 m) between Saipan and Guam, which has a land area more than 4 times as large as the land area of Saipan (Table 3.2c). In general, around most other islands in the Mariana Archipelago, the seafloor area in the depth range of 0–30 m is similar to the seafloor area in the depth range of 30–100 m.

Island	Land Area (km^2)	Seafloor Area at Depths of 0–30 m (km^2)	Seafloor Area at Depths of 30–100 m (km^2)	Seafloor Area at Depths pf 100–200 m (km^2)	Seafloor Area at Depths of 0–200 m (km^2)	Combined Land and Seafloor (0-200 m) Area (km^2)
FDP	2.25	1.38	1.07	2.07	4.52	6.77
SUP	–	0.10	0.20	0.54	0.84	0.84
MAU	2.14	3.17	2.04	3.79	9.00	11.14
ASC	7.86	2.54	2.62	5.96	11.12	18.98
AGR	44.05	9.50	8.70	6.56	24.76	68.81
PAG	47.75	16.29	15.64	14.34	46.27	94.02
ALA	12.96	4.28	4.79	3.73	12.80	25.76
GUG	4.24	2.00	4.18	3.27	9.45	13.69
SAR	4.47	2.00	2.92	6.76	11.68	16.15
ANA	33.91	–	–	–	–	33.91
SAI	118.98	73.04	64.63	28.82	166.49	285.47
TIN	101.22	16.20	26.31	20.04	62.55	163.77
TAT	–	2.26	4.20	3.39	9.85	9.85
AGU	7.01	–	–	–	–	7.01
ROT	85.13	16.03	22.54	18.00	56.57	141.70
GUA	544.34	94.85	63.47	36.67	194.99	739.33
SRR	–	–	–	–	–	–
STI	–	0.21	0.43	0.57	1.21	1.21
PAT	–	0.85	0.51	0.65	2.01	2.01
ARA	–	0.53	0.51	0.48	1.52	1.52

Table 3.2a. Land area per island or bank and seafloor areas categorized in depth ranges around each island and bank in the Mariana Archipelago. The "Combined Area (km^2)" column provides the total of the land area plus the seafloor area at depths of 0–200 m for each island and bank.

Detailed multibeam bathymetry and backscatter products are discussed in the individual island chapters of this report. These results are presented in conjunction with analyses of video from towed optical assessment device (TOAD) surveys and observations from towed-diver surveys to improve understanding of benthic habitats around each island.

Archipelagic comparison of mean slope shows differences in both the land and underwater topographies of many of the islands in this region. Striking differences in slope can be noted between the northern islands, with seafloor slopes of 19°–25°, and the southern islands, with seafloor slopes of 10°–12° (Fig. 3.2d), and between the carbonate and volcanic geology of north and south Guam. Slope, volcanic eruption, and earthquake activity are all factors that influence mass wasting and landslides around each island. These factors along with the more general, worldwide influences of sea-level change, glaciation and deglaciation, and vertical island movement (e.g., sinking and rising) form a complex relationship that determines the growth or destruction of coral reefs through time (Webster et al. 2009, Clague et al. 2002).

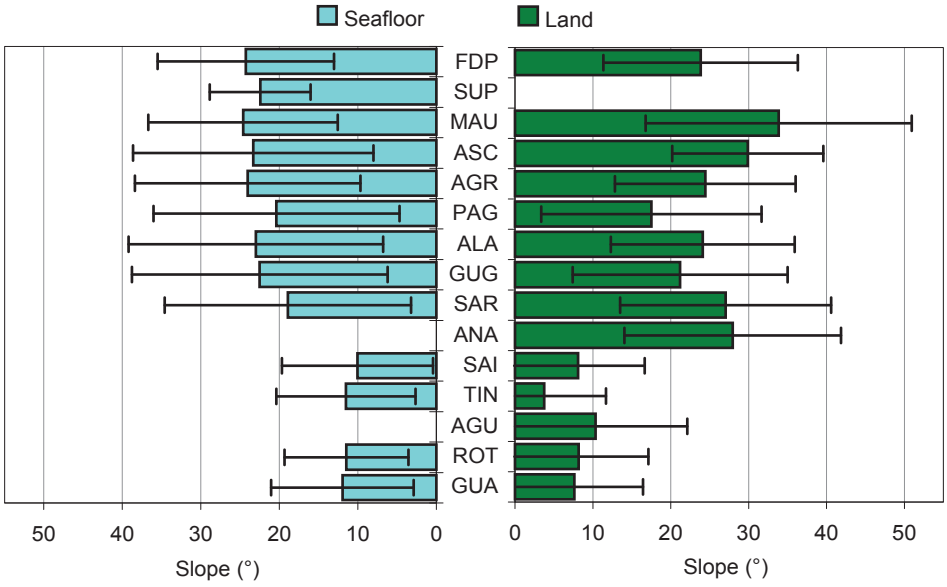


Figure 3.2d. Mean slope (*left*) of reefs around individual islands and Supply Reef in the Mariana Archipelago based on multibeam data collected at depths of ~ 1–2810 m during MARAMP 2003 and 2007 and (*right*) on land based on digital elevation models. Error bars indicate standard error (± 1 SE) of the mean.

Pooled benthic observations from towed-diver surveys conducted during MARAMP 2003, 2005, and 2007 suggest a general decrease in the islandwide means for sand cover progressing from the northern islands to the more populated, southern islands of the Mariana Archipelago (Figs. 3.2e and f).

Active volcanism in the northern part of the Mariana Archipelago likely plays an additional, key role in basaltic sand formation. At Anatahan, for example, the highest level of sand cover for an island in the Mariana Archipelago was recorded with an overall mean of 50% in 2003 (Fig. 3.2 f). Although high values of sand cover were recorded in raw data from towed-diver surveys conducted at Anatahan in 2003, the level of sand cover may likely have been overestimated because of ashfalls from a volcanic eruption that occurred earlier that year (see Chapter 9: "Anatahan," Sections 9.1 and 9.3: "Introduction" and "Benthic Habitat Mapping and Characterization;" for information about substrate categories used during towed-diver surveys, see Chapter 2: "Methods and Operational Background," Section 2.4.4: "Benthic Habitat Complexity and Substrates"). Anatahan, located between Sarigan and Saipan, was surveyed only in 2003.

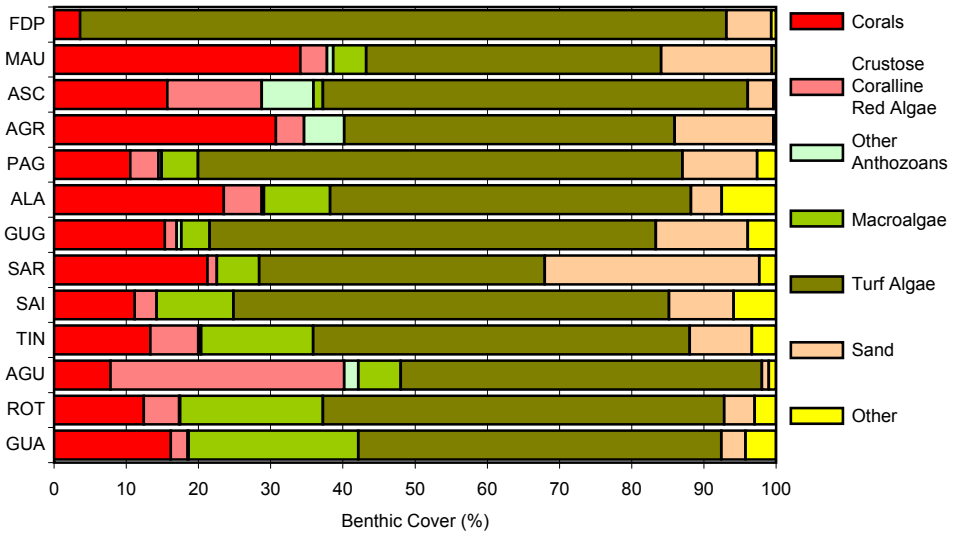


Figure 3.2e. Cover (%) observations for corals, macroalgae, crustose coralline red algae, turf algae, sand, and the category "Other Anthozoans" from REA benthic surveys conducted using the line-point-intercept method on forereef habitats in the Mariana Archipelago during MARAMP 2007.

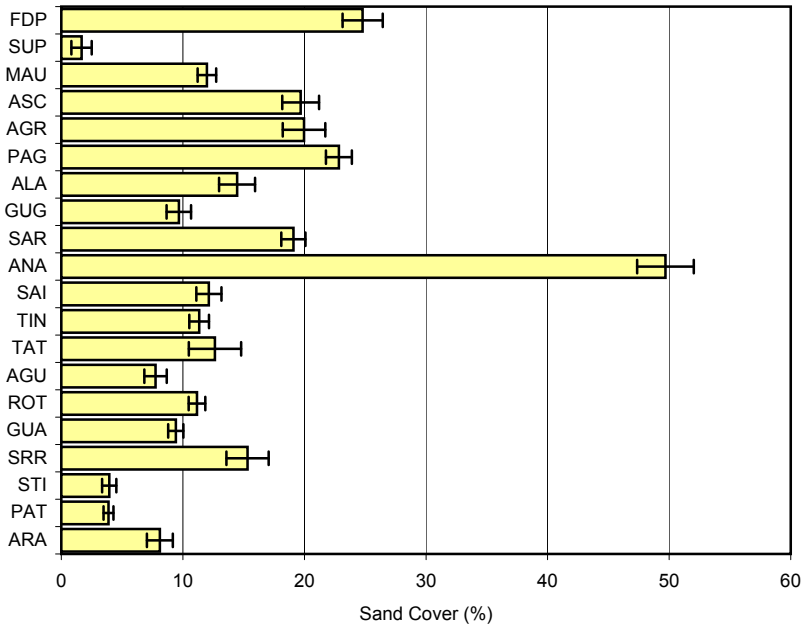


Figure 3.2f. Observations of sand cover (%) from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Benthic observations, pooled from towed-diver surveys conducted during the 3 MARAMP survey periods, also suggest that overall habitat complexity is higher around the 9 northern islands than around the 5 surveyed southern islands (Fig. 3.2g). The geological differences between the northern and southern islands likely contribute to this habitat complexity pattern. The habitat types most consistently recorded at the northern islands during towed-diver surveys were rock boulders, interspersed with continuous reef and pavement. In contrast, reefs surrounding the southern islands were noted for habitats of pavement, continuous reef, and spur and groove. These observations largely match many of the elements in the satellite-derived, hierarchical classification scheme completed by the NOAA National Centers for Coastal Ocean Science (NCCOS) for shallow-water benthic habitats of the CNMI (NCCOS 2005). NCCOS identified dominant rock and boulder habitats around the northern islands of the Mariana Archipelago and classified habitats in the southern islands as pavement, aggregate reef, and spur-and-groove formation. Analysis focused on areas where overlap occurred between the NCCOS benthic classifications and towed-diver-survey tracks.

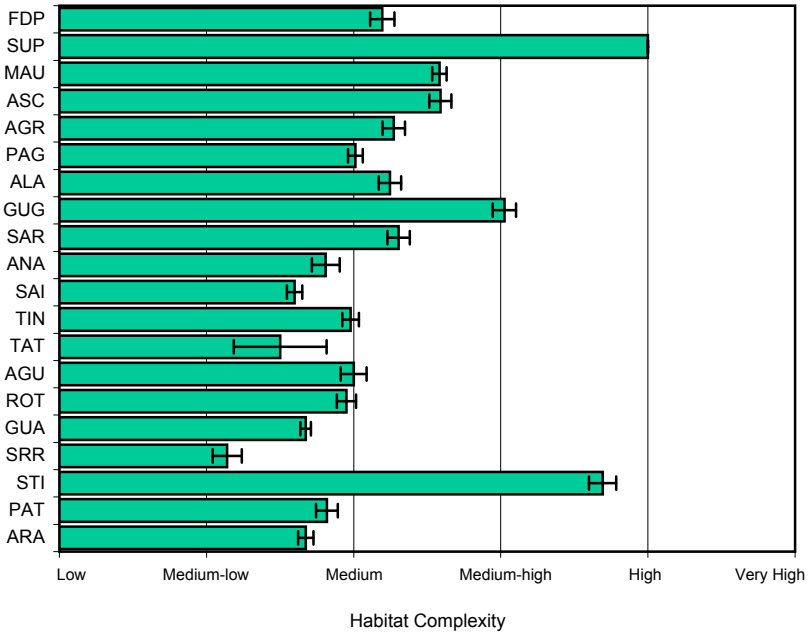


Figure 3.2g. Overall habitat complexity from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Habitat complexity is a relative measure from low to very high (see Chapter 2: "Methods and Operational Background," Section 2.4.4: "Benthic Habitat Complexity and Substrates"). Error bars indicate standard error (± 1 SE) of the mean.

3.3 Oceanography and Water Quality

The marine environment of the Mariana Archipelago is highly variable. Seasonal changes combined with the north–south orientation of this archipelago result in latitudinal gradients in oceanographic and meteorological conditions. This section presents remotely sensed, modeled, and in situ observations in a variety of formats (e.g., maps, time series, and climatologies) and describes long-term climatological averages of pertinent environmental, oceanographic, and meteorological parameters for each season, as well as the seasonal-to-interannual variability of these parameters. Satellite remotely sensed data and numerical modeling products provide important time series and climatological information. In situ data provide nearshore, subsurface information (e.g., nutrient concentrations) that is unattainable from satellites or that fluctuates on scales (spatial and temporal) too small for satellite instruments to measure. Throughout this section, 3 geographic designations are used for convenience to represent groups of islands: the "northernmost islands" encompass Farallon de Pajaros, Maug, and Asuncion, the "central islands" include Agrihan, Pagan, Alamagan, Guguan, Sarigan, and Anatahan, and the "southern islands" encompass Saipan, Tinian, Aguijan, Rota, and Guam.

3.3.1 Seasonal Climatologies

Satellite remote-sensing observations and modeled wave data were used to calculate long-term seasonal climatologies to describe the variability in forcing and latitudinal gradient of key environmental parameters, including wind, surface currents, sea-surface temperature (SST), chlorophyll-*a* (Chl-*a*) concentration, and ocean waves (see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). Climatologies for the region 12°–22° N and 140°–150° E are presented for each season: winter (January–March), spring (April–June), summer (July–September), and fall (October–December).

Wind

Wind climatologies for the Mariana Archipelago suggest seasonal variability in wind speed and direction (Fig. 3.3.1a). Strong mean winds (8–10 m s^{-1}) were consistently observed across the entire Mariana Archipelago during the fall season. During winter, winds were stronger in the southern portion of this archipelago and progressively weaker in the northern islands. A similar, but weaker, south–north gradient in wind speeds was observed in the spring. During summer, this pattern was reversed with stronger winds in the north and weaker winds in the south. Unlike wind speed, latitudinal gradients in wind direction were not evident, although the direction of the wind changed seasonally. Winds tended to originate from the northeast in the fall and winter, from the east in the spring, and from the east-southeast during the summer.

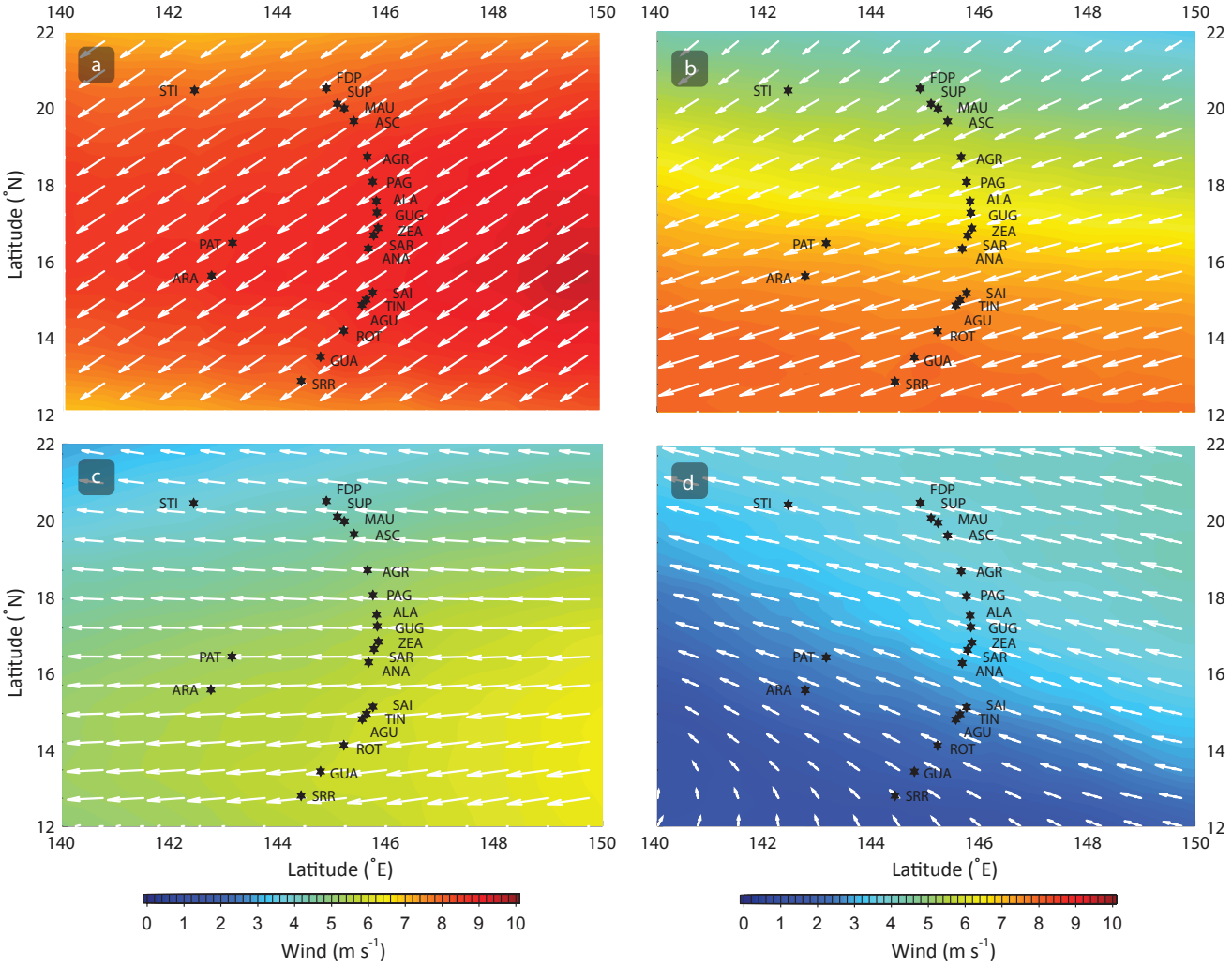


Figure 3.3.1a. Seasonal wind climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September), using NASA QuikSCAT scatterometer winds for the Mariana Archipelago (12°–22° N, 140°–150° E). Wind velocities (m s^{-1}) are color coded and arrows indicate relative magnitude and direction. Climatologies were produced using data from 1997 to 2007.

Ocean Surface Currents

The principal ocean current influencing the Mariana Archipelago is the westward-flowing North Equatorial Current (NEC). Based on seasonal climatologies of ocean surface current, the NEC was stronger in the southern islands than in the northernmost islands, although the strength of this current varied seasonally and was highly dependent upon latitude within this island chain (Fig. 3.3.1b). Across the Mariana Archipelago, the strongest surface current occurred during the fall, with the southern islands experiencing mean flow speeds of 0.20–0.25 m s^{-1}. Surface currents gradually weakened north of Saipan, with speeds at Asuncion, Maug, and Farallon de Pajaros less than half (0.05–0.10 m s^{-1}) of the speeds experienced in the southern islands. Surface currents were slightly weaker in the winter and spring than in the fall, although a similar

north–south gradient existed. The weakest surface currents across the Mariana Archipelago occurred during the summer; however, surface currents south of Tinian were stronger during this season than currents in the northernmost islands during any season. Additionally, in the summer, a weak current reversal (eastward flow) was apparent north of Farallon de Pajaros, and this current may have influenced this island during certain years depending upon interannual variability (Fig. 3.3.1b).

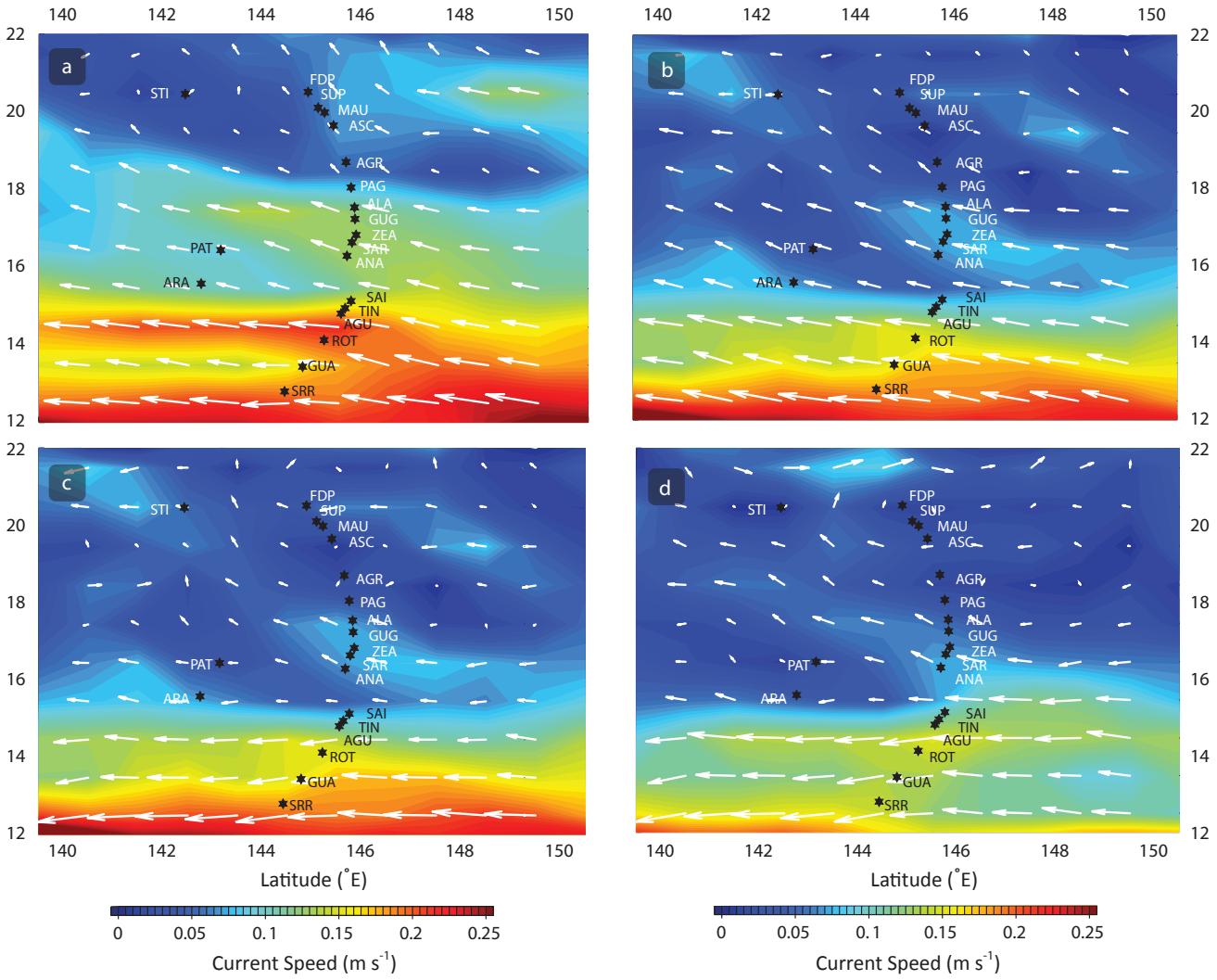


Figure 3.3.1b. Seasonal ocean surface current climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September) using NOAA's OSCAR (http://www.oscar.noaa.gov/). Current velocities (m s^{-1}) are color coded and arrows indicate relative magnitude and direction. Climatologies were produced using data from 1993 to 2009.

Sea-surface Temperature

Mean seasonal SST climatologies exhibit pronounced seasonal cycles and latitudinal gradients across the Mariana Archipelago (Fig. 3.3.1c). Annual temperature differences across this archipelago were as much as 5°C; warm temperatures (29°C–30°C) were observed during summer months, and cooler temperatures (25°C–27°C) occurred during the winter. During fall, winter, and spring, a pronounced SST gradient occurred with warmer waters to the south and cooler waters to the north. An average 2.5°C difference in SST occurred between the northernmost and southern islands in each of the fall, winter, and spring seasons. This SST gradient weakened and became more diffuse during the summer months as the entire archipelago was bathed in warm surface water characteristic of Western Pacific Warm Pool conditions (Yan et al. 1992).

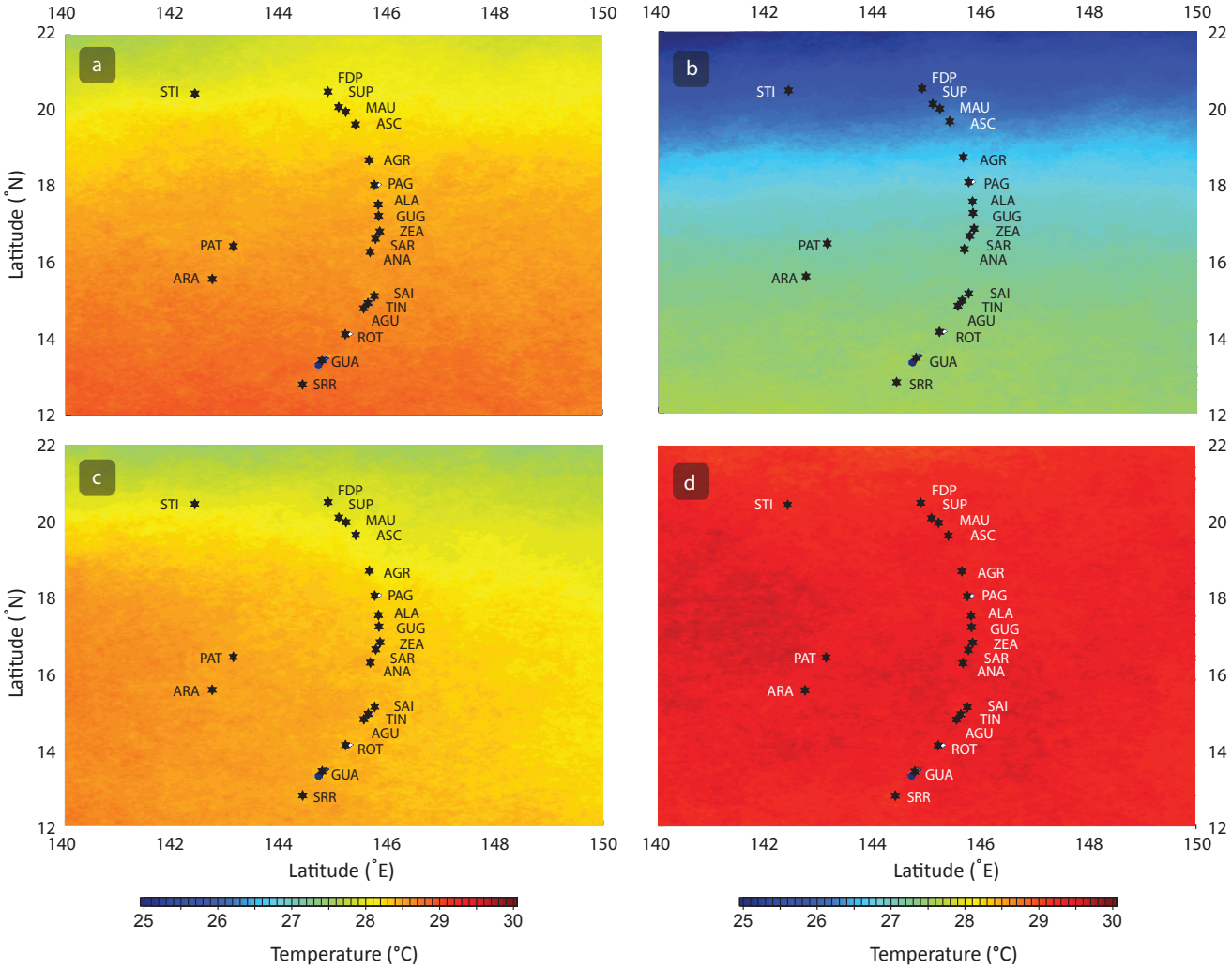


Figure 3.3.1c. Seasonal SST climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September) in the Mariana Archipelago (12°–22° N, 140°–150° E). Satellite-derived data are from Pathfinder 5.0 SST seasonal climatology from 1982 to 2007 produced by the NOAA National Oceanographic Data Center.

Chlorophyll-a

Mean climatological surface Chl-*a* concentrations show strong seasonal variability in the Mariana Archipelago, with the lowest concentrations occurring in the summer and fall seasons and the highest concentrations observed in the spring and winter (Fig. 3.3.1d). Latitudinal gradients in Chl-*a* levels, with higher concentrations in the north compared to the south, were evident in all 4 seasons, particularly in the winter when Chl-*a* concentrations were 0.4–0.6 µg L^{-1} greater in the northernmost islands than in the southern islands. In general, the southern islands were surrounded by oligotrophic (i.e., nutrient poor) waters throughout the year, while the northernmost islands experienced a much greater seasonal variability. Near Anatahan, during spring and summer, a strong (1 µg L^{-1}) Chl-*a* signal was observed. However, this signal was an artifact of enhanced reflectance as a result of volcanic activity and the combination of smoke and surface ash deposits into the surrounding waters, aliasing ocean color in this area, and was, therefore, not an accurate measure of surface Chl-*a* concentration.

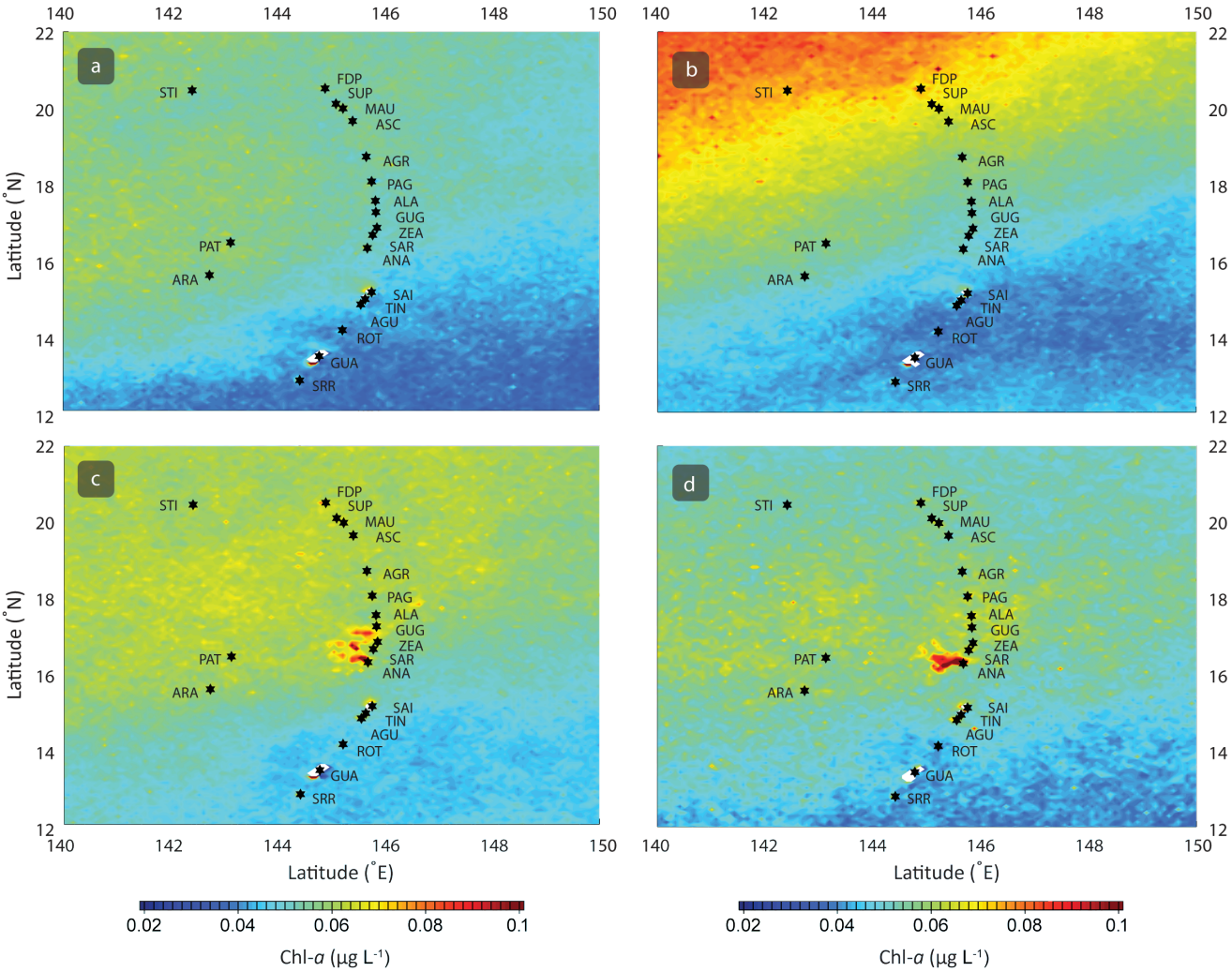


Figure 3.3.1d. Seasonal Chl-*a* climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September) from NASA SeaWiFS imagery for the Mariana Archipelago (12°–22° N, 140°–150° E). Climatologies were produced using data from 1997 to 2007.

Precipitation

Mean seasonal precipitation climatologies exhibit pronounced seasonal variability in the Mariana Archipelago, with the lowest rainfall observed during the winter and spring seasons and the highest rainfall observed during the summer and fall (Fig. 3.3.1e). Latitudinal gradients in precipitation, with lower rainfall in the north compared to the south, were evident in all seasons, although the strongest north–south gradient occurred during the summer and fall, when rainfall was ~ 4 mm d^{-1} greater in the southern islands than in the northernmost islands. Over all seasons, the southern islands experienced a minimum of 2 mm d^{-1} in the winter and a maximum of 12 mm d^{-1} in the summer months, while the northernmost islands experienced the same winter minimum and a much lower summer maximum of 8 mm d^{-1}.

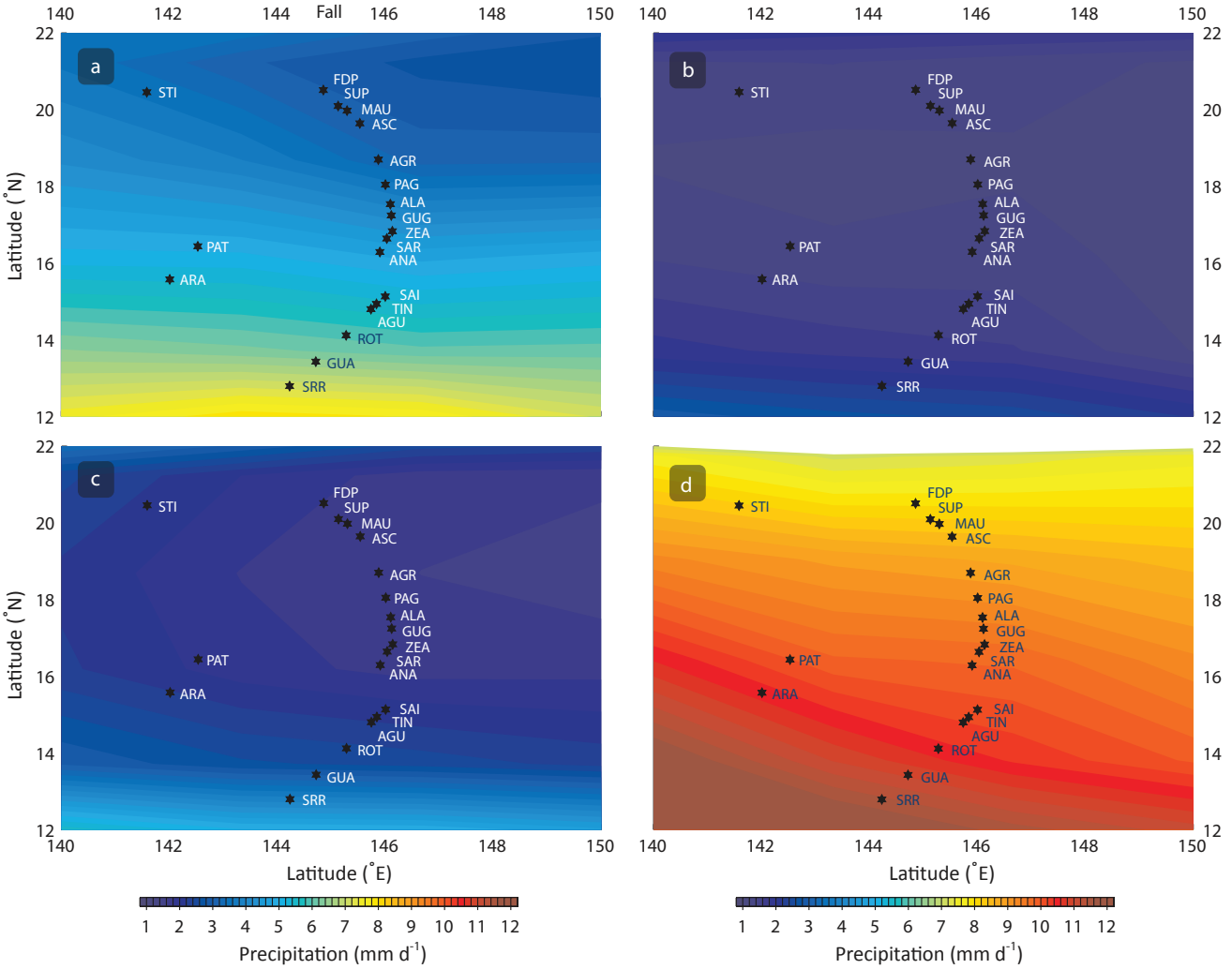


Figure 3.3.1e. Seasonal precipitation climatology for (*a*) fall (October–December), (*b*) winter (January–March), (*c*) spring (April–June), and (*d*) summer (July–September) for the Mariana Archipelago (12°–22° N, 140°–150° E). Climate Prediction Center merged analysis precipitation (CMAP) data are provided by the Physical Sciences Division of the NOAA Earth System Research Laboratory, Boulder, Colo., and are available at http://www.esrl.noaa.gov/psd. Climatologies were produced using data from 1979 to 2010.

Ocean Waves

Annual wave climatologies were derived using the NOAA Wave Watch III model for the period of January 1997 to June 2009 for 4 locations (Maug, Pagan, Saipan, and Guam) spanning the Mariana Archipelago (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). These climatologies suggest a consistent wave regime for this island chain (Fig. 3.3.1f). Ambient wave conditions, or conditions that occurred most frequently through the year, were relatively similar across the Mariana Archipelago, with east and northeast exposures experiencing year-round, relatively short-period (8–10 s), low-amplitude (1–2 m) waves. Episodic wave events, in contrast, were wave episodes that occurred irregularly through the year. These waves were generated by storms that were either within close proximity (tens to hundreds of kilometers) or at great distances (hundreds to thousands of kilometers) from the Mariana Archipelago, and they generally had longer periods and higher amplitudes than waves characterized by ambient conditions. Moderate episodic wave events, storm generated but low to moderately energetic, were evenly distributed around each island and across the Mariana Archipelago. These events had waves with periods of 10–16 s and amplitudes of 1–3 m, and they approached these islands ~ 1–5 times each year. Large episodic wave events, storm generated but highly energetic, were characterized by wave periods of 12–16 s and wave amplitudes > 5 m. These events affected the east-southeast (100°–120°) region of Guam and shifted to a southerly direction toward Saipan (120°–150°), Pagan (150°–180°), and Maug (170°–190°). These large, high-energy waves were most likely generated by typhoons. The shift in peak wave direction from the east-southeast to the south from Guam to Maug was likely a result of typhoon paths curving northward as they traveled west after their formation, which typically

occurred southeast of Guam (Fig. 3.3.1g). Although these large wave events occurred only a few times a year, they likely affected the coral reef communities of the Mariana Archipelago.

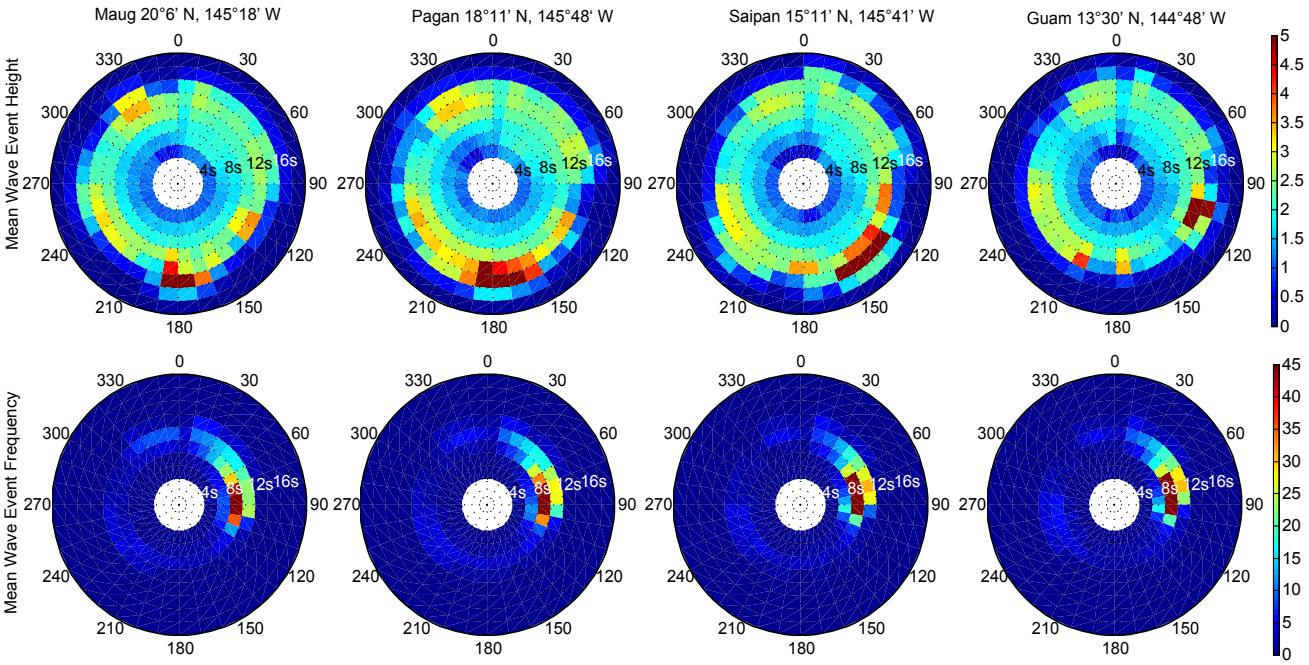


Figure 3.3.1f. Annual event climatology for wave height, direction, and period derived from NOAA Wave Watch III computations at 4-h time steps at Maug (20°6′ N, 145°18′ W), Pagan (18°11′ N, 145°48′ W), Saipan (15°11′ N, 145°41′ W), and Guam (13°30′ N, 144°48′ W) from January 1997 to June 2009. Mean annual wave event height (*top*), indicated by color scale, is represented in given directional and period bins (e.g., an average wave event at Maug with a period of 14–16 s from 180° had a height of 5 m). Mean annual frequency (likelihood) of occurrence (*bottom*), indicated by color scale, is represented in days per year (e.g., a 2-m wave with an 8-s period from 90° occurred on average 45 days a year at Maug).

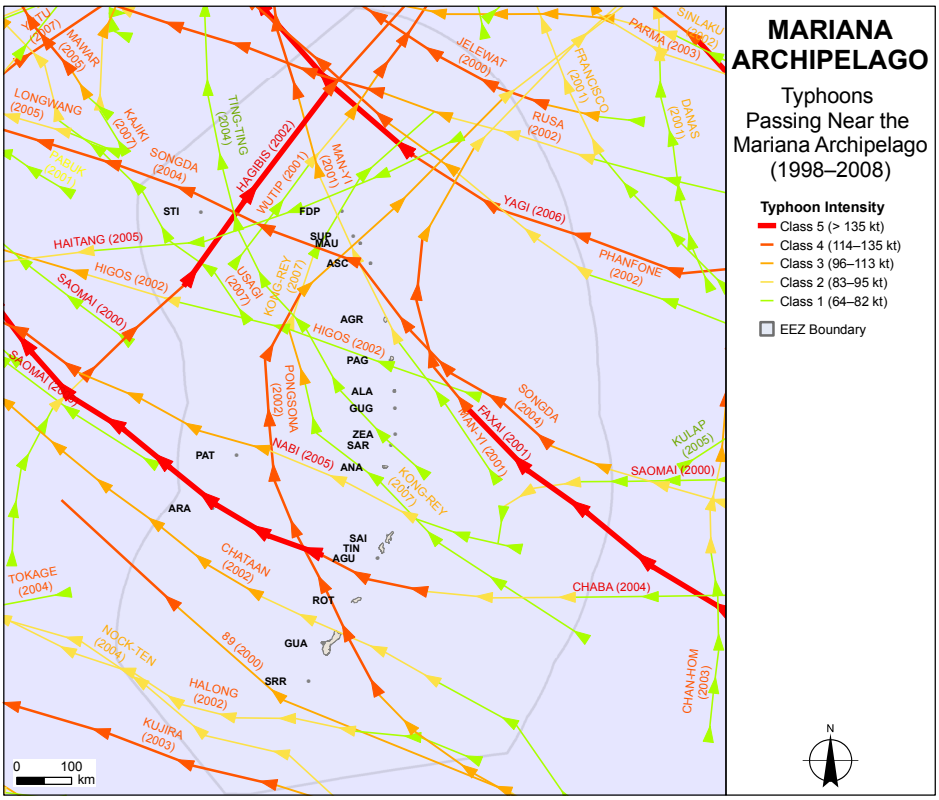


Figure 3.3.1g. Path and intensity of typhoons passing near or across the Mariana Archipelago from 1998 to 2008.

3.3.2 Time-series Observations

In this section, time-series data derived from in situ and satellite remote-sensing observations were used to examine seasonal-to-interannual variability and latitudinal gradients of ecologically significant environmental properties, including wind, surface currents, SST, and Chl-*a* and nutrient concentrations, across the Mariana Archipelago.

Time-series observations of Chl-*a* concentrations, east–west surface currents, and SST from the northernmost, central, and southern islands show distinct latitudinal differences and coupled physical and biological oceanographic variability (Fig. 3.3.2a). Over the 10-year period from 1998 to 2008, Chl-*a* levels were highly variable in each of the 3 island groups; however, the extent of variability, seasonal periodicity, and interannual fluctuations were different for each group (Fig. 3.3.2a, top panel). The time series for the northernmost islands shows relatively high Chl-*a* values and suggests regular seasonal periodicity, with a peak of 0.07–0.09 µg L^{-1} in surface concentrations of Chl-*a* in the winter and a long-term mean of 0.061 µg L^{-1}. The central islands exhibited less seasonal periodicity but more interannual variability than did the northernmost islands, with seasonal peaks in a range of 0.06–0.11 µg L^{-1} during the winter–spring period and a long-term mean of 0.058 µg L^{-1}. Chl-*a* values from May 2003 were removed from the time series because of atmospheric effects from an eruption of Anatahan. The largest peaks (seen in 1998, 2003, and 2005) in the central islands also may have been associated with volcanic activity at Anatahan. The southern islands were characterized by low surface concentrations of Chl-*a* (< 0.05 µg L^{-1}) and moderate periodicity, as seasonal minima tended to occur during the fall–winter period, and a long-term mean of 0.043 µg L^{-1}. Year-to-year differences were observed in the southern islands, although not to the extent seen in the central and northernmost islands, as the range in observed Chl-*a* concentration was relatively small.

Ocean surface currents (east–west only) over the same 10-year period were highly variable from year to year with no clear seasonal periodicity (Fig. 3.3.2a, middle panel). Surface currents in the northernmost islands were relatively weak (magnitude < 0.15 m s^{-1}) and oscillated between eastward (positive) and westward (negative) flows. Pronounced peaks of eastward flow were observed in this time series, although the timing of these peaks varied by year. The central islands experienced increased westward current and increased seasonal periodicity; however, interannual variability was clearly present. Seasonal peaks in westward flow occurred during the fall–winter period, and increased eastward flow was observed during the spring–summer period. The southern islands, in contrast to the central and northernmost islands, were characterized by year-round westward flow, with seasonal increases occurring in the fall–winter transition, particularly from 2003 to 2007. This observation is consistent with the seasonal climatology data, which show a stronger NEC in the southern islands, versus the other island groups, with a seasonal strengthening during the winter months (Fig 3.3.1b).

In contrast to patterns seen for Chl-*a* concentrations and ocean surface currents, SST data show strong seasonal periodicity in all 3 island groups, with the range of variability dependent upon latitude (Fig. 3.3.2a, bottom panel). A seasonal

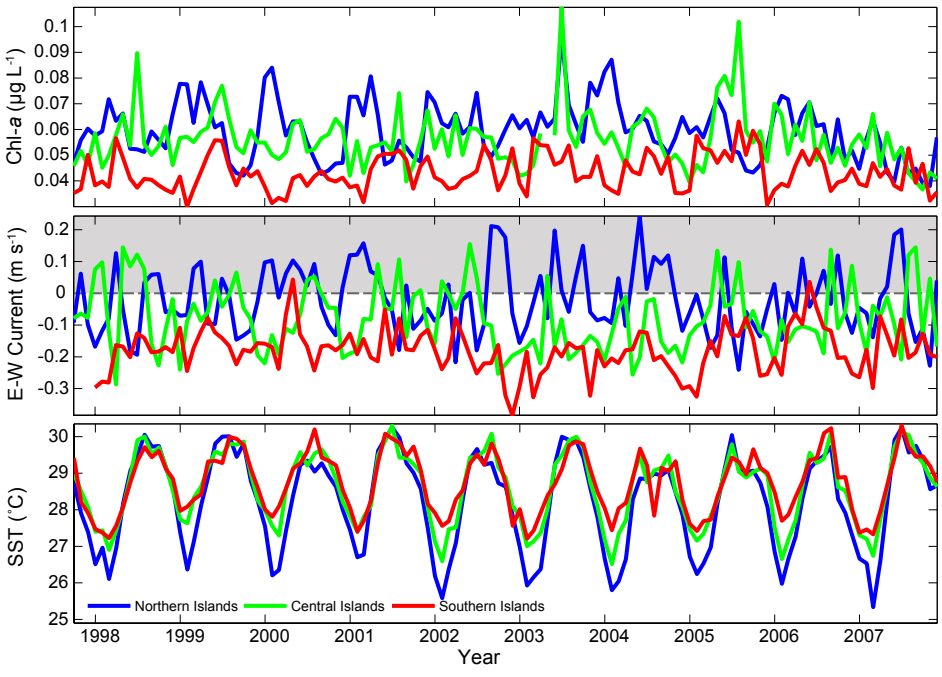


Figure 3.3.2a. Time series of satellite-derived (*top*) Chl-*a* concentration (SeaWIFS), (*middle*) East–West current (OSCAR), and (*bottom*) SST (Pathfinder) from 3 island groups in the Mariana Archipelago, using a box (1° × 1°) centered on 20° N, 144°48′ E for the northernmost islands, 16°30′ N, 145° E for the central islands, and 13° N, 145° E for the southern islands. Note: Chl-*a* data from May 2003 were removed from this time series for the central islands because of an eruption of Anatahan.

maximum in SST was seen in each island group in the summer and a seasonal minimum in the winter. The peaks in SST (~ 30°C) were generally the same for each of the island groups; however, the seasonal minimum was colder (~ 26°C) in the northernmost islands than the minima for the central (~ 27°C) and southern (~ 27.5°C) islands. Interannual forcing is clearly evident in each of the SST time series. Year-to-year temperature variability was greatest in winter in all island groups, with the largest interannual variability observed in the northernmost islands.

Although it is difficult to discern direct correlations between Chl-*a* concentrations, surface currents, and SST on monthly to seasonal time scales, patterns do emerge when analyzing the entire 10-year time series. In the northernmost islands, Chl-*a* concentrations reached their highest levels concurrently with peaks in eastward surface current in 1999, 2000, and 2001 and, to a lesser extent, in 2005 and 2006. These concomitant peaks in Chl-*a* values and surface current tended to occur in the winter, when temperatures were seasonally low. The central islands showed less concurrence, compared to the other island groups, although, in 1998 and 2005, strong peaks in Chl-*a* concentrations were observed during the highest points in eastward flow.

CRED's SST buoys moored at Maug, Pagan, and Guam collected and telemetered in situ, high-resolution, nearshore temperature time-series data that, when combined with remotely sensed, satellite-derived (Pathfinder) SST information, provide a valuable context for evaluating island-scale temperature fluctuations and latitudinal differences.

Throughout the 4-year observational time series from 2003 to 2007, in situ and remotely sensed SST followed similar seasonal patterns, with minimum temperatures observed in January–March and maximum temperatures recorded in July–September (Fig. 3.3.2b). However, in situ SST at all locations at various times showed large deviations from remotely sensed temperatures. During the winter and spring of both 2004 and 2005, for example, in situ temperature at Maug was almost 1°C colder than SST observed via satellite. Additionally, in situ SST at Maug and Pagan contemporaneously dropped 1.5°C–2°C, then sharply rose 2°C–3°C in the summer of 2004. A 1°C change in satellite SST was recorded during that same time frame, as temperatures changed too rapidly for remotely sensed data to match in situ data.

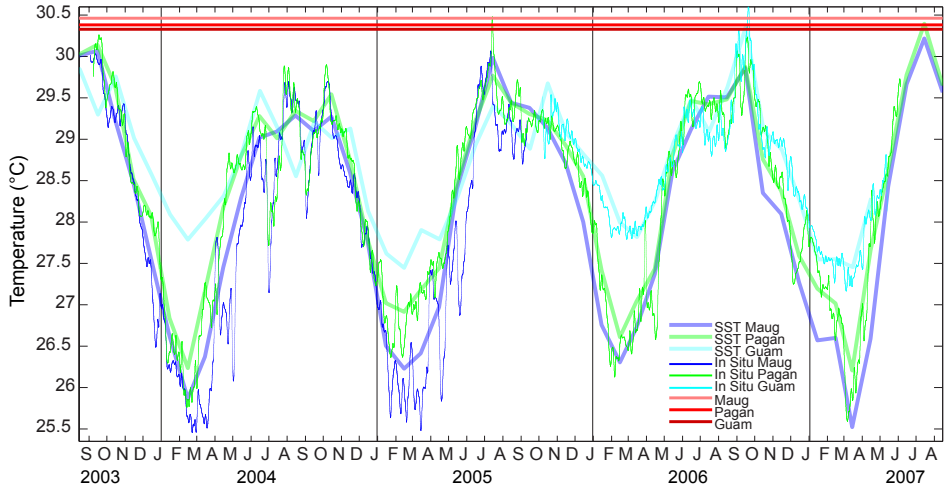


Figure 3.3.2b. Time series of satellite-derived SST (Pathfinder) and in situ SST (when available) from Maug, Pagan, and Guam. The horizontal red lines indicate the coral bleaching threshold, defined as 1°C above the monthly maximum climatological mean, at each island.

Hydrographic Data

Spatial hydrographic surveys—which collect conductivity, temperature, and depth (CTD), oxygen, and fluorescence profiles, as well as in situ information on water-quality conditions—enable assessment of subsurface water column properties pertinent to coral reef communities. CTD and water-quality information presented in this section were averaged by individual island, allowing for archipelagic comparison of oceanographic information, and separated by survey year, in an effort to remove confounding issues associated with seasonal differences in MARAMP survey years (MARAMP 2005 surveys were conducted in September and October and MARAMP 2007 surveys occurred in May and June).

CTD profiles obtained during MARAMP 2005 and 2007 suggest distinct latitudinal gradients in water properties. In 2005, temperatures were uniform and the water well mixed in the upper part of the water column at depths of 50–75 m around all islands in the Mariana Archipelago (Fig. 3.3.2c). Below this depth range, waters around most islands had similar rapid decreases in temperature with depth, but waters around Guguan and Pagan cooled more slowly with depth. At a 200-m

depth, a clear separation of temperatures was found between all islands, and below 300 m, around the northernmost islands, particularly Farallon de Pajaros and Asuncion, recorded temperatures were ~ 5°C warmer than temperatures observed in rest of this island chain.

Salinity profiles from MARAMP 2005 were highly variable between islands. The subsurface salinity maximum was recorded at a depth of 150 m for waters around all islands except Guguan and Pagan, where the maximum occurred at a depth of ~ 220 m. Below 200 m, the waters around all islands showed a separation of salinity values, with the lowest salinity levels recorded in the southern islands.

Oxygen saturation values, as with temperatures, were relatively uniform in 2005 around all islands in the upper water column to a depth of 100 m. With increasing depth, waters around Farallon de Pajaros and Asuncion retained high levels of oxygen saturation, while saturation in waters around the other islands decreased with depth. Below 300 m, a substantial separation of oxygen saturation profiles was recorded, with waters around the southern islands having the lowest recorded levels to a depth of 500 m.

Fluorometry profiles from the water column around each of island in 2005 reveal a wide range of values in the upper water column to a depth of 100 m, with the greatest values recorded around Guam and Aguijan and the lowest values recorded around Farallon de Pajaros and Asuncion. High fluorescence values suggest enhanced productivity. Taking into account human population and island size, island-based sources of nutrients likely entered the nearshore waters of Guam, enhancing surface productivity. Nutrient and Chl-*a* concentrations are presented later in this section.

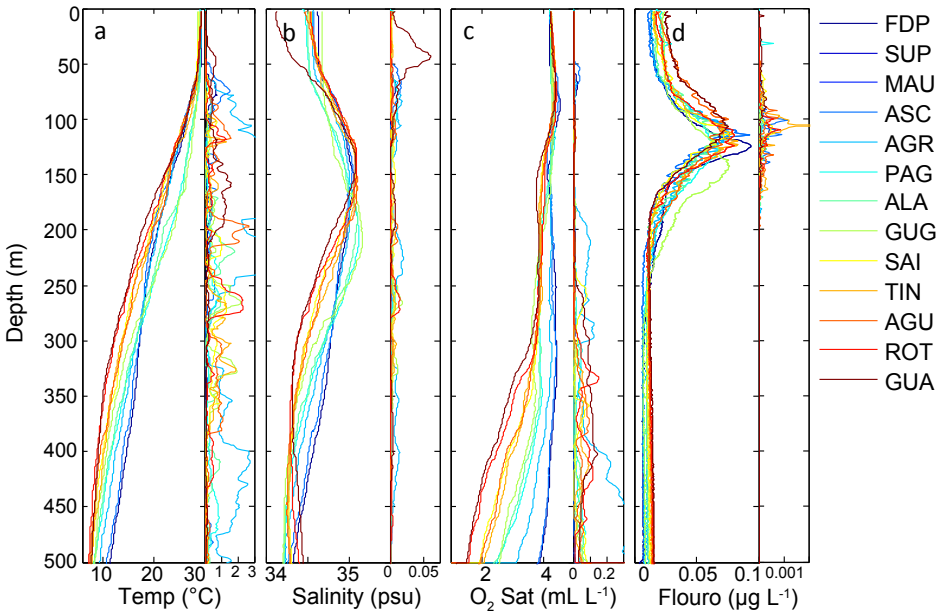


Figure 3.3.2c. Values of (*a*) temperature, (*b*) salinity, (*c*) oxygen saturation, and (*d*) fluorometry from shipboard (depths to 500 m) CTD casts conducted in the Mariana Archipelago during MARAMP 2005. Data were averaged by island with calculated variance shown at the right of each panel.

CTD data obtained during MARAMP 2007 reveal distinct north–south differences in vertical water properties. Waters around Maug and Farallon de Pajaros were ~ 5°C colder in the upper water column to a depth of 50 m than in similar waters around all other islands (Fig. 3.3.2d). The waters at depths of 50–200 m in the northernmost islands were distinctly colder than waters at this depth range in the rest of the Mariana Archipelago, although high variance was observed in the entire water column around Agrihan for reasons that are presently unknown. This north–south temperature orientation abruptly switched at depths > 250 m, where waters of the southernmost islands were colder to depths of 500 m.

Salinity profiles from MARAMP 2007 were far more dispersed and clearly latitudinally oriented in the upper water column compared to temperature profiles, with the lowest salinities recorded in the southern islands and the highest in waters around the northernmost islands. As with temperature, salinity profiles from the water column around Agrihan exhibited a high degree of variance.

Oxygen saturation around all islands was low in the upper water column to the surface in 2007, while, below a depth of 10 m, values were generally higher in waters at the northernmost islands than in waters at the southern islands. This north–south separation continues with increasing depth.

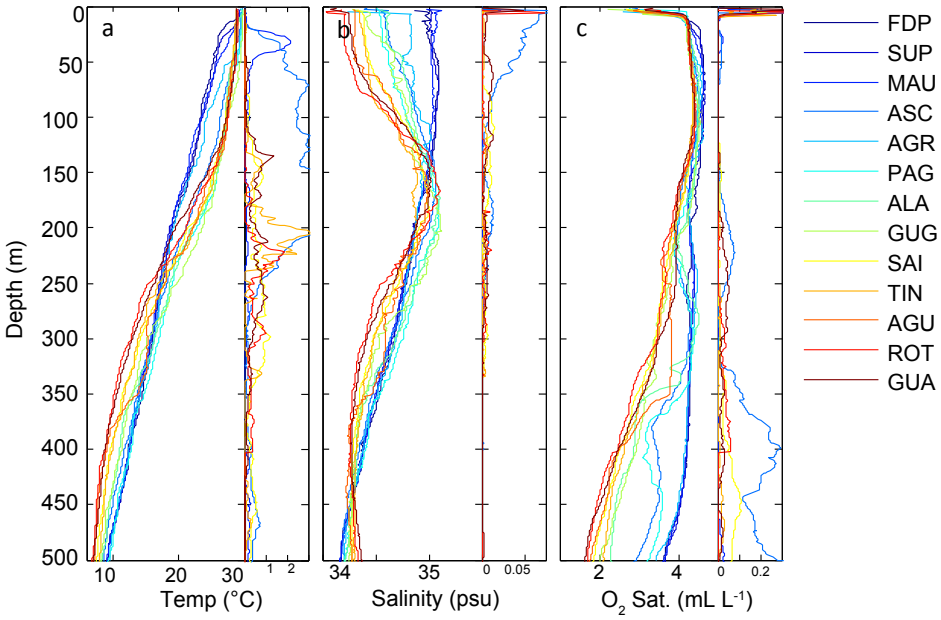


Figure 3.3.2d. Values of (*a*) temperature, (*b*) salinity, and (*c*) oxygen saturation from shipboard (depths to 500 m) CTD casts conducted in the Mariana Archipelago during MARAMP 2007. Data were averaged by island with calculated variance shown at the right of each panel.

Water Quality

In situ observations of water-quality conditions at each island enables comparisons of Chl-*a* and nutrient concentrations across the Mariana Archipelago. Results from nearshore water samples collected during MARAMP 2005 were highly variable with no distinct geographic patterns across this island chain (Fig. 3.3.2e). Silicate ($Si[OH]_4$) concentrations were greatest in waters at Pagan, Guam, Anatahan, and Maug, while nitrate (NO_3^-), concentrations were generally low in waters at all islands except for Tinian and Rota. Nitrite (NO_2^-) values were similarly low throughout the Mariana Archipelago, except at Guam, where much higher values were observed. With regards to phosphate (PO_4^{3-}), waters at Anatahan had nearly twice the concentration recorded at any other island, likely owing to the deposition of ash and other volcanic material resulting from eruptions at this island prior to the MARAMP 2005 surveys.

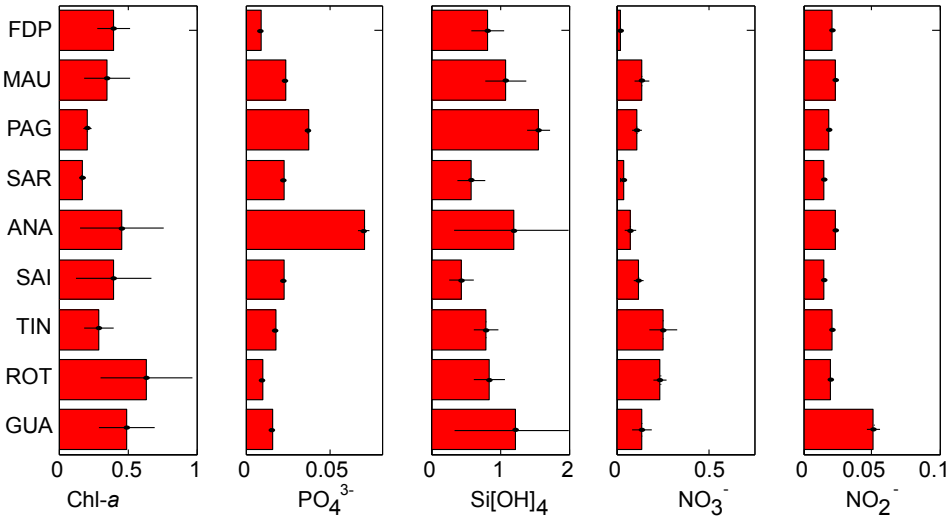


Figure 3.3.2e. In situ concentrations of Chl-*a*, phosphate (PO_4^{3-}), silicate ($Si[OH]_4$), nitrate (NO_3^-), and nitrite (NO_2^-) from nearshore (depths ≤ 30 m) water samples collected during MARAMP 2005. Data represent averages from all samples and all depths at each island. See Chapter 2: "Methods and Operational Background," Section 2.3.3: "Nearshore Spatial Surveys" for data acquisition and processing protocols, and see island chapters for water sample locations. Error bars indicate the standard error (± 1 SE) of the mean.

In contrast to results from MARAMP 2005, which occurred in September and October, data from nearshore water samples collected during MARAMP 2007, which occurred in May and June, suggest distinct patterns in Chl-*a* and nutrient concentrations across the Mariana Archipelago (Fig. 3.3.2f). Island size appeared to heavily influence Chl-*a* concentrations, as the highest levels in 2007 were recorded at 5 of the islands with the largest land areas (Guam, Saipan, Tinian, Pagan, and Anatahan). Phosphate concentrations showed a clear north–south gradient, with the lowest values recorded in the northernmost islands and the highest in the southern islands. Silicate ($Si[OH]_4$) concentrations were greatest in waters in the central islands, relatively high in the northernmost islands, and lowest in the southern islands. Concentrations of nitrate (NO_3^-)

were highest in waters at Guam but decreased rapidly moving northward with each subsequent island in the southern island group, while relatively high concentrations were observed in waters at Sarigan and most of the other central islands. Nitrite (NO_2^-) values were greatest in waters at Asuncion and Pagan.

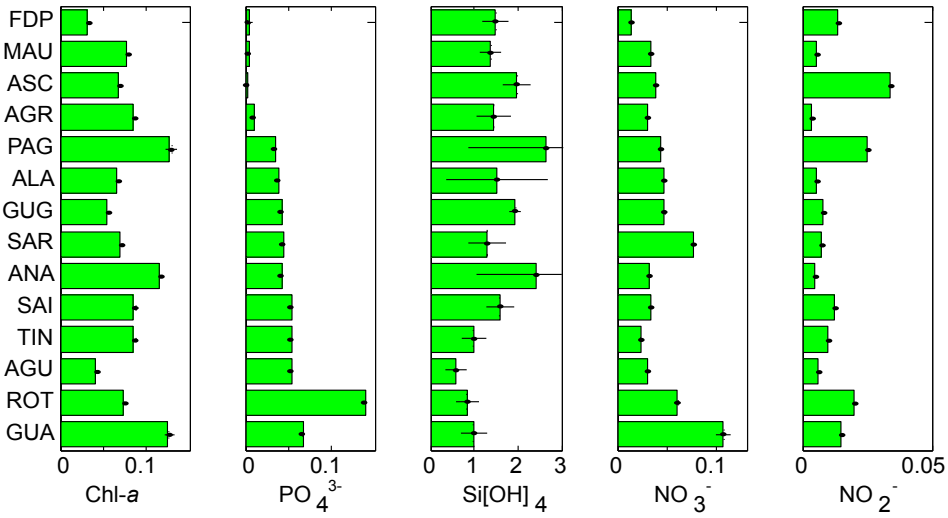


Figure 3.3.2f. In situ concentrations of Chl-*a*, phosphate (PO_4^{3-}), silicate ($Si[OH]_4$), nitrate (NO_3^-), and nitrite (NO_2^-) from nearshore (depths ≤ 30 m) water samples collected during MARAMP 2007. Data represent averages from all samples and all depths at each island. See Chapter 2: "Methods and Operational Background," Section 2.3.3: "Nearshore Spatial Surveys" for data acquisition and processing protocols, and see island chapters for water sample locations. Error bars indicate the standard error (± 1 SE) of the mean.

Results from shipboard water samples collected to depths of 250 m during MARAMP 2007 show latitudinal patterns similar to the ones observed in nearshore sample data for each of the measured parameters. In general, the northernmost and southern islands had moderate to high concentrations of all parameters measured, while the central islands had moderate to low concentrations (Fig. 3.3.2g). Guam had the greatest concentrations of nutrients in the Mariana Archipelago, a result that is not surprising given the population density and size of that island. An obvious exception to these observed trends occurred at Guguan. Despite its location in the middle of the Mariana Arc, Guguan had some of the highest recorded concentrations for all parameters measured. The cause of anomalously high nutrient and Chl-*a* concentrations there is not clear; however, it is possible that a mesoscale oceanographic feature (e.g., mid-ocean eddy) was present during sampling, causing a vertical flux of nutrients and increased productivity in the vicinity of Guguan. This notion is supported by results from nearshore water samples collected in 2007 at Guguan (Fig. 3.3.2f), where nutrient and Chl-*a* concentrations were comparable to levels found at islands near Guguan. If the anomalously high concentrations recorded from the shipboard samples were a result of terrigenous input, groundwater discharge, a locally generated oceanographic phenomenon (e.g., internal tides), or some other island-based source, then data from nearshore water samples also would show anomalously high values. This clear disparity between these 2 concomitant data sets is paradoxical but not improbable, as transient mid-ocean eddies are common in the world's oceans and can lead to increased nutrients and enhanced surface productivity.

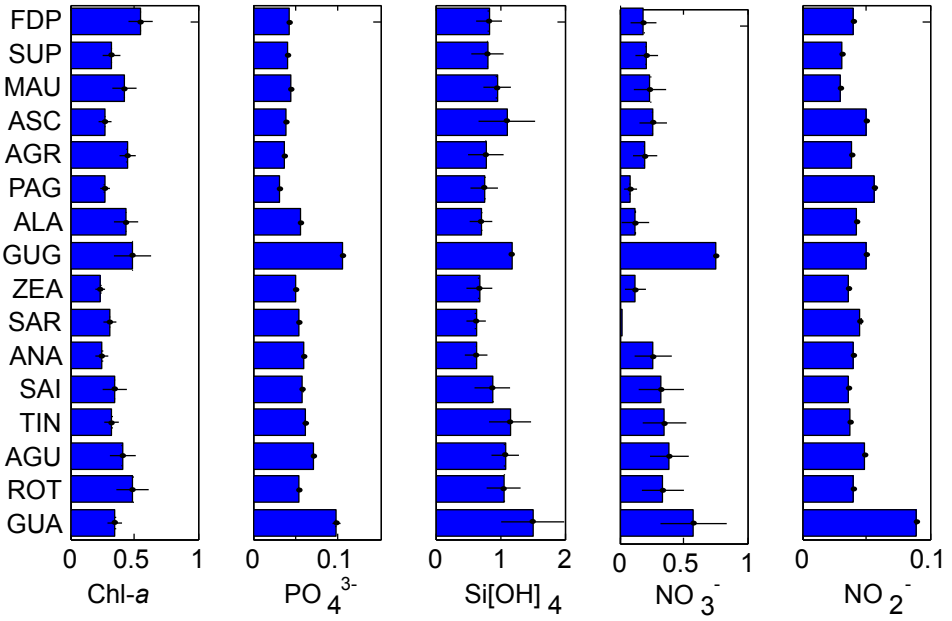


Figure 3.3.2g. In situ concentrations of Chl-*a*, phosphate (PO_4^{3-}), silicate ($Si[OH]_4$), nitrate (NO_3^-), and nitrite (NO_2^-) from shipboard (depths < 250 m) water samples collected during MARAMP 2007. Data represent averages from all samples and all depths at each island or bank. See Chapter 2: "Methods and Operational Background," Section 2.3.2: "Shipboard Surveys" for data acquisition and processing protocols. Error bars indicate the standard error (± 1 SE) of the mean.

3.4 Corals and Coral Disease

3.4.1 Coral Surveys

Coral Cover

Archipelago-wide, estimates of mean cover of live hard corals from towed-diver benthic surveys of forereef habitats were highly variable without obvious spatial or temporal patterns. Looking at results of REA and towed-diver surveys just for 2007, however, suggests that cover levels generally were lower at the southern islands than at the northern islands (Fig. 3.4.1a). Compared to results at other islands in the Mariana Archipelago, the highest level of coral cover was recorded consistently at Maug during MARAMP 2003, 2005, and 2007, with overall means of 27% (SE 1.4), 21% (SE 1.7), and 26% (SE 1.6). Guam, along with Maug, had the highest coral cover recorded at an island in 2005, with an overall mean of 23% (SE 1.2), but observed coral cover in 2007 was lower there, with an islandwide mean of 12% (SE 0.8) (Fig. 3.4.1a). The next-greatest values of coral cover in 2003 were observed at Guguan and Saipan, with overall means of 23% (SE 1.9) and 21% (SE 2.3); Guguan, along with Maug, had the highest coral cover recorded in this archipelago in 2007, with an islandwide mean of 27% (SE 2). Some of the lowest values of coral cover in the Mariana Archipelago were recorded consistently in the 3 MARAMP survey years around Rota, with overall means ranging from 4% (SE 1) to 9% (SE 1.1), and Farallon de Pajaros, with islandwide means ranging from 5% (SE 0.6) to 10% (SE 0.9). Low coral cover was also noted at Anatahan, with an islandwide mean of 8% (SE 0.6) in 2003, the only year in which MARAMP surveys were conducted at this island. Intermediate levels of coral cover were observed at Aguijan, Sarigan, Agrihan, and Asuncion in the 3 survey years, with overall means ranging from 12% (SE 1.2) to 18% (SE 2). Declines in overall mean coral cover were estimated for Saipan between 2003 and 2007 and for Guam between 2005 and 2007, and increases in islandwide mean coral cover were observed at Alamagan and Pagan between 2005 and 2007.

For the remote banks of the West Mariana Ridge, estimates of coral cover from towed-diver surveys were high: 55% (SE 2.7) at Stingray Shoal in 2003 and 25% (SE 1.4) at Pathfinder Reef in 2005 (Fig. 3.4.1a). A 50% change in estimated mean coral cover was observed at Arakane Reef from 24% (SE 1.1) in 2003 to 12% (SE 1.6) in 2005 (survey effort there included 53 survey segments in 2003 versus 30 segments in 2005). Surveys at Santa Rosa Reef, located south of Guam, and at Tatsumi Reef, located south of Tinian, revealed the lowest values of coral cover recorded in the Mariana Archipelago in 2003, with overall means of 7% (SE 0.9) and 8% (SE 1.8). No towed-diver surveys were conducted on the remote and offshore banks in 2007.

In addition to observations of live coral cover, estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors, were recorded as part of towed-diver surveys conducted on forereef habitats during MARAMP 2005 and 2007 (see Chapter 2: "Methods and Operational Background," Section 2.4.5: "Corals and Coral Disease"). In 2005 and 2007, islandwide mean stressed-coral cover ranged from < 1% to 8%. The highest level in 2005 of 5% was observed at both Agrihan (SE 2.4) and Guam (SE 0.6), and the greatest values in 2007 were recorded at Aguijan, Saipan, and Guam with overall means of 8% (SE 1.1), 6% (SE 0.6), and 5% (SE 0.6; Fig. 3.4.1a). Few corals appeared stressed at Guguan and Sarigan, where islandwide mean values were < 1% in both years. Between surveys in 2005 and 2007, overall mean stressed-coral cover increased considerably around 3 southern islands: Aguijan, Saipan, and Tinian. Estimates for Agrihan decreased during that same time period. Observations from towed-diver surveys suggest that the relatively high stressed-coral cover at certain islands was likely a consequence of the high abundance of the crown-of-thorns seastar (*Acanthaster planci*). For more information on densities of the crown-of-thorns seastar, see Section 3.6: "Benthic Macroinvertebrates."

Results from REA benthic surveys, using the line-point-intercept method on forereef habitats in 2007, suggest that mean cover of live hard corals was moderate and similar among the 4 populated, southern islands of the Mariana Archipelago. Conversely, coral cover was more variable among the younger, mostly uninhabited, volcanic, northern islands, where both the highest and the lowest cover values for this archipelago were recorded. The greatest level of coral cover was recorded at Maug, with an overall sample mean of 34.1% (SE 5.7) and high cover of ~ 70% found in some areas, including the *Porites rus* observed inside the caldera off East Island. The next-greatest levels were documented at Agrihan, Alamagan, and Sarigan with overall sample means of 30.7% (SE 6.6), 23.5% (SE 5), and 21.2% (SE 6.9). The lowest overall sample mean for live coral cover from REA surveys in 2007 was observed at Farallon de Pajaros, with 3.6% (SE 0.7), and the next lowest value of 7.8% was estimated at a single REA site at Aguijan. Among the northern islands, the next lowest overall sample means of 10.6% (SE 1.7) and 15.4% (SE 3.5) were recorded at Pagan and Guguan. At all other islands surveyed,

overall sample means ranged from 11.2% to 16.2%. In relatively close agreement with these REA values, islandwide mean coral cover from towed-diver surveys conducted in 2007 was 26% (SE 1.6) around Maug and 5% (SE 0.6) around Farallon de Pajaros and ranged from 10% (SE 0.7) to 16% (SE 1.3) around Guam, Saipan, Pagan, and Asuncion (Fig. 3.4.1a).

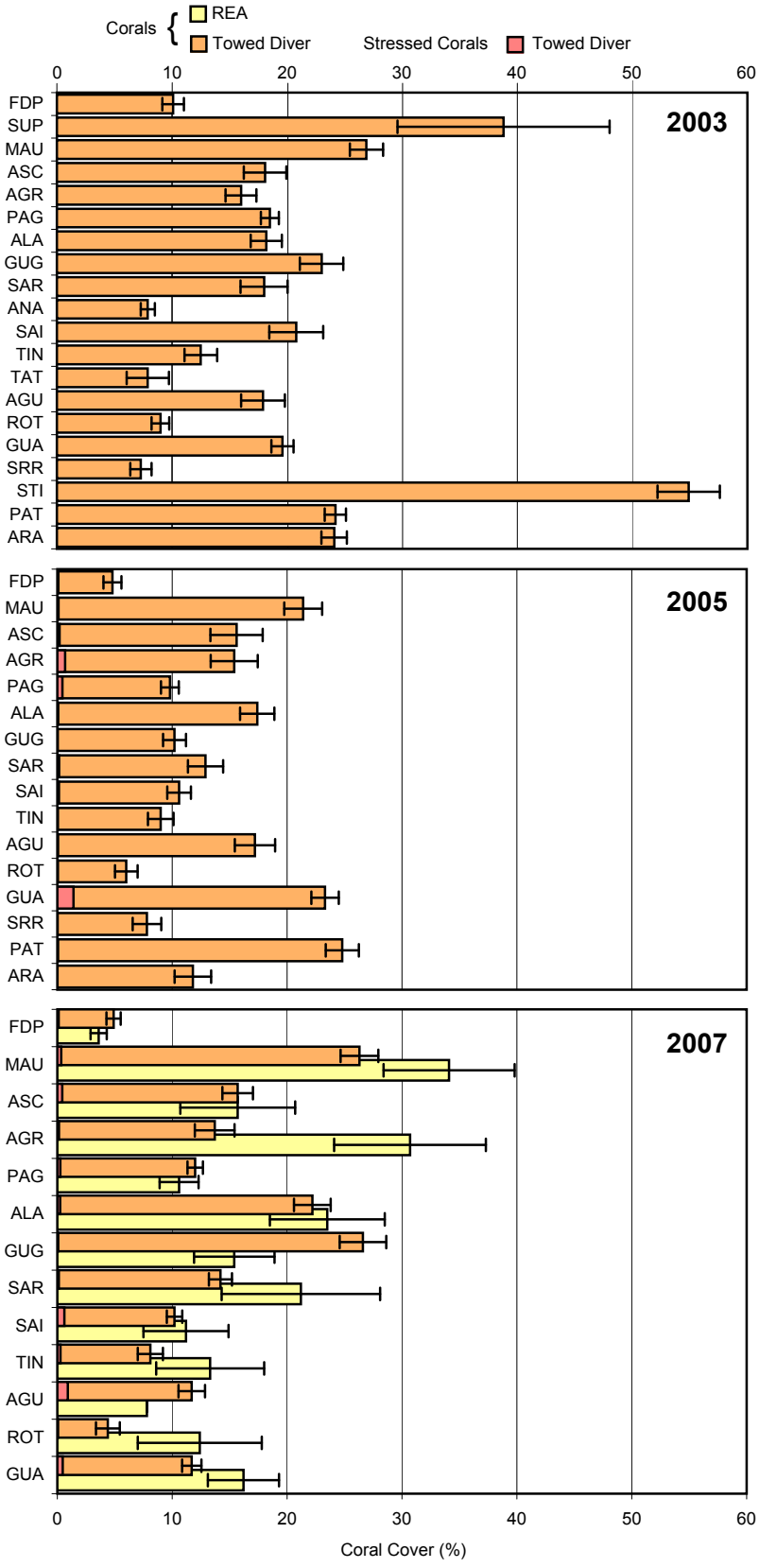


Figure 3.4.1a. Spatial and temporal comparison of mean cover (%) of live and stressed hard corals from REA and towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Surveys of stressed-coral cover were not conducted in 2003. Error bars indicate the standard error (± 1 SE) of the mean.

Coral Generic Richness and Relative Abundance

The Mariana Archipelago contains the most diverse coral reefs of the U.S. Pacific islands, with more than 375 species of hard corals recorded (Richmond et al. 2008; Riegl et al. 2008). Between MARAMP 2003 and 2007, estimates of mean generic richness for anthozoan and hydrozoan corals on forereef habitats typically increased (this change most likely was the result of increased survey effort through time). For the 3 MARAMP survey years combined, archipelago-wide total generic richness ranged from 11 to 38 genera per island (Fig. 3.4.1b). The lowest total generic richness was observed at Arakane Reef, with 11 coral genera found, and the lowest mean richness of 7.6 (SE 1.4) coral genera per site was recorded at Farallon de Pajaros, which also had the lowest total generic richness among the islands of this archipelago with 17 coral genera enumerated. The greatest total generic richness in this archipelago, with 38 coral genera enumerated, was seen at Saipan, where the overall mean richness of 17.3 (SE 1.1) coral genera per site was recorded. Pagan, with 32 coral genera observed, had the highest total generic richness among the northern islands. At least 20 coral genera each were observed at 13 of the 17 islands and banks surveyed using REA methods, and islands providing the largest potential reef areas, measured as the area of seafloor at depths < 30 m, supported the greatest coral generic richness ($r = 0.83$, $p < 0.05$; Spearman Product Moment Correlation). Generally, generic richness decreased moving from south to north along the Mariana Arc. This archipelagic pattern relates to size and geologic differences between the older, inactive, primarily carbonate islands in the south and the younger, volcanically active islands in the north (Richmond et al. 2008).

Throughout the Mariana Archipelago, the genera *Astreopora*, *Cyphastrea*, *Favia*, *Leptastrea*, *Montastrea*, *Montipora*, *Pocillopora*, *Porites,* and *Psammocora* were common and observed at every island and bank. Conversely, the genera *Alveopora*, *Cladiella*, *Diploastrea*, *Merulina*, *Plesiastrea*, *Scolymia*, *Sterionephthya*, *Zoanthus* were rare, occurring at only 1 or 2 islands. The genera *Coscinaraea, Lobophytum, Palythoa, Sacrophyton, and Sinularia* appeared at 3 or more islands but were only seen at southern islands. Other genera, such as the *Euphyllia*, were seen more often in the northern islands than in the southern islands. A summary of the distribution of anthozoan genera across the Mariana Archipelago is presented in Appendix A.

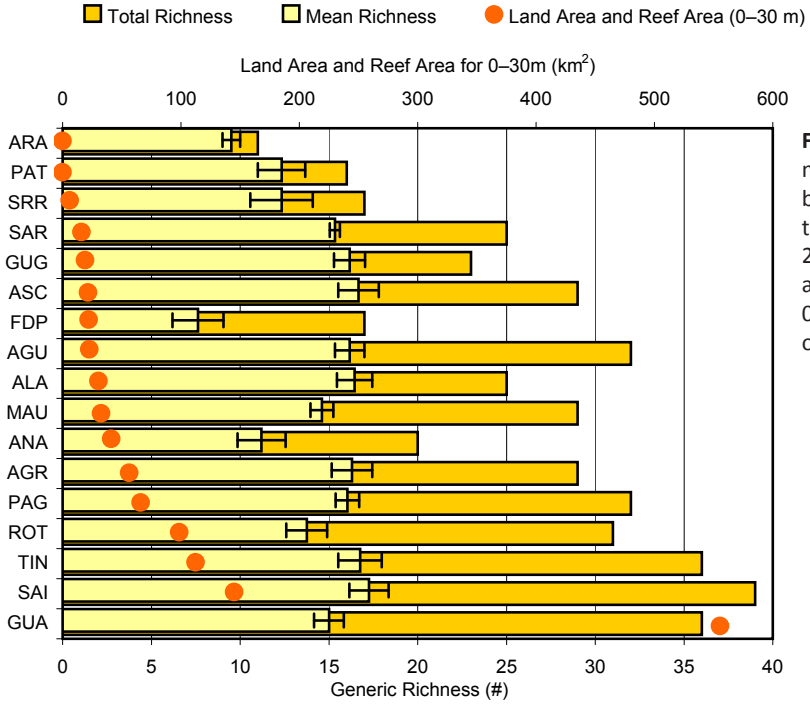


Figure 3.4.1b. Total coral richness and overall mean numbers of coral genera per site from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Red circles represent combined area (km²) of land and of the seafloor at depths of 0–30 m. Error bars indicate standard error (± 1 SE) of the mean.

To assess the contribution of different anthozoan and hydrozoan taxa to the overall composition of the coral community in the Mariana Archipelago, the number of colonies tallied at each REA site surveyed during MARAMP 2003, 2005, and 2007 was used to determine relative numerical abundance. In 2003, *Favia, Pavona, Leptastrea*, and *Pocillopora* were the top ranking coral genera (Fig. 3.4.1c); *Astreopora*, *Goniastera*, and *Porites* together contributed to more than 10% of the observed coral community. Correspondingly, in 2005 and 2007, a combination of the genera *Porities, Pocillopora, Pavona*, and *Astreopora* dominated the coral communities at most islands of the Mariana Archipelago, except for Guguan and Maug, where *Favia* and *Goniastrea* were the principal genera. Colonies of the genus *Leptastrea* also contributed more than 10% to the overall community composition at some islands and banks in each of the 3 MARAMP survey years. The rank

order of taxa by abundance varied among islands and MARAMP survey periods, although *Pocillopora, Pavona, Porites, Astreopora*, and *Favia* generally were the most numerically abundant genera. Some genera, like *Porites* and *Leptastrea*, were more numerically abundant on the forereefs of the southern islands, while other genera, such as *Pocillopora* and *Pavona*, were more numerically abundant on the forereefs of the northern islands. Environmental parameters, such as salinity, wave exposure, and volcanic activity, appear to be important determinants of coral community distribution and diversity in the Mariana Archipelago (Houk and Starmer 2010). In each survey year, the "Other" category made up the largest part of the coral community at most islands, contributing more than 20% of the relative abundance at an island. This category is composed of an assortment of taxa that individually accounted for < 2% of the corals enumerated during REA benthic surveys.

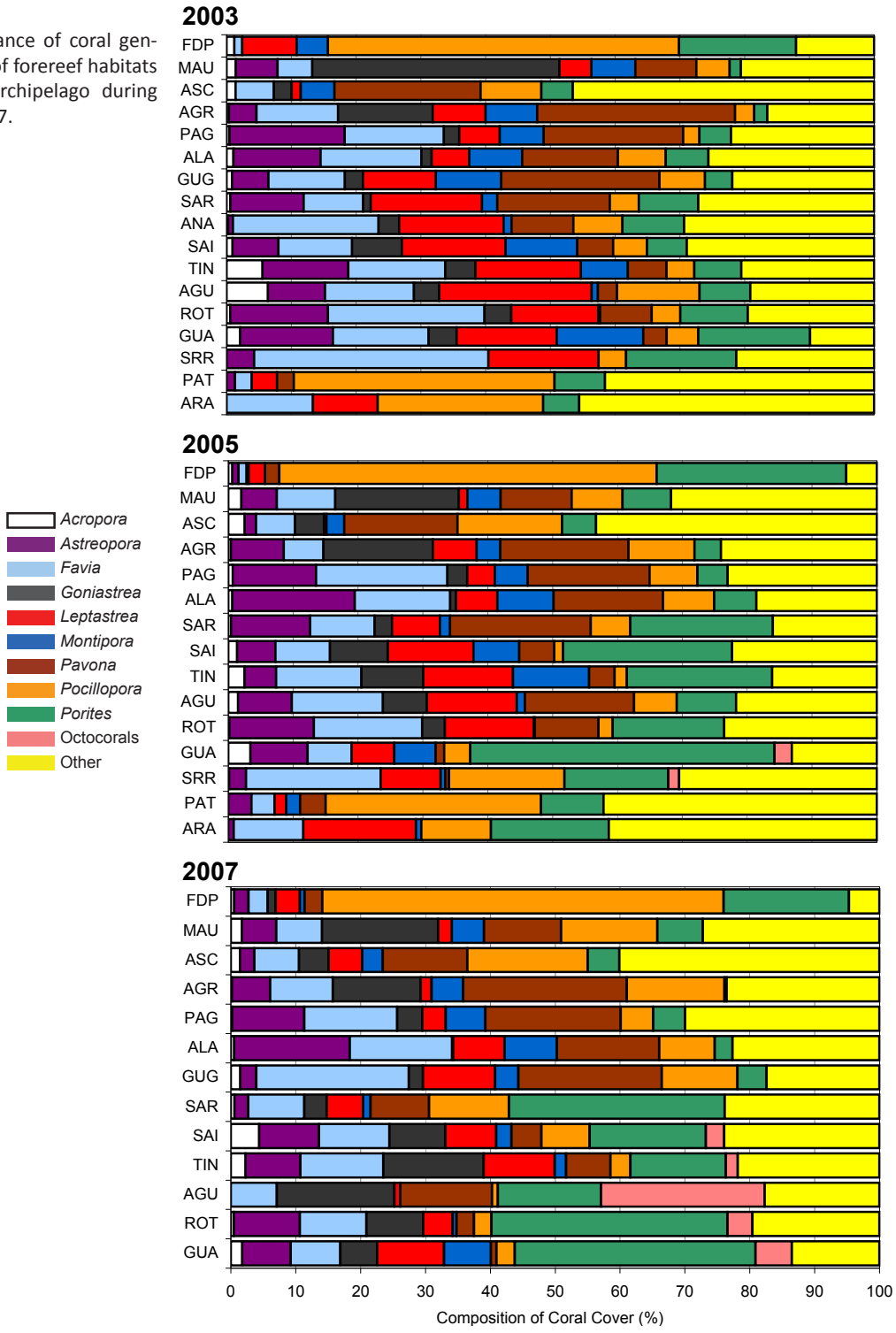


Figure 3.4.1c. Relative abundance of coral genera from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Coral Colony Density and Size-class Distribution

REA benthic surveys were conducted to determine colony density and size-class distribution of hard corals in forereef habitats across the Mariana Archipelago during MARAMP 2007. Two different protocols were implemented to census corals, and islandwide patterns in colony density reflect the intrinsic differences between these methods: two belt transects (25 × 1 m) were surveyed at 5 southern islands and 16 haphazardly placed quadrats (50 × 50 cm) were surveyed at the northern islands (see Chapter 2: "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease"). These methodological disparities preclude quantitative comparisons among islands; nonetheless, regional trends involving all survey sites can be considered.

Among the southern islands, Tinian and Guam in 2007 had the highest coral-colony densities with overall sample means of 6.7 colonies m^{-2} (SE 1) and 6.2 colonies m^{-2} (SE 0.7), while the other 3 southern islands that were surveyed all had overall sample means of ~ 4 colonies m^{-2} (Fig. 3.4.1d). Although elevated colony density can be the result of sexual and asexual reproduction, site-specific differences in reef physiography and biological assemblages may also contribute to differences among islands in mean coral-colony densities. In addition, the frequency and severity of natural and anthropogenic disturbances, including crown-of-thorns seastar (COTS) outbreaks, typhoons, fishing, water-quality degradation, and runoff, may influence the dynamics of coral community structure at these islands (Burdick et al. 2008; Richmond et al. 2008; Starmer et al. 2008; Houk and Starmer 2010). Among the 8 northern islands surveyed in 2007, overall mean colony density was the lowest at Farallon de Pajaros with 33.7 colonies m^{-2} (SE 3.4; Fig. 3.4.1d). At Farallon de Pajaros, the patchy distribution of hard substrate meant that considerable portions of most survey transects covered habitats characterized by unoccupied basalt boulders intermingled with noncarbonate sand. Farallon de Pajaros is an active volcano that has erupted at least 15 times since the mid-19th century (see Chapter 17: "Farallon de Pajaros," Section 17.1: "Introduction"). Marine substrate instability, in combination with recurrent landslides and ash fall, may limit coral recruitment and development in the shallow, well-lit habitats around this island.

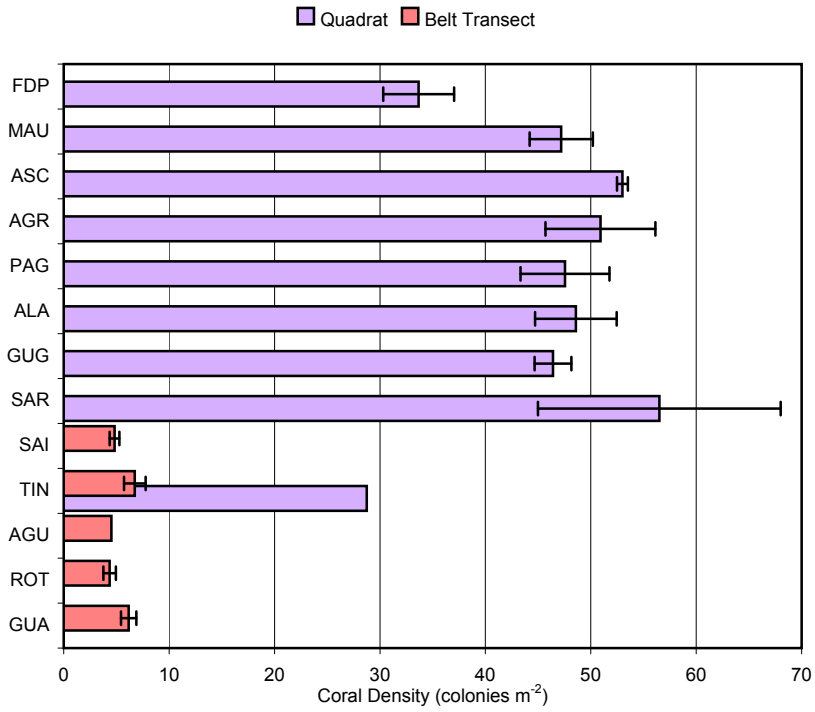
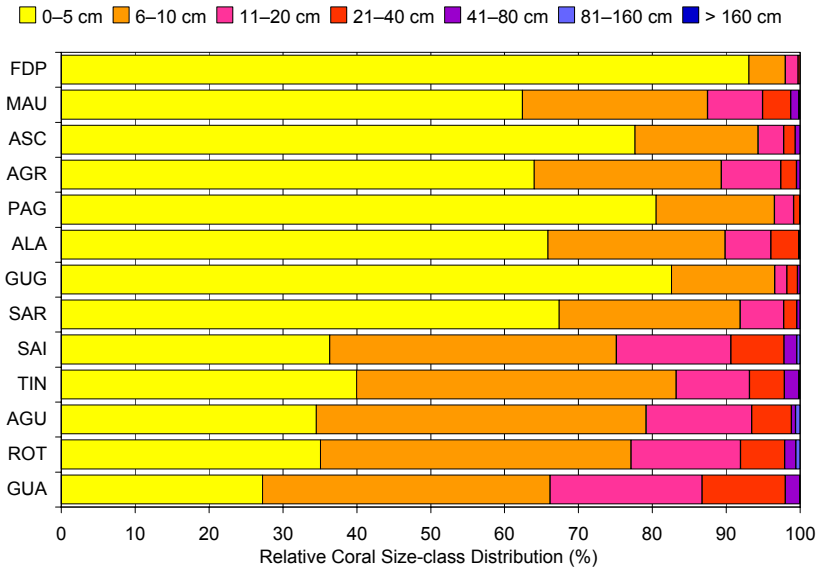


Figure 3.4.1d. Mean overall coral-colony densities of hard corals from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. The quadrat method was used in surveys at the northern islands, and the belt-transect method was used in surveys at 5 southern islands, with the exception of Tinian, where both methods were used. Error bars indicate standard error (± 1 SE) of the mean.

The previously mentioned differences in the methods implemented to census corals during MARAMP 2007 bias survey results relating to size distribution, and, therefore, we only compare size distribution within regions surveyed with the same method (At Tinian in 2007, 4 REA sites were surveyed using the belt-transect method and 1 site was surveyed using the quadrat method. For comparison of estimates among the southern islands, this discussion of size-class distribution excludes data from the single site at Tinian where quadrat surveys were completed.) Among the 5 southern islands surveyed in 2007 using the belt-transect method, size-class distribution did not vary substantially (Fig. 3.4.1e). Of the colonies surveyed at Guam, Rota, Aguijan, Tinian, and Saipan, 68%–81% had maximum diameters ≤ 10 cm, and < 3% had maximum diameters > 40 cm. No colonies with maximum diameters > 160 cm were recorded. At the 8 northern islands surveyed in 2007, where the quadrat method was used, 63%–93% of all colonies exhibited a maximum diameter ≤ 5 cm, with Farallon

de Pajaros having the largest proportion (93%) of small colonies (maximum diameter of 0–5 cm; Fig. 3.4.1e). In addition, at the northern islands, a very small proportion of colonies (< 2%) had maximum diameters > 40 cm, and no colonies with maximum diameters > 160 cm were found.

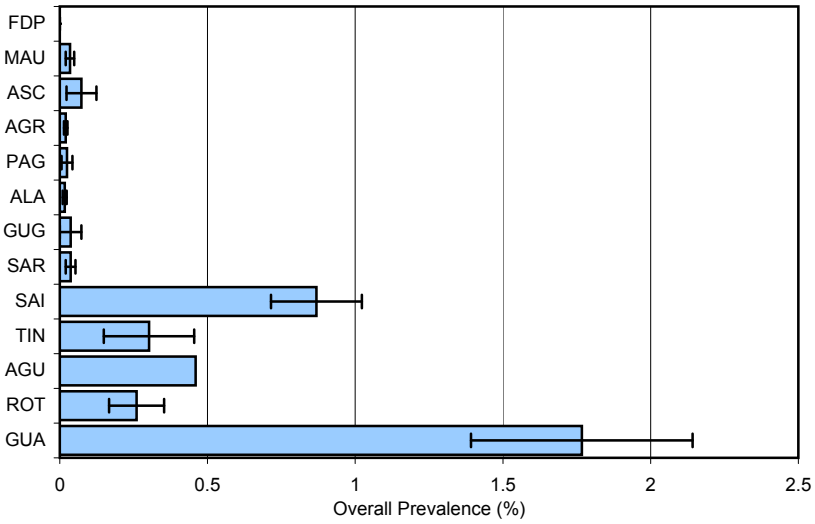
Figure 3.4.1.e. Size-class distribution of hard corals by island from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. The quadrat method was used in surveys at the northern islands, and the belt-transect method was used in surveys at 5 southern islands, with the exception of Tinian, where both methods were used.



3.4.2 Surveys for Coral Disease and Predation

Based on REA benthic surveys of hard corals on forereef habitats, overall mean prevalence of coral disease was highest in the southern islands with the greatest value of 1.4% (SE 0.4) recorded at Guam, where hot spots on the northern and northwestern coasts had the highest number of cases and overall prevalence of 2.7%–3.9%. The next-greatest levels of disease were seen at Saipan with 0.4% (SE 0.2), Tinian with 0.2% (SE 0.1), and Rota with 0.06% (SE 0.03), and overall mean prevalence of coral disease was lowest in the northern islands with mean values ≤ 0.04% (Fig. 3.4.2a; the values of overall prevalence shown in this figure include predation). The southern islands accounted for 74% of cases of bleaching and disease observed in the Mariana Archipelago. Guam and Saipan not only are the largest islands in the Mariana Archipelago but also possess the greatest estimated potential reef areas, likely harboring the most extensive coral reef development in the Mariana Archipelago. Guam and Saipan also have the largest human populations in this region, and the associated deterioration in water quality and habitat might be linked to the greater levels of disease seen at these islands compared to observations at other islands in this archipelago. Elevated water temperatures and disturbances from human activities have been noted as environmental drivers of disease; thus, the coral reef ecosystems at the populated, southern islands may have a greater risk of coral bleaching and marine disease outbreaks than do the reefs at the mostly uninhabited northern islands

Figure 3.4.2a. Mean overall prevalence (%) of coral diseases and predation from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The quadrat method was used in surveys at the northern islands, and the belt-transect method was used in surveys at 5 southern islands, with the exception of Tinian, where both methods were used. Error bars indicate standard error (± 1 SE) of the mean.



(Kaczmarsky 2006; Harvell et al. 2007; Vargas-Ángel and Wheeler 2009). However, because 2 different methods were implemented to census corals, as discussed previously in this section, survey results reflect biases toward lower colony densities and, thus, larger values of disease prevalence for the southern islands and higher colony densities and, thus, smaller values of disease prevalence for the northern islands, making quantitative, interisland comparisons inappropriate.

Bleaching and at least 6 broad disease types (Vargas-Ángel and Wheeler 2009; PIFSC 2009) were identified in 2007 in the Mariana Archipelago. Similar types of disease conditions have been reported for reefs in other Pacific regions, including American Samoa, the Great Barrier Reef, the Philippines, east Africa, and the Red Sea (Raymundo et al. 2008; Brainard et al. 2008; Kaczmarsky 2006; Work and Rameyer 2005; Loya 2004; Willis et al. 2004; Winkler et al. 2004). During MARAMP 2007, fungal infection, bleaching, and pigmentation response ranked as the 3 most common disease conditions archipelago-wide, representing ~ 30%, 23%, and 19% of cases. Although bleaching, pigmentation response, and fungal infections can occur naturally, elevated prevalence and disease hotspots may be indicative of balance shifts between host, agent, and the environment. In addition, recently, University of Guam and CRED scientists have identified the occurrence of additional diseases in this archipelago, including black-band disease, brown-band disease, skeletal eroding band disease, and ulcerative white spot disease, a type of subacute tissue loss (Burdick et al. 2008; LJ Raymundo pers. comm.; B Vargas-Ángel, unpublished data).

Table 3.4.2a Archipelago-wide disease occurrence, measured as percentage of cases, among coral families and genera from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesions of unknown etiology; PRE: predation by COTS or corallivorous snails.

Family	Genus	BLE	WSY	TLS	SGA	PRS	FUN	OTH	Total	PRE
Acroporidae	*Acropora*	–	–	–	0.9	–	–	–	0.9	5.3
	Astreopora	10.6	–	–	0.9	–	0.4	0.4	12.3	12.4
	Montipora	2.1	–	0.9	0.4	–	0.4	0.4	4.3	4.7
Pocilloporidae	*Pocillopora*	–	–	–	–	–	–	0.4	0.4	10.1
	Stylophora	–	–	–	–	–	–	–	–	10.1
Oculinidae	*Galaxea*	–	–	–	–	–	–	0.4	0.4	0.6
Siderastreidae	*Coscinaraea*	–	–	–	–	–	0.4	–	0.4	–
	Psammocora	0.4	–	–	–	–	0.9	–	1.3	–
Agariciidae	*Pavona*	–	–	–	–	–	0.4	1.3	1.7	1.2
	Gardineroseris	–	0.9	–	–	–	–	0.4	1.3	–
Fungidae	*Fungia*	–	–	–	–	–	–	–	–	1.8
Merulinidae	*Hydnophora*	–	–	–	–	–	0.4	–	0.4	–
Dendrophyliidae	*Turbinaria*	–	–	–	–	–	–	0.4	0.4	–
Mussidae	*Lobophyllia*	–	–	–	0.4	–	–	–	0.4	–
Faviidae	*Favia*	0.4	–	–	–	–	0.9	0.4	1.7	4.1
	Favites	–	–	–	–	–	–	–	–	0.6
	Goniastrea	0.9	0.4	–	–	–	–	0.4	1.7	26.6
	Platygyra	3.0	–	–	–	–	–	–	3.0	–
	Leptoria	–	–	–	–	–	–	–	–	0.6
	Plesiastrea	0.4	–	–	–	–	–	–	0.4	–
	Cyphastrea	–	–	–	–	–	19.1	–	19.1	1.2
	Echinopora	0.9	–	–	–	–	–	–	0.9	–
Poritidae	*Porites*	4.7	0.9	7.7	3.0	18.7	6.8	6.0	47.7	20.7
	Goniopora	–	–	0.9	–	–	–	0.4	1.3	–
Total		23.4	2.1	9.4	5.5	18.7	29.8	11.1	100.0	100.0

The diseases enumerated across the Mariana Archipelago affected 24 hard coral genera belonging to 11 families (Table 3.4.2a). The families Poritidae, Faviidae, and Acroporidae accounted for more than 93% of all cases, with *Porites*, *Cyphastrea*, and *Astreopora* each hosting 1 major disease state: pigmentation response, fungal infection, and bleaching, respectively. Collectively, these 3 genera hosted nearly 80% of all disease cases archipelago-wide. Patterns of disease occurrence (percentage of cases) from MARAMP 2007 suggest that the family Poritidae hosted all 7 major disease categories, while Acroporidae and Faviidae hosted 5 and 4 disease states (Table 3.4.2a). The disproportionate susceptibility to disease in the Indo-Pacific of the Poritidae, Faviidae, and Acroporidae has been broadly documented (Willis et al. 2004; Vargas-Ángel 2009; Aeby 2006).

Predation scars inflicted by COTS or corallivorous snails, such as snails from the genus *Drupella*, were common, with 4 islands containing 82% of all cases enumerated during MARAMP 2007. These islands were Saipan, Guam, Maug, and Asuncion. The remaining cases were recorded at Rota, Tinian, Pagan, and Agrihan but at much lower levels. No signs of COTS or snail predation were noted at Farallon de Pajaros, Aguijan, Alamagan, Guguan, or Sarigan. Signs of COTS and snail predation were observed on 14 genera, belonging to 7 families of hard corals, with members of the Faviidae, Acroporidae, Poritidae, and Pocilloporidae presenting more than 96% of all scars (Table 3.4.2.a). In these families, 3 genera alone, *Goniastrea*, *Porites*, and *Astreopora*, presented 60% of all cases. Interestingly, 50% of all scars observed at the northern islands of Asuncion and Maug were seen on colonies of *Goniastrea*, whereas, at the populated, southern islands of Guam and Saipan, *Astreopora*, *Porites*, *Pocillopora*, and *Stylophora* presentend more than 60% of cases (Fig. 3.4.2b). Prey distribution and abundance, as well as predator selectivity, can strongly affect the patterns and intensity of COTS and snail predation on hard-coral benthos.

These results from MARAMP 2007 represent the first comprehensive attempt to quantitatively assess the distribution and prevalence of coral diseases in Guam and the CNMI. Although archipelago-wide means of overall prevalence are relatively low, site-specific hotspots occurred at Guam. In addition, the coral families Poritidae, Acroporidae, and Faviidae appeared to be disproportionately susceptible to disease and predation. Potential outbreaks of host-specific diseases or corallivores can be a source of concern, given that these families are key contributors to reef building and ecosystem structural dynamics across the Mariana Archipelago.

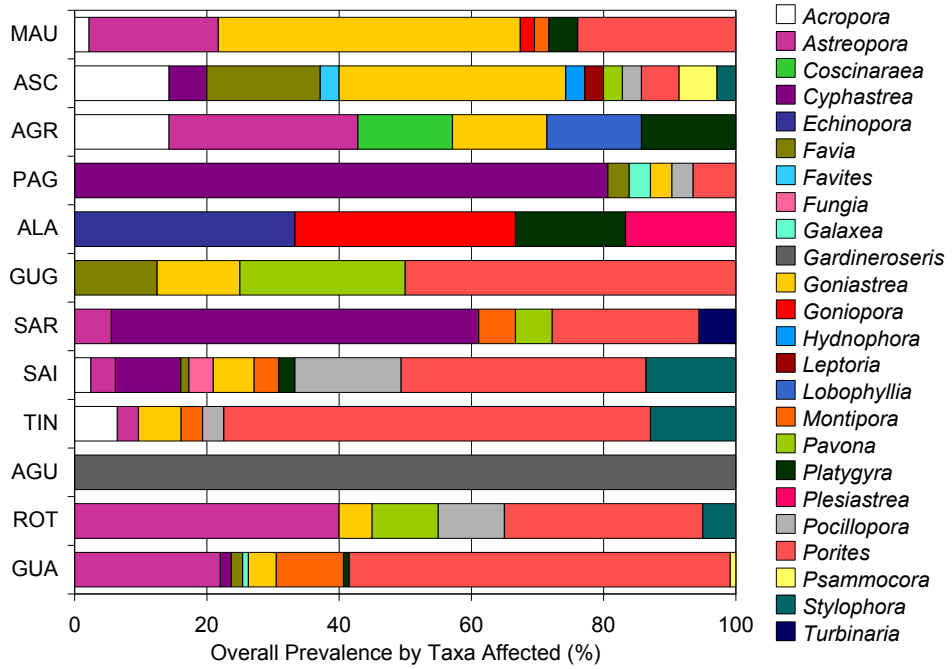


Figure 3.4.2b. Overall mean prevalence (%) observations of hard-coral genera affected by coral diseases and predation from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. The order of taxa presented in the bars is the same as the order in the legend. The quadrat method was used in surveys at the northern islands, and the belt-transect method was used in surveys at 5 southern islands, with the exception of Tinian, where both methods were used.

3.5 Algae and Algal Disease

3.5.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

The most apparent spatial pattern in mean macroalgal cover, based on towed-diver surveys conducted during MARAMP 2005 and 2007, was that observed values were higher at the populated, southern islands than at the northern islands of the Mariana Archipelago (Fig. 3.5.1a). For both of these survey years, among the islands of this archipelago, Guam, Tinian, and Rota registered the highest mean macroalgal cover with overall means ranging from 39% (SE 2) to 56% (SE 1.5). The lowest levels in the Mariana Archipelago were recorded at Farallon de Pajaros and Ascuncion in 2005, with islandwide means of 4% (SE 1.3) and 5% (SE 1.3), and at Farallon de Pajaros in 2007, with an overall mean of 3% (SE 0.4). When considering the offshore and remote reefs and banks, a similar spatial pattern was noted during towed-diver surveys in 2005, with Santa Rosa Reef, located south of Guam, having the highest macroalgal cover in the Mariana Archipelago with an overall mean of 71% (SE 3.1). At Arakane and Pathfinder Reefs on the West Mariana Ridge, mean macroalgal cover was 46% (SE 2.3) and 29% (SE 1.1) in 2005.

A similar spatial pattern in macroalgal cover was observed during REA benthic surveys using the line-point-intercept method during MARAMP 2007: relatively high overall means of macroalgal cover were recorded at the populated, southern islands, and the lowest level of macroalgal cover was observed at northern islands (Fig. 3.5.1a). No macroalgae were recorded at Farallon de Pajaros and Agrihan.

Results from towed-diver surveys conducted during MARAMP 2003 suggest relatively consistent and high values of algal cover in 2003 throughout the Mariana Archipelago (Fig. 3.5.1a) with overall means for macroalgae and turf algae combined ranging from 35% to 68%, excluding the ash-covered reefs of Anatahan, which had much lower algal cover. During MARAMP 2003, the protocol for towed-diver benthic surveys aggregated observations of both turf algae and macroalgae into a single category. In contrast, MARAMP 2005 and 2007 towed-diver surveys recorded macroalgal cover as a distinct category and did not record cover of turf algae within field estimations. Thus, temporal comparisons of estimates for the "macroalgae" category between MARAMP 2003 and the later survey periods are not appropriate.

A general decline in macroalgal cover was observed between MARAMP 2005 and 2007 (Fig. 3.5.1a). Decreases in overall macroalgal cover were noted at 8 of the 13 islands surveyed, with reductions in overall means ranging from 7% at Rota to 19% at Maug. At Guguan, estimates of microalgal cover were 10% higher in 2007 than in 2005. At Asuncion, estimates increased by 14%. Observed overall macroalgal cover essentially remained the same at Saipan, Pagan, and Farallon de Pajaros between 2005 and 2007. No other distinct temporal patterns for macroalgal cover were identified across the Mariana Archipelago between MARAMP 2005 and 2007.

Algal Cover: Crustose Coralline Red Algae

Observations of crustose coralline red algae from towed-diver surveys suggest low cover levels throughout the Mariana Archipelago, compared to values recorded at other areas in the Pacific surveyed through the Pacific RAMP. Around a majority of islands, offshore banks and remote reefs, overall mean cover of crustose coralline red algae was $\leq$ 16% during MARAMP 2003, 2005, and 2007 (Fig. 3.5.1b). An exception was noted for Supply Reef, where the overall observed mean cover of crustose coralline red algae was 35% (SE 5.8) during MARAMP 2003. Low levels of crustose-coralline-red-algal cover also were seen during REA surveys conducted using the line-point-intercept method in 2007, with overall sample means $\leq$ 13%, except for at Aguijan, where an estimate of 32.4% was recorded at the only site surveyed there in 2007.

No difference in cover of crustose coralline red algae was observed between the northern and southern islands, based on results from both towed-diver and REA benthic surveys. No temporal patterns in cover values from towed-diver surveys for crustose coralline red algae were detected across the Mariana Archipelago between the 3 MARAMP surveys (Fig. 3.5.1b).

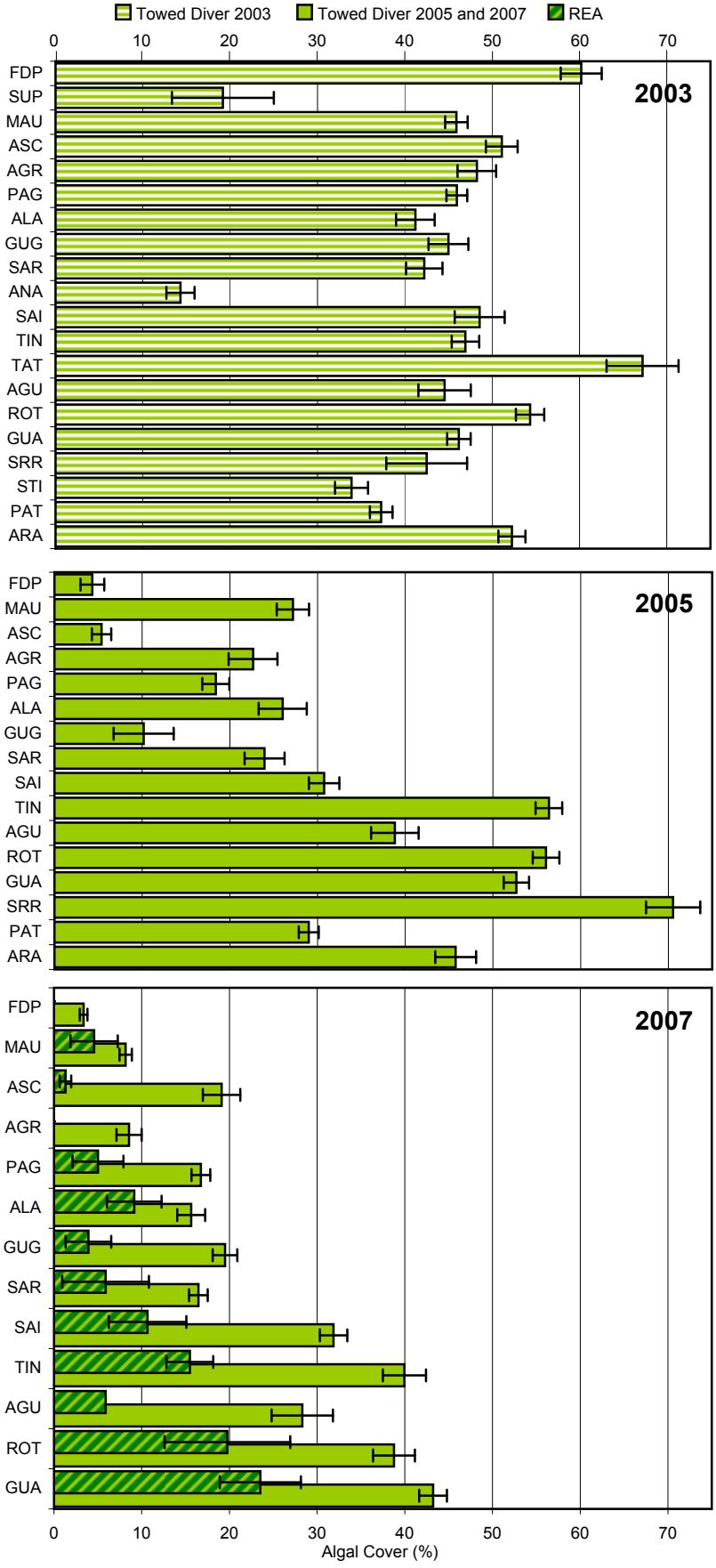


Figure 3.5.1a. Spatial and temporal comparison of mean macroalgal cover (%) from REA and towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. The 2003 panel shows towed-diver observations of both macroalgae and turf (towed-diver surveys included turf algae only during MARAMP 2003). Error bars indicate standard error (± 1 SE) of the mean.

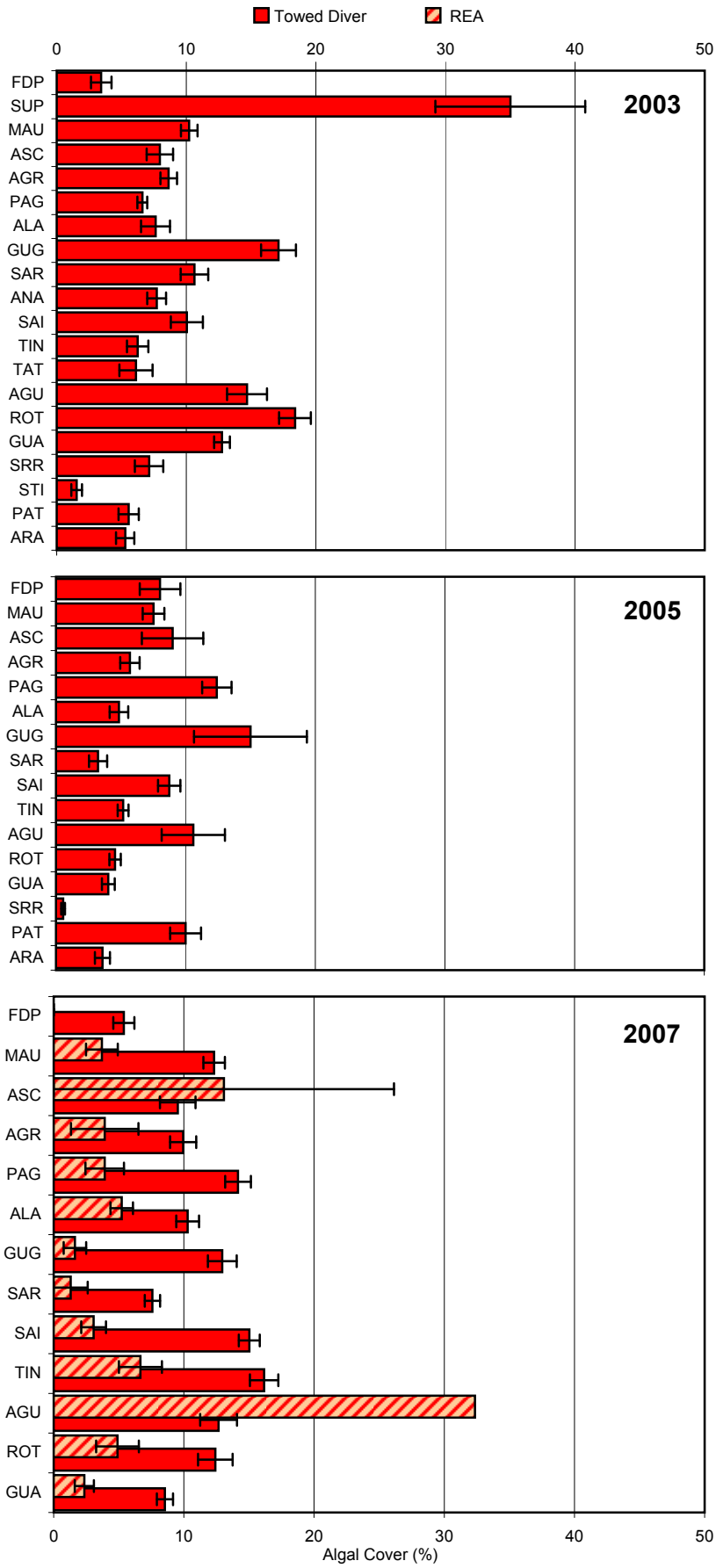


Figure 3.5.1b. Spatial and temporal comparison of mean crustose-coralline-red-algal cover (%) from REA and towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Occurrence and Abundance: Macroalgal Genera and Functional Groups

Tribollet and Vroom (2007) used CRED data from REA benthic surveys to examine spatial and temporal trends of macroalgal distribution and abundance in the Mariana Archipelago between 2003 and 2005. They found considerable differences in algal communities between the volcanic, northern islands and carbonate, southern islands and hypothesized that, in this archipelago, larger islands likely harbor greater algal diversity than do smaller islands. In support of this premise, data from REA benthic surveys conducted during the 3 MARAMP survey years, suggest that total generic richness for macroalgae was tied to island and reef size, as the larger, southern islands contained the largest reef areas (at depths < 30 m) and supported more macroalgal genera than did the smaller, northern islands (Table 3.5.1a and Fig. 3.5.1c).

This difference in generic richness was expected, since larger islands typically contain a more diverse array of habitats and, consequently, more niches that can support more biologically diverse populations. Still, it was of concern that the higher number of species encountered at larger islands may have been the result of skewed sampling efforts (e.g., larger islands received a greater survey effort than smaller islands during MARAMP surveys) until the overall means for each island were compared. When the average number of macroalgal genera found at each REA site per island was plotted against island and reef size, sites at larger islands still appeared to contain greater diversity than sites at smaller islands, suggesting that larger islands likely support more diverse algal communities than do smaller islands (Fig. 3.5.1c).

The greatest diversity of macroalgae was observed at Guam, where 54 macroalgal genera were recorded across the 3 MARAMP survey years (Fig. 3.5.1c and Table 3.5.1a). Looking at average generic richness for macroalgae, the highest values were recorded at Rota, Guam, and Tinian with overall means of 13.1(SE 0.74), 13 (SE 0.68), and 12.7 (SE 1.25) genera per site. Among the islands surveyed, excluding Anatahan, where surveys were conducted only in 2003, Farallon de Pajaros had the lowest macroalgal diversity with 13 total genera observed and an overall mean of 6 (SE 0.47) genera per site. Among the northern islands, Pagan had the highest macroalgal diversity with 40 total genera enumerated and an overall mean richness of 11.1 (SE 0.61) genera per site. Note that the generic richness numbers presented in this chapter include data data from roving-diver surveys in addition to photoquadrat surveys. The counts of taxa provided in the island chapters, however, include only data from photoquadrats (see Chapter 2: "Methods and Operational Background," Section 2.4.6: "Algae and Algal Disease").

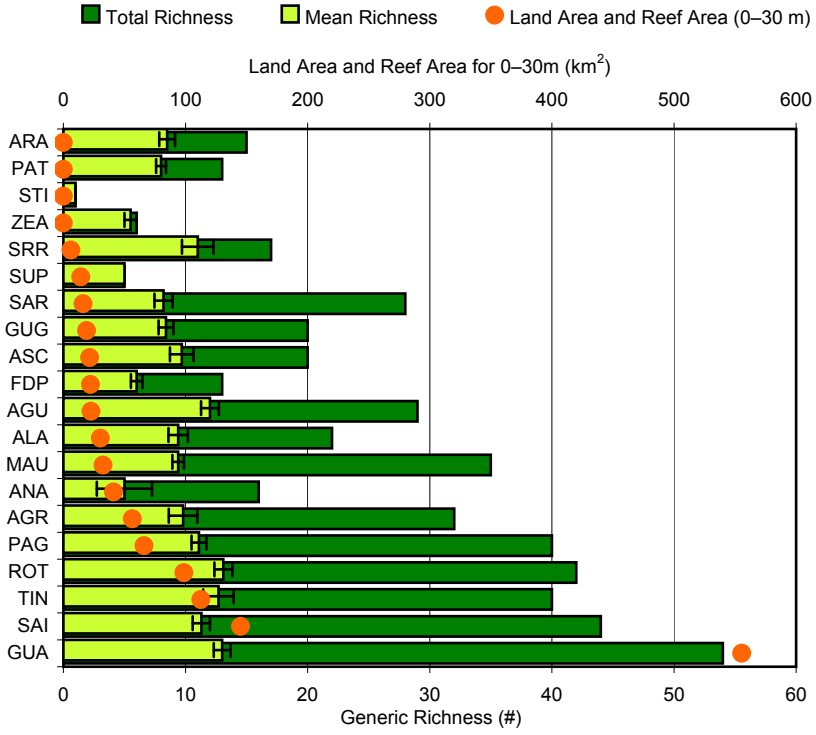


Figure 3.5.1c. Total macroalgal richness and overall mean numbers of macroalgal genera per site from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005 and 2007. Red circles represent combined area (km^2) of land and of the seafloor at depths of 0–30 m. Error bars indicate standard error (± 1 SE) of the mean.

Island	Survey Year	Number of Genera or Functional Group				
		Green Macroalgae	Red Macroalgae	Brown Macroalgae	Macroalgal Total	Algal Functional Group
FDP	2003	7	0	3	10	2
	2005	6	1	3	10	1
	2007	4	3	2	9	3
	Total	7	3	3	13	3
SUP	2003	3	1	1	5	3
MAU	2003	10	9	4	23	3
	2005	10	7	3	20	4
	2007	8	8	6	22	3
	Total	14	15	6	35	4
ASC	2003	8	7	3	18	3
	2005	7	2	3	12	3
	2007	7	5	3	15	3
	Total	9	8	3	20	3
AGR	2003	10	9	4	23	3
	2005	8	4	3	15	4
	2007	6	10	4	20	3
	Total	11	15	6	32	4
PAG	2003	11	12	4	27	3
	2005	11	13	3	27	4
	2007	10	17	4	31	3
	Total	13	22	5	40	4
ALA	2003	5	8	1	14	3
	2005	5	8	2	15	3
	2007	5	6	2	13	3
	Total	8	11	3	22	3
GUG	2003	8	5	1	14	3
	2005	3	1	1	5	2
	2007	7	6	2	15	3
	Total	10	8	2	20	3
ZEA	2003	5	1	0	6	1
SAR	2003	8	2	0	10	2
	2005	8	10	2	20	2
	2007	5	4	2	11	3
	Total	12	13	3	28	3
ANA	2003	7	7	2	16	3
SAI	2003	9	9	2	20	3
	2005	12	13	4	29	4
	2007	13	17	2	32	3
	Total	16	24	4	44	2
TIN	2003	6	8	2	16	3
	2005	15	14	4	33	4
	2007	8	13	2	23	3
	Total	15	21	4	40	4
AGU	2003	9	7	0	16	3
	2005	11	7	4	22	4
	2007	7	5	0	12	3
	Total	13	12	4	29	4
ROT	2003	14	15	3	32	4
	2005	15	12	4	31	3
	2007	11	10	3	24	3
	Total	16	22	4	42	4
GUA	2003	14	15	3	32	4
	2005	15	22	3	40	4
	2007	13	19	5	37	3
	Total	19	30	5	54	4
SRR	2003	8	3	0	11	4
	2005	11	3	1	15	4
	Total	12	4	1	17	4
STI	2003	0	1	0	1	1
PAT	2003	6	3	0	9	3
	2005	7	3	1	11	3
	Total	7	5	1	13	3
ARA	2003	9	1	0	10	3
	2005	9	3	1	13	3
	Total	11	3	1	15	3

Table 3.5.1a. Total number of macroalgal genera and algal functional groups observed at each island or reef from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005 and 2007. The last column counts the total number of groups in addition to macroalgae: turf algae, crustose coralline red algae, branched non-geniculate coralline red algae, and cyanophytes. See Appendices B and C for lists of genera found at each island or reef.

Distribution of individual macroalgal genera across the Mariana Archipelago during the 3 MARAMP survey years is presented in Appendices B and C. Among green algae, the genera *Caulerpa*, *Dictyosphaeria*, *Halimeda*, *Neomeris*, and *Ventricaria* were ubiquitous across all islands and banks in the Mariana Archipelago. Such broad distributions were not as common among genera of red and brown algae, with only the red algal genus *Dichotomaria* and brown algal genus *Dictyota* commonly occurring throughout both the islands and banks of this archipelago. Other algae, such as the red genera *Actinotrichia*, *Jania*, and *Peyssonnelia*, the brown genera *Padina* and *Turbinaria*, and the green genus *Tydemania* were encountered primarily in reef habitats surrounding emergent islands and rarely on submerged banks.

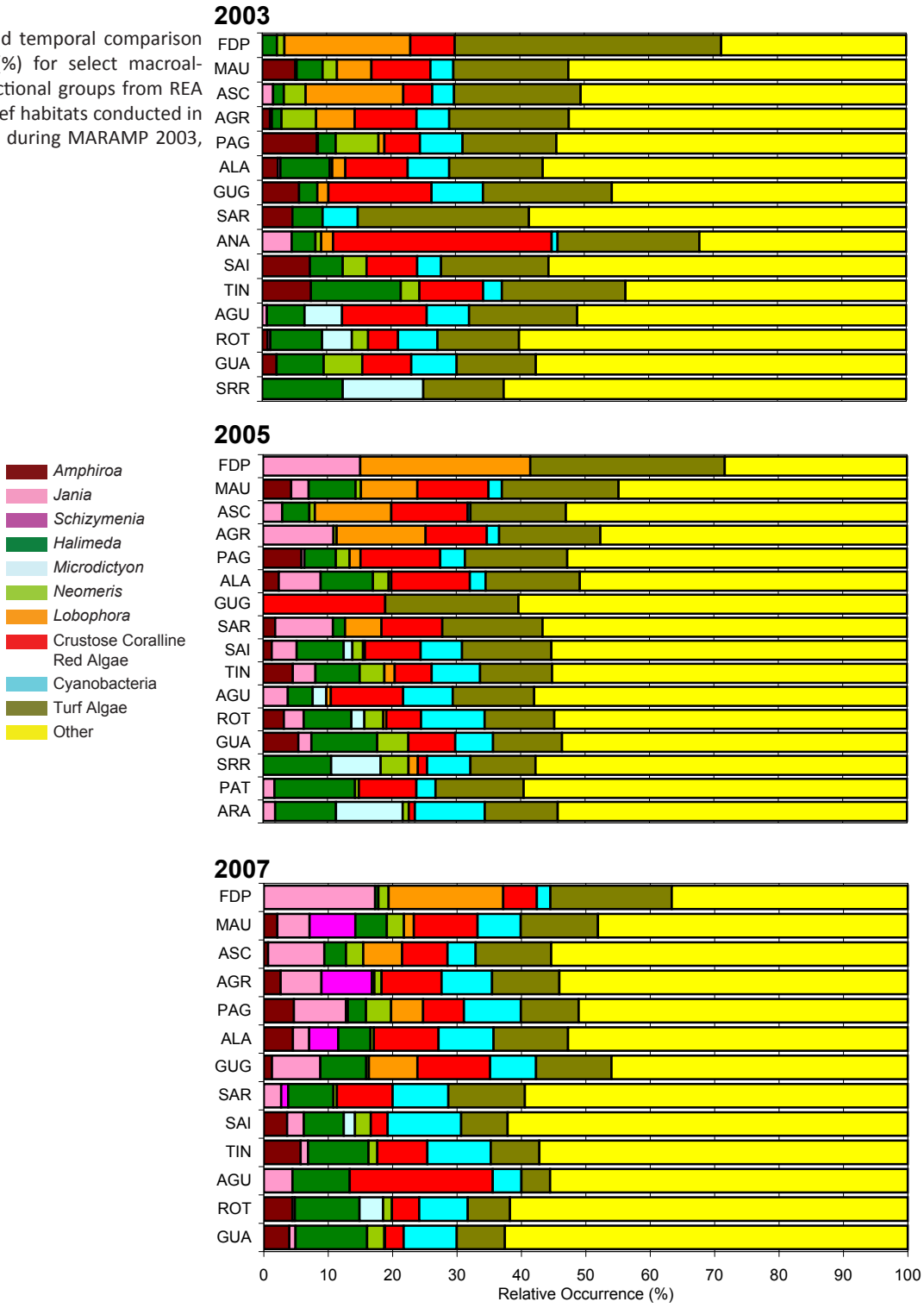


Figure 3.5.1d. Spatial and temporal comparison of relative occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Differences in macroalgal biodiversity between the volcanically active, northern islands and carbonate, southern islands were also obvious, especially among red algae (Appendices B and C). The red algal genera *Amansia*, *Crouania*, *Gelidiella*, *Haloplegma*, *Halymenia*, and *Predaea* were common at southern islands, but they were rare or absent during surveys conducted at islands north of Saipan. An opposite distribution was observed for the red algal genera *Cheilosporum* and *Dasya*, which commonly occurred at northern islands rather than at southern islands.

Table 3.5.1b. Observations of occurrence (%) for select macroalgal genera and algal functional groups at each island or reef from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Island	Survey Year	Green Macroalgal Genera			Red Macroalgal Genera			Brown Macroalgal Genera	Algal Functional Group		
		Halimeda	*Microdictyon*	*Neomeris*	*Amphiroa*	*Jania*	*Schizymenia*	*Lobophora*	Crustose Coralline Red Algae	Cyanobacteria	Turf Algae
FDP	2003	4.2	0.0	2.1	0.0	0.0	0.0	35.4	12.5	0.0	75.0
	2005	0.0	0.0	0.0	0.0	44.4	0.0	77.8	0.0	0.0	88.9
	2007	2.8	0.0	8.3	0.0	91.7	0.0	94.4	27.8	11.1	100.0
MAU	2003	18.8	0.0	10.4	24.0	1.0	0.0	25.0	42.7	16.7	83.3
	2005	32.4	0.0	3.7	19.4	12.0	0.0	38.9	49.1	9.3	80.6
	2007	32.4	0.0	17.6	13.9	33.3	47.2	10.2	65.7	44.4	79.6
ASC	2003	8.3	0.0	16.7	0.0	8.3	0.0	75.0	22.2	16.7	97.2
	2005	27.8	0.0	5.6	0.0	19.4	0.0	77.8	77.8	2.8	97.2
	2007	27.8	0.0	22.2	5.6	72.2	0.0	50.0	58.3	36.1	97.2
AGR	2003	6.9	0.0	25.0	5.6	1.4	0.0	27.8	44.4	23.6	86.1
	2005	0.0	0.0	2.8	0.0	63.9	0.0	80.6	55.6	11.1	91.7
	2007	2.8	0.0	8.3	19.4	47.2	58.3	0.0	69.4	58.3	77.8
PAG	2003	15.6	0.0	37.5	47.9	1.0	0.0	5.2	31.3	37.5	82.3
	2005	29.6	0.0	13.0	36.1	2.8	0.0	10.2	75.0	23.1	96.3
	2007	26.9	0.0	37.0	44.4	76.9	2.8	47.2	60.2	84.3	85.2
ALA	2003	52.8	0.0	2.8	16.7	2.8	0.0	13.9	66.7	44.4	100.0
	2005	55.6	0.0	16.7	16.7	44.4	0.0	2.8	83.3	16.7	100.0
	2007	41.7	0.0	4.2	37.5	20.8	37.5	0.0	83.3	70.8	95.8
GUG	2003	13.9	0.0	0.0	27.8	0.0	0.0	8.3	77.8	38.9	97.2
	2005	0.0	0.0	0.0	0.0	0.0	0.0	0.0	91.7	0.0	100.0
	2007	56.7	0.0	3.3	10.0	60.0	0.0	60.0	90.0	56.7	93.3
SAR	2003	16.7	0.0	0.0	16.7	0.0	0.0	0.0	0.0	19.4	94.4
	2005	11.1	0.0	0.0	11.1	52.8	0.0	33.3	55.6	0.0	91.7
	2007	36.1	0.0	2.8	0.0	13.9	5.6	0.0	44.4	44.4	61.1
ANA	2003	8.3	0.0	2.1	0.0	10.4	0.0	4.2	77.1	2.1	50.0
SAI	2003	30.6	0.0	22.2	44.4	0.0	0.0	0.0	47.2	22.2	100.0
	2005	51.0	9.4	11.5	9.4	27.1	0.0	2.1	60.4	44.8	96.9
	2007	44.8	12.5	17.7	26.0	18.8	0.0	0.0	18.8	82.3	52.1
TIN	2003	66.7	0.0	13.9	36.1	0.0	0.0	0.0	47.2	13.9	91.7
	2005	59.7	0.0	33.3	40.3	30.6	0.0	13.9	50.0	65.3	97.2
	2007	68.3	0.0	10.0	41.7	8.3	0.0	0.0	56.7	71.7	55.0
AGU	2003	33.3	33.3	0.0	0.0	4.2	0.0	0.0	75.0	37.5	95.8
	2005	30.6	16.7	0.0	0.0	30.6	0.0	5.6	88.9	61.1	100.0
	2007	33.3	0.0	0.0	0.0	16.7	0.0	0.0	83.3	16.7	16.7
ROT	2003	63.3	36.7	20.0	6.7	3.3	0.0	0.0	36.7	48.3	100.0
	2005	66.7	18.1	26.4	29.2	27.8	0.0	4.2	48.6	88.9	97.2
	2007	72.2	26.4	9.7	31.9	2.8	0.0	0.0	30.6	54.2	47.2
GUA	2003	58.3	0.0	47.9	17.7	0.0	0.0	0.0	60.4	56.3	97.9
	2005	95.2	0.0	45.2	51.2	19.0	0.0	0.0	67.9	54.8	100.0
	2007	86.7	0.0	20.8	30.8	7.5	0.0	0.8	22.5	64.2	58.3
SRR	2003	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	2005	91.7	66.7	37.5	0.0	0.0	0.0	12.5	12.5	58.3	87.5
PAT	2005	87.5	0.0	4.2	0.0	12.5	0.0	0.0	62.5	20.8	95.8
ARA	2005	83.3	91.7	8.3	0.0	16.7	0.0	0.0	8.3	95.8	100.0

Algal diversity is expected to change seasonally, which can confound comparisons of results among MARAMP survey periods that occurred during different times of year (MARAMP 2003 and 2005 occurred during the fall, but MARAMP 2007 occurred during the spring). For example, the red algal genus *Schizymenia* was only recorded in 2007 and not in 2003 or 2005 (Appendix B). Whether this difference was caused by seasonal preferences for the macroscopic phase of this alga or an actual permanent increase in population density cannot be determined from the data collected. The majority of algal genera encountered did not appear to show seasonal preferences, and estimates of their occurrence remained relatively static throughout the 3 MARAMP survey years presented in this report.

Occurrence, measured as the percentage of photoquadrats in which an algal genus was recorded, was compared among islands and years for select algal genera and functional groups to provide an idea of whether composition of common algal components differed spatially or temporally across the Mariana Archipelago (Fig. 3.5.1d and Table 3.5.1b). Some genera, such as the calcified, sediment-producing, green alga *Halimeda*, were commonly found at all islands across this archipelago (see also Tribollet and Vroom 2007), although younger reef systems, such as the reefs found at Farallon de Pajaros, had a lower abundance of this genus than older reefs located toward the southern end of the Mariana Arc. Other genera, such as the green alga *Microdictyon*, were not recorded in photoquadrats at northern islands but occurred in relatively dense populations on southern islands and banks. In contrast, the brown algal genus *Lobophora* was common on reefs surrounding volcanic, northern islands but was uncommon on reefs at carbonate, southern islands (Table 3.5.1b).

Temporally, observations for some macroalgal genera, such as *Halimeda* and the red alga *Amphiroa*, did not show changes in occurrence from 2003 to 2007 (Table 3.5.1b). For other taxa, such as the red algal genera *Jania* and *Schizymenia*, changes in population density over time were observed. The genus *Jania* was relatively scarce in 2003 and became very abundant in 2005 and then slightly less common by 2007. The genus *Schizymenia* was not recorded at all until MARAMP 2007, when it became extremely abundant at 3 islands on the northern end of the Mariana Arc: Maug, Agrihan, and Alamagan (Table 3.5.1b).

Crustose coralline red algae and turf algae were ubiquitous across the Mariana Archipelago in each of the 3 MARAMP survey periods (Table 3.5.1b). This finding is not surprising, since both of these functional groups are known to play dominant roles in healthy reef ecosystems globally. Crustose coralline red algae are critical for cementing together loose rubble and consolidating reefs, and they serve as necessary settling surfaces for many invertebrate larvae. Turf algae are essential food sources for many marine herbivores. Cyanobacteria were typically less prevalent than other algal functional groups at northern islands; however, their abundance was greater at populated, southern islands during each of the 3 MARAMP survey years with percentages of occurrence comparable to the levels seen for turf algae and crustose coralline red algae (Table 3.5.1b)

3.5.2 Surveys for Coralline-algal Disease

During MARAMP 2007, coralline-algal diseases were recorded at 9 of the 13 islands surveyed, with no disease found at Sarigan, Alamagan, Agrihan, and Farallon de Pajaros (Fig. 3.5.2a). Correspondingly, disease conditions were observed at 25 (~ 38%) of the 66 REA sites surveyed, with Tinian alone containing more than 26% of all cases enumerated in 2007. The northern islands as a group accounted for only 13% of cases documented. Records for all sites combined yielded an archipelago-wide mean density of 0.9 cases 100 m^{-2} (SE 0.3), with values ranging from a minimum of 0.3 cases 100 m^{-2} at several sites at the populated, southern islands of Tinian, Saipan, and Rota to a maximum of 15.4 cases 100 m^{-2} at a north-facing site off the coast of Aguijan. Excluding Aguijan, where only one site was surveyed, the highest overall observed mean density of coralline-algal disease was found at Tinian with 2.8 cases 100 m^{-2} (SE 1.5), followed by Guam with 1.6 cases 100 m^{-2} (SE 0.8), Rota with 0.8 cases 100 m^{-2} (SE 0.4), Saipan with 0.7 cases 100 m^{-2} (SE 0.3), and Maug with 0.4 cases 100 m^{-2} (SE 0.3). Overall means were < 0.1 cases 100 m^{-2} for each of the other 3 islands that contained coralline-algal disease.

Three broad disease categories were recorded during MARAMP 2007: coralline lethal orange disease, coralline white band syndrome, and coralline cyanobacterial disease. Although prior field surveys (Starmer et al. 2008; T.J. Goreau, Global Coral Reef Alliance, pers. comm.) have identified the presence of coralline-algal disease in this region, the results from MARAMP 2007 represent the first attempt to quantitatively evaluate the occurrence of these diseases in the Mariana Archipelago. In this context, patterns of disease distribution and abundance indicate that some disease states were common and widespread and others were uncommon and rare. Of the 124 coralline-algal disease cases enumerated in 2007, more than 87% were cases of coralline lethal orange disease, followed by coralline white band syndrome (12%), and coralline cyanobacterial disease (~ 1%). Coralline lethal orange disease was not only the most widespread coralline-algal disease

but also the only disease condition identified at 4 of the 9 islands containing disease: Guam, Rota, Aguijan, and Maug. Conditions of coralline white band syndrome were enumerated at both Saipan and Tinian, with Tinian containing 93% of all cases of this syndrome. Lastly, only one case of coralline cyanobacterial disease, at Saipan between Puntans Halaihai and Laolao Kattan in the east region, was detected during disease surveys in this archipelago.

Although archipelago-wide mean density of coralline-algal diseases was low with 0.9 cases 100 m^{-2} (SE 0.3), elevated site-specific densities occurred at Aguijan with 15.4 cases 100 m^{-2}, Tinian with 8.3 cases 100 m^{-2}, and Guam with 8 cases 100 m^{-2}. These findings suggest that these areas offer biological and environmental conditions that may favor the proliferation of coralline-algal disease. Rapidly declining populations of coralline algae in many tropical reefs are the result of not only reduced water quality and sedimentation (Fabricius and De'ath 2001; Mallela 2007) but also increased levels of disease (Littler and Littler 1995; Goreau et al. 1998). As such, given the critical importance of coralline algae to coral reef formation, continued assessment and monitoring surveys will allow a better understanding of regional disease and enable the development of mitigation and management strategies.

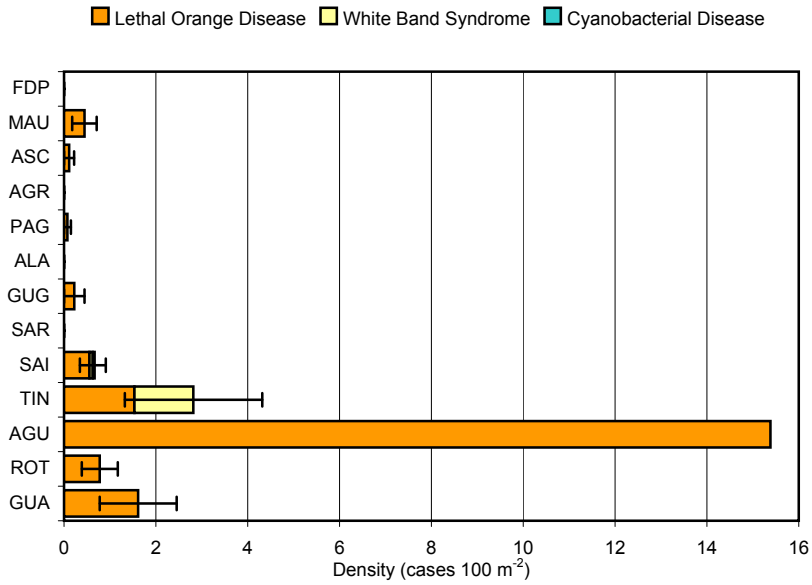


Figure 3.5.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007. Error bars indicate standard error (± 1 SE) of the mean.

3.6 Benthic Macroinvertebrates

3.6.1 Density Distribution: Giant Clams, Sea Urchins, and Sea Cucumbers

Based on towed-diver benthic surveys of forereef habitats averaged over the 3 MARAMP survey years, the archipelago-wide spatial patterns for density of giant clams suggest that densities generally were higher in the northern islands of the Mariana Archipelago than in the populated, southern islands (Fig. 3.6.1a). Maug had the greatest density of giant clams with 0.405 organisms 100 m^{-2} (SE 0.059), and the next highest estimate recorded at an island was 0.107 organisms 100 m^{-2} (SE 0.023) at Guguan. Anatahan had the lowest density of giant clams in this archipelago with 0.004 organisms 100 m^{-2} (SE 0.002). However, this result is not remarkable, given the extremely low visibility caused by volcanic ash in the water form eruptions of Anatahan Volcano that started in 2003 and continued through 2008. Of the surveyed offshore banks and remote reefs, Arakane and Pathfinder Reefs had the greatest densities of giant clams with 0.092 organisms 100 m^{-2} (SE 0.012) and 0.073 organisms 100 m^{-2} (SE 0.01). Among the 5 southern islands that were surveyed, uninhabited Aguijan had the greatest density of clams with 0.053 organisms 100 m^{-2} (SE 0.008). Densities at the remaining southern islands were low, relative to the rest of the Mariana Archipelago, with Guam having the lowest estimate of 0.006 organisms 100 m^{-2} (SE 0.001).

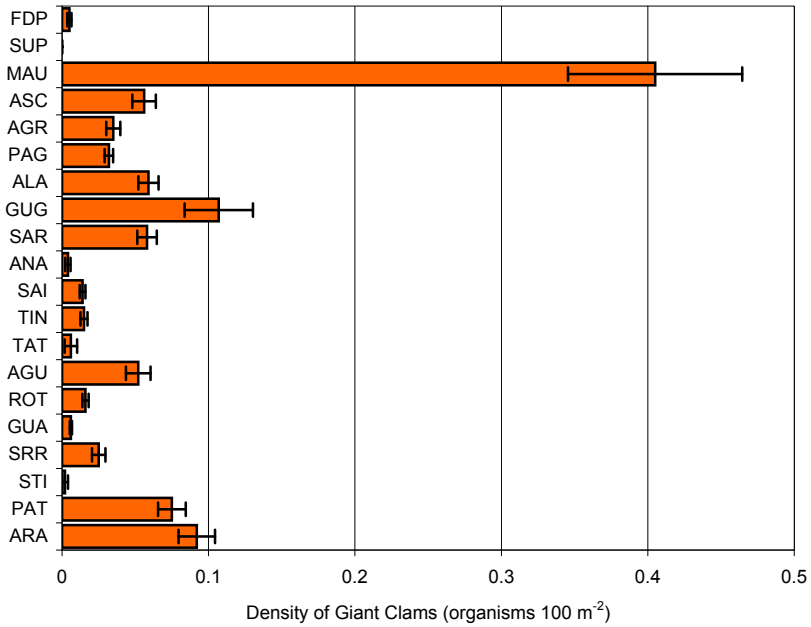


Figure 3.6.1a. Mean overall densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

In contrast to densities of giant clams, the archipelago-wide spatial patterns for sea urchins suggest that daytime densities were higher in the southern islands than in the northern islands and that the remote Pathfinder and Arakane Reefs had the greatest densities of sea urchins observed in the Marina Archipelago (Fig. 3.6.1b) with 7.73 organisms 100 m^{-2} (SE 0.63) and 11.15 organisms 100 m^{-2} (SE 0.1). Rota and Tinian had the next highest densities of sea urchins with 5.39 organisms 100 m^{-2} (SE 0.48) and 4.54 organisms 100 m^{-2} (SE 0.63). Guam had the lowest density of sea urchins among the southern islands with 0.79 organisms 100 m^{-2} (SE 0.09). Compared to the densities recorded at the southern islands, excluding Guam, densities of sea urchins were low in the northern islands, except for at Maug and Pagan with 3.71 organisms 100 m^{-2} (SE 0.49) and 3.04 organisms 100 m^{-2} (SE 0.4).

Similar to the survey results for sea urchins, the southern islands of the Mariana Archipelago tended to have greater densities of sea cucumbers than did the northern islands (Fig. 3.6.1c), although Pagan had the highest daytime density of sea cucumbers in the Mariana Archipelago with 0.84 organisms 100 m^{-2} (SE 0.08). The surveyed remote reefs and offshore banks were nearly devoid of sea cucumbers with the exception of Tatsumi and Santa Rosa Reefs.

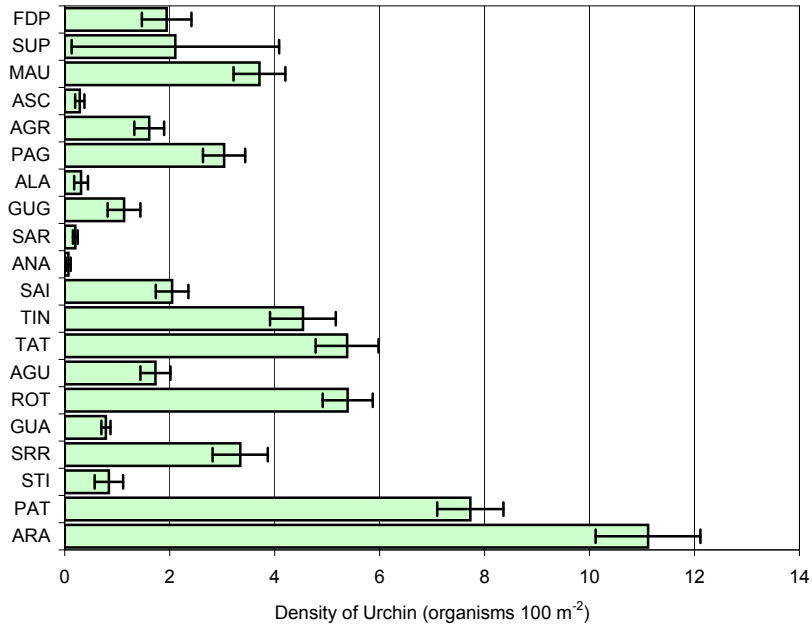


Figure 3.6.1b. Mean overall densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

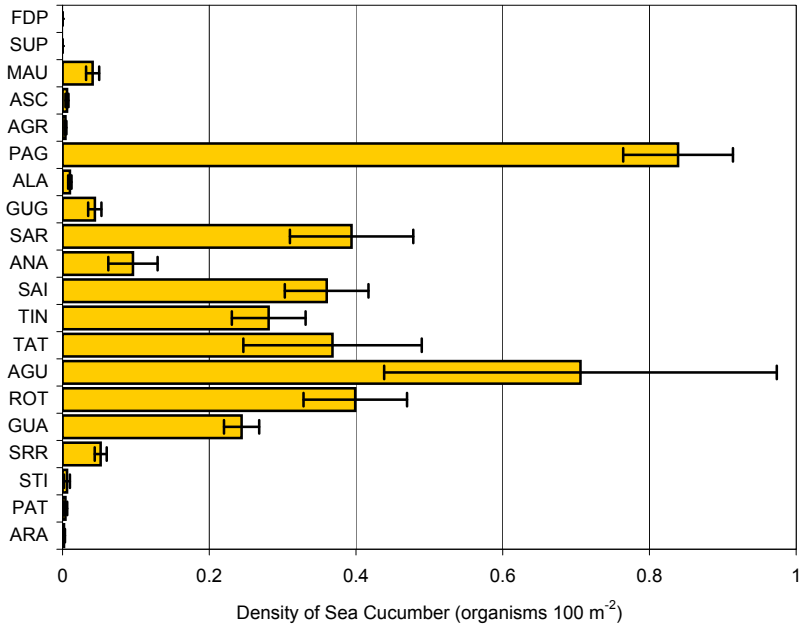


Figure 3.6.1c. Mean overall densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

3.6.2 Species Richness: Sea Cucumbers and Sea Urchins

The archipelago-wide spatial patterns for species richness of macroinvertebrates based on REA benthic surveys of forereef habitats combined for the 3 MARAMP survey years suggest that daytime species richness for sea cucumbers was higher in the southern islands (55 total surveyed sites) than in the northern islands (104 total surveyed sites), but no spatial pattern was observed for sea urchins (Fig. 3.6.2a). In the Mariana Archipelago, during the 3 survey periods, 15 species of sea cucumbers (Table 3.6.2a) and 11 species of sea urchins (Table 3.6.2b) were identified.

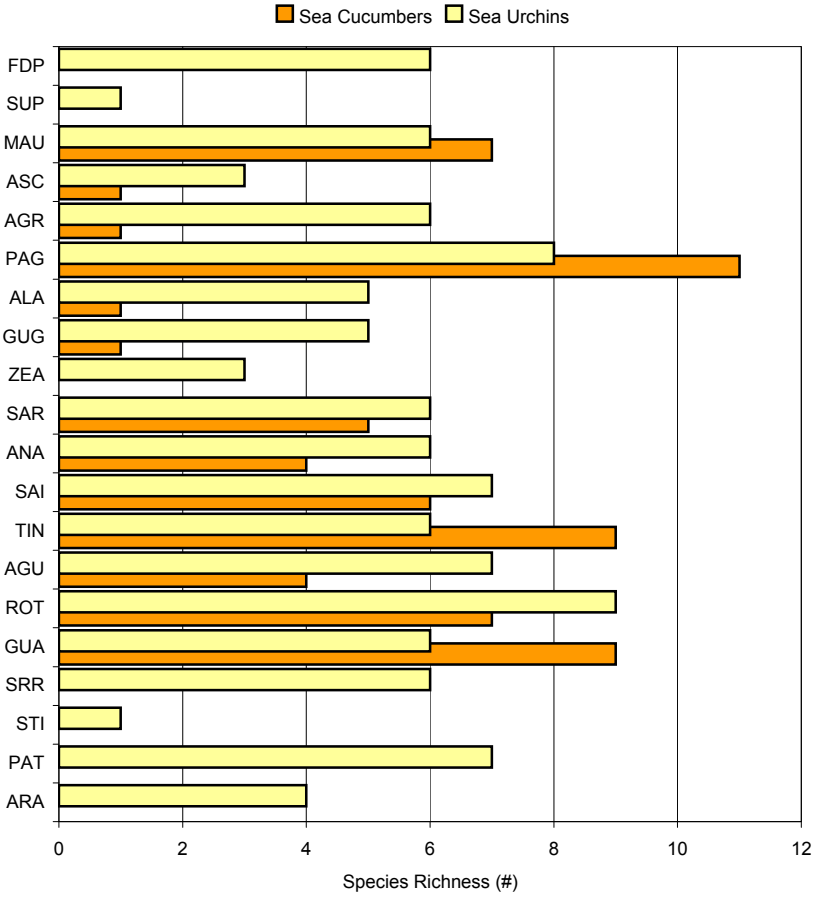


Figure 3.6.2a. Mean total species richness of sea cucumbers and sea urchins by island or bank from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

As noted in the previous section, densities of sea cucumbers also were higher in the southern islands than in the northern islands (Fig. 3.6.1c). Among the southern islands, Aguijan had the greatest overall mean density of sea cucumbers from towed-diver benthic surveys but the lowest number of species observed during REA surveys (Fig. 3.6.2a). Low richness at Aguijan was likely a reflection of survey effort considering that only 5 sites were surveyed there. Conversely, Guam had the lowest density of sea cucumbers from towed-diver surveys conducted at the southern islands, but this island was one of the most species rich from REA surveys. The high richness found at Guam relates to the level of survey effort (18 surveyed sites), which was greater there than at other southern islands. Pagan, which had the second-highest survey effort in the Mariana Archipelago with 24 sites surveyed over 3 years, had the greatest observed diversity of sea cucumbers with 11 species identified. Only 1 species was observed at each of 4 islands nearest to Pagan: Alamagan and Guguan to the south and Agrihan and Ascuncion to the north. Of the 15 species of sea cucumbers recorded (Table 3.6.2a), 2 species, *Thelenota ananas* and *Holothuria fuscopunctata*, were not observed in the northern islands, while 2 species, *Actinopyga palauensis* and *Bohadschia marmorata*, were not observed in the southern islands.

Species richness of sea urchins was distributed fairly evenly across the Mariana Archipelago (Fig. 3.6.2a). The highest daytime species richness of sea urchins was found at Rota with 9 species recorded, followed by Pagan with 8 species observed. Of the 11 species recorded archipelago-wide, *Colobocentrotus atratus* was not observed in the southern islands and *Tripneustes gratilla* was not observed in the northern islands.

Table 3.6.2a. Species of sea cucumbers recorded at each island from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Island	Species															
	Actinopyga echinites	*Actinopyga mauritiana*	*Actinopyga palauensis*	*Actinopyga sp.*	*Bohadschia argus*	*Bohadschia marmorata*	*Holothuria atra*	*Holothuria edulis*	*Holothuria fuscopunctata*	*Holothuria nobilis*	*Holothuria whitmaei*	*Pearsonothuria graeffei*	*Stichopus chloronotus*	*Stichopus horrens*	*Thelenota ananas*	Total
FDP																0
MAU		●		●	●		●	●				●	●			7
ASC											●					1
AGR		●														1
PAG	●	●	●		●	●	●			●	●	●	●	●		11
ALA		●														1
GUG		●														1
SAR		●								●	●	●	●			5
ANA		●			●		●						●			4
SAI		●			●		●	●					●	●		6
TIN		●		●			●	●	●	●		●	●		●	9
AGU		●			●		●						●			4
ROT		●			●		●				●	●	●		●	7
GUA	●			●	●		●	●			●		●	●	●	9

Island	Species											
	Colobocentrotus atratus	*Diadema savignyi*	*Diadema sp.*	*Echinometra mathaei*	*Echinometra sp.*	*Echinostrephus aciculatus*	*Echinostrephus molaris*	*Echinothrix calamaris*	*Echinothrix diadema*	*Heterocentrotus sp.*	*Tripneustes gratilla*	Total
FDP			●	●	●	●		●	●			6
SUP									●			1
MAU				●	●	●	●	●	●			6
ASC				●		●		●				3
AGR		●		●		●	●	●	●			6
PAG		●		●	●	●	●	●	●	●		8
ALA				●	●	●		●	●			5
GUG		●		●		●		●	●			5
ZEA						●		●	●			3
SAR	●	●		●		●		●	●			6
ANA		●		●		●	●	●	●			6
SAI		●	●	●	●	●		●	●			7
TIN		●	●	●	●	●			●			6
AGU				●		●		●	●	●	●	6
ROT		●	●	●	●	●	●	●	●	●		9
GUA		●		●		●		●	●			5
SRR		●		●		●		●	●			5
STI						●						1
PAT			●		●	●		●	●			5
ARA			●			●		●	●			4

Table 3.6.2b. Species of sea urchins recorded at each island or bank from REA benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

3.6.3 Density Distribution: Crown-of-thorns Seastars

Densities of crown-of-thorns seastars (*Acanthaster planci*) from towed-diver benthic surveys of forereef habitats varied among geographic regions in the Mariana Archipelago and among the 3 MARAMP survey years. To facilitate discussion and visual representation of densities of crown-of-thorns seastars (COTS), means from towed-diver surveys were combined to produce density values for each geographic region defined around each island or bank (Figs. 3.6.3a–d). Understanding whether or not these densities signify an outbreak is important, since these corallivorous seastars can decimate a reef. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure for MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms km^{-2} (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of COTS density and considering each geographic region as an individual reef area, localized areas undergoing an outbreak were found during each MARAMP survey year.

During MARAMP 2003, the northern islands of the Mariana Archipelago were virtually devoid of COTS, with the exception of a potential small, localized outbreak in the west caldera region at Maug (Fig. 3.6.3a[A and B]). Meanwhile, COTS were abundant at all southern islands with the exception of Tinian (Fig. 3.6.3a[C]). The west region of Rota had a localized outbreak. The western shoreline of Guam, southern coast of Rota, and southeast region of Saipan all had densities that nearly met the definition of an outbreak; populations in these regions possibly were either growing into a potential localized outbreak or declining from one.

Densities of COTS in the northern islands of the Mariana Archipelago were much higher in 2005 than in 2003 (Fig. 3.6.3b[A and B]), suggesting that a larval recruitment pulse occurred sometime between 2003 and 2005. Localized outbreaks, for example, were seen during MARAMP 2005 around much of Pagan (Fig. 3.6.3b[B]), where islandwide

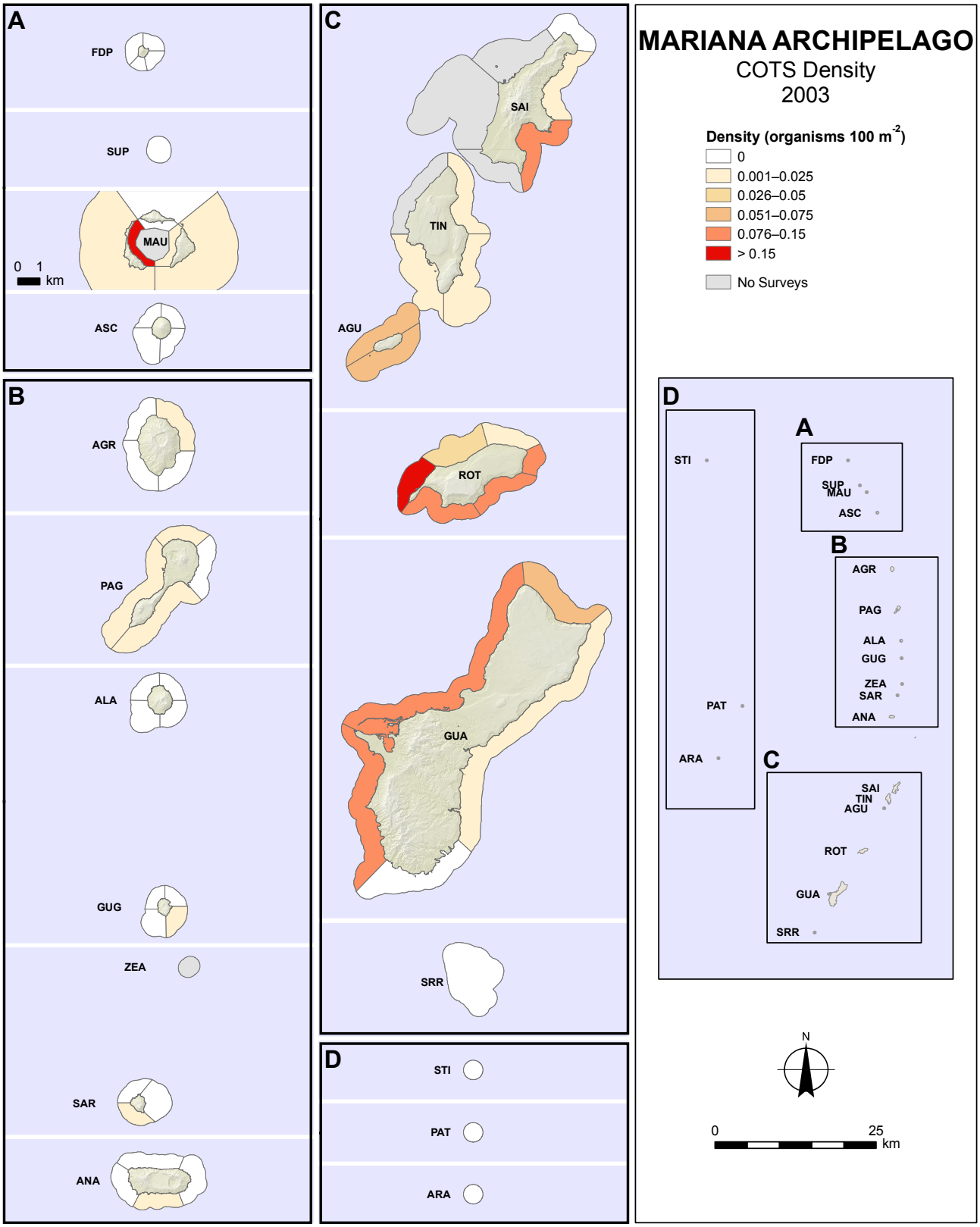


Figure 3.6.3a. Mean densities (organisms 100 m^{-2}) of COTS by geographic region from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003.

mean densities rose more than 100-fold from 0.002 organisms 100 m^{-2} (SE 0.001) in 2003 to 0.237 organisms 100 m^{-2} (SE 0.054) in 2005. Overall observed densities around Agrihan, Asuncion, and Guguan in 2003 were ≤ 0.01 organisms 100 m^{-2}; however, by 2005, islandwide mean densities for those islands had increased to 0.062 organisms 100 m^{-2}, (SE

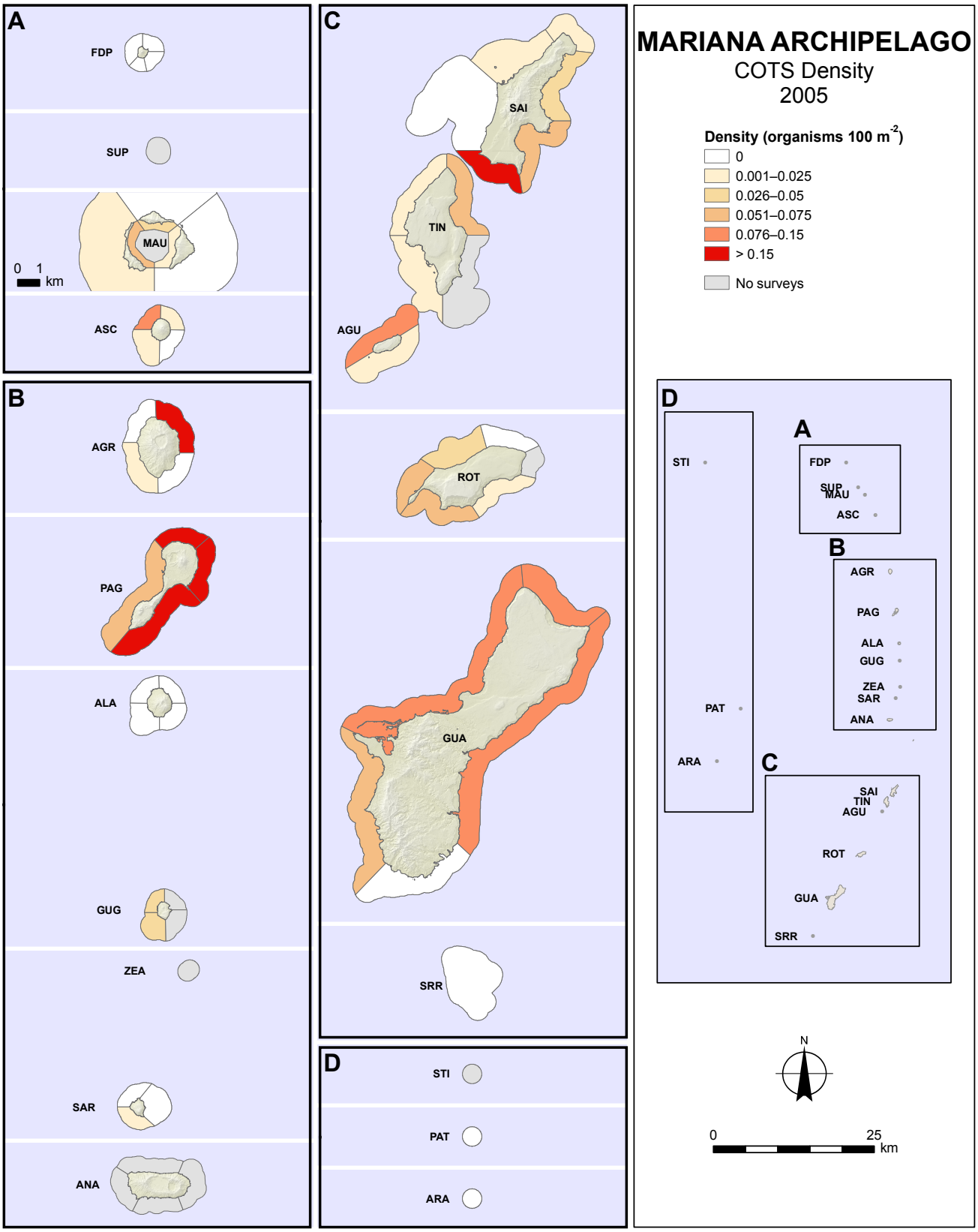


Figure 3.6.3b. Mean densities (organisms 100 m^{-2}) of COTS by geographic region from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2005.

0.028), 0.027 organisms 100 m^{-2} (SE 0.011), and 0.042 organisms 100 m^{-2} (SE 0.02). A decline in COTS populations between 2003 and 2005 was seen only at Maug, Sarigan, and Rota. At all the southern islands, except for Rota, most COTS populations remained relatively stable or increased slightly. Densities at Rota decreased nearly 3-fold from 0.106 organisms 100 m^{-2} (SE 0.014) to 0.037 organisms 100 m^{-2} (SE 0.006). Mean overall densities remained relatively stable at Agu-

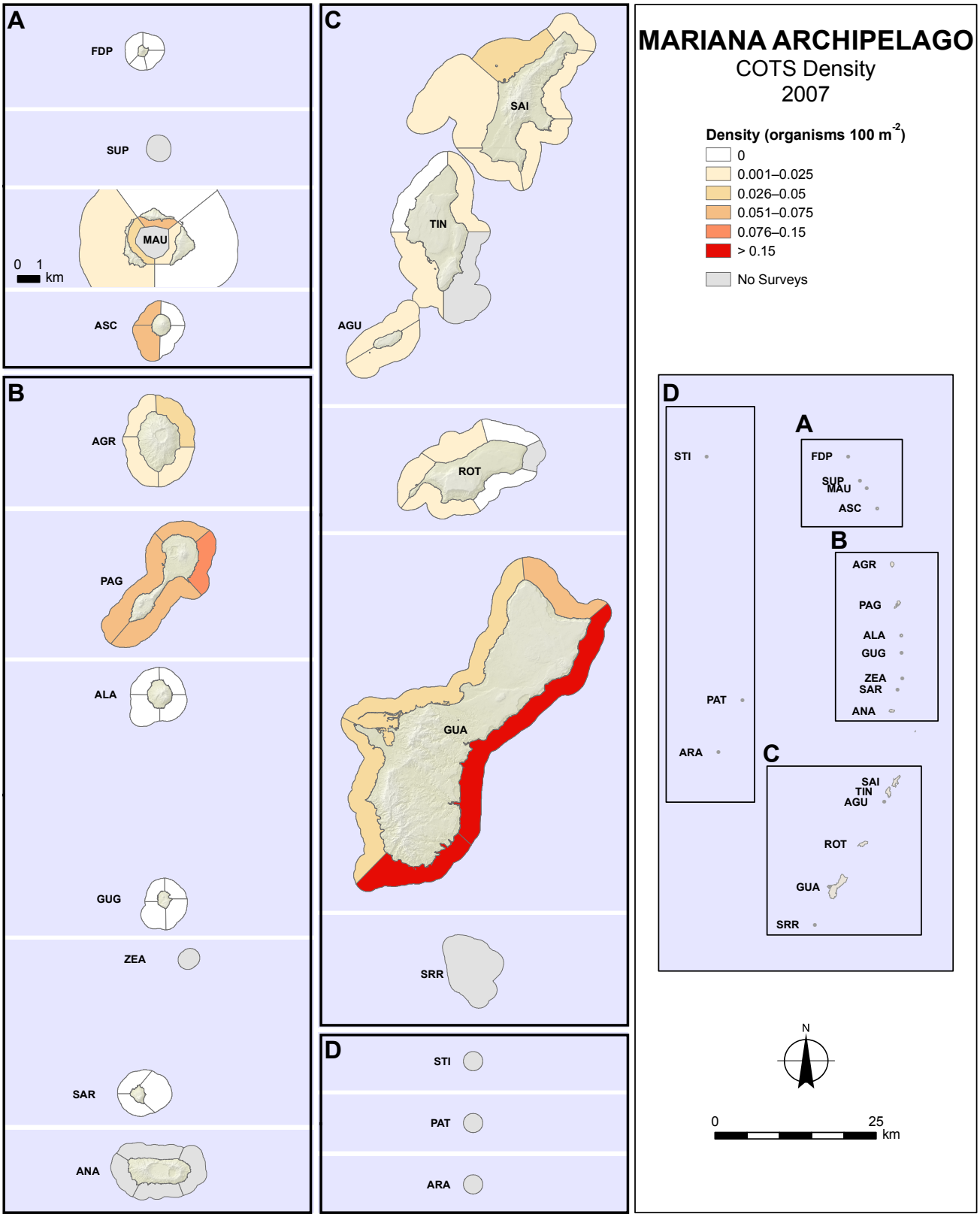


Figure 3.6.3c. Mean densities (organisms 100 m^{-2}) of COTS by geographic region from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2007.

jian and Tinan between 2003 and 2005, but concentrations shifted to different areas. At Saipan, overall mean densities increased slightly from 0.046 organisms 100 m^{-2} (SE 0.035) to 0.063 organisms 100 m^{-2} (SE 0.017), and localized outbreaks were recorded in this island's southeast region in 2003 and south region in 2005 (Fig. 3.6.3b[C]). COTS densities at Guam increased from 0.049 (SE 0.015) to 0.098 organisms 100 m^{-2} (SE 0.027), and the locations of greatest COTS concentrations shifted. In 2003, the highest densities at Guam occurred along the western shoreline, but, in 2005, the highest densities were found in the east region, followed by the northwestern and north regions. This change suggests that a recruitment pulse took place along the eastern shore of Guam sometime between 2003 and 2005.

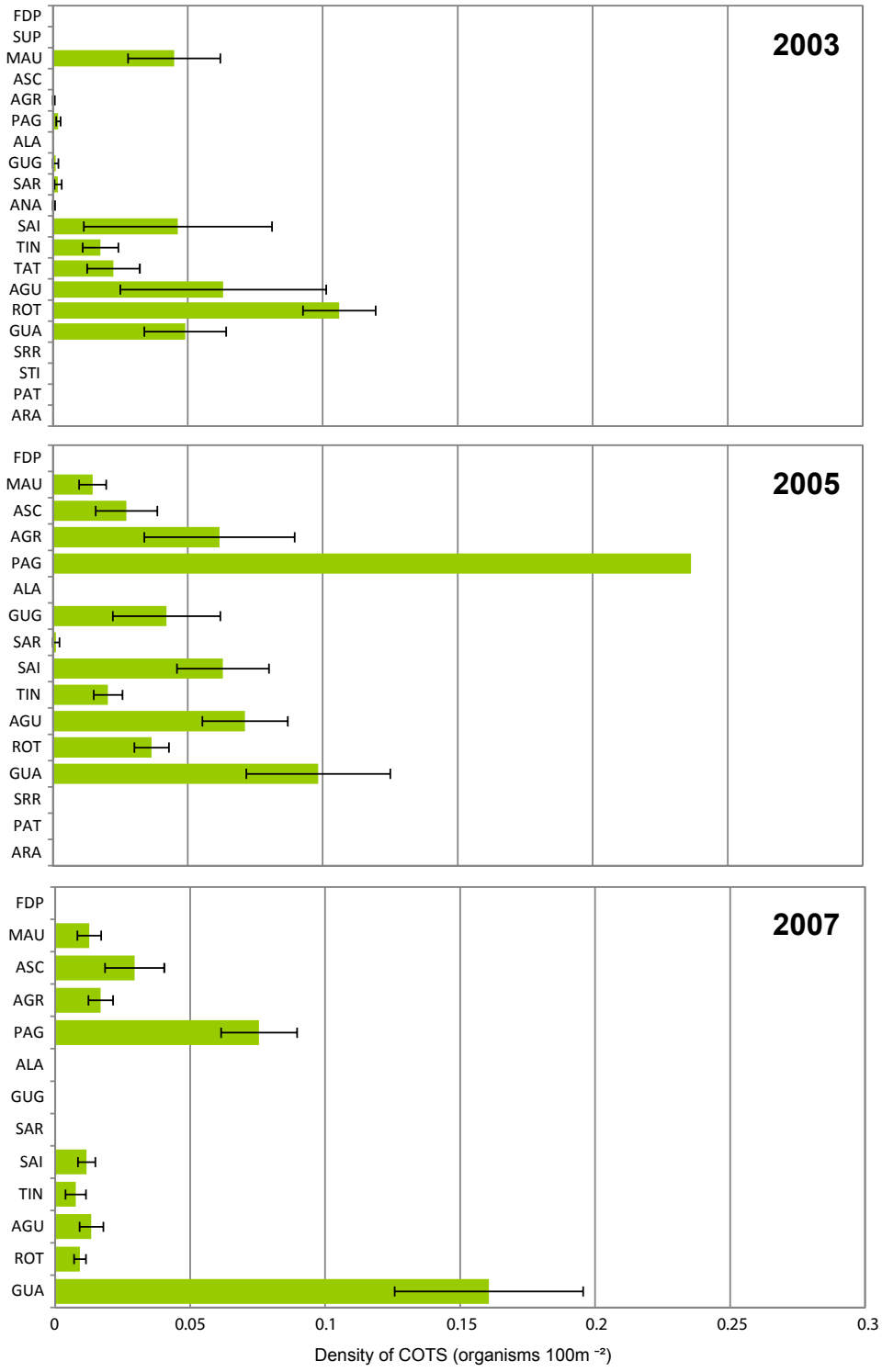


Figure 3.6.3d. Spatial and temporal comparison of mean densities (organisms 100 m^{-2}) of COTS from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate the standard error (± 1 SE) of the mean.

COTS densities recorded in the northern islands during towed-diver benthic surveys in the Mariana Archipelago were much lower in 2007 than in 2005 (Fig. 3.6.3c[A and B]). Densities observed around Pagan, Agrihan, and Guguan decreased 3-fold between MARAMP 2005 and 2007. Only around Asuncion was a slight increase (0.002 organisms 100 m^{-2}) in overall observed density recorded between 2005 and 2007. Likewise, COTS populations in the southern islands, except at Guam, decreased significantly by 2007 (Fig. 3.6.3c[C]). Densities increased by 60% around Guam from 0.098 organisms 100 m^{-2} (SE 0.027) in 2005 to 0.161 organisms 100 m^{-2} (SE 0.035) in 2007. Localized outbreaks were occurring along much of the eastern shoreline of Guam in 2007. This increase in density substantiates the idea that a recruitment pulse occurred along the eastern shore of this island sometime between 2003 and 2007. Since COTS densities naturally fluctuate with food availability and successful recruitment events (Birkeland and Lucas 1990; Fabricius et al. 2010; Yamaguchi 1987), the oscillation in this archipelago of population densities between the 3 MARAMP survey years is not extraordinary.

3.7 Reef Fishes

3.7.1 Reef Fish Surveys

Other than at Asuncion, where several reef sharks (Carcharhinidae) and large jacks (Carangidae) were seen in 2005 and 2007 but not in 2003, total fish biomass, calculated as weight per unit area, remained relatively stable in the Mariana Archipelago during the MARAMP survey period of 2003–2007. Annual means for the Mariana Archipelago, from REA fish surveys in forereef habitats, excluding Asuncion, ranged from 6.24 kg 100 m^{-2} to 8.17 kg 100 m^{-2}. Including Asuncion, annual means ranged from 7.38 kg 100 m^{-2} to 11.28 kg 100 m^{-2}. However, biomass levels differed greatly between sections of the Mariana Archipelago. Data from REA fish surveys suggest that the 9 northern islands, from Anatahan north to Farallon de Pajaros, as a group harbored more than 3 times the biomass of the 5 surveyed southern islands (Saipan, Tinian, Aguijan, Rota, and Guam), with total fish biomass of 12.00 kg 100 m^{-2} (SE 2.37) at northern islands and 3.63 kg 100 m^{-2} (SE 0.53) at southern islands (Fig. 3.7.1a). Observations from towed-diver surveys of large fishes (≥ 50 cm in total length [TL]) were dominated by piscivores, such as sharks and jacks. Results from these surveys of forereef habitats show a pattern similar to the one seen in data from REA surveys of fishes of all sizes with recorded biomass higher in the northern islands than in the southern islands (Fig. 3.7.1b): 0.92 kg 100 m^{-2} (SE 0.18) versus 0.22 kg 100 m^{-2} (SE 0.04). Similar broad patterns were seen in shark abundance from towed-divers surveys, with the number of sharks encountered per unit area surveyed 10 times higher in the northern islands, with 174.5 individuals km^{-2}, than in the southern islands, with 17.6 individuals km^{-2}.

Results from REA fish surveys suggest that biomass values for all trophic groups were higher in the northern islands than in the southern islands. These north–south differences, however, were greatest for piscivores, for which mean biomass around the northern islands, at 4.04 kg 100 m^{-2} (SE 1.22), was more than 13 times the mean biomass of 0.30 kg 100 m^{-2} (SE 0.03) around the southern islands. Overall, piscivores made up 34% of estimated biomass from REA fish surveys of northern islands but only 8% of biomass recorded at the southern islands. Fish assemblages at the southern islands were dominated by herbivores, which accounted for 54% of total biomass there (Fig. 3.7.1a). Still, biomass of herbivorous fishes, including

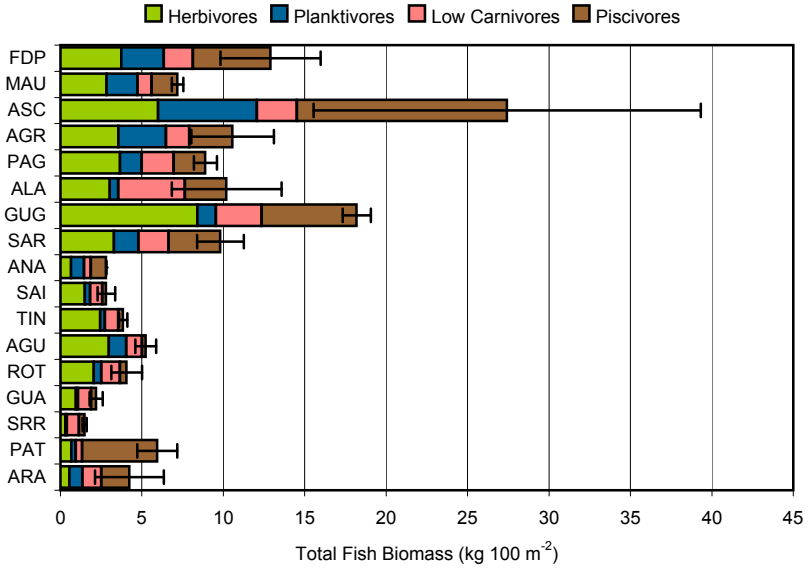


Figure 3.7.1a. Estimates of mean total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys conducted in forereef habitats during MARAMP 2003, 2005, and 2007. Biomass values were averaged for the 3 survey years and divided into 4 trophic groups. Error bars indicate standard error (± 1 SE) of the mean.

surgeonfishes (Acanthuridae) and parrotfishes (Scaridae), was twice as high at the northern islands than at the southern islands. These patterns in total biomass and trophic composition are consistent with those found along anthropogenic gradients in other archipelagoes in the central Pacific (Williams et al. 2011; Stevenson et al. 2007; Friedlander et al. 2008; Friedlander and DeMartini 2002). As noted above, overall mean total biomass was highly variable at Asuncion. The low number of surveys conducted there, at 3 REA sites per year, meant that estimated total biomass for this island was heavily influenced by isolated sightings like the 6 large (> 100 cm in TL) giant trevally (*Caranx ignobilis*) recorded at a single REA site in 2007.

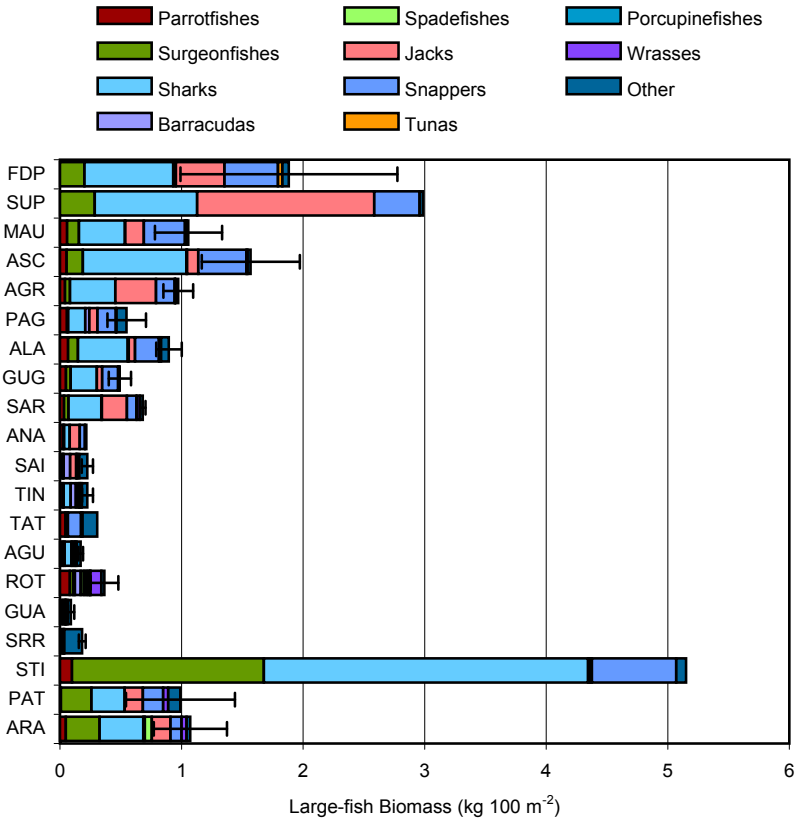


Figure 3.7.1b. Estimates of mean biomass (kg 100 m^{-2}) of large fishes (≥ 50 cm in total length) from towed-diver surveys of forereef habitats conducted during MARAMP 2003, 2005, and 2007. Large-fish biomass values were averaged for the 3 survey years and divided into 10 main family groups and an "Other" group. Error bars indicate standard error (± 1 SE) of the mean.

Summarized temporal trends (Fig. 3.7.1c) suggest relative stability in observed fish biomass in the southern islands of Guam, Rota, Saipan, Aguijan, and Tinian from both REA surveys of all fishes and from towed-diver surveys of large fishes. Estimated biomass at the northern islands, as a group, was more variable among years, with error bars much larger for the northern islands than for the southern islands, and relatively high variability among years. Both types of variability reflect-

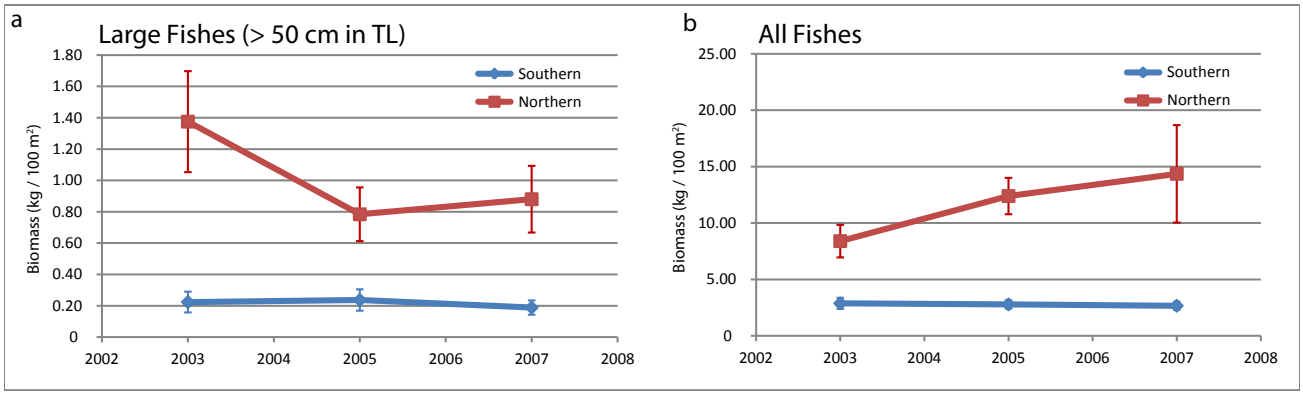


Figure 3.7.1c. Trends in fish biomass for (*a*) all fishes from REA surveys and (*b*) large fishes from towed-diver surveys at the northern islands and southern islands of the Mariana Archipelago. To increase comparability among regions and years, these graphs use only data from forereef habitats and from islands surveyed in each of MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

ed the effect of occasional estimates of very high biomass in some surveys of northern islands (e.g., where several sharks or other large predators were seen in a single survey). Nevertheless, trends through time for MARAMP 2003, 2005, and 2007 pooled at this scale suggest that biomass was consistently higher at the northern islands than at the southern islands in all survey periods for both REA and towed-diver surveys, with between 3.3 and 6.1 times the biomass of large fishes and 2.9 to 5.4 times the biomass of all fishes combined in the northern islands versus the southern islands, depending on the year.

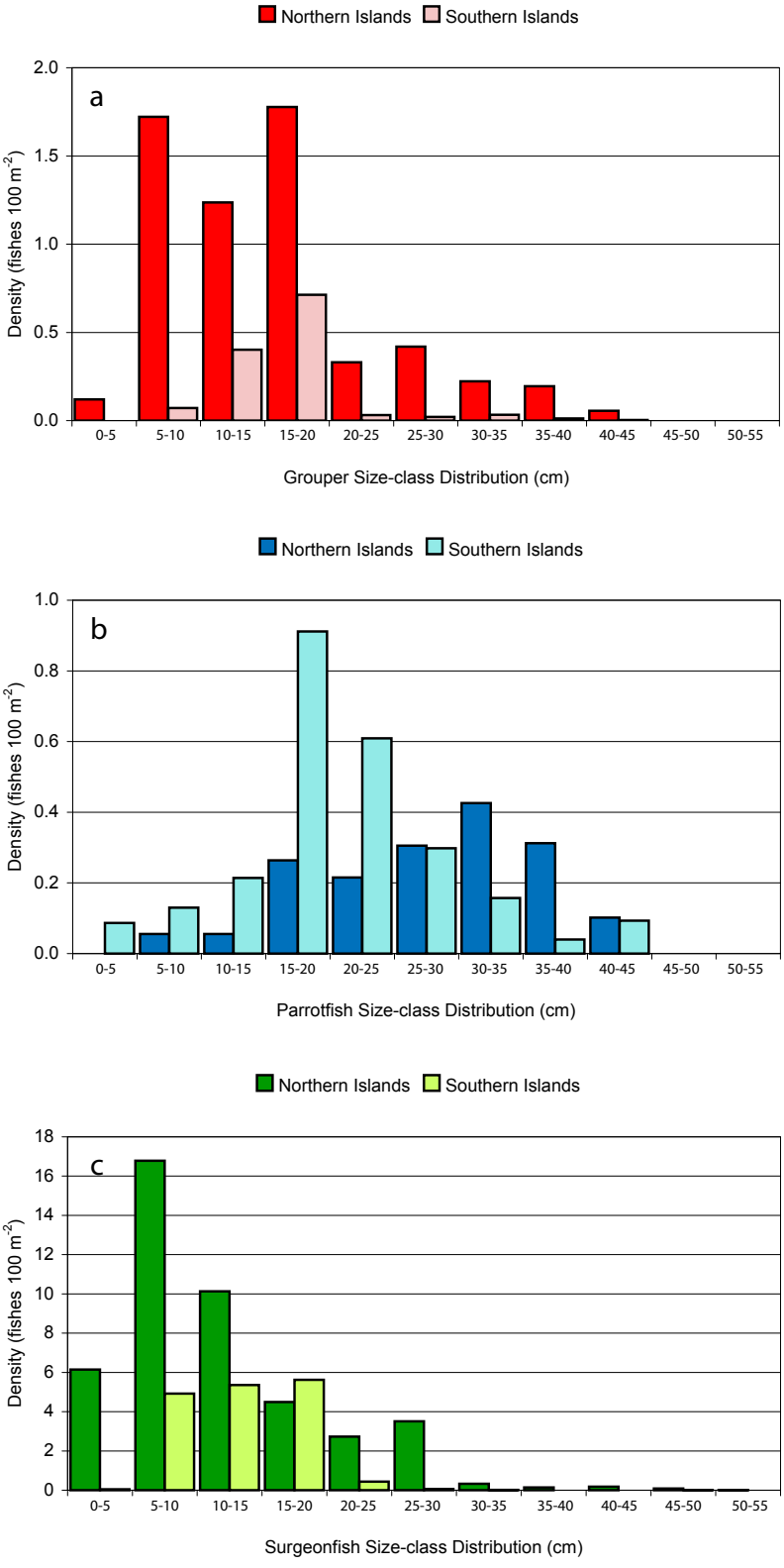


Figure 3.7.1d. Size-class distribution (TL in cm) for (*a*) groupers, (*b*) parrotfishes, and (*c*) surgeonfishes from REA fish surveys of forereef habitats conducted at the 9 northern islands (from Anatahan north through Farallon de Pajaros) and 5 surveyed southern islands (Guam, Rota, Aguijan, Tinian, and Saipan) of the Mariana Archipelago during MARAMP 2007.

Observations of size-class distribution for 3 families of fishes from REA surveys conducted in 2007 in the Mariana Archipelago show that densities of large size classes were higher in the northern islands than in the southern islands (Fig. 3.7.1d). Groupers (Serranidae) of all size classes were more abundant in the northern islands. Size classes of fishes > 30 cm in TL were commonly encountered in the northern islands but rare in the southern islands. Parrotfishes displayed more of a bimodal distribution with large individuals more common in the northern islands and small individuals more common in the southern islands. Although the surgeonfish community was dominated by small size classes, the overall range of fish sizes was greater in the northern islands, where densities were higher for all but the size class of 15–20 cm.

Species richness, measured as the number of fish species encountered per 100 square meters and averaged across MARAMP 2003, 2005, and 2007, was higher in the northern islands, excluding Anatahan, with 30.6–43.6 species 100 m^{-2} than around the southern islands with 20.2–30.0 species 100 m^{-2} (Fig. 3.7.1e). Mean richness was very low at Anatahan in 2003, the one year that it was surveyed, with mean richness of 14.1 species 100m^{-2}, which may have been a consequence of low visibility caused by high amounts of ash and debris in the water from a recent volcanic eruption. The species diversity of fishes on Arakane Reef and Pathfinder Reef of the West Mariana Ridge and on Santa Rosa Reef south of Guam was rather low by archipelagic standards with mean richness of 23.5, 24.1, and 13.9 species 100 m^{-2} (Fig. 3.7.1e).

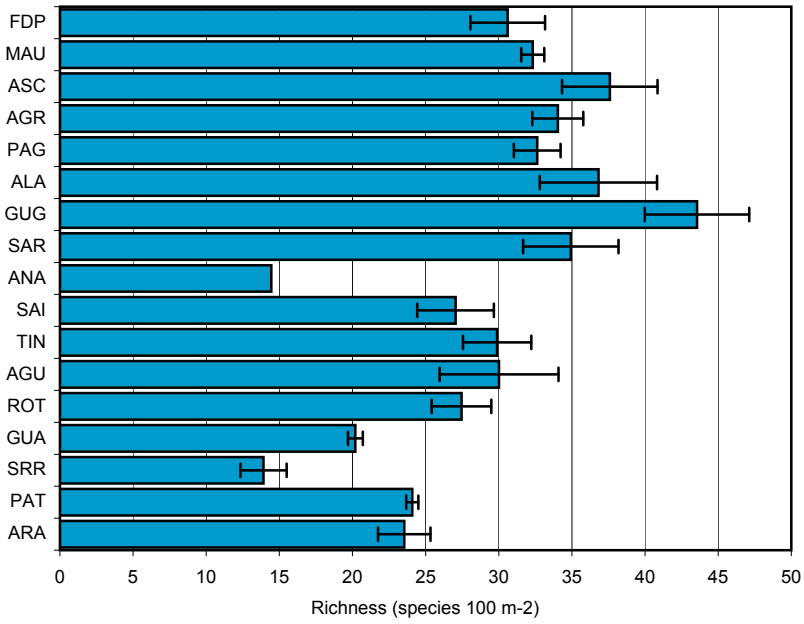


Figure 3.7.1e. Mean fish species richness (species 100 m^{-2}) from REA fish surveys conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

3.8 Species of Concern

Efforts to determine the status of species of concern—rare large fishes and sea turtles—in the Mariana Archipelago were made using data from towed-diver surveys of forereef habitats conducted during MARAMP 2003, 2005, and 2007. This section discusses the total mean abundance, measured as the number of individuals per square kilometer, of rare large fishes (≥ 50 cm in TL), and sighting frequency, measured as the number of individuals per kilometer, of sea turtles observed during MARAMP 2003, 2005, and 2007 (Tables 3.8a and b). All species identified are listed under the International Union for Conservation of Nature (IUCN) Red List with the grey reef shark (*Carcharhinus amblyrhynchos*), blacktip reef shark (*C. melanopterus*), and whitetip reef shark (*Triaenodon obesus*) listed as near threatened, the tawny nurse shark (*Nebrius ferrugenius*) and bumphead parrotfish (*Bolbometopon muricatum*) listed as vulnerable, the humphead wrasse (*Cheilinus undulatus*) and green sea turtle (*Chelonia mydas*) listed as endangered, and the hawksbill turtle (*Eretmochelys imbricata*) listed as critically endangered under the IUCN Red List Categories (Smale 2005a; Heupel 2005;. Smale 2005b; Pillans 2003; Chan et al. 2007; Russell 2004; Seminoff 2004; Mortimer and Donnelly 2008).

Based on averages from towed-diver surveys conducted during the 3 MARAMP survey periods, the abundance of reef sharks (Carcharhinidae) was highest at Stingray Shoal and generally higher at the islands from Alamagan north and at Supply and Pathfinder Reefs than at other areas in the Mariana Archipelago (Table 3.8a). Excluding locations that were sampled with fewer than 10 towed-diver surveys in total, the highest densities of reef sharks were observed at the more

northerly islands. Farallon de Pajaros, Maug, Asuncion, Agrihan, and Alamagan all had reef shark densities > 200 individuals km^{-2}. In contrast, all islands from Sarigan south to Guam had densities < 50 individuals km^{-2}. Similarly, nurse sharks (Ginglymostomatidae) were relatively abundant at the northernmost islands, from Sarigan north to Farallon de Pajaros, where mean abundance of tawny nurse sharks ranged from 9.5 individuals km^{-2} (SE 2.4) to 39.7 individuals km^{-2} (SE 23.7). Nurse sharks were rarely encountered around the southern islands, among which the greatest mean density of 1.6 individuals km^{-2} (SE 1.6) was recorded at Tinian.

In contrast to the patterns for sharks, humphead wrasse were most frequently encountered during towed-diver surveys conducted in the southern islands, with the highest mean density of 39.5 individuals km^{-2} (SE 9.1) recorded at Rota. Only one humphead wrasse was observed north of Alamagan during the 3 MARAMP survey periods, at Agrihan in 2003, strongly indicating that its abundance was very low in the northern part of this archipelago.

In total, only 2 bumphead parrotfish were observed during the 3 survey periods, both of them at Pagan in 2003, so data are insufficient to draw meaningful conclusions about the distribution patterns of this species, other than that it appears to be rare at shallow depths throughout the Mariana Archipelago.

Sea turtles (Cheloniidae) were tallied by towed divers whenever they were observed during a survey (i.e., recorded sightings were not limited to the 10-m swath or width of a towed-diver-survey area). Thus, estimates of turtle abundance are given as the number of turtles observed per kilometer of distance covered during surveys. By that measure, sea turtles were most frequently encountered in the southern islands, particularly at Tinian and Saipan (Table 3.8b), where mean encounter rates were 1.69 individuals km^{-1} (SE 0.13) and 1.12 individuals km^{-1} (SE 0.24). The lowest turtle abundance values were found at the remote and offshore reefs where turtles were rarely encountered; none at all were seen during towed-diver surveys conducted at Stingray Shoal, Pathfinder Reef, Supply Reef, Tatsumi Reef, and Santa Rosa Reef, and one was observed at Arakane Reef in 2003. While turtles were present on some of the banks where they were not observed during towed-diver surveys (e.g., a single turtle was seen during an REA survey at Supply Reef in 2003), the combined results of towed-diver surveys from MARAMP 2003 and 2005 suggest low turtle densities on the offshore and remote banks of the Mariana Archipelago (for additional analysis of sea turtle data from MARAMP 2003, see Kolinski et al. 2005).

Table 3.8a. Total mean abundance, or number of individuals observed per square kilometer, of rare large-fish (≥ 50 cm in TL) species from towed-diver surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, 2007. Values in parentheses indicate standard error (± 1 SE) of the mean .

Island	Total Number of Surveys (all years)	Reef Sharks (Carcharhinidae)				Nurse Sharks (Ginglymostomatidae)	Wrasse (Labridae)	Parrotfishes (Scaridae)
		Gray reef shark (*Carcharhinus amblyrhynchos*)	Blacktip reef shark (*Carcharhinus melanopterus*)	Whitetip reef shark (*Triaenodon obesus*)	Total	Tawny nurse shark (*Nebrius ferrugineus*)	Humphead wrasse (*Cheilinus undulatus*)	Bumphead Parrotfish (*Bolbometopn muricatum*)
Farallon de Pajaros	16	114.4 (102.9)	0	140.5 (61.7)	254.9 (162.1)	39.7 (23.7)	0	0
Supply	1	304.6	0	203.1	507.7	0	0	0
Maug	36	167.2 (59.4)	0	97.4 (13.0)	264.7 (70.0)	9.5 (2.4)	0	0
Asuncion	16	295.3 (140.3)	39.0 (39.0)	60.0 (18.4)	394.4 (159.4)	32.2 (7.9)	0	0
Agrihan	23	138.0 (47.1)	4.5 (4.5)	59.6 (20.4)	202.0 (34.5)	19.0 (2.9)	1.5 (1.5)	0
Pagan	54	0	1.1 (1.1)	29.0 (4.1)	30.0 (4.6)	18.6 (6.4)	0	1.7 (1.7)
Alamagan	18	129.4 (17.1)	0	114.8 (45.2)	244.2 (56.0)	18.8 (12.1)	6.6 (6.6)	0
Guguan	14	41.6 (19.5)	3.2 (3.2)	55. 6 (2.1)	100.4 (17.6)	11.8 (7.5)	3.2 (3.2)	0
Sarigan	17	24.4 (24.4)	6.6 (6.6)	15.6 (3.7)	46.6 (18.4)	27.7 (9.8)	8.6 (4.7)	0
Anatahan	12	23.6	0	9.4	33.0	0	0	0
Saipan	39	5.6 (5.6)	1.9 (1.0)	0	7.6 (4.7)	0	6.7 (3.4)	0
Tinian	26	0	3.3 (3.3)	24.7 (10.7)	29.0 (13.2)	1.6 (1.6)	2.6 (2.6)	0
Tatsumi	2	0	0	0	0	0	0	0
Aguijan	13	0	26.1 (11.4)	10.6 (10.6)	36.7 (7.1)	0	0	0
Rota	33	0	5.4 (3.3)	5.5 (1.0)	10.9 (4.3)	0	39.5 (9.1)	0
Guam	62	0.7 (0.7)	2.0 (2.0)	2.1 (1.2)	4.8 (2.9)	1.3 (1.3)	5.5 (0.8)	0
Santa Rosa	6	0	0	0	0	0	0	0
Stingray	4	1312.6	0	121.2	1433.8	0	0	0
Pathfinder	7	93.8 (12.6)	0	138.1 (8.3)	231.9 (20.9)	0	8.1 (8.1)	0
Arakane	9	12.4 (3.0)	0	72.9 (35.3)	85.3 (38.4)	4.7 (4.7)	9.4 (9.4)	0

Island	Total Number of Surveys (all years)	Sea Turtles (Cheloniidae)
Farallon de Pajaros	16	0.20 (0.04)
Supply	1	0
Maug	36	0.30 (0.04)
Asuncion	16	0.25 (0.15)
Agrihan	23	0.33 (0.10)
Pagan	54	0.34 (0.02)
Alamagan	18	0.52 (0.27)
Guguan	14	0.40 (0.20)
Sarigan	17	0.54 (0.24)
Anatahan	12	0.61
Saipan	39	1.12 (0.24)
Tinian	26	1.69 (0.13)
Tatsumi	2	0
Aguijan	13	0.35 (0.07)
Rota	33	0.66 (0.24)
Guam	62	0.61 (0.11)
Santa Rosa	6	0
Stingray	4	0
Pathfinder	7	0
Arakane	9	0.05 (0.05)

Table 3.8b. Total mean sighting frequency, or number of individuals observed per kilometer, of sea turtles from towed-diver surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, 2007. Values in parentheses indicate standard error (± 1 SE) of the mean.

3.9 Marine Debris

3.9.1 Marine Debris Surveys

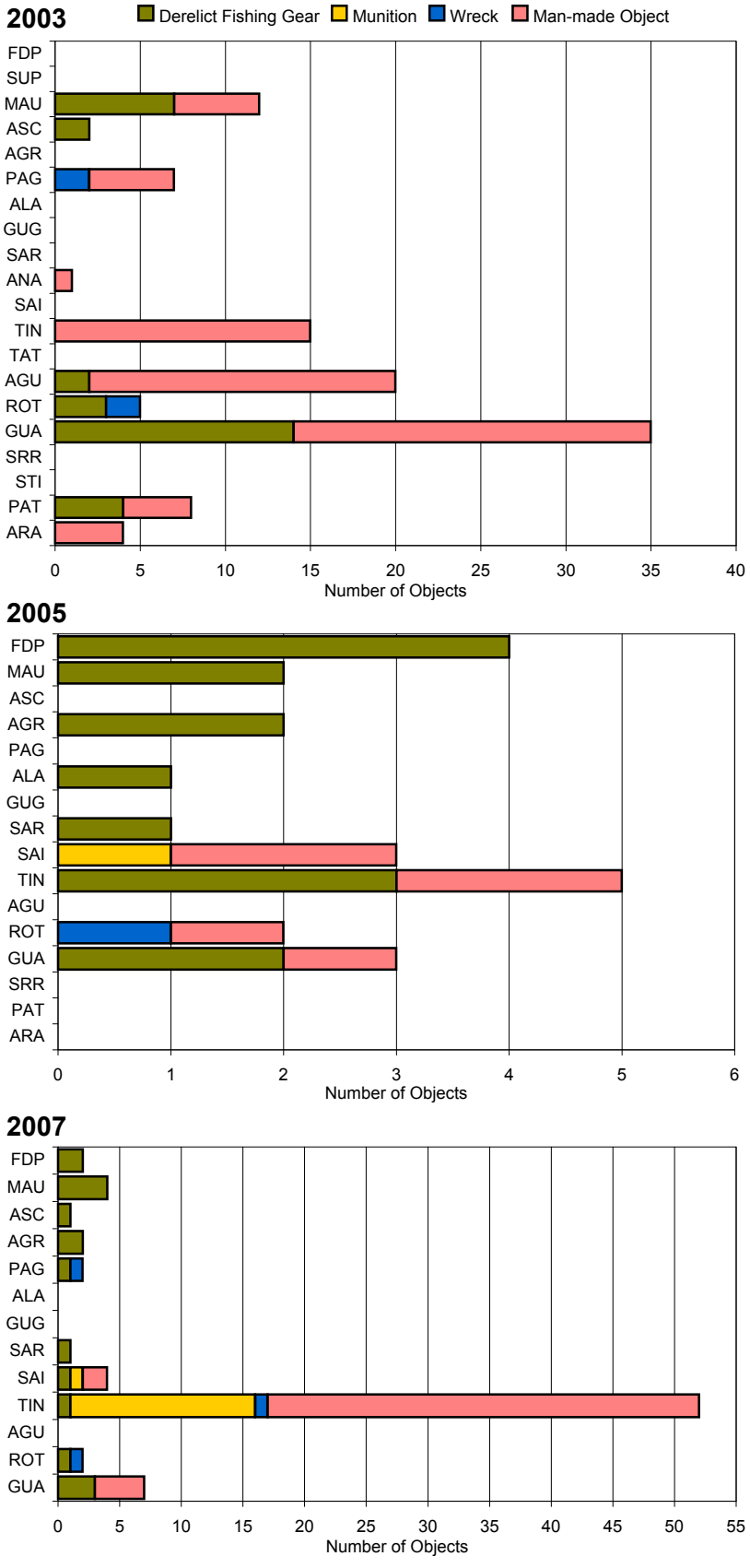
Temporal comparisons of qualitative observations of marine debris made across the Mariana Archipelago are limited because debris sightings were recorded differently among MARAMP survey years (for information about technique changes and data limitations, see Chapter 2: "Methods and Operational Background," Sections 2.4.2: "Overview of Towed-diver Surveys" and 2.4.10: "Marine Debris"). Nonetheless, several observations from spatial comparisons remain notable.

A broad, archipelagic pattern was evident from spatial comparison of MARAMP towed-diver surveys, namely that overall abundance of marine debris generally was greater at the southern, populated islands of the Mariana Archipelago than at the sparsely populated or unpopulated northern islands (Fig. 3.9.1a). The abundance of derelict fishing gear and other man-made objects, based on the mean number of sightings recorded during the 3 MARAMP survey periods, was higher at Guam and Tinian than at other islands in the Mariana Archipelago. However, looking at values for single survey years and only for derelict fishing gear, Maug had the second-highest abundance of derelict fishing gear in 2003 with 7 net sightings recorded and the highest abundance in 2007 with 4 net sightings documented, and Farallon de Pajaros had the greatest abundance of derelict fishing gear in 2005 with 4 net sightings recorded and the third-highest abundance in 2007 with 2 net sightings documented. The high numbers of sightings of derelict fishing gear at these northernmost islands despite their remote location, relative to survey results at other islands in this archipelago, could indicate a number of effects from oceanographic influences to unidentified fishing pressures.

Sightings of derelict fishing gear, generally around the Mariana Archipelago, were dominated by identifications of small nets, net fragments, or lines, with larger nets reported only occasionally (e.g., near Cocos Island off Guam). Other man-made objects encountered during towed-diver surveys consisted largely of anchors and associated ground tackle, discarded or abandoned mooring blocks, or metal scrap. Sightings of munitions were rare, with 1 sighting recorded at Saipan in both 2005 and 2007 and 1 sighting of 15 clustered munitions identified off the airport runway at Tinian in 2007. Shipwreck sightings also were rare, with 2 sightings each noted at both Pagan and Rota in 2003 and 1 sighting each recorded at Pagan, Rota, and Tinian in 2007.

Several sightings of marine debris remained consistent between 2005 and 2007. These observations included a munitions sighting off the northwestern shore of Saipan, a shipwreck sighting off the south coast of Rota, and a sighting of an apparent dump site at Tinian in the vicinity of Puntan Lamanibot Sanhilo. In both 2003 and 2007, a shipwreck was identified near Bandera Peninsula at Pagan.

Figure 3.9.1a. Spatial and temporal comparison of mean numbers of sightings of specific types of marine debris from towed-diver benthic surveys of forereef habitats conducted in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.



3.10 Ecosystem Integration

To compare the status of coral reef ecosystems across the Mariana Archipelago, CRED developed the *Archipelagic Coral Reef Condition Index*, a composite metric of biological variables from towed-diver surveys of forereef habitats conducted during MARAMP 2005 and 2007. Two other composite metrics make up this index: the *Archipelagic Benthic Condition Index* and *Archipelagic Fish Condition Index*. These indices integrate multiple components to describe benthic and reef-fish communities, either independently or together, and provide a simple means to evaluate the relative condition of different coral reef areas. The 5 benthic components are cover of live hard corals, cover of stressed corals, cover of macroalgae (both calcified and fleshy), cover of crustose coralline red algae, and density of COTS. The density and biomass of large fishes (≥ 50 cm in TL) are the 2 fish components. The ranks in these condition indices, for the purposes of discussion and visual representation, are grouped as high, medium, or low. A high rank means superior condition relative to other geographic regions in the Mariana Archipelago, typically characterized by high cover values of hard corals and crustose coralline red algae, high levels of fish density and biomass, and low values of stressed-coral cover, COTS density, and macroalgal cover (Fig. 3.10a). A low rank indicates that a geographic region, relative to estimates from others regions in this archipelago, have low values of coral cover, crustose-coralline-red-algal cover, and fish density and biomass and high levels of stressed-coral cover, COTS density, and macroalgal cover. Data from towed-diver surveys were rank-transformed and integrated into these weighted, additive indices (see Chapter 2:"Methods and Operational Background" for towed-diver-survey field techniques and details about condition index methods, and see Appendix D for the ranks of each biological component for each geographic region). Spatial patterns in benthic, fish, and overall coral reef index ranks are presented in this section in maps by geographic region for the Mariana Archipelago (Figs. 3.10b, c, and d).

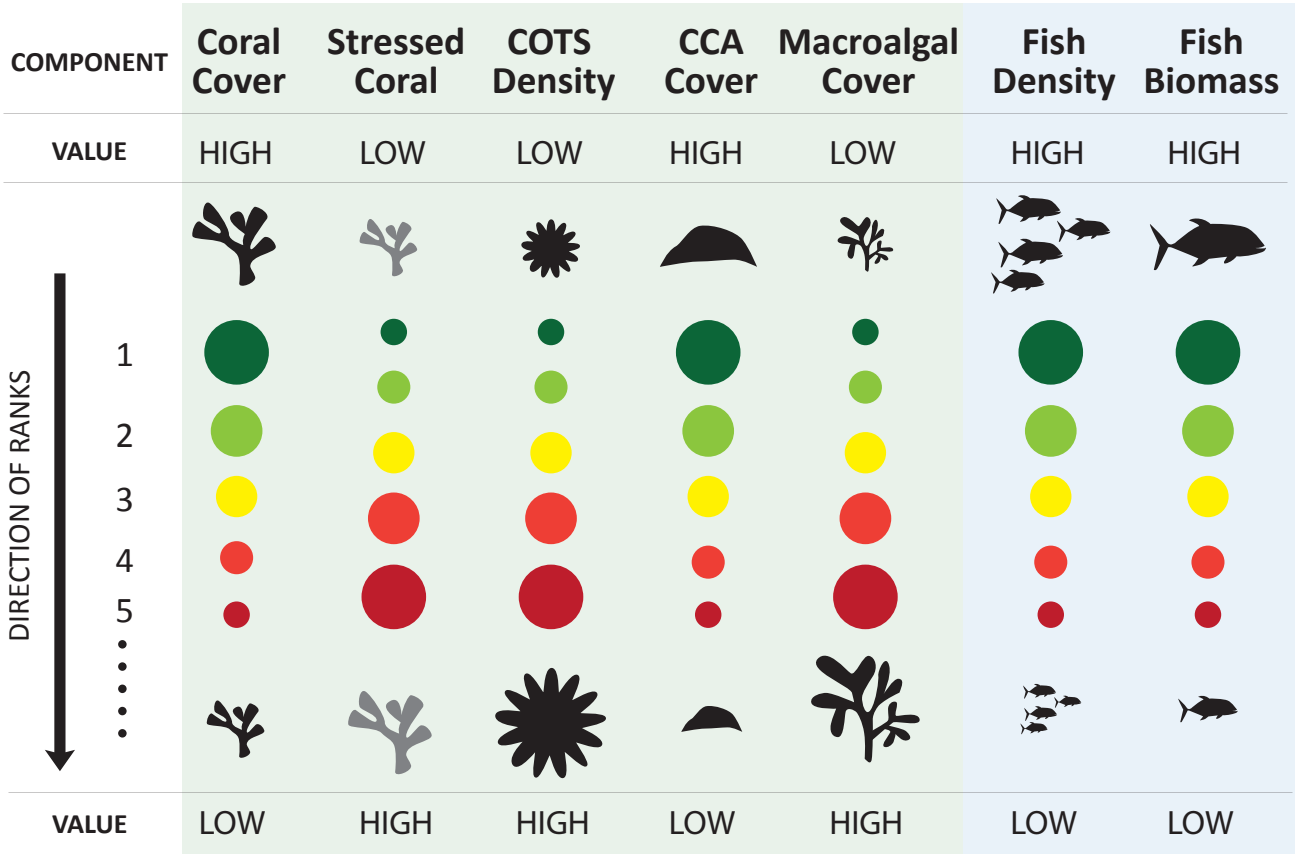


Figure 3.10a. Diagram showing the benthic and fish components and the directions of their ranks used in the Coral Reef Condition Index. CCA: crustose coralline red algae. High coral cover, for example indicated with a large green symbol, can result in a high rank.

The benthic conditions of geographic regions in the Mariana Archipelago in 2005 and 2007 generally decreased from the northernmost islands to the southern islands (Fig. 3.10b). The 2005 and 2007 ranks in the Archipelagic Benthic Condition Index indicate that the benthic conditions of forereefs around Maug, Alamagan, Sarigan, and Guguan were superior to the status of forereefs observed at other islands, a result of high or increasing levels of coral cover and low values of stressed-coral cover and COTS density. Although the benthic conditions of Asuncion and Farallon de Pajaros were also favorably ranked, certain geographic regions around these islands had lower index ranks for 2007 than for 2005 because of a decrease

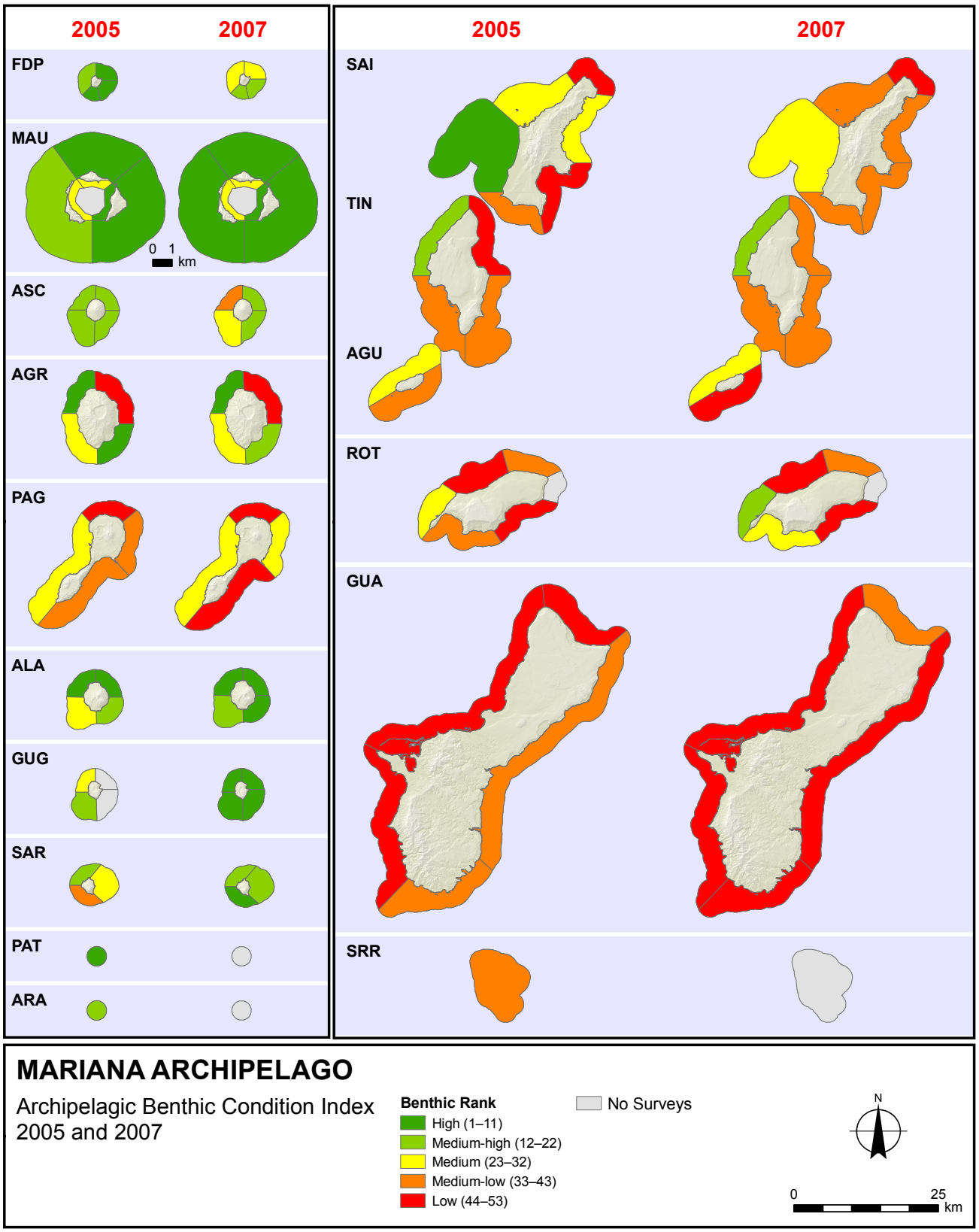


Figure 3.10b. The Archipelagic Benthic Condition Index for 2005 and 2007, based on towed-diver surveys of forereef habitats, reflects the status of the benthic communities for each geographic region, *relative to other regions across the Mariana Archipelago*. The red color, for example, indicates a geographic region, such as the northeast region of Tinian during MARAMP 2005, with high index ranks that typically result from high cover values of corals and crustose coralline red algae and high levels of COTS densities and stressed-coral and macroalgal cover.

in cover of corals and crustose coralline red algae. A similar pattern of variable trends in benthic conditions was observed at Pagan and Agrihan, where geographic regions with high COTS densities had declining ranks. The benthic conditions for the northwest regions of Agrihan and Alamagan were consistently superior with high ranks for both survey years.

At the southern islands of Saipan, Tinian, Aguijan, Rota, and Guam, similar or decreasing benthic conditions were observed in most reef areas surveyed, except for the southeast region of Saipan, northeast region of Tinian, the west side of Rota, and the north region of Guam. The lower benthic index ranks for these islands, compared to the status for the northern islands, reflect relatively high levels of stressed-coral cover and macroalgal cover and low levels of coral cover.

The Archipelagic Fish Condition Index (Fig. 3.10c) demonstrates a north–south pattern of decreasing ranks for geographic regions in the Mariana Archipelago similar to the one seen for 2005 and 2007 in the Archipelagic Benthic Condition Index. However, this index shows a more stable temporal trend between MARAMP survey years. Maug, Asuncion, and Alamagan consistently had the best-ranking large-fish conditions in the Mariana Archipelago in 2005 and 2007 (Ranks for Farallon de Pajaros were high only for 2007). Geographic regions of the other northern islands, Agrihan, Pagan, Guguan, and Sarigan, had a mix of medium ranks in the Fish Condition Index. The southern islands generally had inferior ranks or decreasing large-fish conditions, although 1–2 geographic regions improved in rank at Saipan, Tinian, and Rota.

The Archipelagic Coral Reef Condition Index for geographic regions of the Mariana Archipelago illustrates a general decrease in benthic and large-fish conditions from the northern islands to the southern islands (Fig. 3.10d). Maug, Farallon de Pajaros, Alamagan, and Asuncion had the highest ranks in the Archipelagic Coral Reef Condition Index, resulting from high levels of coral cover and large-fish density and biomass and from low levels of stressed-coral cover. Ranks for most of the geographic regions around Agrihan varied because of high COTS densities and decreasing values of coral cover, particularly in the northeast region. The regions of the southern islands of Guam, Rota, Aguijan, Tinian, and Saipan generally had low or decreasing coral reef conditions, relative to conditions observed in the regions of other islands, with the exceptions of the east region of Saipan, where the rank changed from low to high from 2005 to 2007, and the northwest and southeast regions of Tinian and the north region of Aguijan, each of which had ranks of medium for 2007. Habitat protection and limitations on resource use in marine protected areas on the east side of Saipan might be a factor in the enhanced coral reef conditions there.

The Archipelagic Coral Reef Condition Index and the associated benthic and fish indices (Figs. 3.10b–d) all illustrate striking differences in the conditions of benthic and fish communities: ranks in derived condition indices declined moving from the northern islands to the southern islands. These spatial patterns coincide with patterns in human population, island geology, and latitude. A temporal comparison of ranks in the Archipelagic Coral Reef Condition Index demonstrates the stability of the spatial trends between the 2 MARAMP survey periods: approximately two-thirds of the index ranks (high, medium, or low) were the same in 2005 and 2007. The other one-third of geographic regions, then, may have been areas of change identified by the shift in their index ranks between years.

It is important to note that because of differences in geomorphology, as well as in exposure to typhoons and other acute and impactful physical disturbances, it is likely that coral reef ecosystems differed naturally between the northern and southern islands. Differences in the mix of benthic characters observed at southern reefs do not necessarily imply that those reefs were degraded only because of human activities. The carbonate, southern islands, for example, may naturally experience conditions that promote higher macroalgal growth than the growth seen in the volcanic, northern islands.

In another temporal comparison, the ranges in values of the biological components used in the condition indices were generally consistent between MARAMP 2005 and 2007 for all geographic regions, with slight declines in the maximum values observed for coral cover, macroalgal cover, COTS density, stressed-coral cover, and large-fish density (Table 3.10a). In addition, the maximum observed values of crustose-coralline-red-algal cover and large-fish biomass increased slightly.

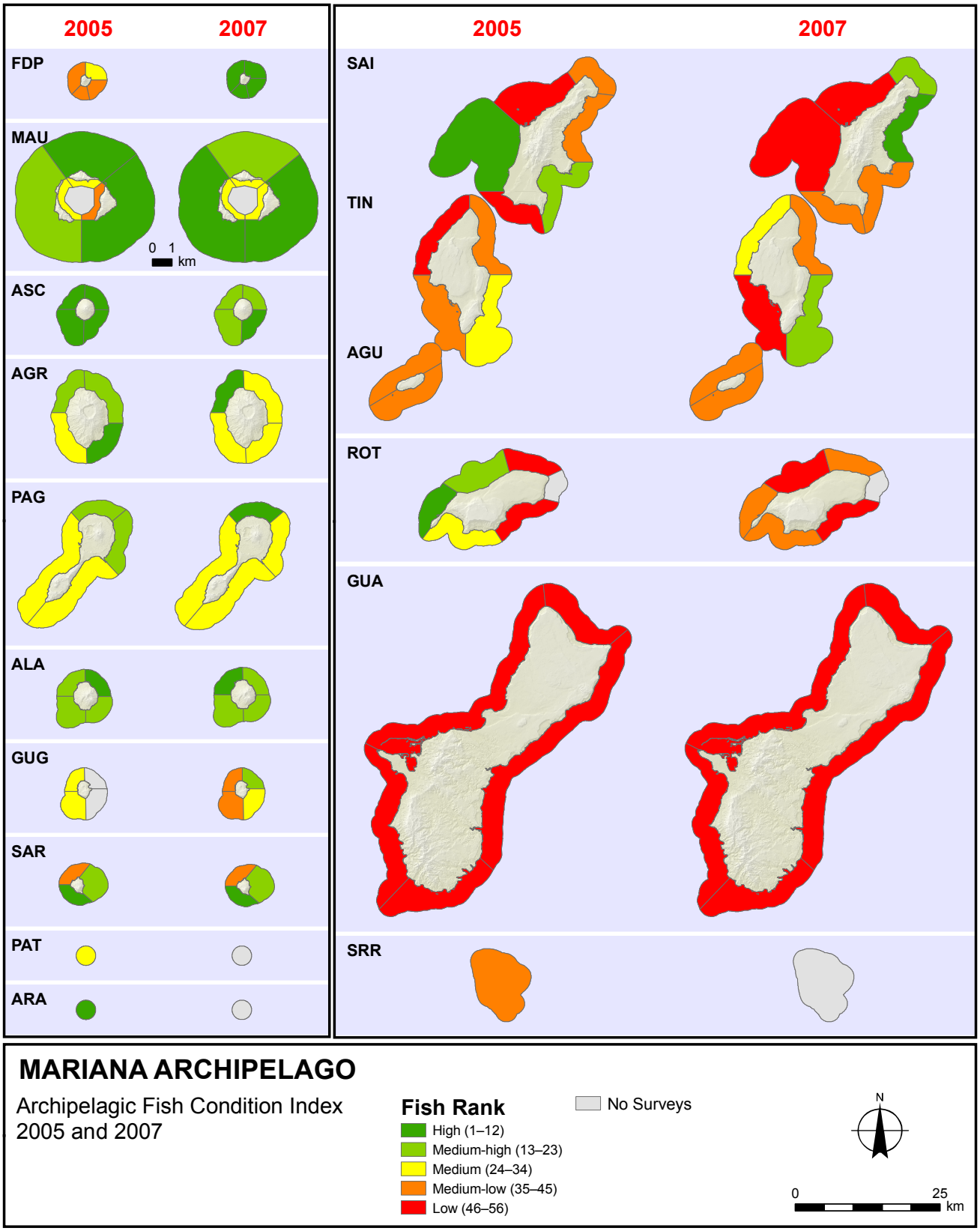


Figure 3.10c. The Archipelagic Fish Condition Index for 2005 and 2007, based on towed-diver surveys of forereef habitats, reflects the status of the benthic communities for each geographic region, *relative to other regions across the Mariana Archipelago*. The bright green color, for example, indicates geographic regions, such as the regions around Farallon de Pajaros during MARAMP 2007, with high index ranks that typically result from high fish density and biomass.

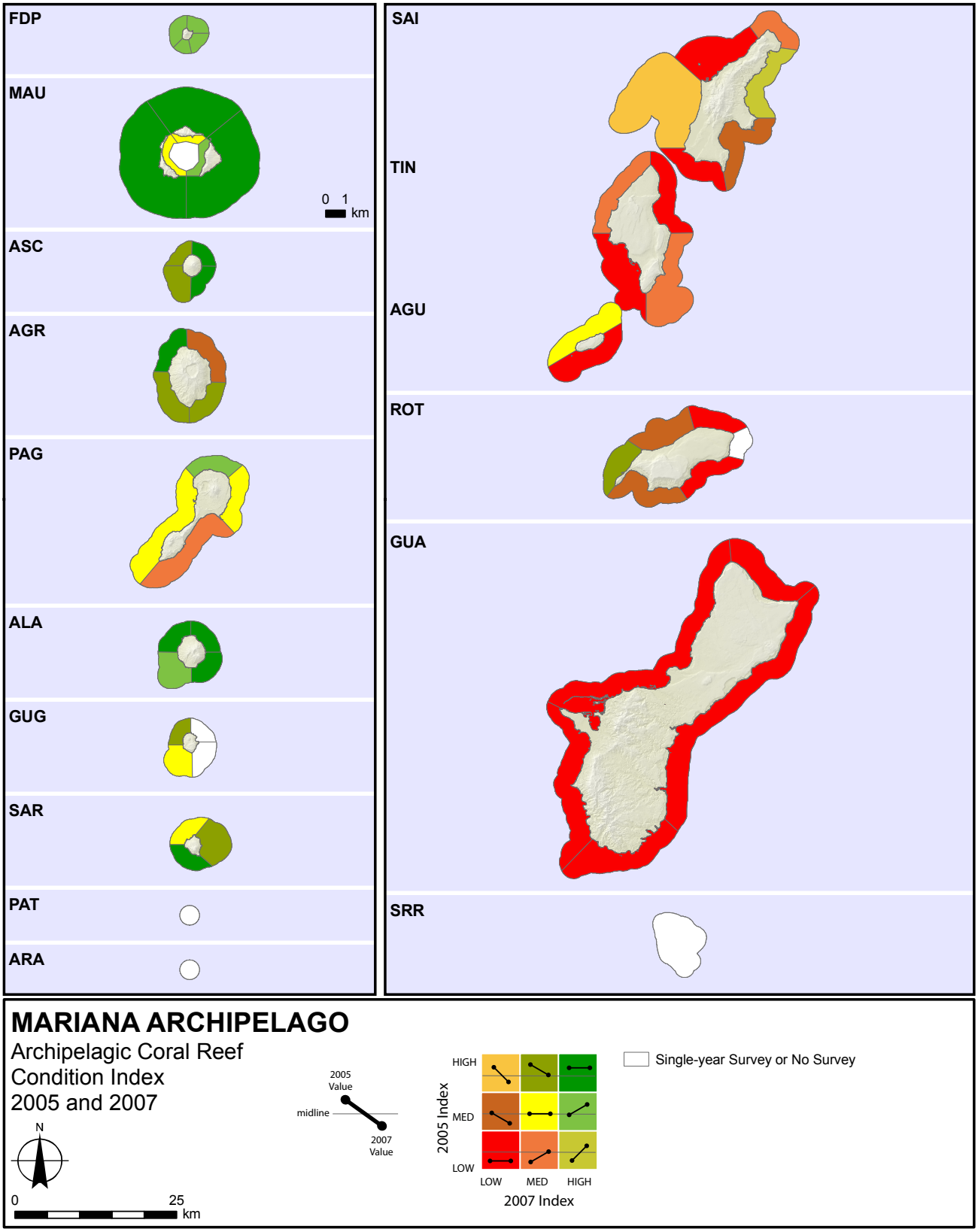


Figure 3.10d. The Archipelagic Coral Reef Condition Index, based on towed-diver surveys of forereef habitats conducted in 2005 and 2007, reflects the integrated condition of the benthic and fish communities for each geographic region, *relative to other regions across the Mariana Archipelago*. These maps indicate changes in index ranks between MARAMP 2005 and 2007 for each region. No index value is calculated for areas with only one year of survey data. A high rank means superior condition relative to other regions in this archipelago. The regions around Maug, for example, have high index ranks for both 2005 and 2007. Thus, they are all assigned the bright-green color that corresponds to the top-right square in the legend. The position of the horizontal bar above the midline in this square also reflects that those regions maintained a high rank in both years.

Table 3.10a. The ranges in mean values for geographic regions of the components used in the condition indices and measured during towed-diver surveys of forereef habitats in the Mariana Archipelago during MARAMP 2005 and 2007.

Year	Cover of Live Hard Corals (%)	Cover of Crustose Coralline Red Algae (%)	Cover of Stressed Corals (%)	Cover of Macroalgae (%)	Density of Crown-of-thorns Seastars (organisms 100 km^{-2})	Density of Large Fishes (individuals km^{-2})	Biomass of Large Fishes (kg 100 m^{-2})
2005	0.5–38	0.1–31.3	0–24.2	0.6–70.8	0–0.54	0.04–3.18	0.14–5.09
2007	0.8–31	0–34.2	0–14.4	1.5–60.1	0–0.34	0.04–1.42	0.19–4.69

3.11 Summary

Archipelagic comparisons of the biotic and abiotic constituents of coral reef ecosystems across the Mariana Archipelago revealed complex, north–south spatial patterns coupled with physical, oceanographic, environmental, and human dimensions. The islands of Guam, Rota, Tinian, and Saipan at the southern end of the Mariana Archipelago support more than 99% of the human population in this region. Consequently, urbanization on these islands has resulted in gradients of anthropogenic use and effects, including construction, deforestation, pollution, erosion, recreational use, and fishing.

The 5 southern islands and associated offshore banks surveyed as part of MARAMP share a common geological origin that consists of extinct volcanoes formed 15–20 million years ago and covered by layered carbonate formations. Except for uninhabited Aguijan, these southern islands are the largest islands in the Mariana Archipelago, with land areas of 85–544 km^2, and they are typically characterized by low to moderate slopes (means of ~ 10° on the seafloor) and flat-lying, step-like limestone terrains and karst topographies. However, southern Guam is atypical in that the volcanic terrain is not covered by carbonate terraces.

Oceanographically, the north–south orientation of the Mariana Archipelago results in latitudinal gradients in seasonal climatologies for SST, wind, currents, and Chl-*a*, with the southern islands exhibiting warmer SSTs, stronger wind conditions and surface currents, and less productive waters, when compared to the northern islands. Not surprisingly, because of natural and human-induced coastal processes, considerable spatial and temporal variability in water-quality parameters, including inorganic nitrogen and Chl-*a*, was observed from water samples collected in nearshore waters around the southern islands, particularly around Guam.

The shallow (depths of < 30 m) areas of potential benthic habitat are larger around the populated, southern islands than around the northern islands. These greater shallow reef areas support a wider range of habitat types and oceanographic conditions. Likely an effect of this greater variety in environments, benthic assemblage diversity—measured as total and mean generic richness of corals and macroalgae, as observed during REA benthic surveys of hard-bottom, forereef habitats—was greater for islands at the southern end of the Mariana Archipelago. Across the 3 MARAMP survey periods combined, the greatest total number of coral genera was recorded at Saipan with 38 genera enumerated, while the highest diversity of macroalgae was observed at Guam with 54 genera documented. Within this context, some coral taxa were restricted to and some algal taxa were particularly widespread in the southern islands, compared to survey results for the northern islands. These taxa included the hard corals *Diploastrea*, *Plesiastrea*, *Alveopora*, and *Coscinaraea* and the red algae *Amansia*, *Crouania*, *Gelidiella*, *Haloplegma*, *Halymenia*, and *Predaea*. Substrate type (carbonate versus basalt), habitat diversity, productivity, and life history are among the potential determinants of geographical patterns in species distribution.

The greater algal richness observed during REA benthic surveys among the populated, southern islands, versus the northern islands, was coupled with higher levels of mean macroalgal cover recorded on forereef habitats during broad-scale towed-diver benthic surveys in 2005 and 2007 and REA benthic surveys in 2007. Densities of sea urchins also were generally greater around the southern islands, as were species richness and densities of sea cucumbers. Estimates of live coral cover were variable spatially and temporally, and a north–south pattern for live coral cover was less clear than the one seen for macroalgal cover. Still, looking at survey results for REA and towed-diver benthic surveys conducted in 2007, cover levels generally were lower in the southern islands than in the northern islands. Stressed-coral cover, observed during towed-diver benthic surveys, was higher in the southern islands than in the northern islands, especially in 2007. Bleaching, siltation, and typhoons may have affected coral health, particularly around Rota, where some of the lowest coral cover values archipelago-wide were detected in the 3 MARAMP survey years.

Overall mean prevalence of coral bleaching and disease, based on REA benthic surveys conducted in 2007, was highest around the southern islands, a pattern exemplified by the presence of hot spots at Guam. Because elevated water temperatures and anthropogenic disturbances have been identified as environmental drivers of disease, the populated, southern

islands may have a greater risk of coral bleaching and marine disease outbreaks than do the mostly uninhabited northern islands. Also, a large percentage of disease cases seen in the Mariana Archipelago disproportionately affected important coral reef building taxa, including hard corals in the families Poritidae, Acroporidae, and Faviidae as well as calcium-carbonate-producing crustose coralline red algae. Another factor influencing the condition of coral reef ecosystems in the Mariana Archipelago was the fluctuating populations of the corallivorous COTS, which were observed in some areas at densities high enough to suggest that an outbreak was occurring.

Total mean fish biomass, based on REA surveys for fishes from all species and size classes, was lower at the populated, southern islands than at the northern islands, with overall means for the two island groups at 3.63 kg 100 m^{-2} versus 12.00 kg 100 m^{-2}. This difference was the result of lower fish abundances coupled with smaller average fish sizes at the southern islands compared to the northern islands. Fish species richness followed a similar pattern. MARAMP data are in agreement with other studies that suggest lower fish biomass and sizes are likely to occur in association with higher densities of human populations and greater resource use. In addition, the overall abundance of marine debris as observed in towed-diver surveys was greater around the southern islands than around the northern islands, with the greatest mean numbers of sightings of derelict fishing gear and other man-made objects, such as anchors, ground tackle, mooring blocks, and metal scrap, found at Guam and Tinian.

As indicated above, many of the anthropogenic activities and associated effects to the coral reef ecosystems in the Mariana Archipelago are concentrated around the populated, southern islands. Conversely, the 9 northern islands are sparsely inhabited with total fluctuating populations of 0–100 persons on Agrihan, Pagan, Alamagan, and Anatahan since WWII. With relatively low levels of anthropogenic disturbance, other than feral animals, introduced species, and some resource overuse at the northern islands, natural events, such as storms, thermal stress, and volcanic eruptions, are among the main environmental factors that affect the coral reef ecosystems there.

Geologically, all the northern islands are active or dormant stratovolcanoes, formed along the tectonically active part of the Mariana Arc. Many of these islands have erupted on several occasions within recorded history. Except for Pagan and Agrihan, which have land areas of 48 and 44 km^2, the northern islands are the smallest in the Mariana Archipelago, with land areas of 2–34 km^2. These islands are characterized by moderate to steep slopes (means of ~ 20°–25° on the seafloor) and covered with layers of hardened lava, cinder, or ash. Oceanographically, climatologies show that the northern islands exhibit cooler SSTs, are less windy, have weaker surface currents, and are more productive compared to the southern islands, regardless of season. Episodic volcanic eruptions, ash discharge, and landslides can effectively modify the quality and chemistry of the surrounding coastal waters on a temporal basis.

The notion that potential habitat size, in concert with disturbance frequency (primarily volcanic activity) is a likely predictor of taxonomic richness is exemplified in results from REA benthic surveys conducted at Farallon de Pajaros, which has a land area of 2 km^2 and had frequent volcanic activity during the 19th century and recurrent eruptions in the 1940s to 1960s. Farallon de Pajaros harbored the lowest total and overall mean richness of corals and macroalgae recorded at an island in the Mariana Archipelago, with overall mean numbers of genera per site of 7.6 for corals and 6 for macroalgae across the 3 MARAMP survey years. Comparatively, Pagan, which has the largest land area among the northern islands, harbored the greatest coral and algal diversity observed in the northern islands over the 3 survey years, with 32 total coral genera and 40 total macroalgal genera enumerated. Despite these general patterns, however, some taxa, including the hard coral genera *Merulina* and *Euphyllia* and the red algae *Cheilosporum* and *Dasya*, were found at 2–4 northern islands but rare or absent in the southern islands, suggesting that the northern islands offer biological and environmental conditions favorable for the proliferation of selected coral and algal taxa. Similarly, the northern islands also harbored the largest populations of giant clams of the genus *Tridacna*.

Macroalgal cover from REA and towed-diver surveys followed the same north–south pattern as algal richness, with values lower at the volcanic, northern islands than at the southern islands. In contrast, the opposite pattern was observed for estimates of live coral cover from REA and towed-diver benthic surveys conducted in 2007, except for at Farallon de Pajaros and Pagan. Excluding these two islands, coral cover was moderately high at the northern islands, with overall sample means from REA benthic surveys ranging from 15.4% at Guguan to 34.1% at Maug. Selected habitats at Maug, such as the eastern flank of the caldera, harbored exceptionally high cover (~ 70%) aggregations of the hard coral *Porites rus* (Fig. 3.11a). It appeared that Farallon de Pajaros, where overall mean coral cover was 3.6% from REA surveys, was geologically too unstable to promote the development of substantial coral communities and reef buildups. Alternatively, the low coral cover observed at Pagan, with an overall sample mean of 10.6%, may not have been caused by geological and volcanic activity but rather may have resulted from COTS outbreak conditions observed around much of Pagan in 2005 and 2007

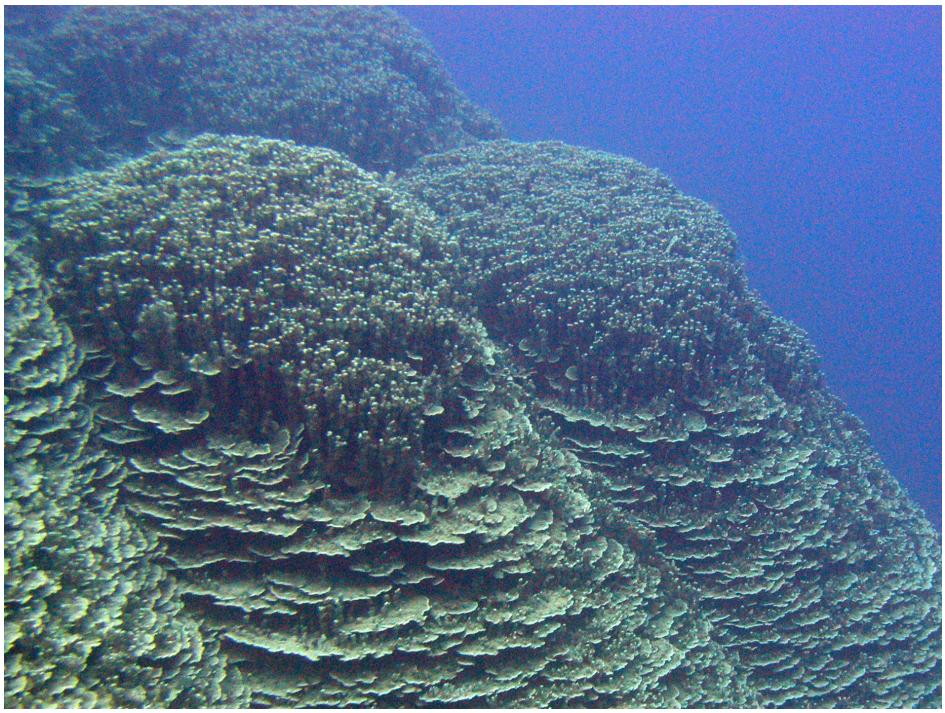


Figure 3.11a. Towering *Porites rus* formations on the eastern side of Maug's caldera. *NOAA photo by Bernardo Vargas-Ángel*

Compared to observations at the southern islands, coral bleaching and coral and coralline-algal diseases occurred at lower levels or were absent in the northern islands of the Mariana Archipelago, based on estimates of prevalence or densities from REA benthic surveys conducted during MARAMP 2007. The presence and distribution of coral and coralline-algal disease corroborates the potential linkage with higher water temperatures and the presence of humans, since only 26% and 13% of disease cases, respectively, were documented at the largely uninhabited, northern islands.

Mean total fish biomass from REA surveys was more than 3 times greater in the northern islands than in the southern islands of the Mariana Archipelago, a result of greater fish abundance and average sizes. A similar pattern of species richness emerged: the northern islands exhibited higher average richness, with a range of 30.6–43.6 species 100 m^{-2} excluding Anatahan, than did the southern islands, with a range of 20.2–30.0 species 100 m^{-2}. Biomass of herbivorous fishes, including surgeonfishes (Acanthuridae) and parrotfishes (Scaridae), was twice as high at the northern islands than at the southern islands. Piscivores, including jacks (Carangidae) and sharks (Carcharhinidae and Ginglymostomatidae), accounted for 34% of the total fish biomass in the northern islands, and mean biomass of piscivores was more than 13 times greater in the northern islands than in the southern islands. Data from towed-diver fish surveys in forereef habitats show similar broad patterns in shark abundance; the number of sharks encountered per unit area surveyed in the northern islands was 174.5 individuals km^{-2}—nearly 10 times the abundance recorded in the southern islands.

Lastly, a general pattern of decreasing conditions from the northern islands to the southern islands was observed in the Archipelagic Coral Reef Condition Index, Archipelagic Benthic Condition Index, and Archipelagic Fish Condition Index, the composite metrics of biological variables derived to describe the relative status of coral reefs throughout the Mariana Archipelago. The geographic regions of the southern islands of Guam, Rota, Tinian, Aguijan, and Saipan, for the most part, had low or declining ranks in the overall Archipelagic Coral Reef Condition Index, compared to the conditions observed and ranked for other regions in this archipelago. The main exception was the east region of Saipan, where marine protected areas have been established. Maug, Farallon de Pajaros, Alamagan, and Asuncion had the highest ranks in the Archipelagic Coral Reef Condition Index, attributable to high coral cover, low stressed-coral cover, and high large-fish density and biomass. Three of these islands, Maug, Farallon de Pajaros, and Asuncion, are the northernmost islands of the Mariana Archipelago and are part of the Marianas Trench Marine National Monument.

4 GUAM & ADJACENT REEFS

4.1 Introduction

The island of Guam, or Guåhan in the native Chamorro language, is centered at 13°28′ N, 144°47′ E and is the only major island in the United States territory of Guam. With a total area of 544.34 km^2, Guam is the largest island in the Mariana Archipelago. The highest point on Guam is Mount Lamlam at 406 m. The major population centers are in a central section of this island near Apra Harbor, Hagåtña, and Tumon Bay as well as in a northern section in a stretch of development between Tumon Bay and Andersen Air Force Base (Fig. 4.1.4b). Tumon Bay is the main tourist center with numerous hotels, the Guam International Airport, and other tourist facilities in the immediate area. Apra Harbor on the central west coast of Guam is one of the largest harbors in the western Pacific and supports both military and civilian commerce. The geology of Guam is unique in the Mariana Archipelago because the northern half is flat, uplifted limestone but the southern half is of Eocene volcanic origin and highly susceptible to erosion. Three shallow banks, all popular fishing areas, are located offshore: Santa Rosa Reef lies 46 km southwest of Guam and has a least depth of 8 m, Galvez Bank lies 22 km southwest of Guam and has a least depth of 25 m, and 11-mile Reef lies 17 km west of the southern point of Guam and has a least depth of 20 m.

4.1.1 History and Demographics

A brief summary of Guam's history and political structure is presented here. The history of the Mariana Archipelago and the political structure of Guam and the Commonwealth of the Northern Mariana Islands (CNMI) are discussed in Chapter 1: "Introduction."

The history of Guam runs parallel to that of many other islands of the Mariana Archipelago until the late 1800s. A native Chamorro population was established as early as 3500 years ago (Rogers 1995). Ferdinand Magellan established contact with Guam in 1521, and Spain ruled between 1565 and 1898 (Rogers 1995). Guam was ceded to the United States in 1898 after the Spanish American War and purchased in 1899 for US$20 million. Guam was used as a refueling and communications station and was on the Pan American Airways *China Clipper* route between 1935 and World War II (WWII) (Rogers 1995). For the first 4 decades of U.S. control, from 1898 to WWII, Guam was administered by the U.S. Navy with a naval officer serving as governor.

Japanese forces invaded Guam in 1941 and held it until 1944, when American forces reclaimed the island. Thereafter, this island was used as the command post for the U.S. western Pacific until 1945, and U.S. Navy control was re-established in 1946 (Rogers 1995). Administration of Guam was transferred in 1950 from the Department of Defense to the Department of the Interior, Office of Insular Affairs. Guam became an organized, unincorporated territory of the United States when the U.S. Congress passed the *Organic Act of Guam* in 1950. The *Organic Act* gave the people of Guam U.S. citizenship, a status for which they had petitioned since 1902 (Rogers 1995). As an unincorporated territory Guam belongs to, but is not a part of, the United States, and no guarantee of eventual statehood is implied. The United States appointed the governor of Guam until 1968, when the *Organic Act* was amended to authorize the holding of an election; the first election for governor was held in 1970. Federal legislation awarded Guam a delegate in the U.S. House of Representatives in 1972. This delegate can participate and vote in House committees and has limited rights for voting on floor amendments. The *Organic Act* also transformed the existing Guam Congress into a lawmaking body, but Guam's legislation is still subject to the will of the U.S. Congress (Howe et al. 1994). Under the U.S. Constitution, residents of unincorporated territories, such as Guam, do not vote in elections for U.S. president and vice president; however, they may vote in presidential primary elections. The governor and lieutenant governor of Guam are chosen jointly with a single vote applicable to both offices for 4-year terms (Governor… 2006).

Guam had an estimated human population of 159,358 persons in 2010, a 3% increase from the island's population in 2000 and a 50% jump from its population in 1980 (Fig. 4.1.1a; U.S. Bureau of the Census 1982, 2002, 2011b). A major population increase is expected in the next decade, since the United States plans to relocate between 4700 and 8000 Marines with accompanying dependents and support personnel to Guam from Okinawa, Japan (Parrish 2012; Hart 2012). The military-related population on Guam, which in 2008 included ~ 14,000 service members stationed on this island, could grow by an

estimated 24,713 service members, military dependents, and support staff over the next decade (U.S. Department of the Navy 2010; Weaver 2008). An increase in civilian population also is anticipated as additional construction and service jobs become available in the private sector.

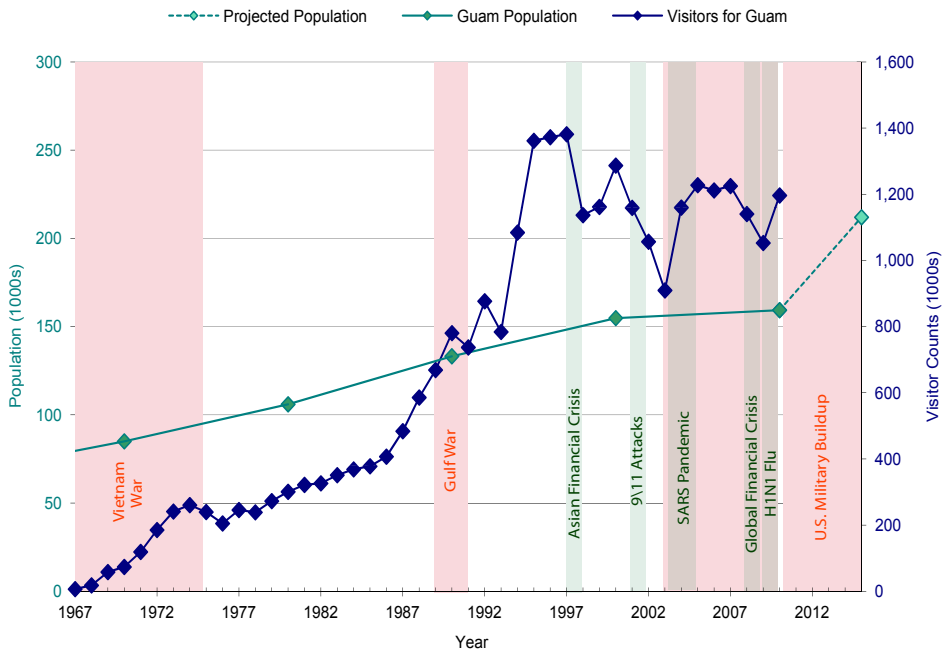


Figure 4.1.1a. Population growth (U.S. Bureau of the Census 1982, 1992, 2002, 2011b; Secretariat of the Pacific Community 2011; U.S. Department of Defense) and visitor count (A Cid, Guam Visitors Bureau, pers. comm.) trends on Guam during the period of 1967–2015.

4.1.2 Land Use

Current land use on Guam is predominantly characterized as urban, forest, and shrub (Fig. 4.1.2a). This island's northern limestone plateau was once heavily forested, but significant changes to that vegetation have taken place during and after WWII as a result of military activities and urbanization (Minton 2005). This area is now the major population center with some scattered areas of remaining forest. U.S military installations on Guam cover 160 km², ~ 29% of this island's total land area. The largest installations are Naval Base Guam, most of which is located on Orote Peninsula on the central west side of Guam, and Andersen Air Force Base in the northeast corner of Guam. The southern volcanic area is largely rangeland and savannah with some lightly populated areas on the young limestone terrain along the east coast. This mountainous, southern area has numerous barren areas created by wildfires (Fig. 4.1.2a) that occur at an average of more than 700 per year and are reportedly set by poachers and hunters, and these barren areas contribute to erosion problems in the steep volcanic terrain (Burdick et al. 2008).

Guam has 5 marine protected areas (MPAs) including; Piti Bomb Holes Marine Preserve, Sasa Bay Marine Preserve, Tumon Bay Marine Preserve, Pati Point Marine Preserve, and Achang Reef Flat Marine Preserve. Established in 1997 by the government of Guam, these MPAs cover more than 10% of Guam's coastline and a total area of ~ 36 km². In addition, the U.S. Fish and Wildlife Service has established the Guam National Wildlife Refuge at Ritidian Point, and the Navy has established 2 ecological reserves at Orote Point and Haputo (Burdick et al. 2008).

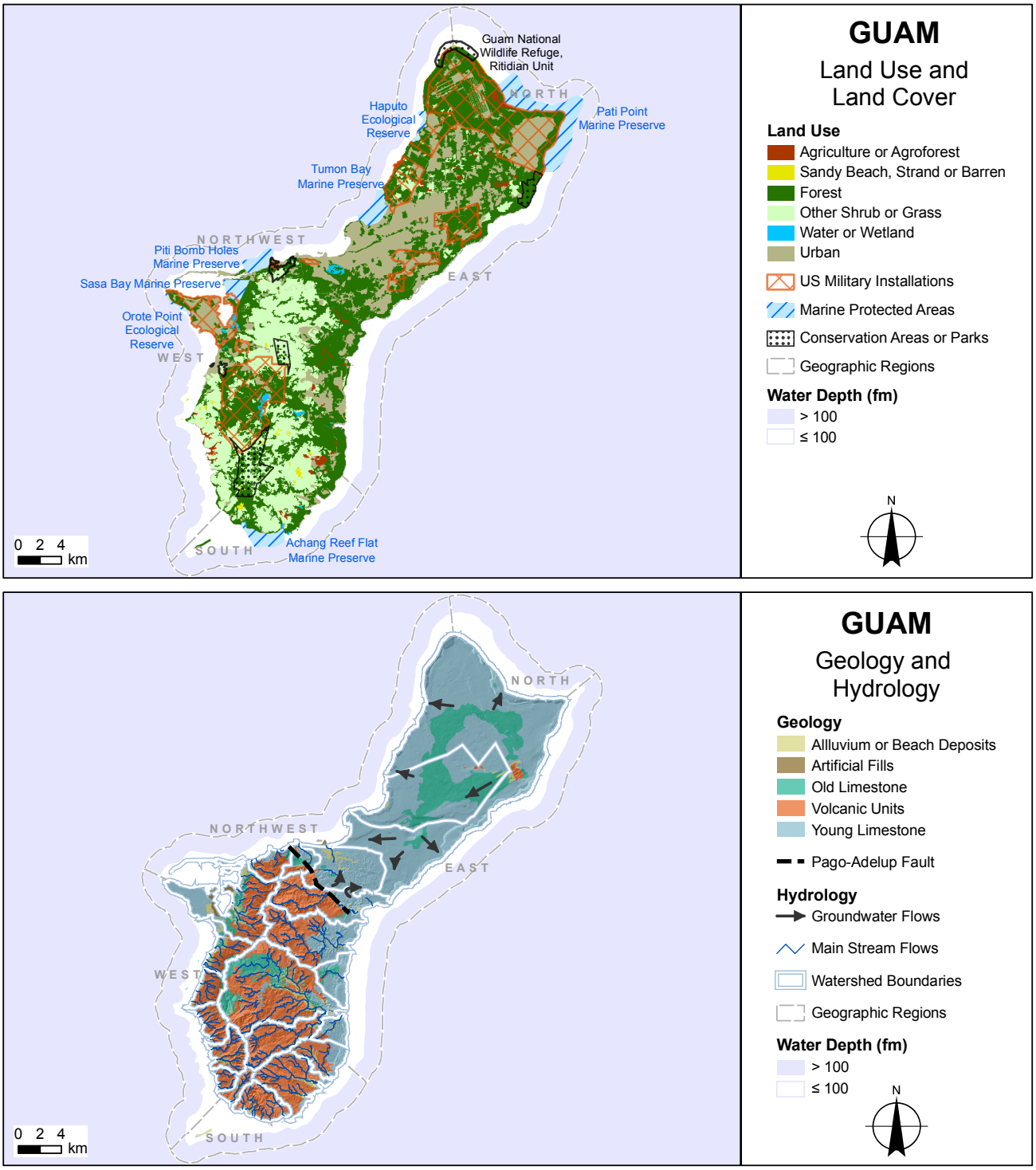


Figure 4.1.2a. Land use (U.S. Department of Agriculture Forest Service 2006c), military installations (U.S. Bureau of the Census 2008), conservation areas and parks (Burdick et al. 2008), and marine protected areas (MPAs; NOAA Marine Protected Areas Center 2008) on Guam are represented over a vegetation cover map (*top*; Liu and Fischer 2006). Geology (Water and Environmental Research Institute of the Western Pacific and Island Research and Education Initiative 2009; Tracey et al. 1964; Gingerich 2003), watersheds (Guam Environmental Protection Agency 2008), main stream flows (U.S. Geological Survey 2005c), and groundwater flows (Gingerich 2003) on Guam (*bottom*).

4.1.3 Geography

Guam is the southernmost island of the Mariana Archipelago, one of a series of volcanic arcs that extend north to Japan. Guam lies in the southern, inactive Mariana Arc, rather than in the volcanically active northern Mariana Arc. The oldest

geologic formations on Guam date as far back as the mid- to late-Eocene epoch or 33–48 million years ago (Hawkins 2003). This island is tectonically active and has undergone repeated uplift and subsidence related to subduction of the Pacific Plate and associated seamounts into the Mariana Trench, ~ 100 km to the east (Riegl et al. 2008).

The island of Guam has a distinctive north–south divide, which is highlighted by both the geologic map (Fig. 4.1.2a) and the combined onshore-offshore slope map (Fig. 4.1.3a). The southern part of this island is dominated by volcanic features, while the northern part's flat, uplifted, coral limestone is similar to the geology of Rota, Tinian, Aguijan, and Saipan. Formerly densely forested but now mixed urban and forest land, the northern limestone plateau on Guam is surrounded by cliffs. The plateau is separated from the southern half of Guam by the major northwest–southeast trending Pago-Adelup fault (Taboroši et al. 2005). Southern Guam is more mountainous than the northern part, and its geology is dominated by basalt, relic volcanoes that have erupted through uplifted coral limestone. This volcanic region's flanks have numerous bays, canyons, and valleys, and much of this area is covered by grasslands (Kingston 2004).

Because of its geology, Guam's water supply comes from 3 distinct sources. The flat, porous, carbonate plateau in the north has no surface rivers or streams and, thus, no true watersheds. Virtually all rainfall in northern Guam infiltrates the porous limestone and is stored as groundwater (Fig. 4.1.2a), which flows into an underlying Ghyben-Herzberg lens of water that is accessed via wells (Gingerich 2003). Springs in this island's central area, near the Pago-Adelup fault, supply ~ 3% of the water on Guam. The southern volcanic area, which has more than 40 streams and stream-cut valleys and 14 major watersheds, is very steep on the west side (Fig. 4.3.1g in Section 4.3: "Benthic Habitat Mapping and Characterization"). The volcanic laterite soils in the barren areas on Guam are subject to severe erosion (Water and Environmental Research Institute of the Western Pacific 2009); laterite soil is a red, hard, or gravel-like soil or subsoil formed in the tropics that has been leached of soluble minerals leaving insoluble iron and aluminum. A small volume of water penetrates the volcanic rock to form a subsurface lens in the volcanic areas, and the water supply in this area is primarily drawn from the Ugam River and the Fena Reservoir. The primary water suppliers are the Guam Waterworks Authority, the U.S. Navy, and the U.S. Air Force. (Kingston 2004).

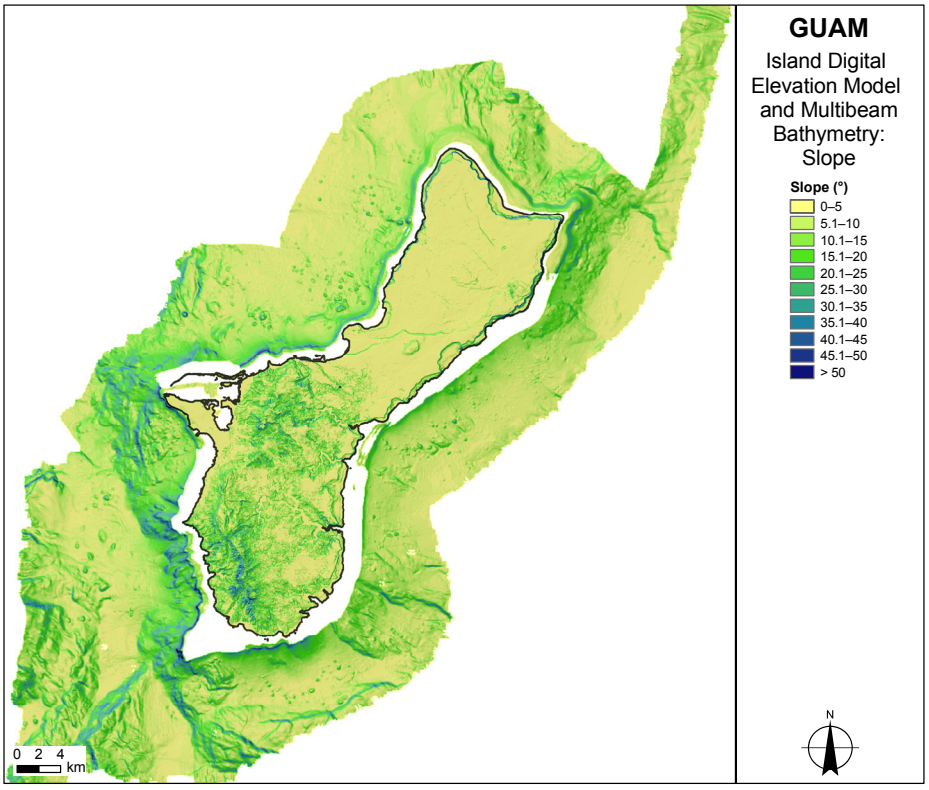


Figure 4.1.3a. Combined slope map using the digital elevation model and multibeam bathymetric data for Guam.

4.1.4 Economy

The 2 most important sectors of the Guam economy are tourism and U.S. government spending (including for military installations). Other sources of income include local government, local business, and fishing. A recent estimate of total

economic activity in Guam for 2000 was $3.4 billion (Allen and Bartram 2008). In 2008, the services sector of Guam's economy employed 16,605 people, accounting for 26.8% of the workforce on Guam, and the sectors with the next-greatest proportion of employment were retail trade, the government of Guam, and construction with 19.5%, 18.9%, and 10.6% (Guam Department of Labor 2008). The government of Guam was the single largest employer (Allen and Bartram 2008). In the 1960s, the federal government, including the military, accounted for 75% of Guam's economy; this percentage decreased to 30% in 2003 (Guam Visitors Bureau 2004).

Tourism provides the majority of Guam's nongovernmental income with ~ 1.2 million tourists visiting each year. The tourism industry has had many ups and downs (Fig. 4.1.1a) over the past 20 years, with a peak of 1.4 million tourists visiting in 1995 and 1997 and numerous lows associated with a weak Asian economy, the events of September 11, 2001, typhoons, and recent worldwide economic problems (Allen and Bartram 2008).

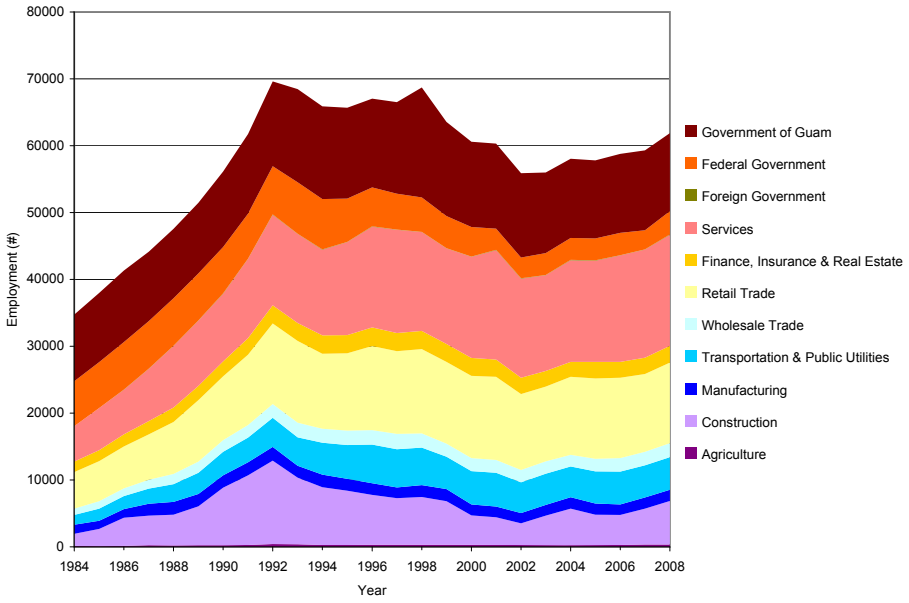


Figure 4.1.4a. Employment by sector on Guam during the period of 1984–2008 (Guam Department of Labor 2008).

Japan is the source of 80% of tourists to Guam, who stay an average of only 3 nights (Guam Economic Development Authority 2009b). Korea, Taiwan, Hong Kong, the Philippines, and the United States are the other main sources of tourists and the number of tourists from Russia and China has increased in recent years (Guam Visistors Bureau). Since the region's immigration laws were federalized in May 2008, officials from both Guam and the CNMI have been seeking visa waivers for Russian and Chinese visitors to bolster tourism and their economies (Casas 2009). The area near Tumon Bay, which was designated as a marine preserve in 1997, is the primary area for tourism with more than 20 hotels and other facilities. Many tourism activities, including golfing, scuba diving, beach going, and deep-sea fishing, are dependent upon and impact Guam's natural resources (Fig. 4.1.4b).

Guam has been the location of strategic U.S. military posts in the Pacific for over a century. With the withdrawal of troops from the Philippines in the 1980s and the planned move of troops from Okinawa in the next decade, Guam has become even more critical as a location for strategic U.S. military operations (Pessin 2006). The annual military spending in Guam ranged from $883 million to $1.1 billion from 1993 to 2000 (Allen and Bartram 2008). A large increase in construction activities is planned as a result of this military buildup including construction of an aircraft carrier pier, turning basin, expansion of the commercial port, housing construction, and expansion of infrastructure. It has been estimated that $15 billion would be spent over a period of 10 years for military activities in Guam (Laney 2008).

While commercial fishing has not been a major contributor to Guam's economy, the territory has been a major regional fish transshipment center and resupply base of domestic and foreign tuna fishing fleets; however, Guam's role as a transshipment center has declined in the past several years (Allen and Bartram 2008). Local fishing in Guam is important because it contributes to the subsistence needs of the indigenous Chamorro population and preserves culture and identity. Guam's coral reef fisheries currently target a large number of reef fishes and invertebrates. Harbors and marinas, which serve as primary fishing access points, are located in the south, west, and northwest regions of Guam (Fig. 4.1.4b). Sport fishing ves-

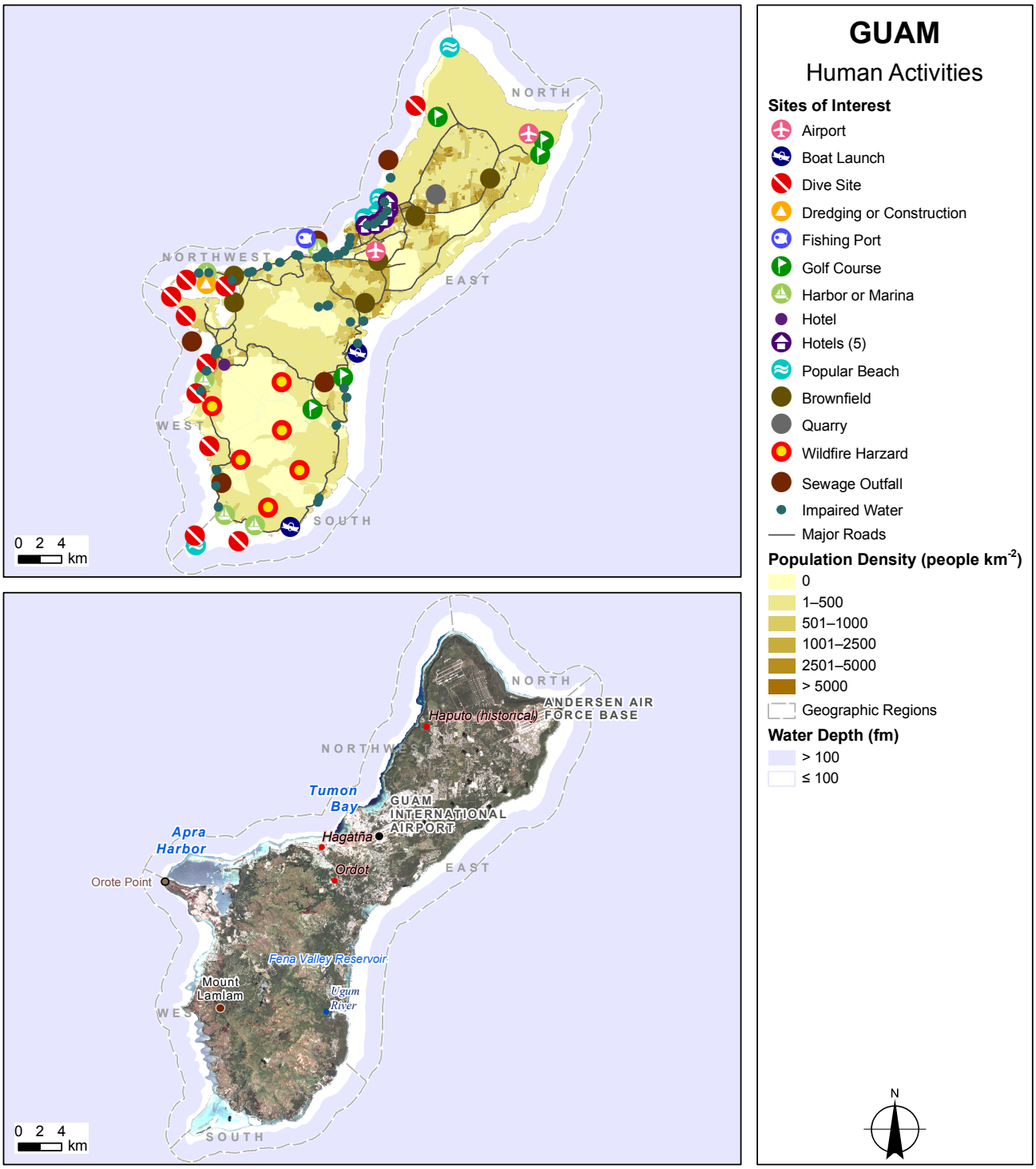


Figure 4.1.4b. Major locations of human activities (*top*) on Guam that have the potential to affect the marine environment (Burdick et al. 2008; Franko Maps Ltd.; Guam Economic Development Authority 2009b; Placenames.com; U.S. Geological Survey 2005d; AL Guerrero, Guam Environmental Protection Agency, pers. comm.) are represented over a population-density map (U.S. Bureau of the Census 2002, 2008). Satellite imagery of Guam (*bottom*, includes material © 2006 DigitalGlobe Inc. All rights reserved), labeled with places of interest (U.S. Geological Survey).

sels and the Guam Fishermen's Cooperative Association, an active commercial fishing cooperative, are located in Hagåtña Harbor. Two boat launching ramps on windward shores in the east and south regions are seldom used, according to local residents (V Brown, JIMAR, pers. comm.). In the mid-1980s, a rapid shift from subsistence to commercial fishing activities occurred in response to increased tourism and development (Richmond et al. 2008). Four studies discussed in Burdick et al. (2008) show that the catch per unit effort and harvest have declined over the past 20 years for shore-based fisheries.

To combat the decline of fish stocks, the government of Guam created a system of marine preserves designed to increase fish stocks through limited-take or no-take zones. Subsequently, fish stocks in these preserves have increased (Burdick et al. 2008). Legislation (Public Law 29-127) that passed in late 2008 could open some of these no-take marine preserves to fishing by indigenous people (Naylor-Gesick 2008).

The Division of Aquatic and Wildlife Resources (DAWR) of the Guam Department of Agriculture, with technical assistance from the Western Pacific Fisheries Information Network (WPacFIN) of the NOAA Pacific Islands Fisheries Science Center, has been collecting nearshore fisheries-dependent creel survey data in Guam continuously since 1982, allowing for exploration of temporal trends in the local fisheries of this territory. According to this survey data (DAWR), fishermen around Guam who target nearshore species typically use one of the following methods: spearing (scuba or freediving), nets, trolling, or bottom fishing. These fishermen can be based on shore or in a boat. Trolling almost exclusively captures tunas and mackerels (Scombridae), which together account for 99% of landed catch by weight from trolling. Bottom fishing captures mostly deep species of emperors (Lethrinidae), snappers (Lutjanidae), and jacks (Carangidae), which account for a combined 70% of landed catch by weight from bottom fishing and are not currently surveyed as part of MARAMP. Spearing and netting data are reported in more detail here, because these methods capture the nearshore species typically found on coral reefs. Around Guam, boat-based spearfishermen mostly capture surgeonfishes (Acanthuridae) and parrotfishes (Scaridae; Fig. 4.1.4c), which together account for 66% of landed catch by weight from boat-based spearfishing—a proportion that has been remarkably constant for nearly 30 years. Interestingly, parrotfishes have decreased from 40% of the landed catch by weight from boat-based spearfishermen in the 1980s to 20% in recent years (Fig. 4.1.4d). Conversely, surgeonfish catch has increased from 20% to 40% of landed catch by weight. Other important families found in spearfishing landings are groupers (Serranidae, 14%), snappers (9%), and jacks (5%). Gillnet landings are composed mostly of goatfishes (Mullidae, 48%), followed by surgeonfishes (17%) and rabbitfishes (Siganidae, 10%).

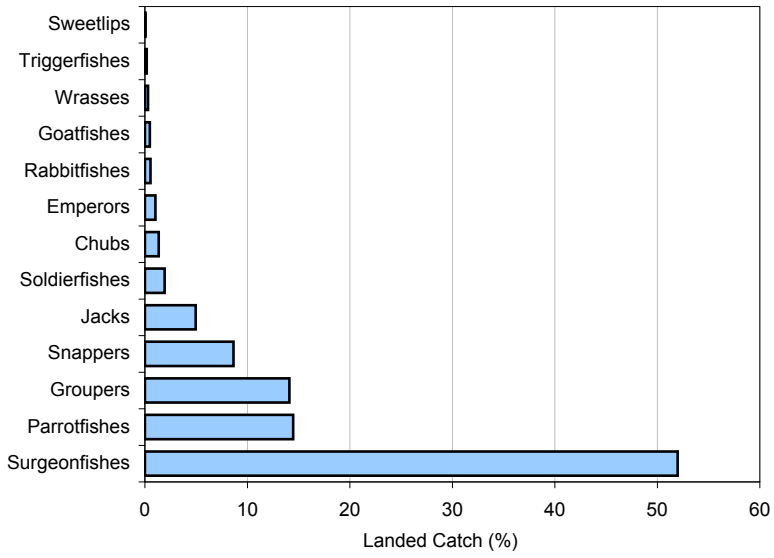


Figure 4.1.4c. Family composition of the landed catch of spearfishermen, by weight as a proportion of total catch, around Guam in 2008 (DAWR). Data were collected from boat-based creel surveys conducted by the Guam DAWR and extrapolated to estimate total catch with assistance from the WPacFIN.

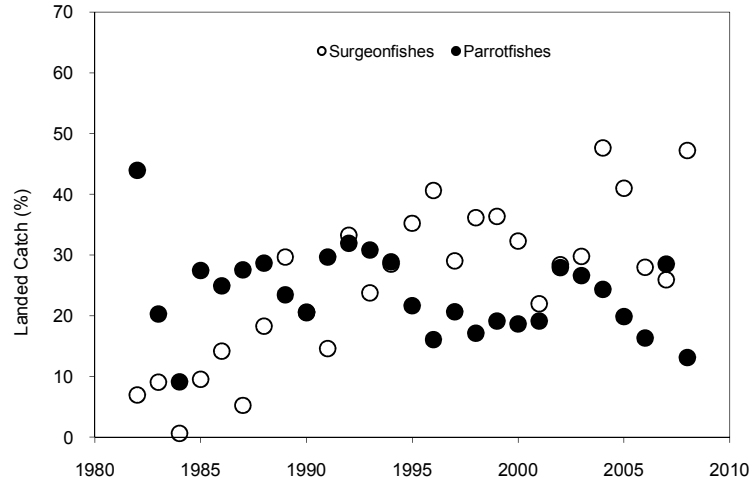


Figure 4.1.4d. Estimated landed catch (%) of parrotfishes and surgeonfishes as a proportion of total landed catch by boat-based spearfishing. These catch estimates come from an expanded data set based on creel surveys conducted by the Guam DAWR.

4.1.5 Environmental Issues on Guam

The condition of Guam's coral reefs ranges from excellent to highly degraded by human impacts (Burdick et al. 2008). Local assessment and monitoring projects on Guam, primarily in accessible areas on the west and northwest regions have been conducted intermittently since the 1970s (Richmond et al. 2008). The Pacific RAMP began conducting biennial surveys around the coasts of Guam in 2003.

Although climate change—including potential increases in coral bleaching and resultant coral disease, ocean acidification, and increased storm frequency—has not been documented to have caused problems in Guam (Burdick et al. 2008), these global issues are considered by many to be the overall greatest threats to coral reefs in the coming decades (Hoegh-Guldberg et al. 2007). In addition, rises in sea level could impact water supplies, particularly in northern Guam where the Ghyben-Herzberg lens, a body of rain-fed freshwater depressing and overlying a body of sea-fed saltwater, lies near sea level (Maas 2007).

The Guam Environmental Protection Agency (GEPA) has numerous programs in place that support the protection and improvement of water quality on and around Guam. The U.S. Environmental Protection Agency (EPA) approved on June 1, 2009, a list of sites where impaired or threatened waters were found in accordance with Section 303(d) of the *Clean Water Act*. In this approved list and in a water-quality monitoring and assessment report, titled "2008 Integrated Report," the GEPA identifies impaired or threatened waters at 43 sites around Guam, including bays, coral reefs, sea grass beds, and estuarine systems (for the locations of these sites, see Fig. 4.10b in Section 4.10: "Ecosystem Integration;" Guam Environmental Protection Agency [GEPA] 2008).

Impaired waters are identified when a site does not meet general and numeric criteria. According to general criteria, waters must meet aesthetic qualifications, be capable of supporting "desirable aquatic life," and be free from substances or conditions attributable to discharges (domestic, commercial, or industrial) agriculture, construction, land-use practices, or other human activities. Numeric requirements set thresholds or ranges for the levels of concentrations of bacteria and nutrients, pH, dissolved oxygen, salinity, suspended solids, turbidity, temperature change, petroleum products, and toxic substances (GEPA 2001).

Of the 15.08 km of shoreline monitored around Guam, 0.74 km attained Guam water-quality standards (GWQS) in 2007, a drop from 1.11 km in 2006. Bacteria impaired 13.97 km of coastline in 2006 and 14.34 km in 2007. Impaired waters at recreational beaches were primarily caused by *Enterococcus* bacteria, a pathogen indicator. Still, marine waters around Guam were generally classified as "good," meaning that waters were of "sufficient quality to allow for the propagation and survival of marine organisms, particularly shellfish and other similarly harvested aquatic organisms, corals and other reef-related resources, and whole body contact recreation. Other important and intended uses include mariculture activities, aesthetic enjoyment, and related activities." (GEPA 2008)

Impacts generally have not been well documented, but numerous controversial local environmental issues on Guam (Burdick et al. 2008; Rodda and Savidge 2007) affect coral reefs, including the following issues:

- Sedimentation and runoff caused by
    - Coastal development
    - Dredging and construction in Apra Harbor
    - Severe upland erosion caused by deforestation and illegal burning by hunters and farmers, particularly on the southwest coast
- Coastal pollution caused by
    - Outfalls from sewage treatment plants near coral reefs
    - Inadequate sewage treatment facilities
    - Leakage into groundwater from septic tanks and sewage spills (nitrate, protozoa, bacteria, and viruses)
    - Storm water drainage, especially during heavy rainfall
    - Urban runoff, which can include inorganic and organic pesticides, halogenated solvents, petroleum compounds, and nitrates
    - Nutrients from farms and golf courses (pesticides and fertilizers)
    - Polychlorinated biphenyls (PCBs) from military dumps
    - Potential contamination from the 50-year-old dump, which was ordered closed in 2007, at Ordot
    - Overuse or misuse of popular scuba and snorkeling sites
    - Use of mechanical beach cleaning equipment at Tumon Bay and east Hagåtña Bay
    - Personal water craft

- Declining fish catch caused by
  - Fishing pressures
  - Fishing methods and practices
  - Habitat loss because of sedimentation, pollution, and physical damage
- Damage to coral reefs caused by frequent typhoons
  - Physical damage from large offshore waves
  - Increased influx of contaminated rainwater from the land
- Periodic outbreaks of crown-of-thorns seastars (*Acanthaster planci)*
- Damage to the environment by the brown tree snake (*Boiga irregularis*)
  - Extinction of 10 out of the 12 native forest bird species, leading to reductions in avian seed dispersal, subsequent alteration or loss of plant cover, and increased runoff

The predicted 25% increase in Guam's population (Weaver 2008) over the next decade is expected to exacerbate many of these environmental threats to terrestrial and coral reef ecosystems. Increased military and commercial construction projects, along with associated environmental assessments and planning, are already overburdening limited environmental government agencies and their available resources (Burdick et al. 2008). Construction of infrastructure—including expansion and improvement of public landfills, water supply, and sewage treatment facilities—is necessary to support a large influx of military personnel and their dependents over the next decade, and there are concerns that these activities could potentially increase coastal runoff and pollution (Burdick et al. 2008). During this time of rapid growth and development, both sound ecosystem-based management and frequent, continued monitoring become even more critical to the conservation and preservation of coral reef ecosystems around Guam.

4.2 Survey Effort

Extensive biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing coral reef ecosystems around the island of Guam since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 5 geographic regions around Guam are delineated in Figure 4.2a; wave exposure and breaks in survey locations were considered when defining these geo-

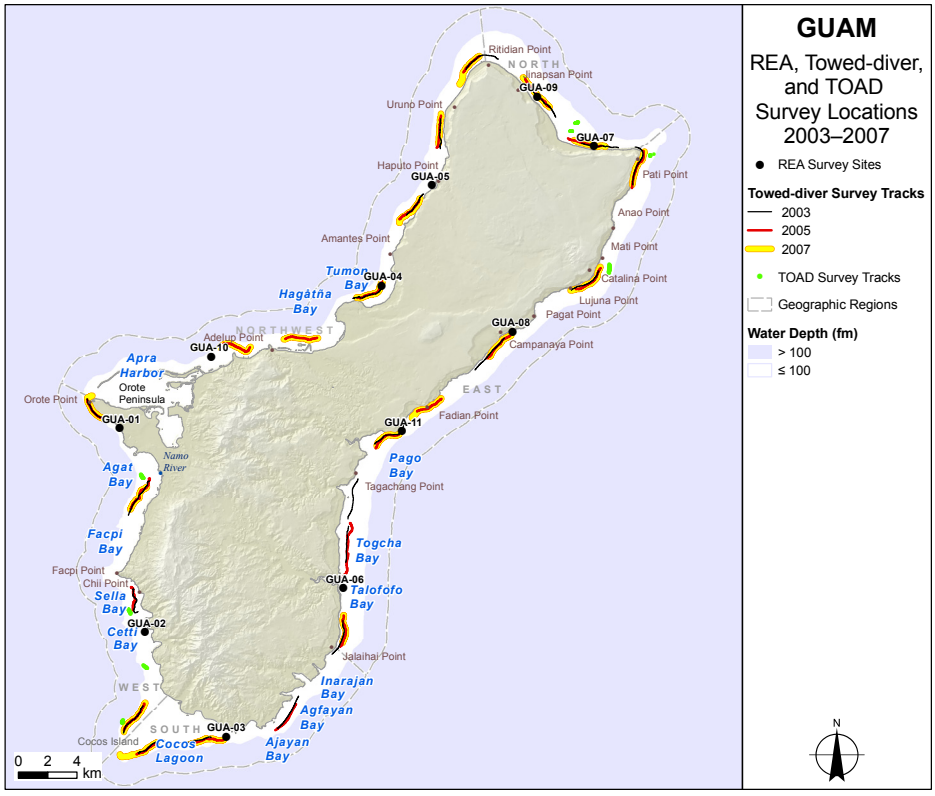


Figure 4.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Guam during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 5 geographic regions: north, east, south, west, and northwest.

graphic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Guam. Potential reef habitat around this island is represented by a 100-fm contour shown in white on this map.

Benthic habitat mapping data were collected around Guam using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around this island with multibeam sonar covered a total area of 25.7 km^2 in 2003 and 1633 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 4.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Guam was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 4.5–4.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 4.2a, along with their mean depths and total areas or length.

Table 4.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Guam during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	9	9	10
	Mean Depth (m)	12 (SD 1)	12.1 (SD 1.2)	12.1 (SD 1.1)
Benthic	Number of Surveys	9	9	10
	Mean Depth (m)	12 (SD 1)	12.1 (SD 1.2)	12.1 (SD 1.1)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	20	23	19
	Total Survey Area (ha)	49.7	51.2	45.5
	Mean Depth (m)	12.2 (SD 1.8)	16.3 (SD 1.4)	14.8 (SD 1.4)
TOAD		**2003**		
	Number of Surveys	8		
	Total Length (km)	2.49		

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Guam were collected using (1) two types of moored instruments designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007 (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). Results for some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced. A summary of deployed instruments and collection activities is provided in Table 4.2b, and results are discussed in Section: 4.4: "Oceanography and Water Quality."

Table 4.2b. Numbers of oceanographic instruments deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Guam during MARAMP 2003, 2005, and 2007. Three types of instruments were moored around Guam: ecological acoustic recorder (EAR), sea-surface temperature (SST) buoy, and subsurface temperature recorder (STR). Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
SST	1	1	1	1	1	1	–
STR	–	–	3	3	4	4	–
EAR	–	–	–	–	1	1	–
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	29	83		44			156
Deepwater Casts	–	6		6			12
Water Samples		**2005**		**2007**			**Total**
		10		13			23

Towed-diver Surveys: Depths

Figures 4.2b–e illustrate the locations and depths of towed-diver-survey tracks around Guam and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

During MARAMP 2003, 20 towed-diver surveys were conducted along the forereef slopes around most of Guam (Figs. 4.2b and c). The mean depth of all survey segments was 12.2 m (SD 1.8), and the mean depths of individual surveys ranged from 8.9 m (SD 3.8) to 16.6 m (SD 2.7).

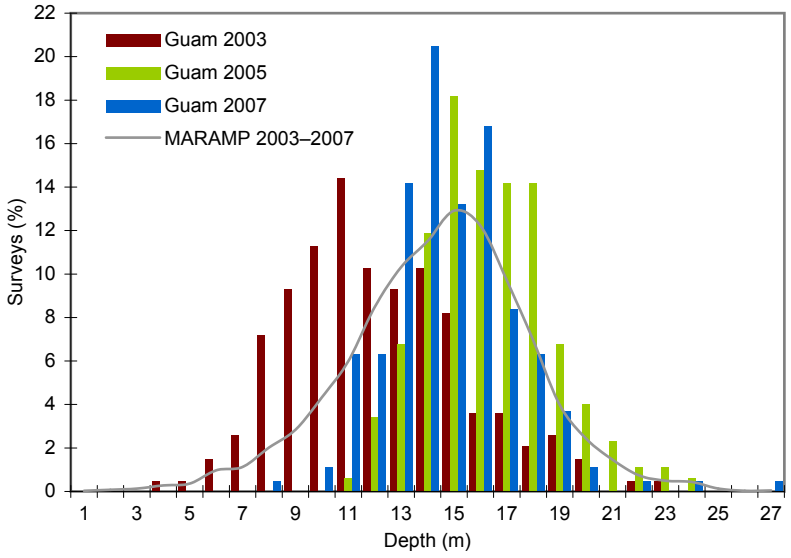
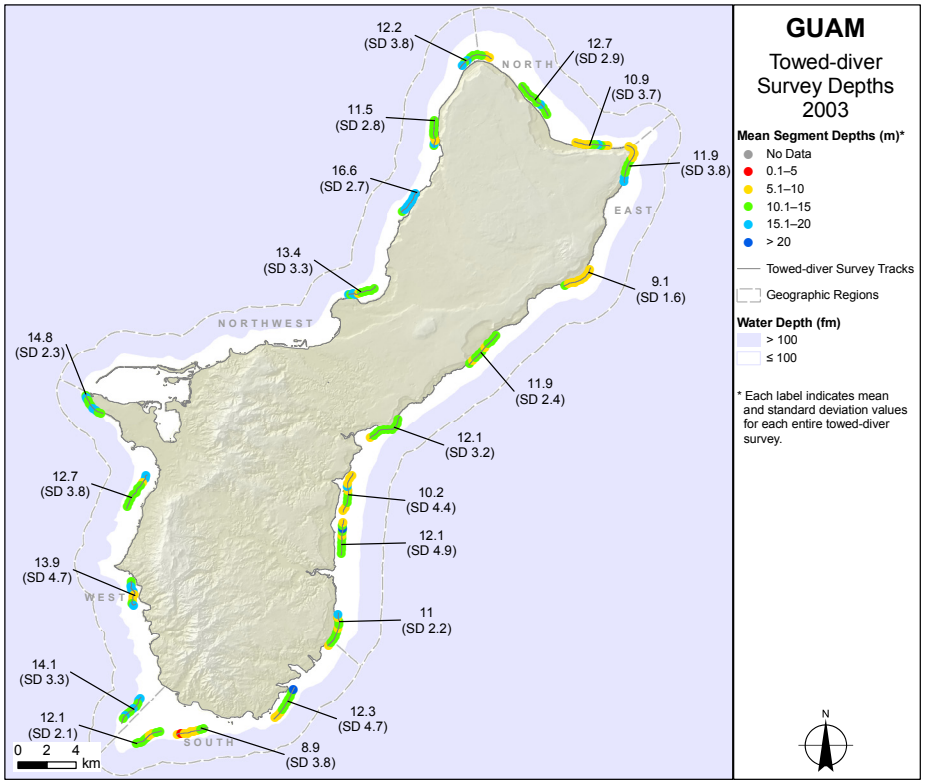


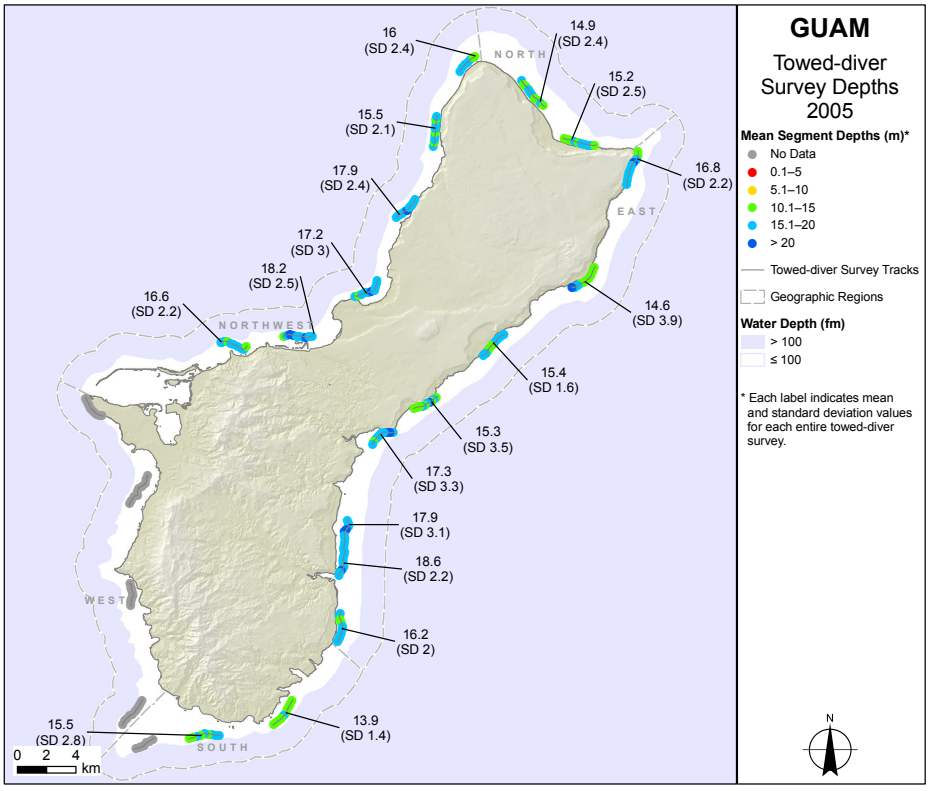
Figure 4.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Figure 4.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Guam during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.



During MARAMP 2005, 23 towed-diver surveys were conducted along the forereef slopes around most of Guam (Figs. 4.2b and d). The mean depth of all survey segments was 16.3 m (SD 1.4), and the mean depths of individual surveys ranged from 13.9 m (SD 1.4) to 18.6 m (SD 2.2). Note: depths were not recorded for 4 surveys in the west region and 1 survey in the south region because of an equipment malfunction.

Figure 4.2d. Depths and tracks of towed-diver surveys conducted on forereef habitats around Guam during MARAMP 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.



During MARAMP 2007, 19 towed-diver surveys were conducted along the forereef slopes around most of Guam (Figs. 4.2b and e). The mean depth of all survey segments was 14.8 m (SD 1.4), and the mean depths of individual surveys ranged from 11.5 m (SD 1.4) to 18.3 m (SD 3.6).

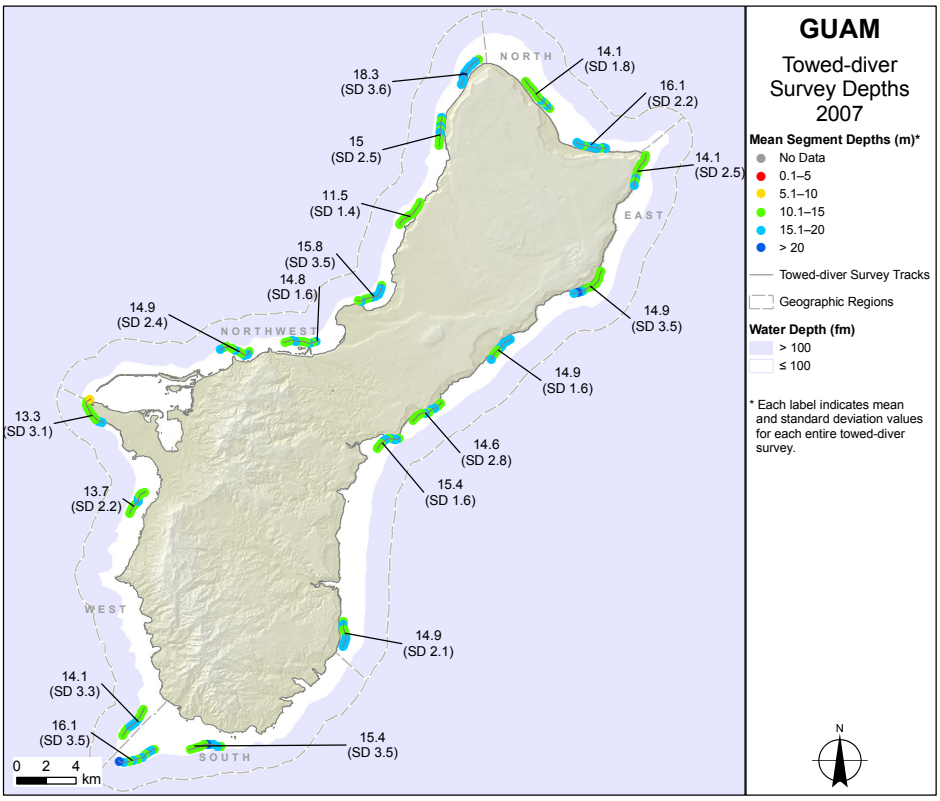


Figure 4.2e. Depths and tracks of towed-diver surveys conducted on forereef habitats around Guam during MARAMP 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

4.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Guam were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 5–2500 m. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of ~ 10–200 m.

Additional bathymetric data for Guam were obtained from the NOAA Office of Coast Survey (OCS) and the Naval Oceanographic Office (NAVOCEANO). NAVOCEANO collected lidar and singlebeam data over large areas of the inshore waters of Guam in 2001. Later, in 2008, OCS and NAVOCEANO collaboratively surveyed Apra Harbor for the purpose of updating nautical charts. Only bathymetric data and no backscatter data were available from these additional surveys. Therefore, these data could not supplement the multibeam backscatter data collected by the Coral Reef Ecosystem Division (CRED) but have been used in combination with CRED high-resolution multibeam data.

4.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 4.3.1a) collected by CRED around Guam during MARAMP 2003 and 2007 encompasses an area of 1659 km².

Multibeam bathymetry acquired around Guam (Fig. 4.3.1a, top panel) emphasizes the distinct seascapes that reflect the different onshore landscapes observed on either side of the Pago-Adelup fault, which runs between Pago Bay and Adelup Point (for place-names and their locations, see Figure 4.2a in Section 4.2: "Survey Effort"). South of the fault, the landscape is characterized by volcanic rock with numerous streams and rivers draining the mountainous topography. North of this fault, the volcanic rock is capped with limestone that ranges from 0 to ~ 500 m in thickness, creating a relatively flat

landscape with little surface water.

As described in Chapter 2: "Methods," Section 2.2.2: "Acoustic Mapping: Bathymetry and Backscatter Derivatives," multibeam backscatter intensity can provide information about the roughness and hardness of the seafloor. Backscatter data acquired around Guam show relatively uniform intensity around the north of Guam with a few notable exceptions

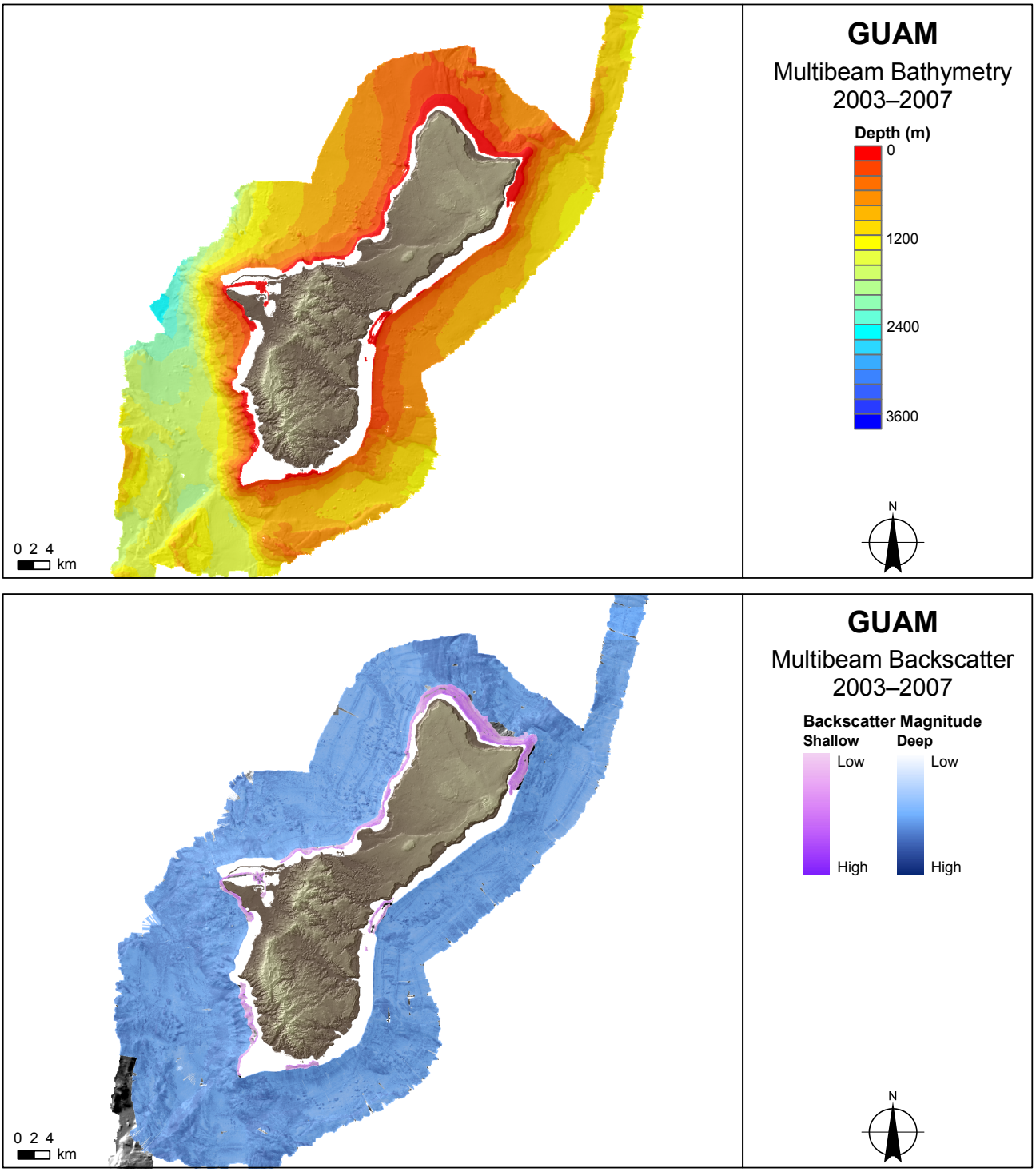


Figure 4.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Guam during MARAMP 2003 and 2007 at depths of ~ 5–2500 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

(Fig. 4.3.1a, bottom panel). Associated with the erosion deposits to the northwest and the ridge features to the north, distinct patches of high-intensity backscatter are observed. These patches suggest that hard or more rugged substrata may be associated with these topographic features. Similarly, patches of high-intensity backscatter are associated with the more complex bathymetry observed in Agat Bay. Backscatter imagery of the submarine canyons southwest of Guam show a distinct pattern, with low backscatter values within the canyons and higher backscatter values on top of the ridges. Low backscatter values are also seen at the base of the canyons in the deep channel south of Guam.

Bathymetry and Derivatives

The final Guam depth map is a mosaic of multibeam and lidar data obtained from 3 different sources (Fig 4.3.1b). The primary multibeam bathymetry was collected by CRED during MARAMP 2003 and 2007. Shallow-water acquisition on the NOAA R/V *AHI* focused on areas not previously covered by lidar data and on priority areas that were identified by resource management agencies. Thus, data were acquired in 7 key areas: northern Guam (including the Ritidian Unit of the Guam National Wildlife Refuge and Pati Point Preserve), Pago Bay, Ajayan Bay (including Achang Reef Flat Preserve), Cetti Bay, the southern coast of the Orote Peninsula, Apra Harbor, Hagåtña Bay, and Tumon Bay. Full survey coverage of areas deeper than these key areas was achieved from the NOAA Ship *Hi`ialakai* during MARAMP 2007.

Additional multibeam data for Apra Harbor were collected in 2008 by OCS and NAVOCEANO using the U.S. Naval Survey Vessel *Swamp Fox*, fitted with a 455-kHz Reson SeaBat 8125 multibeam echosounder (Naval Oceanographic Office and National Ocean Service 2009).

Bathymetric lidar data and, in waters deeper than ~ 40 m, singlebeam bathymetric data were collected in 2001 by NAVOCEANO (Naval Oceanographic Office 2004). These lidar data were used in areas where no multibeam data were available, primarily in waters shallower than 20 m.

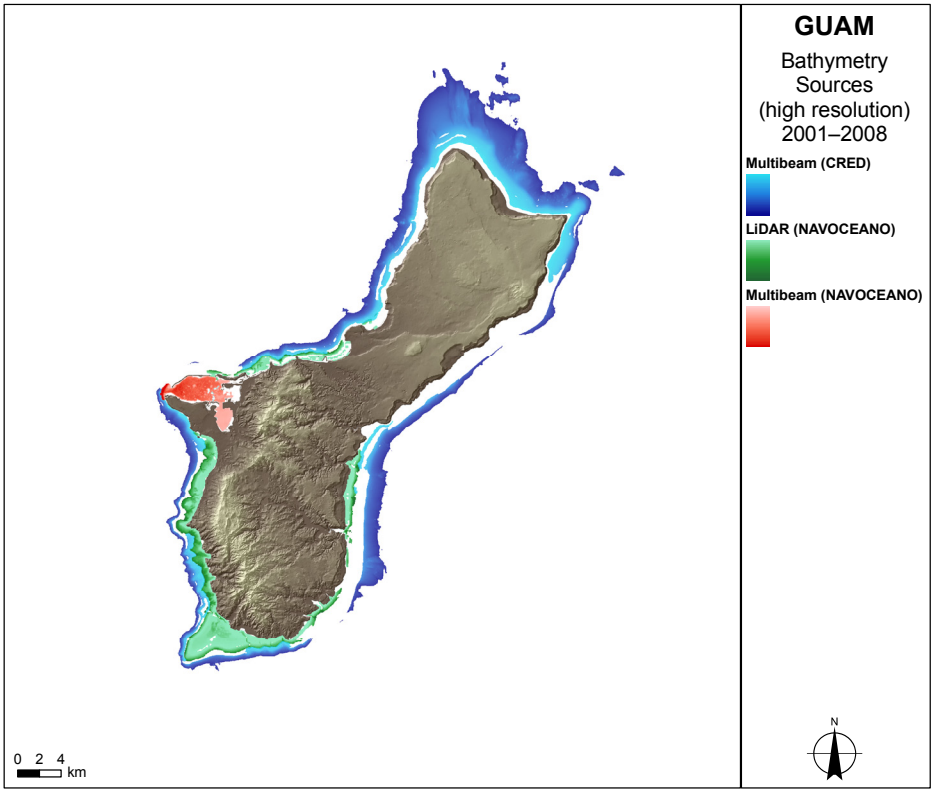


Figure 4.3.1b. Location of multibeam data collected by CRED (shown in blue), multibeam data collected by OCS and NAVOCEANO (shown in red), and lidar and singlebeam data collected by NAVOCEANO (shown in green).

Bathymetric data collected in nearshore (depths of 0–400 m) waters around Guam were combined into a grid at 5-m resolution to allow for the identification of fine-scaled features (Figs. 4.3.1c and f). These high-resolution data were used to derive maps of slope (Figs. 4.3.1d and g) and rugosity (Figs. 4.3.1e and h) for the 4 areas where the greatest coverage was achieved. Slope and rugosity around the whole island were derived from the 60-m bathymetric grids (Figs. 4.3.1i and j). Bathymetric position index (BPI) zones (Fig. 4.3.1k) were derived from the 60-m grid. Together, these maps provide layers of information to characterize the benthic habitats around Guam.

The 3 ridges extending north from Ritidian Point are shown in detail on the high-resolution bathymetry and slope maps (Figs. 4.3.1c and d, top panels) that highlight the steep slopes on the east side of these ridges. The shallow pavement on the north coast has several successively deeper platforms, the edges of which are identified by increased slope relative to their surrounding platforms. Steep slopes are also associated with areas of erosional debris in deep waters around Guam. The highest levels of rugosity (Fig. 4.3.1e, top panel) appear associated with the steepest slopes, suggesting that the topography in these areas may be rougher than in areas where slopes are less steep—although the high-rugosity values are also influenced by the slope itself.

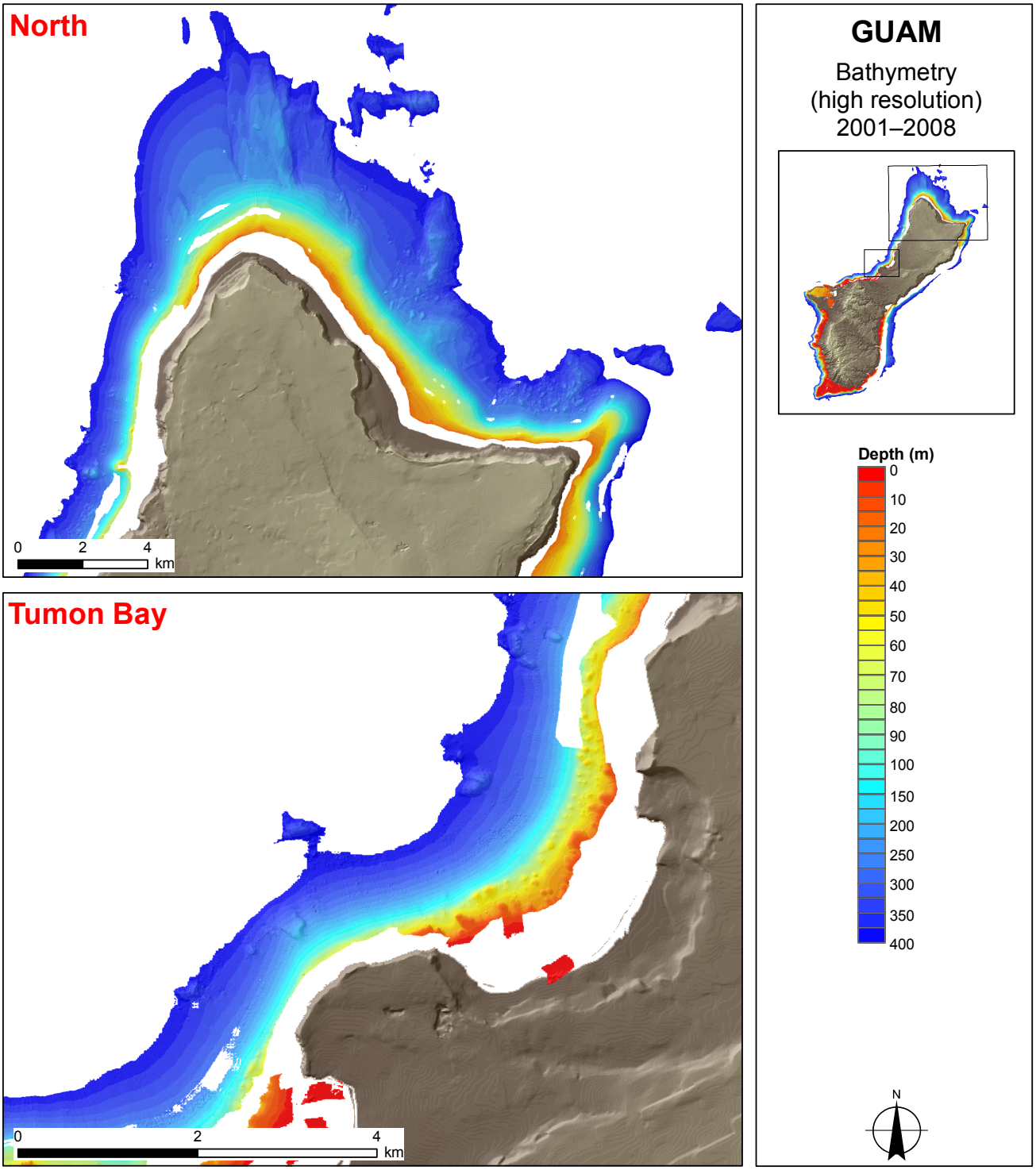


Figure 4.3.1c. High-resolution bathymetry (grid cell size: 5 m) collected between 2001 and 2008 (*top*) around north Guam and (*bottom*) in Tumon Bay.

Bathymetry (Fig. 4 3.1.c, bottom panel) within Tumon Bay shows that the shallowest mapped seabed is characterized by a series of spurs, the edges of which are delineated by their slopes and high rugosity (Figs. 4 3.1.d and e, bottom panels). The slope and rugosity maps reveal numerous small mounds.

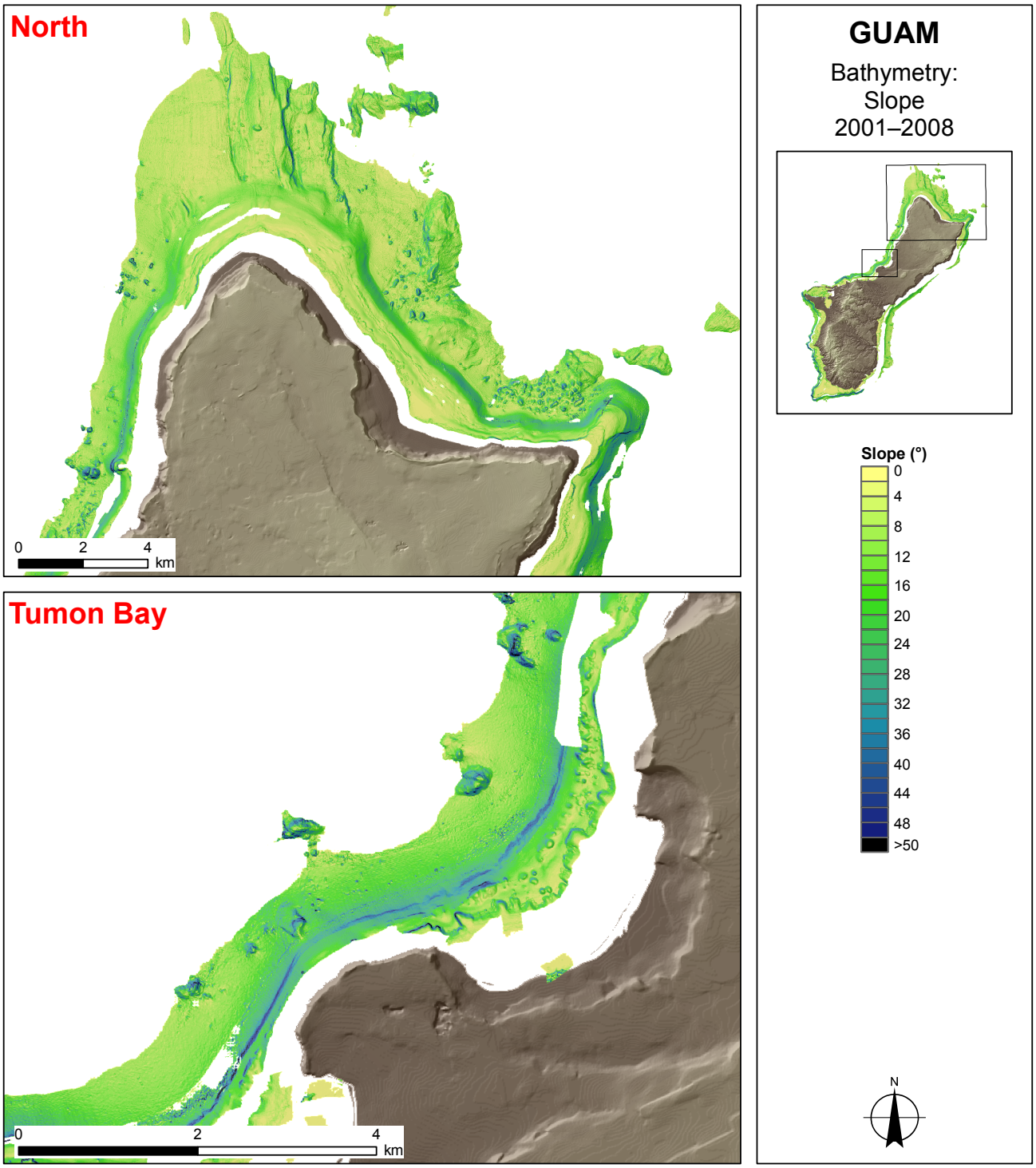


Figure 4.3.1d. Slope (°) of 5-m bathymetric grid (*top*) around north Guam and (*bottom*) in Tumon Bay. Derived from data collected between 2001 and 2008, these maps reflect the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest blue shades and the flattest areas in yellow shades.

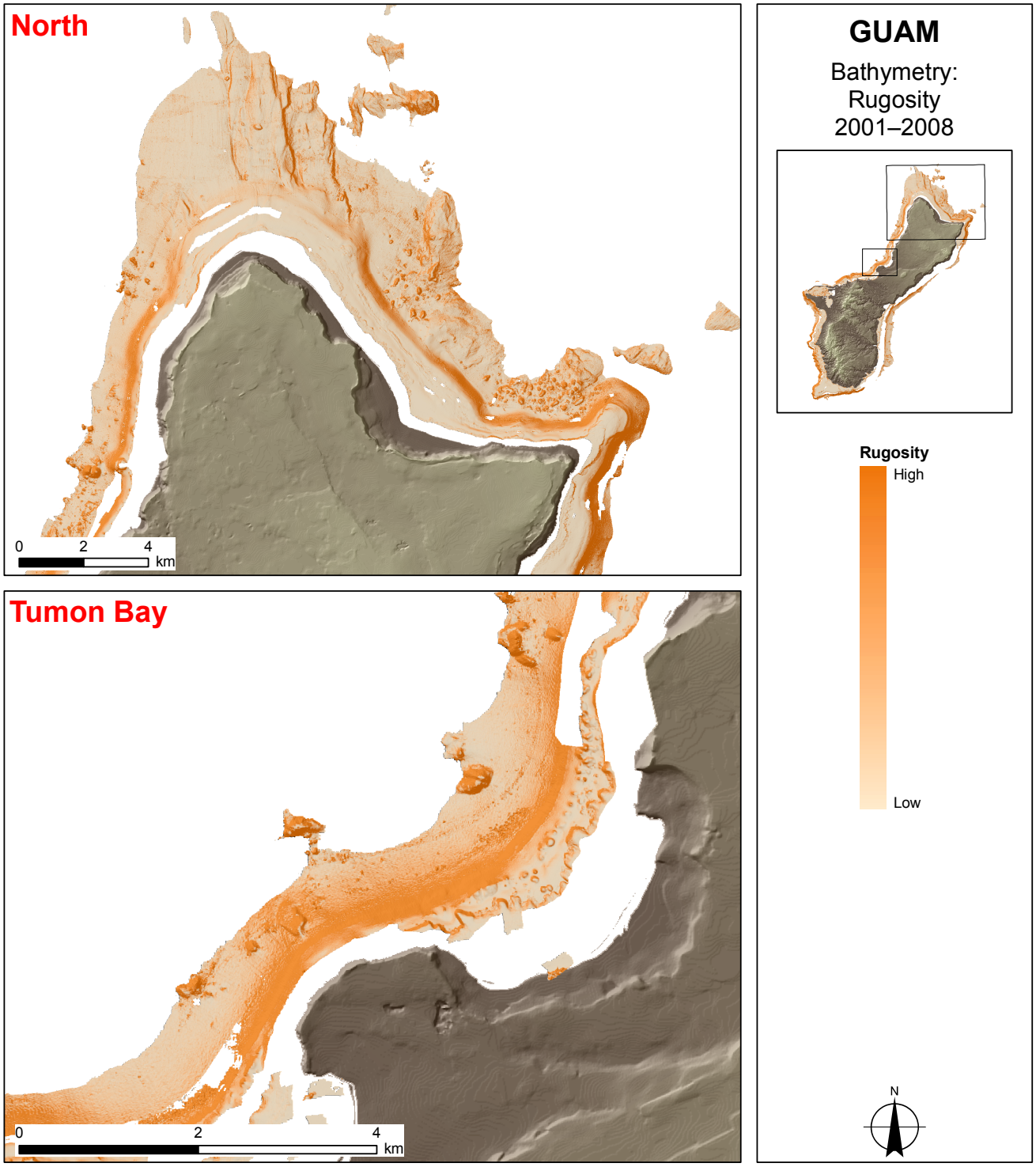


Figure 4.3.1e. Rugosity of 5-m bathymetric grid (*top*) around north Guam and (*bottom*) in Tumon Bay. Derived from data collected between 2001 and 2008, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness. Dark shades represent high rugosity and light shades represent low rugosity.

High-resolution bathymetric data acquired within Apra Harbor and along the south coast of the Orote Peninsula reveal some interesting topographic features. Within Apra Harbor, the available bathymetric data show numerous mounds up to 300 m in diameter (Fig. 4.3.1f, top panel), the edges of which are particularly accentuated by their high slopes in an otherwise naturally flat area of seabed, in contrast to the actively dredged areas of seabed within the inner harbor where no such mounds are found (Fig. 4.3.1g, top panel). Along the south coast of the Orote Peninsula, a number of narrow platforms are separated by very steep slopes. Within this area of interest, the BPI terrain analysis identifies very few areas of flat seabed, and the data as a whole suggest an area of high topographic complexity (Fig. 4.3.1k).

Lidar bathymetry of Cocos Lagoon suggests that much of the seabed within this lagoon is very shallow with depths < 2 m (Fig. 4.3.1f, bottom panel) and flat (Fig. 4.3.1g, bottom panel) with low rugosity (Fig. 4.3.1h, bottom panel). In the inner part of this lagoon, a deeper basin has depths of 4–8 m and mounds rising steeply to near the surface; this area in the north part of this lagoon can best be identified in the bathymetry (orange shades in Fig. 4.3.1f, bottom panel) and slope (Fig. 4.3.1g, bottom panel) plots. Within this area, 2 even deeper depressions have depths of 12–13 m. North of Cocos Lagoon, there is a series of submarine canyons. The slope and rugosity maps highlight very steep slopes along the canyon edges and a complex and rugged topography along the top of the canyons and on the ridges. These observations are supported by the BPI terrain analysis that reveals a seafloor landscape primarily characterized by slopes, ridges, and depressions (Fig.

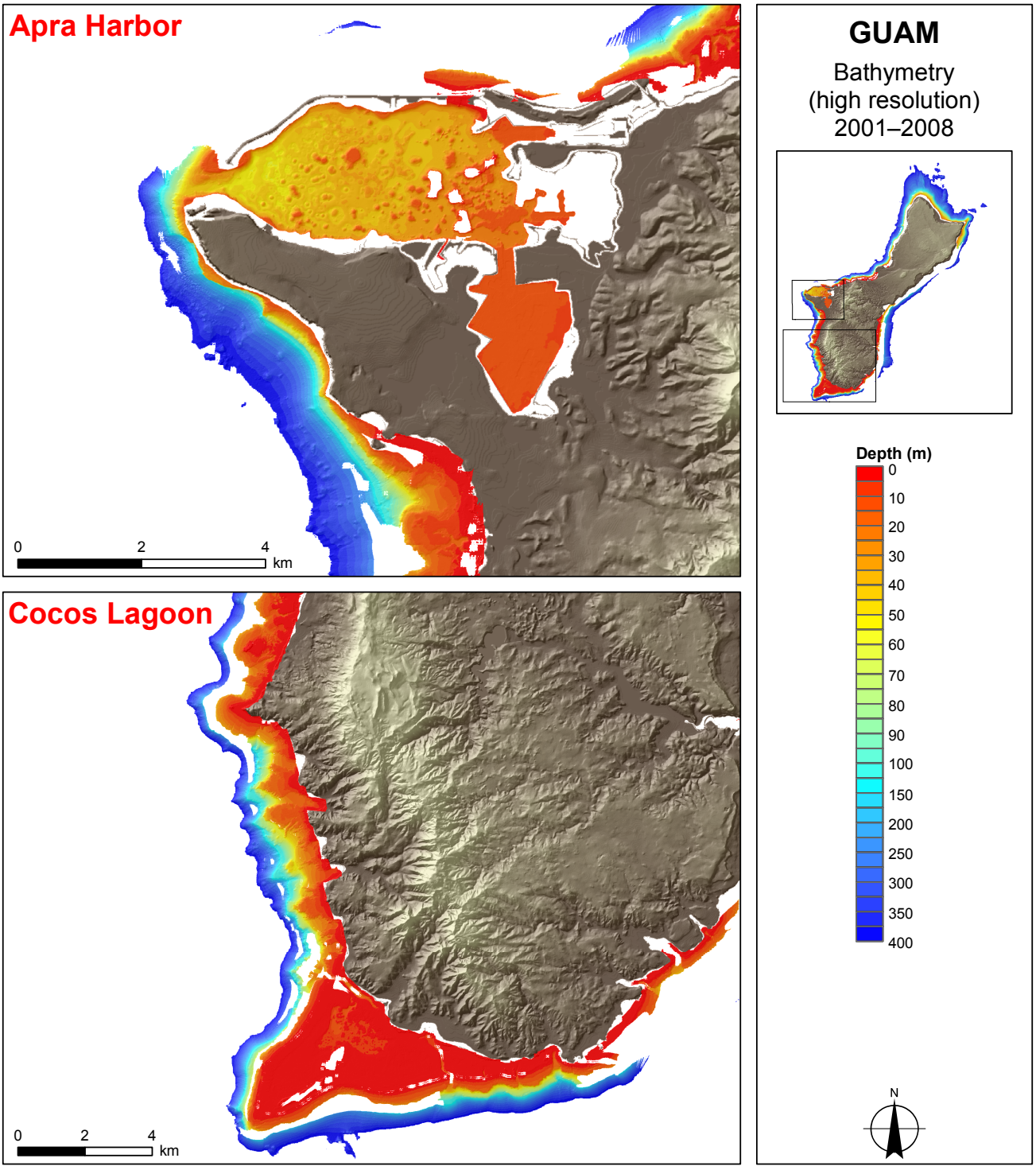


Figure 4.3.1f. High-resolution bathymetry (grid cell size: 5 m) collected between 2001 and 2008 within (*top*) Apra Harbor and (*bottom*) Cocos Lagoon.

4.3.1k). South of Cocos Lagoon, the high-resolution slope map shows a series of narrow flat platforms separated by steep slopes. Low rugosity values are observed on the top of these platforms with higher rugosity values on the slopes.

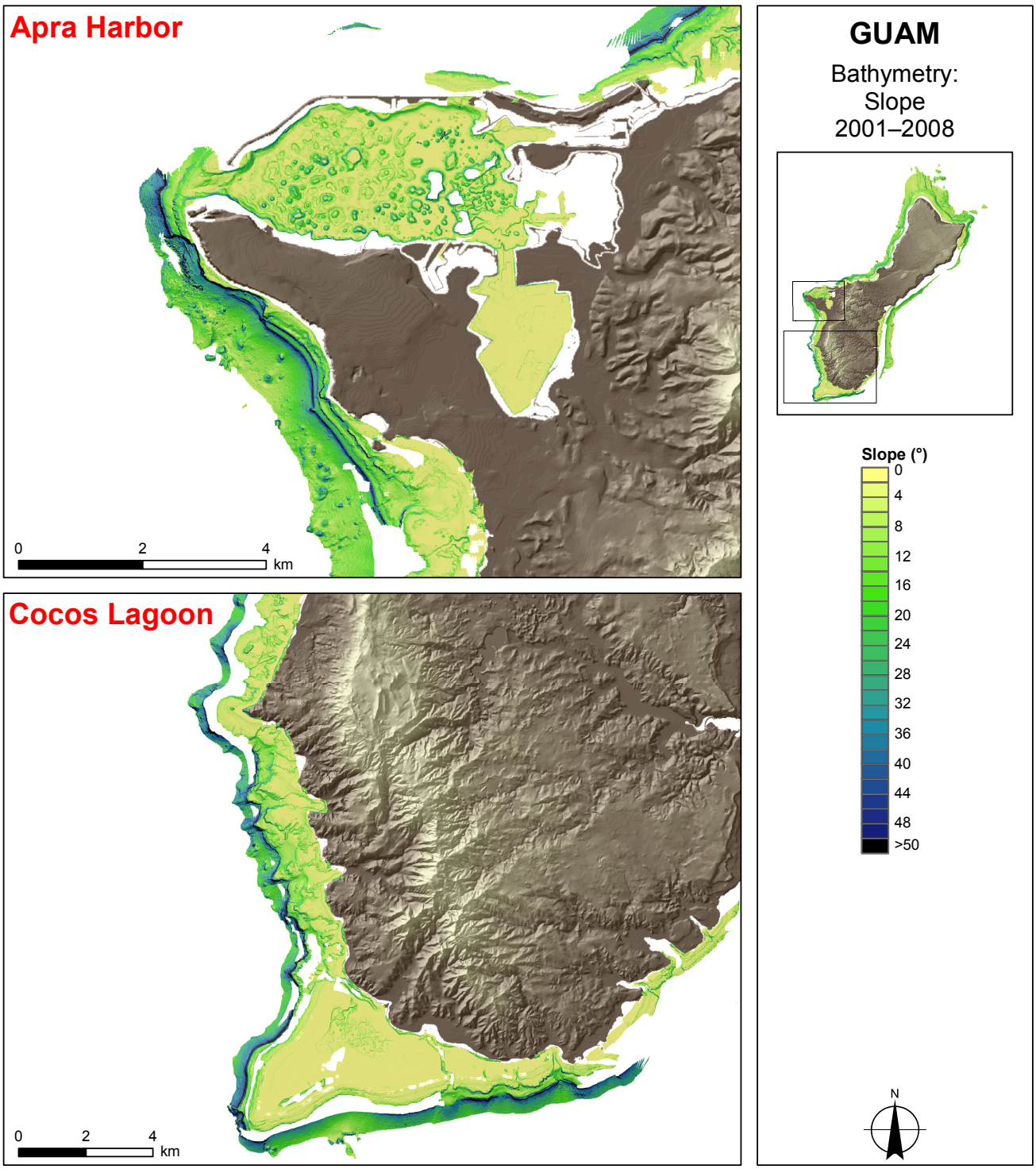


Figure 4.3.1g. Slope (°) of 5-m bathymetric grid within (*top*) Apra Harbor and (*bottom*) Cocos Lagoon. Derived from data collected between 2001 and 2008, these maps reflect the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest blue shades and the flattest areas in yellow shades.

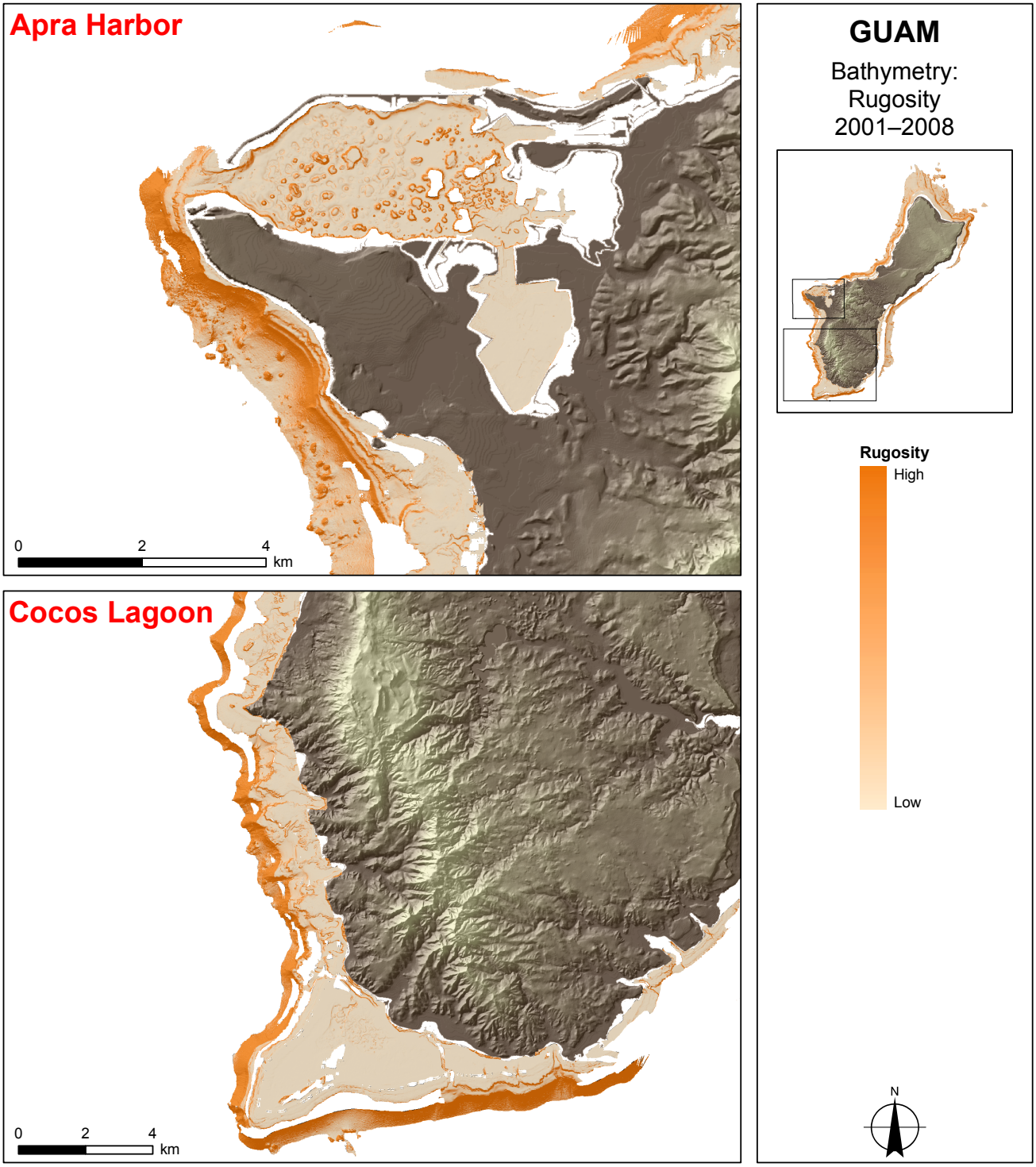


Figure 4.3.1h. Rugosity of 5-m bathymetric grid within (*top*) Apra Harbor and (*bottom*) Cocos Lagoon. Derived from data collected between 2001 and 2008, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness. Dark shades represent high rugosity and light shades represent low rugosity.

Slope and rugosity, derived from the low-resolution bathymetry data (60-m bathymetric grid), both highlight the different characters of the benthic habitats north and south of Guam that are also reflected in the onshore geology. The slope and rugosity maps (Figs. 4.3.1i and j) reveal a relatively flat, low-rugosity seabed around northern Guam, with very few steep slopes recorded, other than around Pati Point. Around southern Guam, the seabed topography is more varied with many areas of high slope and rugosity, particularly around the submerged canyons in Cetti Bay. Maximum recorded slopes are 50°–55°.

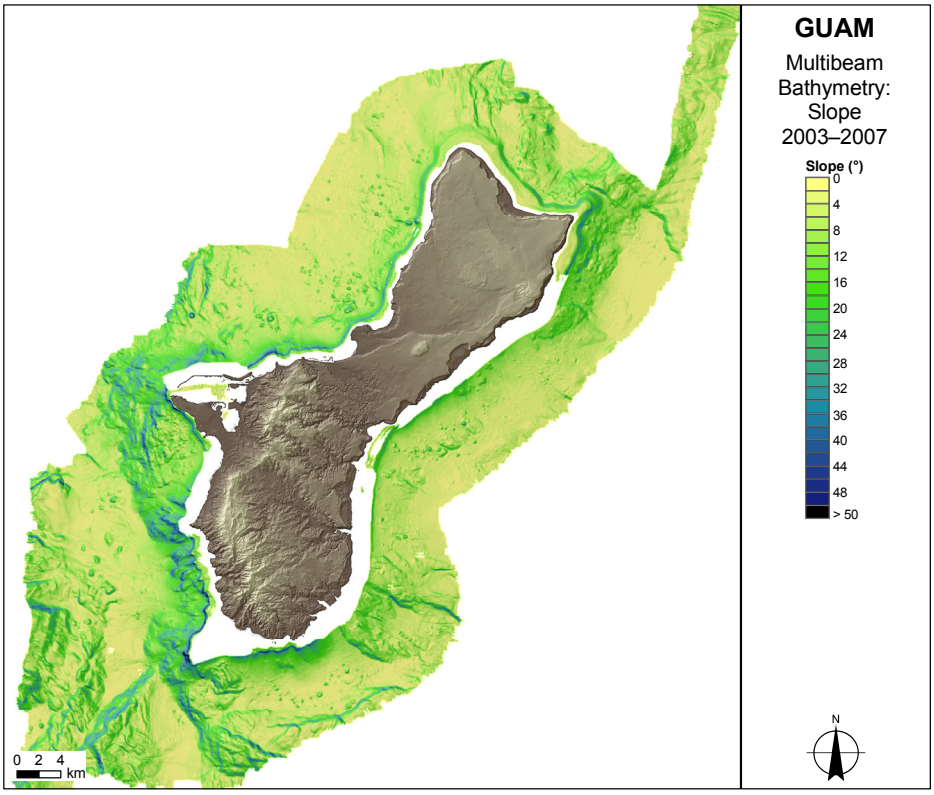


Figure 4.3.1i. Slope (°) of 60-m bathymetric grid around Guam. Derived from data collected between 2003 and 2007, these maps reflect the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest blue shades and the flattest areas in yellow shades.

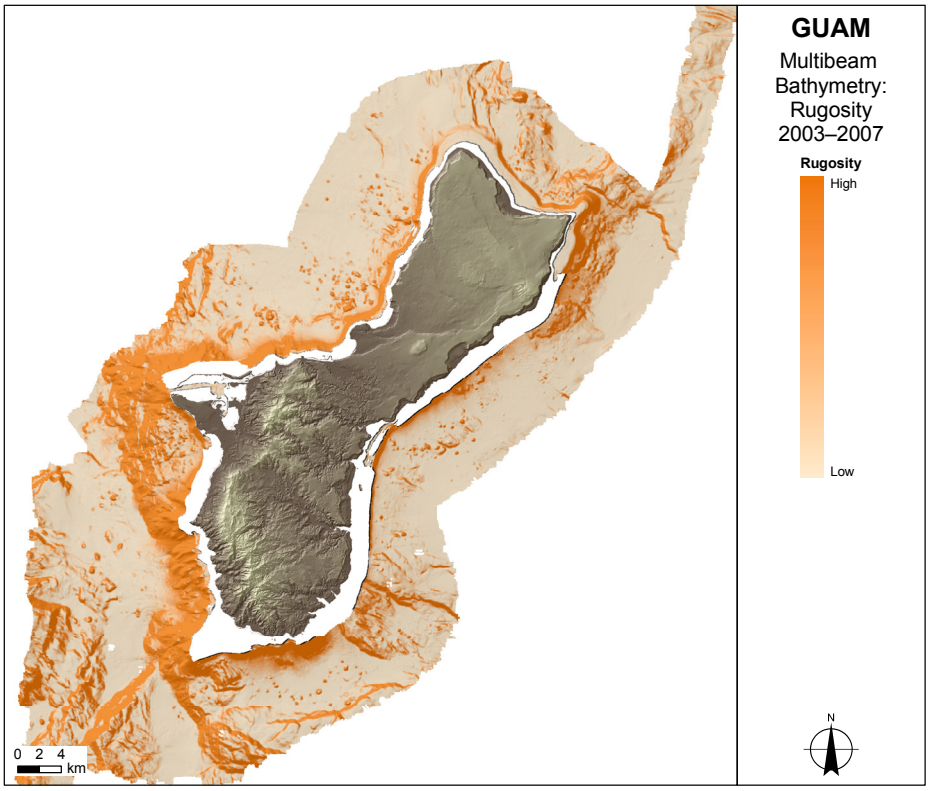


Figure 4.3.1j. Rugosity of 60-m bathymetric grid around Guam. Derived from data collected between 2003 and 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness. Dark shades represent high rugosity and light shades represent low rugosity.

The patterns revealed by the slope and rugosity maps are supported by what the BPI zones map (Fig. 4.3.1k) shows: the seabed around northern Guam is characterized predominantly by flats with slopes found close to shore. In the shallowest waters surveyed, the BPI analysis identifies reef crests. However, this classification is likely an artifact of the methodology, since no data are available for immediately inshore areas and no comparison can be made to the innermost cells of the grid. Instead, these areas probably should be characterized as slopes.

The seabed around southern Guam has a much more varied terrain, with a mixture of slopes, crests, and depressions associated with canyons and ridges. At the base of these slopes, a flat area corresponds to the deep channel identified in the multibeam bathymetry.

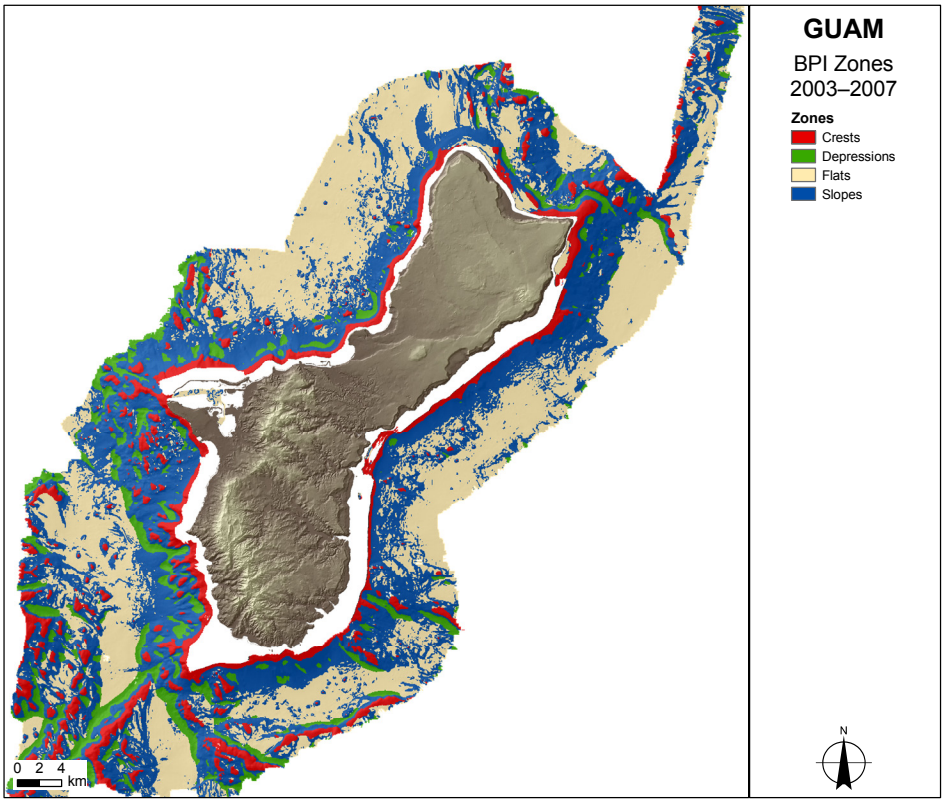


Figure 4.3.1k. BPI Zones of 60-m bathymetric grid around Guam derived from data collected between 2003 and 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—have been used in this analysis.

High-resolution Multibeam Backscatter and Derivatives

Because very little multibeam data were acquired in shallow water, discussion of the high-resolution backscatter data is limited here to 3 areas of interest: north Guam, Apra Harbor, and Cocos Lagoon. Since no obvious artifacts are observed within the very limited data collected, all of the shallow backscatter data were used to generate the hard–soft substrate map, and no clipping of the data was performed.

In northern Guam, high-intensity backscatter values that suggest a hard seafloor are seen along the top of the shallow shelf, and moderate backscatter values suggest increased sediments on the adjoining slopes (Fig. 4.3.1l, top panel). Where the seabed plateaus at a depth of ~ 200 m, low-intensity backscatter values suggest sediment areas. This distinction between the soft seabed in deep areas and the hard seabed on the shallow shelf and slope is reflected in the hard–soft classification (Fig. 4.3.1m, top panel). Low-intensity backscatter values are seen in a channel at the center of Jinapsan Beach, presumably a result of accumulated sediment lining the floor of the channel.

The hard–soft classification suggests that Apra Harbor is characterized by a mixture of hard and soft substrate, and the mound features seen in the slope map are generally characterized by hard substrate (Fig. 4. 3.1m, middle panel). South of Orote Peninsula, high backscatter values are observed on the shallow shelf area with lower values on the slopes. This pattern is shown on the hard–soft substrate map, suggesting a hard and shallow shelf descending to sediment-covered slopes.

Around the submerged canyons north of Cocos Lagoon, high-resolution backscatter data reveal high backscatter values on the canyon ridges and low values within the canyon gullies (Fig. 4. 3.1l, bottom panel). The hard–soft substrate map more clearly highlights this pattern of hard and soft substrates alternating between the ridges and gullies (Fig. 4. 3.1m, bottom panel). This pattern is likely caused by downward transport and accumulation of sediments within the canyons. Along the south coast, as in other parts of this island, the shallow shelf is characterized by high-intensity backscatter indicative of hard substrates, whereas the deeper slopes are characterized by low-intensity backscatter indicative of soft substrates.

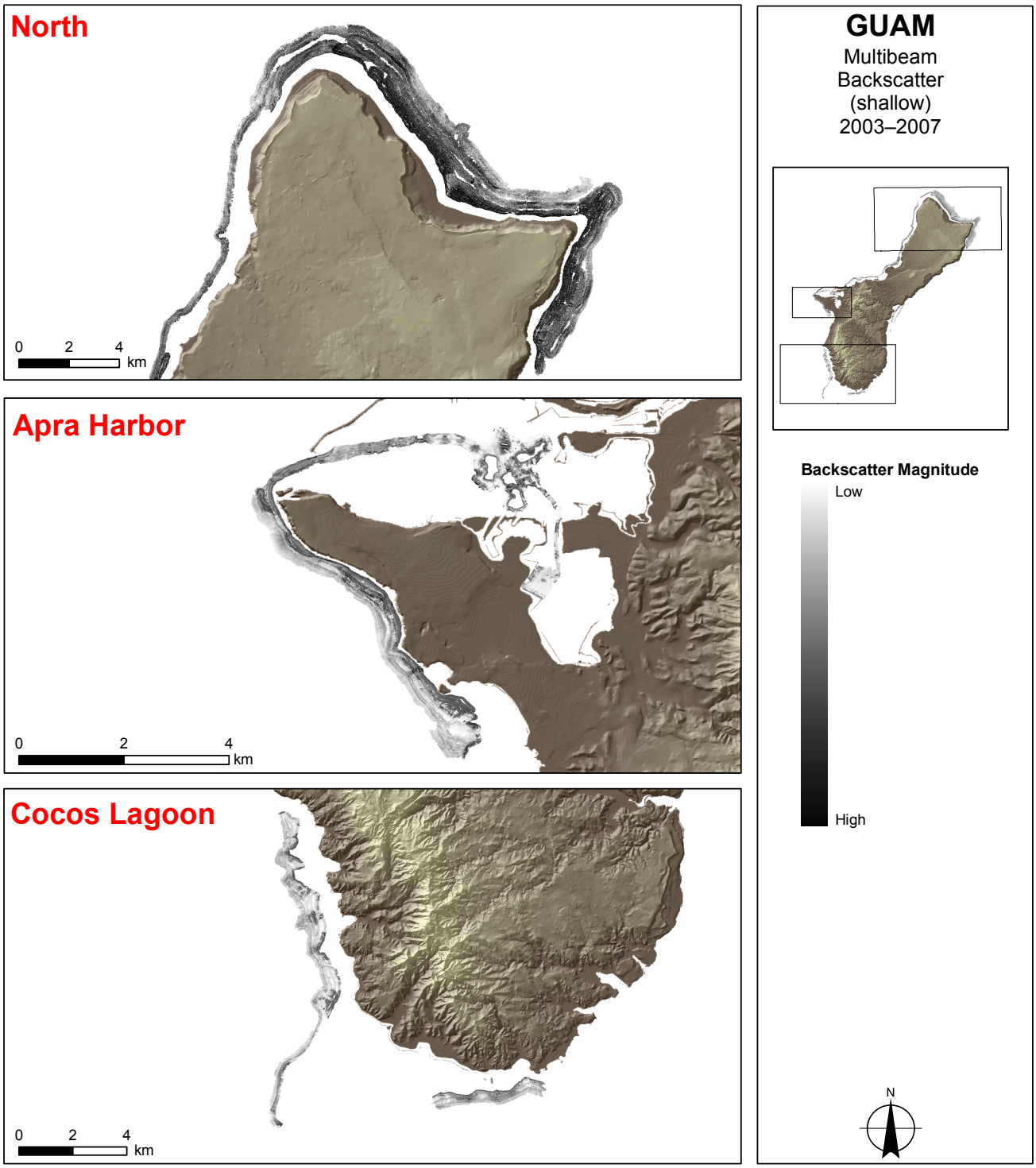


Figure 4.3.1l. Gridded, high-resolution, multibeam backscatter data (grid cell size: 5 m) collected within 3 areas of interest around Guam during MARAMP 2003 and 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

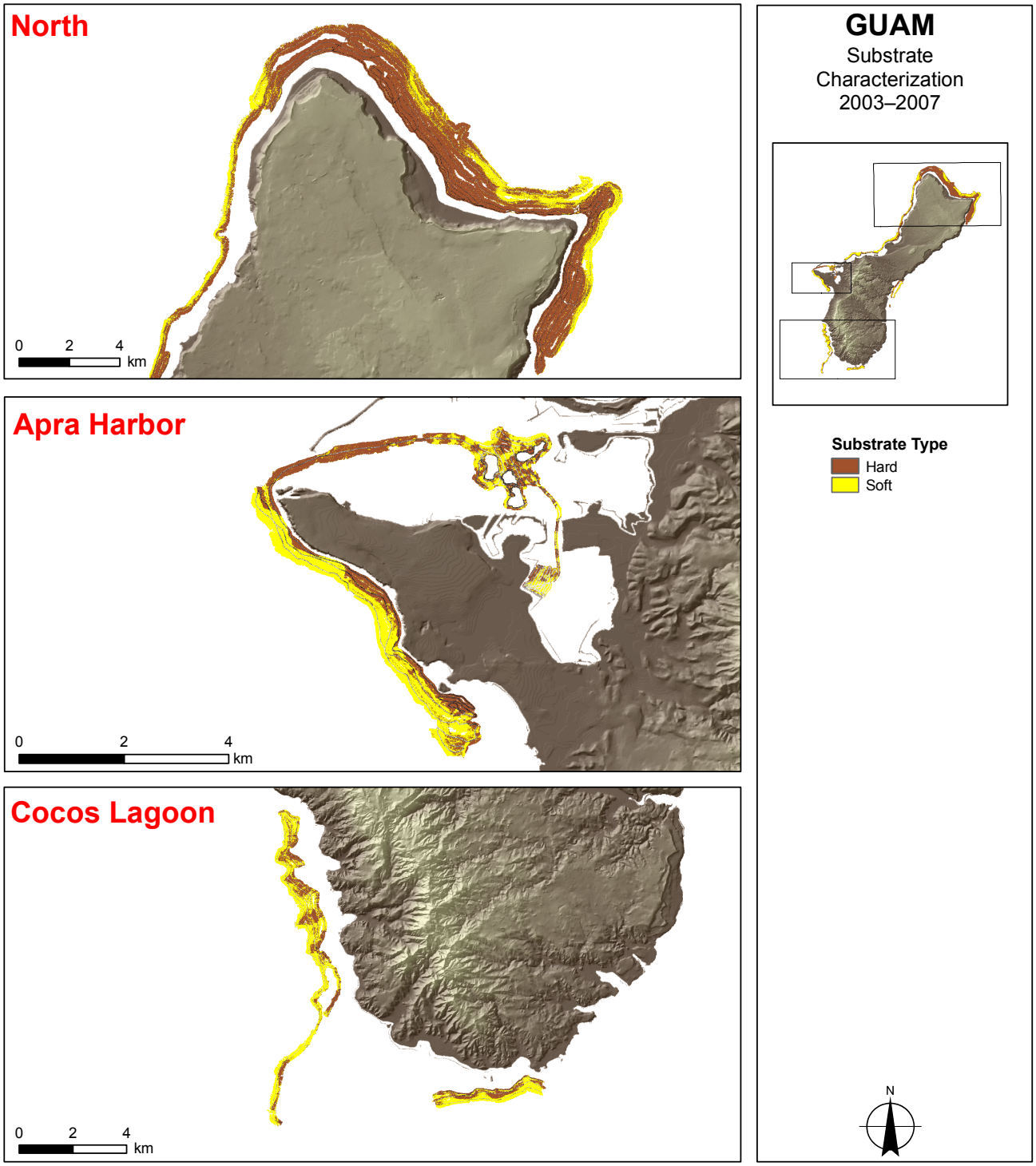


Figure 4.3.1m. Hard and soft substrates (grid cell size: 5 m) around or in (*top*) north Guam, (*middle*) Apra Harbor, and (*bottom*) Cocos Lagoon, based upon an unsupervised classification of multibeam bathymetry and backscatter data acquired around Guam between 2003 and 2007.

4.3.2 Optical Validation

During MARAMP 2003, 8 TOAD optical-validation surveys were conducted around Guam at depths of 15–200 m (Fig. 4.3.2a). Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live-hard-coral cover.

Covering a distance of 146 km at depths of 4–27 m, 62 towed-diver optical-validation surveys of forereef habitats were conducted around Guam during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

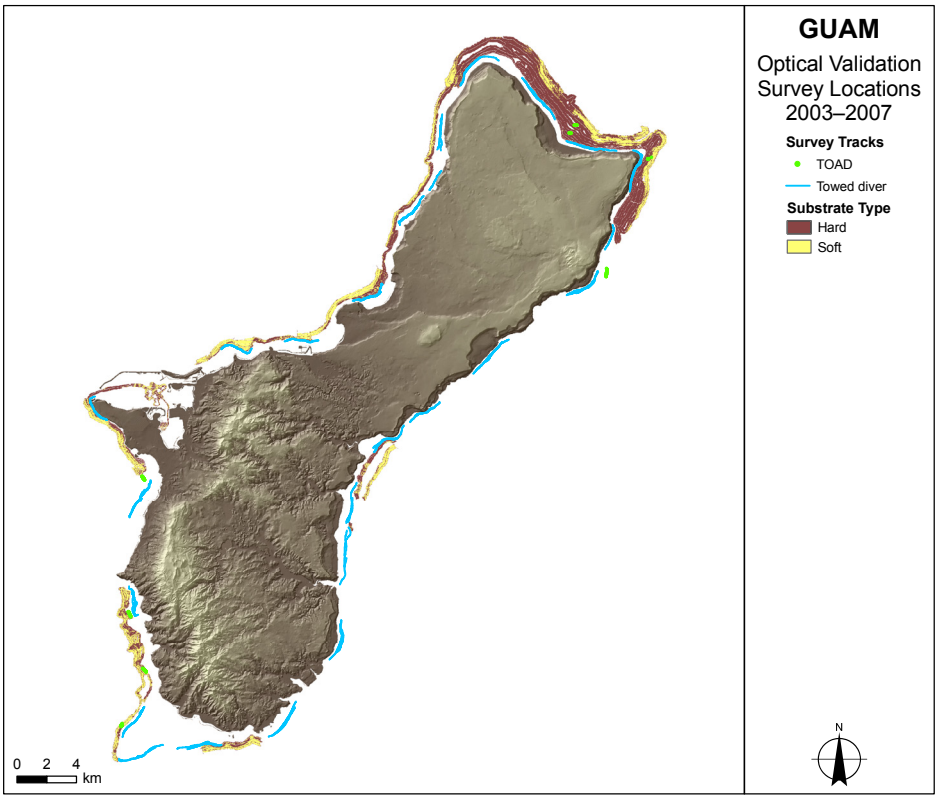


Figure 4.3.2a. Towed-diver tracks from surveys of forereef habitats conducted around Guam during MARAMP 2003, 2005, and 2007 and TOAD camera-sled tracks for MARAMP 2003. Survey tracks are displayed over the multibeam hard–soft substrate map. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

4.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Guam are discussed in this section. These descriptions are organized by the 5 geographic regions around Guam, beginning with the north region and moving clockwise. Sand cover observed by towed divers around Guam was low in most areas suggesting predominantly hard-substrate habitats in the nearshore environment; however, discrete patches of higher sand cover were noted at the mouths of some rivers (Fig. 4.3.3a). The extent to which these hard substrates supported live hard corals was variable (Fig. 4.3.3c). Habitat complexity around Guam was less variable, since it was predominantly classified as ranging from medium-low to medium-high; some areas outside of this range are noted later (Fig. 4.3.3b). The remainder of this section provides more detail about habitat complexity, live coral cover, and sand cover.

The habitats of low to medium complexity observed by towed divers around northern Guam were characterized by moderately low sand cover (< 30%). Higher sand cover was observed around Ritidian Point in the north region in an area of very low live coral cover. The highest levels of coral cover observed in this region were off Jinapsan Point and within the large bay to the east where interpolated live-coral-cover values of up to 62.5% were recorded. TOAD surveys were conducted in deeper waters north of this patch of high coral cover, but analyses of this acquired video suggested that there was no live coral cover and that the seabed was composed of unconsolidated sediment with macroalgae.

North of Pago Bay in the east region of Guam, habitats of medium-low to medium-high complexity were predominantly characterized by low sand cover with low cover of live corals. High sand cover was observed by towed divers at and just south of Campanaya Point. The highest coral cover within this area was around Catalina Point, where interpolated live coral cover reached 62.5%. Because it was not possible to fully classify video from the 2 TOAD surveys conducted off Pati Point, the sediment observed in that video footage was described as unconsolidated, but it was not possible to further discriminate the nature of this sediment. Live coral cover observed in video from these surveys was 40.1%–60% at a depth of ~ 55 m.

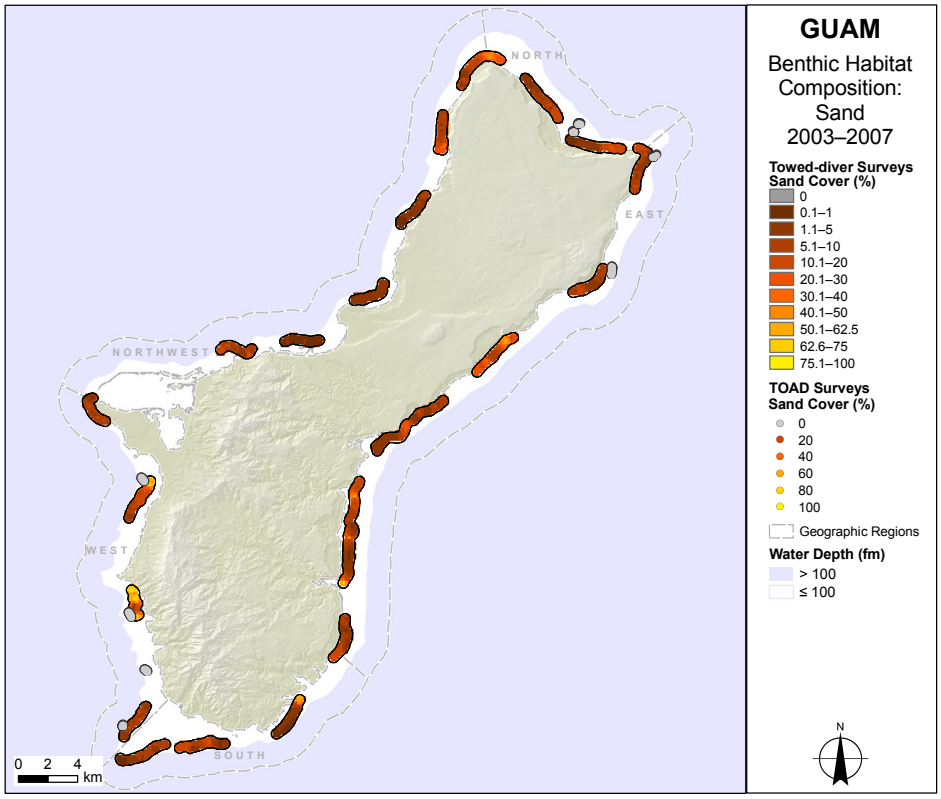


Figure 4.3.3a. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Guam during MARAMP 2003, 2005, and 2007.

From Pago Bay south to Agfayan Bay, live coral cover observed by towed divers was higher (10.1%–62.5%), in an area of low sand cover and habitat of medium-high complexity. In the south region, around the forereef of Cocos Lagoon, habitats of low to medium-low complexity support moderate cover of live corals (5.1%–50%).

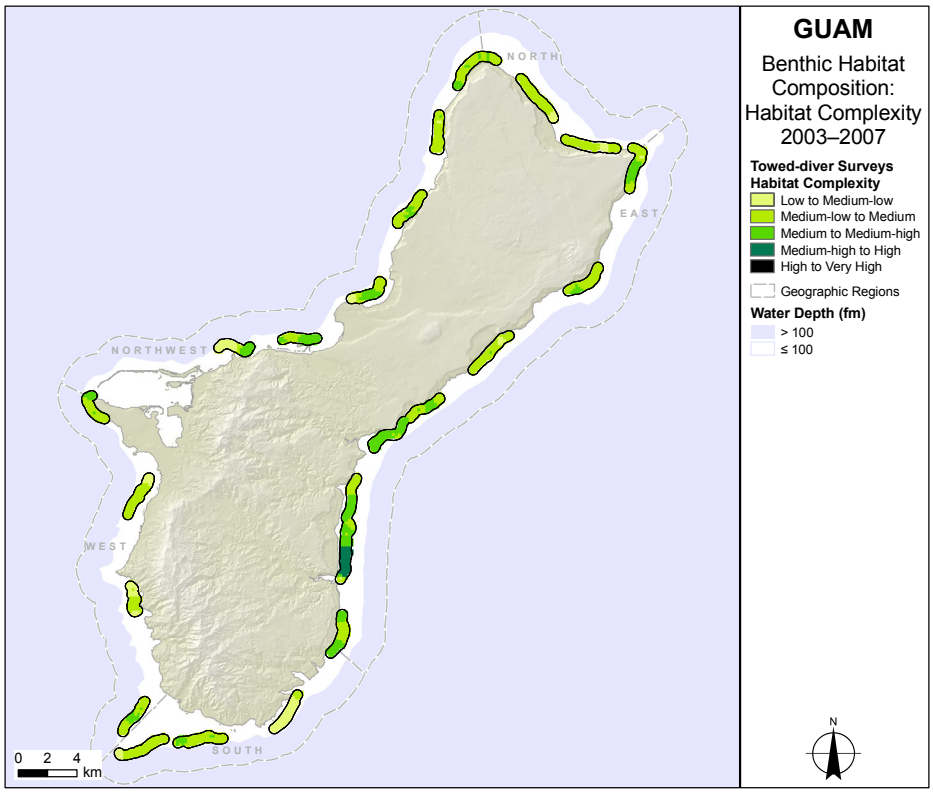


Figure 4.3.3b. Observations of benthic habitat complexity from towed-diver surveys of forereef habitats conducted around Guam during MARAMP 2003, 2005, and 2007.

Live coral cover observed by towed divers in the west region was consistently < 20%, and habitats there had low to medium complexity and were a mixture of hard and soft sediment with the sandiest areas found at the mouth of Namo River and within Sella Bay. The soft sediment habitat observed by Namo River was not seen in the TOAD video obtained farther offshore at depths of 16–32 m, where sand cover was 0% and the habitats encountered were predominantly characterized by hard substrates. No live coral cover was observed within this TOAD video footage. Analyses of video from a TOAD survey made within Sella Bay showed mixed substrates, with 3 video frames at depths of 28 m, 43 m, and 50 m suggesting that live coral cover was 20% there. Analyses of video footage from 2 TOAD surveys conducted in Cetti Bay and west of Cocos Lagoon at depths of 42–204 m suggested no live coral cover, and substrates there were mainly classified as 100% unconsolidated sediment, as video quality precluded distinguishing between sand and other unconsolidated sediments.

In the northwest region, habitat complexity recorded by towed divers was predominantly categorized as medium-low to medium. Very low sand cover was observed, and coral cover was variable, with interpolated live coral cover ranging from 0.1%–1% to 40.1%–50%, with the highest levels recorded south of Haputo Point.

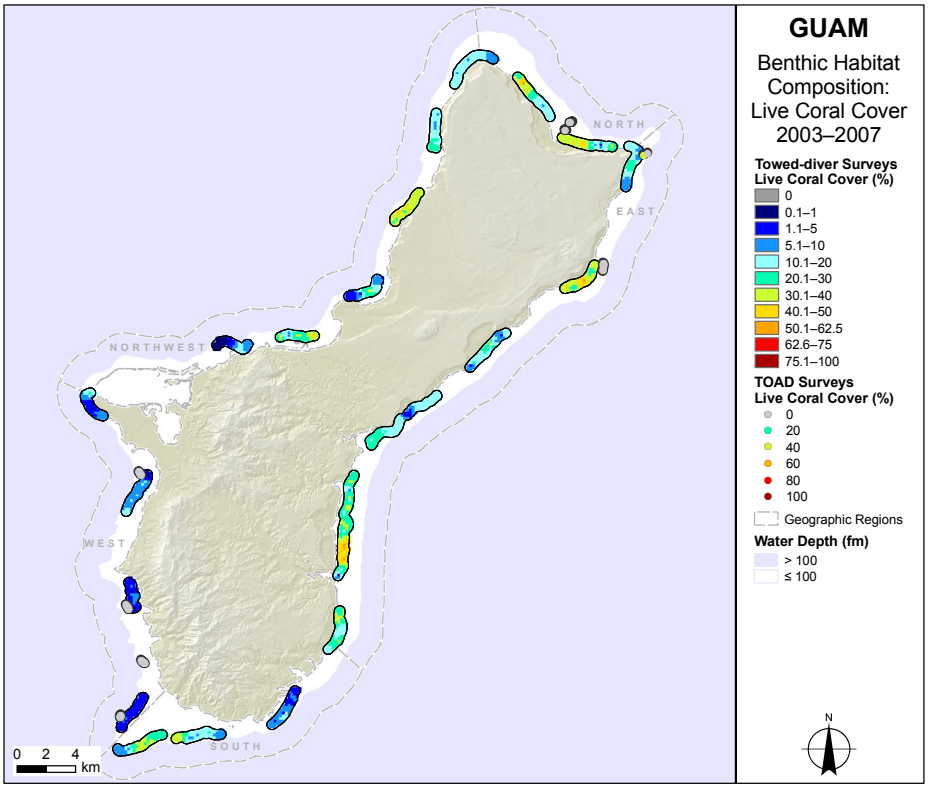


Figure 4.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Guam during MARAMP 2003, 2005, and 2007.

4.4 Oceanography and Water Quality

4.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 29 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters at the island of Guam over the period of September 22–25. Temperature, salinity, and density values from these casts varied both spatially and vertically. Spatial comparisons of water properties at a depth of 10 m suggest a moderate range in temperature (0.68°C) values, with waters in the west and northwest regions warmer than waters in the north and

east regions (Fig. 4.4.1a). Vertical comparisons of CTD profiles (Fig. 4.4.1b) reveal water properties with broad ranges in temperature (1.5°C), salinity (1.5 psu), and density (1.3 kg m^{-3}) values. Two areas with cool temperature (~ 28.7°C), high salinity (~ 34.7 psu), and high density (~ 21.9 kg m^{-3}) values, relative to other cast locations at Guam, were recorded: one at the northeast end of this island near Pati Point (casts 12–15) and the other also in the east region but farther south (casts 17–22, for place-names and their locations, see Figure 4.2a in Section 4.2: "Survey Effort"). Both of these cool areas likely were formed by local upwelling processes. Mild vertical mixing by easterly trade winds of relatively cool, saline, and turbid waters was apparent along the entire east region. The highest temperatures from CTD casts at Guam of ~ 30.2°C—corresponding with relatively low salinities of ~ 34 psu and low densities of ~ 21 kg m^{-3}—were recorded in the west region (casts 23–27) in Cetti, Sella, and Facpi Bays and in Apra Harbor in the northwest region (cast 1). In these areas, sheltered from easterly winds by the mountains in the south of Guam, vertical mixing upward of deeper, cooler subsurface waters did not occur.

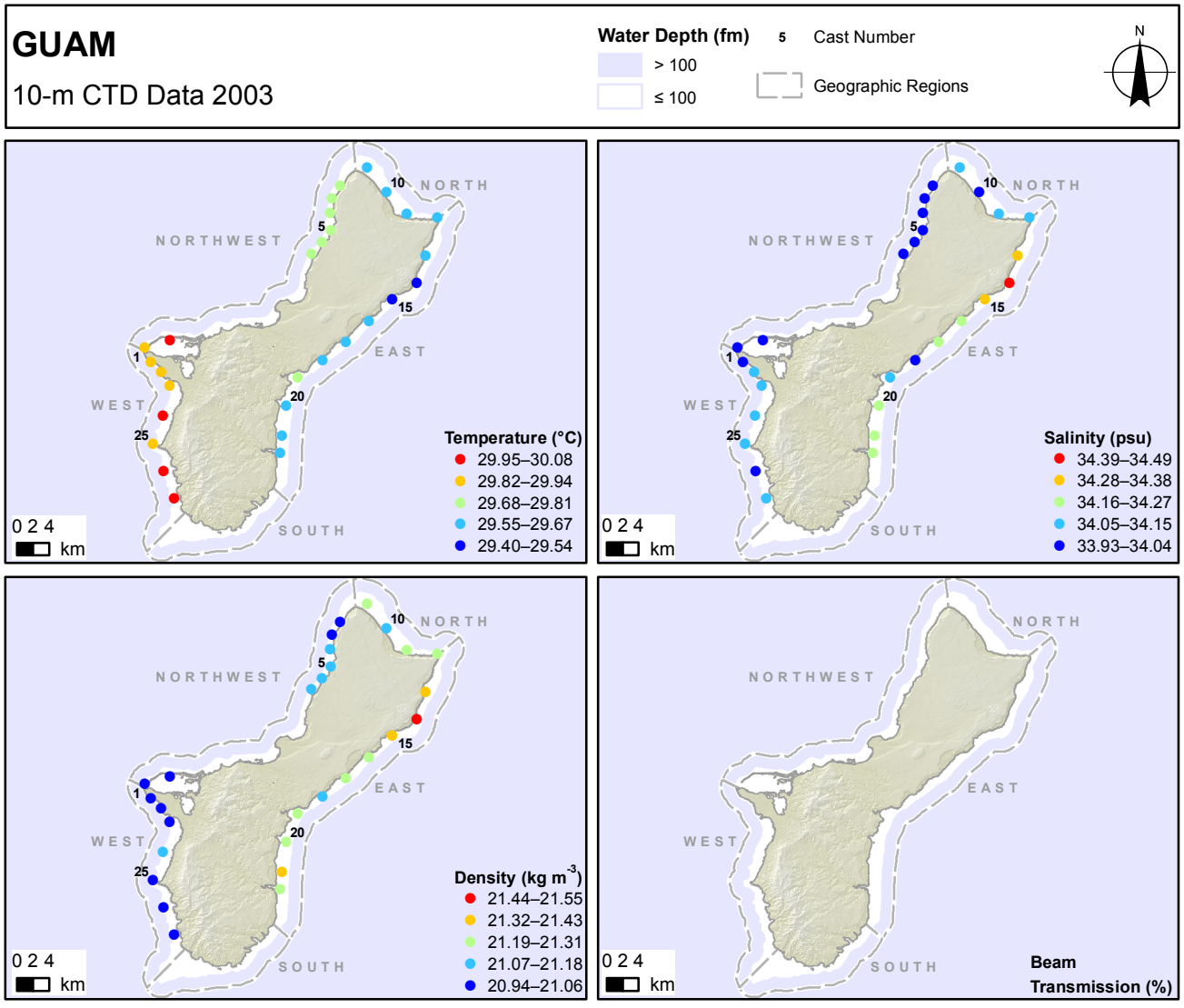


Figure 4.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts at Guam on September 22–25 during MARAMP 2003.

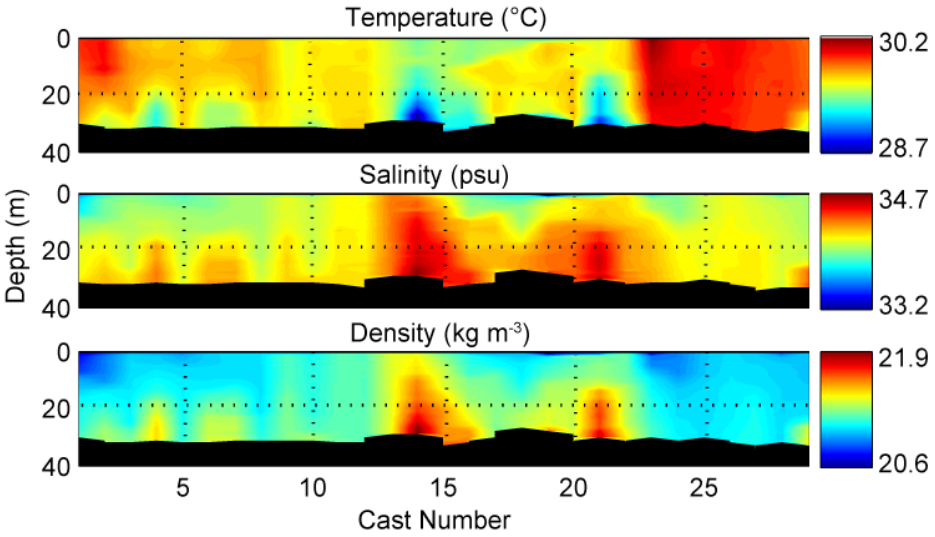


Figure 4.4.1b. Shallow-water CTD cast profiles to a 30-m depth at Guam on September 22–25 during MARAMP 2003, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–29 in a clockwise direction around Guam. For cast locations and numbers around this island in 2003, see Figure 4.4.1a.

2005 Spatial Surveys

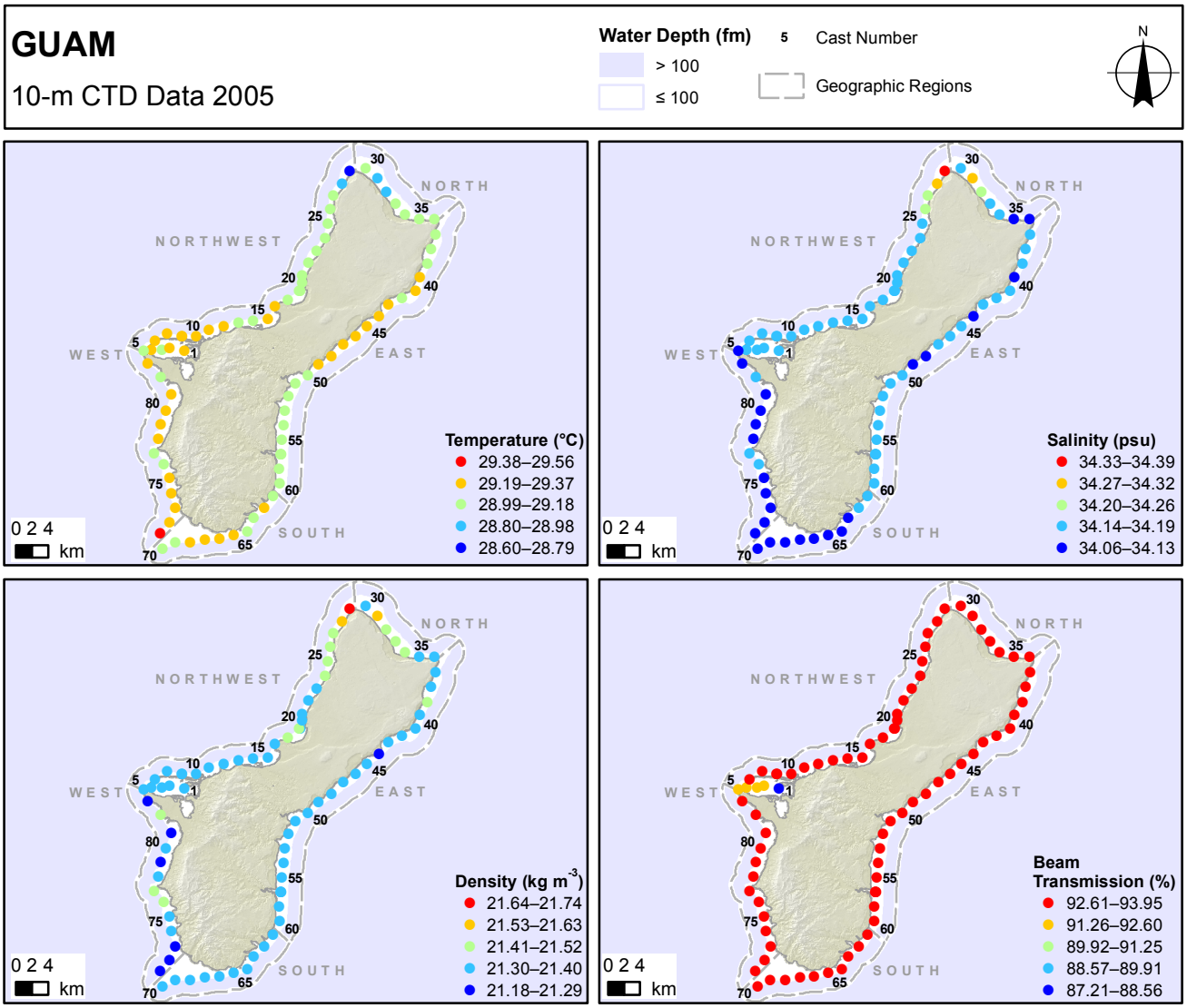


Figure 4.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Guam on October 3–8 during MARAMP 2005.

During MARAMP 2005, 83 shallow-water CTD casts were conducted in nearshore waters around Guam over the period of October 3–8. Temperature, salinity, density, and beam transmission values from these casts varied both spatially and vertically (Figs. 4.4.1c and d). Spatial comparisons of water properties at a depth of 10 m suggest broad ranges around this island: temperature differences as large as 0.96°C with warm water in the west region (cast 71) off Cocos Island and cool water in the northwest region (cast 29) near Ritidian Point (Fig. 4.4.1c). Vertical comparisons of CTD profiles (Fig. 4.4.1d) reveal water properties with broad ranges in temperature (1.6°C), salinity (0.9 psu), density (1.1 kg m^{-3}), and beam transmission (23.6%) values. At the northwest corner of this island around Ritidian Point (cast 29), an intrusion of waters was recorded with cool temperatures of ~ 28.4°C, high salinities of ~ 34.4 psu, and high densities of ~ 21.8 kg m^{-3}, relative to other cast locations around Guam. A series of weaker, cold-water intrusions, similar in both depth (20–30 m) and magnitude to the one in the northwest, were documented around the remainder of Guam (casts 51–52, 59–60, 77–78, and 82). These features were likely formed by the same physical forcing mechanism that resulted in the upwelling of deep water to the near surface. A high temperature of ~ 29.9°C, low salinity of ~ 34 psu, and low density of ~ 21 kg m^{-3} were recorded for surface waters in the west region (cast 71). This warm area probably is associated with surface heating, since it is sheltered from easterly winds by the mountains in southern Guam. Beam transmission values were lowest in Apra Harbor with 70.4% but varied little around the rest of island with 92%–94%.

Water samples were collected in concert with shallow-water CTD casts at select locations around Guam in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.25–1.09 µg L^{-1}; total nitrogen (TN), 0.04–0.40 µM; nitrate (NO_3^-), 0.03–0.34 µM; nitrite (NO_2^-), 0.02–0.07 µM; phosphate (PO_4^{3-}), 0.00–0.03 µM; and silicate [$Si(OH)_4$], 0.20–0.98 µM. Minimum phosphate values (0.00) were below measureable levels. Based on data from 8 sample locations, nearly all parameters were lowest in the south region and the southernmost area in the east region (Fig. 4.4.1e). Compared to conditions around the rest of Guam, Chl-*a*, phosphate, and silicate concentrations were all high inside heavily industrialized Apra Harbor, which is in the southern end of the northwest region. Farther north in the same region, total nitrogen, nitrate, and nitrite values were all highest at Tumon Bay. Elevated nutrient and Chl-*a* levels within Apra Harbor are likely a result of high residence times within this anchorage and potentially an outcome of high runoff. Also, lower concentrations of nitrogen and elevated levels of Chl-*a* within this harbor, relative to other locations around Guam, could indicate terrestrial runoff is enhancing biological productivity there.

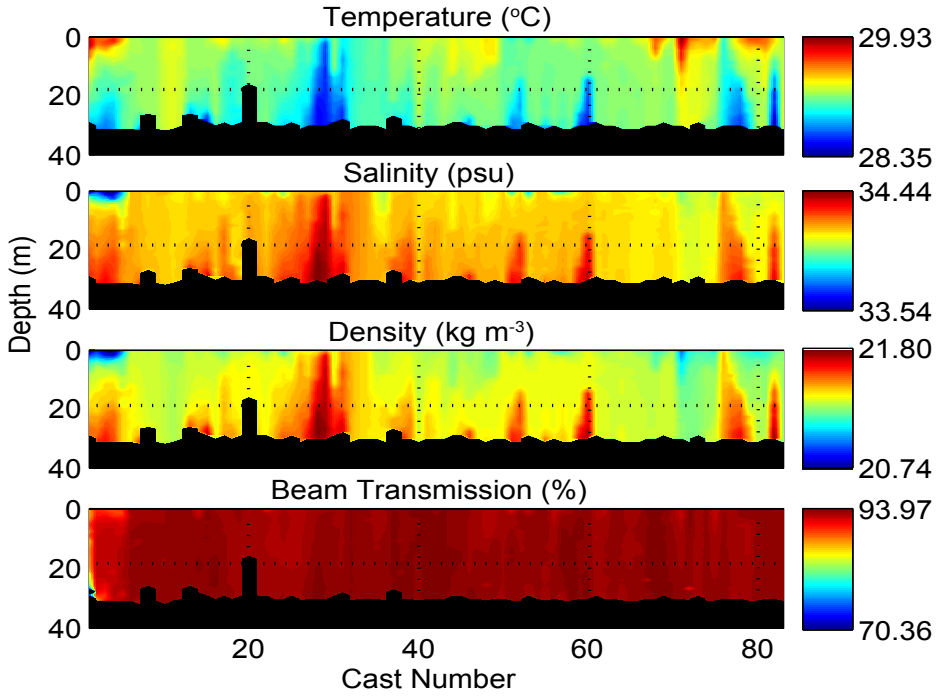


Figure 4.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Guam on October 3–8 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in the graph above, correspond to cast locations that are numbered sequentially 1–83 in a clockwise direction around Guam. For cast locations and numbers around this island in 2005, see Figure 4.4.1c.

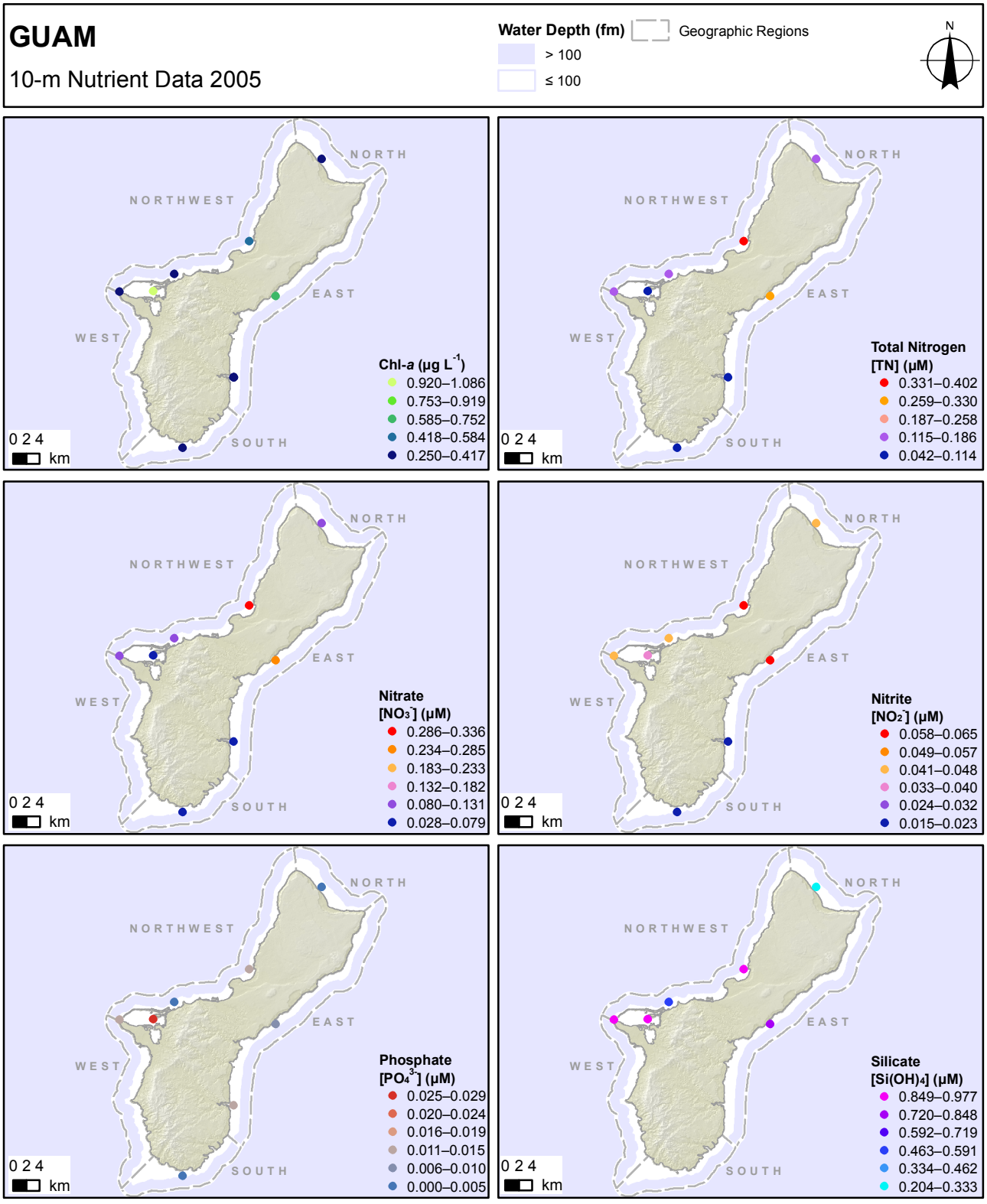


Figure 4.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected around Guam on October 3–8 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, shallow-water CTD casts were conducted in nearshore waters around Guam over the period of May 11–15. Temperature, salinity, density, and beam transmission values from 40 of these casts varied both spatially and vertically (Figs. 4.4.1f and g). Spatial comparisons of water properties at a depth of 10 m suggest moderate ranges around this island with temperature differences as large as 0.6°C (Fig. 4.4.1f). The northern part of the west region near Agat Bay and the northwest and north regions (casts 38–17), compared to other cast locations around Guam, had cool temperatures of ~ 28.47°C, high salinities of ~ 34.36 psu, and high densities of ~ 21.76 kg m^{-3}. In the east and south regions of Guam from Pati Point to Cocos Island (casts 18–34), relatively warm temperatures of ~ 29.07°C, low salinities of ~ 34.18 psu, and low densities of ~ 21.46 kg m^{-3} were recorded. Vertical comparisons of CTD profiles (Fig. 4.4.1g) reveal water properties with broad ranges in temperature (1.3°C), density (0.7 kg m^{-3}), and beam transmission (6.1%) values and a moderate range in salinity (0.3 psu) values. Strong gradients in water properties were documented near Pati Point, the northeastern tip of this island (cast 17). Additionally, near Togcha Bay in the east region, an intrusion of cold water with a temperature of 27.9°C was recorded below the area of surface waters with the warmest temperature of 29.2°C (cast 27). Beam transmission around Guam showed a weak positive correlation with temperature and varied broadly by ~ 6%—except in Apra Harbor, where beam transmission of 88.3% was the lowest value around this island.

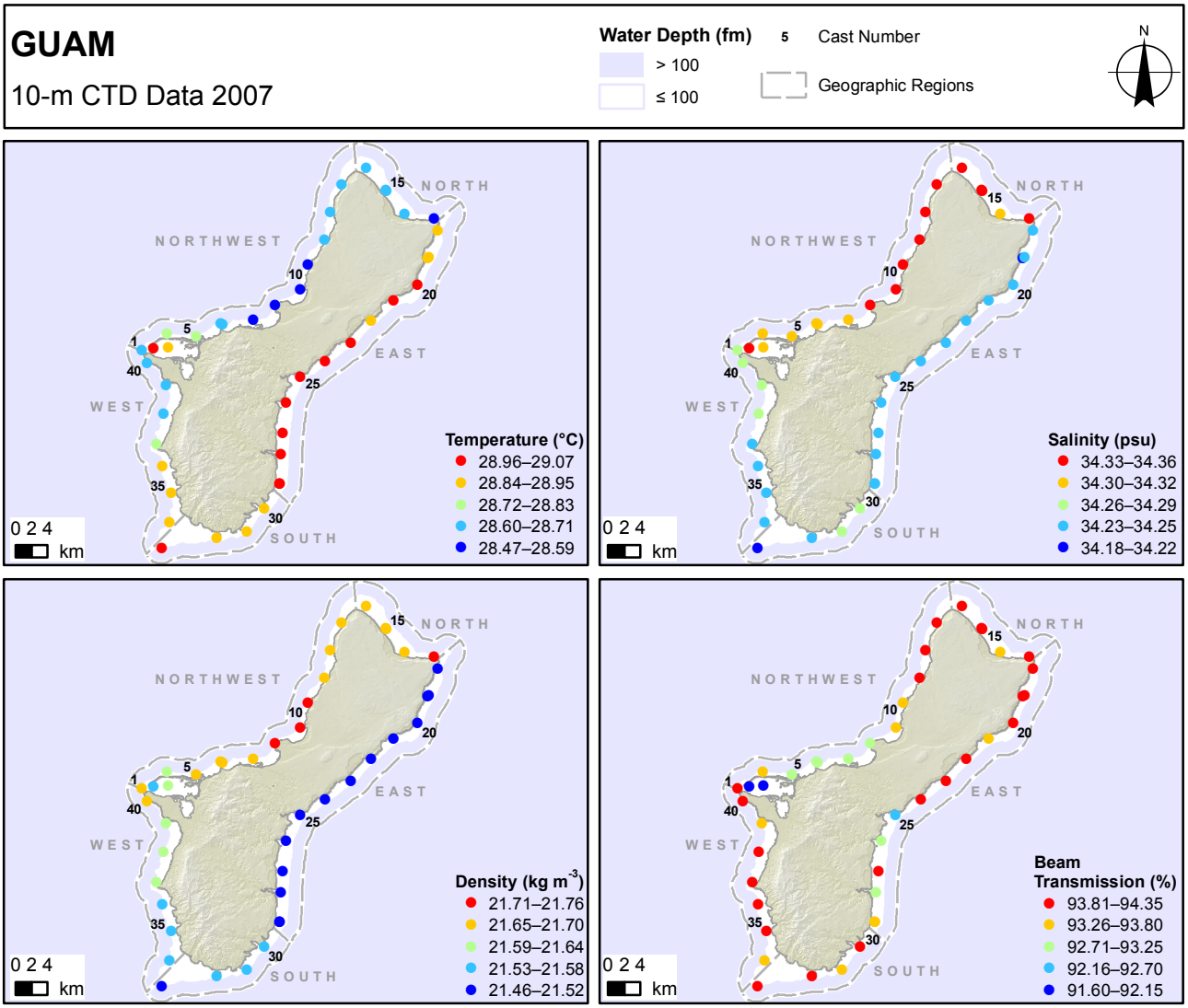


Figure 4.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Guam on May 11–15 during MARAMP 2007.

Water samples were collected in concert with shallow-water CTD casts at 13 select locations around Guam in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: Chl-*a*, 0.01–0.27 µg L^{-1}; total nitrogen (TN), 0.01–0.23 µM; nitrate (NO_3^-), 0.00–0.22 µM; nitrite (NO_2^-), 0.01–0.02 µM; phosphate (PO_4^{3-}), 0.02–0.12 µM; and silicate [$Si(OH)_4$], 0.75–1.68 µM. Minimum nitrate values (0.00) were below measureable levels. Based on data from these samples around Guam, the greatest Chl-*a* value was recorded in the northwest region, where nitrite was also at peak concentration. In the west region, nearly all parameters were at their lowest concentrations, with the exception of nitrite, which was in the middle of the observed range of values for Guam. Elevated levels of Chl-*a*, silicate, and nitrite concentrations were found in Apra Harbor. Nitrite concentrations were also elevated just outside this harbor, but all other measured parameters were recorded in the middle to low end of the observed ranges for Guam.

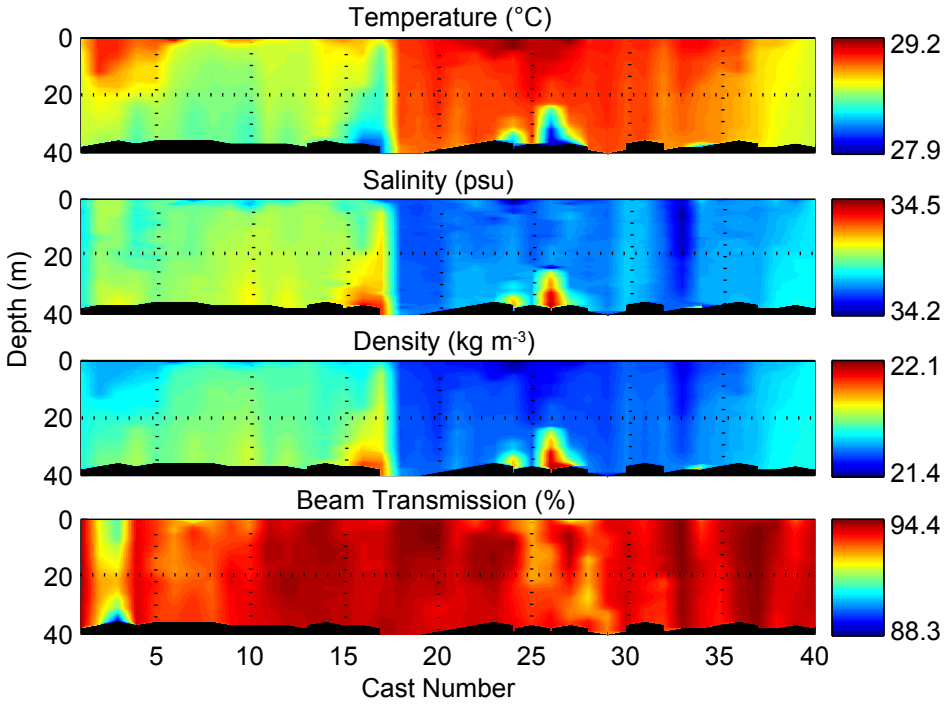


Figure 4.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Guam on May 11–15 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–40 in a clockwise direction around Guam. For cast locations and numbers around this island in 2003, see Figure 4.4.1f.

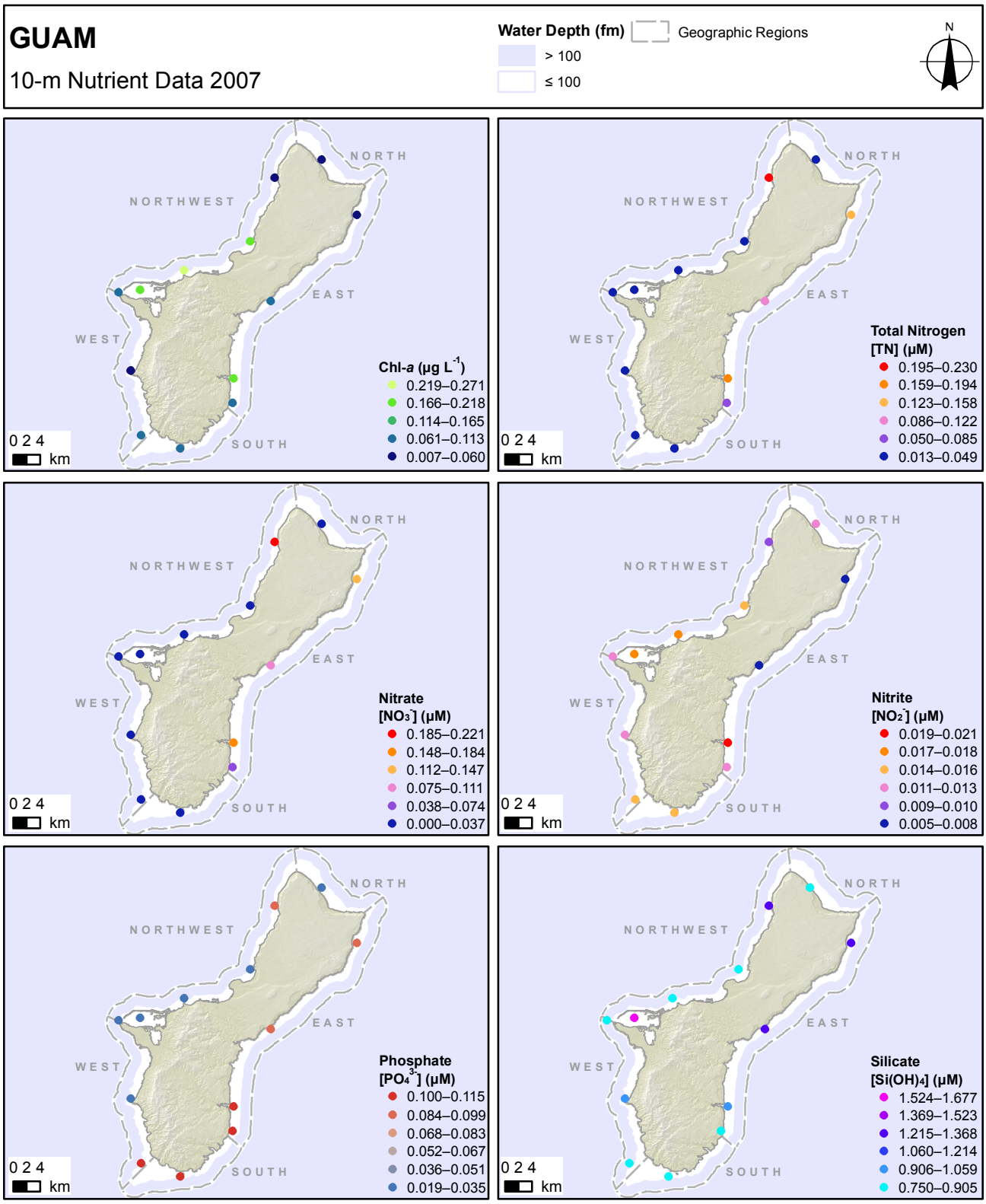


Figure 4.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected around Guam on May 11–15 during MARAMP 2007.

Temporal Comparison

Temperature ranges around Guam were > 1°C from all shallow-water CTD casts conducted during MARAMP 2003, 2005, and 2007, although the maximum and minimum temperatures recorded during each survey period decreased with each subsequent survey year. Intrusions of cold water originating from 30 m below the ocean surface were recorded during each survey period; however, they were most prevalent during MARAMP 2005. Strong east–west gradients in water properties were documented during each survey year. During MARAMP 2003 and 2005, waters in the east region were cooler than waters in the west and northwest regions; these differences were likely a result of vertical mixing that was induced by trade winds and mixed cooler subsurface waters into the upper 30 m of the water column. Data from MARAMP 2007, however, shows the opposite pattern: temperatures were warmer on the east side than on the west side. Beam transmission was lowest in Apra Harbor during each survey period. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May, and MARAMP 2003 and 2005 occurred in September and October. This change was made to avoid the typhoon season and reduce the probability of weather disruptions. Wind and wave conditions are generally higher during the wet season (July–December) than during the rest of the year, with stronger trade winds prominent on the east side of Guam. Higher winds and waves likely caused more mixing during MARAMP 2003 and 2005, and calmer weather potentially allowed for increased stratification in 2007. Further investigation will help make these particular results and patterns more apparent.

The number of locations where water samples were collected in 2007 was almost double the number in 2005. Some differences in water conditions between MARAMP 2005 and 2007 were observed, although similarities, such as water quality in Apra Harbor, existed. Using the maximum value bins measured for total nitrogen and phosphate, the calculated nitrogen-to-phosphorus (N:P) or Redfield ratio was 2:1 for samples from MARAMP 2007 (Redfield 1958). A low ratio of < 16:1 suggests a potential nitrogen limitation, while a high ratio of > 16:1 suggests a limitation in the primary production of phytoplankton. The N:P ratio for MARAMP 2005 for the same constituents was 15:1, closer to the expected Redfield ratio of 16:1. To elucidate the forcing factors present to produce an N:P ratio of 2:1 in 2007 would require further studies. Still, it is worth noting that highly variable N:P ratios around Guam have been recorded. Maximum Chl-*a* and total nitrogen were greater in 2007 than in 2005, while phosphate and silicate maximums were lower. These trends could be linked to seasonal weather patterns, terrigenous runoff, or nutrient limitation.

4.4.2 Time-series Observations

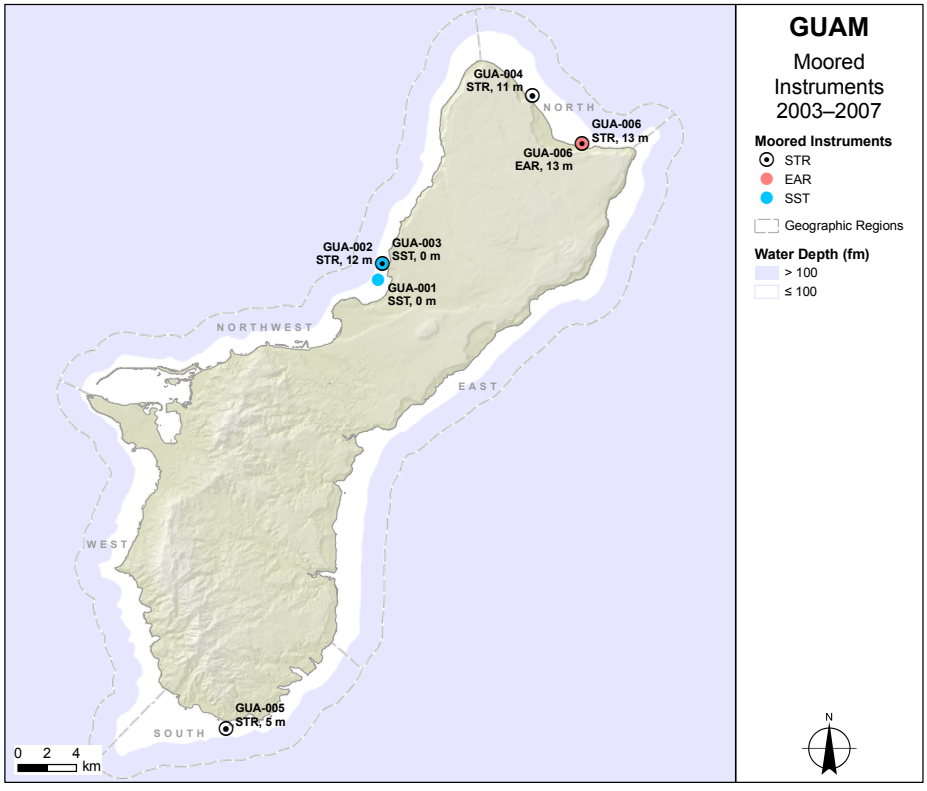


Figure 4.4.2a. Locations, depths, and types of oceanographic instrument moorings deployed at Guam during MARAMP 2003, 2005, and 2007. Three types of instruments were moored at Guam: ecological acoustic recorder (EAR), sea-surface temperature (SST) buoy, and subsurface temperature recorder (STR).

Between 2003 and 2007, a suite of moored instruments was deployed at Guam to collect time-series observations of key oceanographic parameters. The locations, depths, time frames, and other details about these deployments are provided in Figures 4.4.2a and b.

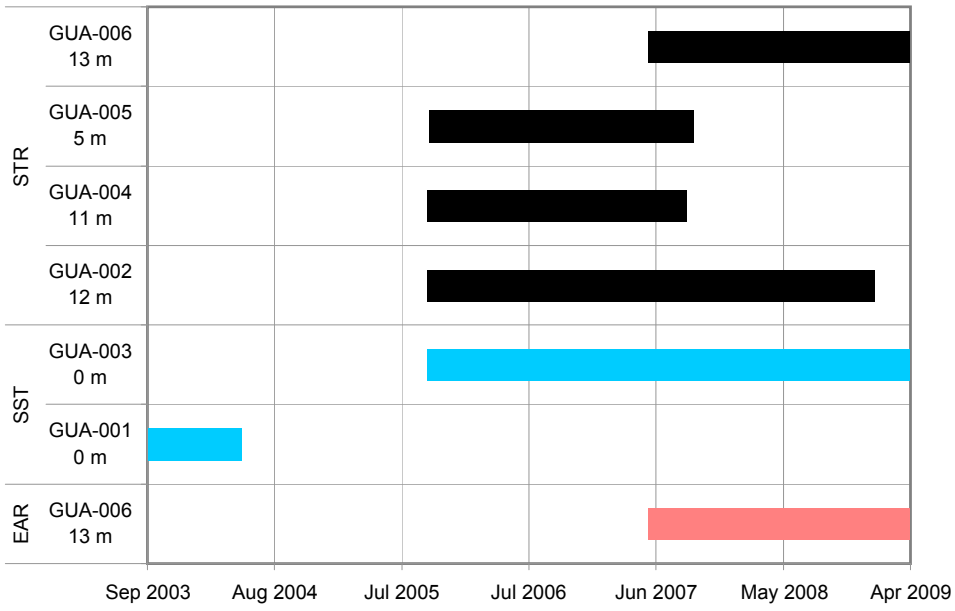


Figure 4.4.2b. Deployment timelines and depths of oceanographic instruments moored at Guam during the period from September 2003 to April 2009. A solid bar indicates the period for which data were collected by a single instrument or a series of them deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 4.2b in Section 4.2: "Survey Effort."

Satellite-derived (Pathfinder) sea-surface temperature (SST) and in situ temperature observations around Guam reveal that the seasonal maxima for water temperatures around Guam are typically reached in late August or September; the monthly maximum climatological mean from Pathfinder SST was 29.5°C (Fig. 4.4.2c[a]). Winter minima occured in February with a monthly minimum climatological mean of 27.1°C. Data from the SST buoys near Tumon Bay and 3 subsurface temperature recorders (STRs) show that water temperatures around Guam in August–September 2006 rose above the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean (Figs. 4.4.2c[a] and d). Still, given the relatively short duration and small magnitude of this period of elevated temperature, widespread mass coral bleaching likely did not occur. It's important to note that satellite-derived SST represents the upper few millimeters of oceanographic temperatures within the region of an island, as opposed to site- or reef-specific temperatures.

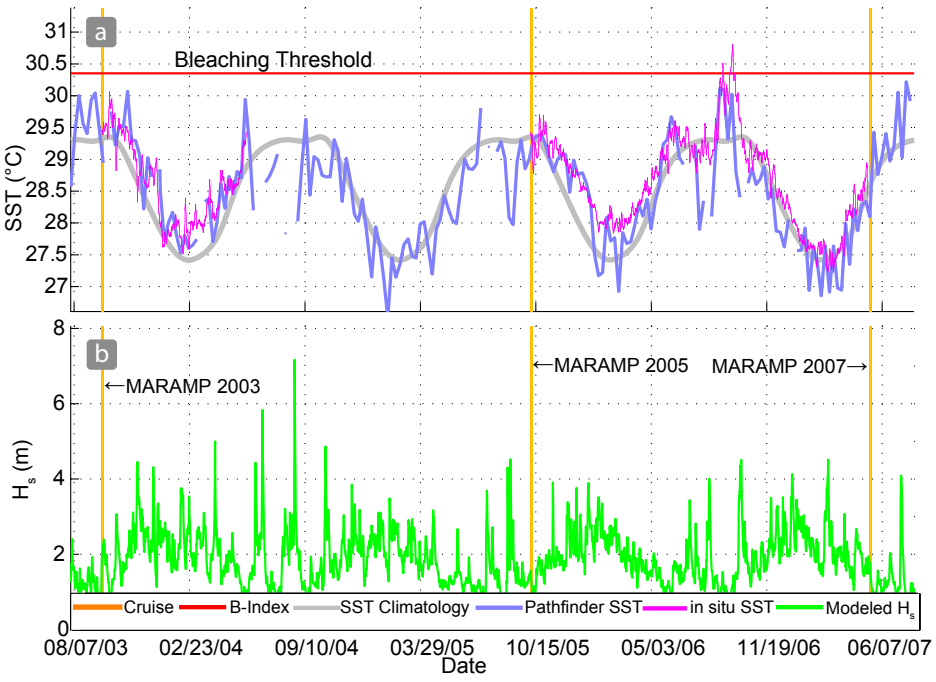


Figure 4.4.2c. Time-series observations of (*a*) SST and (*b*) wave height around Guam for the period between August 2003 and June 2007. Remotely sensed data (SST climatology and weekly Pathfinder-derived SST) and modeled significant wave height (H_s) derived from Wave Watch III are shown with CRED in situ temperature data from SST buoys (see Figure 4.4.2a for buoy locations). The 2 high points in the modeled wave height in the summer of 2004 show the occurrences of Typhoons Tingting and Chaba. The horizontal red and vertical orange bars represent the satellite-derived bleaching threshold and the MARAMP research cruise dates, respectively.

Periods of elevated mean wave heights of 3–4 m were usually more frequent during winter (Fig. 4.4.2c[b]). The largest episodic events of wave heights > 4 m, however, tended to happen during periods of warm temperatures. Warm temperatures typically occur during the period of August–December, when wave heights of > 4 m are generally associated with typhoons. This pattern was especially noticeable during the summer of 2004 with the passages of Typhoons Tingting and Chaba.

Three subsurface temperature recorders (STRs) were deployed at depths of 5, 11, and 12 m around Guam beginning in October 2005. Data from all of these STRs show seasonal temperature variability of 2°C–3°C (Fig. 4.4.2d). Water temperatures reached ~ 30.5°C during the months of June–October and fell to a low of ~ 27°C during the months of January–May. Temperature at these 3 locations exceeded the coral bleaching threshold for the region in September 2006, with the temperature at the shallowest sensor reaching almost 1°C higher than the bleaching threshold of 30°C. Diurnal temperature fluctuations were ~ 0.5°C for this shallowest sensor and ~ 0.3°C for the 2 deeper sensors. Solar heating and cooling caused the greater diurnal temperature fluctuation that was recorded at the shallowest deployment.

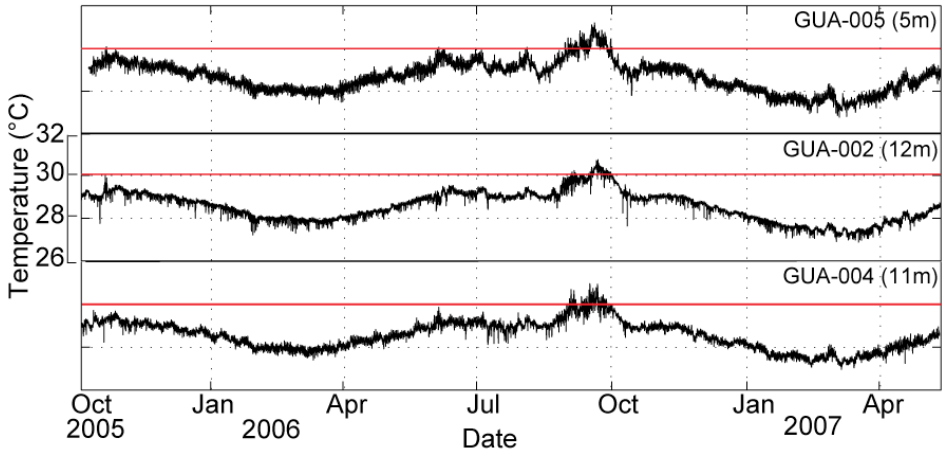


Figure 4.4.2d. Time-series observations of temperature over the period between October 2005 and May 2007 collected from 3 STR mooring sites at different locations and depths around Guam (see Figure 4.4.2a for mooring locations). The red lines indicate the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

Precipitation at Guam from 2001 to mid-2008 was highly seasonal with the greatest rainfall occurring in the months of August–September and the lowest occurring in the months of February–April (Fig. 4.4.2e). MARAMP 2003 and 2005 cruises were conducted in September and October, which are months characterized by seasonally high precipitation. In contrast, MARAMP 2007 was conducted in May when rainfall was seasonally low.

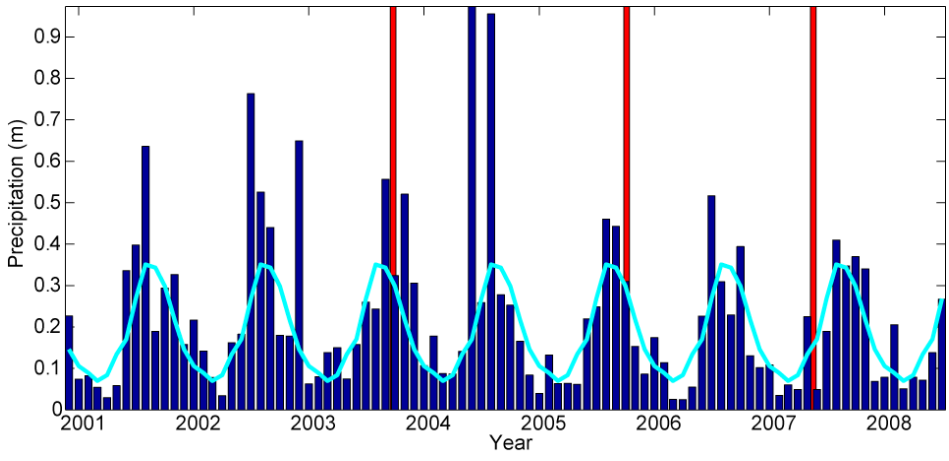


Figure 4.4.2e. Average monthly rainfall (m) from the Guam International Airport from January 2001 to July 2008. The cyan line indicates precipitation climatology (1958–2008), and the vertical red bars indicate MARAMP cruise periods. Source: National Weather Service, Honolulu (http://www.prh.noaa.gov/hnl/).

4.4.3 Wave Watch III Climatology

Seasonal wave climatology for Guam (Fig. 4.4.3a) was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008, and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (~ 75°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the southeast (~ 110°), but they could originate from a broad directional source (90°–180°). These large, episodic waves were generated primarily by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from the west-southwest (~ 250°) and probably were associated with episodic storms. Similar to the regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) also was characterized by frequent (> 30 d per season), short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season), long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this period and originated from the southwest (~ 240°).

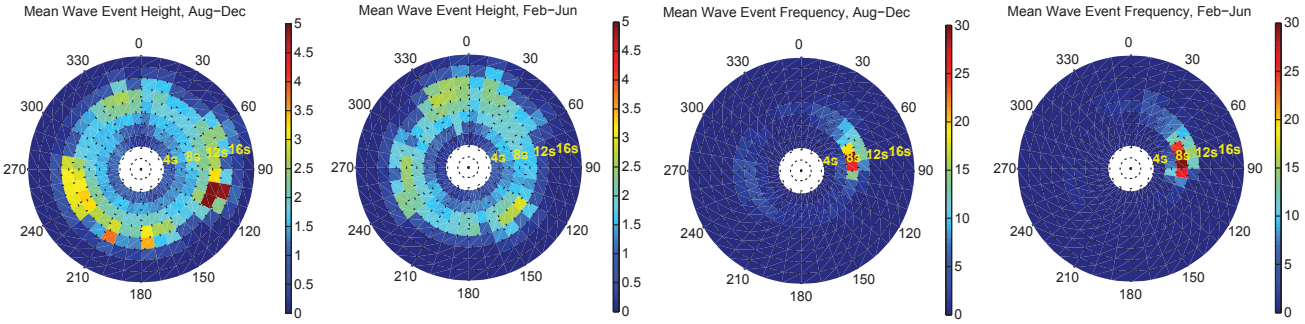


Figure 4.4.3a. NOAA Wave Watch III directional wave climatology for Guam from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Guam (13° N, 145° E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

4.4.4 Bioacoustic Observations

In the north region just west of Pati Point, an ecological acoustic recorder (EAR) unit was deployed on May 14, 2007. Programmed to record the ambient sound field at a sample rate of 40 kHz for 30 s every 10 min, this EAR unit was also programmed to detect and record high-amplitude noise events, such as the engine sounds of passing vessels. Unfortunately, this unit was flooded and no data are available to report. A replacement EAR was deployed in May 2009.

4.5 Corals and Coral Disease

4.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Guam was 19% (SE 1). Coral cover was lowest in the west region (Fig. 4.5.1a), with a mean of 7% for 39 survey segments, and was variable in all other regions. The highest cover was observed in the north region with a mean of 25% for 20 segments and in the east region with a mean of 25% for 67 segments. Localized areas of high coral cover were observed on the forereef off Jalaihai Point, near the boundary between the east and south regions, over 3 segments with a mean of 42% and along Catalina Point, in the northern portion of the east region, for 7 segments with a mean of 45% (for place-names and their locations, see Figure 4.2a in Section 4.2: "Survey Effort").

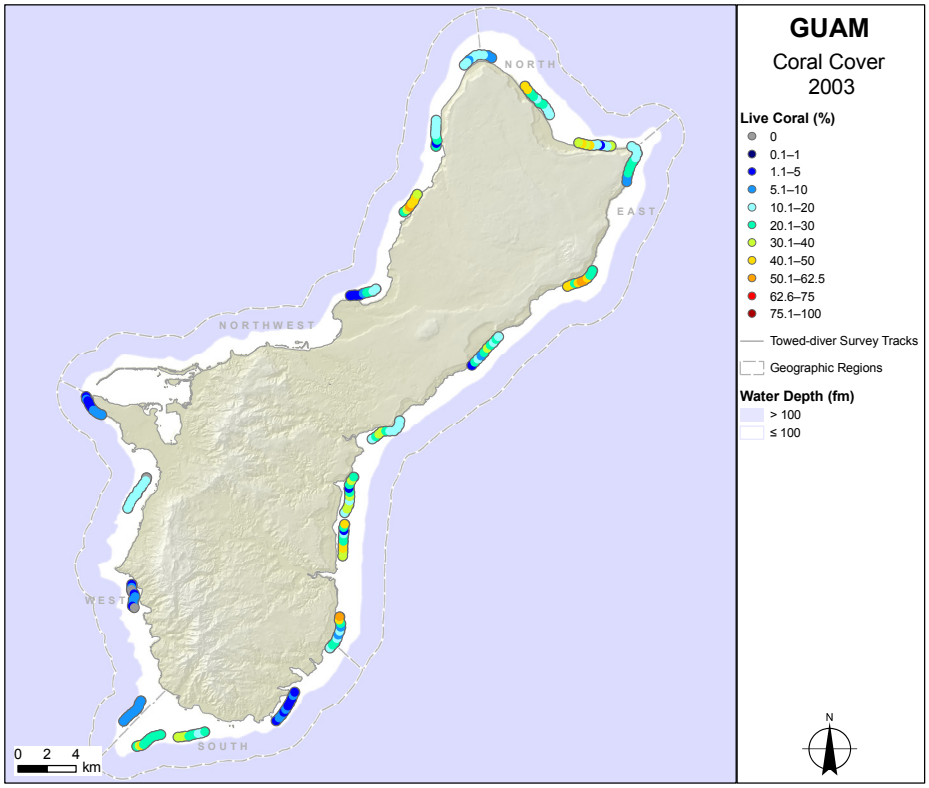


Figure 4.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 x 10 m (~ 2000 m^2).

During MARAMP 2003, 8 REA benthic surveys using the quadrat method on forereef habitats around Guam documented 718 coral colonies within a total survey area of 30 m^2. Site-specific colony density ranged from 11.7 to 33.9 colonies m^{-2} with an overall sample mean of 24.6 colonies m^{-2} (SE 2.8) around Guam. The highest colony density was recorded at GUA-09 near Jinapsan Point, and the lowest colony density was observed in the west region at GUA-01 near Orote Peninsula and GUA-02 in Cetti Bay (Fig. 4.5.1b).

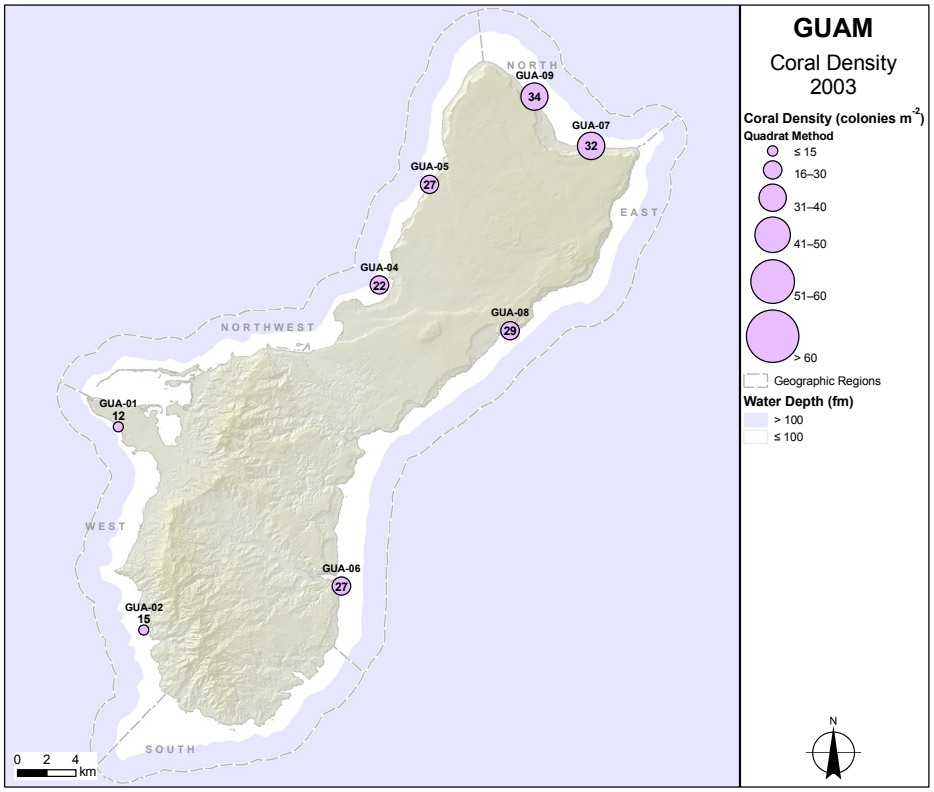


Figure 4.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2003. Values are provided within or above each symbol. The quadrat method was used in 2003 to assess coral-colony density.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Guam was 23% (SE 1.2). Similar to surveys in 2003, coral cover was lowest within the west region (Fig. 4.5.1c), with a mean of 5% over 39 segments. Coral cover was variable in all other regions with the highest mean coral cover in the north region, for 20 segments with a mean of 34%, and east region, over 80 segments with a mean of 29%. Localized areas of high coral cover were recorded south of Cocos Island for 7 segments with a mean of 51%, off of Haputo Point in the northwest region over 10 segments with a mean of 49%, off of Jalaihai Point for 4 segments with a mean of 48%, and along Catalina Point over 5 segments with a mean of 44%.

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 5% (SE 0.6) of coral cover observed on forereef habitats around Guam appeared stressed in 2005. Stressed-coral cover was highest in the south and east regions (Fig. 4.5.1c) with means of 9% and 7% and lowest in the west region with a mean of 1%. Some observations of stressed corals appeared related to crown-of-thorns seastar (*Acanthaster planci*) abundance, which was highest between Togcha and Talofofo Bays in the east region. Divers recorded more than 100 crown-of-thorns seastars (COTS) during a 5-min segment just south of Togcha Bay. For more about COTS around Guam, see Section 4.7.1: "Benthic Macroinvertebrate Surveys."

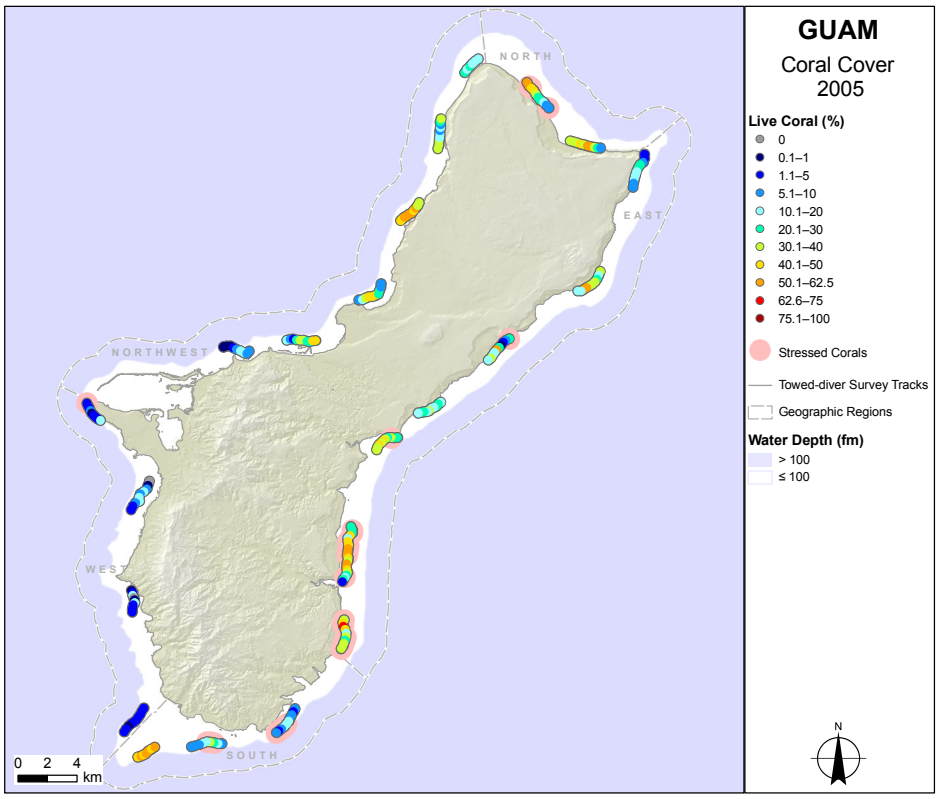


Figure 4.5.1c. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2005. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 x 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005.

During MARAMP 2005, 7 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats around Guam. Site-specific estimates of live-hard-coral cover from these surveys ranged from 11.8% to 38.2% (Fig. 4.5.1d) with an overall sample mean of 26.1% (SE 3.6). Live coral cover was not assessed at GUA-08 and GUA-11 in the east region because of personnel limitations. In the north region at GUA-09 and GUA-07 and in the northwest region at GUA-04, levels of live coral cover were found at the high end of this range: 38.2%, 30.4%, and 33.3%. The lowest coral cover of 11.8% was recorded at GUA-02 in Cetti Bay.

During MARAMP 2005, 9 REA benthic surveys using the belt-transect method on forereef habitats around Guam documented 5018 coral colonies within a total survey area of 750 m^2. Site-specific colony density ranged from 3.1 to 12.3 colonies m^{-2} with an overall sample mean of 6.5 colonies m^{-2} (SE 0.9) around Guam. The highest colony density was recorded at GUA-04 in Tumon Bay (Fig. 4.5.1d), the site with the second-highest coral cover. Similar to results from 2003 surveys, GUA-01 and GUA-02 in the west region were among the sites with the lowest coral densities of 3.1 and 4.7 colonies m^{-2}; they were also the 2 sites with the lowest coral cover.

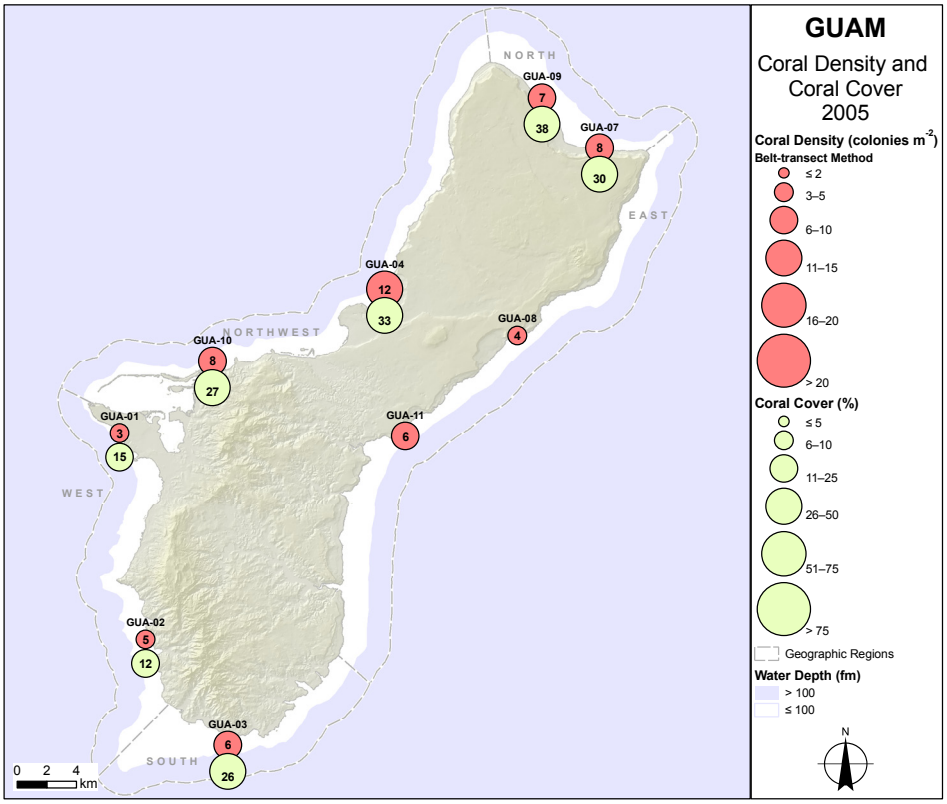


Figure 4.5.1d. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2005. Values are provided within each symbol. The belt-transect method was used in 2005 to assess coral-colony density.

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Guam was 12% (SE 0.8). Again, coral cover was lowest in the west region (Fig. 4.5.1e), with a mean of 4% for 30 segments, and highest in the north region with a mean of 21% over 20 segments. Areas of relatively high, continuous coral cover were observed just west of Pati Point in the north region, over 6 segments with a mean of 35%, and along Catalina Point with a mean of 35% for 10 segments.

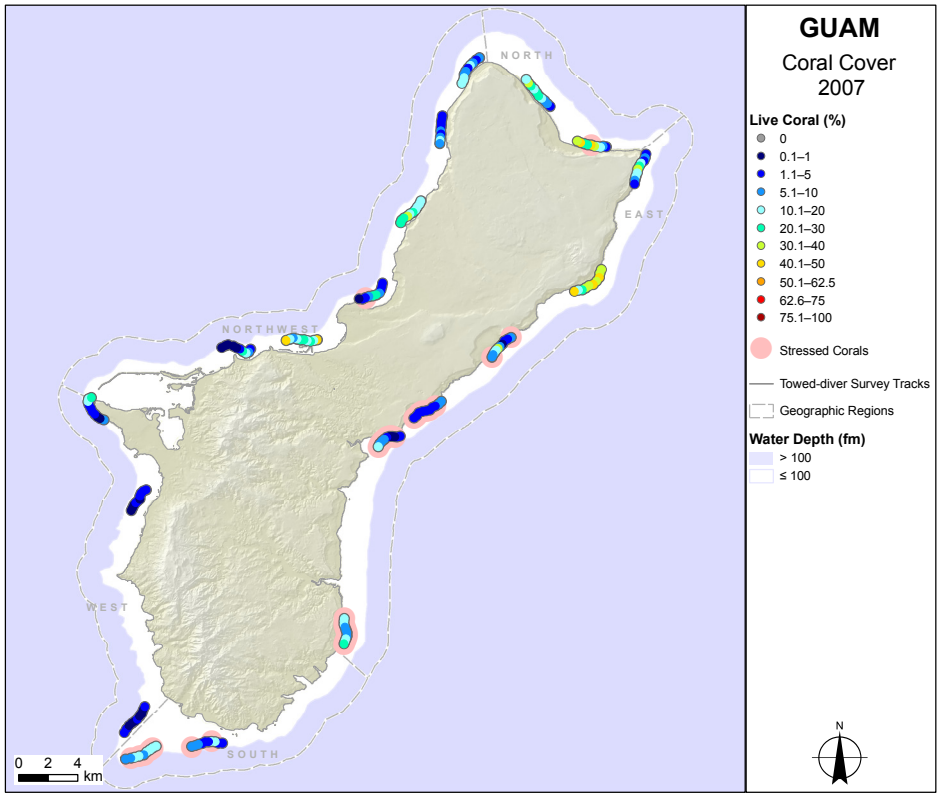


Figure 4.5.1e. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 x 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2007.

Overall, 5% (SE 0.6) of coral cover observed on forereef habitats around Guam appeared stressed in 2007 (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease). Similar to 2005 findings, stressed-coral cover was highest in the south and east regions (Fig. 4.5.1e). In these 2 regions, where stressed-coral cover was recorded with means of 8% and 10%, divers noted that predation scars and COTS presence were common. The highest overall cover of stressed corals was located south of Talofofo Bay to Jalaihai Point. A localized increase in stressed-coral cover was noted around Fadian Point, where observers recorded abundant COTS and predation scars affecting up to 40% of live corals.

During MARAMP 2007, 10 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats around Guam. Site-specific estimates of live-hard-coral cover from these surveys ranged from 4.9% to 39.2% (Fig. 4.5.1f) with an overall sample mean of 16.2% (SE 3.1). Live coral cover was highest at GUA-08 near Campanaya Point, which had not been assessed for cover of live corals during 2005 surveys. Similar to results from the 2005 surveys, relatively high values of coral cover were found at the 2 sites in the north region, GUA-07 and GUA-09, and the lowest coral cover was recorded at GUA-02 in Cetti Bay in the west region. All REA sites surveyed for coral cover in 2005 showed a decline in 2007.

During MARAMP 2007, 10 REA benthic surveys using the belt-transect method on forereef habitats around Guam documented 3080 coral colonies within a total survey area of 500 m^2. Site-specific colony density ranged from 3.4 to 11.1 colonies m^{-2} with an overall sample mean of 6.2 colonies m^{-2} (SE 0.7) around Guam. The highest colony density was recorded at GUA-10 near Adelup Point in the northwest region (Fig. 4.5.1f). As in the 2003 and 2005 surveys, GUA-02 in Cetti Bay with 3.9 colonies m^{-2} ranked among the sites with the lowest coral densities.

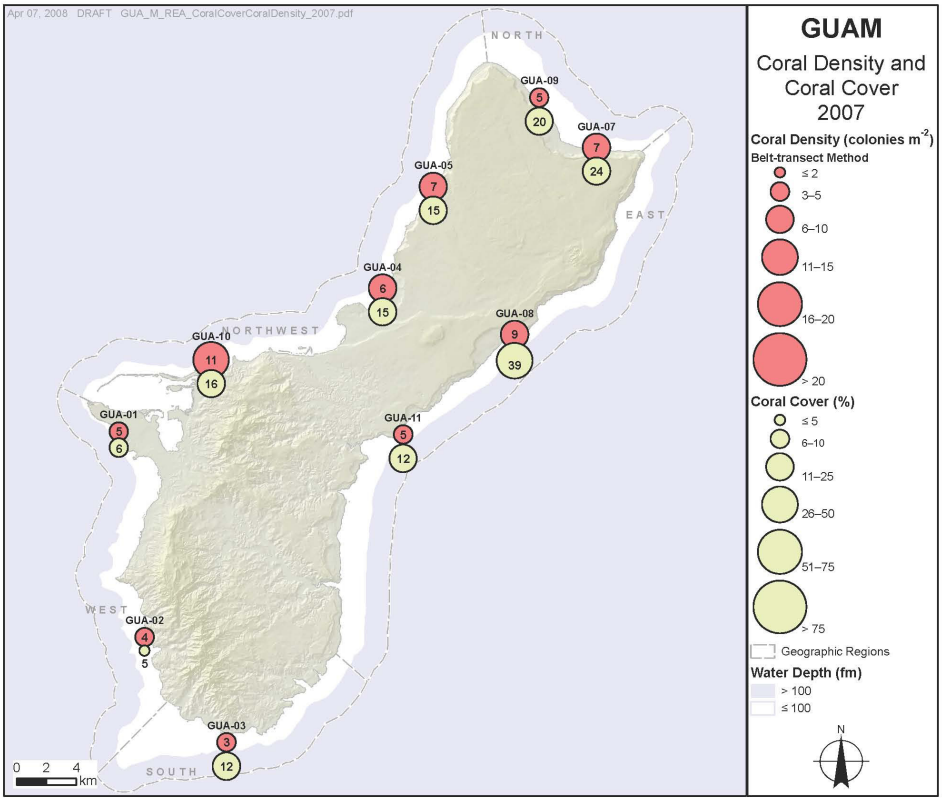


Figure 4.5.1f. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2007. Values are provided within each symbol. The belt-transect method was used in 2007 to assess coral-colony density.

Islandwide mean cover of live corals estimated from towed-diver surveys of forereef habitats varied between years, rising from 20% (SE 1) in 2003 to 23% (SE 1.2) in 2005 then falling to 12% (SE 0.8) in 2007 (Fig. 4.5.1g). In close agreement with these values, overall mean estimates of coral cover around Guam from site-specific REA surveys decreased from 26.1% (SE 3.6) in 2005 to 16.2% (SE 3.1) in 2007 with coral cover decreasing at all 7 sites surveyed in both 2005 and 2007 (Guam was not surveyed for live coral cover using the line-point-intercept method in 2003). This congruence of data from surveys using 2 separate methods over different spatial scales suggests that this decrease in coral cover was genuine rather than an artifact of environmental heterogeneity, interobserver bias, or variable locations of survey tracks and REA sites between years.

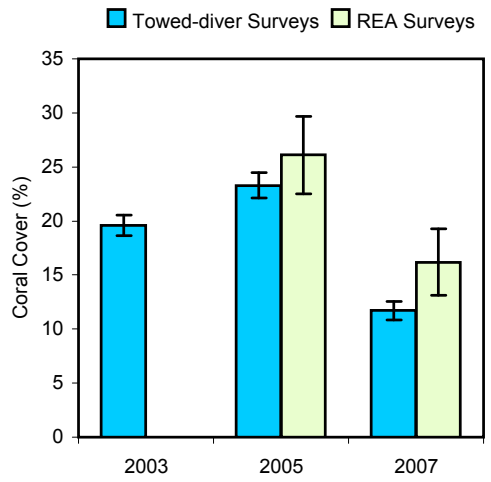


Figure 4.5.1g. Temporal comparison of mean live-coral-cover (%) values from REA and towed-diver benthic surveys conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted around Guam in 2003. Error bars indicate standard error (± 1 SE) of the mean.

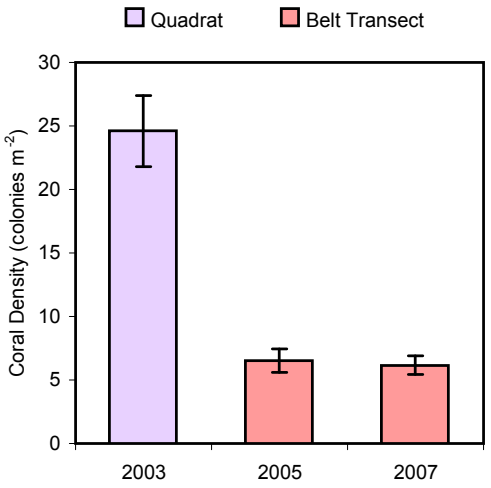


Figure 4.5.1h. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 to measure coral colony density, but the belt-transect method was used in 2005 and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Between MARAMP towed-diver survey efforts, estimates of high coral cover remained consistent in the north and east regions, where coral cover was 23% and 25% in 2003 and 34% and 29% in 2005. In the north region, towed-diver surveys overlapped with GUA-09 and GUA-07, where values of coral cover were among the highest recorded around the island in both years. Localized areas of high coral cover were also noted in the east region: at Catalina Point, where it averaged 45% over 7 segments in 2003, 44% over 5 segments in 2005, and 35% over 10 segments in 2007, and at Jalaihai Point for 3 segments with a mean of 42% in 2003 and for 4 segments with a mean of 49% in 2005. Finally, low values of coral cover were recorded every year in the west region: 7% in 2003, 5% in 2005, and 3% in 2007.

Overall, stressed-coral cover observed on forereef habitats was consistently highest in the south and east regions, where it was recorded at 9% and 7% in 2005 and 9% and 10% in 2007. High values of stressed-coral cover in both years and regions may have resulted from a number of causes, including but not limited to COTS predation, as well as disease and sedimentation, both of which were noted by divers during MARAMP 2005 surveys between Tagachang and Jalaihai Points.

Overall mean coral-colony density from REA benthic surveys of forereef habitats around Guam did not vary substantially between MARAMP 2005 and 2007, when the belt-transect method was used, remaining steady at 6.5 colonies m^{-2} (SE 0.9) and 6.2 colonies m^{-2} (SE 0.7), respectively (Fig. 4.5.1h). Site-specific coral-colony densities appeared substantially higher in 2003, as did the overall mean density for Guam at 24.6 colonies m^{-2} (SE 2.8), than in 2005 and 2007. However, this disparity is likely an artifact of the different method used to assess colony density in 2003 than in 2005 and 2007. The method of placing quadrats used in 2003 was highly biased toward surveying hard-bottom substrate where corals were present, whereas the belt-transect method used in 2005 and 2007 assessed benthos that fell within transect belts regardless of the nature of the substrate.

Coral Generic Richness and Relative Abundance

Eight REA benthic surveys of forereef habitats were conducted using the quadrat method around Guam during MARAMP 2003. At least 29 coral genera were observed around Guam. Generic richness ranged from 7 to 17 with a mean of 12 (SE 1) coral genera per site (Fig. 4.5.1i). The highest generic diversity was seen at GUA-09 near Jinapsan Point in the north region, and the lowest generic diversity was recorded at GUA-01 on the west side of Orote Peninsula.

Porites, *Leptastrea*, *Favia*, *Astreopora*, and *Montipora* were the most numerically abundant genera, contributing 19.8%, 16.8%, 13.5%, 14.2%, and 12.4% of the total number of colonies enumerated around Guam during MARAMP 2003. All other genera individually contributed < 10% of the total number of colonies. *Porites* dominated the coral fauna at GUA-02 in Cetti Bay and GUA-04 in Tumon Bay (Fig. 4.5.1i). *Leptastrea* dominated the coral fauna at GUA-01 in the west region, GUA-05 in the northwest region, and GUA-07 in the north region. *Favia* dominated the coral fauna at GUA-06 and GUA-08 in the east region and GUA-09 in the north region. The values of relative abundance of coral genera at GUA-06 and GUA-08 were highly similar.

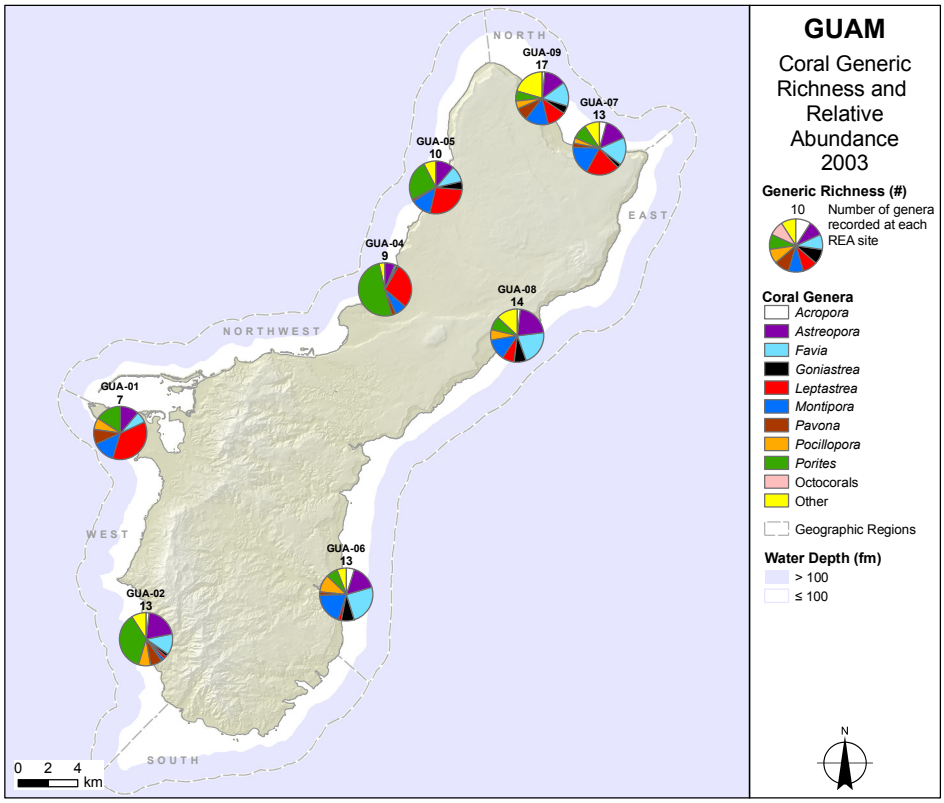


Figure 4.5.1i. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2003. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to survey coral genera.

Nine REA benthic surveys of forereef habitats were conducted using the belt-transect method around Guam during MARAMP 2005. At least 28 coral genera were observed around Guam. Generic richness ranged from 6 to 21 with a mean of 14.6 (SE 1.7) coral genera per site (Fig. 4.5.1j). The highest generic diversities were seen at GUA-02 in Cetti Bay in the west region and GUA-03 in the south region with 21 and 20 coral genera, respectively, and the lowest generic diversity was recorded at GUA-08 in the east region. However, due to a diving impairment, the lead coral biologist was unable to survey GUA-08 and GUA-11 in the east region. Instead, these sites were surveyed by a diver who was less experienced in identifying rarer taxa; this fact likely accounts for the lower generic richness at these 2 sites.

Porites and *Astreopora* were the most numerically abundant genera, contributing 38.1% and 10.7% of the total number of colonies enumerated around Guam during MARAMP 2005. All other genera individually contributed < 10% of the total number of colonies. *Porites* dominated the fauna at most sites, with the exception of GUA-08 and GUA-11 in the east region, where colonies of *Acropora* or *Montipora* were more abundant (Fig. 4.5.1j). The greatest relative abundance of *Astreopora* colonies was found at GUA-01 and GUA-02 in the west region and GUA-03 in the south region.

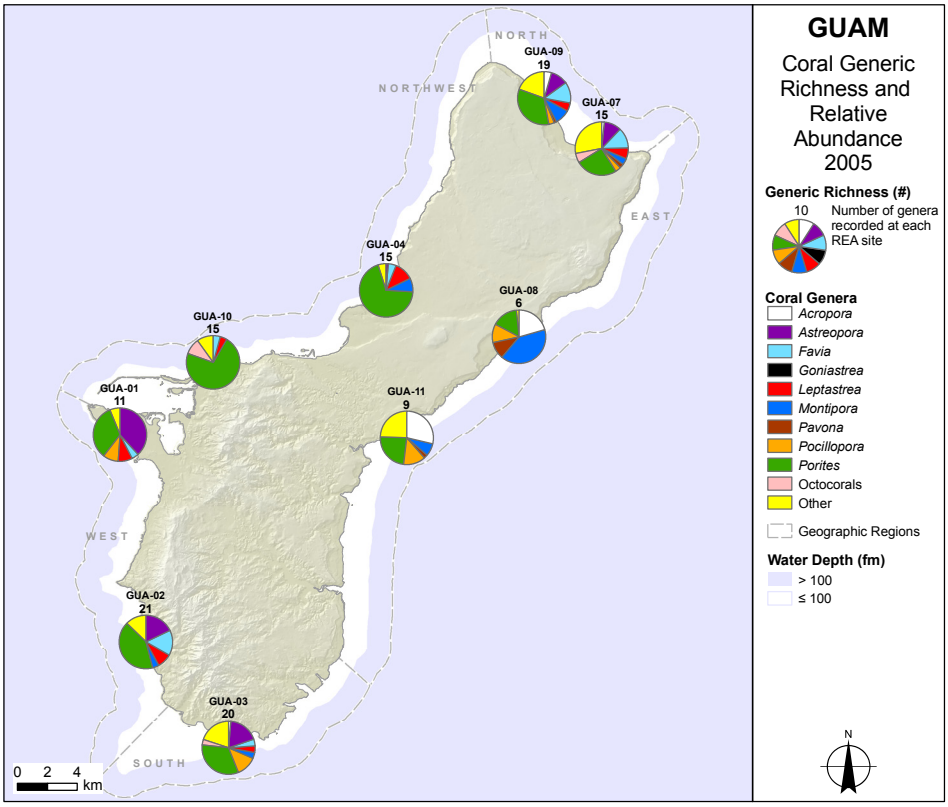


Figure 4.5.1j. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2005. The pie charts indicate percentages of relative abundance of key coral genera. The belt-transect method was used in 2005 to survey coral genera.

Ten REA benthic surveys of forereef habitats were conducted using the belt-transect method around Guam during MARAMP 2007. At least 34 coral genera were observed around Guam. Generic richness ranged from 14 to 23 with a mean of 17.8 (SE 0.8) coral genera per site (Fig. 4.5.1k). The highest generic diversity was seen at GUA-09 near Jinapsan Point in the north region, and the lowest generic diversities of 14 and 15 coral genera were recorded, respectively, at GUA-01 in the west region and GUA-04 in Tumon Bay.

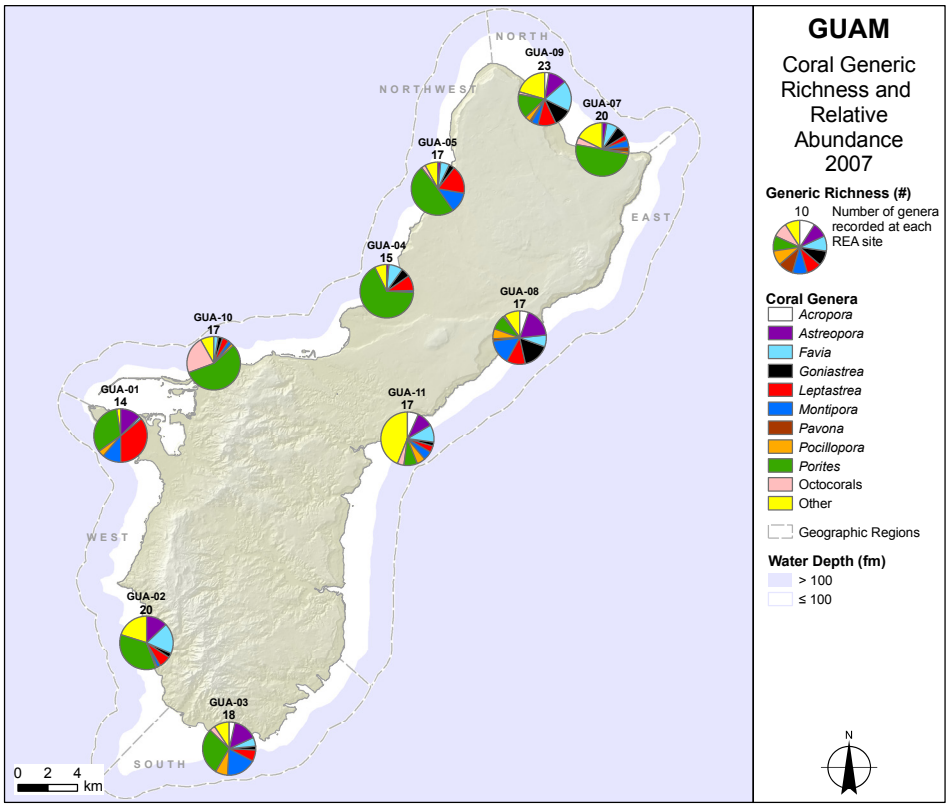


Figure 4.5.1k. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2007. The pie charts indicate percentages of relative abundance of key coral genera. The belt-transect method was used in 2007 to survey coral genera.

Porites and *Leptastrea* were the most numerically abundant genera, contributing 34.9% and 11% of the total number of colonies enumerated around Guam during MARAMP 2007. All other genera individually contributed < 10% of the total number of colonies. *Porites* dominated the fauna at most sites, although *Leptastrea* was the most numerically abundant genus at GUA-01 in the west region and *Galaxea* was the most numerically abundant genus at GUA-11 north of Pago Bay in the east region (Fig. 4.5.1k). At GUA-03 in the south region and GUA-08 in the east region near Campanaya Point, relative abundance of coral colonies was more evenly distributed among the 10 most common genera.

Site-specific estimates of generic richness across the 3 MARAMP survey years ranged from 6 to 23 on forereef habitats around Guam. Site-specific and overall mean generic-richness values (Fig. 4.5.1l) were higher in 2005 and 2007 with means of 14.6 (SE 1.7) and 17.8 (SE 0.8) coral genera per site than in 2003 with a mean of 12 (SE 1.1) coral genera per site. The variation between 2003 and both 2005 and 2007 is likely because of the difference in the size of the areas in which corals were censused: the survey area in 2005 and 2007 was 50–100 m^2 per site, much larger than the 3.75 m^2 per site in 2003 (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease). Additionally, the only octocoral genus assessed in 2003 was *Heliopora*, whereas all octocoral genera were assessed in 2005 and 2007. The increase between 2005 and 2007 arises because a few colonies of several genera recorded in 2007 were not recorded in previous years (i.e., *Cladiella*, *Cycloseris*, *Lobophyllia*, *Scapophyllia*, and *Stereonepthya*) and because 3 genera of octocorals (*Lobophytum*, *Sarcophyton*, and *Sinularia*) were distinguished in 2007 but pooled together in previous years.

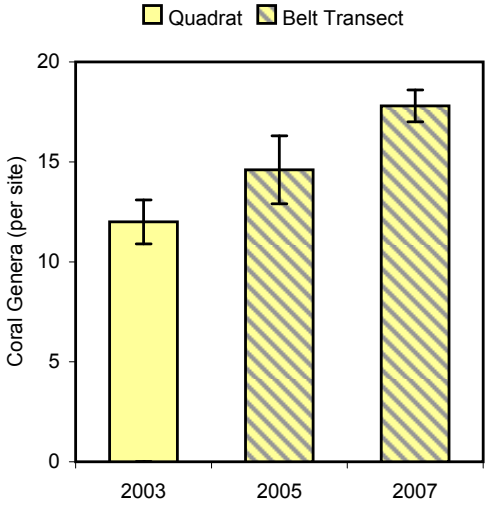


Figure 4.5.1l. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 to survey coral genera, but the belt-transect method was used in 2005 and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Across the 3 MARAMP survey years, 34 coral genera were observed on forereef habitats around Guam. *Porites*, *Leptastrea*, *Astreopora*, *Favia*, and *Montipora* were important components of the coral fauna. *Porites* was the most numerically abundant component of the coral fauna in each survey year, accounting for 19.8%, 38.1%, and 34.9% of the total number of colonies enumerated around Guam in 2003, 2005, and 2007. *Leptastrea* was the second-most numerically abundant taxon in 2003 and 2007, contributing 16.8% and 11% of the total number of colonies. *Astreopora* was the second-most numerically abundant taxon in 2005, contributing 10.7% of the total number of colonies. *Favia* and *Montipora* were also important components of the coral fauna in 2003, contributing 15% and 12.4% of the total number of colonies.

Coral Size-class Distribution

During MARAMP 2003, 8 REA benthic surveys of forereef habitats were conducted around Guam using the quadrat method. The coral size-class distribution from these surveys shows that the majority (63.5%) of corals had maximum diameters ≤ 5 cm (Fig. 4.5.1m). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 25.7%, 9.4%, and 1.4% of colonies recorded. No colonies with maximum diameters > 40 cm were recorded. The highest proportions (97.7% and 94.5%) of small (≤ 10 cm) colonies were found at GUA-01 and GUA-02 in the west region. The highest proportions of midsize colonies (11–40 cm) were found at GUA-06 in Talofofo Bay in the east region with 18.6%, GUA-07 in the north region with 16%, and GUA-05 near Haputo Point in the northwest region with 16%.

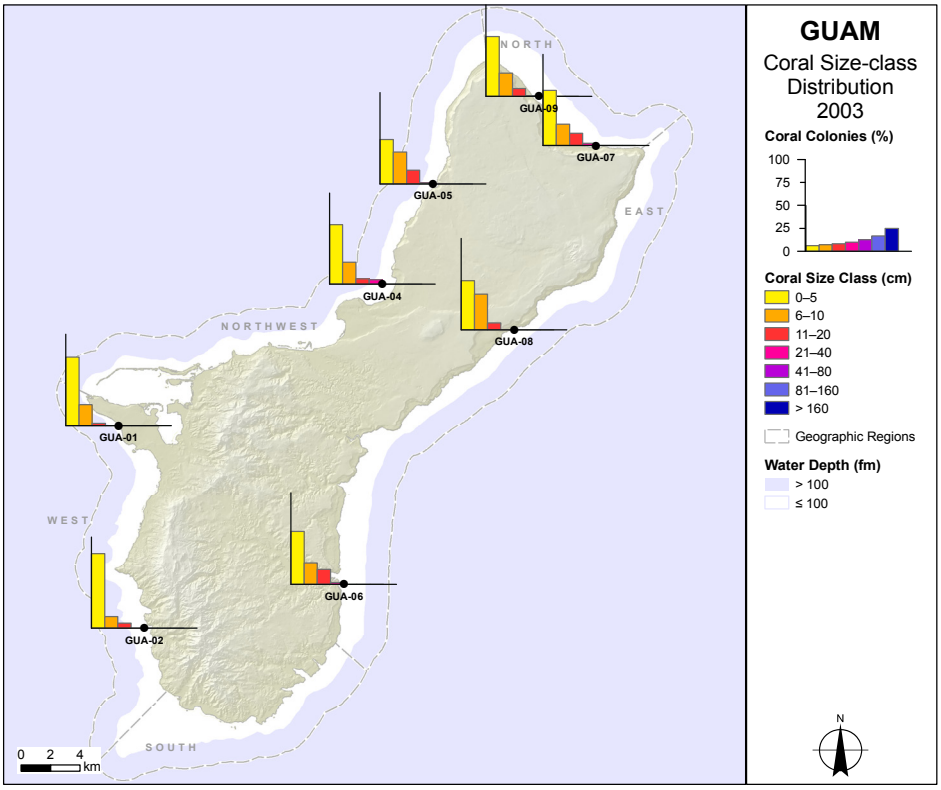


Figure 4.5.1m. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.

During MARAMP 2005, 9 REA benthic surveys of forereef habitats were conducted around Guam using the belt-transect method. The coral size-class distribution from these surveys shows that the majority (50.9%) of corals had maximum diameters > 10 cm and only 2.1% had maximum diameters > 40 cm (Fig. 4.5.1n). The first 4 size classes (0–5, 6–10, 11–20, and 21–40 cm) accounted for 17%, 32.1%, 31.7 %, and 17.1% of colonies recorded. The highest proportion (84.2%) of midsize colonies (11–40 cm) was found at GUA-08 in the east region, and the highest proportion (74.6%) of small (≤ 10 cm) colonies was found at GUA-01 in the west region.

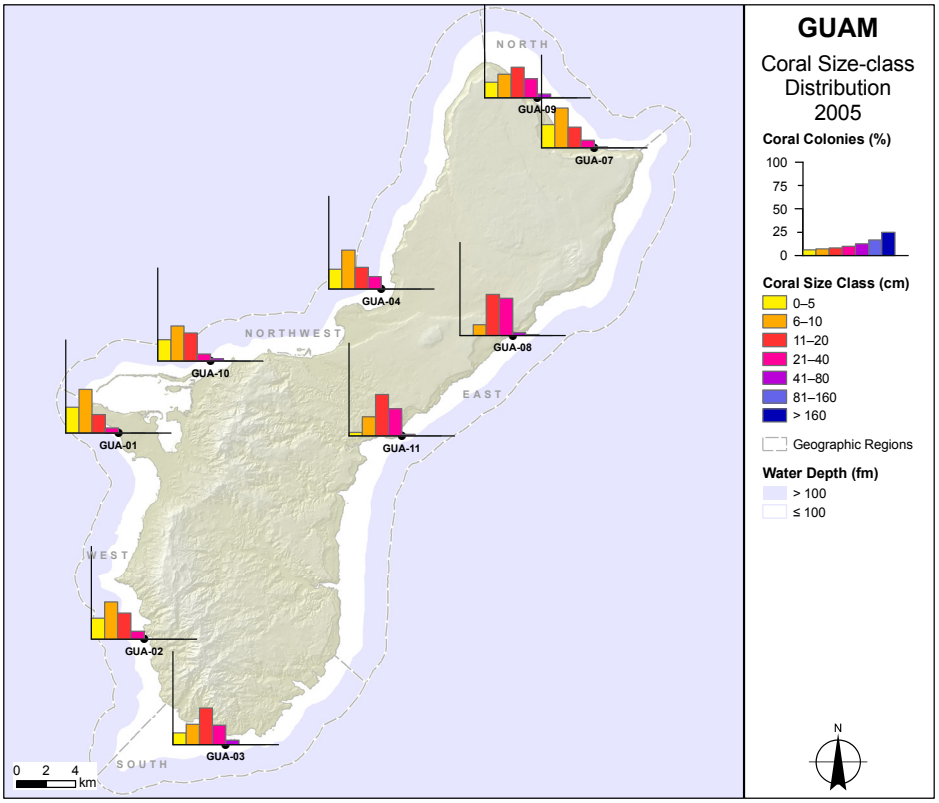


Figure 4.5.1n. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2005. The observed size classes are color coded in a size-frequency chart at each REA site. The belt-transect method was used in 2005 to size corals.

During MARAMP 2007, 10 REA benthic surveys of forereef habitats were conducted around Guam using the belt-transect method. The coral size-class distribution from these surveys shows that the majority (67.5%) of corals had maximum diameters ≤ 10 cm and only 1.8% had maximum diameters > 40 cm (Fig. 4.5.1o). The first 4 size classes (0–5, 6–10, 11–20, and 21–40 cm) accounted for 28.5%, 39%, 20.1 %, and 10.6% of colonies observed. Similar to surveys in 2005, the highest proportion (57.5%) of midsize colonies (11–40 cm) was found at GUA-08 near Campanaya Point in the east region, and the highest proportion (90.1%) of small (≤ 10 cm) colonies was found at GUA-01 in the west region.

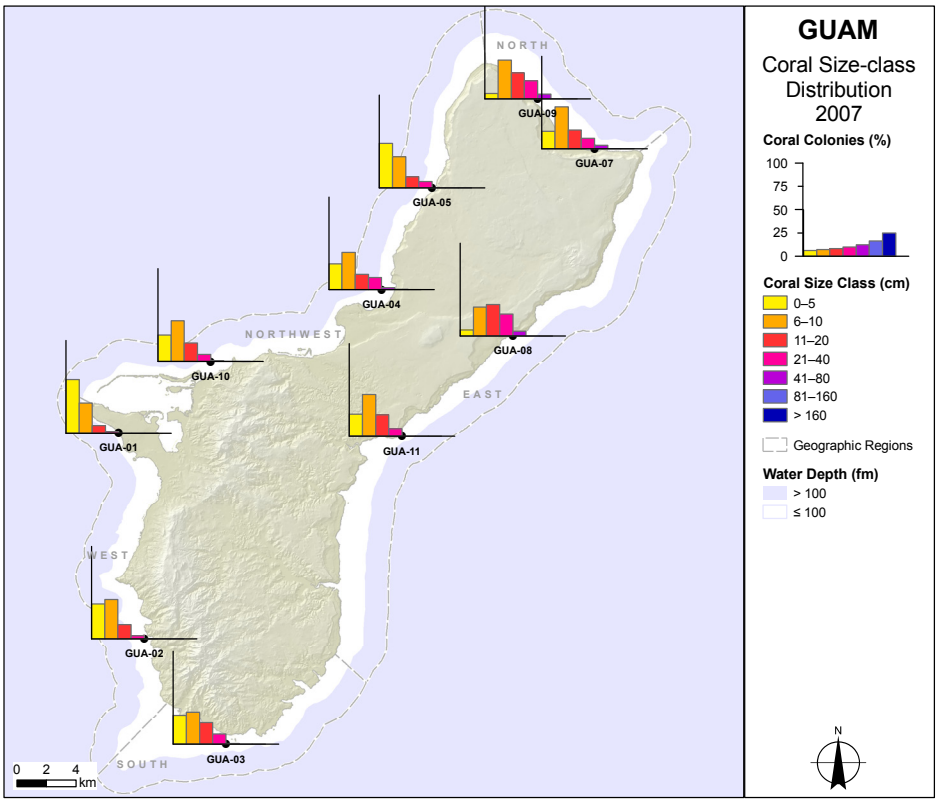


Figure 4.5.1o. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The belt-transect method was used in 2007 to size corals.

Site-specific and overall coral size-class distributions on forereef habitats around Guam reflect inherent biases in the methods used to census and size corals. During MARAMP 2003, corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 such quadrats were examined (total survey area = 3.75 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. During MARAMP 2005 and 2007, corals whose center fell within a belt transect (1 or 2 m × 25 m) were tallied and binned into 1 of 7 size classes based on visual estimates of maximum colony diameter. This method is better suited to capturing large colonies, but the larger census area likely reduces the number of very small colonies (≤ 5 cm) that are observed and recorded. For more on these survey methods, see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease."

These methodological biases are reflected in the size-class data by survey year. In 2003, more than half (63.5%) of all colonies censused on forereef habitats around Guam had a maximum diameter ≤ 5 cm, whereas in 2005 and 2007 a far smaller proportion (17% and 28.5%) of colonies were in this smallest size class. Comparing size-class data between survey years when different methods were used is, therefore, inappropriate. For the suite of 9 sites surveyed around Guam with the belt-transect method in both 2005 and 2007, overall size-class distribution did not vary appreciably (Fig. 4.5.1p), although a number of site-specific size-class distributions did vary between 2005 and 2007.

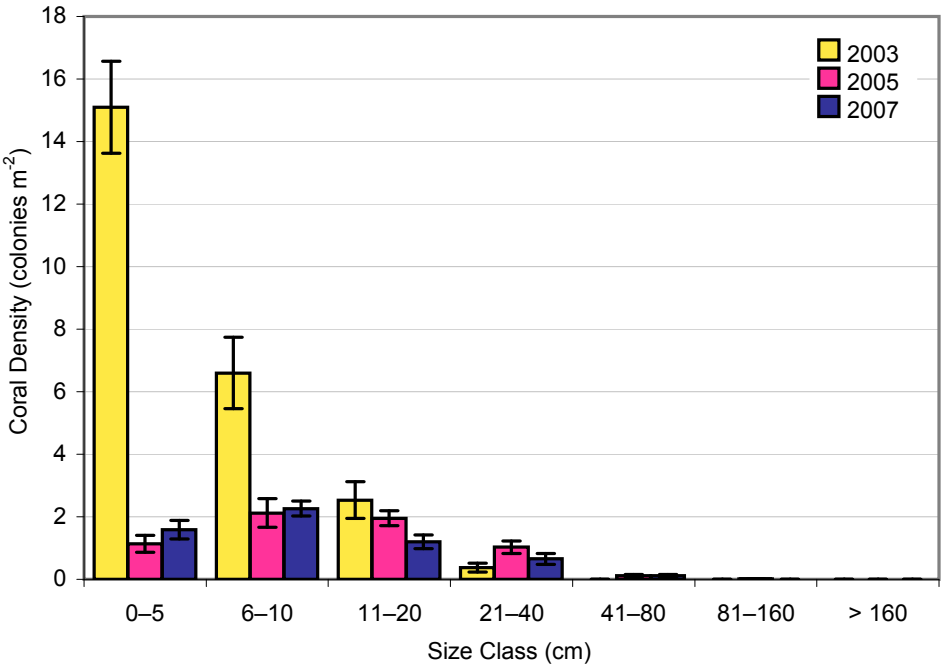


Figure 4.5.1p. Mean coral-colony densities (colonies m-2) by size class from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 to size corals, but the belt-transect method was used in 2005 and 2007. Error bars indicate standard error (± 1 SE) of the mean.

4.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted using the belt-transect method at 10 sites on forereef habitats around Guam, covering a total area of more than 1600 m^2. Surveys detected 85 cases of disease, translating to an overall mean prevalence of 1.4% (SE 0.4), excluding predation. Seven major disease conditions were observed around Guam: bleaching, white syndrome, subacute tissue loss, skeletal growth anomalies, pigmentation response, fungal infection, and other syndromes of unknown etiology. Although all 10 sites contained disease (Fig. 4.5.2a), the greatest numbers of cases were recorded at GUA-05 and GUA-09 with 16 and 12 cases. Relative to colony density, GUA-07 and GUA-09 in the north region had the highest disease prevalence, each with 3.1% (Fig. 4.5.2b; the values of overall prevalence shown in Figure 4.5.2a include predation).

Bleaching was the most common affliction encountered with 39% of cases; bleaching was widely distributed among sites in the east, south, and west regions (Figs. 4.5.2a and b). Although nearly 60% of bleaching cases were recorded on *Astreopora*, corals in the genera *Montipora*, *Porites*, *Goniastrea*, *Favia*, *Platygyra*, and *Psammocora* were also affected. For the most part, bleaching conditions were mild and focal, and overall prevalence only amounted to 0.4% (SE 0.2) around Guam.

Lesions involving pigmentation response on *Porites* were the second-most abundant syndrome, accounting for 26% of disease cases. These lesions were detected as most abundant in the north region at GUA-09 and GUA-07 with overall prevalence values of 2.1% and 2.7%. Often, but not exclusively, lesions appeared associated with areas of tissue loss or fungal and filamentous algal infections.

Conditions involving subacute tissue loss were recorded in the north, northwest, and east regions. Mean overall prevalence of these lesions was low, amounting to 0.3% (SE 0.2) overall around Guam. Of all the sites surveyed, GUA-05 near Haputo Point had the greatest concentration of these lesions with a site-specific overall prevalence of 1.8%. Tissue loss conditions occurred almost exclusively on the genus *Porites*. And, in many instances, these lesions occurred in association with extensive, old partial mortality and turf algal infections.

Other coral diseases present around Guam included fungal infection with a mean overall prevalence of 0.09% (SE 0.04), white syndrome with 0.03% (SE 0.03), algal and cyanophyte infections with 0.02% (SE 0.02), and skeletal growth anomalies with 0.01 (SE 0.01). These conditions were recorded on a variety of coral genera including *Porites* and *Montipora*.

Cases of coral predation attributable to COTS or corallivorous snails, such as snails from the genus *Drupella*, were also observed around Guam, particularly at GUA-04 in Tumon Bay, GUA-11 in Pago Bay, and GUA-09 near Jinapsan Point (Fig. 4.5.2b). The genera *Porites* and *Astreopora* were the main prey of COTS and snails.

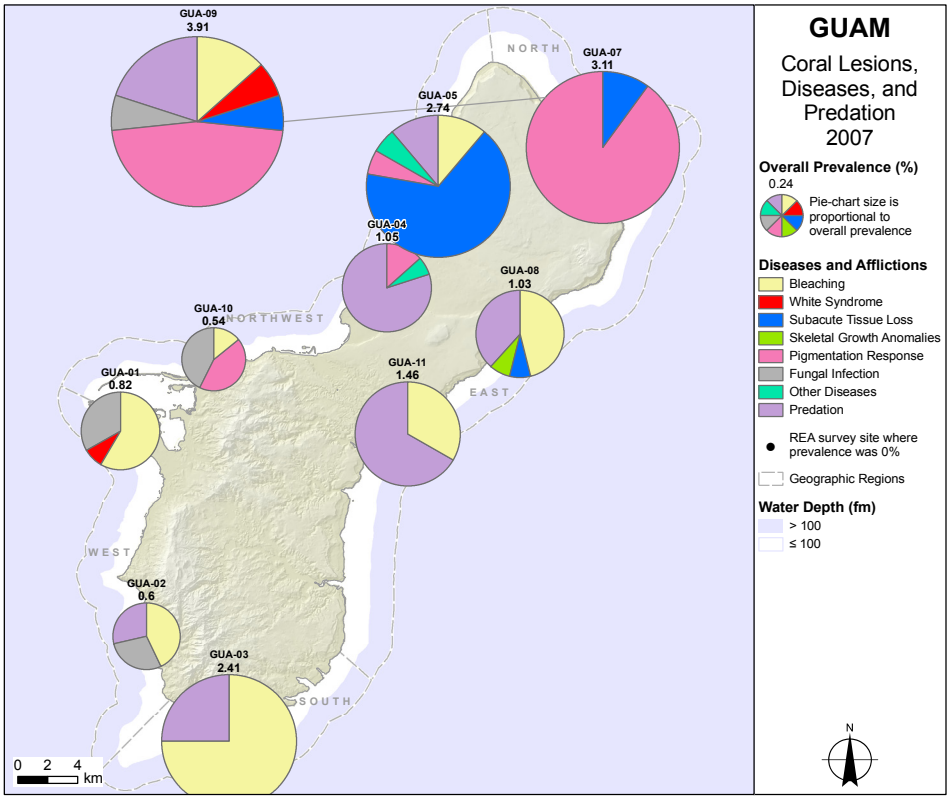


Figure 4.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie charts indicate disease-specific prevalence.

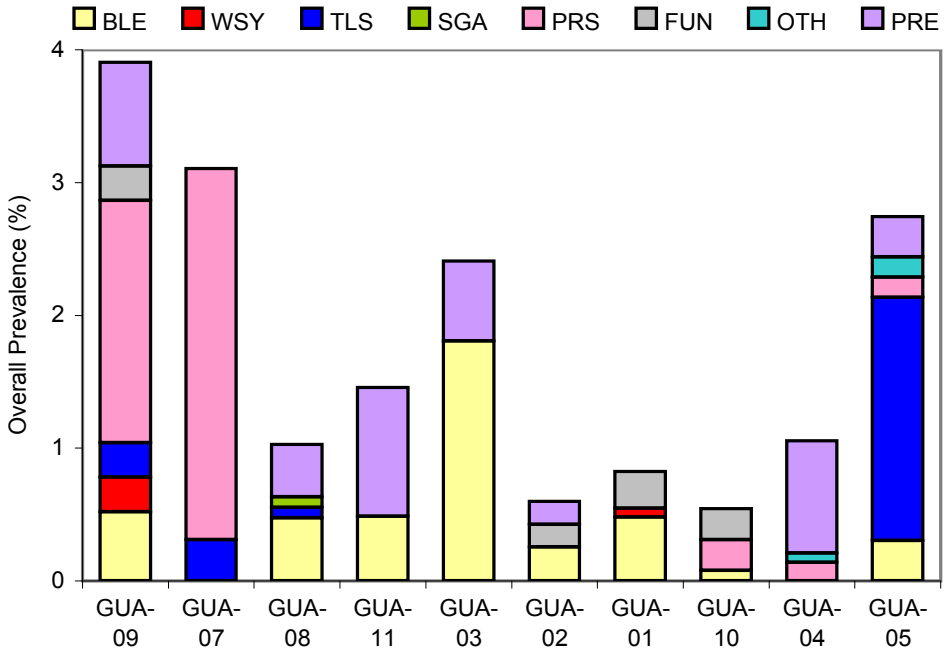


Figure 4.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesions of unknown etiology; PRE: predation by COTS or coralli-vorous snails.

4.6 Algae and Algal Disease

4.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Guam was 46% (SE 1.4). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 82%, within a range of 30.1%–100%, occurred south of Agfayan Bay in the south region (Fig. 4.6.1a, top left panel; for place-names and their locations, see Figure 4.2a in Section 4.2: "Survey Effort"). Habitats in this area primarily comprised low-relief, spur-and-groove pavement, dominated by species of Halimeda, a genus of calcified, jointed green algae. The Orote Peninsula Ecological Reserve in the west region and Tumon Bay in the northwest region of this island also exhibited high macroalgal cover with means of 68% and 60%. These areas were classified as low to medium-low complexity, pavement habitat—with the exception of a medium-high complexity, continuous-reef section located in Tumon Bay. Remaining surveys found fairly consistent values of algal cover typically within a range of 30.1%–50% and with the high values commonly recorded in pavement habitats of moderately low complexity.

TOAD surveys completed at Guam during MARAMP 2003 were conducted at depths of 15–200 m. Analyses of TOAD video footage obtained from 2 surveys in the middle of the north region and 3 surveys in the east region (2 near Pati Point and 1 near Catalina Point) suggest that macroalgal cover was high with 60%–100%, at least as seen in a majority of images (Fig. 4.6.1a, top left panel). Additionally, 3 TOAD surveys in the west region between Chii Point and Cocos Island and 1 survey near Agat Bay and the Namo River recorded little macroalgae.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Guam was 53% (SE 1.4). The survey with the highest mean macroalgal cover of 86%, within a range of 62.6%–100%, occurred in the south region along low-relief, spur-and-groove pavement habitat near Agfayan Bay (Fig. 4.6.1a, middle left panel). Additional benthic observations included the macroalgal overgrowth of live and dead corals. Surveys recorded the highest macroalgal cover along the Orote Peninsula Ecological Reserve in the west region. From Hagåtña Bay in the northwest region to the area south of Agat Bay in the west region, surveys reported high mean macroalgal cover of 59%–81%. Finally, reefs southwest of Ajayan Bay near GUA-03, reefs northwest of Cocos Island in the west region, and reefs near Ritidian Point in the north region exhibited high macroalgal cover with means of 64%, 65%, and 60%, respectively.

During MARAMP 2005, 7 REA benthic surveys of forereef habitats around Guam were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover from these surveys ranged from 16.7% to 68.6% with an overall mean of 43% (SE 7.6) around Guam. The survey with the highest macroalgal cover of 68.6% occurred in the west region at GUA-02 near Cetti Bay (Fig. 4.6.1b). Relatively high macroalgal-cover values of 64.7% and 54.9% were also found in the west region at GUA-01 and in the south region at GUA-03. The lowest macroalgal cover of 16.7% occurred in Tumon Bay in the northwest region at GUA-04.

Turf-algal cover from these REA benthic surveys in 2005 ranged from 1% to 32.4% with an overall mean of 17 % (SE 4.9). The highest turf-algal cover of 32.4% was observed at GUA-04 in the northwest region. The survey with the lowest turf-algal cover of 1% occurred in the west region at GUA-02.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats around Guam was 43% (SE 1.6). The survey with the highest mean macroalgal cover of 78%, within a range of 62.6%–100%, occurred in the west region along the reefs of Agat Bay (Fig. 4.6.1a, bottom left panel) in a habitat primarily consisting of moderately sloped, carbonate pavements. Species of Halimeda and the brown alga Padina dominated this substrate with half of the surveyed area exhibiting > 75% macroalgal cover. Two towed-diver surveys completed southwest of Ajayan Bay, along the southern edge of Cocos Lagoon, also reported high macroalgal cover with a mean of 44%, within a range of 5.1%–100%, over spur-and-groove pavement habitat. Species of Halimeda and Padina formed the dominant benthic components. Additionally, the survey north of Pago Bay in the east region with a mean of 61%, within a range of 50.1%–100%, recorded values of macroalgal cover that were higher than those values observed in other geographic regions around Guam. Species of the green algae Halimeda and Caulerpa accounted for the majority of coverage among the medium-complexity, spur-and-groove habitat. Remaining surveys reported mean or slightly less than mean values for macroalgal cover—with the exception of 1 survey in the south region off of Cocos Island with a mean of 10% within a range of 5.1%–20%.

During MARAMP 2007, 10 REA benthic surveys of forereef habitats around Guam were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 1% to 45.1% with an overall mean of 24% (SE 4.6) around Guam. Two surveys had the highest macroalgal cover of 45.1%, 1 in the west region at GUA-02 near Cetti Bay and 1 at GUA-04 in the northwest region in Tumon Bay (Fig. 4.6.1c). Relatively high macroalgal-cover values of 32.4% and 28.4% were also found in the east region at GUA-11 north of Pago Bay and in the south region at GUA-03 near the Achang Reef Flat Marine Preserve. The survey with the lowest macroalgal cover of 1% occurred in the east region at GUA-08 near Campanaya Point.

Turf-algal cover from these REA benthic surveys ranged from 31.4% to 70.6% with an overall mean of 50% (SE 4.1). The highest turf-algal cover of 70.6% was observed in the west region at GUA-01. The survey with the lowest turf-algal see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Guam was 13% (SE 0.6). The survey with the highest mean crustose-coralline-red-algal cover of 24%, within a range of 10.1%–40%, occurred in Tumon Bay (Fig. 4.6.1a, top right panel), where the habitat consisted of pavement and continuous reef of low to medium-high complexity. A survey near Ritidian Point, the northernmost tip of this island, reported spur-and-groove pavement habitat of medium to medium-high complexity and a mean crustose-coralline-red-algal cover of 23% within a range of 10.1%–40%. The majority of remaining surveys around Guam reported relatively low cover values for crustose coralline red algae, particularly south of Agfayan Bay, where no cover was observed.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Guam was 4% (SE 0.5). The survey with the highest mean crustose-coralline-red-algal cover of 22.6%, within a range of 0.1%–50%, occurred along the northeast coast at Pati Point (Fig. 4.6.1a, middle right panel) in an area of medium-complexity pavement reefs. Other areas that exhibited comparatively high coverage included Jalaihai Point in the south region and Tumon Bay in the northwest region with mean cover values of 13% and 10%. Pavement, continuous reef, and medium-complexity spur-and-groove habitats were the primary benthic components.

During MARAMP 2005, 7 REA benthic surveys of forereef habitats around Guam were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 11.8% with an overall mean of 5% (SE 1.4). The survey with the highest crustose-coralline-red-algal cover of 11.8% occurred in the north region at GUA-09 near Jinapsan Point (Fig. 4.6.1b). The lowest crustose-coralline-red-algal cover of 0% was recorded at GUA-01 in the west region in the Orote Peninsula Ecological Reserve.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Guam was 9% (SE 0.6). The survey with the highest mean crustose-coralline-red-algal cover of 23%, within a range of 5.1%–50%, occurred northwest of Cocos Island (Fig. 4.6.1a, bottom right panel), where the predominant habitat type was medium-complexity pavement. Remaining surveys reported relatively low cover values for crustose coralline red algae with slightly elevated cover along the north and east coasts. Continuous pavement reef appeared to dominate the overall benthic structure but sometimes alternated with spur-and-groove habitat.

During MARAMP 2007, 10 REA benthic surveys of forereef habitats around Guam were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 7.8% with an overall mean of 2% (SE 0.7). The survey with the highest crustose-coralline-red-algal cover of 7.8% occurred in the northwest region at GUA-10 (Fig. 4.6.1c). The lowest crustose-coralline-red-algal cover of 0% was recorded in the west region at GUA-01 and in the south region at GUA-03.

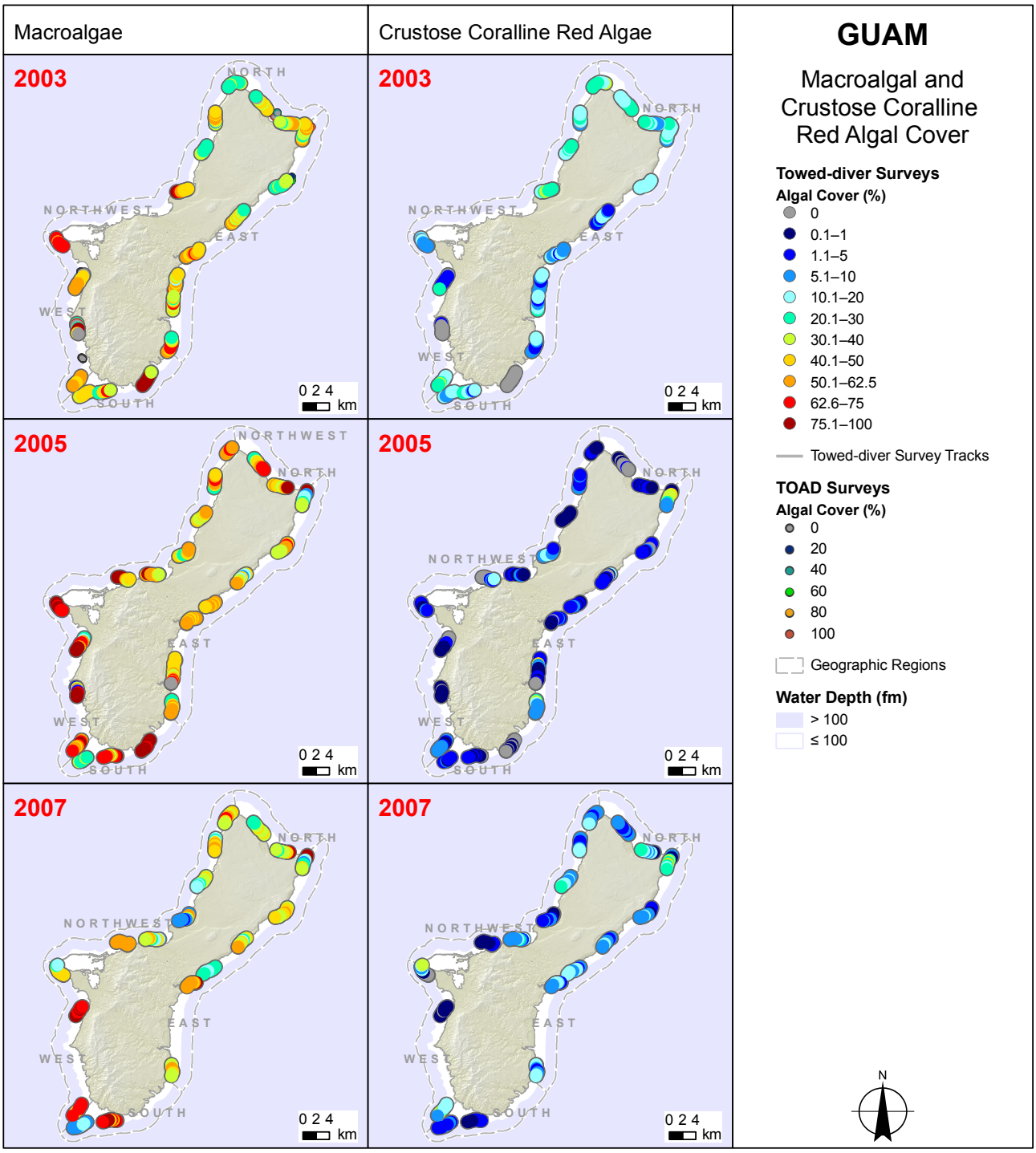


Figure 4.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

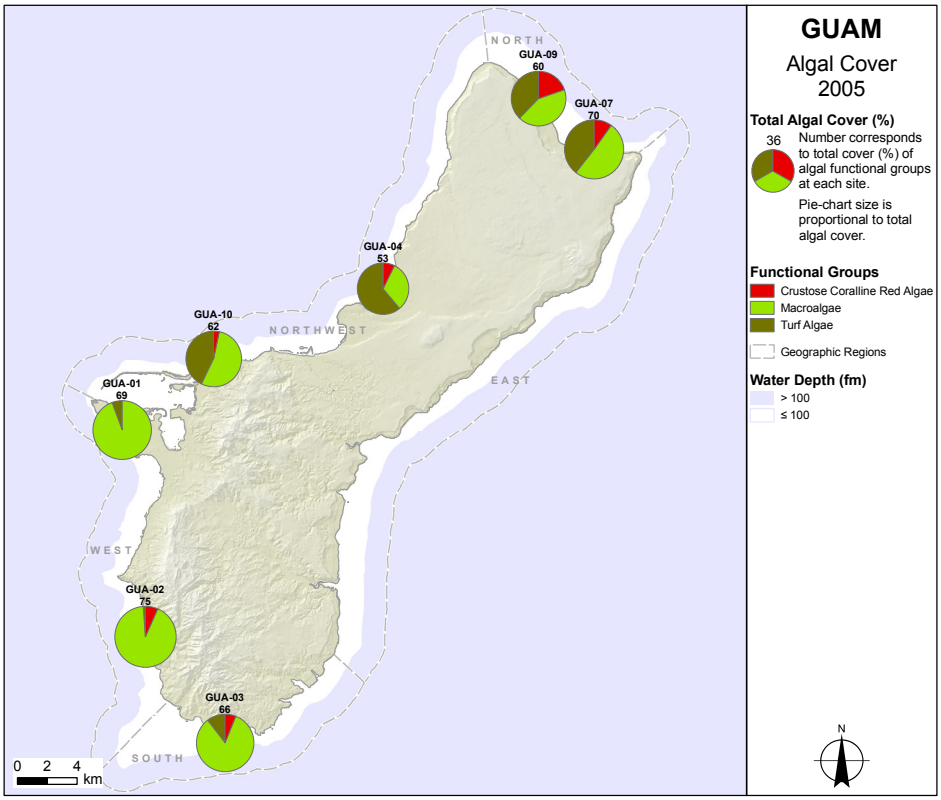


Figure 4.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method around Guam during MARAMP 2005. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

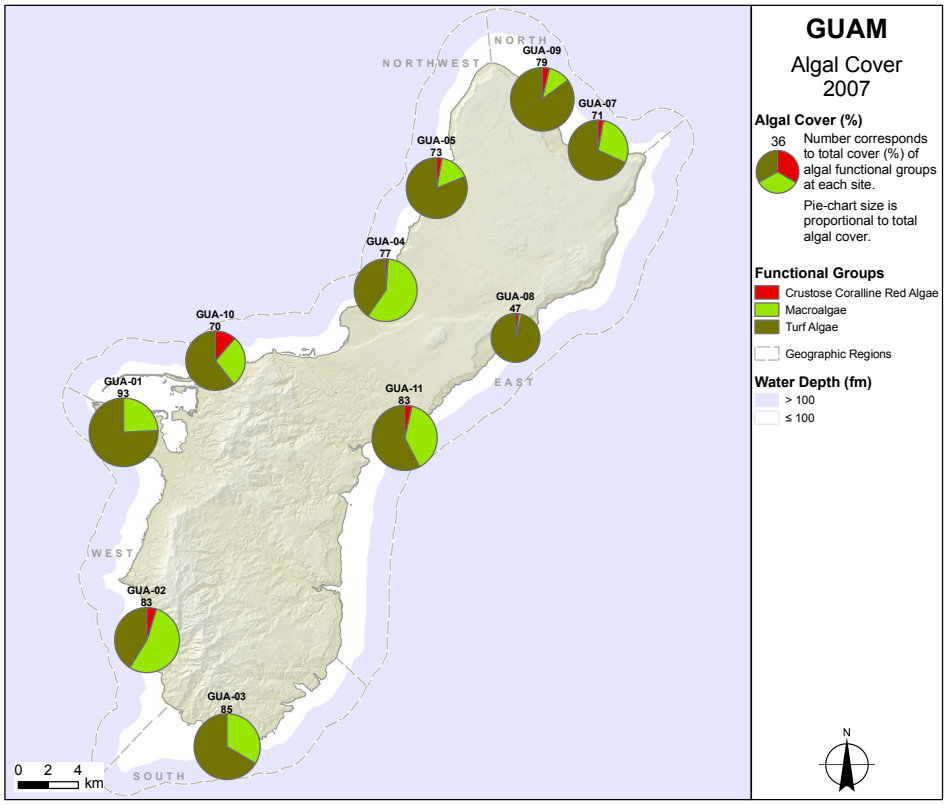


Figure 4.6.1c. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method around Guam during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, islandwide mean cover of macroalgal populations around Guam, based on towed-diver surveys of forereef habitats, varied by 10% (Fig. 4.6.1d). In general, macroalgae most commonly inhabited pavement habitats of low-to-medium complexity, and the most noticeable macroalgal genera were *Caulerpa*, *Halimeda*, *Padina*, and the red alga *Asparagopsis*. When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

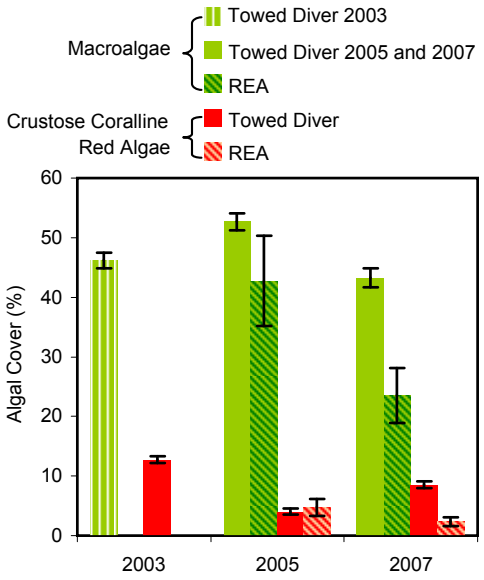


Figure 4.6.1d. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted in 2003. Error bars indicate standard error (± 1 SE) of the mean.

The highest macroalgal cover recorded in 2005 was 86%—with this observation occurring immediately south of Agfayan Bay. Because this area south of Agfayan Bay was not surveyed during MARAMP 2007, it is unknown how algal populations there in 2007 would compare to algae observed in 2005.

The highest cover of macroalgae was found during MARAMP 2007 in the west region in an area that experienced a significant increase in algal abundance from the previous survey year. The majority of MARAMP 2007 surveys reported decreased cover values, particularly in the areas near Orote Point in the west region, north of Jalaihai Point in the south region, near Pago Bay in the east region, and near Ritidian Point.

Crustose-coralline-red-algal populations around Guam, based on towed-diver surveys of forereef habitats, varied as much as 9% in average cover of the benthos between MARAMP survey years. Crustose coralline red algae most commonly inhabited regions of medium to medium-high complexity.

An overall mean decrease of 9% in crustose-coralline-red-algal cover occurred between MARAMP 2003 and 2005 (Fig. 4.6.1d), although an increase was reported for the area near Pati Point, the most northern point in the east region. The MARAMP 2007 survey conducted in this same area also reported elevated cover values for crustose coralline red algae when compared with other towed-diver surveys conducted around Guam, suggesting that this trend was not likely a result of observer differences.

The greatest decrease in cover of crustose coralline red algae was observed at Tumon Bay, Ritidian Point, Haputo Point, and the area northwest of Cocos Island. An islandwide mean increase of 5% in crustose-coralline-red-algal cover occurred between MARAMP 2005 and 2007. The greatest increases were recorded during surveys near Orote Point, east of Pati Point, and northwest of Cocos Island.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites has not been undertaken yet for the southern islands of the Mariana Archipelago. Ultimately, based on this microscopic analysis that may be done in the future, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 8 sites on forereef habitats around Guam. In the field, 22 macroalgal genera (9 red, 10 green, and 3 brown), containing at least 26 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, branched nongeniculate coralline red algae, and cyanophytes—were observed. GUA-01, located in the Orote Peninsula Ecological Reserve, had the highest macroalgal generic diversity with 11 genera, containing 12 species, documented in the field. The lowest macroalgal generic diversity was found at GUA-05 with 4 species representing 4 genera recorded.

Species of the green macroalgal genera *Halimeda* and *Neomeris* were common at every site surveyed around Guam in 2003 (Fig. 4.6.1e), occurring in 58% and 48% of sampled photoquadrats. At the species level, most of the 26 taxa tentatively identified occurred only at 1 or 2 sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae around Guam. However, some exceptions were found. Both *Halimeda opuntia* and the red alga *Portieria hornemannii* were found only at GUA-07 and GUA-09 in the north region and at GUA-08 in the east region near Campanaya Point, suggesting that oceanographic conditions might favor growth of these algae in these locations. A species of *Padina* was found only along the west coast of Guam, occurring at GUA-04 in Tumon Bay in the northwest region, GUA-01 near Orote Peninsula, and GUA-02 in Cetti Bay. The red alga *Tricleocarpa fragilis* was only recorded during surveys conducted around the southern half of Guam at GUA-01 and GUA-02 in the west region and GUA-06 in the east region.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2003, occurring in 98%, 60%, and 56% of photoquadrats sampled around Guam. Turf-algal communities were ubiquitous at all sites, and, although crustose coralline red algae typically occurred in > 75% of sampled photoquadrats at most sites, this functional group was completely absent from both sites surveyed in the west region: GUA-01 and GUA-02. Cyanobacteria, observed at all sites, were found in 25%–92% of sampled photoquadrats.

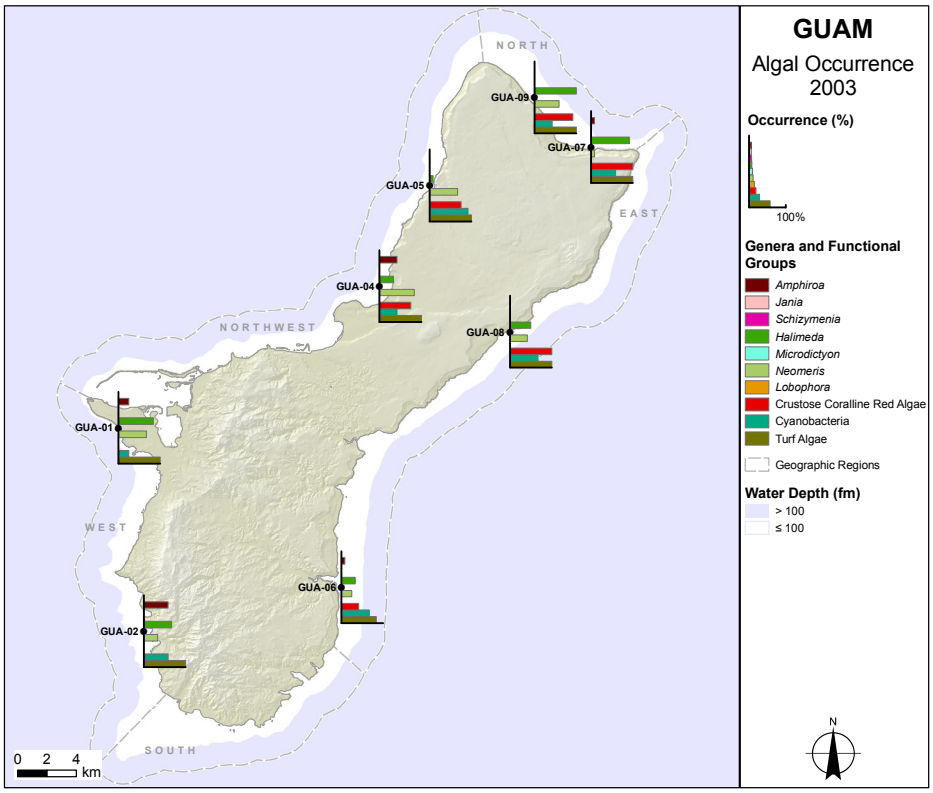


Figure 4.6.1e. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2005, REA benthic surveys were conducted at 7 sites on forereef habitats around Guam. In the field, 28 macroalgal genera (14 red, 11 green, and 3 brown), containing at least 29 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, branched nongeniculate coralline red algae, and cyanophytes—were observed. GUA-04, located in Tumon Bay in the northwest region, had the highest macroalgal generic diversity with 15 genera, containing 16 species, documented in the field. The lowest macroalgal generic diversity was found at GUA-08 near Campanaya Point in the east region with 8 species representing 8 genera recorded.

Species of the genera *Halimeda* and *Neomeris* were common at every site surveyed around Guam in 2005 (Fig. 4.6.1f), occurring in 95% and 45% of sampled photoquadrats. Although species of the red algal genus Amphiroa were absent or of low abundance at GUA-07 and GUA-09 in the north region and at GUA-08 in the east region, it occurred in 58%–100% of photoquadrats sampled at all other sites. For the majority of the 29 algal species tentatively identified, no strong spatial pattern of distribution was observed around Guam. Exceptions include a species of the red algal genus *Galaxaura* that only occurred at GUA-07 and GUA-09 in the north region and GUA-08, the most northern site in the east region, and species of the green algal genus *Dictyosphaeria* that were found everywhere except 3 sites in the southern half of Guam: GUA-02, GUA-03, and GUA-11. Species of the red algal genus *Martensia* and the calcified green algal genus *Udotea*, in contrast to the trend seen with species of *Dictyosphaeria*, occurred only at locales in the south: GUA-03 and GUA-11 as well as GUA-02 and GUA-03 for each genus, respectively. Species of the genus *Padina* were absent from the east side of Guam, recorded only from the northernmost and southernmost sites (GUA-02, GUA-03, GUA-07, and GUA-09) and from GUA-04 in Tumon Bay in the northwest region.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2005, occurring in 100%, 68%, and 55% of photoquadrats sampled around Guam. Both turf-algal and crustose-coralline-red-algal communities were prevalent at all sites surveyed. However, cyanobacteria were of low abundance at or completely lacking from GUA-02 in Cetti Bay and GUA-03 in the south region.

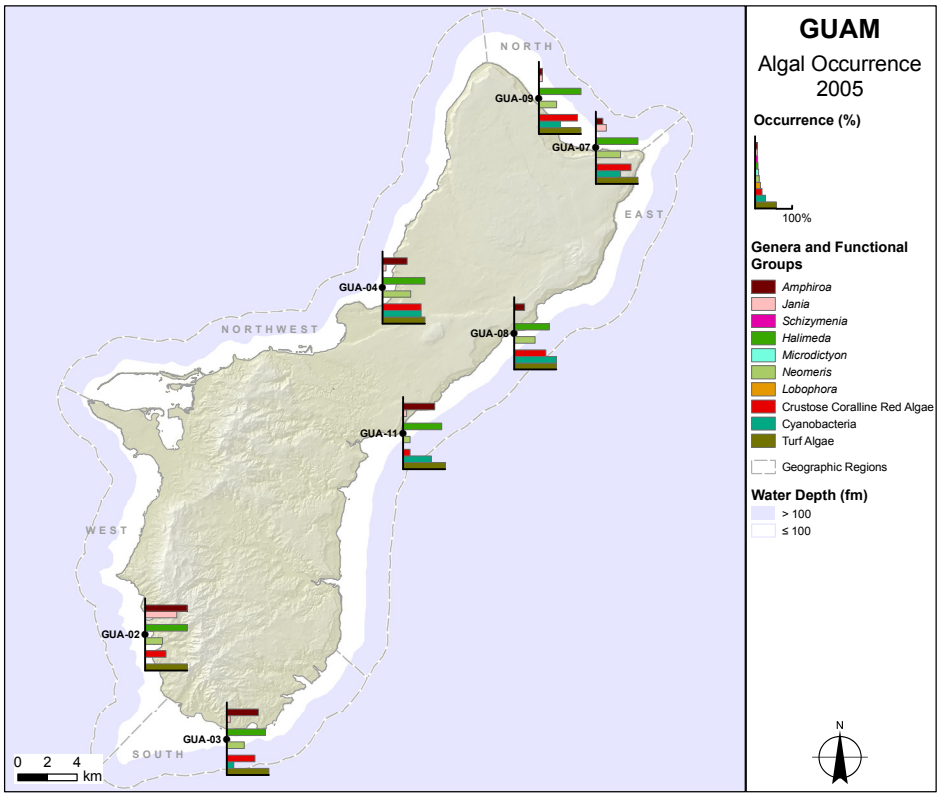


Figure 4.6.1f. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2007, REA benthic surveys were conducted at 10 sites on forereef habitats around Guam. In the field, 30 macroalgal genera (14 red, 11 green, and 5 brown), containing at least 46 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. GUA-03, located close to the Achang Reef Flat Marine Preserve, and GUA-11 near Pago Bay had the highest number of macroalgal taxa recorded in the field. Although 17 genera were documented at GUA-03 and only 14 at GUA-11, multiple species for some genera led to a total of 18 species observed at each site. The lowest macroalgal generic diversity was found at GUA-08 in the east region near Campanaya Point with 4 species representing 3 genera recorded.

Species of the genus *Halimeda* were ubiquitous at every site surveyed around Guam in 2007 (Fig. 4.6.1g), occurring in 87% of sampled photoquadrats. Of the 46 macroalgal species tentatively identified in the field, only a select few showed any spatial patterns of distribution. *Galaxaura adhaerens*, the green algae *Avrainvillea lacerata* and *Boodlea vanbosseae*,

and the brown alga Dictyota bartayresiana, occurred only at some of the sites on the southern half of Guam: GUA-01, GUA-02, GUA-03, and GUA-11. Alternatively, *Neomeris vanbosseae* and the red alga *Botryocladia skottsbergii* both only occurred at 2 of the sites on the west side: GUA-01 and GUA-10.

Turf algae and cyanobacteria were fairly common in 2007, occurring in 58% and 64% of photoquadrats sampled around Guam. Although crustose coralline red algae occurred in 8%–42% of sampled photoquadrats at most sites, this functional group was also completely absent from GUA-03 near the Achang Reef Flat Marine Preserve. Cyanobacteria occurred at all sites, with individuals being found in 8%–100% of sampled photoquadrats.

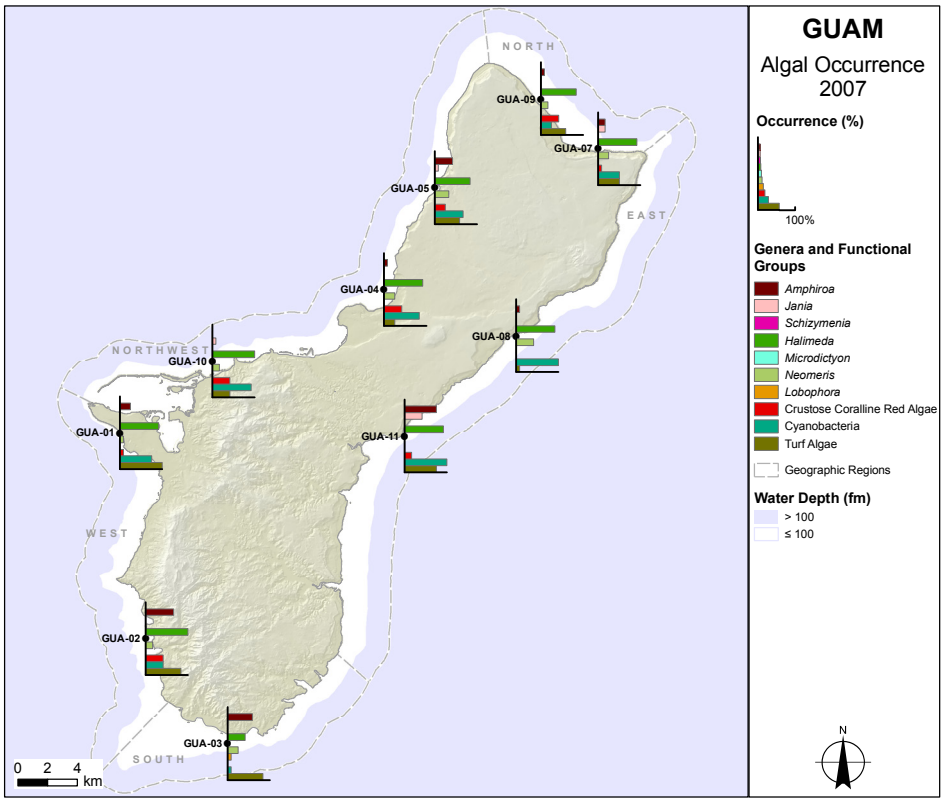


Figure 4.6.1g. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted around Guam during MARAMP 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

The number of macroalgal genera recorded on forereef habitats around Guam increased from 22 to 28 between MARAMP 2003 and 2005—and rose by an additional 2 genera up to 30 observed during MARAMP 2007. Meanwhile, the increase in species diversity for the same period was more pronounced, increasing from 26 in 2003 to 29 in 2005 and then to 46 in 2007. Differences in survey effort and other factors likely can account for this increase in estimated macroalgal diversity (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). One less site was surveyed in 2005 than in 2003, although a slight increase in the number of unique genera and species was recorded. Similarly, the number of sites surveyed increased from 8 in 2003 to 10 in 2007, and this greater survey effort may account for the marginal increase in the number of genera observed from 2005 to 2007.

The composition of algal species at 3 sites made much of the northeast coastline unique during most MARAMP survey years. GUA-07 and GUA-09 in the north region and GUA-08 in the east region were the only sites to contain *Halimeda opuntia* and *Portieria hornemannii* in 2003; they were the only sites containing a species of *Galaxaura* and the only ones lacking species of *Amphiroa* in 2005.

Similarly, sites located around the southern half of Guam often contained algal species that were lacking at sites in the north. During MARAMP 2003, GUA-01 near Orote Peninsula, GUA-02 near Cetti Bay, and GUA-06 near Talofofo Bay were the only sites to contain *Tricleocarpa fragilis*. The presence of species of *Martensia* and *Udotea* and the absence of species of *Dictyosphaeria* during MARAMP 2005 were unique to GUA-02, GUA-03 in the south region, and GUA-11 near Pago Bay in the east region. *Avrainvillea lacerata*, *Boodlea vanbosseae*, *Galaxaura adhaerens*, and *Dicyota bartayresiana* were all restricted to GUA-01, GUA-02, GUA-03, and GUA-11 during MARAMP 2007.

The percentages of occurrence of both crustose coralline red algae and turf algae on forereef habitats around Guam differed only slightly from 2003 to 2005, then decreased substantially in 2007 from 68% to 23% and from 100% to 58%, respectively (Fig. 4.6.1h). No subsequent increase in occurrence for macroalgal genera was apparent, suggesting that either the decreases in these functional groups' occurrence values reflected reality (possibly because of seasonal differences) or incongruent definitions for crustose coralline red algae or turf algae were used by observers between MARAMP 2005 and 2007. Cyanobacteria varied only slightly between survey years and occurred in 56%–64% of sampled photoquadrats at each site.

Across the 3 MARAMP survey years, species of the calcified green alga *Halimeda* had the highest occurrence, ranging from 58% in 2003 to 95% in 2005 and 87% in 2007. During the initial survey for MARAMP 2003, species of another calcified green alga *Neomeris* were recorded with the second-highest occurrence, but by 2005, species of the calcified red algal genus *Amphiroa* had the second-highest occurrence and retained that ascendency in 2007. A noticeable increase in percentage of occurrence was observed for species of *Avrainvillea*, *Codium*, *Dictyota*, and *Portieria* from 2003 to 2005, only to be followed by a decrease in 2007 similar to percentages recorded in 2003.

Members of the red algal family Gelidiaceae and species of the genus *Tricleocarpa* were observed in 28% and 19% of the photoquadrats surveyed during MARAMP 2003. By MARAMP 2005, the occurrence of these taxa was reduced to < 2%, and both remained in only 1% of the photoqradrats surveyed during MARAMP 2007.

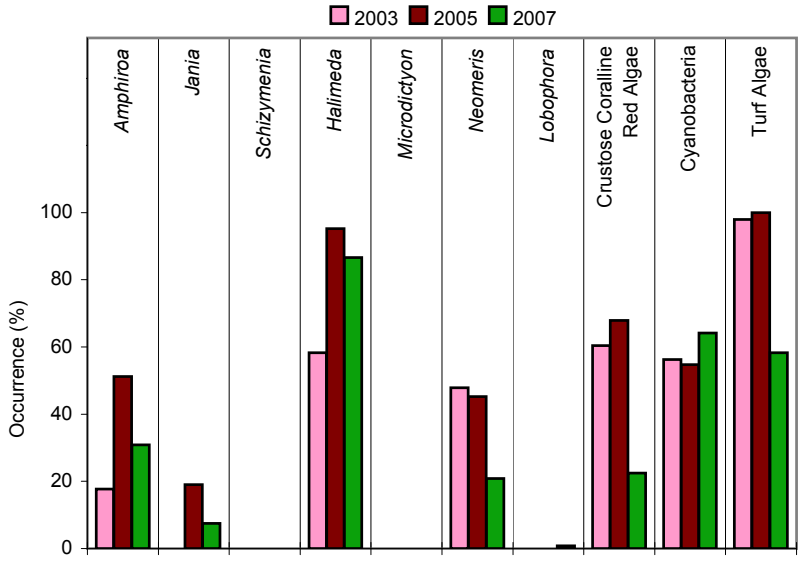


Figure 4.6.1h. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007.

4.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 10 sites on forereef habitats around Guam. These surveys covered a total reef area of more than 1600 m^2 and detected 18 cases. These numbers translate to an overall mean density of 1.6 cases 100 m^{-2} (SE 0.8), and disease was found only at reefs in the north and northwest regions (Figs. 4.6.2a). Only 1 major type of coralline-algal disease was observed around Guam: coralline lethal orange disease, present at 4 of the 10 sites surveyed. The greatest density of 8 cases 100 m^{-2} was found at GUA-07 off Jinapsan Point. Tumon Bay also contained disease but did so with a much lower density of 3.6 cases 100 m^{-2}.

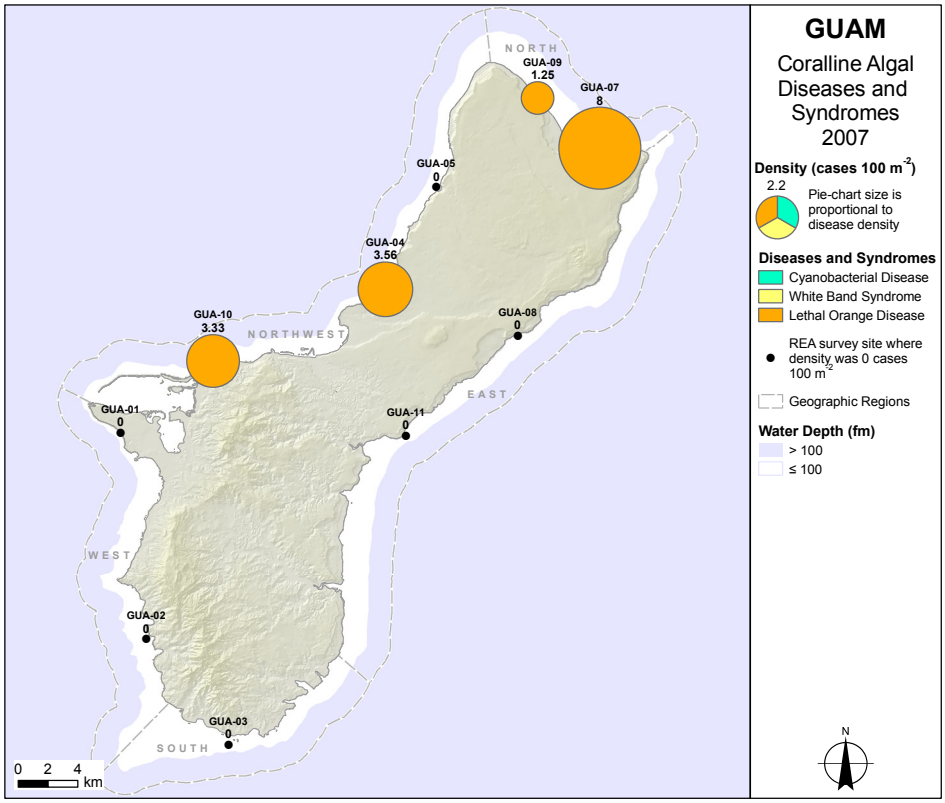


Figure 4.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats around Guam during MARAMP 2007.

4.7 Benthic Macroinvertebrates

4.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Guam through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 9 REA benthic surveys and 20 towed-diver surveys were conducted, and, in 2005, 9 REA benthic surveys and 23 towed-diver surveys were performed around Guam. In 2007, because of the lack of a scientific diver with expertise in invertebrates, no REA surveys for macroinvertebrates were conducted; however, 19 towed-diver benthic surveys were completed. Also, when considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, both REA and towed-diver surveys suggested low daytime macroinvertebrate abundance on forereef habitats around Guam compared to the rest of the Mariana Archipelago. Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density around Guam—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 4.7.1d, h, l, and p). Because of differences in survey methodology and in REA survey effort, with 9 surveys in both 2003 and 2005 but no surveys in 2007, temporal comparisons of REA data are not presented (see Chapter 2: "Methods and Operational Background," Section 2.4.7: "Benthic Macroinvertebrates").

Giant Clams

During MARAMP 2003, species of Tridacna giant clams were observed at 3 of the 9 REA sites surveyed and in 15 of the 20 towed-diver surveys conducted around Guam (Fig. 4.7.1a). The overall mean density of giant clams from REA surveys was 0.55 organisms 100 m^{-2} (SE 0.28), and the islandwide mean density from towed-diver surveys was 0.008 organisms 100 m^{-2} (SE 0.001). Survey results suggest that giant clams were most abundant at REA site GUA-09 in the north region near Jinapsan Point and at GUA-08 in the east region near Campanaya Point (for place-names and their locations, see Figure 4.2a in Section 4.2: "Survey Effort"). At both of these REA sites, the density of giant clams was 2 organisms 100 m^{-2}. Among all towed-diver surveys around this island, the survey completed between Togcha and Talofofo Bays in the east region had the highest mean density of giant clams with 0.018 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.12 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.02 organisms 100 m^{-2}, recorded in the south region just west of Ajayan Bay; segment densities ranged from 0 to 0.14 organisms 100 m^{-2}.

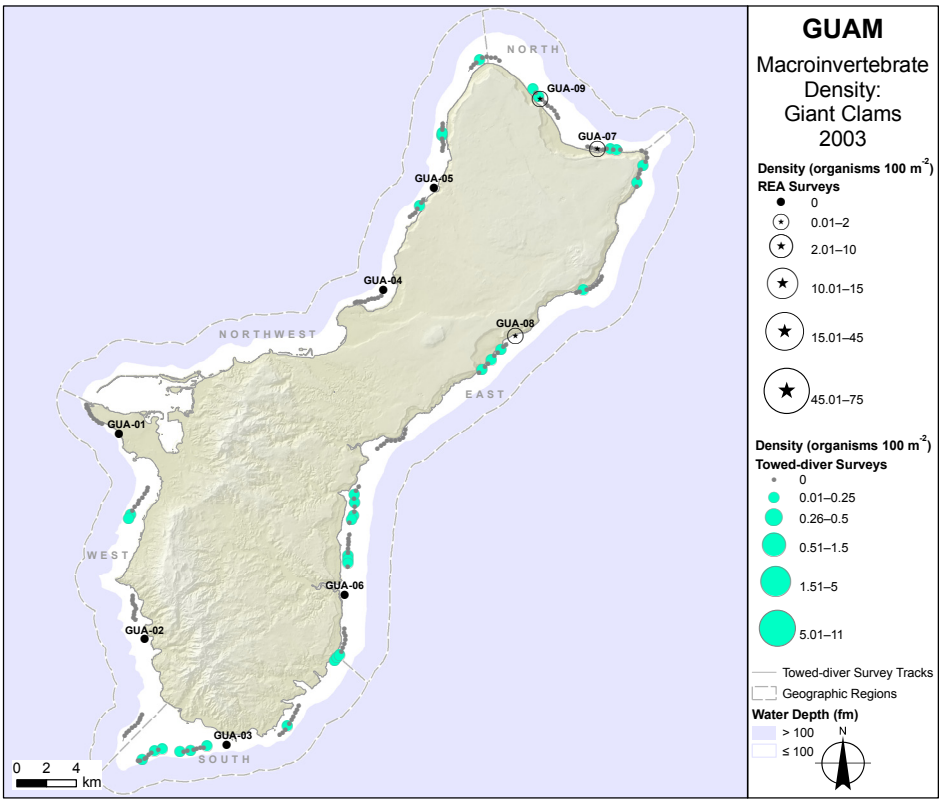


Figure 4.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2003.

During MARAMP 2005, giant clams were observed at 6 of the 9 REA sites surveyed and in 15 of the 23 towed-diver surveys conducted around Guam (Fig. 4.7.1b). The overall mean density of giant clams from REA surveys was 1 organism 100 m^{-2} (SE 0.31), and the islandwide mean density from towed-diver surveys was 0.006 organisms 100 m^{-2} (SE 0.001). Survey results suggest that giant clams were most abundant at GUA-07, located west of Pati Point in the north region, with 3 organisms 100 m^{-2}, followed by GUA-09 near Jinapsan Point, also in the north region, with 2 organisms 100 m^{-2}. Among all towed-diver surveys around this island, the survey completed between Lujuna and Mati Points in the east region had the highest mean density of giant clams with 0.019 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.1 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.017 organisms 100 m^{-2}, recorded in the north region near Jinapsan Point. The next-greatest mean densities were 0.016 and 0.015 organisms 100 m^{-2}, recorded near Pago Bay and north of Cocos Lagoon.

During MARAMP 2007, giant clams were observed in 12 of the 19 towed-diver surveys conducted around Guam (Fig. 4.7.1c) with an islandwide mean density of 0.005 organisms 100 m^{-2} (SE 0.001). Among all towed-diver surveys around this island, the 2 surveys completed in the north region, between Pati and Jinapsan Points, had the highest mean densities of giant clams with 0.019 and 0.015 organisms 100 m^{-2}; segment densities from these 2 surveys ranged from 0 and 0.1 organisms 100 m^{-2}. The third-greatest mean density of giant clams was 0.013 organisms 100 m^{-2}, recorded in the south region just inside Cocos Lagoon and west of Ajayan Bay; segment densities from this survey ranged from 0 to 0.13 organisms 100 m^{-2}.

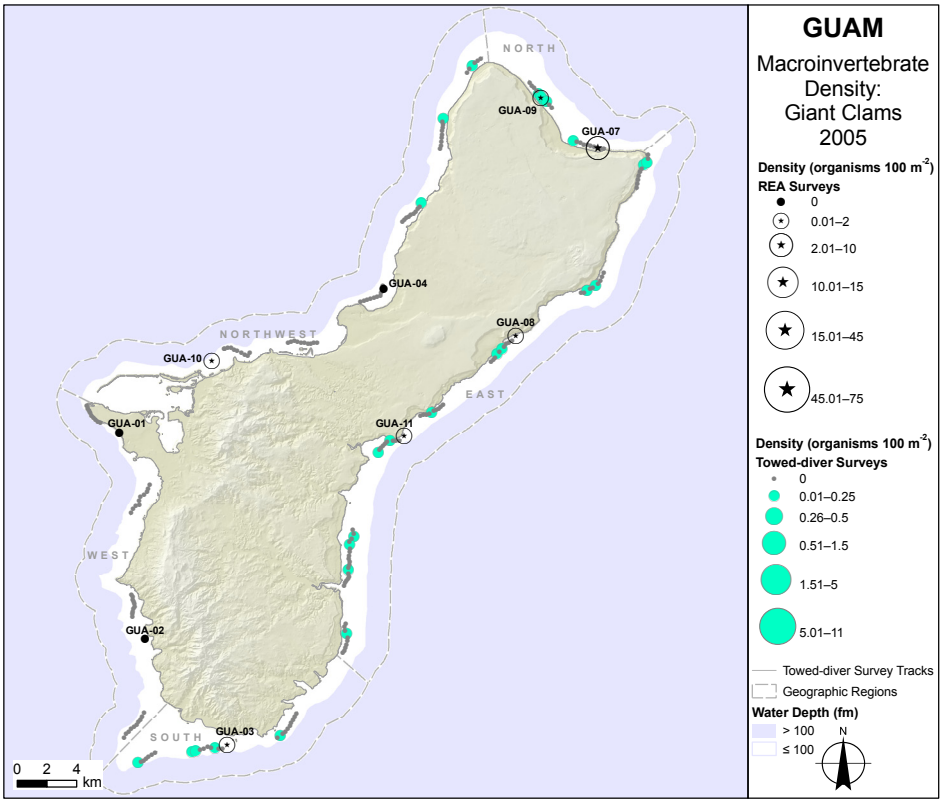


Figure 4.7.1b. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2005.

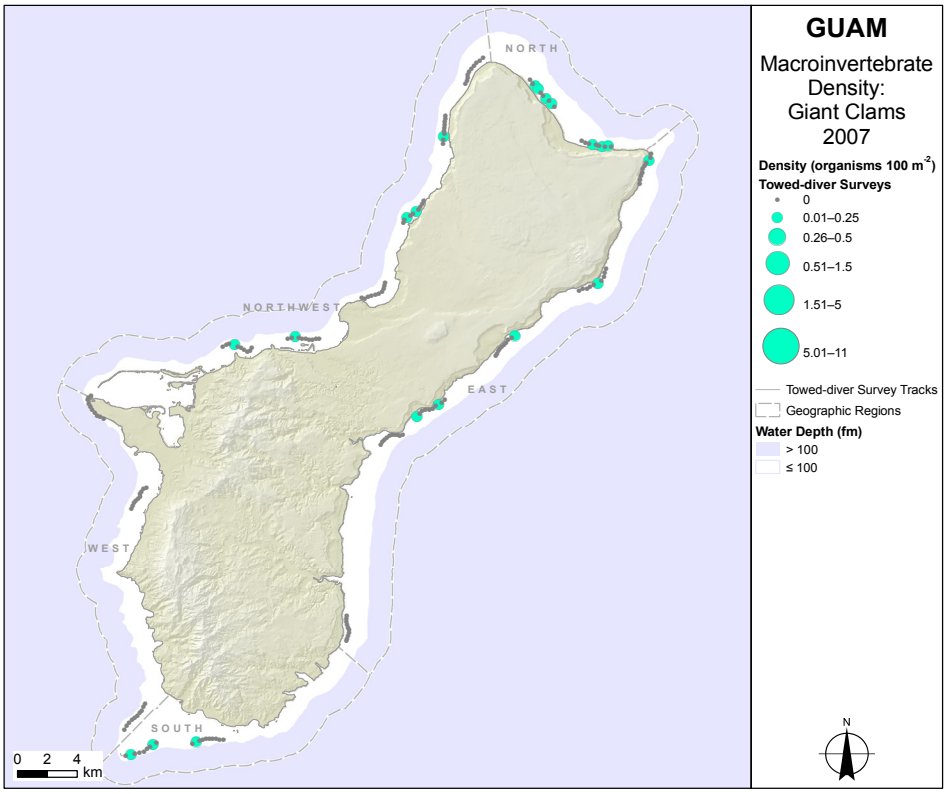


Figure 4.7.1c. Densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2007.

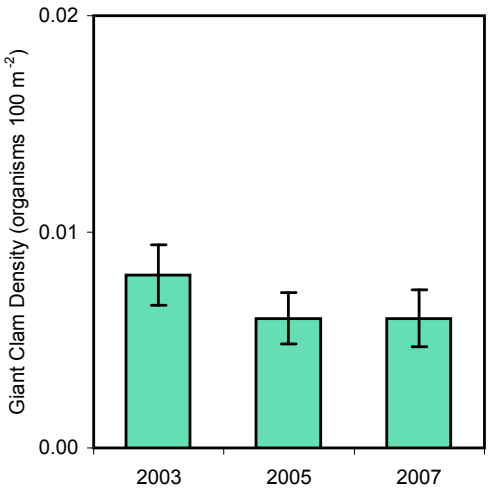


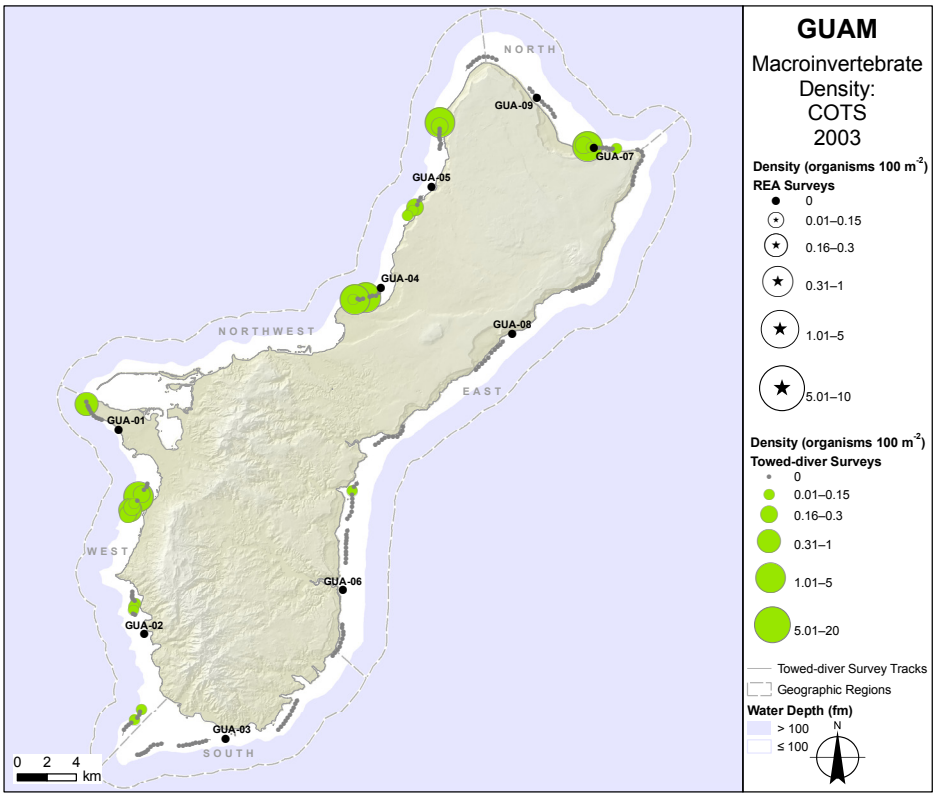
Figure 4.7.1d. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested low abundance of giant clams around Guam during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago (Fig. 4.7.1d). The west region had the fewest giant clams for all survey years. Minor fluctuations in density were observed, but this variation is not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Crown-of-thorns Seastars

During MARAMP 2003, no crown-of-thorns seastars (*Acanthaster planci*) were observed at the 9 REA sites surveyed around Guam, but 9 of the 20 towed-diver surveys had recordings of COTS (Fig. 4.7.1e), with an islandwide mean density of 0.05 organisms 100 m^{-2} (SE 0.02). During towed-diver surveys, COTS appeared more concentrated along the west side than in other areas. Among all towed-diver surveys around this island, the survey completed in Agat Bay had the highest mean density of COTS with 0.3 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.94 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey of 0.23 organisms 100 m^{-2} was recorded

Figure 4.7.1e. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2003.



in Tumon Bay; segment densities from this survey ranged from 0 to 1.17 organisms 100 m^{-2}. The towed-diver survey performed south of Uruno Point in the northwest region had a COTS density of 0.14 organisms 100 m^{-2} with segment densities ranging from 0 to 1.19 organisms 100 m^{-2}.

During MARAMP 2005, COTS were observed at 2 of the 9 REA sites surveyed and in 14 of the 23 towed-diver surveys conducted around Guam (Fig. 4.7.1f). The overall mean density of COTS from REA surveys was 0.67 organisms 100 m^{-2} (SE 0.47), and the islandwide mean density from towed-diver surveys was 0.1 organisms 100 m^{-2} (SE 0.03). Survey results suggest that COTS were most abundant at GUA-02 in Cetti Bay with a mean density of 4 organisms 100 m^{-2}, followed by GUA-09 near Jinapsan Point with 2 organisms 100 m^{-2}. During towed-diver surveys, COTS appeared concentrated on the west side of Guam and in the east region between Togcha and Talofofo Bays. Among all towed-diver surveys around this island, the 2 surveys completed nearest to Togcha Bay had the highest mean COTS densities with 0.82 and 0.29 organisms 100 m^{-2}; segment densities from these surveys ranged from 0 to 4.79 organisms 100 m^{-2}. The 2 next-greatest COTS densities were 0.19 and 0.28 organisms 100 m^{-2}, recorded between Uruno and Amantes Points in the northwest region; segment densities from these surveys ranged from 0 to 0.92 organisms 100 m^{-2}.

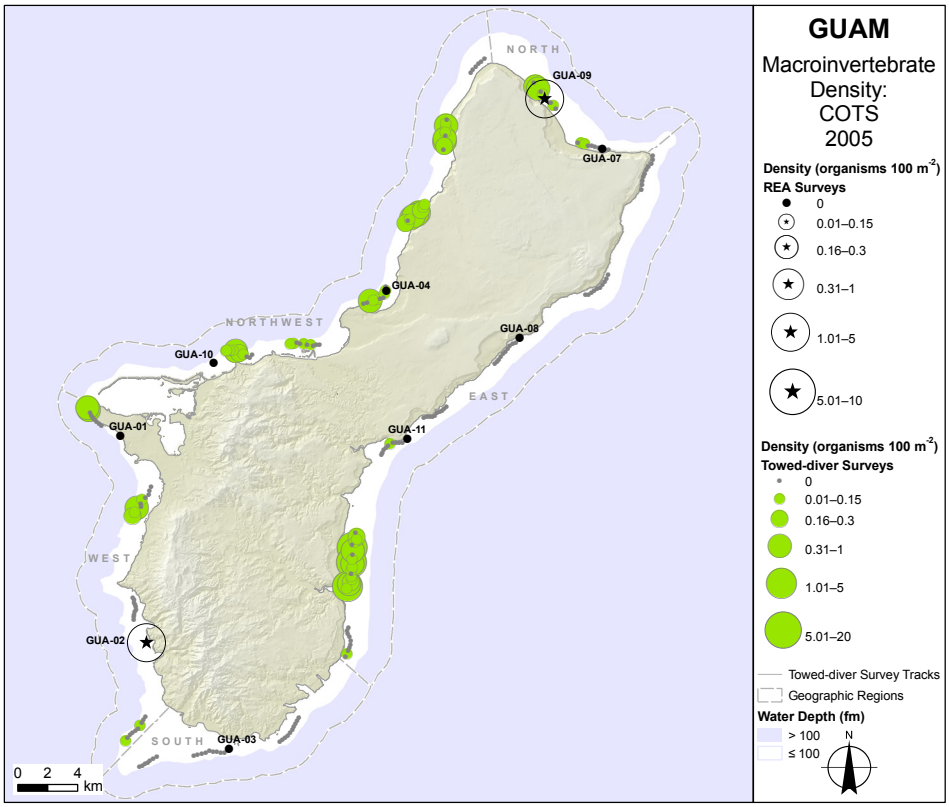


Figure 4.7.1f. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2005.

During MARAMP 2007, COTS were observed in 18 of the 19 towed-diver surveys conducted around Guam (Fig. 4.7.1g) with an islandwide mean density of 0.16 organisms 100 m^{-2} (SE 0.04). COTS were found around the entire island; however, they appeared more concentrated in the east and south regions. Among all the towed-diver surveys around this island, the survey completed along Fadian Point had the greatest mean density of COTS with 0.77 organisms 100 m^{-2}; segment densities from this survey ranged from 0.09 to 3.24 organisms 100 m^{-2}. A little farther north, also in the east region, the second-greatest mean density of COTS from a towed-diver survey of 0.55 organisms 100 m^{-2} was recorded near Campanaya Point; segment densities ranged from 0 to 4 organisms 100 m^{-2}. A survey north of Jalaihai Point had a mean density of 0.49 organisms 100 m^{-2} with segment densities ranging from 0 to 2.1 organisms 100 m^{-2}, and a survey in the south near the east side of Cocos Island, had a mean density of 0.41 organisms 100 m^{-2} with segment densities ranging from 0.04 to 2.75 organisms 100 m^{-2}.

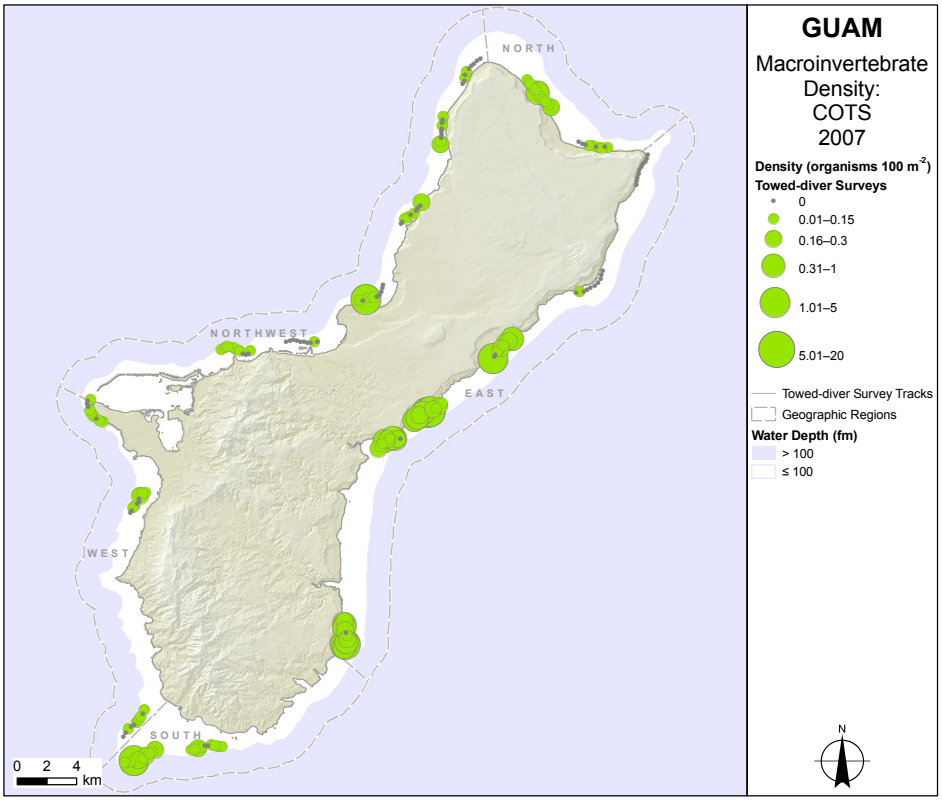


Figure 4.7.1g. Densities (organisms 100 m^{-2}) of COTS from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2007.

Towed-diver surveys suggested relatively high daytime densities of COTS around Guam during MARAMP 2003, 2005, and 2007, compared to the rest of the Mariana Archipelago, and a linear increase in abundance between MARAMP survey years (Fig. 4.7.1.h). Given that these corallivorous seastars can decimate a reef, understanding whether their observed densities signify an outbreak is important. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure established for using scuba divers to conduct MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of A. planci was > 1500 organisms km^{-2} (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of density and considering each towed-diver survey as an individual reef area, localized areas with relatively high densities that suggest that they were undergoing an outbreak were found during each MARAMP survey year. Based on MARAMP 2003 surveys, such areas were located in Tumon Bay in the northwest region and in Agat Bay in the west region with densities of 0.23 and 0.3 organisms 100 m^{-2}. During MARAMP 2005, the aforementioned density criterion was met in several surveyed areas: near Haputo and Uruno Points in the northwest region with COTS densities of 0.28 and 0.2 organisms 100 m^{-2}, Jinapsan Point in the north region with 0.18 organisms 100 m^{-2}, and Togcha and Talofofo Bays in the east region with 0.82 and 0.29 organisms 100 m^{-2}. By MARAMP 2007, nearly all surveys along the east shores of Guam between Pagat Point and Cocos Island found densities suggesting outbreaks with a range of 0.24 to 0.77 organisms 100 m^{-2}. Also meeting the criterion in 2007, surveys in Tumon Bay recorded 0.17 organisms 100 m^{-2}.

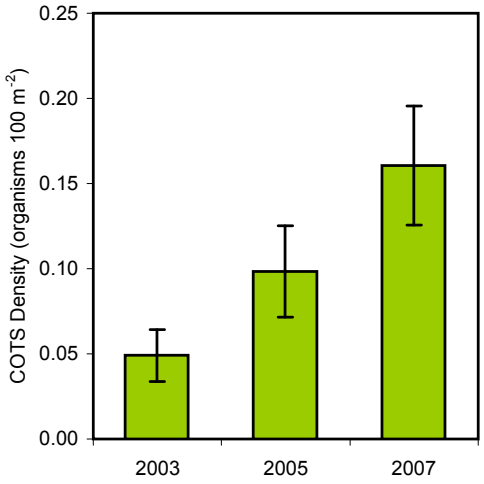


Figure 4.7.1h. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

MARAMP survey results make evident that COTS populations increased from 2003 to 2005 and again from 2005 to 2007. COTS density naturally fluctuates with food availability and variation in recruitment success (Birkeland and Lucas 1990;

Fabricius et al. 2010; and Yamaguchi 1987). A recruitment pulse could have occurred in 2005 along the east side of this island, for example, and COTS could have possibly increased in density and spread along the east coast by 2007 as the more cryptic juveniles became adults, searching for available food.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at only 2 of the 9 REA sites surveyed and in 15 of the 20 towed-diver surveys conducted around Guam (Fig. 4.7.1i). The overall mean density of sea cucumbers from REA surveys was 2.44 organisms 100 m^{-2} (SE 1.63), and the islandwide mean density from towed-diver surveys was 0.25 organisms 100 m^{-2} (SE 0.04). Survey results suggest that sea cucumbers were most abundant at GUA-04 in Tumon Bay with a mean density of 12 organisms 100 m^{-2} and at GUA-07 west of Pati Point in the north region with 10 organisms 100 m^{-2}. Species from 3 genera were observed during REA surveys: *Thelenota*, *Stichopus*, and *Holothuria*. Only sea cucumber species from the genus *Stichopus* were recorded at GUA-07, whereas species from the genera *Thelenota*, *Stichopus*, and *Holothuria* were observed at GUA-04. Of all recorded sea cucumbers, 73% were species from the genus *Stichopus*.

During towed-diver surveys conducted around Guam in 2003, sea cucumbers were observed predominantly along the west coast. Among all towed-diver surveys around this island, the survey completed north of Cocos Island had the highest mean density of sea cucumbers with 1.26 organisms 100 m^{-2}; segment densities from this survey ranged from 0.21 to 3.32 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 1.09 organisms 100 m^{-2}, recorded just west of Ajayan Bay in the south region, and the next-highest mean density of 0.64 organisms 100 m^{-2} was observed in the north region between Pati and Jinapsan Points.

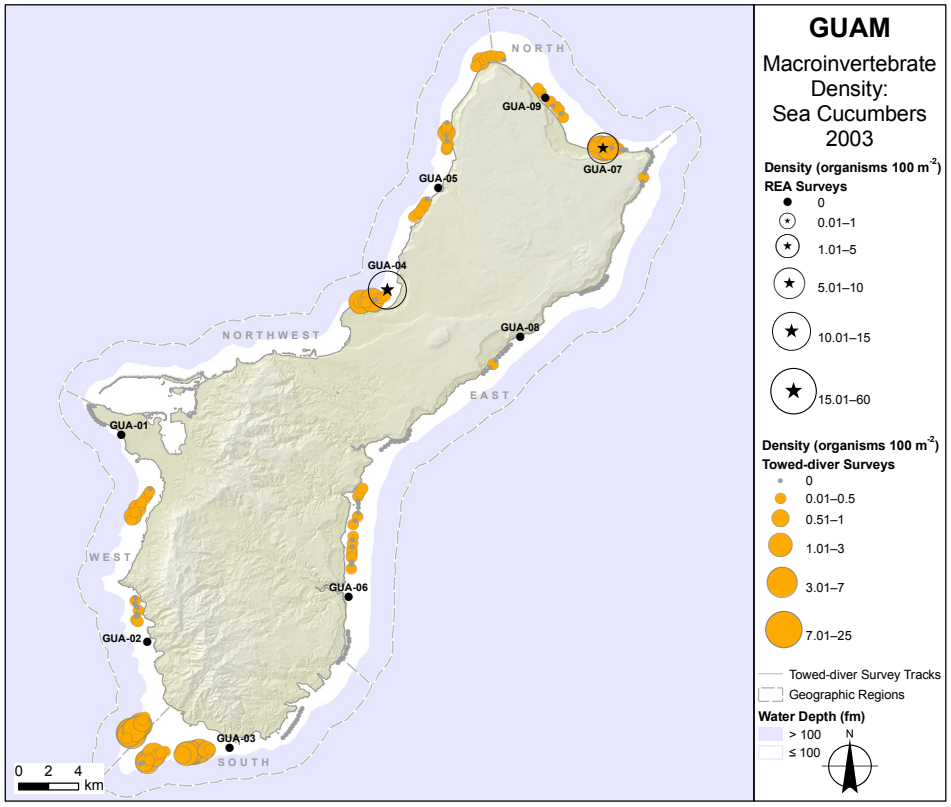


Figure 4.7.1i. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2003.

During MARAMP 2005, sea cucumbers were observed at 4 of the 9 REA sites surveyed and in 15 of the 23 towed-diver surveys conducted around Guam (Fig. 4.7.1.j). The overall mean density of sea cucumbers from REA surveys was 2.89 organisms 100 m^{-2} (SE 1.53), and the islandwide mean density from towed-diver surveys was 0.14 organisms 100 m^{-2} (SE 0.02). Survey results suggest that sea cucumbers were most abundant at GUA-04 in Tumon Bay with a mean density of 13 organisms 100 m^{-2}. GUA-10 at Adelup Point, also in the northwest region, had the second-greatest mean density of sea cucumbers with 7 organisms 100 m^{-2}. Sea cucumber species from the genera *Stichopus*, *Actinopyga*, *Bohadschia*, and *Holothuria* were observed; however, species from the genus *Stichopus* represented 80% of recorded sea cucumbers.

During towed-diver surveys conducted around Guam in 2005, sea cucumbers were observed predominantly along the west coast, as they were during MARAMP 2003. Among all towed-diver surveys around this island, the survey completed along the western edge of Cocos Lagoon in the west region had the highest mean density of sea cucumbers with 0.8 organisms 100 m^{-2}; segment densities from this survey ranged from 0.09 to 1.67 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.75 organisms 100 m^{-2}, recorded in Tumon Bay; segment densities ranged from 0 to 1.64 organisms 100 m^{-2}.

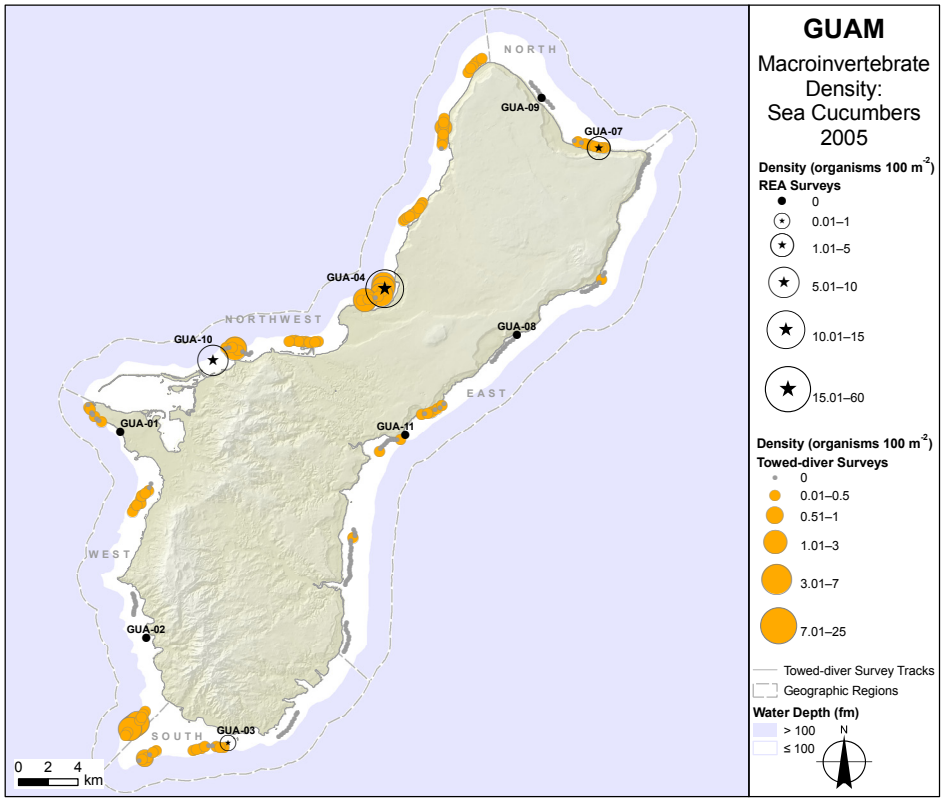


Figure 4.7.1j. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2005.

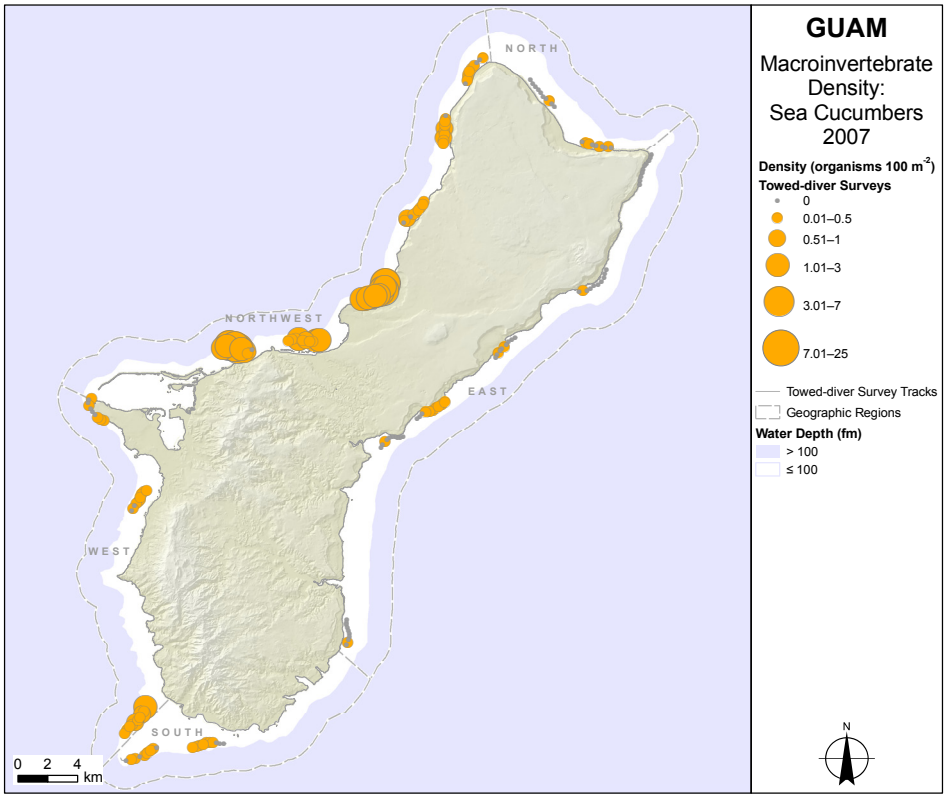


Figure 4.7.1k. Densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2007.

During MARAMP 2007, sea cucumbers were observed in 18 of the 19 towed-diver surveys conducted around Guam (Fig. 4.7.1k) with an islandwide mean density of 0.34 organisms 100 m^{-2} (SE 0.06). The 3 surveys with the highest mean densities of sea cucumbers all were performed in the northwest region. Among all towed-diver surveys around this island, the survey completed in Tumon Bay had the greatest mean density of sea cucumbers with 2.36 organisms 100 m^{-2}; segment densities from this survey ranged from 1.42 to 6.76 organisms 100 m^{-2}. The next-highest mean densities of sea cucumbers were 1.86 and 0.71 organisms 100 m^{-2}, recorded around Adelup Point and near Hagåtña Bay.

Towed-diver surveys suggested low daytime abundance of sea cucumbers around Guam during MARAMP 2003, 2005, and 2007, relative to the rest of the Mariana Archipelago. However, during the 3 survey years, high sea cucumber densities were observed in the northwest region between Tumon Bay and Adelup Point. Although sea cucumbers were not recorded to genus during towed-diver surveys, REA surveys suggested that over 90% of the sea cucumbers observed in this region were species from the genus *Stichopus*.

The overall observed mean density of sea cucumbers around Guam was higher in 2007 than in 2003 and 2005 (Fig. 4.7.1l). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

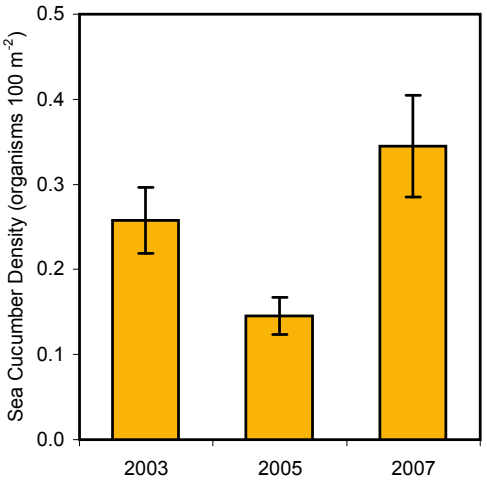


Figure 4.7.1l. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Urchins

During MARAMP 2003, sea urchins were observed at all 9 REA sites surveyed and in 17 of the 20 towed-diver surveys conducted around Guam (Fig. 4.7.1m). The overall mean density of sea urchins from REA surveys was 9 organisms

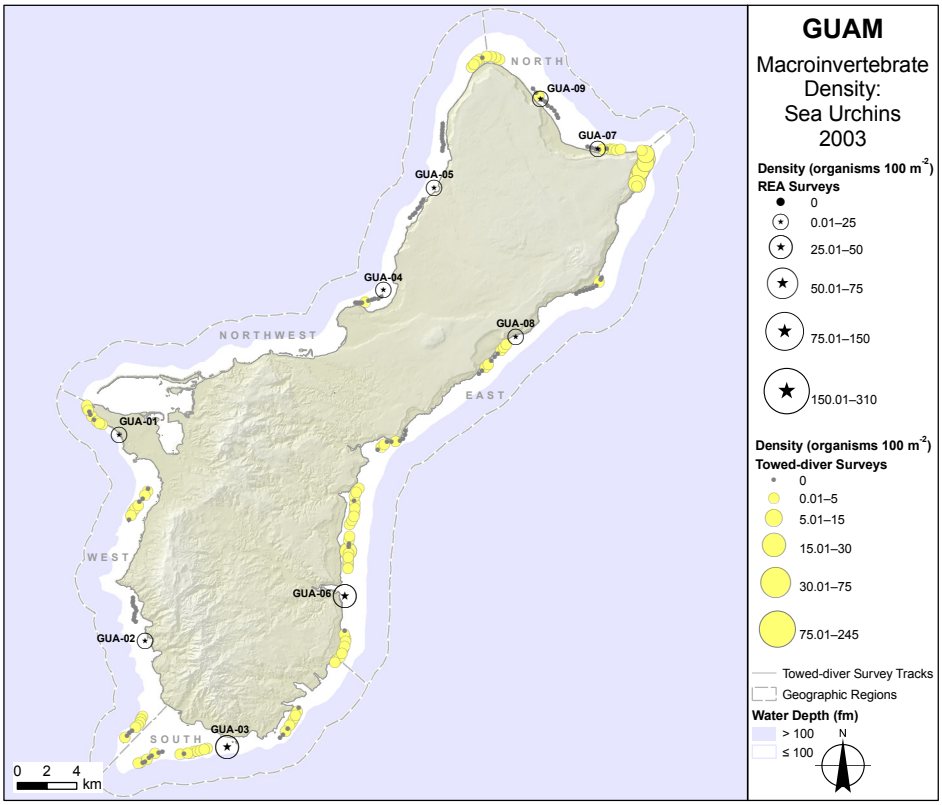


Figure 4.7.1m. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2003.

100 m^{-2} (SE 3.7), and the islandwide mean density from towed-diver surveys was 0.95 organisms 100 m^{-2} (SE 0.13). Survey results suggest that sea urchins were most abundant at GUA-03, located in the south region just west of Ajayan Bay, with a mean density of 29 organisms 100 m^{-2} and at GUA-06 in the east region in Talofofo Bay with 27 organism 100 m^{-2}. Rock-boring urchins from the genus *Echinostrephus* were the dominant macroinvertebrates at all sites, accounting for 96% of recorded urchins. GUA-07 east of Pati Point in the north region had the highest species diversity with representatives from the genera *Echinostephus*, *Echinothrix*, and *Diadema*.

Among all towed-diver surveys conducted around Guam in 2003, the survey completed around Pati Point in the east region had the highest mean density of sea urchins at 6.23 organisms 100 m^{-2}; segment densities from this survey ranged from 0.04 to 12.53 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 2.52 organisms 100 m^{-2}, recorded between Ajayan Bay and Cocos Island in the south region; segment densities ranged from 0 to 3.69 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed at 8 of the 9 REA sites surveyed and in 14 of the 23 towed-diver surveys conducted around Guam (Fig. 4.7.1n). The overall mean density of sea urchins from REA surveys was 7.33 organisms 100 m^{-2} (SE 3.86), and the islandwide mean density from towed-diver surveys was 0.45 organisms 100 m^{-2} (SE 0.07). Survey results suggest that sea urchins were most abundant at GUA-11 in the east region, between Fadian Point and Pago Bay, with a mean density of 35 organisms 100 m^{-2}. The second-greatest density of 17 organisms 100 m^{-2} was recorded at GUA-03 west of Ajayan Bay in the south region. The rock-boring urchin *Echinostrephus* was the dominant macroinvertebrate genus overall and the only one recorded at all sites but one; species from the genus *Echinothrix* were also observed at GUA-11. Species from *Echinostrephus* accounted for 92% of recorded urchins.

Among all towed-diver surveys conducted around Guam in 2005, the survey completed along Fadian Point in the east region had the highest mean density of sea urchins with 2.09 organisms 100 m^{-2}; segment densities from this survey ranged from 0.38 to 4.22 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 1.98 organisms 100 m^{-2}, recorded during the survey that rounded Pati Point; segment densities ranged from 0.4 to 6.91 organisms 100 m^{-2}.

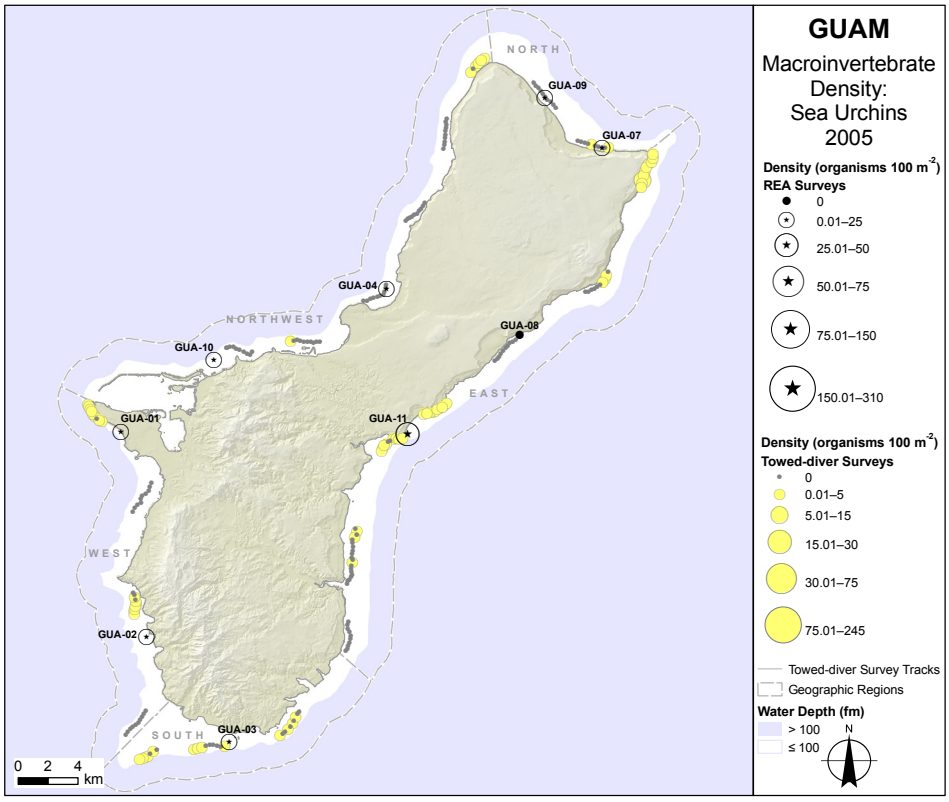


Figure 4.7.1n. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2005.

During MARAMP 2007, sea urchins were observed in 18 of the 19 towed-diver surveys conducted around Guam (Fig. 4.7.1o) with an islandwide mean density of 1 organisms 100 m^{-2} (SE 0.23). Among all towed-diver surveys around this island, the survey that rounded Pati Point had the highest mean density of sea urchins with 12.93 organisms 100 m^{-2}; segment densities from this survey ranged from 6.77 to 16.68 organisms 100 m^{-2}. The second-greatest mean density of sea urchins was 2.76 organisms 100 m^{-2}, recorded during the survey near Orote Point in the west region; segment densities ranged from 0 to 7.93 organisms 100 m^{-2}.

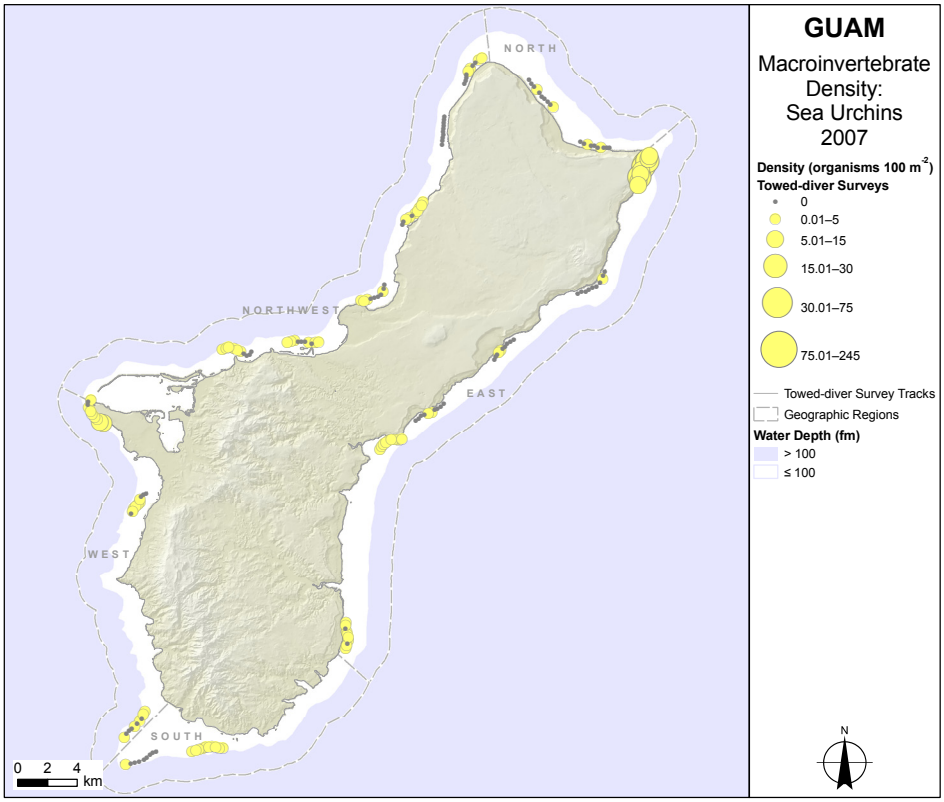


Figure 4.7.1o. Densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2007.

Towed-diver surveys suggested low daytime abundance of sea urchins around Guam during MARAMP 2003, 2005, and 2007, compared to the rest of the Mariana Archipelago. The overall observed mean density of sea urchins around Guam was higher in 2007 than in 2005 (Fig. 4.7.1p). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Although sea urchins were not recorded down to the genus level during towed-diver surveys, REA surveys suggested that more than 90% of the sea urchin species observed around Guam were rock-boring urchins from the genus *Echinostrephus*.

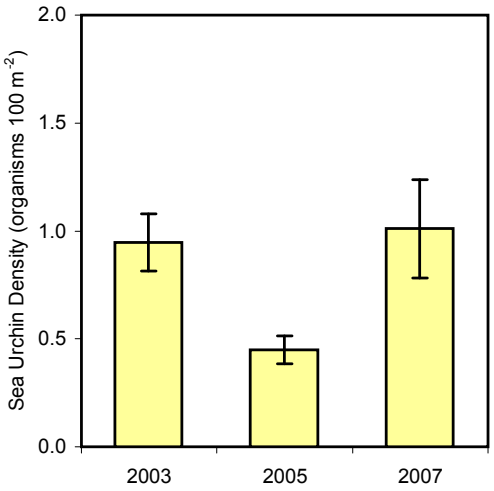


Figure 4.7.1p. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Guam during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

4.8 Reef Fishes

4.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 20 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Guam. The overall estimated mean biomass of large fishes around this island, calculated as weight per unit area, was 0.14 kg 100 m^{-2} (SE 0.05), a low value compared to other survey areas in the Mariana Archipelago. No clear spatial patterns were seen in the distribution of large-fish biomass around Guam (Fig. 4.8.1a). Parrotfishes (Scaridae) accounted for the greatest proportion (29%) or 0.04 kg 100 m^{-2} of overall mean large-fish biomass. The filament-finned parrotfish (*Scarus altipinnis*) was the most abundant parrotfish species, contributing more than 30% of parrotfish biomass. Surgeonfishes (Acanthuridae) composed the second-greatest proportion (27%) of overall large-fish biomass, and the bulbnose unicornfish (*Naso tonganus*) was the most abundant surgeonfish species. Five reef sharks (Carcharhinidae) were observed around Guam, and 4 of them were seen along the northern coasts of this island: 3 near Pati Point in the east region and 1 just south of Uruno Point in the northwest region (for place-names and their locations, see Figure 4.2a in Section 4.2: "Survey Effort"). These sharks comprise 3 blacktip reef shark (*Carcharhinus melanopterus*) and 2 whitetip reef shark (*Triaenodon obesus*).

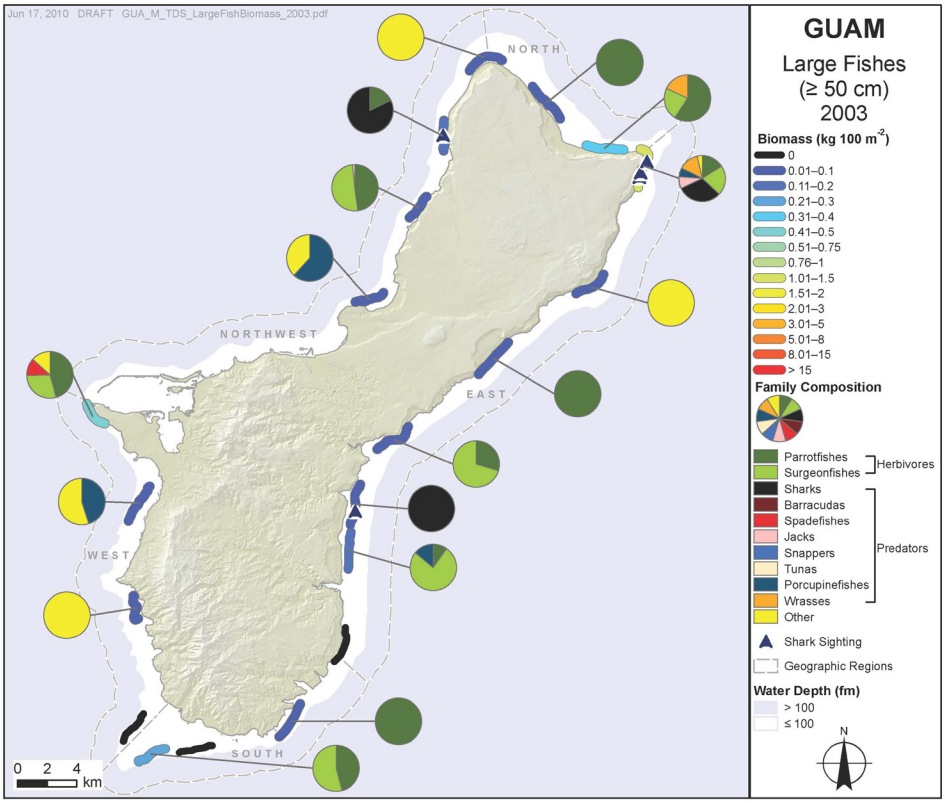


Figure 4.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted around Guam during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

During MARAMP 2005, 23 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Guam. The overall estimated mean biomass of large fishes around this island was 0.06 kg 100 m^{-2} (SE 0.03), a value lower than the already low biomass observed in 2003. Only select surveys in the west region and the northern part of the east region showed moderate biomass (Fig. 4.8.1b). The eagle ray (*Aetobatus narinari*) accounted for the greatest proportion (33%) of islandwide mean large-fish biomass with 4 individuals recorded during 1 survey. Wrasses (Labridae) and snappers (Lutjanidae) were also abundant, contributing 21% and 11% of overall mean large-fish biomass around Guam. The humphead wrasse (*Cheilinus undulatus*) was the most abundant wrasse species with 3 individuals constituting biomass of 0.01 kg 100 m^{-2}. The twinspot snapper (*Lutjanus bohar*) was the most abundant snapper species, composing more than 90% of snapper biomass. No sharks were observed during this survey period.

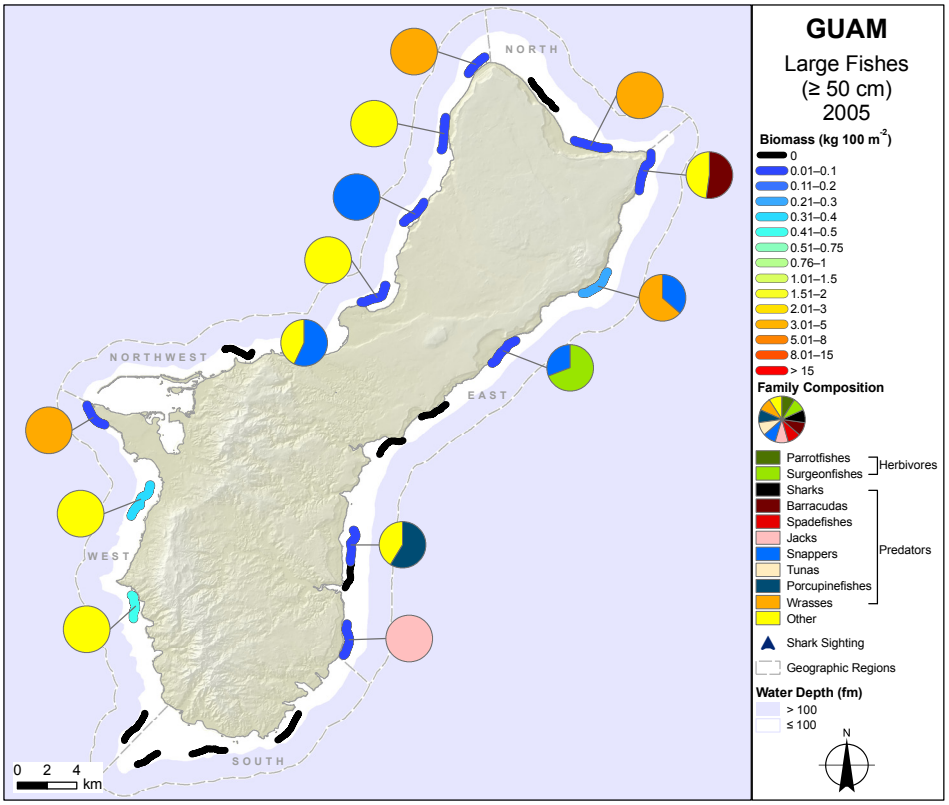


Figure 4.8.1b. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted around Guam during MARAMP 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

During MARAMP 2007, 19 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Guam. The overall estimated mean biomass of large fishes around this island was 0.07 kg 100 m^{-2} (SE 0.02), a low value compared to other survey areas in the Mariana Archipelago and consistent with the low values observed around Guam in 2005. Biomass values for large fishes were highest in the northwest region and near Pati Point, the northernmost tip of the east region; however, biomass levels in these areas were not anomalously higher than in other survey areas around

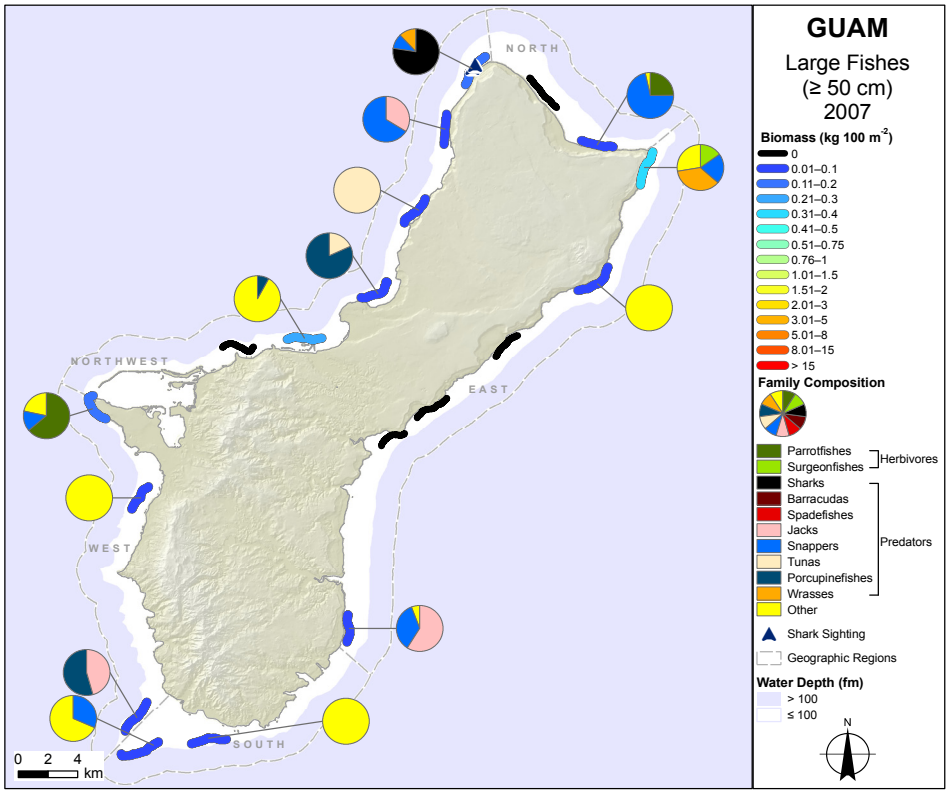


Figure 4.8.1c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted around Guam during MARAMP 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

this island (Fig. 4.8.1c). Similar to observations made in 2005, eagle ray accounted for the greatest proportion (27%) of islandwide large-fish biomass with 2 individuals contributing 0.03 kg 100 m^{-2} to overall mean large-fish biomass. Snappers composed the second-greatest proportion (15%) of overall mean large-fish biomass around Guam, with the twinspot snapper accounting for more than 60% or 0.01 kg 100 m^{-2} of snapper biomass. Near Ritidian Point in the northwest region, 2 reef sharks were observed: 1 grey reef shark (*Carcharhinus amblyrhynchos*) and 1 whitetip reef shark. Other notable observations included sightings of 3 humphead wrasse and 3 dogtooth tuna (*Gymnosarda unicolor*) during this survey period.

Large-fish biomass from towed-diver surveys of forereef habitats was generally higher during MARAMP 2003, with an islandwide mean of 0.14 kg 100 m^{-2} (SE 0.05), than during later survey periods, when islandwide means were 0.06 kg 100 m^{-2} (SE 0.03) in 2005 and 0.07 kg 100 m^{-2} (SE 0.02) in 2007 (Fig. 4.8.1d). Decreases in sightings of large parrotfishes, surgeonfishes, and reef sharks were responsible for this pattern: 5 reef sharks were sighted around Guam in 2003, none in 2005, and only 2 in 2007. Shark sightings generally occurred at this island's more remote areas in the northwest region and near Pati Point, the northernmost point in the east region. Large-fish biomass around Guam was low with a mean of 0.09 kg 100 m^{-2} (SE 0.03) among all areas surveyed around Guam during the 3 MARAMP survey periods. This large-fish-biomass value, which represents only 12% of the mean large-fish biomass observed for the Mariana Archipelago over the same time period, is the lowest value recorded for any island surveyed during the MARAMP.

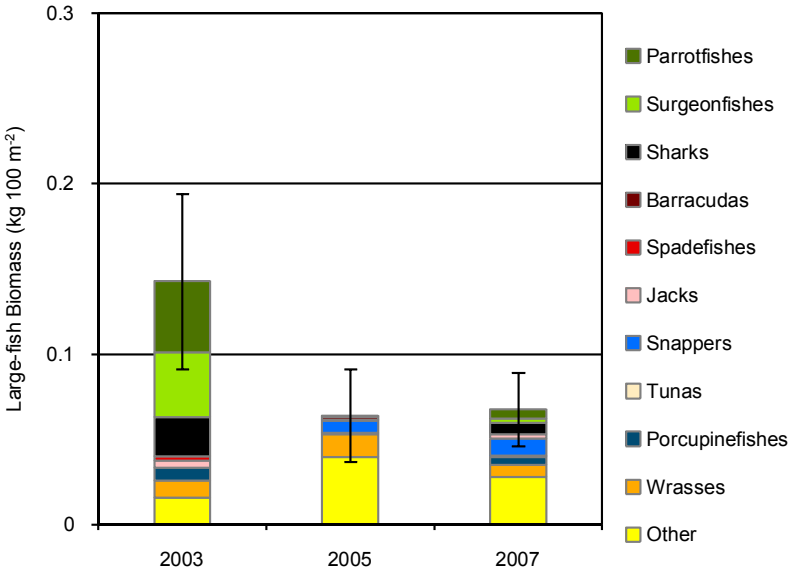


Figure 4.8.1d. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Guam during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Total fish biomass for the 9 REA sites surveyed in forereef habitats around Guam during MARAMP 2003 was low, compared to other sites in the Mariana Archipelago, with an overall sample mean of 2.66 kg 100 m-2 (SE 0.84). The highest biomass of 8.71 kg 100 m^{-2} was observed at GUA-05 in the northwest region, and the lowest biomass of 0.28 kg 100 m^{-2} was found at GUA-02 near Cetti Bay in the west region (Fig. 4.8.1e). Surgeonfishes accounted for the largest proportion (30%) or 0.10 kg 100 m^{-2} of total fish biomass around Guam, and the brown surgeonfish (*Acanthurus nigrofuscus*) was the most abundant species. Emperors (Lethrinidae), parrotfishes, and wrasses were also common, contributing 20%, 18%, and 8%, respectively, of total fish biomass around Guam. Although surveys suggest that large fishes were uncommon around Guam, the greatest number of fishes > 25 cm in TL observed around Guam occurred in the north and northwest regions. Juveniles were present but not abundant, and no reef sharks were observed during site-specific fish surveys.

Based on REA surveys conducted during MARAMP 2003, species richness around Guam was relatively low with a range of 13–26 species 100 m^{-2}. The lowest diversity was seen at GUA-02 in the west region, while the highest diversity was found at GUA-08 (Fig. 4.8.1e). Wrasses were observed in the greatest diversity with 22 species recorded in 2003. The fivestripe wrasse (*Thalassoma quinquevittatum*) was the most abundant wrasse species. Damselfishes (Pomacentridae) were the most abundant fish taxa overall, and the ocellate damselfish (*Pomacentrus vaiuli*) was the most common species with 7 individuals 100 m^{-2} recorded around Guam.

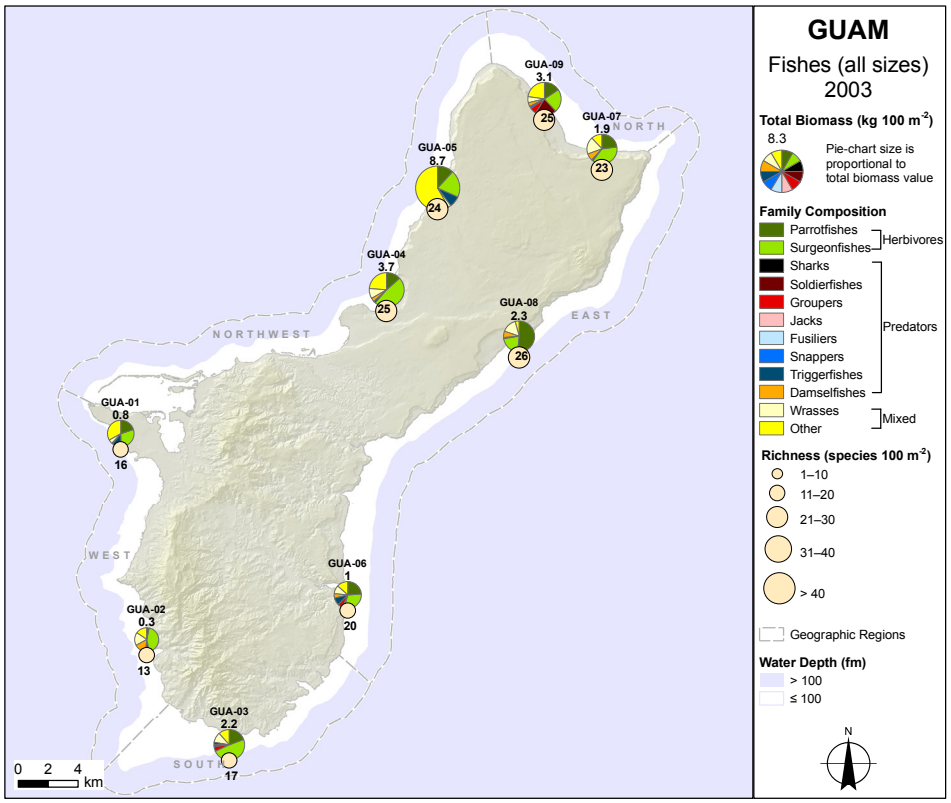


Figure 4.8.1e. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats around Guam during MARAMP 2003

Total fish biomass for the 9 REA sites surveyed in forereef habitats around Guam during MARAMP 2005 was very low, compared to other sites in the Mariana Archipelago, with an overall sample mean of 1.40 kg 100 m^{-2} (SE 0.29). Biomass was slightly higher in the north and east regions as well as in the Tumon Bay and Pati Point Marine Preserves (Fig. 4.8.1f). Very few large and medium–large (> 20 cm in TL) fishes were recorded in the west region; however, they were observed in fair abundance in the north and northwest regions. Surgeonfishes accounted for the largest proportion (21%) or

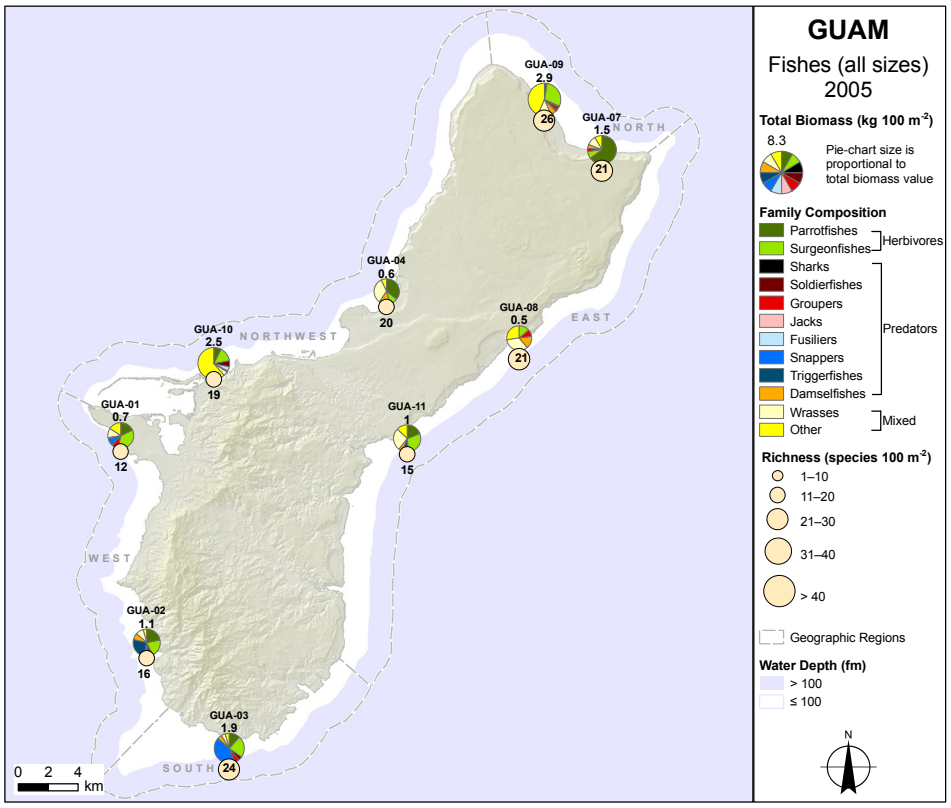


Figure 4.8.1f. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats around Guam during MARAMP 2005.

0.30 kg 100 m^{-2} of total fish biomass around Guam. Emperors, parrotfishes, and wrasses were also common, accounting for 17%, 17%, and 12% of total fish biomass around Guam. The abundance and diversity of damselfishes, wrasses, surgeonfishes, and parrotfishes at GUA-03 in the south region may be related to this site's location inside the Achang Reef Flat Marine Preserve, which was established in 1997 through Guam Public Law 24-21.

Based on REA surveys conducted during MARAMP 2005, species richness around Guam was relatively low and similar to levels observed in 2003 with a range of 12–26 species 100 m^{-2}. The lowest diversity was seen at GUA-01 in the west region, while the highest diversity was found at GUA-09 near Jinapsan Point in the north region (Fig. 4.8.1f). Wrasses were observed in the greatest diversity with 20 species recorded around Guam in 2005. Consistent with values found in 2003, the fivestripe wrasse was the most abundant wrasse species. Also as in 2003, damselfishes were the most abundant fish taxa overall, and the ocellate damselfish was the most common species with 12 individuals 100 m^{-2} recorded around Guam.

Total fish biomass for the 10 REA sites surveyed in forereef habitats around Guam during MARAMP 2007 was low, compared to other sites in the Mariana Archipelago, with an overall sample mean of 2.53 kg 100 m^{-2} (SE 0.61). The highest biomass was seen in the northwest region at GUA-10 near Adelup Point and GUA-04 in Tumon Bay (Fig. 4.8.1g). Moray eels accounted for the largest proportion (19%) or 0.49 kg 100 m^{-2} of total fish biomass around Guam. Surgeonfishes, parrotfishes and wrasses were also common, contributing 16%, 15% and 11% of total fish biomass around Guam. A whitetip reef shark was recorded at GUA-07 in the north region.

Based on REA surveys conducted during MARAMP 2007, species richness around Guam was relatively low around this island with a range of 12–25 species 100 m^{-2}. The lowest diversity was seen at GUA-01 near Orote Peninsula in the west region (Fig. 4.8.1g). As in 2003 and 2005, wrasses were observed in the greatest diversity with 30 species recorded in 2007. Damselfishes again were the most abundant fish taxa overall, and the ocellate damselfish was the most common species with 21 individuals 100 m^{-2} recorded around Guam.

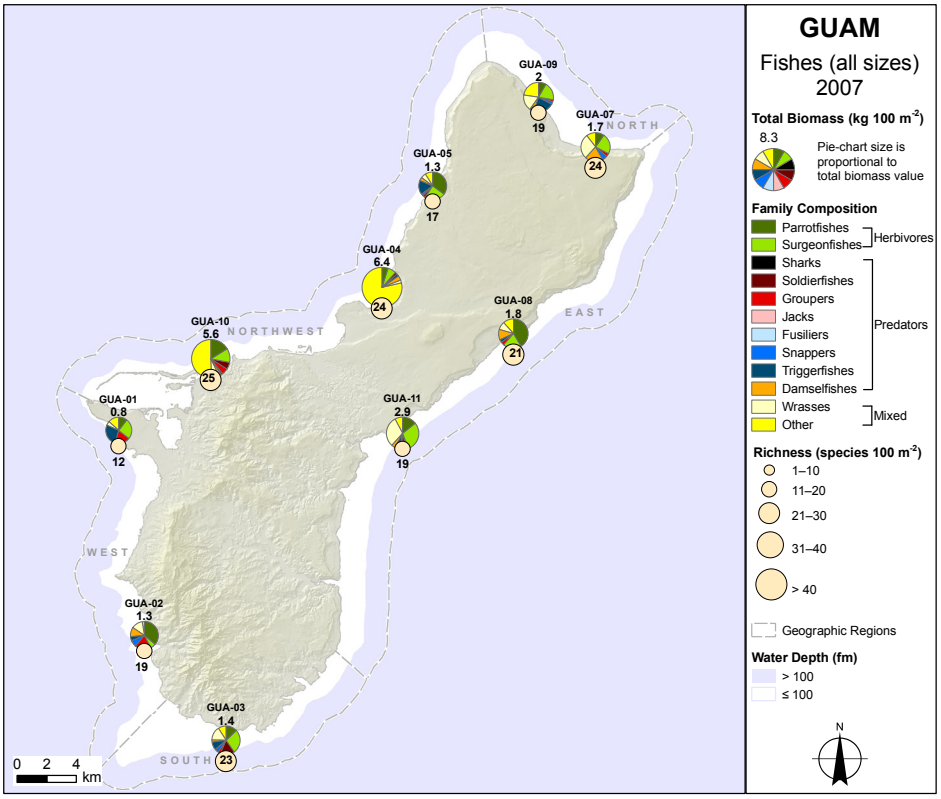


Figure 4.8.1g. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats around Guam during MARAMP 2007.

No persistent spatial patterns were observed for total fish biomass in forereef habitats around Guam between the 3 MARAMP survey periods. Biomass was slightly higher around the northern half of this island in 2003, but this pattern was less clear in following years. The majority of biomass recorded around Guam during the 3 survey years was composed of surgeonfishes, emperors, parrotfishes, and wrasses. Total fish biomass was consistently low between MARAMP survey years (Fig. 4.81h) with overall means for Guam between 1.40 kg 100 m^{-2} (SE 0.29) and 2.66 kg 100 m^{-2} (SE 0.84). Across the 3 MARAMP survey years combined, total fish biomass around Guam was the lowest in the Mariana Archipelago with an overall mean of 2.20 kg 100 m^{-2} (SE 0.40).

Species richness was relatively uniform around Guam in the 3 MARAMP survey years, except in the west region at GUA-01 near Orote Peninsula, where richness was consistently lower than values found at other sites. The average fish species richness around Guam was relatively low but consistent with the 20.2 species 100 m^{-2} (SE 0.5) observed during all REA fish surveys conducted during MARAMP 2003, 2005, and 2007. Wrasses were consistently represented with the most diversity with an average of 24 species observed across the survey years. Damselfishes were the most abundant taxa of fishes overall and dominated counts in each of the 3 survey periods.

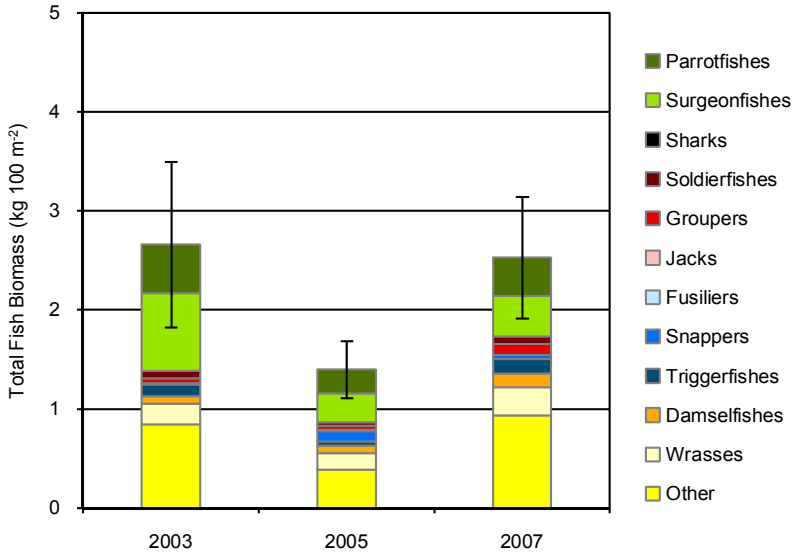


Figure 4.8.1h. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted around Guam during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

4.9 Marine Debris

4.9.1 Marine Debris Surveys

During MARAMP 2003, 14 sightings of derelict fishing gear and 21 sightings of other man-made objects were recorded in the 20 towed-diver surveys conducted on forereef habitats around the island of Guam (Fig. 4.9.1a). The highest number of sightings of derelict fishing gear was noted in the east region, while the highest number of man-made objects was observed in the west region, specifically near Agat Bay (for place-names and their locations, see Figure 4.2a in Section 4.2: "Survey Effort"). Items near Agat Bay included 4 anchors, 1 pipe, and 1 steel cable. No additional descriptive information about the remaining sightings of derelict fishing gear and man-made objects was recorded during towed-diver surveys. No munitions or wrecks were identified.

During MARAMP 2005, 2 sightings of derelict fishing gear and 1 sighting of a man-made object were recorded in the 23 towed-diver surveys conducted on forereef habitats around Guam (Fig. 4.9.1b). These 2 sightings of derelict fishing gear included a single large trawl or seine net off Cocos Island in the south region, most of it located in a depth of 21–30 m and the rest extending to an undetermined depth. In shallower water upslope of this net, an area of damaged coral was noted, suggesting that this net had previously tumbled to its observed location. The other observed debris included a trawl net near Togcha Bay in the east region and an old automobile south of Adelup Point in the northwest region. No munitions or wrecks were identified.

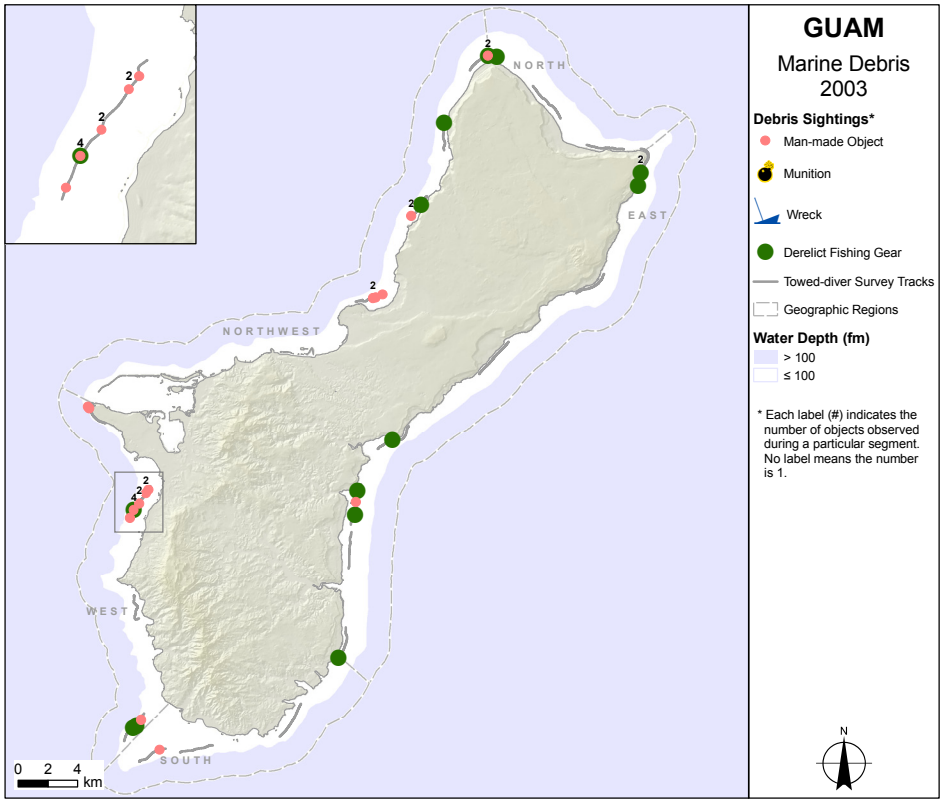


Figure 4.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2003. Symbols indicate the presence of specific debris types.

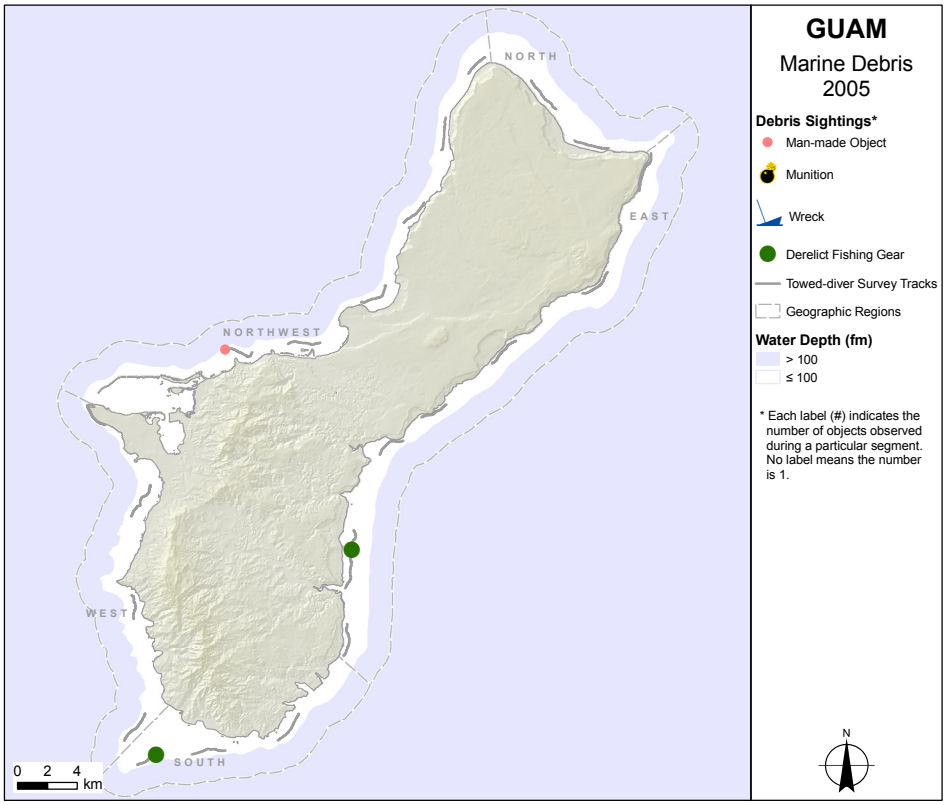


Figure 4.9.1b. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2005. Symbols indicate the presence of specific debris types.

During MARAMP 2007, 3 sightings of derelict fishing gear and 4 sightings of other man-made objects were recorded in the 19 towed-diver surveys conducted on forereef habitats around Guam (Fig. 4.9.1c). The 3 sightings of derelict gear contained fishing lines and were noted 1 each in the northwest, west, and east regions. In each of the northwest and west regions, 2 man-made objects were recorded, with 3 of them noted as anchors. No munitions or wrecks were identified.

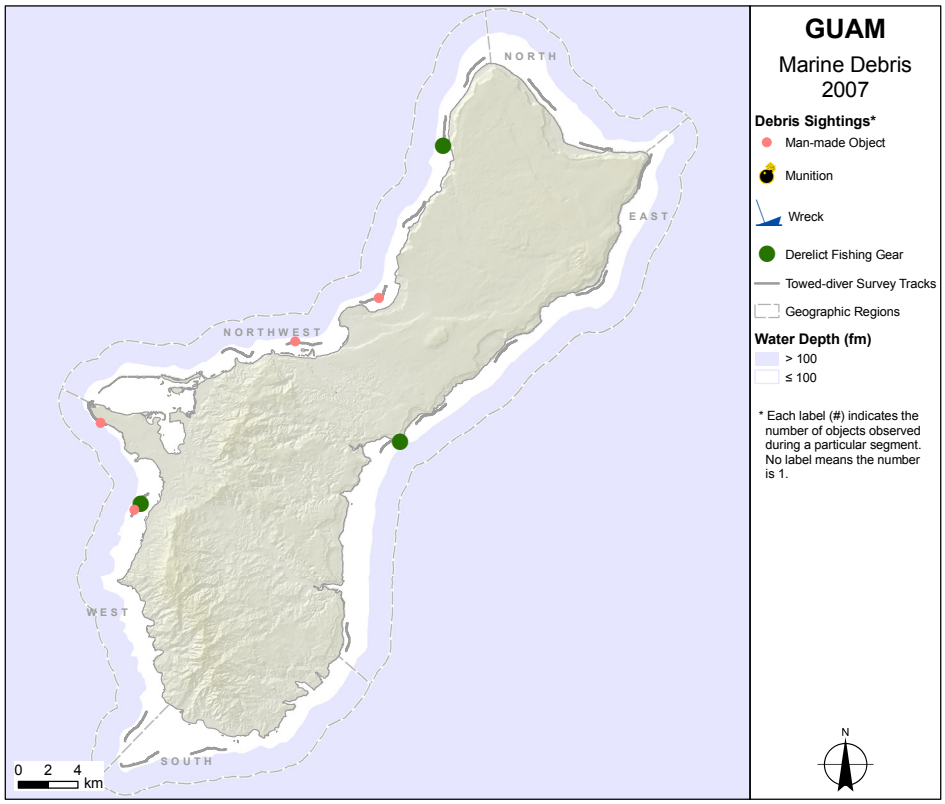


Figure 4.9.1c. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Guam during MARAMP 2007. Symbols indicate the presence of specific debris types.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments.

4.10 Reefs and Banks

4.10.1 Introduction

In addition to forereef areas around the island of Guam, MARAMP surveys examined 3 nearby reefs: 11-mile Reef, Galvez Bank, and Santa Rosa Reef. All 3 reefs form a continuation of the southern Mariana Arc, and they are oriented in a northeast–southwest direction. The farthest from Guam, Santa Rosa Reef lies some 50 km south-southwest from the southern tip of Guam and is ~ 20 × 25 km in size. Galvez Bank at ~ 35 km in length is the largest of these 3 reefs and is located 22 km south-southwest of Guam. As its name suggests, 11-mile Reef is ~ 11 mi or 17 km southwest of Guam and is the smallest of the 3 banks with a length of ~ 15 km.

4.10.2 Survey Effort

Limited biological and physical observations of some of the conditions and processes influencing the coral reef ecosystems on Santa Rosa Reef have been collected since 2003 as part of the MARAMP. Benthic habitat mapping conducted on Santa Rosa Reef with multibeam sonar covered a total area of 164 km^2 in 2007. Ocean data platforms (ODPs) captured observations of temperature, salinity, and wave height from 2003 to 2007 (Table 4.10.2a). Limited information on the condition, abundance, diversity, and distribution of some biological communities on Santa Rosa Reef was collected using REA, towed-diver, and TOAD surveys in 2003 and 2005 (Table 4.10.2b).

In addition, on 11-mile Reef and Galvez Bank during MARAMP 2003, TOAD surveys documented estimates of sand cover, live-hard-coral cover, and habitat complexity (Table 4.10.2c).

The spatial extent and timeframe of towed-diver surveys are discussed in this section. Figure 4.10.2a displays the locations of the REA, towed-diver, and TOAD surveys conducted on these 3 banks. Potential reef habitat is represented by a 100-fm contour shown in white on this map.

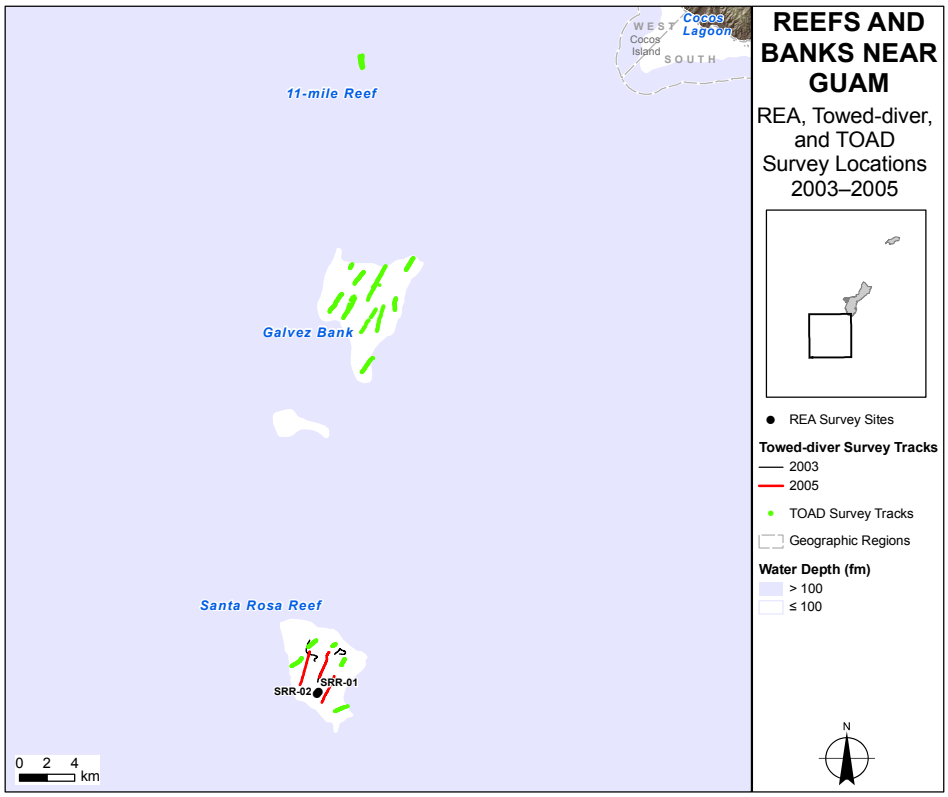


Figure 4.10.2a. Locations of REA, towed-diver, and TOAD surveys conducted on banks adjacent to Guam during MARAMP 2003 and 2005.

Table 4.10.2a. Numbers of ocean data platforms (ODPs) deployed on Santa Rosa Reef during MARAMP 2003, 2005, and 2007.

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
ODP	1	1	1	1	–	–	–

Table 4.10.2b. Numbers, mean depths (m), total areas (ha), and total lengths (km) of REA, towed-diver, and TOAD surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. REA survey information is provided for both fish and benthic surveys.

Survey Type	Survey Detail	Year	
REA		**2003**	**2005**
Fish	Number of Surveys	2	2
	Mean Depth (m)	12.5 (SD 0.7)	12.5 (SD 0.7)
Benthic	Number of Surveys	2	2
	Mean Depth (m)	12.5 (SD 0.7)	12.5 (SD 0.7)
Towed Diver		**2003**	**2005**
	Number of Surveys	3	3
	Total Survey Area (ha)	5.9	6.9
	Mean Depth (m)	16.1 (SD 3.9)	15.1 (SD 3.7)
TOAD		**2003**	
	Number of Surveys	5	
	Total Length (km)	3.61	

Table 4.10.2c. Numbers and total lengths (km) of TOAD surveys conducted on 11-mile Reef and Galvez Bank during MARAMP 2003.

Survey Type	Survey Detail	Year
TOAD		**2003**
11-mile Reef	Number of Surveys	2
	Total Length (km)	1.85
Galvez Bank	Number of Surveys	11
	Total Length (km)	17.43

Towed-diver Surveys: Depths

Figures 4.10.2b and c illustrate the locations and depths of towed-diver-survey tracks on Santa Rosa Reef and should be referenced when further examining results of towed-diver surveys from MARAMP 2003 and 2005.

During MARAMP 2003, 3 towed-diver surveys were conducted on Santa Rosa Reef. The mean depth of all survey segments was 16.1 m (SD 3.9), and the mean depths of individual surveys ranged from 11.6 m (SD 0.7) to 18.5 m (SD 3.2).

During MARAMP 2005, 3 towed-diver surveys were conducted on Santa Rosa Reef. The mean depth of all survey segments was 15.1 m (SD 3.7), and the mean depths of individual surveys ranged from 12.2 m (SD 1) to 19.2 m (SD 3.2).

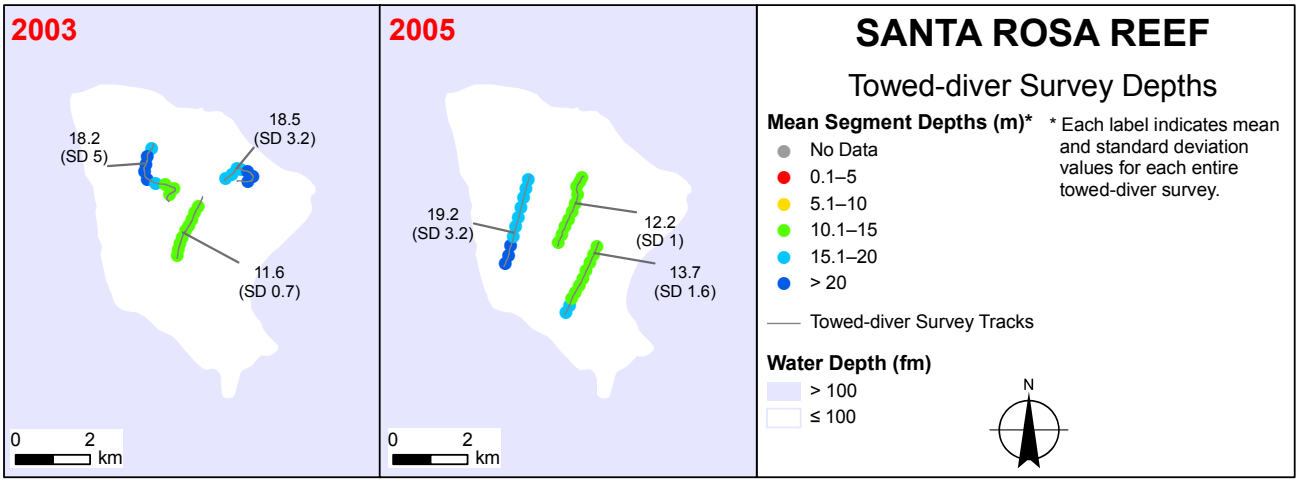


Figure 4.10.2b. Depths and tracks of towed-diver surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. Towed-diver survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

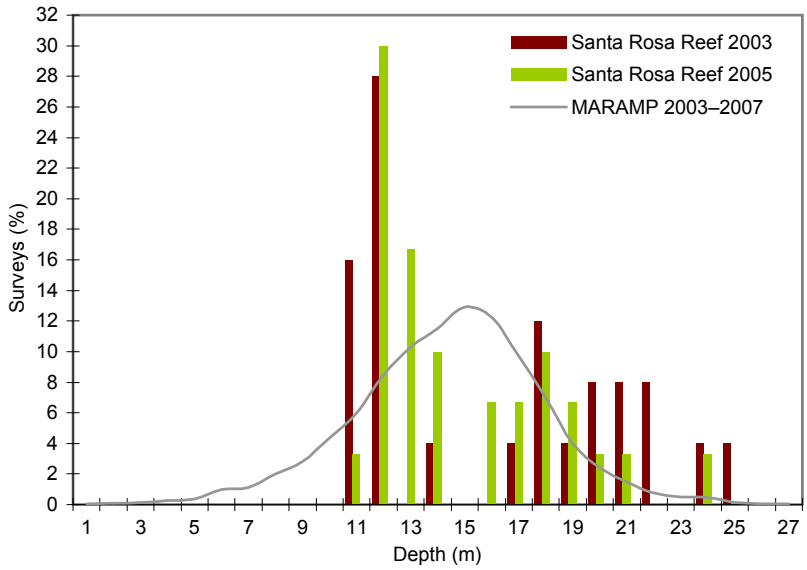


Figure 4.10.2c. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded are excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago from 2003 to 2007.

4.10.3 Benthic Habitat Mapping and Characterization

Acoustic Mapping

In addition to the benthic habitat mapping and characterization of nearshore waters around Guam, limited surveys were undertaken on Santa Rosa Reef, Galvez Bank, and 11-mile Reef, using acoustic multibeam sonar, underwater video and still imagery, and towed-diver surveys during MARAMP 2003 and 2005. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of ~ 10–88 m.

Time constraints meant a full multibeam survey on these reefs was not possible; however, one swath was obtained during transit, providing data along the eastern edge of these 3 reefs at depths of ~ 150–1800 m. For a more complete picture of the topography of these reefs, these limited multibeam bathymetry data are presented over a bathymetry grid with a 30-arc-second (~ 900-m) resolution and based on a satellite-gravity model calibrated with depth soundings (Becker et al. 2009; Fig. 4.10.3a). No backscatter data are presented here because of the extremely limited coverage.

Located ~ 15 km west of Guam's Cocos Lagoon, 11-mile Reef is separated from Guam by a deep (~ 1.7 km) channel. Galvez Bank is joined to the tip of Cocos Lagoon by a ridge that is ~ 15 km long and ~ 1 km deep, and this bank also appears from the modeled bathymetry data (Becker et al. 2009) to be nearly continuous with Santa Rosa Reef to the south.

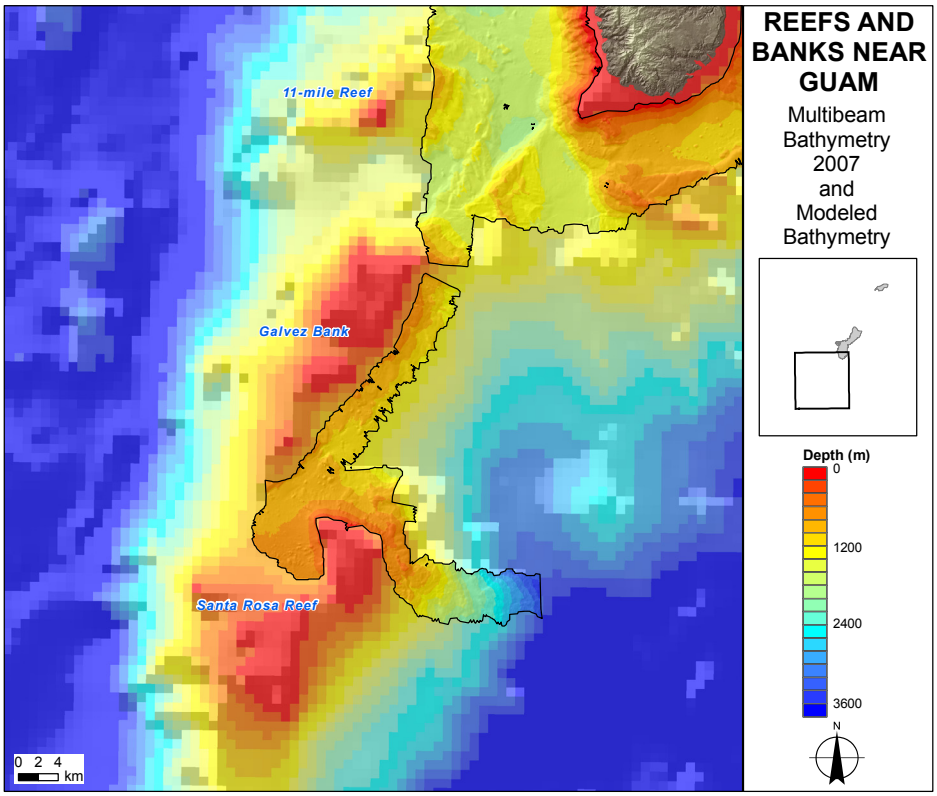


Figure 4.10.3a. Gridded multibeam bathymetry (grid cell size: 60 m) collected by CRED during MARAMP 2007 at depths of 5–2500 m using a 30-kHz Kongsberg EM 300 sonar are shown in the area outlined in black. Shown elsewhere are modeled bathymetry data (grid cell size: 30 arc-second or ~ 900 m; Becker et al. 2009).

Optical Validation

During MARAMP 2003, 5 TOAD optical-validation surveys were conducted on Santa Rosa Reef at depths of 50–100 m, 11 TOAD surveys were completed on Galvez Bank at depths of ~ 20–88 m and 2 TOAD surveys were completed on 11-mile Reef at depths of < 70 m (Fig. 4.10.2a). Subsequent analysis of the acquired video provided estimates of the percentages of both sand cover and live-hard-coral cover.

During MARAMP 2003 and 2005, 3 towed-diver optical-validation surveys each were conducted on Santa Rosa Reef, covering a distance of 12 km at depths of 11–25 m (Fig. 4.10.2a). At 5-min intervals within each survey, divers recorded percentages of sand cover and live coral cover and habitat complexity using a 6-level categorical scale from low to very high.

Habitat Characterization

Optical-validation surveys conducted on Santa Rosa Reef revealed that its reef top had predominantly hard substrate, generally with sand cover of < 30% observed during towed-diver surveys and in TOAD videos (Fig. 4.10.3b[a]). A small number of areas with higher sand cover were found, including an area on the western part of this reef, where towed-diver surveys recorded sand cover of 75.1%–100%. Habitat complexity observed by towed divers in all areas surveyed ranged from low to medium (Fig. 4.10.3b[c]). Live coral cover, recorded during both towed-diver and TOAD surveys, was low (Fig. 4.10.3b[e]). Coral cover was < 20% in all areas surveyed, except for a few, very small areas during a single towed-diver survey. Similarly, only a small number of video frames from TOAD footage collected at depths of 15–22 m had live coral cover of 20.1%–100%.

On Galvez Bank, 11 TOAD surveys were conducted at depths of 25–83 m. Survey results for the western part of this bank at depths of 27–83 m revealed a predominantly sandy substrate (Fig. 4.10.3b[b]). A more mixed substrate for the eastern part of Galvez Bank was suggested by analysis of TOAD video footage. Live corals were observed in a small number of analyzed frames, with 9 video frames from TOAD footage collected at depths of 27–66 m revealing substrate with very high coral cover (Fig. 4.10.3b[f]).

On 11-mile Reef, 2 TOAD surveys were conducted at depths of < 70 m. Because of this limited number of optical-validation surveys, results from these 2 surveys are not presented on Figure 4.10.3b. Analysis of TOAD video footage revealed that the substrate on this reef was predominantly hard (66% of analyzed video frames). Only 4 (8%) of analyzed video frames from TOAD footage had live coral cover of 40%–80%.

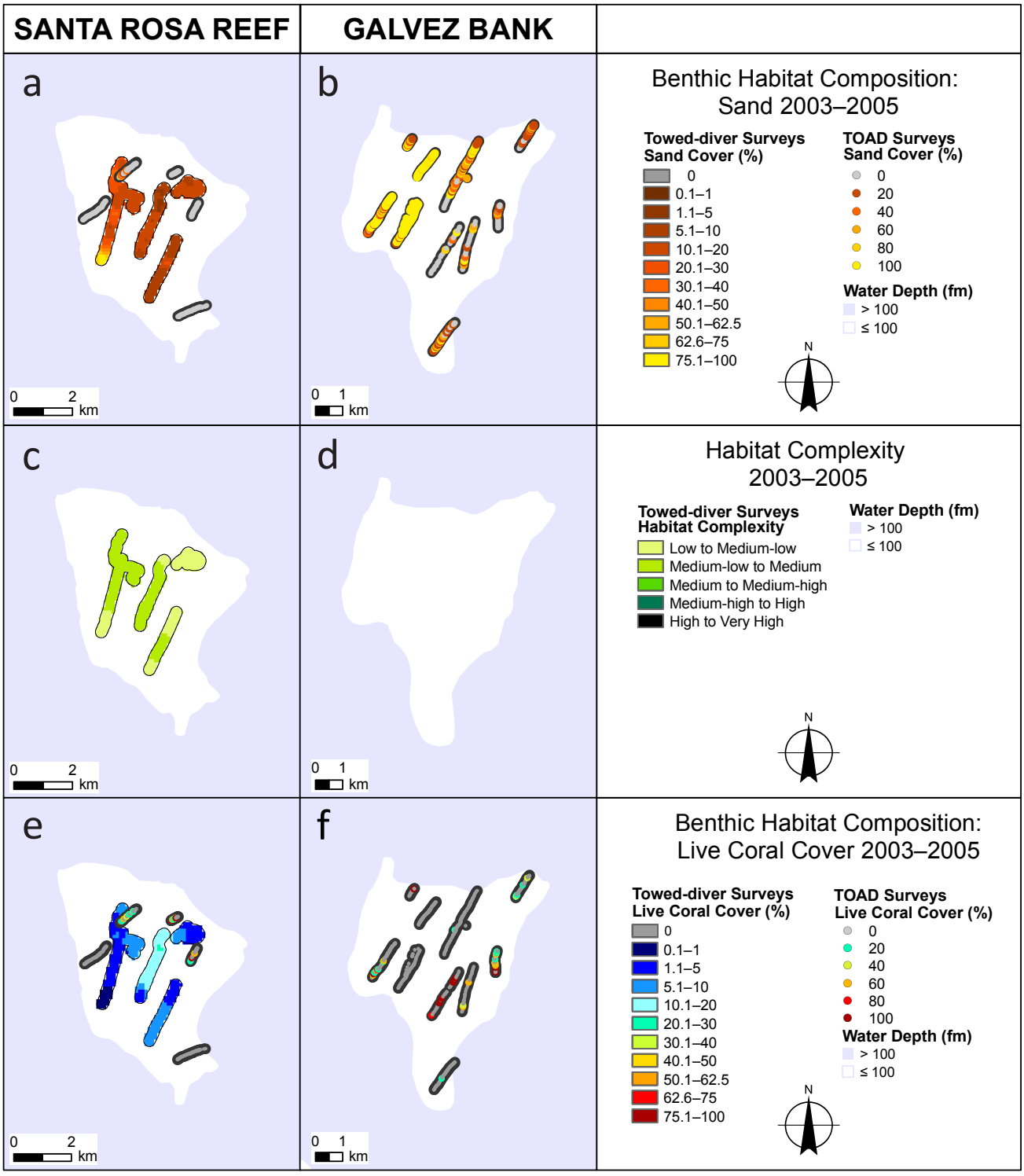


Figure 4.10.3b. Observations of (a, b) sand cover (%), (c, d) benthic habitat complexity, and (e, f) cover (%) of live hard corals from towed-diver surveys conducted and analysis of TOAD videos collected on Santa Rosa Reef and Galvez Bank during MARAMP 2003 and 2005.

4.10.4 Oceanography and Water Quality

Time-series Observations

One ocean data platform (ODP) mooring site was established at a depth of 20 m on Santa Rosa Reef. Temperature and salinity data from this ODP site show primarily seasonal oscillations, although intraseasonal–interannual variability is discernable (Fig. 4.10.4a). Seasonal temperature fluctuations were characterized by temperatures of ~ 30°C during the months of June–October and ~ 27.5°C during the months of January–March. Intraseasonal temperature variability was observed during summer 2004 when temperatures varied 0.5°C–1°C every few weeks for a 5-month period. Similar oscillations were observed in summer 2006, although this period was dominated by a major warming event in September 2006 that surpassed the bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean. Salinity values are generally negatively correlated with temperature; decreases in salinity co-occur with increases in temperature. However, this overall time series for Santa Rosa Reef shows less seasonal periodicity in salinity values than in temperature values from ODP data.

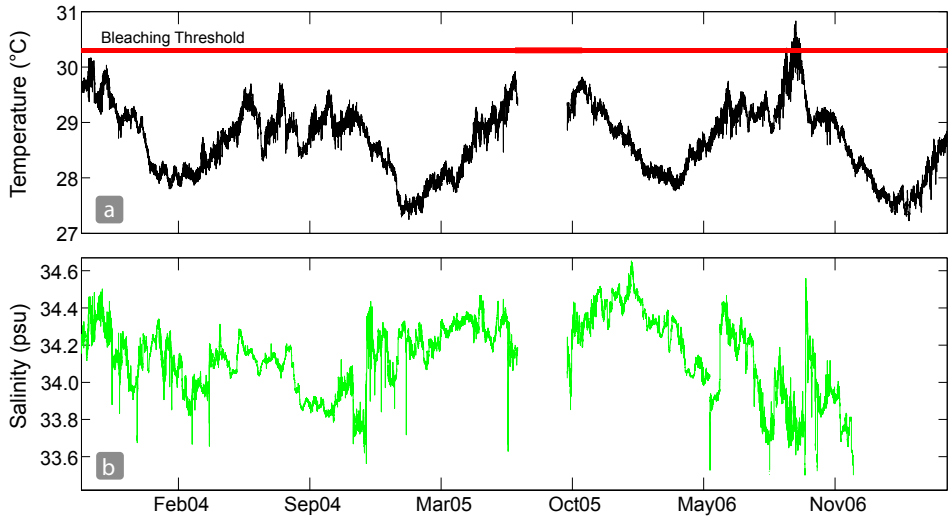


Figure 4.10.4a. Time-series observations of (*a*) temperature and (*b*) salinity over the period between September 2003 and June 2007 collected from ODPs deployed on Santa Rosa Reef at a 20-m depth. The horizontal red line indicates the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

Wave heights were measured on Santa Rosa Reef from September 2003 to May 2007. Wave heights were generally dominated by a seasonal pattern, with the highest ambient wave heights occurring during winter and the lowest during summer. Superimposed on these seasonal fluctuations were episodic wave events that were characterized by brief periods of high (> 3 m) wave heights—which are typically associated with the typhoon season of August–December but are also observed during other time periods. Wave conditions can be highly variable from year to year. Wave conditions were characterized in 2004 by a few large (> 5 m) wave events but in 2006 by fewer and less energetic episodic events; yet, wave conditions in 2006 had higher ambient wave heights through the winter than they had in the previous 2 years (Fig. 4.10.4b).

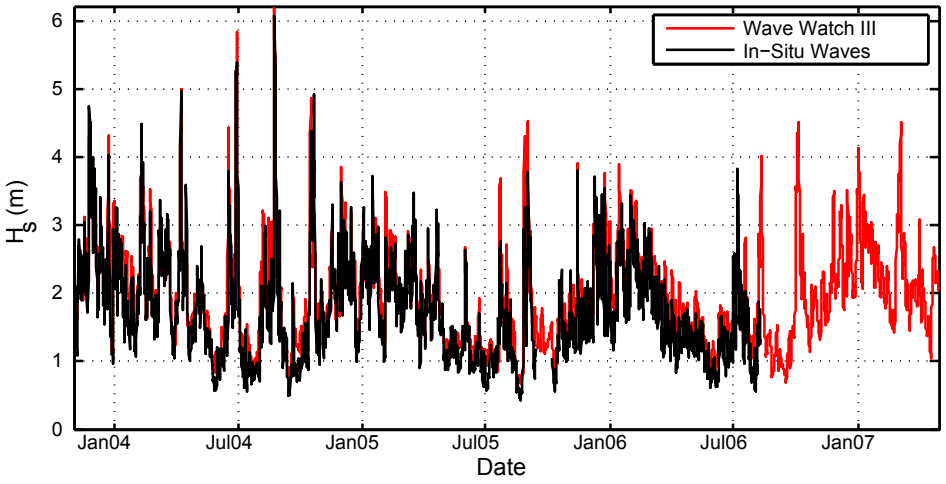


Figure 4.10.4b. Time-series observations of in situ (black line) and modeled (red line) significant wave height during the period between September 2003 and May 2007 collected from ODPs moored on Santa Rosa Reef at a depth of 20 m. Modeled wave data is derived from the NOAA Wave Watch III wave model.

4.10.5 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on Santa Rosa Reef was 7% (SE 0.9). The highest mean coral cover was observed in the center of Santa Rosa Reef with a mean of 15% for 6 survey segments (Fig. 4.10.5a, left panel). All other segments recorded coral cover ≤ 10%.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on Santa Rosa Reef was 8% (SE 1.2). The highest coral cover was observed in the center of Santa Rosa Reef with a mean of 17.5% for 8 segments (Fig. 4.10.5a, right panel). All other segments recorded coral cover ≤ 10%, with the lowest coral cover of 0.1%–1% noted for 3 segments along the southwestern area of Santa Rosa Reef.

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that was fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5: "Corals and Coral Disease"). Overall, 0.3% (SE 0.1) of observed coral cover appeared stressed on Santa Rosa Reef.

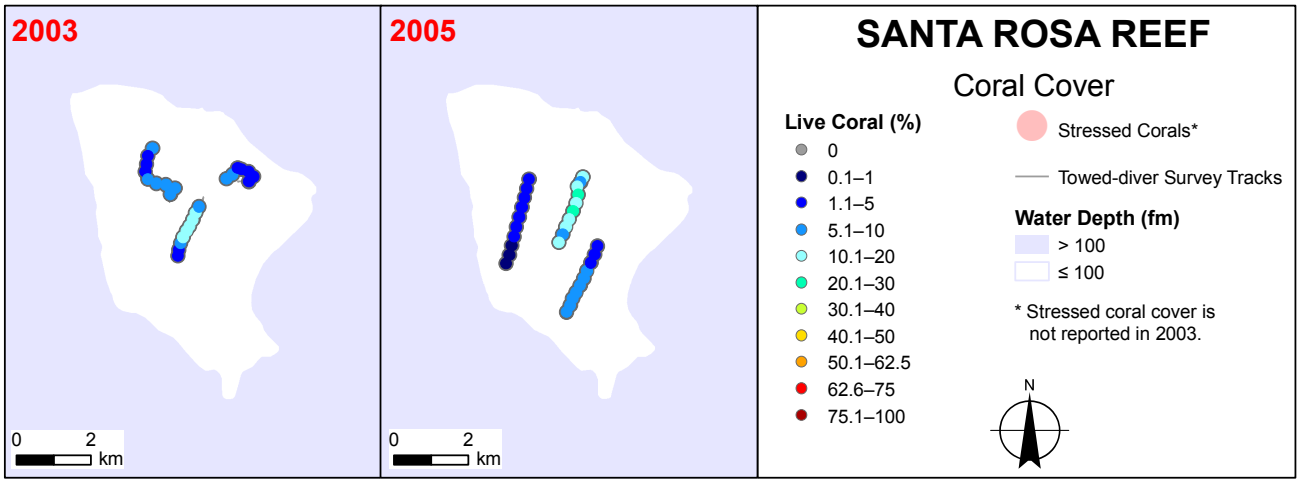


Figure 4.10.5a. Cover (%) observations of live hard corals from towed-diver benthic surveys conducted at Santa Rosa Reef during MARAMP 2003 and 2005. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Stressed-coral cover was measured as a percentage of overall coral cover in 2005; no pink symbols appear in the 2005 panel because no areas had stressed-coral cover > 10%.

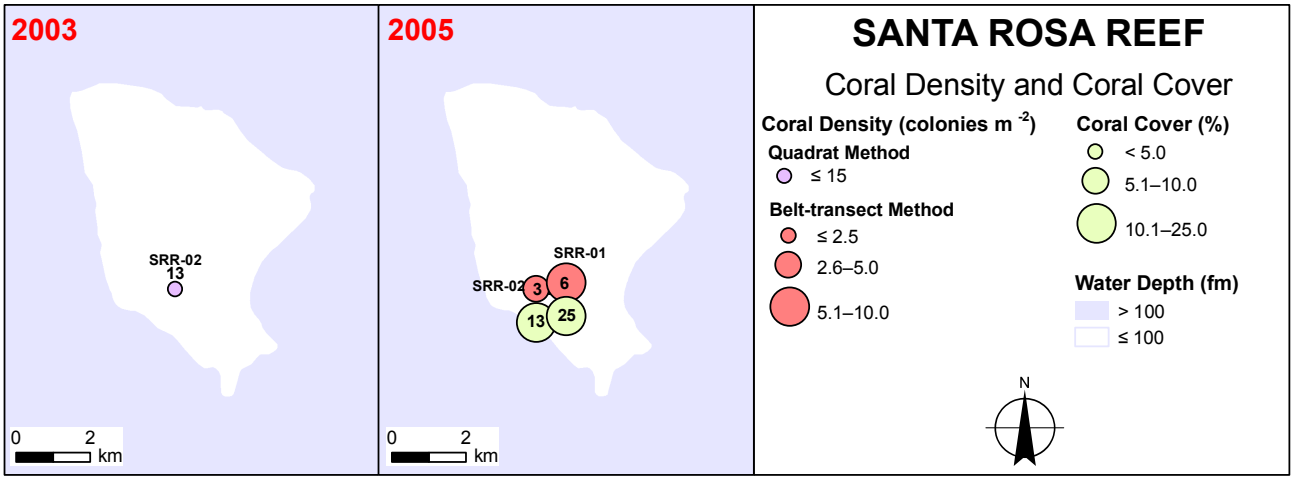


Figure 4.10.5b. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. Values are provided within each symbol.

During MARAMP 2003, 1 REA benthic survey using the quadrat method on Santa Rosa Reef at SRR-02 documented 47 coral colonies within a survey area of 3.75 m^2. Site-specific colony density was 12.5 colonies m-2 (Fig. 4.10.5b, left panel).

During MARAMP 2005, 2 REA benthic surveys using the belt-transect method on Santa Rosa Reef documented 843 coral colonies within a total survey area of 200 m^2. Site-specific colony density was 2.8 colonies m^{-2} at SRR-02 and 5.7 colonies m^{-2} at SRR-01 (Fig. 4.10.5b, right panel).

Site-specific estimates of live-hard-coral cover, from MARAMP 2005 REA benthic surveys conducted using the line-point-intercept method on Santa Rosa Reef, were 12.7% at SRR-02 and 25.5% at SRR-01 (Fig. 4.10.5b, right panel).

Mean live-coral-cover estimates from towed-diver surveys were similar during both MARAMP survey years with 7% in 2003 and 8% in 2005 (Fig. 4.10.5c). In both years, peak coral cover was noted for the central portion of Santa Rosa Reef, and the lowest value of coral cover for this reef were recorded towards the perimeter. In 2005, the single year in which REA surveys for coral cover were conducted on this reef, mean coral cover for the 2 sites surveyed was 19.1%. Estimates of live coral cover from REA surveys generally exceed estimates from towed-diver surveys because REA surveys target hard-bottom communities whereas towed-diver surveys include both hard- and soft-bottom substrates.

Coral-colony density from REA surveys at SRR-02 was substantially lower in 2005 than in 2003 (Fig. 4.10.5d). However, this apparent decline is likely an artifact of the use of different methods to assess colony density during the 2 MARAMP survey years. The placement of quadrats used in 2003 was highly biased towards surveying hard-bottom substrate where corals were present, whereas the belt-transect method used in 2005 assessed benthos that fell within the transect belt regardless of the nature of the substrate. The considerable difference in apparent colony density at SRR-02, with 12.5 colonies m^{-2} in 2003 and 2.8 colonies m^{-2} 2005, strengthens the supposition that the quadrat method yielded higher density values than did the belt-transect method.

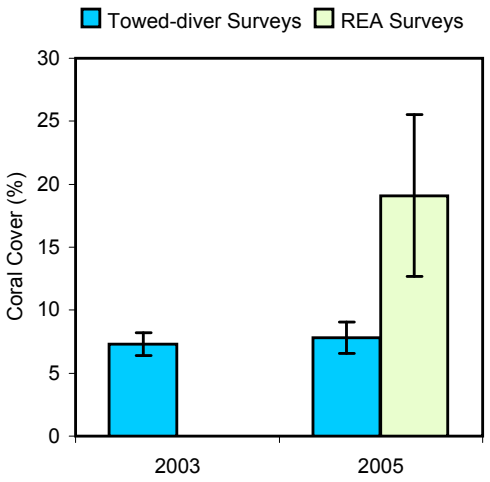


Figure 4.10.5c. Temporal comparison of mean live-coral-cover (%) values from REA and towed-diver benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. No REA surveys using the line-point-intercept method were conducted on this reef in 2003. Error bars indicate standard error (± 1 SE) of the mean.

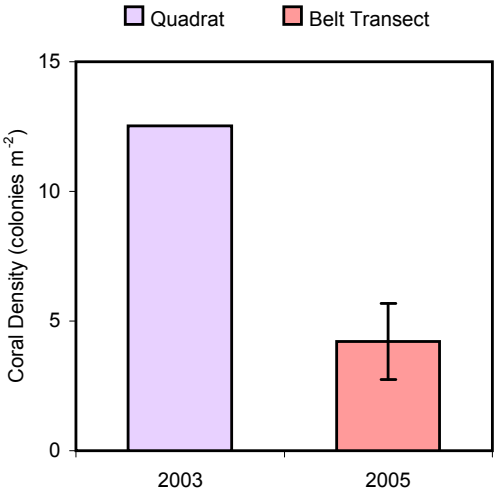


Figure 4.10.5d. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. The quadrat method was used in 2003 at the single site surveyed to measure colony density, but in 2005 the belt-transect method was used. Error bars indicate standard error (± 1 SE) of the mean.

Coral Generic Richness and Relative Abundance

One REA benthic survey was conducted using the quadrat method during MARAMP 2003 to determine generic richness and relative abundance at Santa Rosa Reef. At least 9 coral genera were observed (Fig. 4.10.5e, left panel). *Favia*, *Leptastrea*, and *Porites* were the most numerically abundant genera, accounting for 36.2%, 17%, and 17% of the total number of colonies enumerated at SRR-02. All other genera individually accounted for < 10% of the total number of observed colonies.

Two REA benthic surveys were conducted using the belt-transect method during MARAMP 2005 to determine generic richness and relative abundance on Santa Rosa Reef. At least 16 coral genera were observed. Generic richness was 13 at SRR-02 and 15 at SRR-01 (Fig. 4.10.5e, right panel). *Favia*, *Pocillopora*, *Porites*, and *Leptastrea* were the most numerically abundant genera, accounting for 22.8%, 17.2%, 13.8%, and 11.9% of the total number of colonies enumerated on this reef during MARAMP 2005. All other genera individually accounted for < 10% of the total number of observed colonies. *Porites*, *Pocillopora*, and *Favia* dominated the coral fauna at SRR-01, accounting for 20.2%, 18.8%, and 16.9% of the total number of observed colonies, while *Favia*, *Leptastrea*, and *Pocillopora* dominated at SRR-02, accounting for 28.7%, 19.6%, and 15.6% of the total number of observed colonies.

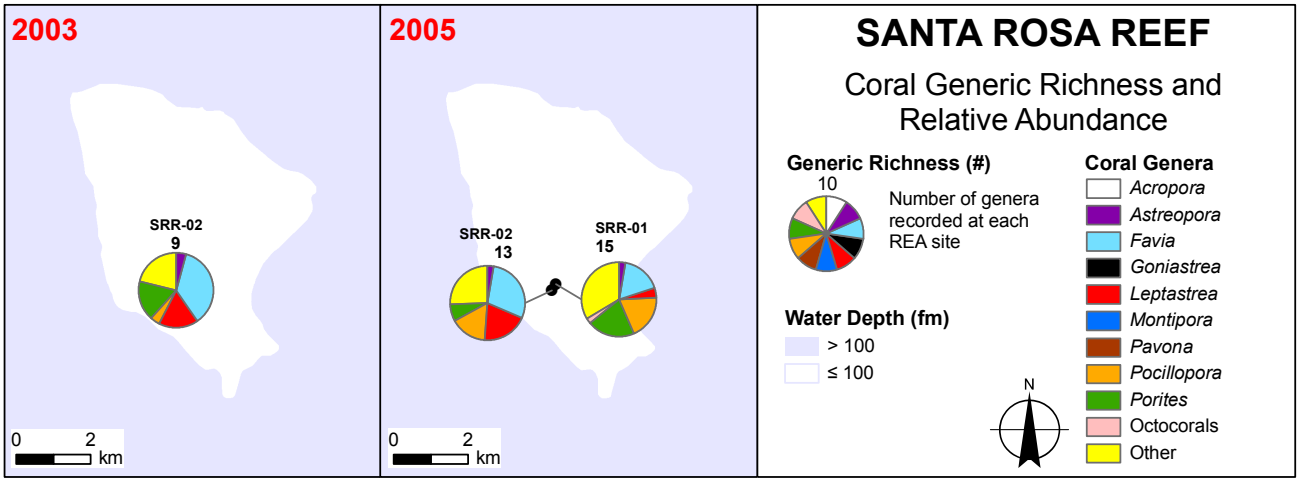


Figure 4.10.5e. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. The pie charts indicate percentages of relative abundance of key coral genera.

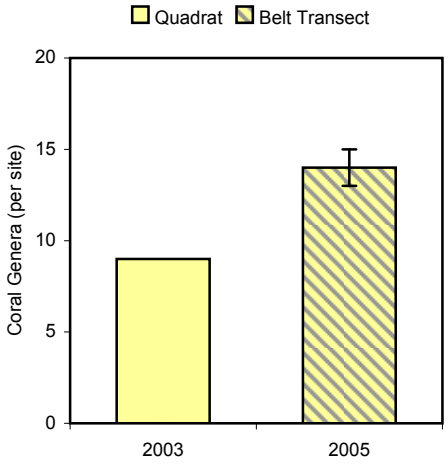


Figure 4.10.5f. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. The quadrat method was used at a single site in 2003, and the belt-transect method was used at 2 sites in 2005. Error bars indicate standard error (± 1 SE) of the mean.

At least 17 coral genera were observed during the 2 MARAMP survey years, with a higher number of genera recorded in 2005 than in 2003 (Fig. 4.10.5f). Six genera not recorded in 2003 were observed in 2005, because in 2005 an additional site was surveyed and a larger area of 100 m^2 was surveyed at each site, versus the 3.75 m^2 surveyed per site in 2003. Also, the only octocoral genus assessed in 2003 was *Heliopora*, but all octocoral genera were assessed in 2005. *Favia*, *Porites*, and *Leptastrea* were important components of the coral fauna, accounting for > 10% of the total number of colonies enumerated on this reef in both years. *Favia* was the most abundant taxon in 2003 and 2005, accounting for 36.2% and 22.8% of the total number of observed colonies. *Pocillopora* was an important component of the coral fauna in 2005 but accounted for < 5% of the total number of observed colonies at SRR-02, the single site surveyed in 2003.

Coral Size-class Distribution

During MARAMP 2003, a coral size-class distribution from the single REA benthic survey conducted using the quadrat method showed the majority (93.6%) of corals had maximum diameters < 5 cm (Fig. 4.10.5g). The remaining corals belonged to the next-largest size class (6–10 cm); no coral colonies > 10 cm were observed.

During MARAMP 2005, coral size-class distributions from REA benthic surveys conducted using the belt-transect method showed the majority (57.3%) of corals had maximum diameters < 10 cm (Fig. 4.10.5g). The next 3 size classes (11–20, 21–40, and 41–80) accounted for 31.8%, 9.1%, and 1.3% of colonies recorded.

As discussed in greater detail in the coral-size-class-distribution section for Guam, these results reflect the respective biases of each method in capturing very small (≤ 5 cm) colonies (quadrat method) or large colonies (belt-transect method). Comparing size-class data between MARAMP survey years when different methods were used is inappropriate. The difference in size-class distribution at SRR-02 in 2003 and 2005 does not reflect substantial growth by the majority of colonies at that site, since *Favia*, *Porites*, and *Leptastrea*, the dominant corals at SRR-02, do not grow fast enough to produce such a radical change in distribution over a 2-year period. Instead, the change in the size-class distribution can be attributed to the use of different methods and the varied placement of quadrats and transect belts. For more on these survey methods, see "Chapter 2: "Methods and Operational Background", Section 2.4.5: "Corals and Coral Disease."

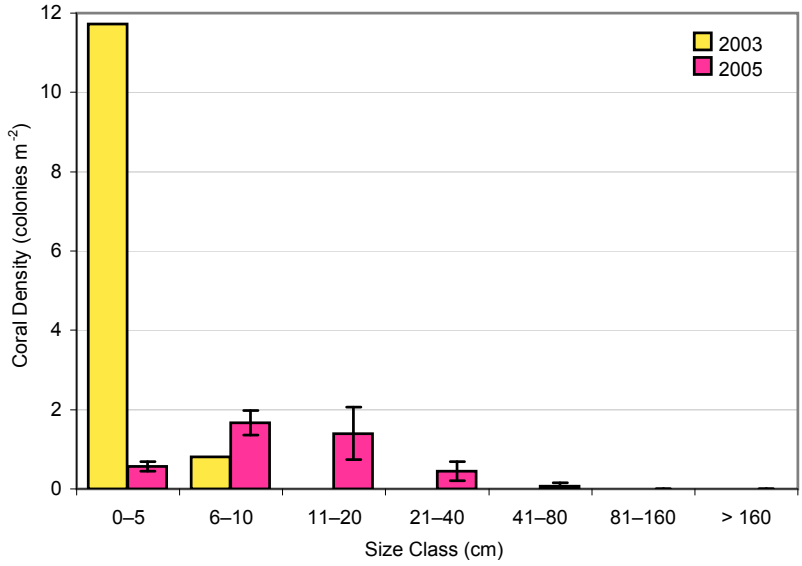


Figure 4.10.5g. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. The quadrat method was used in 2003 to size corals, and the belt-transect method was used in 2005. Error bars indicate standard error (± 1 SE) of the mean.

4.10.6 Algal Surveys

Algal Cover

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on Santa Rosa Reef was 42% (SE 4.6). The 3 surveys on this reef recorded macroalgal-cover values of 5.4%, 52.2%, and 58.8% (Fig. 4.10.6a, top left panel). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. Results from the first 2 surveys suggest mostly spur-and-groove habitat of medium-low complexity. The third survey primarily reported low complexity pavement in addition to limited spur-and-groove formations.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on Santa Rosa Reef was 71% (SE 3.1). The 3 surveys on this reef recorded macroalgal-cover values of 74.4%, 78.1%, and 59.1% (Fig. 4.10.6a, bottom left panel). Medium complexity substrates were the most common habitat encountered.

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on Santa Rosa Reef was 7% (SE 1.1). The 3 surveys conducted on this reef had mean cover values for crustose coralline red algae of 0%, 9.2%, and 10% (Fig. 4.10.6.a, top right panel).

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on Santa Rosa Reef was 0.5% (SE 0.1). The 3 surveys conducted on this reef had mean cover values for crustose coralline red algae of 0%, 0.5%, and 1.1% (Fig. 4.10.6a, bottom right panel).

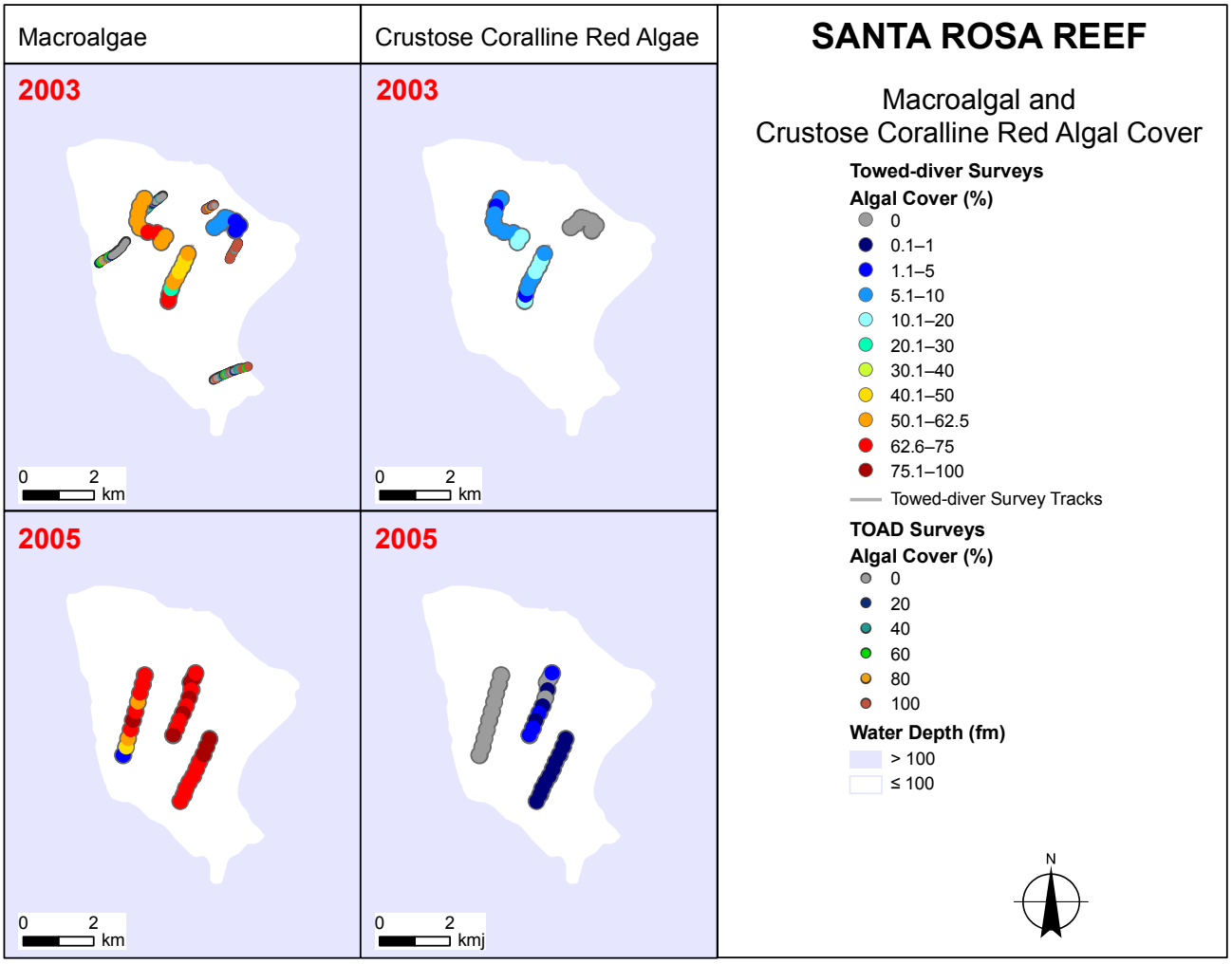


Figure 4.10.6a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver and TOAD benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. Each large, colored point represents an integrated estimate over a 5-min observation segment covering a survey swath of ~ 200 × 10 m (~ 2000 m^2). In both 2003 panels, each small, colored point represents an estimate of algal cover from TOAD surveys. The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003).

During MARAMP 2005, 2 REA benthic surveys were conducted using the line-point-intercept method on Santa Rosa Reef. Site-specific estimates of macroalgal cover on this reef in 2005 were 60.8% at SRR-02 and 44.1% at SRR-01 (Fig. 4.10.6b). No crustose coralline red algae were observed at SRR-02, and cover of crustose coralline red algae at SRR-1 was 4.9%. Finally, turf-algal cover was 8.8% at SRR-02 and 9.8% at SRR-01.

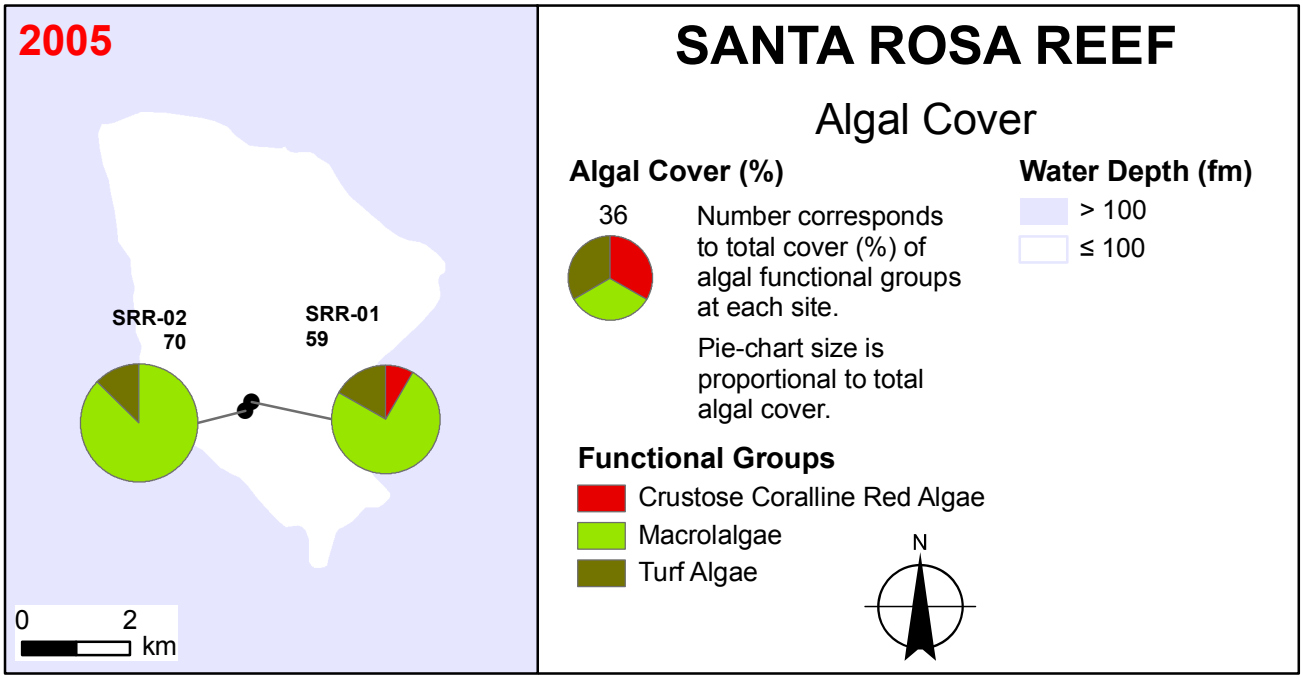


Figure 4.10.6b. Observations of algal cover (%) from REA benthic surveys conducted using the line-point-intercept method on Santa Rosa Reef during MARAMP 2005. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Between MARAMP survey years, overall mean macroalgal cover for Santa Rosa Reef increased from 42% in 2003 to 71% in 2005 (Fig. 4.10.6c). Meanwhile, overall mean cover values for crustose coralline red algae at this reef declined by 93% from 7% in 2003 to 0.5% in 2005. These results were from towed-diver surveys completed at a nearly identical time of year, in late September 2003 and early October 2005, and, thus, a seasonal shift in algal composition does not explain this algal cover variation between survey years. Also, turf algae were included in surveys of macroalgal cover in 2003 but not in 2005 (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

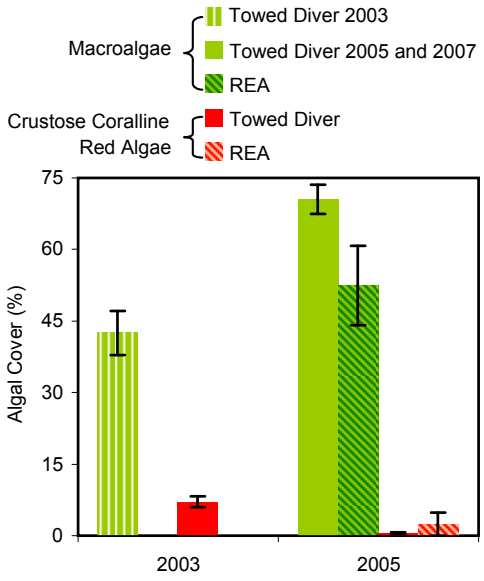


Figure 4.10.6c. Temporal comparison of algal-cover (%) values from surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted on Santa Rosa Reef in 2003. Error bars indicate standard error (± 1 SE) of the mean.

Macroalgal Genera and Functional Groups

When considering these results, keep in mind that the tentative generic names reported in this section from field surveys may change and algal diversity for each site will increase once laboratory-based taxonomic identification of all algal species is completed (see Chapter 2: "Methods and Operational Background," Section 2.4.6: "Algae and Algal Disease").

During MARAMP 2003, REA benthic surveys were conducted at 1 site on Santa Rosa Reef. Eight macroalgal genera (1 red, 6 green, and 1 brown), containing at least 9 species and 1 additional algal functional group, turf algae, were observed in the field.

The most widely distributed algal genera at the single site surveyed on Santa Rosa Reef in 2003 were the chlorophytes *Halimeda* and *Microdictyon*, occurring in 100% of sampled photoquadrats (Fig. 4.10.6d, left panel). Species of the algal genus *Dictyosphaeria* were also common, occurring in 75% of sampled photoquadrats. The genus *Udotea* was observed in 58.3% of the photoquadrats sampled at SRR-02. Species of the genera *Avrainvillea* and *Caulerpa* and the brown algal genus *Lobophora* were equally frequent, each occurring in 16.7% of sampled photoquadrats. Members of the red algal order Gelidiales occurred in 91.7% of sampled photoquadrats.

Turf algae were exceptionally common, occurring in 100% of sampled photoquadrats (Fig. 4.10.6d, left panel). In addition to macroalgae, turf algae made up the only other functional group recorded at the 1 site surveyed in 2003.

During MARAMP 2005, REA benthic surveys were conducted at 2 sites on Santa Rosa Reef. Thirteen macroalgal genera (2 red, 10 green, and 1 brown), containing at least 17 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, branched nongeniculate calcified red algae, and cyanophytes—were observed in the field. Macroalgal generic diversity was approximately equal at both sites with 10 genera observed at each site.

The most widely distributed algal genera at the sites surveyed on Santa Rosa Reef in 2005 included species of the green algal genera *Halimeda* and *Dictyosphaeria*, which occurred in 91.7% and 79.2% of sampled photoquadrats (Fig. 4.10.6d, right panel). Species of the algal genera *Avrainvillea*, *Caulerpa*, and *Microdictyon* were also common, occurring in 62.5%, 62.5%, and 66.7% of sampled photoquadrats. The genus *Udotea* was observed in 58.3% of sampled photoquadrats. *Chondrophycus*, *Liagora*, and *Lobophora* were the only red or brown algal genera recorded at these sites. Although spatial trends are difficult to determine based on the small number of surveys conducted, it was noted that species of both *Chondrophycus* and *Liagora* only occurred at SRR-02, while species of *Neomeris* only occurred at SRR-01.

Turf algae and cyanobacteria were both common, occurring in 87.5% and 58.3% of photoquadrats sampled on this reef (Fig. 4.10.6d, right panel). Turf-algal communities, ubiquitous at both sites, were found in 75%–100% of sampled photoquadrats. At both sites, cyanobacteria were observed in 41.7%–75% of sampled photoquadrats, and branched non-geniculate coralline red algae were a prominent component of the algal community at SRR-01, occurring in 50% of sampled photoquadrats.

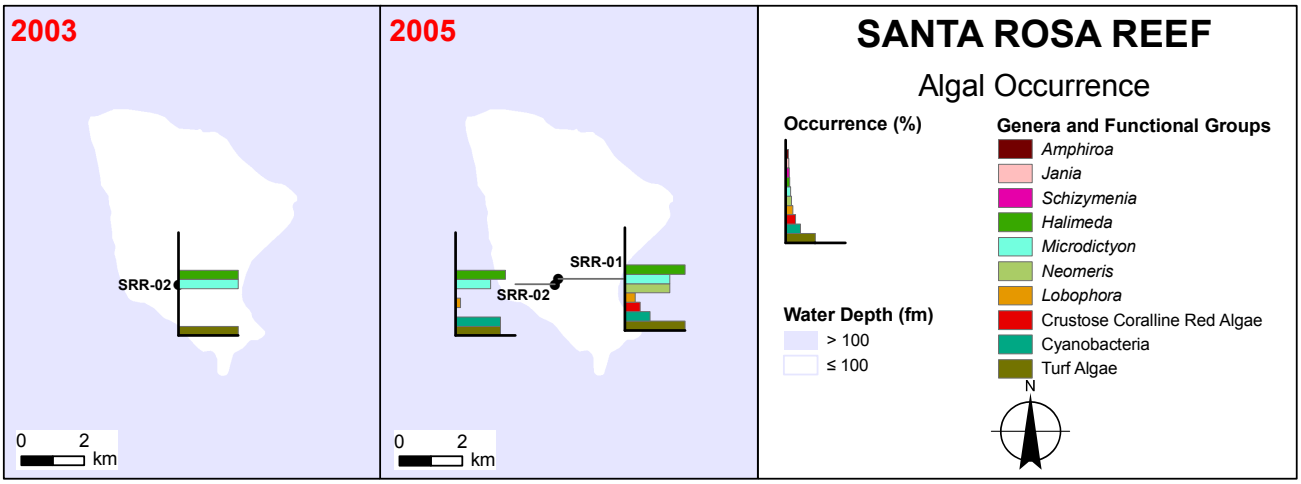
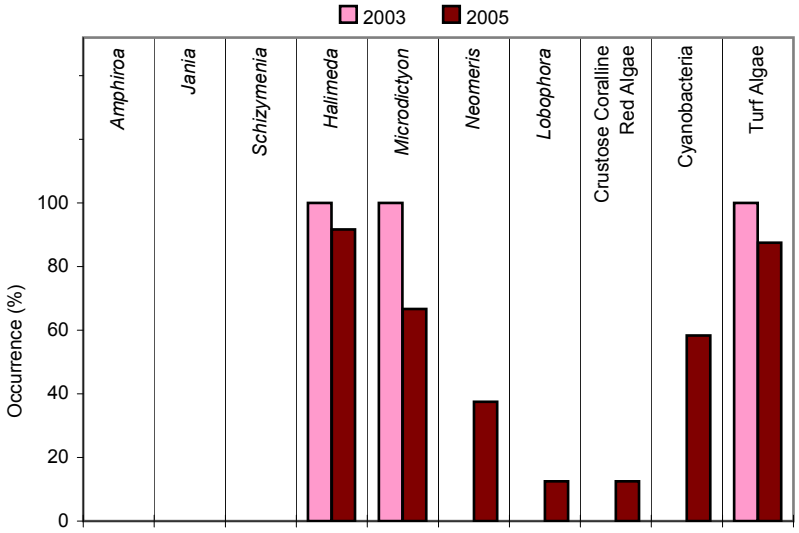


Figure 4.10.6d. Observations of occurrence (%) of select macroalgal genera and algal functional groups from REA benthic surveys on Santa Rosa Reef during MARAMP 2003 and 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

The overall occurrence of macroalgal genera on Santa Rosa Reef did not fluctuate greatly between MARAMP 2003 and 2005. Species of the genera *Halimeda* and *Microdictyon*, during both survey years, consistently were observed at the highest mean occurrence values of 91.7%–100% and 66.7%–100% (Fig. 4.10.6e). The occurrence of the genus *Caulerpa* was low in 2003, when it was only recorded in 16.7% of the photoquadrats sampled at SRR-02; however, its occurrence increased drastically to 58.3% in 2005 at the same site. The occurrence of the genus *Liagora* was low in 2003, when it was not recorded in the photoquadrats sampled at SRR-02; however, its occurrence increased to 25% in 2005 at the same site. The occurrence of members of the order Gelidiales was high in 2003, when they were recorded in 91.7% of sampled photoquadrats; however, their occurrence decreased drastically to 0% in 2005. Green algae were dominant at SRR-02 during the 2 survey years and at SRR-01 during the 1 year it was surveyed—and members of the order Gelidiales and the genera *Chondrophycus*, *Liagora*, and *Lobophora* were the only brown or red algal taxa recorded at these sites.

During MARAMP 2003 and 2005, turf algae occurred in 100% and 87.5% of photoquadrats sampled on Santa Rosa Reef (Fig. 4.10.6e). Crustose coralline red algae occurred in 0%–12.5% of sampled photoquadrats across survey years, while cyanobacteria occurred in 0%–58.3% of sampled photoquadrats, and branched, nongeniculate, calcified red algae occurred in only 0%–25% of sampled photoquadrats. These patterns of increasing occurrence may result from the increased survey effort in 2005, and additional observations are necessary for confirmation.

The number of macroalgal genera recorded on Santa Rosa Reef increased from 9 to 13 between MARAMP 2003 and 2005. Such an increase in generic diversity is not enough to suggest environmental or benthic compositional change, since seasonal variability can greatly affect algal abundance. Additionally, other factors could contribute to minor differences in observed biodiversity (see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").



igure 4.10.6e. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups on Santa Rosa Reef during MARAMP 2003 and 2005.

4.10.7 Macroinvertebrate Surveys

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at 1 of the 2 REA sites surveyed and in all 3 of the towed-diver surveys conducted on Santa Rosa Reef (Fig. 4.10.7a, left panel; Fig. 4.10.7b). The density of giant clams at SRR-02 was 1 organism 100 m^{-2}. The overall mean density of giant clams from towed-diver surveys was 0.023 organisms 100 m^{-2} (SE 0.006). The highest mean density of giant clams from a towed-diver survey was 0.027 organisms 100 m^{-2} with segment densities ranging from 0 to 0.099 organisms 100 m^{-2}.

During MARAMP 2005, giant clams were observed in all 3 of the towed-diver surveys conducted on Santa Rosa Reef (Fig. 4.10.7a, right panel) with an overall mean density of giant clams of 0.028 organisms 100 m^{-2} (SE 0.007). The highest mean density of giant clams from a towed-diver survey was 0.036 organisms 100 m^{-2} with segment densities ranging from 0 to 0.162 organisms 100 m^{-2}.

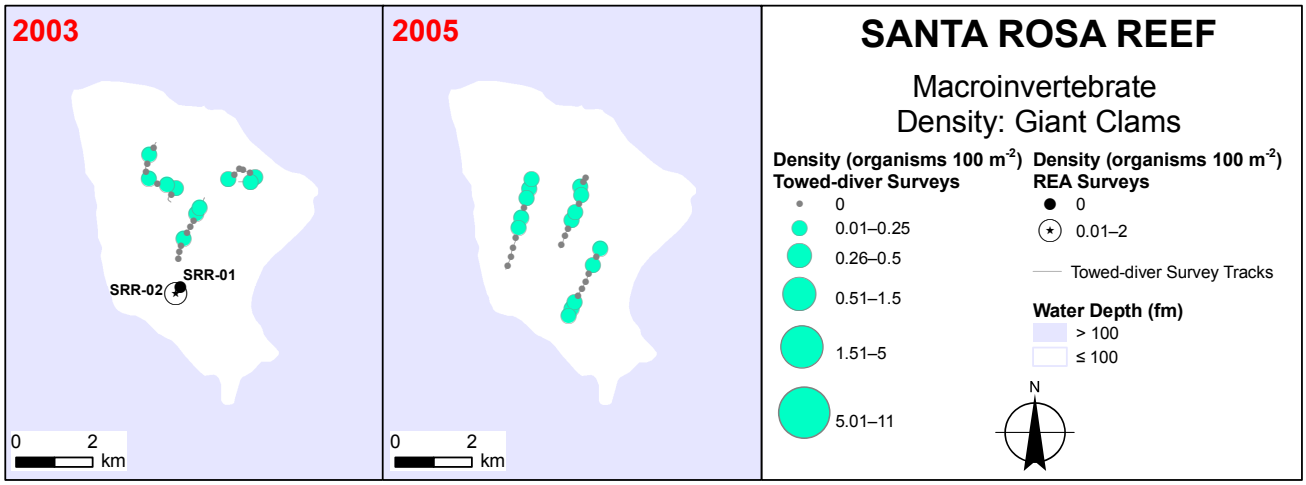


Figure 4.10.7a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005.

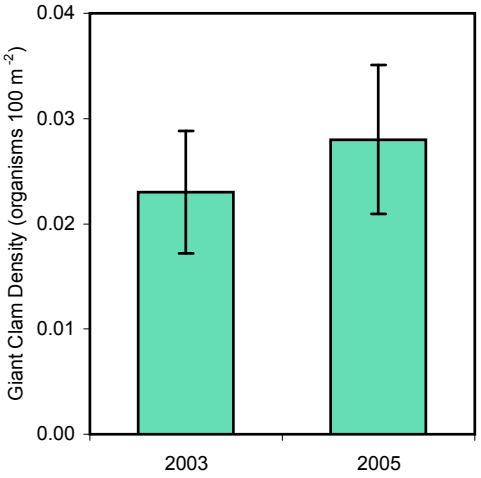


Figure 4.10.7b. Temporal comparison of mean densities (organisms m^{-2}) of giant clams from towed-diver benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Crown-of-thorns Seastars

During MARAMP 2003 and 2005, no crown-of-thorns seastars were found during towed-diver surveys on Santa Rosa Reef.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed in all 3 of the towed-diver surveys conducted but were not seen at either of the 2 REA sites surveyed on Santa Rosa Reef (Fig. 4.10.7c, left panel; Fig. 4.10.7d). The overall mean density of sea cucumbers from towed-diver surveys was 0.068 organisms 100 m^{-2} (SE 0.013). The highest mean density of sea cucumbers from a towed-diver survey was 0.139 organisms 100 m^{-2} with segment densities ranging from 0.047 to 0.246 organisms 100 m^{-2}.

During MARAMP 2005, sea cucumbers were observed in all 3 of the towed-diver surveys conducted on Santa Rosa Reef (Fig. 4.10.7c, right panel) with an overall mean density of 0.047 organisms 100 m^{-2} (SE 0.010). The highest mean density of sea cucumbers from a towed-diver survey was 0.09 organisms 100 m^{-2} with segment densities ranging from 0 to 0.179 organisms 100 m^{-2}.

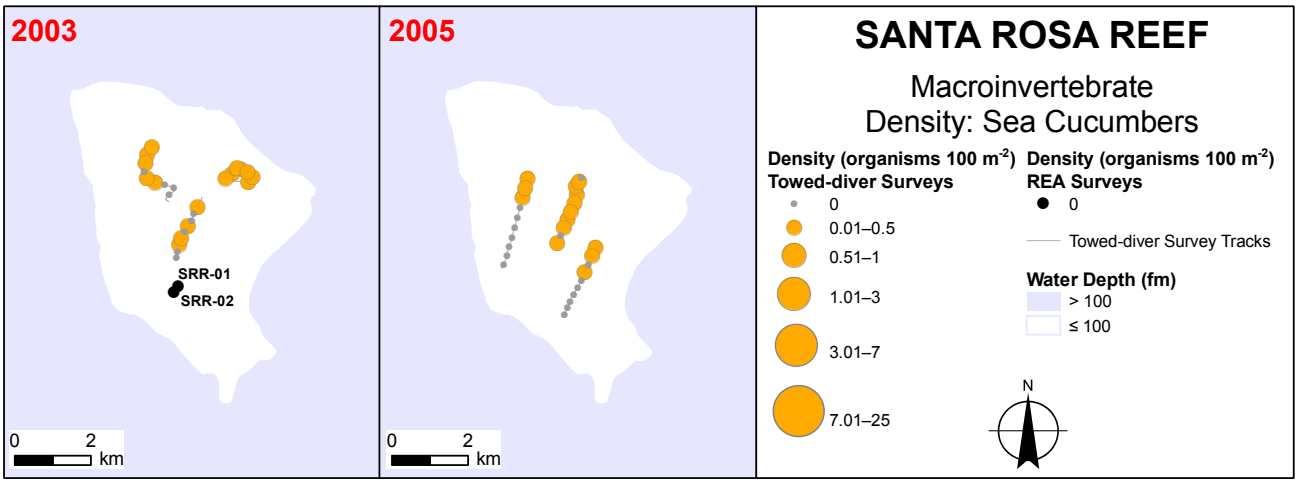


Figure 4.10.7c. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys conducted on Santa Rosa Reef during MARAMP 2003.

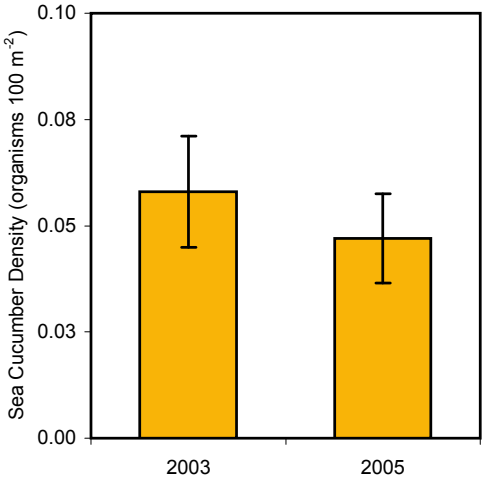


Figure 4.10.7d. Temporal comparison of mean densities (organisms m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Sea Urchins

During MARAMP 2003, sea urchins were observed at 1 of the 2 REA sites surveyed and in all 3 of the towed-diver surveys conducted on Santa Rosa Reef (Fig. 4.10.7e, left panel; Fig. 4.10.7f). The density of sea urchins at SRR-02 was 25 organisms 100 m^{-2}. The overall mean density of sea urchins from towed-diver surveys was 5.28 organisms 100 m^{-2} (SE 0.957). The highest mean density of sea urchins from a towed-diver survey was 10.7 organisms 100 m^{-2} with segment densities ranging from 8.97 to 12.55 organisms 100 m^{-2}. Three species were observed on Santa Rosa Reef: blue-black urchin (*Echinothrix diadema*) and rock-boring urchins *Echinometra mathei* and *Echinostrephus aciculatus*. The rock-boring urchin *E. aciculatus* accounted for 60% of sea-urchin density in 2003.

During MARAMP 2005, sea urchins were observed in all 3 of the towed-diver surveys conducted on Santa Rosa Reef (Fig. 4.10.7e, right panel) with an overall mean density of 1.63 organisms 100 m^{-2} (SE 0.240). The highest mean density of sea urchins from a towed-diver survey was 2.83 organisms 100 m^{-2} with segment densities ranging from 1.61 to 5.26 organisms 100 m^{-2}.

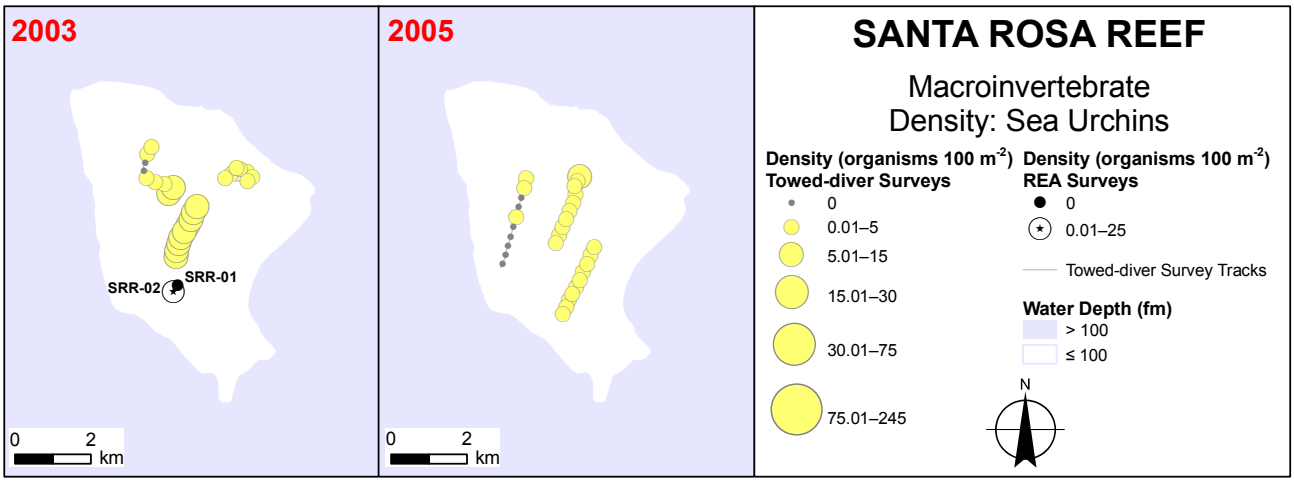


Figure 4.10.7e. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005.

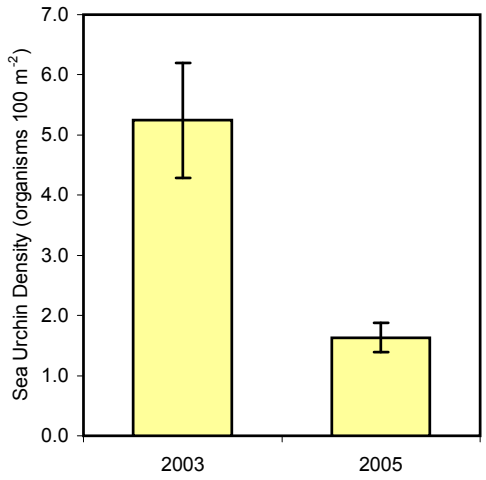


Figure 4.10.7f. Temporal comparison of mean densities (organisms m^{-2}) of sea urchins from towed-diver benthic surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

4.10.8 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 3 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted on Santa Rosa Reef (Fig. 4.10.8a, left panel), revealing an overall mean of 0.16 kg 100 m^{-2} (SE 0.1) for the biomass of large fishes on this reef (biomass values were calculated as weight per unit area). A single eagle ray (*Aetobatus narinari*) accounted for more than half of overall large-fish biomass: 54% or 0.09 kg 100 m^{-2}. Parrotfishes (Scaridae) accounted for the second-greatest proportion of large-fish biomass: 28% or 0.05 kg 100 m^{-2}. The steephead parrotfish (*Chorurus microrhinos*) was the most abundant parrotfish among large-fish species, accounting for 83% of parrotfish biomass. Surgeonfishes (Acanthuridae) were also common during this survey period, and the bulbnose unicornfish (*Naso tonganus*) was the most common species, contributing 0.02 kg 100 m^{-2} to large-fish biomass. No sharks were observed at Santa Rosa Reef in 2003.

During MARAMP 2005, 3 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted on Santa Rosa Reef (Fig. 4.10.8a, right panel), revealing an overall mean of 0.22 kg 100 m^{-2} (SE 0.16) for the biomass large fishes on this reef. A single porcupine ray (*Urogymnus africanus*), accounted for the highest proportion of overall large-fish biomass: 82% or 0.18 kg 100 m^{-2}. Grunts (Haemulidae) accounted for the second-greatest proportion (15%) of large-fish biomass, and the painted sweetlips (*Plectorhinchus picus*) was the most abundant grunt, contributing 0.03 kg 100 m^{-2} to large-fish biomass. Snappers (Lutjanidae) accounted for the remainder (3%) of large-fish biomass but were not commonly observed. The twinspot snapper (*Lutjanus bohar*) was the only snapper species recorded during this survey period. As with MARAMP 2003 observations, no sharks were observed at Santa Rosa Reef in 2005.

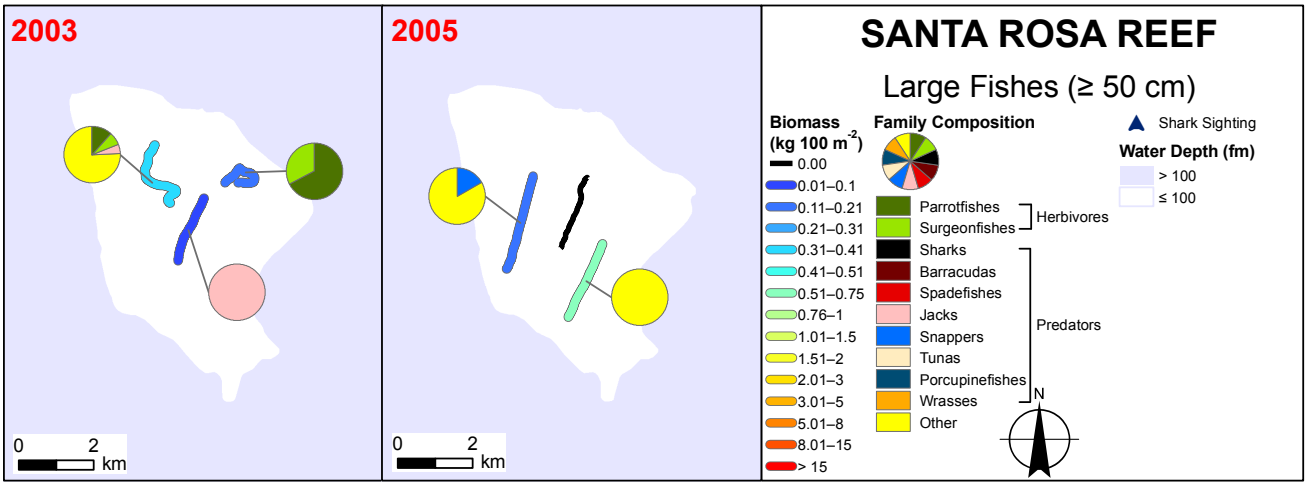


Figure 4.10.8a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) and family composition on Santa Rosa Reef during MARAMP 2003 and 2005. No sharks were observed.

Overall, estimates of large-fish biomass from towed-diver surveys conducted on Santa Rosa Reef were moderately low during MARAMP 2003 and 2005, compared to observations made at other survey areas in the Mariana Archipelago, with means of 0.15 (SE 0.10) and 0.21 kg 100 m^{-2} (SE 0.16, Fig. 4.10.8b). During both survey years, no single species consistently accounted for the greatest proportion of large-fish biomass from towed-diver surveys, and no clear spatial patterns were seen in the distribution of large-fish biomass. Of note was the lack of sightings of large, predatory species like reef sharks (Carcharhinidae) during either survey period. Additionally, no humphead wrasse (*Cheilinus undulatus*) were observed.

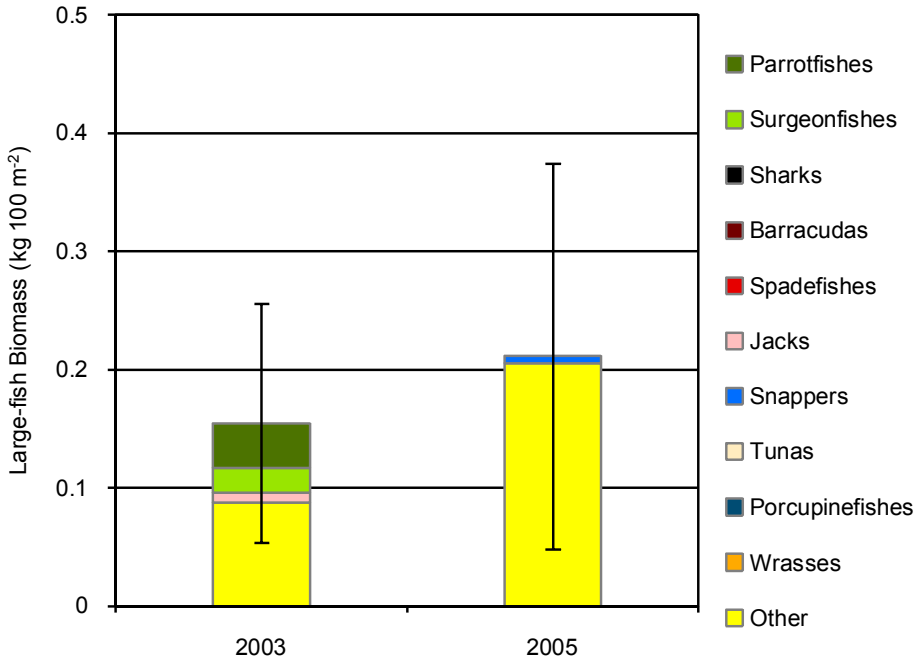


Figure 4.10.8b. Temporal comparison of mean values of large-fish biomass (kg 100 m^{-2}) from towed-diver fish surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Total fish biomass from the single REA site surveyed on Santa Rosa Reef during MARAMP 2003 was 1.61 kg 100 m^{-2} (Fig. 4.10.8c, left panel), very low compared to other sites in the Mariana Archipelago. Emperors (Lethrinidae) accounted for the greatest proportion of total fish biomass: 54% or 0.87 kg 100 m^{-2}, and the spotcheek emperor (*Lethrinus rubrioperculatus*) was the only emperor species recorded. Surgeonfishes accounted for the second-greatest proportion of total fish biomass: 17% or 0.28 kg 100 m^{-2}. The orangespot surgeonfish (*Acanthurus olivaceus*) accounted for 97% of surgeonfish biomass. No large, predatory species, such as reef sharks, were observed in 2003.

Based on the single REA survey conducted during MARAMP 2003, species richness was low on this reef compared to other survey sites in the Mariana Archipelago with 12 species 100 m^{-2} (Fig. 4.10.8c, left panel) and a total of 21 species observed. Wrasses (Labridae) were the most represented family with 7 species observed. The pink-belly wrasse (*Halichoeres margaritaceus*) was the most abundant species overall with 15 individuals 100 m^{-2}. The manybar goatfish (*Parupeneus multifasciatus*) was also abundant with 13 individuals 100 m^{-2}.

Total fish biomass for the 2 REA sites surveyed on Santa Rosa Reef during MARAMP 2005 was very low compared to other sites surveyed in the Mariana Archipelago. The highest total fish biomass of 1.63 kg 100 m^{-2} was observed at SRR-01 in the central region of this reef (Fig. 4.10.8c, right panel). Wrasses accounted for the greatest proportion (32%) of total fish biomass. Katherine's wrasse (*Cirrhilabrus katherinae*) and the pink-belly wrasse were the 2 major wrasses by biomass, contributing 0.12 kg 100 m^{-2} and 0.11 kg 100 m^{-2} to total fish biomass. Surgeonfishes and jacks (Carangidae) accounted for the second- and third-greatest proportions (19% and 17%) of total fish biomass. The brown surgeonfish (*Acathurus nigrofuscus*) was the major surgeonfish species by biomass and accounted 76% or 0.20 kg 100 m^{-2} of surgeonfish biomass. The island trevally (*Carangoides orthogrammus*) was the only jack species observed on this reef. No reef sharks were observed in 2005.

Based on REA surveys conducted during MARAMP 2005, diversity was heterogeneous between sites on Santa Rosa Reef with 20 and 30 species observed at SRR-02 and SRR-01 (Fig. 4.10.8c, right panel). Species richness was 20 species 100 m^{-2} at SRR-01 and 11 species 100 m^{-2} at SRR-02. Wrasses and damselfishes (Pomacentridae) were the 2 most represented families, each with 6 species observed in 2005. Katherine's wrasse was the most abundant species overall with more than 40 individuals 100 m^{-2}.

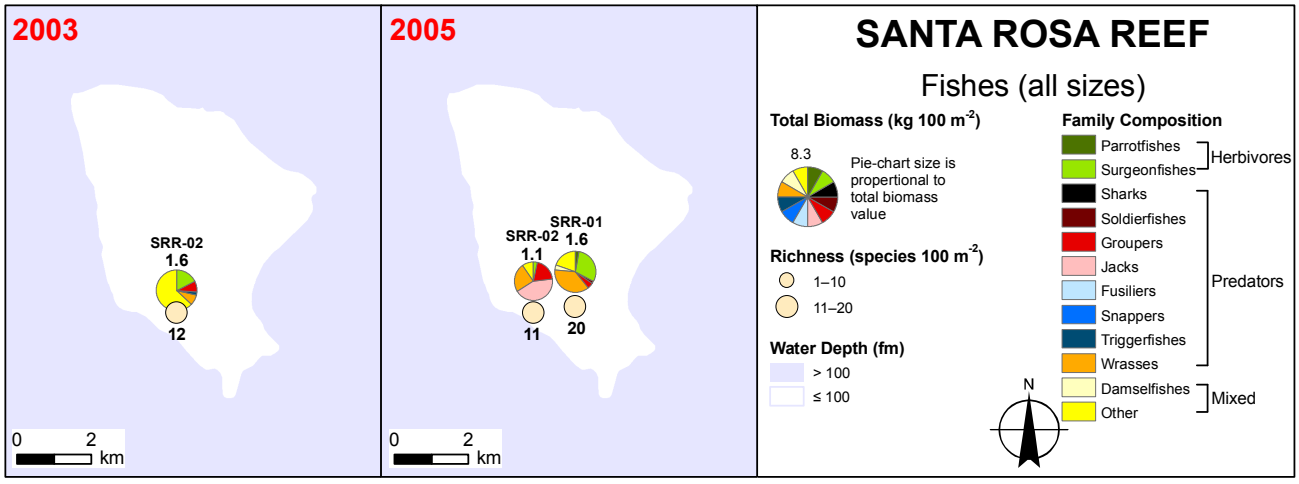


Figure 4.10.8c. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method on Santa Rosa Reef during MARAMP 2003 and 2005.

Compared to the rest of the Mariana Archipelago, total fish biomass from REA surveys conducted on this reef was low (Fig. 4.10.8d) with a sample mean over both MARAMP 2003 and 2005 of 1.49 kg 100 m^{-2} (SE 0.13). No spatial patterns in total fish biomass could be identified because of the limited number of sites surveyed. Surgeonfishes accounted for the second-greatest proportion of total fish biomass in both survey years, with the orangespot surgeonfish and brown surgeonfish as the 2 main surgeonfish species by biomass in 2003 and 2005. Large, predatory species, such as reef sharks, were not observed during either survey period.

The total number of species observed during MARAMP 2003 and 2005 ranged from 20 to 30 species with mean species richness of 14 species 100 m^{-2} (SE 1.6) over both survey periods. Wrasses were consistently the most represented family with an average of 6.5 species observed over the 2 survey periods. No single species was the most abundant for both survey periods. However, Katherine's wrasse and the pink-belly wrasse were some of the most abundant species in 2003 and 2005.

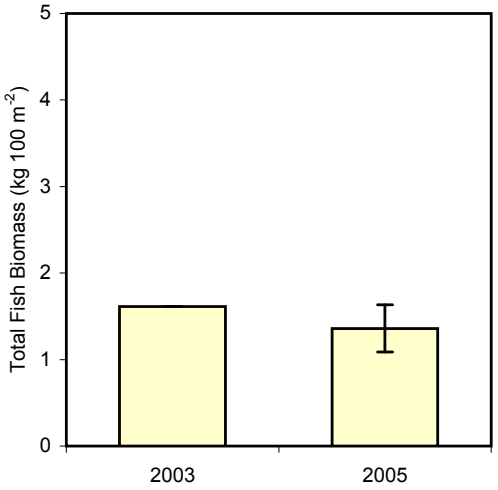


Figure 4.10.8d Temporal comparison of mean values of total fish biomass (kg 100 m^{-2}) from REA fish surveys conducted on Santa Rosa Reef during MARAMP 2003 and 2005. The error bar indicates standard error (± 1 SE) of the mean.

4.11 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Guam are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. Biological information from towed-diver surveys was integrated to derive 3 composite indices that provide assessments of the relative ecological conditions of forereef habitats in the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan.

The *Benthic Condition Index* for Guam, Rota, Tinian, and Saipan was derived by equally weighting observations of the following 5 parameters from towed-diver benthic surveys around these 4 islands: cover of live hard corals, stressed corals, macroalgae, and crustose coralline red algae and density of crown-of-thorns seastars (COTS). The *Fish Condition Index* for Guam, Rota, Tinian, and Saipan was derived from 2 equally weighted parameters from towed-diver fish surveys: density and biomass of large fishes (≥ 50 cm in TL). The overall *Coral Reef Condition Index* for Guam, Rota, Tinian, and Saipan was derived from an equal weighting of these benthic and fish indices. These condition indices were calculated using ranks assigned to the biological variables from towed-diver surveys conducted around Guam, relative to all surveys performed around the 4 populated, southern islands for each survey year. To indicate changes in these ranks between survey years, these indices were visualized on a map within survey areas, which are represented by color-coded and irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007 (towed-diver-survey tracks were often similar but not exactly the same in each survey year). For more details about the methodology *behind these indices, see Chapter 2: "Methods," Section 2.5: "Ecosystem Integration." Each of these 3 condition indices is presented for Guam on a map in Figure 4.11a. Reef condition indices for the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparison," providing ranks for Guam as well as the 13 islands of the CNMI that are also covered in this report.

Surveys around Pati and Ritidian Points

Portions of the Pati Point Marine Preserve around the northeastern corner of Guam stand out as areas with overall reef conditions that are among the best when compared to conditions around the other populated, southern islands in the Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan (Fig. 4.11a). Pati Point Marine Preserve, which is shown in Figure 4.11b, extends along the northeastern perimeter of Andersen Air Force Base. The geomorphology and habitat within this preserve are diverse, with seagrass and both shallow-water and deepwater coral ecosystems. A well-defined channel is found within this preserve (NOAA 2006). Guam Public Law 24-21 established this preserve in 1997 along with 4 other marine preserves around Guam (Burdick et al. 2008), and enforcement within these preserves began in 2001. Hook-and-line fishing from shore is allowed in this preserve for all species. Trolling is allowed only for pelagic fishes, such as tunas (Scombridae) and billfishes (Scomberesocidae), in all the preserves seaward from the reef margin. In addition to its inclusion in an MPA, the area around Pati Point derives further protection from the limited accessibility associated with its proximity to Andersen Air Force Base.

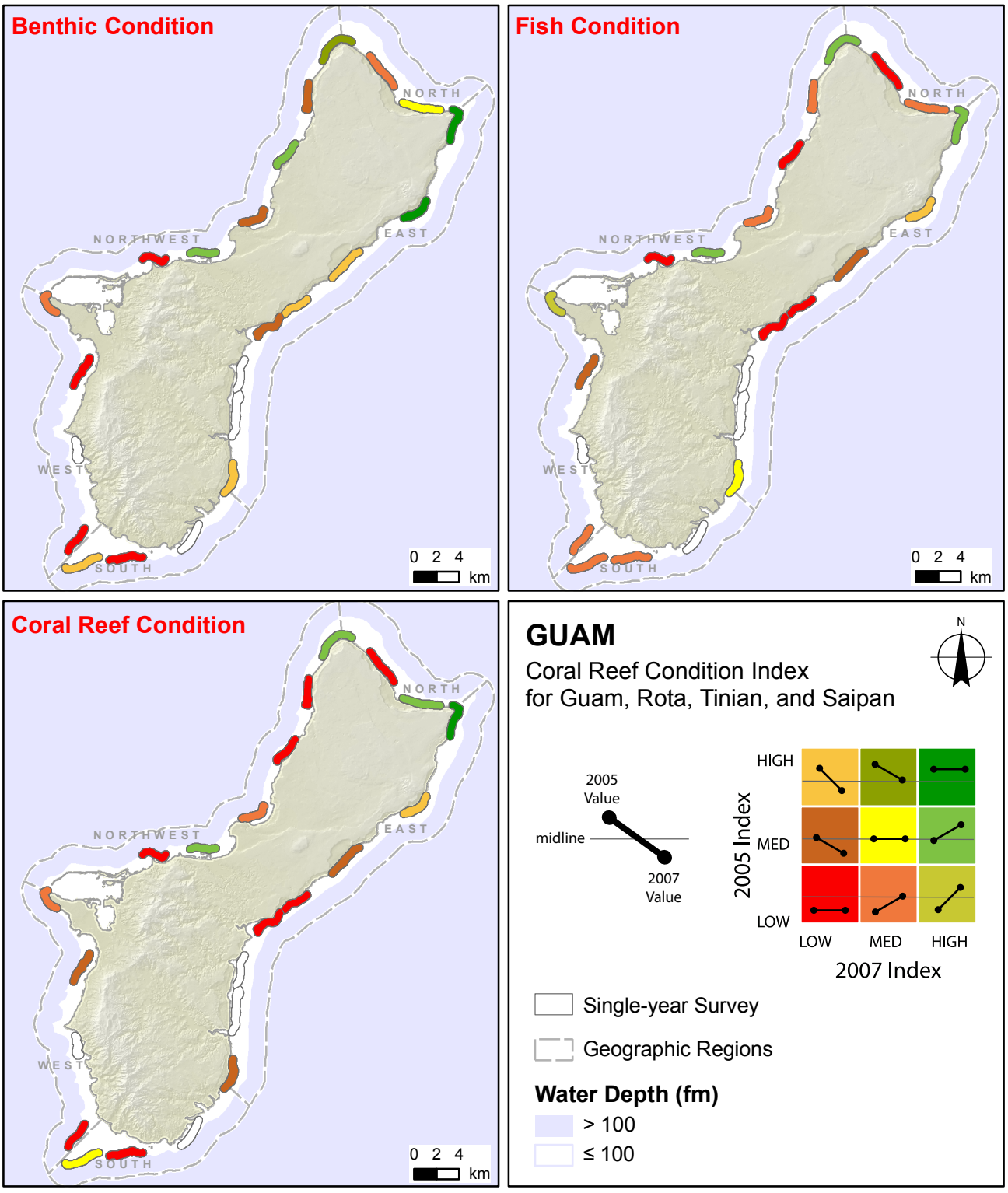


Figure 4.11a. The Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan, as well as the associated Benthic Condition Index and Fish Condition Index, reflects the condition of the benthic and fish communities and their integrated ecosystem for each towed-diver-survey area, *relative to other survey areas around the 4 populated, southern islands.* These maps indicate changes in index ranks between MARAMP 2005 and 2007 for towed-diver-survey areas around Guam. Survey areas are represented by irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007. No index value is calculated for areas with only one year of survey data. A high rank means superior condition relative to other survey areas around the 4 populated, southern islands. The survey area around Pati Point, the northeastern point, for example, has a high rank for both 2005 (y-axis) and 2007 (x-axis) and, thus, is assigned the bright-green color that corresponds to the top-right square in the legend. The position of the horizontal bar above the midline in this square also reflects that this survey area maintained a high rank in both years.

The highest biomass of large fishes (≥ 50 cm in TL) of 1.23 kg 100 m^{-2} was found during the MARAMP 2003 towed-diver survey conducted around Pati Point, with 3 reef sharks (Carcharhinidae) recorded in this area (for place-names and their locations, see Figure 4.2a in Section 4.2: "Survey Effort"). Additionally, the Fish Condition Index for Guam, Rota, Tinian, and Saipan, which uses MARAMP 2005 and 2007 data only, shows that, relative to other areas around the populated, southern islands, the fish community around Pati Point was in good condition. Parrotfishes (Scaridae) and other fish families that are heavily exploited around Guam were commonly observed around Pati Point, and 1 whitetip reef shark (*Triaenodon obesus*) was observed in 2005 at REA site GUA-07. The Fish Condition Index value for the area around and south of Pati Point increased from medium in 2005 to high in 2007, and the rank in this index for the survey area west of Pati Point in the north region increased from low in 2005 to medium in 2007.

Interestingly, these indices suggest that the benthic communities to the west and south of Pati Point were markedly different. Cover values for live hard corals from towed-diver surveys were higher west of Pati Point than south of it, with mean coral cover across the 3 MARAMP survey years of 30% west of Pati Point and 14% south of it. In the Benthic Condition Index for Guam, Rota, Tinian, and Saipan, values for both survey areas were relatively stable. The index rank for the area west of Pati Point was medium in both 2005 and 2007. The index value for the survey area around and south of this point was high in both years (Fig. 4.11a) because, in 2005 and 2007, the ratio of mean cover values for crustose coralline red algae to macroalgae was relatively high, the levels of stressed-coral cover were relatively low, and no COTS were observed. Benthic habitat characterization also reveals differences between these 2 towed-diver-survey areas near Pati Point. South of this point, irregular pavement flats and areas of high rugosity habitat with rocky pillars and boulders were seen. In contrast, the habitat west of Pati Point was more sheltered and consisted of rolling reef. These observed differences in benthic habitats and coral communities south and west of Pati Point were likely a result of mean annual wave forcing; both episodic storm and trade wind waves impact Guam from the east, hindering coral recruitment. A secondary potential reason for these differences was that transient eddies form off the west and south points of Guam (Wolanski et al. 2003b).

Ritidian Point, which is the northernmost tip of Guam and northwest of Pati Point, had moderate values on the Benthic, Fish, and Coral Reef Condition indices (Fig. 4.11a). Still, the coral reefs around Ritidian Point were notable for condition ranks that were high relative to other locations around the populated, southern islands of Guam, Rota, Tinian, and Saipan. This area in 2005, again relative to other locations around these 4 populated islands, had a high value in the Benthic Condition Index because no COTS were observed there and the mean coral cover of 18% was in the upper range of values seen around these populated islands. The Benthic Condition Index value for this area in 2007 declined to medium, given a reduction in the percentage of live coral cover and increases in the levels of stressed-coral cover and COTS density. The Fish Condition Index value around Ritidian Point was also relatively high compared to other locations, with a rating of medium in 2005 based on a slightly above-average density and biomass of large fishes. For this area in 2007, the Fish Condition Index value increased to high. This improvement was caused by an increase in large-fish biomass that in turn was largely a result of observations of several sharks, which were rarely seen elsewhere around the populated, southern islands.

Surveys around Southern and Southeastern Guam

The conditions of the coral reefs in the areas around southern and southeastern Guam, ranging from Cocos Island in the south region up to Fadian Point in the east region, were of particular concern. In these areas, many important watersheds drain into a number of coral-abundant communities. Across the 3 MARAMP survey years, it appeared that these communities were negatively affected by varying degrees of stressed-coral cover and COTS infestation.

The geology of southeastern Guam substantially influences nearshore reef habitats. A volcanic ridge on the west side of Guam drains into moderately sloped areas of forest and farmland before entering the ocean via numerous river outlets along the east and west coasts. The coral reefs around the southern half of Guam are subjected to a number of significant sediment-related stressors, including upland erosion that is exacerbated by high levels of rainfall and large numbers of forest fires (Burdick et al. 2008).

Each of the 3 MARAMP survey periods coincided with or shortly followed periods of moderate-to-heavy precipitation. MARAMP 2003 surveys were conducted in September, the peak of the rainy season; MARAMP 2005 surveys occurred in October, 1 month after the rainy season; and MARAMP 2007 surveys were conducted in May, 1 month after a slight precipitation increase (see Figure 4.4.2e in Section 4.4.2: "Time-series Observations"). The largest watershed on Guam is the Talofofo River, the mouth of which flows into Talofofo Bay, which is centrally located along the southeastern coast near REA site GUA-06 and within the proximity of several towed-diver-survey tracks. Talofofo River drains an estimated area of ~ 72.8 km^2 (Best and Davidson 1981) and is likely a major influence on nearby coral reefs to the south and north of its entry into the ocean.

Several locations along this southeastern coast have impaired or threatened water quality, according to testing conducted by the Guam Environmental Protection Agency (GEPA) in 2006 and 2007 (GEPA 2008). Among the GEPA's top-10 sources of water impairment on Guam are urban runoff and the application of fertilizers and pesticides, both of which potentially occur in some combination among the small communities, farmland, and 2 golf courses (The Country Club of the Pacific and the Onward Talofofo Golf Club) in southeastern Guam. Depending on the combination of nearshore currents driven by trade wind swells and seasonal fluctuations in the North Equatorial Current, introduced nutrient- and contaminant-enriched sediment and water may be carried either north or south before settling into the marine environment. Such sediment may settle on and directly smother benthic organisms, depending on hydrodynamic conditions like waves and currents. Excess nutrients have been shown to alter the relative composition of benthic communities, for example, by promoting algal growth at the expense of corals (Wolanski et. al. 2003a, 2003b). Observations of sedimentation and evidence of coral disease were recorded during MARAMP 2005 towed-diver surveys conducted between Tagachang Point and Jalaihai Point.

Despite the previously described effects, the benthic communities off the southern and southeastern coasts of Guam were notable for supporting moderately high levels of live coral cover—with the exception of 1 towed-diver-survey area in the south region south of Agfayan Bay where habitat was dominated by macroalgae (Fig. 4.11b). All other surveys conducted in the south and southeast regions reported mean live coral cover of > 10%, and during 2 surveys in 2005—1 south of Cocos Island and 1 just north of Talofofo Bay—mean coral cover ranged close to 40%. The survey area off Jalaihai Point, located at the border of the east and south regions, also supported localized, elevated levels of live coral cover across all 3 survey years. REA surveys at GUA-03 in the south region recorded live coral cover of 26% in 2005, and surveys at GUA-11 in Pago Bay and at GUA-03 both recorded mean coral cover of 12% in 2007.

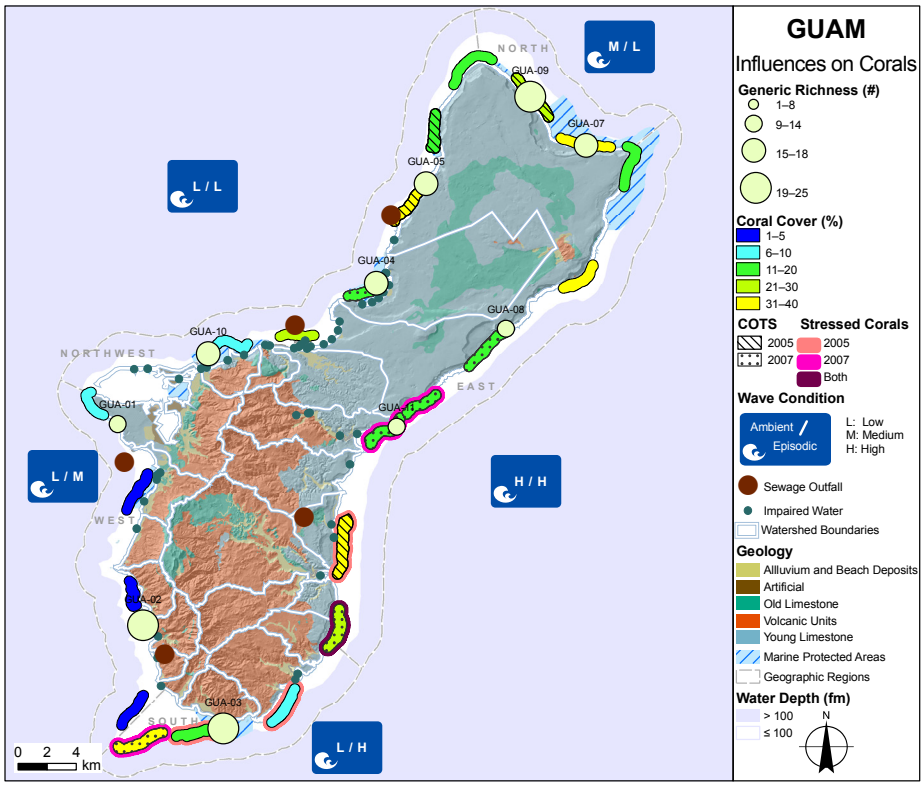


Figure 4.11b. Cover (%) observations of live and stressed corals from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Guam during MARAMP 2005 and 2007, presented with geology, watersheds, impaired water sites and other factors (WERI 2009; Gingerich 2003; Tracey et al. 1964; Taboroši et al. 2005; GEPA 2008). Values of coral cover and generic richness represent averages from both survey years, where available; otherwise values represent data from the single year surveyed. Towed-diver-survey areas combine overlapping survey tracks for both MARAMP survey years. Colored outlines represent areas where estimates of stressed-coral cover were > 10%, and diagonal lines or dots indicate areas where COTS density was > 0.15 organisms 100 m^{-2}. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.

Inconsistent REA and towed-diver-survey efforts around southeastern Guam make comparison across survey years difficult. Still, where towed-diver surveys covered essentially the same area in both 2005 and 2007, it is possible to compare Benthic Condition Index ranks. Declines in Benthic Condition Index values were observed for 1 towed-diver-survey area near Jalaihai Point, located at the border between the east and south regions, and for 2 survey areas south of Cocos Lagoon in the south region (Fig. 4.11a). East of Jalaihai Point, the Benthic Condition Index value was high in 2005 but low in 2007. This drop is attributable to a decline in coral cover, since other benthic parameters remained relatively constant. South of Cocos Lagoon, the Benthic Condition Index values for 2 towed-diver surveys decreased from medium and high in 2005 to low and medium in 2007. Again, declines were mainly because of drops in live coral cover, although, for the most southwestern towed-diver survey, levels of stressed-coral cover and COTS density increased in 2007 from levels in 2005.

One relatively consistent theme for the southeastern coast of Guam was elevated levels of stressed-coral cover. Overall, stressed-coral cover was consistently high in the south and east regions across survey years. COTS predation and bleaching were recorded as the dominant cause of stressed corals. Localized bleaching in Pago Bay in 2004 was reported as a likely result of a large influx of freshwater from Tropical Storm Tingting, and Pago Bay and Achang Reef Flat Marine Preserve were 2 of several areas around Guam where bleaching events, associated with high sea-surface temperatures, were observed in 2006 (Burdick et al. 2008).

COTS were indeed abundant in these regions during MARAMP 2005 and 2007. The highest COTS density for Guam in 2005 was documented during 2 towed-diver surveys conducted north of Talofofo Bay, with certain segments recording densities as large as 4.8 organisms 100 m^{-2}. In 2007, towed-diver surveys recorded 3 of the 4 greatest COTS densities islandwide around southern and southeastern Guam. The greatest densities occurred off Fadian Point, located north of Pago Bay along the east central coast, with certain segments recording as many as 3.2 organisms 100 m^{-2}. Similarly, Burdick et al. (2008) reported that high densities of COTS were observed in Pago Bay in 2006. The third- and fourth-greatest COTS densities observed around Guam during MARAMP 2007 surveys were recorded off Jalaihai Point and to the south of Cocos Island, where segment densities reached as high as 2.1 and 2.7 organisms 100 m^{-2}, respectively.

Fish biomass around southeastern Guam was consistently low, as it was around most of this island, relative to the rest of the Mariana Archipelago (Fig. 4.11c). Although the human population in southeastern Guam is lower than in other locations around this island, 2 boat launches in the south region provide access to reef resources in this area, and the biomass of large fishes observed around the southeastern coast was not in a higher range than the biomass values recorded around more populated locations.

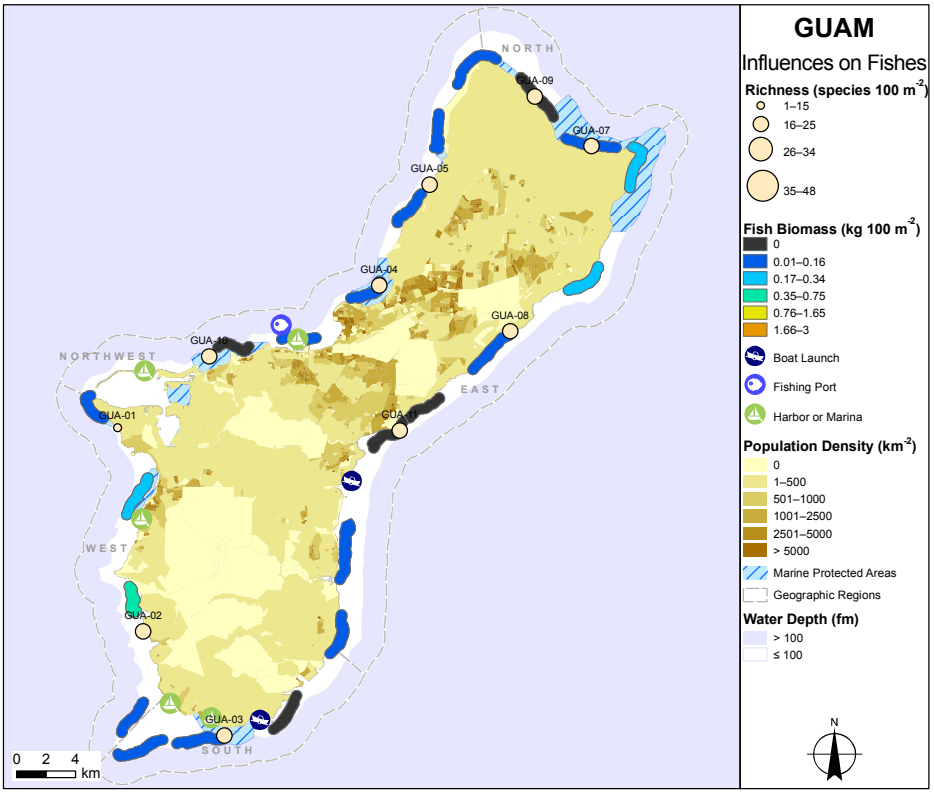


Figure 4.11c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver surveys and species richness from REA surveys conducted on forereef habitats around Guam during MARAMP 2005 and 2007, presented over a map of human population density (U.S. Bureau of the Census 2000, 2008). Biomass and richness values represent averages of data from both survey years, but, if surveys were conducted during one year only, then values represent data from that single year. Towed-diver-survey areas combine overlapping survey tracks for both MARAMP survey years; survey tracks are often similar but not necessarily the same between survey years.

Surveys around Southwestern Guam

In contrast to the east side, the southwestern coast of Guam, in the west geographic region, was notable for supporting some of the lowest levels of live coral cover found around this island (Fig. 4.11b). Mean live coral cover from towed-diver surveys conducted in the west region was 5% in 2003 and 2005 and 3% in 2007, compared to islandwide means of 20% and 23% in 2003 and 2005 and 12% in 2007. Similarly, the lowest coral-cover values in both 2005 and 2007 were recorded at the 2 REA sites in the west region: GUA-02 in Cetti Bay and GUA-01 on the south coast of the Orote Peninsula. Divers described corals at GUA-01 as predominantly small encrusting or nodular varieties and their habitat as low topographic complexity.

The benthic habitats of southwestern Guam were characterized by relatively low live coral cover and high macroalgal cover; together, these 2 ecological parameters resulted in low Benthic Condition Index values for survey areas in the west region (Fig. 4.11a). Among MARAMP 2003 towed-diver surveys, the highest macroalgal cover around Guam was found south of the Orote Peninsula where mean macroalgal cover was 68%. Also in 2003, the highest macroalgal diversity from REA surveys conducted around Guam was recorded at GUA-01. In 2005 and 2007, mean macroalgal-cover values from all 3 towed-diver surveys conducted within the west region were high: more than half of the surveyed area had macroalgal cover of > 75%. The dominant genera observed were the calcareous green alga *Halimeda* and the brown alga *Padina*. Similar results were found at the 2 REA sites surveyed in the west region, revealing algal communities dominated by *Halimeda* and turf algae and relatively low levels of crustose coralline red algae. Extensive mats of turf algae and cyanobacteria were also reported at those sites.

Habitat maps suggest that the pattern of macroalgae-dominated reefs observed in MARAMP survey areas in the west region is typical for the west region as a whole. Created by the NOAA Center for Coastal Monitoring and Assessment by interpreting IKONOS satellite imagery, these maps also show widespread dominance of turf algae in nearshore (< 40 m) reef communities (NOAA 2005).

The nature of the reef community along the southwest coast of Guam is likely a result of both natural and anthropogenic factors. Influences on the habitat type in this area include onshore and nearshore geology and topography, which is characterized by steeply sloping volcanic rock forming ridges and valleys. This geologic setting differs from other parts of Guam, such as the northern area, where an onshore limestone plateau is mirrored in the adjacent coastal waters by a series of flat, carbonate terraces. These terraces provide large areas of shallow, hard substrate that are conducive to reef development.

As discussed earlier in this section, the volcanic landscape of southwestern Guam is characterized by many streams that drain the upland watersheds, transporting terrigenous sediments into nearby coastal waters. Sediment loading and associated freshwater input result in reduced reef development in the coastal areas immediately adjacent to river mouths (Burdick et al. 2008). These factors also influence the composition of the benthic substrate with sandy channels forming in the coastal waters downstream of river mouths, which are shown on the hard-soft and hill-shaded bathymetric maps (Fig. 4.11d). Divers described the habitat in this area as sloping pavement, dropping off to sand, and they noted the presence of sand channels.

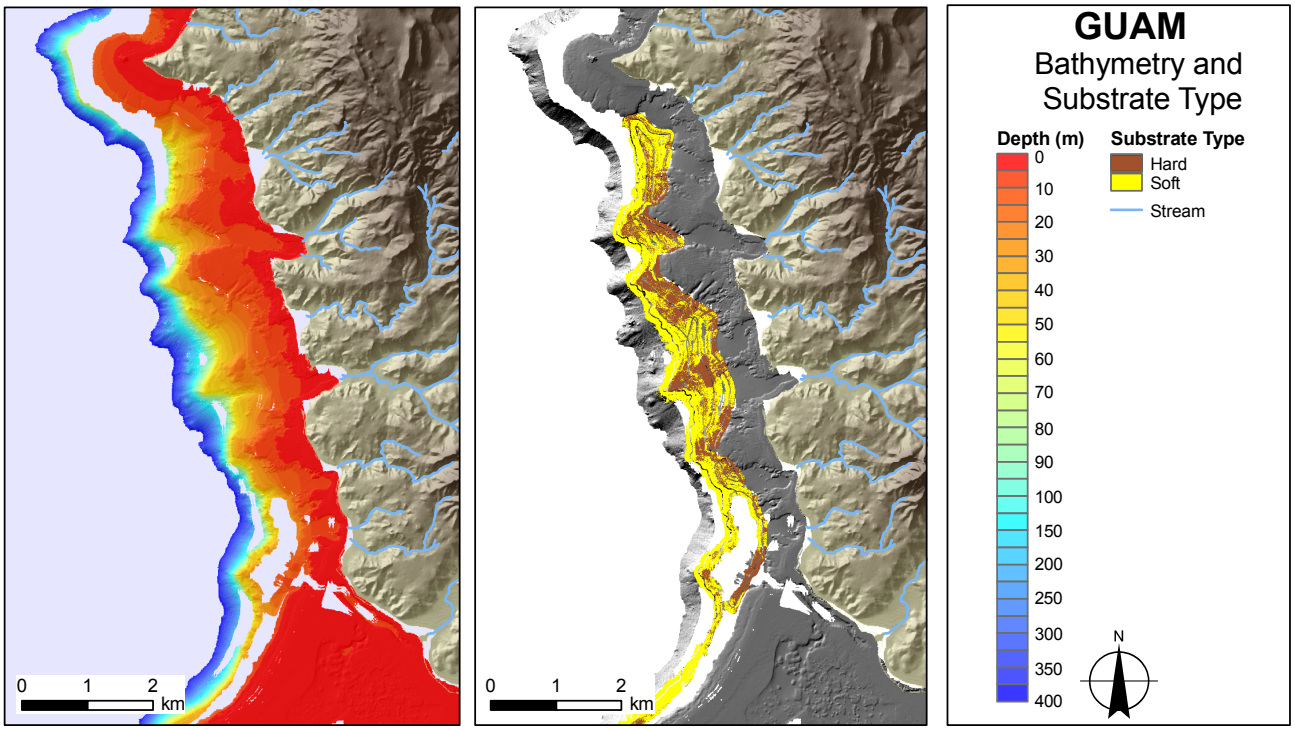


Figure 4.11d. The southwestern coast of Guam, showing (*left*) river channels and associated channels in multibeam bathymetry and (*right*) distribution of soft sediment in relation to river mouths and submarine channels.

In addition to a lack of favorable substrate for reef development and elevated terrigenous sediment input, another factor potentially influencing reef communities around southwestern Guam is the poor water quality of portions of the coastline in this area. Close to Agat Bay, the Agat-Santa Rita Wastewater Treatment Plant has had many documented failures to meet standards of discharge limitations for biological oxygen demand, suspended solids, bacteria, and metals. Incidences of impaired water quality have also been observed farther south close to Cetti Bay (Burdick et al. 2008; GEPA 2008).

Despite low coral cover, coral diversity at GUA-02 in Cetti Bay was relatively high with at least 20 coral genera observed at this site in 2007, compared to the range of 15–23 genera found at REA sites around Guam. In addition to relatively high levels of generic richness, values of stressed-coral cover from towed-diver surveys were relatively low in this area with < 10% for both MARAMP 2005 and 2007. Similarly, in 2007, REA coral-disease surveys recorded prevalence values of only 0.8% and 0.6% at sites GUA-01 and GUA-02, compared to an island maximum of 3.9%; these low levels of coral disease are not surprising given the low levels of coral cover. The main causes of stressed corals were bleaching, predation, and fungal infection.

The reef-fish community surveyed at GUA-01 and GUA-02, the 2 REA sites located in the west region on the southwestern coast of Guam, had some of the lowest biomass and species richness recorded at any of the sites around Guam. The biomass of large fishes from towed-diver surveys was low in this region relative to the rest of Guam (Fig. 4.11c). These results may be in part a consequence of the low structural complexity of the habitat together with limited coral cover and associated shelter habitat that are important to many reef-fish species.

Surveys in Tumon Bay

A final area of interest is Tumon Bay in the northwest region. The entire bay is encompassed by the Tumon Bay Marine Preserve, a broad crescent-shaped limestone platform. Tumon Bay is 3.2 km in length and this reef platform is as wide as 440 m. A major road parallels the beach around this bay ~ 300 m from the high-water mark, making Tumon Bay an important center for recreational activity (NOAA 2006).

Tumon Bay is the focal point of Guam's tourism industry. Most of the hotels and shopping malls on Guam are located in this area, and development along this bay has been rapid in the recent past (Burdick et al. 2008). This area also has the highest human population density on Guam. This area is subject to a variety of anthropogenic impacts, including impaired water quality, sedimentation (siltation stress, re-suspension, etc.), contaminated groundwater, and physical damage to reefs associated with high levels of recreation (Burdick et al. 2008). Further, relatively high densities of COTS were observed during towed-diver surveys conducted along the forereef habitats within Tumon Bay in both 2003 and 2007 (Fig. 4.11e).

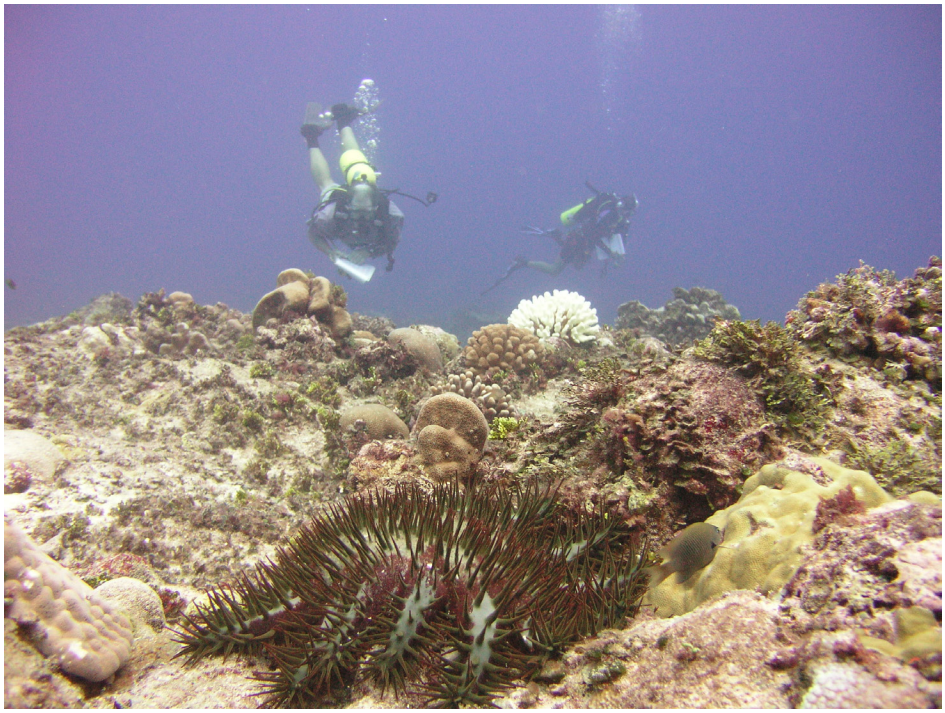


Figure 4.11e. A crown-of-thorns seastar (*Acanthaster planci*) preys on corals in Tumon Bay. NOAA photo by Robert Schroeder

Despite the large human population near and frequent use of Tumon Bay and the numerous associated impacts, the Benthic Condition Index value for this area was medium in both 2005 and 2007 (Fig. 4.11a). This stability may reflect that many potential impacts have been occurring for some time and the ecosystem in this area may have been damaged prior to the first MARAMP survey period in September 2003. Also, many potential land-based impacts likely take place on the shallow reef flat of the backreef that was not covered by MARAMP surveys. Relatively low values of stressed-coral cover were recorded in Tumon Bay during towed-diver surveys, with stressed corals observed during only a few survey segments in 2007. In 2006 and 2007, coral bleaching was documented within the Tumon Bay Marine Preserve, and Brown (2007) reported that more than 60% of the corals there were affected by bleaching and suffered either partial or full mortality. However, MARAMP towed-diver surveys conducted in 2007 associated observations of stressed-coral cover with COTS predation, and bleaching was not recorded. This difference may result from the fact the coral bleaching reported by Brown was documented at depths < 7 m, shallower than the habitat usually covered by MARAMP towed-diver surveys.

Within the Tumon Bay Marine Preserve, regulations prohibit various fishing activities. Fishing from shore by hook and line or cast net, per Guam Public Law 24-21, is allowed for rabbitfishes (Siganidae), juvenile goatfishes (Mullidae), juvenile jacks (Carangidae), and convict tangs (Acanthuridae). Use of cast nets along the reef margin is also allowed for rabbitfishes and convict tangs. Regulations prohibit "bottom fishing" in this preserve at depths < 30.5 m. Trolling for pelagic fishes, including all billfishes and any other migratory oceangoing fishes, is allowed in all the marine preserves around Guam from the reef margin seaward. Despite this remaining degree of fisheries protection in this preserve, towed-diver surveys of the forereefs of Tumon Bay recorded very low biomass of large (≥ 50 cm in TL) fishes in all years, generally with only a few individuals per survey. Across the 3 MARAMP survey years combined, mean total fish biomass at GUA-04 was 3.8 kg 100 m^{-2}, slightly higher than the overall mean of 3.2 kg 100 m^{-2} (SE 0.8) for Guam, which was the lowest value of mean total fish biomass for any island surveyed in the Mariana Archipelago.

4.12 Summary

This section presents an overview of the status of coral reef ecosystems around the island of Guam and some of its adjacent banks as well as some of the key natural processes and anthropogenic activities influencing these ecosystems. MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Guam. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Guam chapter are included in the appropriate discipline sections. One noteworthy limitation, for example, is the focus of MARAMP observations on forereef habitats to the exclusion of the many shallow backreef flats around Guam. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter.

To simplify interpretation of ecosystem conditions around Guam, a Benthic Condition Index, a Fish Condition Index, and an integrated Coral Reef Condition Index were developed to reflect ecosystem conditions at specific locations around Guam, relative to locations around the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan and based on MARAMP 2005 and 2007 surveys only (see Section 4.11: "Ecosystem Integration"). By synthesizing large amounts of complex, interdisciplinary information, these reef condition indices assist resource managers in identifying potential relationships between various ecosystem components. The condition of the fish and benthic communities and of the overall ecosystem around Guam, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

The following summary highlights key attributes of the coral reef ecosystems around Guam and its surrounding reefs and banks (for place-names and their locations, see Figure 4.2a in Section 4.2: "Survey Effort"):

- Guam is by far the largest island in the Mariana Achipelago and supports 70%–75% of this archipelago's human population. The bulk of Guam's population is centered on the northern part of this island.

- Divided by the Pago-Adelup fault, the northern and southern halves of Guam have distinct geologic characteristics. Uplifted, volcanic rock is capped by limestone in the northern half, creating a flat setting with little surface water. Volcanic rock in the southern half results in a steep, rugged landscape drained by numerous streams and rivers.

- The benthic seascape north and south of the Pago-Adelup fault reflects Guam's onshore landscape. Around northern Guam, a series of low-rugosity carbonate platforms with shallow terraces are separated by relatively steep slopes

from deeper waters. These relatively deep areas have steep ridges and debris resulting from mass-wasting. In contrast, around southern Guam, fewer platforms are present, and they are narrow. There are some areas of steep-sided canyons, for example, along the south and southwest coasts. Overall, the southern half of Guam has a more topographically complex seabed with fewer flat areas in comparison to the seabed around northern Guam.

- One of the major economic drivers on Guam is tourism. Tourism is concentrated in the Tumon Bay area, which has the highest population density on this island. This area is subject to a variety of anthropogenic impacts, including impaired water quality, sedimentation, contaminated groundwater, and physical damage to reefs associated with high levels of recreation. In the Benthic Condition Index for Guam, Rota, Tinian, and Saipan, the rank for this area was similar (medium) for both MARAMP 2005 and 2007. That this area is an MPA, established in 1997, suggests how an area so heavily populated and stressed by tourism and overfishing may have been able to maintain a medium condition for benthic populations. Total fish biomass, calculated as weight per unit area, however, was low in Tumon Bay during both survey years.

- A major factor in Guam's economic future is the expansion of U.S. military facilities on Guam, given plans to move ~ 25,000 military personnel and family members, including at least 4700 Marines from Japan, to Guam in the next decade. This influx of people would represent an increase of ~ 25% in this island's population. Major construction projects would include expansion of commercial piers, construction of docking facilities for an aircraft carrier, and construction of housing and facilities. Along with development related to tourism, this added population and construction load is expected to have significant environmental impacts, both on land and to the coral reef ecosystems of Guam.

- Wave model output shows typical trade wind swells from the north and east as well as high wave energy from storm tracks from the southeast. Vertical gradients in all oceanographic parameters measured were consistently stronger in the areas sheltered from easterly trade winds than in other areas around Guam.

- STR and satellite-derived (Pathfinder) SST data show that temperatures surpassed the bleaching threshold for a brief period in September 2006.

- Turbidity was very low with beam transmission > 90% at most CTD cast locations at Guam; however, lower beam transmissions was observed in Apra Harbor.

- Islandwide estimates of live-hard-coral cover from towed-diver surveys revealed variation between survey years, with mean values of 19% in 2003 and 23% in 2005 decreasing to 12% in 2007. A comparable pattern was discernible from estimates based on site-specific data from REA surveys: overall mean coral cover around Guam decreased from 26.1% in 2005 to 16.2% in 2007, with declines seen at all of the 7 sites surveyed in both 2005 and 2007. Despite this temporal trend, mean coral cover for Guam was intermediate (~ 10%–20%) relative to values observed around other islands in the Mariana Archipelago.

- The highest level of coral disease was documented in the north region near Jinapsan Point; however, observations of disease prevalence in this area were still relatively low with ~ 3%. Coral disease was assessed only during MARAMP 2007, and all REA sites surveyed contained disease. Bleaching was the most common affliction encountered, with 39% of cases, and was widely distributed around Guam.

- Fish biomass, from both REA and towed-diver surveys, was lowest around Guam compared to the rest of the Mariana Archipelago in all years surveyed. No clear geographic trend in overall fish biomass was observed across years. Large-fish-biomass values from towed-diver surveys conducted around Guam were generally highest in the most remote areas of Guam, including near Pati Point, the northeastern tip of this island, where large surgeonfishes (Acanthuridae), parrotfishes (Scaridae), and reef sharks (Charcharhinidae) were observed.

- Ranks from the Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan and the Benthic Condition Index for the survey area around Ritidian Point, where the Guam National Wildlife Refuge is located, were high in 2005, but values from both indices for this area declined to medium by 2007 (a high rank reflects superior condition relative to other survey areas around the 4 populated, southern islands). These drops in both indices represent a potential cause for concern, and close review of future monitoring information for this area is recommended. Ritiadian Point is one of the few places where sharks were sighted in all 3 survey years.

- The condition of the reef in the Pati Point Marine Preserve was among the best observed around the 4 populated, southern islands. The highest numbers of large fishes (≥ 50 cm in TL) were observed in this area in 2007. Ranks from both the Benthic Condition Index and Coral Reef Condition Index were high in both 2005 and 2007.

- In the central area of the east region, from Pago Bay to Campanaya Point, the coral reef ecosystem appeared to be in relatively poor health—with low ranks in all 3 condition indices (Benthic, Fish, and Coral Reef) in 2007. Known, long-term issues of water quality in Pago Bay may affect reef health. Stressed-coral cover and high densities of crown-of-thorns seastars (*Acanthaster planci*) were observed in 2006 (see Section 4.11: "Ecosystem Integration") and in 2007. Also, in 2004 localized bleaching occurred in Pago Bay as a result of a large freshwater input from Tropical Storm Tingting, and high sea-surface temperatures were associated with bleaching on reefs in several areas around Guam, including Pago Bay, in 2006.

- Some of the highest levels of live coral cover were observed near Catalina Point during towed-diver surveys conducted around Guam. Data from towed-diver surveys conducted over all 3 years revealed absence of stressed-coral cover and low densities of crown-of-thorns seastars (COTS) in this area. Macroalgal cover here was moderate to low in comparison to other areas around Guam. These results are reflected in the Benthic Condition Index rank of high for this area in both 2005 and 2007. A possible factor behind these "good" conditions may be this area's distance from Guam's main population centers and their associated anthropogenic impacts. This area is adjacent to Anao Conservation Reserve and just south of Pati Point Marine Preserve.

- The areas along the southern and southeastern shores of Guam, from Cocos Island in the south region up to Faidan Point in the east region, were of particular concern for this island. Many watersheds are located in these areas, so the amount of runoff that flows into the ocean certainly influences nearby coral reef ecosystems. At several locations (see Fig. 4.11b in Section 4.11: "Ecosystem Integration") along this coastline, the Guam Environmental Protection Agency has identified impaired or threatened waters. Despite these pressures, moderately high levels of coral cover were observed off the southern and southeastern shores of Guam. In 2005, COTS predation was greatest between Togcha and Talofofo Bays, where towed-diver surveys documented more than 100 individual COTS during a 5-min segment just south of Togcha Bay. During MARAMP 2003, no COTS were recorded in this area. In 2007, the highest level of stressed-coral cover was observed from Agfayan Bay to Pagat Point, and 91 individual COTS were recorded there, suggesting COTS predation was a factor in this area's elevated levels of stressed-coral cover. Total fish biomass from REA surveys conducted in this area was consistently low.

- The southwestern coast of Guam supported the lowest levels of live coral cover found around this island. These algal-dominated reefs had the highest macroalgal cover found south of Orote Peninsula. Similar to hydrology of the southeastern shore, many streams drain upland watersheds, transporting terrigenous sediments into the adjacent coastal waters. Despite low coral-cover values in Cetti Bay, coral diversity was relatively high around southwestern Guam. Values of stressed-coral cover and coral-disease prevalence were low in this area. Some of the lowest levels of total fish biomass and species richness around Guam were observed here.

- Estimates of live coral cover around Santa Rosa Reef, from towed-diver surveys, revealed stability between survey years, with mean values of 7% in 2003 and 8% in 2005. Elevated coral-cover values were consistently recorded towards the central coasts, rather than perimeter areas, of Santa Rosa Reef.

5 ROTA

5.1 Introduction

The island of Rota, called *Luta* in the Chamorro language, is the third largest of the 14 islands of the Commonwealth of the Northern Mariana Islands (CNMI) and the fourth largest in the Mariana Archipelago with an area of 85.13 km². This island is located 62 km north of Guam and 90 km south of Tinian at 14°11′ N, 145°15′ E. Rota reaches a height of 496 m on the prominent Sabana plateau on the southwest corner of this island (Fig. 5.1a). This peak is the highest point in the

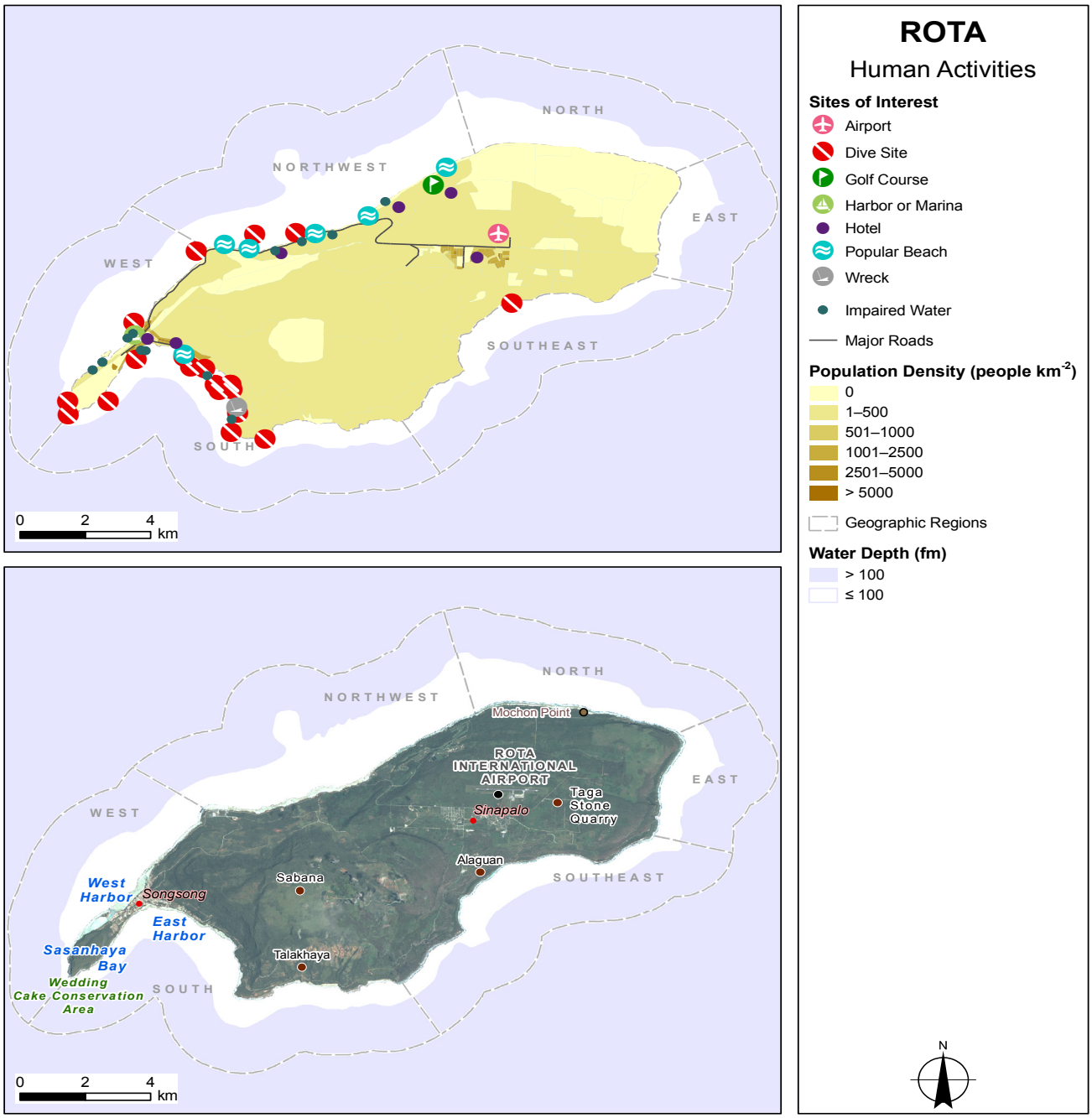


Figure 5.1a. Major locations of human activities (*top*) on Rota that have the potential to affect the marine environment (Bearden et al. 2008; Dive Rota; Marianas Visitors Authority 2002; Placenames.com; U.S. Geological Survey 2005b; U.S. Geological Survey) are represented over a population-density map (U.S. Bureau of the Census 2003, 2008) and (*bottom*) satellite imagery of Rota (includes material © 2005 DigitalGlobe Inc. All rights reserved), labeled with places of interest (U.S. Geological Survey).

southern Mariana Archipelago. The only rivers on Rota are located on the steep, southern flank of the Sabana plateau. On the western end of this island, a low-lying isthmus connects the main part of this island with a small terraced headland, which is called the Wedding Cake (Fig. 5.1b) because of its layered structure. Rota's coastline consists of narrow, fringing coral reefs and reef platforms with numerous patches of raised limestone benches and limestone cliffs that drop abruptly to sea. One of this island's most unique characteristics is the amount of remaining native limestone forest. Rota was not invaded during World War II (WWII), and, thus, vegetation was not destroyed as it was on Guam, Saipan, and Tinian.



Figure 5.1b. Wedding Cake is a flat-lying, uplifted carbonate structure on the southern shore of Rota. *NOAA photo*

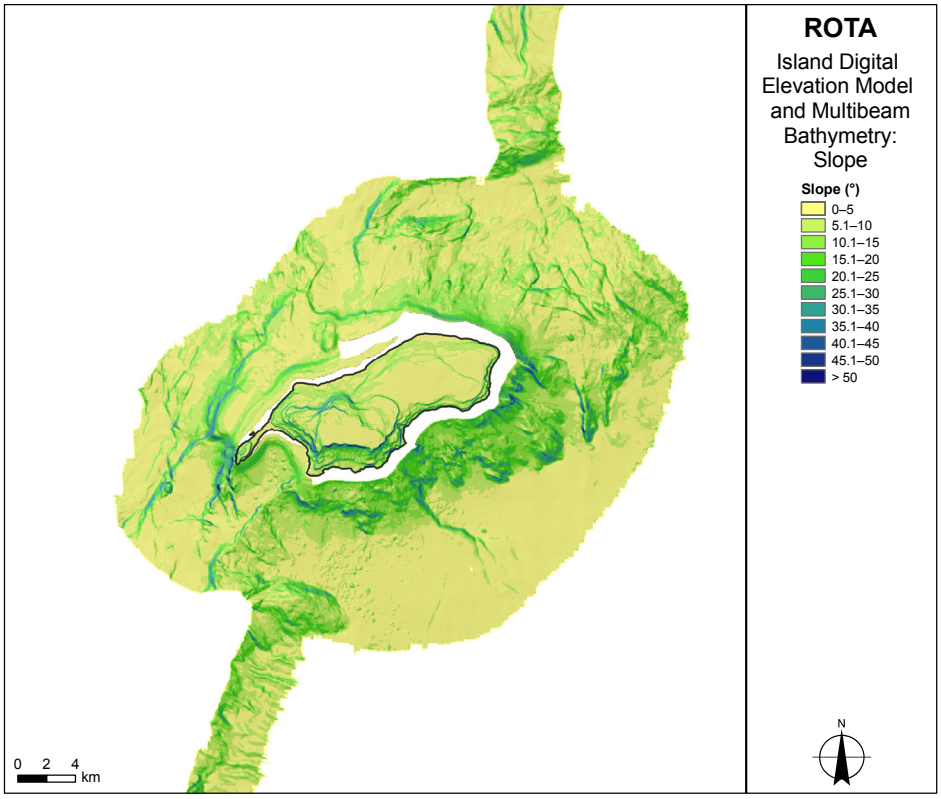


Figure 5.1c. Combined slope map using the digital elevation model and multibeam bathymetric data for Rota.

Rota is the smallest of the 3 southern, inhabited islands in the CNMI, both in size and population. This island's primary population centers are Songsong on the southwestern peninsula and Sinapalo, a village south of Rota International Airport on the eastern side of this island. Two harbors, West Harbor and East Harbor, lie on either side of this island's peninsula. One major hotel, the Rota Resort and Country Club, is located on the northwest side of Rota and has an 18-hole golf course near the shoreline. This resort also has one of the only large wetland areas on Rota; other smaller wetlands are scattered around this island. About 7 other small hotels or motels are located on Rota. The transition of land use from public to private ownership that has been occurring over several decades is expected to continue: in 2005, land that was flat or of low slopes (Fig. 5.1c) and most suitable to development made up 66% of Rota's land, and at least 75% of that land was or was expected to soon be privately owned (National Park Service [NPS] 2005). The remaining 34% of land on Rota consists of cliffs or steep slopes (Fig. 5.1c), areas that contain a majority of the remaining undisturbed native forests (NPS 2005).

5.1.1 History and Demographics

Rota was first populated when the Chamorro arrived about 3500 year ago and has been continuously inhabited since then. This island contains the best remaining examples of what is known as the Latte Phase (AD 1100–1521) of the cultural tradition of the Chamorro people of the Mariana Archipelago (Fig. 5.1.1a). The Latte Phase is named for the distinctive limestone architectural elements that began to appear throughout this archipelago ~ 800–1000 years ago. Rota has 2 well-preserved ancient Chamorro villages, 1 at Mochon Point on the north coast and 1 at Alaguan on the southeast coast. Other architectural elements include an intact latte stone quarry, the Taga Stone Quarry, near the eastern end of the airport and a cave along the east coast with pictographs showing ancient Chamorro rock art (NPS 2005). Fishing and agriculture were the foundations of the pre-historic Chamorro economy (Rogers 1995). Archeological evidence on Rota shows that some areas were terraced in ancient times for the cultivation of rice and taro (NPS 2005).



Figure 5.1.1a. The latte stone quarry at Taga on Rota. *Photo by Christopher T. Snow,* available under a Creative Commons license on Flickr (http://www.flickr.com/photos/ctsnow/95312116).

The islands of the Mariana Archipelago were claimed by Spain in 1565. An estimated 24,000 to 30,000 Chamorro remained on all islands of this archipelago in 1668, but by 1710 the Chamorro population plummeted to just over 3500 on Guam and Rota because of epidemics and conflicts with the Spanish (Rogers 1995). Because the indigenous Chamorro population of Rota dropped significantly during the 200 years of occupation by Spain, the native vegetation recovered, even on areas that had been completely cleared for subsistence agriculture.

Rota and Guam were the only islands of the Mariana Archipelago that were continuously populated during the period of rule by Spain from 1521 to 1899, because Spain relocated all Chamorro from the northern islands to these 2 islands. Like most of the other islands of the Mariana Archipelago, Rota was under rule by Germany from 1899 to 1914, when all of this archipelago's islands except Guam became a protectorate of Japan. In the 1920s and 1930s, the Japanese developed phosphate mining and sugar plantations on Rota. An estimated 60% of land on Rota was cleared of native forest for these sugar plantations, and later, during WWII, the Japanese built defensive fortifications and roads to all parts of this island (NPS 2005). The Allied Forces did not invade Rota during WWII; thus, some of the best-preserved Japanese fortifications in the Mariana Archipelago are found on Rota, which the Japanese surrendered to the United States on September 2, 1945. The social changes and economic developments that have taken place on and reshaped Guam, Saipan, and Tinian since the end of WWII have had comparatively little effect on Rota.

The human population on Rota in 2010 was 2527, a 23% drop from the estimate made in 2000 but nearly double the population estimate for 1980 (U.S. Bureau of the Census 1983, 2011a). Despite the decline between to the two most recent U.S. Census estimates, Rota in 2010 still made up ~ 5% of the total CNMI population, as it had in 2000 (Fig. 5.1.1b; U.S. Bureau of the Census 2011a). The overall decline in the CNMI's population is related partly to a fall in tourism (Fig. 5.1.1b) caused by a weak worldwide economy and the demise of the garment industry on Saipan.

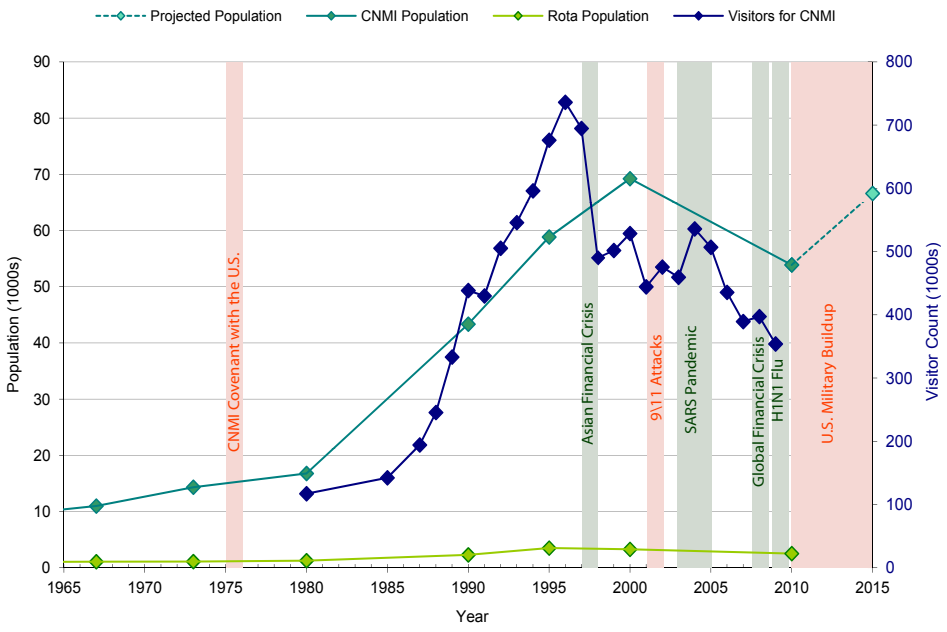


Figure 5.1.1b. Population growth (U.S. Census Bureau 2003, 2011a; CNMI Department of Commerce 2002a; Secretariat of the Pacific Community 2011) and visitor count (Bank of Hawaii 1995; Lucas et al. 1990; U.S. Department of the Interior 1996; CNMI Department of Commerce 2002b; Marianas Visitors Authority) trends on Rota and in the CNMI during the period of 1965–2015.

5.1.2 Geography

Like Saipan, Tinian, Aguijan and Guam, the island of Rota is composed of a series of coralline limestone terraces that rise one above the other. These limestone terraces lie on top of a volcanic core, which emerges from these terraces in only a few places on the southern side of this island on the Sabana plateau. No comprehensive geologic studies have been carried out on Rota, and no geologic map exists. However, Keel et al. (2005) studied the karst geomorphology of Rota and mapped 120 caves on this island.

The Sabana plateau is the center of Rota's primary watershed. There, the volcanic core is exposed for ~ 0.25 km² along the steep, dissected slopes of this island's south coast, where all of the surface streams on Rota are located. Water emerges at an elevation of ~ 335 m, and many contact caves are found where porous limestone meets the impermeable volcanic core (Keel et al. 2005).

5.1.3 Economy

Tourism is the principal economic industry on Rota, and the service sector accounts for ~ 50% of employment on this island (Fig. 5.1.3a). Visitors to Rota currently make up only about 2% of the total visitors to the CNMI (CNMI Department of Commerce 2002b). However, business leaders consider tourism the most promising industry for the future, and, in October 2009, the governor's office announced that an investor is planning a new casino complex and water bottling plant there (CNMI Office of the Governor 2009). Many small-scale subsistence farms operate throughout Rota. Some large-scale farms and ranches exist, especially on the eastern part of this island. However, limestone soils on Rota are not well suited for either agriculture or grazing (NPS 2005). Community farms are present on the highest plateau of the Sabana watershed, but most of the farming in this area has been discontinued in recent years because of concerns about adverse impacts to the domestic water supply (NPS 2005). In 2008, a shrimp farm was established on Rota, the second site in the nascent aquaculture industry in the CNMI.

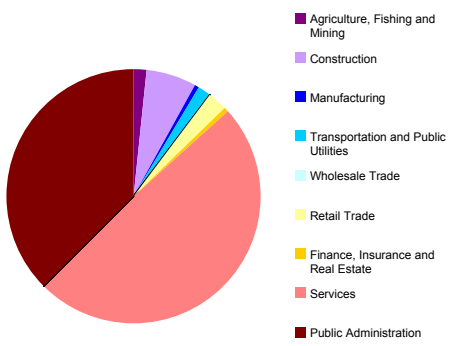


Figure 5.1.3a. Employment by sector on Rota in 2005 (CNMI Department of Commerce 2008). The services category includes professional services, education, health and social services, arts and entertainment, and recreation.

The 1996 Rota Economic Master Plan emphasized the importance of some of Rota's environmental and cultural attributes, not only to the people of Rota but also to the entire CNMI, and of conserving these attributes. This plan pointed out that tourism would benefit from the conservation of parts of the environment on Rota. Recent studies have found that Rota's natural and cultural values would be ideally suited for the development of ecotourism. (NPS 2005)

The CNMI Comprehensive Economic Development Strategic Plan for 2009–2014 (Comprehensive Economic Development Strategy [CEDS] Commission 2009) noted that one of the challenges for the CNMI government is the provision of infrastructure for power, water, sewage, and other public services on 3 major islands, of which Rota is the smallest and least economically developed. In addition, a weak global economy, rising fuel prices, and falling tourism rates have resulted in a 40% decrease in revenue in the CNMI from $248 million in 2006 to a projected $154 million in 2009. This plan proposes a number of projects to improve the Rota economy, including those listed below that may have potential impacts on the coral reef ecosystems:

- Rehabilitation of West Harbor
- Construction of a fuel farm at Rota International Airport
- Widening of the airport runway
- Relocation of the sanitary landfill
- Construction of a sewage treatment plan
- Significant enlargement of Rota's West Harbor to make this island's agricultural industry competitive (local farmers on Rota have developed a number of root and other crops that are available for export, but equipment and transportation infrastructure is lacking)
- Enhancement of tourism facilities, including opening up and preserving additional ancient Chamorro sites through a grant and building up beach and water sport parks through private partnerships
- Construction of a casino

5.1.4 Environmental Issues on Rota

Native limestone forest now covers well over half of this island (Fig. 5.1.4a). A 1976 survey by the U.S. Forest Service identified 12,147 acres of native limestone forest on Rota but only 1714 and 1182 acres on the larger islands of Tinian and Saipan (NPS 2005). The lower limestone terraces on the southeastern side of the Sabana plateau contain native forest in good condition with some extremely rare trees. Mid-elevation limestone terraces also contain native forest in good condition, and, on the upper limestone terraces, forest changes to a wetter, luxuriant type of vegetation with a full canopy. A considerable area on the southwestern summit of the Sabana plateau is pitted and pinnacled, a result of phosphate mining during the period of Japanese rule (NPS 2005).

Wildfires intentionally set by hunters have damaged the Talakhaya Watershed (Fig 5.1.4a) for decades. Hunters set fires because they want to attract the Sambar deer (*Cervus unicolor*) by creating new vegetation growth. These fires eliminate

established vegetation and devastate habitat, causing considerable soil erosion and slumping, especially during the rainy season of July to September, leading to significant sedimentation in adjacent marine environments and freshwater streams. Since 2006, Rota schools have participated in revegetation efforts in the Talakhaya area (Saipan Tribune 2007).

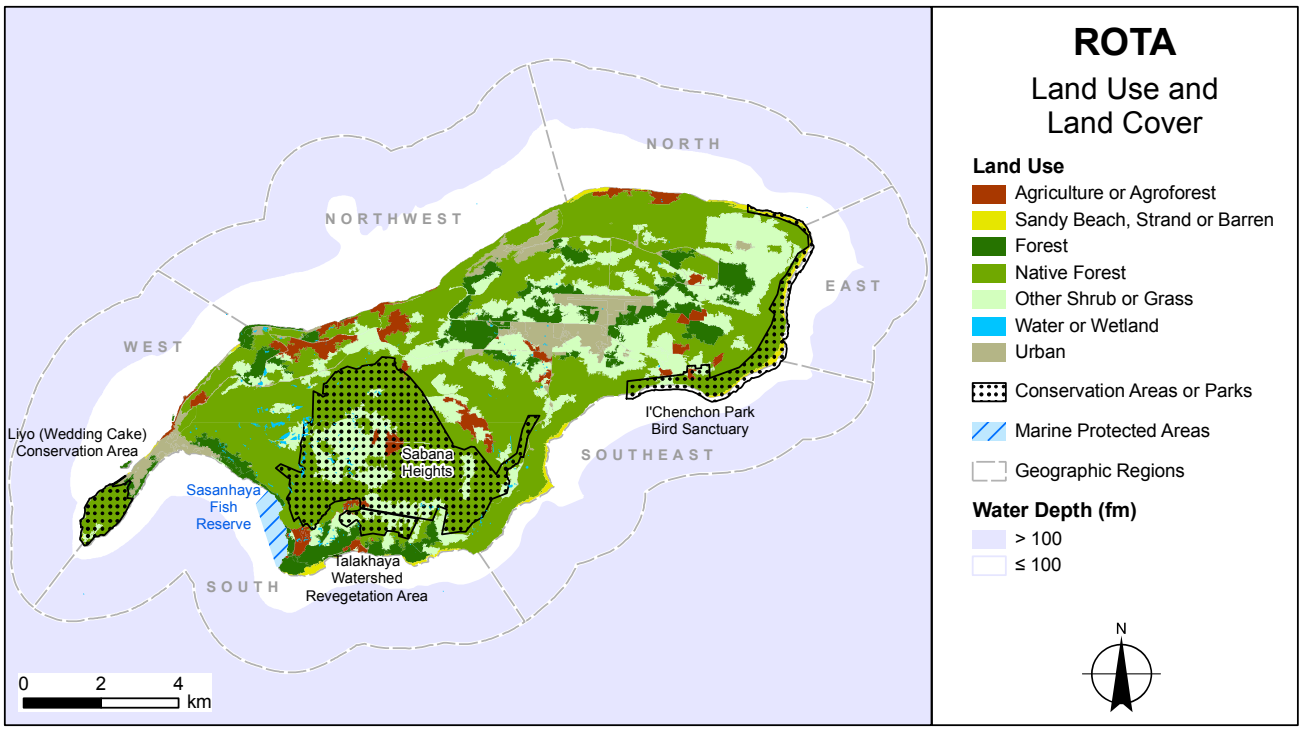


Figure 5.1.4a. Land use, conservation areas, parks, and marine protected areas (MPAs) on Rota are represented over a vegetation cover map (Liu and Fisher 2006).

Rota has 2 tree species and 1 herbaceous species that are Federally listed as endangered (U.S. Fish and Wildlife Service), and few specimens of any of these 3 species remain. Three introduced ungulates, Philippine deer (*Rusa Marianna*), feral pig, and domestic cattle are thought to play a role in the destruction of these tree species. Three bird species, the Mariana crow (*Corvus kubaryi*), Rota bridled white-eye (*Zosterops rotensis*), and Mariana common moorhen (*Gallinula chloropus guami*), are Federally listed as endangered, and the Mariana fruit bat (*Pteropus mariannus mariannus*) is listed as threatened (U.S. Fish and Wildlife Service). All 4 of these species are listed locally as threatened or endangered (Berger et al. 2005). Analysis conducted by the CNMI Division of Fish and Wildlife (DFW) has shown that most other bird populations on Rota also have declined substantially over the past few decades (NPS 2005). One issue is introduction of the brown tree snake (*Boiga irregularis*) from Guam, which is only 62 km south of Rota, and the potential threat it posed to all birds on this island (Fritts and Leasman-Tanner 2001; Marianas Avifauna Conservation Working Group 2008). The CNMI DFW sponsors extensive efforts to minimize the risk of brown tree snake introduction.

Both the green sea turtle (*Chelonia mydas*) and hawksbill sea turtle (*Eretmochelys imbricata*) are Federally listed as endangered in the Mariana Archipelago and locally listed as threatened or endangered (U.S. Fish and Wildlife Service; Berger et al. 2005). Few green turtles and no hawskbills have been documented as nesting on Rota in recent years. Rota is an important habitat for several species of sea birds, including the red-footed booby (*Sula sula*), brown booby (*Sula leucogaster*), white (fairy) tern (*Gygis alba*), great frigatebird (*Fregata minor*), brown noddy (*Anous stolidus*), and white-tailed tropic bird (*Phaethon lepturus*).

Major portions of public lands on Rota and their natural resources are currently protected under CNMI and local laws, including Rota Local Law Nos. 9-1, 9-2, 9-3, and 15-8, as watersheds, sea bird sanctuaries, or conservation areas for forests and wildlife (Fig. 5.1.4a; NPS 2005):

- I`Chenchon Park Bird Sanctuary on this island's eastern coastline is the largest sea bird nesting colony in the Mariana Archipelago.

- Sasanhaya Fish Reserve, a no-take zone on the southern shore of Rota, was the first marine protected area (MPA) designated in the CNMI.

- Coral Gardens Marine Reserve is a biological reserve at the eastern end of Sasanhaya Bay that extends out to a depth of ~ 30 m.
- Sabana Protected Area, which covers a high plateau area (Sabana Heights) in the southwestern portion of this island, was established to provide watershed protection and wildlife and forest conservation as well as allow for community farming, hunting, and medicinal plant gathering.
- Talakhaya Watershed Revegetation Area contains Rota's only flowing waters and serves as the major source for this island's public water supply.
- Liyo (Wedding Cake) Conservation Area at the western tip of this island is a wildlife protection area where no take is allowed of plant or animal species.
- Small cultural sites, such as Mochon prehistoric village and Taga Stone Quarry, are managed by the Historic Preservation Office.

Several specific environmental issues have been identified on Rota, including the ones listed here:

- Non-point pollution from soil erosion on the south side of the Sabana plateau in the Talakhaya region, which was stripped as part of phosphate mining by the Japanese and is subject to fires set by hunters. Coral reefs along this coastline show signs of decreasing health caused by significant soil and debris deposition originating from that upland erosion (NPS 2005).
- There has been little enforcement at the Sasanhaya Fish Reserve. Unpublished research from the CNMI's DFW suggests that fisheries recovery rates at this reserve are lower than at other MPAs where no-take rules have been more consistently enforced (Starmer et al. 2008).
- The current refuse disposal site on Rota is an open-air dump, and no heavy equipment is available at the landfill to properly maintain, reposition, and operate this existing landfill. An alternative site has not been finalized, but this "dump must be closed" (CEDS Commission 2009).
- Rota's primary sources of drinking water as of 1995 were exceeding standards set by the federal *Safe Drinking Water Act* (CEDS Commission 2009).
- Upgrades to Rota's sewer system are needed. This variable-grade sewer system serves only a portion of the Songsong village. Gravity and septic sewers serve the remainder of Songsong and other villages (CEDS Commission 2009).
- Upgrades to roads around this island are needed to reduce sediment runoff and improve transportation. Currently, only 19.3 of the 140 km of road on Rota are paved, and 48.3 km are classified as "improved" (CEDS Commission 2009).
- Rota storm drainage improvements could be included as part of the design and construction of roads to incorporate ground absorption infiltrators and retention ponds. The current system uses a combination of gutters, ditches, and cross-gutters. Paving village streets is part of a proposed solution for drainage (CEDS Commission 2009).

5.2 Survey Effort

Biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing coral reef ecosystems around the island of Rota since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 6 geographic regions around Rota are delineated in Figure 5.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Rota. Potential reef habitat around this island is delineated by the 100-fm contour and shown in white on this map.

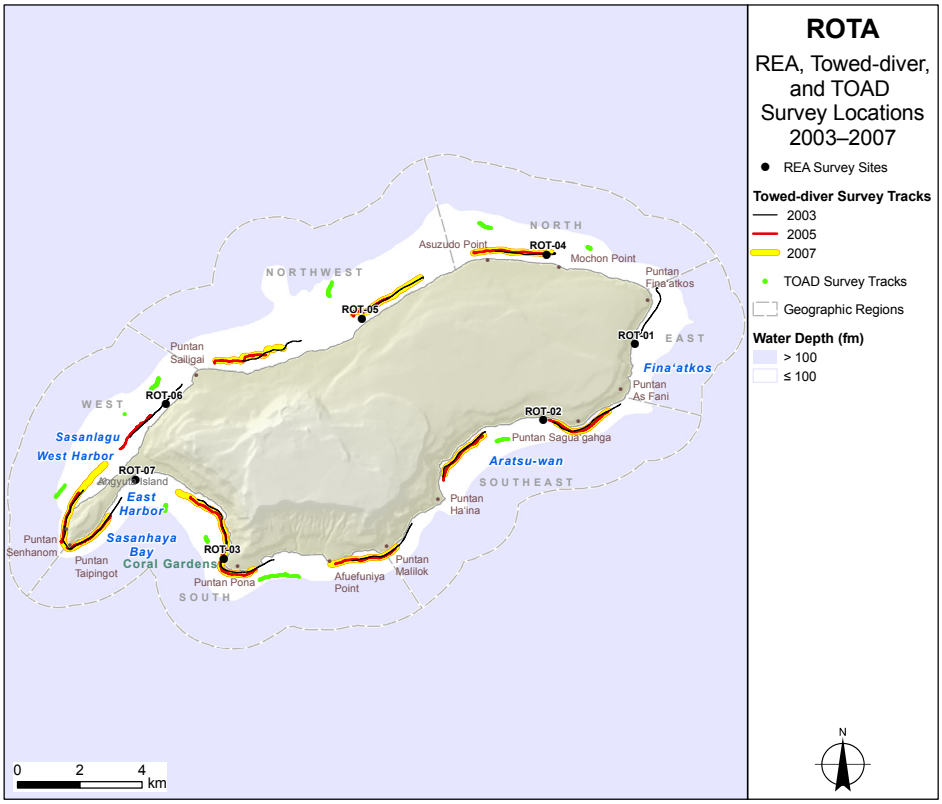


Figure 5.2a. Locations of REA, towed-diver, and TOAD benthic surveys conducted around Rota during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 6 geographic regions: north, east, southeast, south, west, and northwest.

Benthic habitat mapping data were collected around Rota using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around this island with multibeam sonar covered a total area of 5.1 km^2 in 2003 and 800 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented cover of live hard corals, sand cover, and habitat complexity. The results of these efforts are discussed in Section 5.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Rota was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 5.5–5.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 5.2a, along with their mean depths and total

Table 5.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Rota during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	6	6	6
	Mean Depth (m)	12.4 (SD 0.6)	11.7 (SD 2.1)	11.7 (SD 2.1)
Benthic	Number of Surveys	6	6	6
	Mean Depth (m)	12.4 (SD 0.6)	11.7 (SD 2.1)	11.7 (SD 2.1)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	12	11	10
	Total Survey Area (ha)	26.3	21.4	23.2
	Mean Depth (m)	12.6 (SD 1.6)	16.1 (SD 1.2)	15.9 (SD 1.2)
TOAD		**2003**		
	Number of Surveys	10		
	Total Length (km)	4.13		

areas or length. For surveys of reef fishes, belt-transect surveys were conducted at 5 REA sites and stationary-point-count surveys were done at 1 additional site (only belt-transect data are provided in this report).

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Rota were collected using (1) two types of moored instruments designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007. Results for some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 5.2b, and results are discussed in Section: 5.4: "Oceanography and Water Quality."

Table 5.2b. Numbers of oceanographic instruments deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Rota during MARAMP 2003, 2005, and 2007. Two types of instruments were moored at Rota: sea-surface temperature (SST) buoy and subsurace temperature recorder (STR). Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Additional deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
SST	1	–	1	1	1	–	2
STR	–	–	2	2	3	1	1
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	21	28		29			78
Deepwater Casts	–	4		3			7
Water Samples		**2005**		**2007**			**Total**
		4		5			9

Towed-diver Surveys: Depths

Figures 5.2b–e illustrate the locations and depths of towed-diver-survey tracks around Rota and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

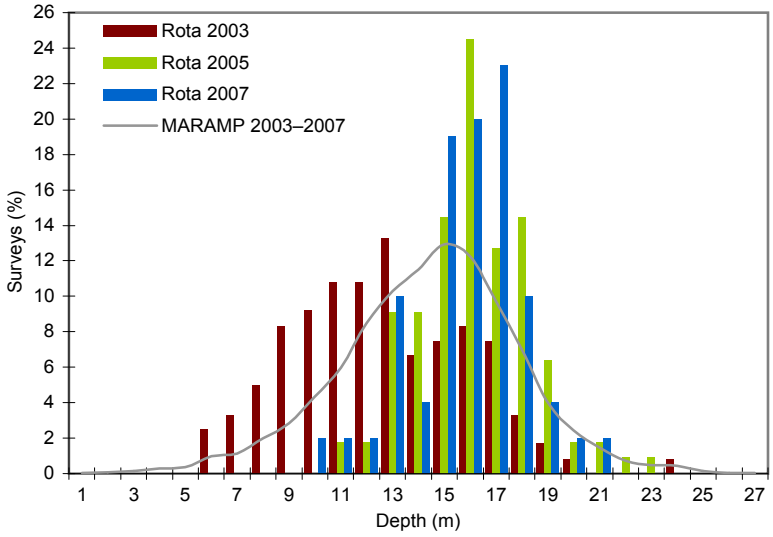
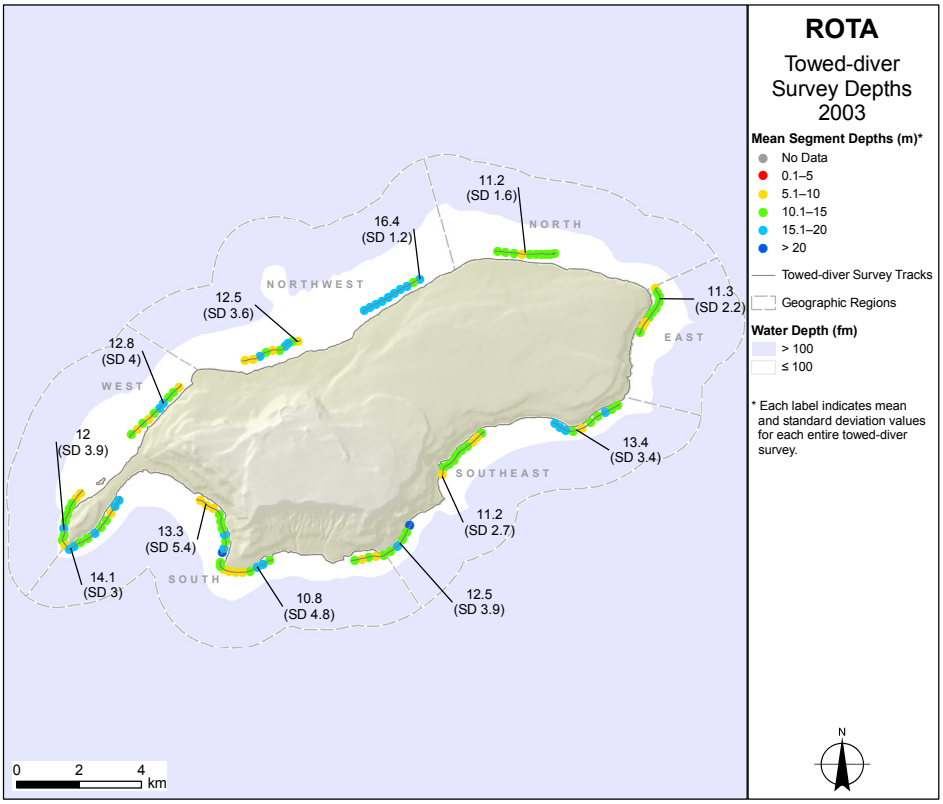


Figure 5.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Rota during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

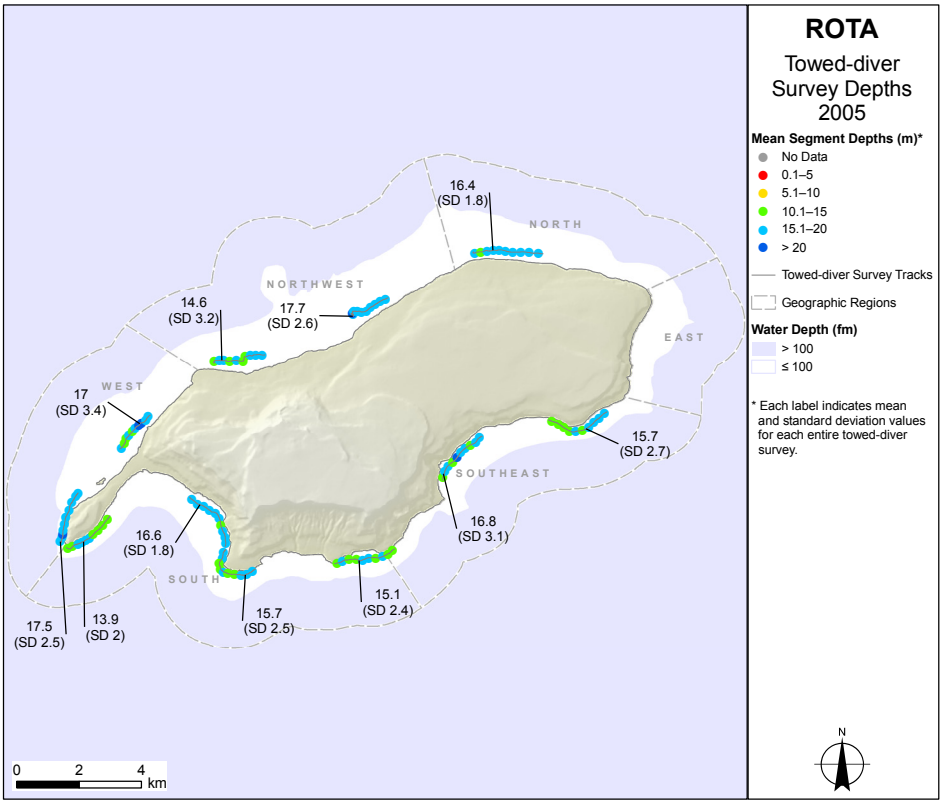
During MARAMP 2003, 12 towed-diver surveys were conducted along the forereef slopes around most of Rota (Figs. 5.2b and c). The mean depth of all survey segments was 12.6 m (SD 1.6), and the mean depths of individual surveys ranged from 10.8 m (SD 4.8) to 16.4 m (SD 1.2).

Figure 5.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Rota during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.



During MARAMP 2005, 11 towed-diver surveys were conducted along the forereef slopes in most geographic regions of Rota (Figs. 5.2b and d). The mean depth of all survey segments was 16.1 m (SD 1.2), and the mean depths of individual surveys ranged from 13.9 m (SD 2) to 17.7 m (SD 2.6).

Figure 5.2d. Depths and tracks of towed-diver surveys conducted on forereef habitats around Rota during MARAMP 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.



During MARAMP 2007, 10 towed-diver surveys were conducted along the forereef slopes around most geographic regions of Rota (Figs. 5.2b and e). The mean depth of all survey segments was 15.9 m (SD 1.2), and the mean depths of individual surveys ranged from 13.5 m (SD 2.9) to 17.5 m (SD 4.1).

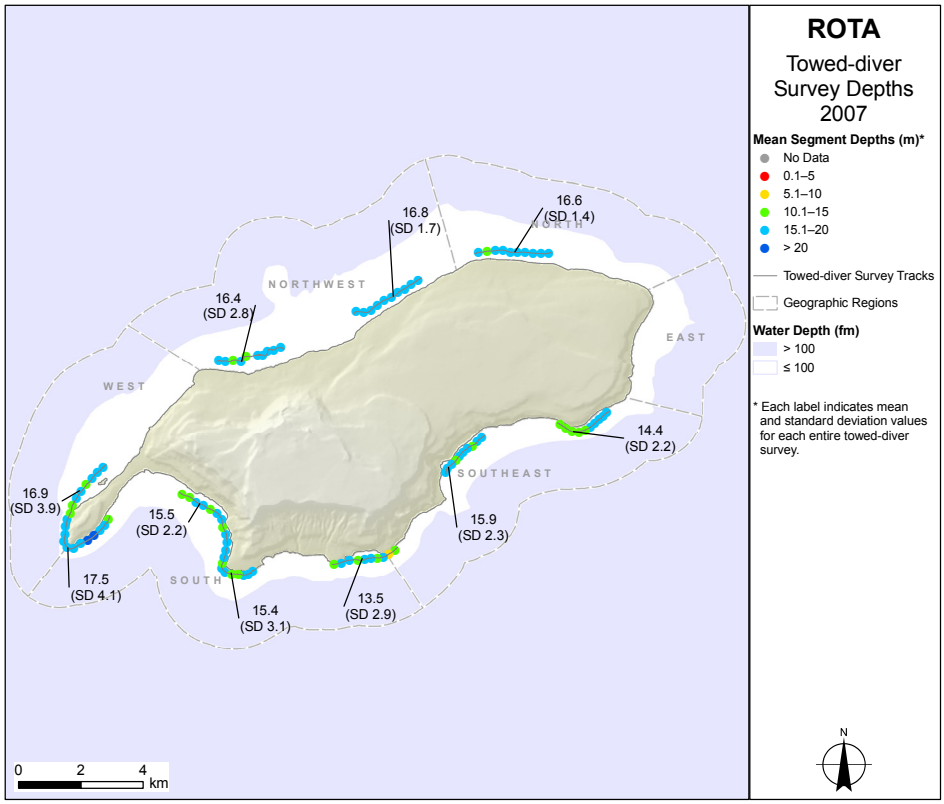


Figure 5.2e. Depths and tracks of towed-diver surveys conducted on forereef habitats around Rota during MARAMP 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

5.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Rota during MARAMP 2003, 2005, and 2007 were conducted using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of 1–1800 m. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed at depths < 188 m.

5.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 5.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around Rota during MARAMP 2003 and 2007 encompassed an area of 805.1 km^2. Because of a lack of time, acquisition of high-resolution multibeam data was limited in extent, covering only parts of the northwest, west, and south geographic regions. Multibeam data of lower resolution were obtained with the 30-kHz Kongsberg EM 300 sonar on the NOAA Ship *Hi`ialakai*, providing complete coverage to a depth of 1275 m west of Rota and a depth of 1800 m to the east.

Multibeam bathymetry acquired around Rota reveals a fairly irregular topography, with many scarps, ridges, and canyons (Fig. 5.3.1a, top panel). North of Rota a series of ridges are observed radiating away from this island, with narrow canyons formed between them. Scarps and fissures at depths of 800–1400 m run at various orientations, with 2 longer, more prominent scarps running southwest–northeast, and another 2 running southeast–northwest.

Southwest of Rota, three scarps run on a northeast–southwest orientation. On the more gentle slopes on the back of the scarps, the bathymetry shows fissures cutting into otherwise smooth slopes. The seabed south of Rota is littered with large blocks of material that probably result from mass-wasting (movement of soil and surface materials by gravity).

The seabed east of Rota descends much more steeply from the coast in comparison to north, west and south of this island, with the depth of 1000 m reached within 2.5–4 km of the coast. Here, narrow ridges descend to 1500 m, forming wide, curved canyons. Below this area, the seabed descends more gradually.

Backscatter data collected around Rota show clear patterns, with marked areas of higher and lower backscatter intensity (Fig. 5.3.1a, bottom panel). Some of the broader patterns can be clearly related to features in the topography; however, some of the finer-scaled patterns are more difficult to interpret. A wide swath of low-intensity backscatter is shown north of Rota, indicating a large area of soft sediments. East of this low-intensity swath, an area of seabed marked with fissures

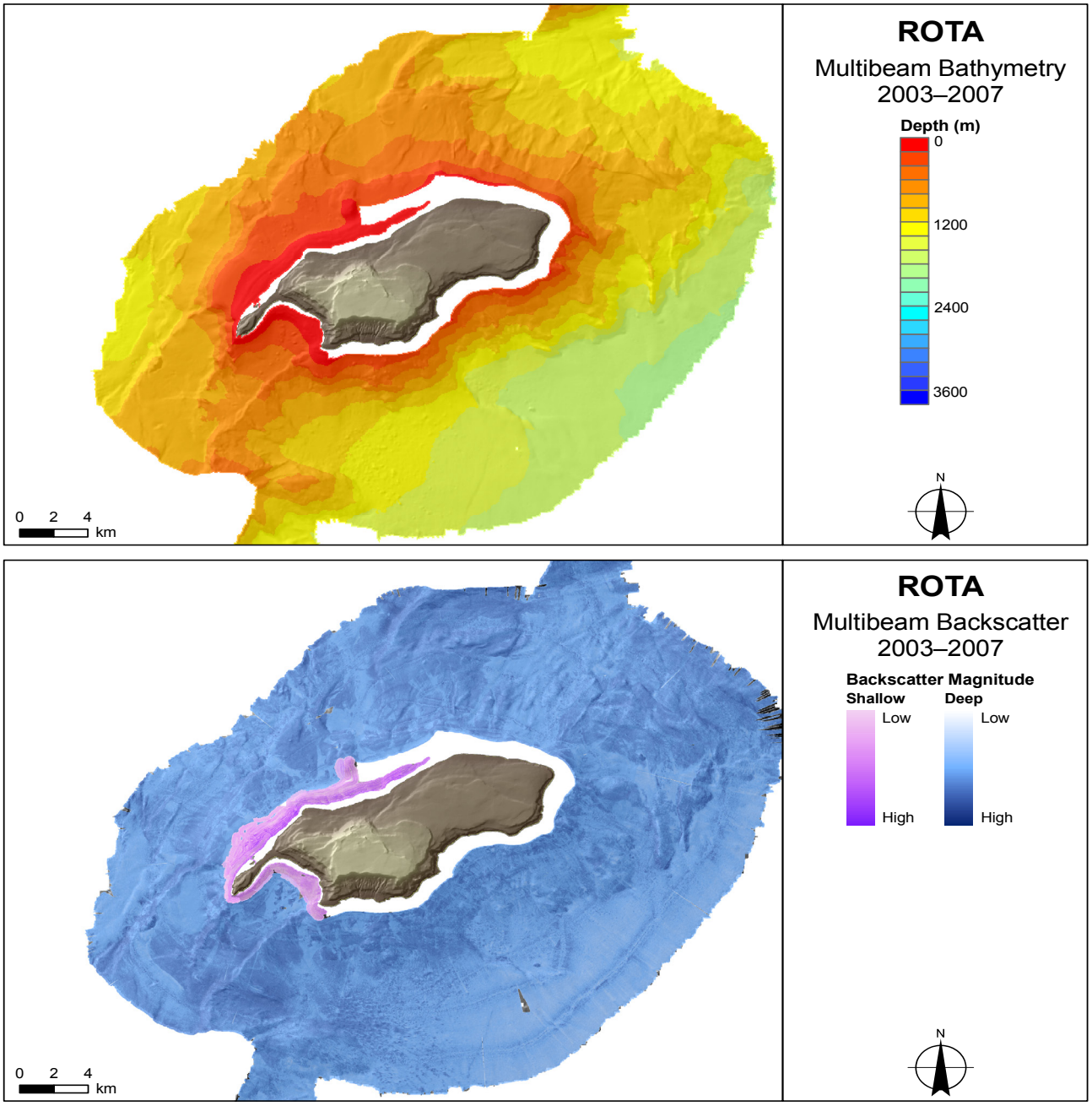


Figure 5.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Rota during MARAMP 2003 and 2007 at depths of 1–1800 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

and scarps is revealed to have higher-intensity backscatter, suggesting that within this area, the seabed is characterized by harder substrates. North of Rota, a flat-bottomed channel is likely to be characterized by soft sediments, as suggested by the low backscatter values recorded there. One of the scarps running southwest of Rota has a clear band of high-intensity backscatter, which runs along the scarp edge, suggesting that this area may have hard substrates at or near the seabed surface, in comparison to the more gentle slopes on the back of the scarps, where lower backscatter values were recorded. Variations in backscatter intensity observed south of Rota are less distinct, and despite the clear topographic features observed in the bathymetry in this area, it is not possible to clearly relate these features to changes in backscatter.

Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in nearshore (depths of 0–800 m) waters around Rota (Fig. 5.3.1b) were gridded at a 5-m resolution to allow for the identification of fine-scaled features. These high-resolution data have also been used to derive maps showing slope (Fig. 5.3.1c), rugosity (Fig. 5.3.1d), and bathymetric position index (BPI) zones (Fig. 5.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Rota.

Because of the limited time available to survey Rota, the coverage of high-resolution bathymetry data focused on the west and south of this island. To provide a more complete picture of the seabed character around Rota, the low-resolution (60-m grid) multibeam data also have been used to derive maps showing slope (Fig 5.3.1f), rugosity (Fig. 5.3.1g), and BPI zones (Fig. 5.3.1h).

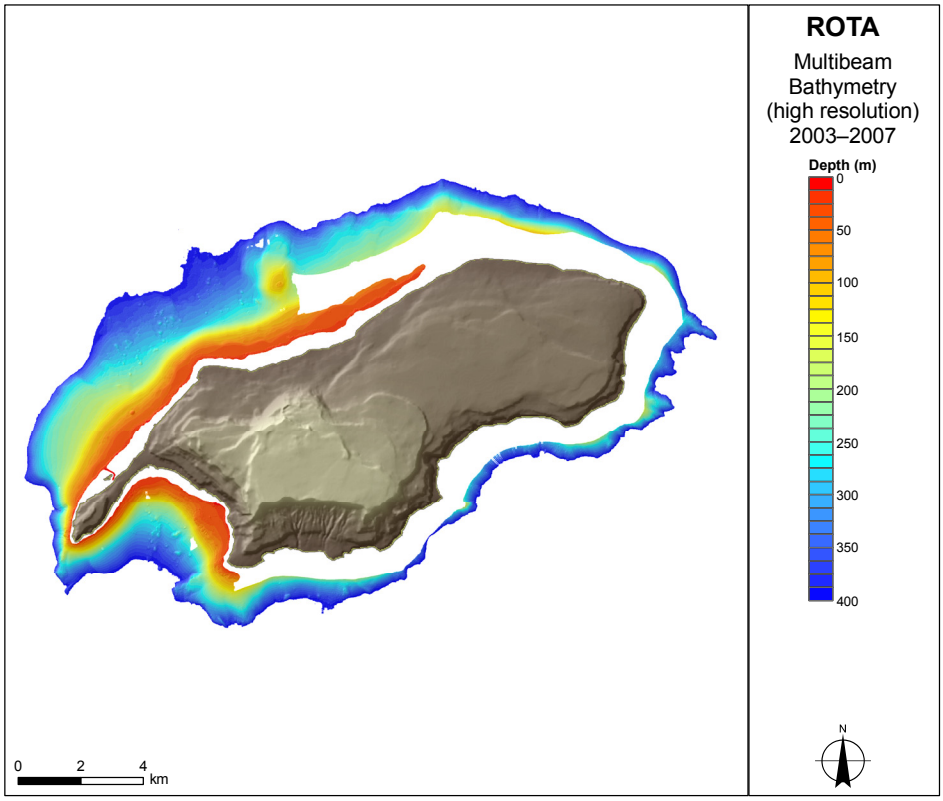


Figure 5.3.1b. High-resolution multibeam bathymetry collected around Rota during MARAMP 2003 and 2007. This 5-m bathymetry grid, clipped at 400 m, is used as the basis for slope, rugosity, and BPI derivatives.

The shallowest waters mapped around Rota are characterized by a narrow series of terraces that are likely related to previous sea-levels. The edges of these terraces are most clearly shown in the slope map (Fig. 5.3.1c), which highlights the flat terraces and the steeper slopes of 15°–30° that separate them. Northwest and west of Rota, these terraces are fairly narrow, ~ 600 m at the widest point, and continue to a depth of 100–110 m. Below this series of terraces, a zone of sloping seabed delineated by the BPI analysis (Fig. 5.3.1e) continues to a depth of 200–300 m, which is characterized by slopes < 25°. The seabed below a depth of ~ 300 m is characterized by very low slopes, with the BPI analysis characterizing the area as being composed of a mixture of crests, slopes and flat zones. Large blocks of material, probably resulting from mass wasting, are scattered across the seabed as revealed by all four of the high-resolution bathymetry and derivative maps. Other than around the slopes of these blocks of material, rugosity values across the terraces and on the slopes were generally low.

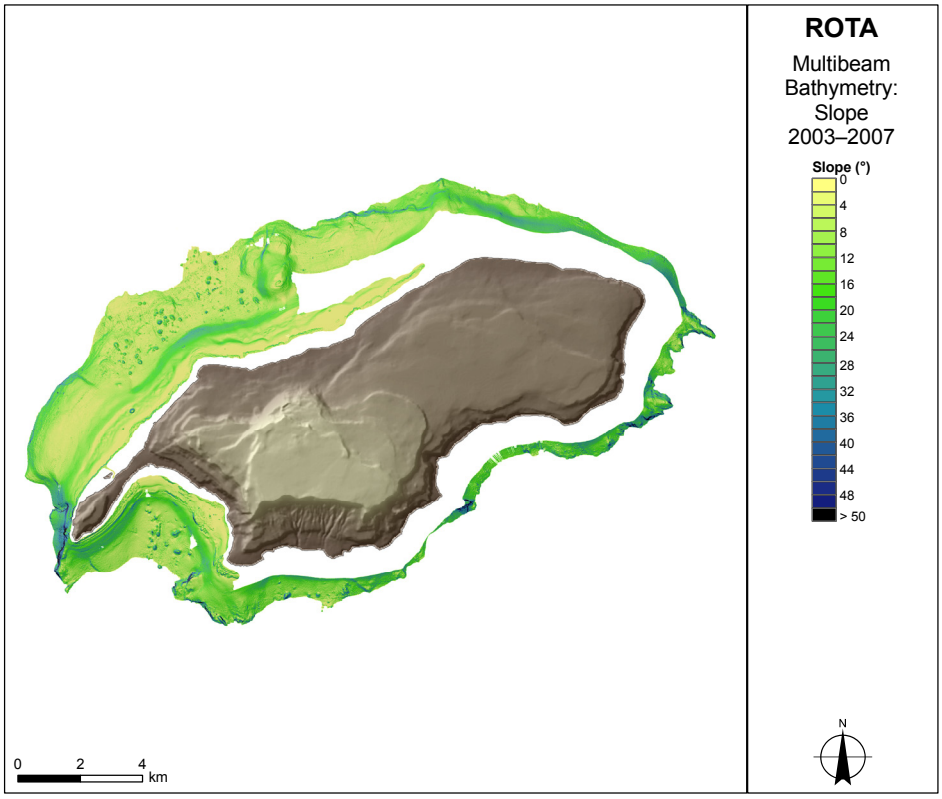


Figure 5.3.1c. Slope (°) of 5-m bathymetric grid around Rota. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades.

In the northwest region, the high-resolution multibeam and slope maps reveal a pinnacle that rises from a depth of ~ 300 m to a depth of 90 m. As with other areas mapped around Rota, the moderately sloping flanks of this pinnacle were characterized by fairly low rugosity levels (Fig. 5.3.1d).

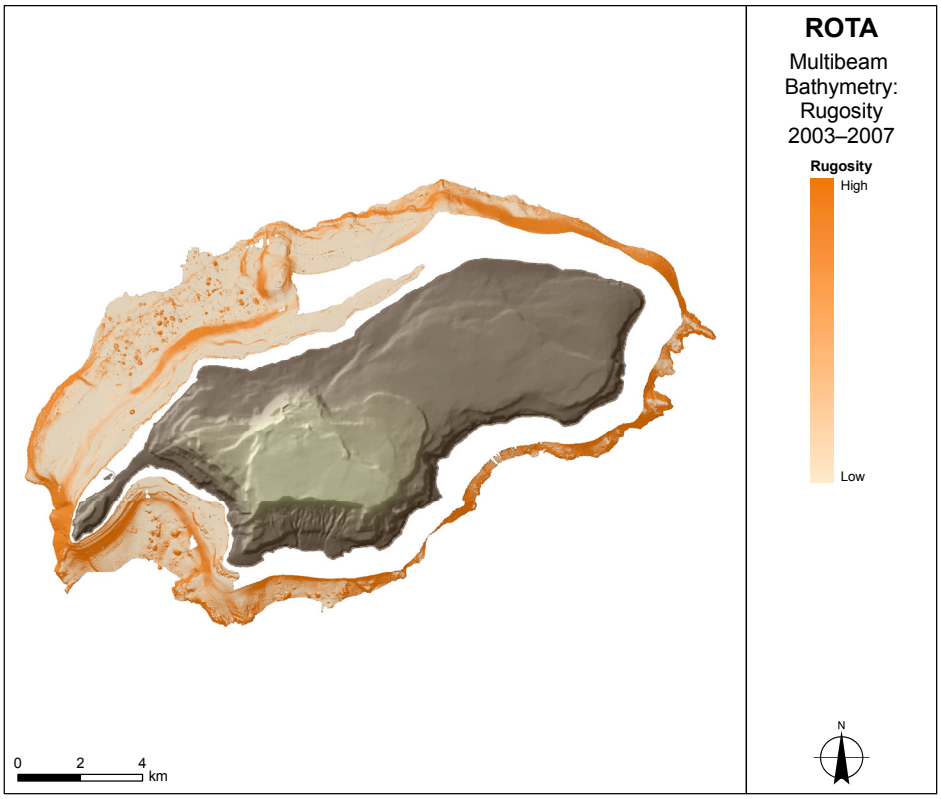


Figure 5.3.1d. Rugosity of 5-m bathymetric grid around Rota. Derived from data collected between 2003 and 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

South of Rota, within Sasanhaya Bay (for place-names and their locations, see Figure 5.2a in Section 5.2: "Survey Effort"), the slope map (Fig. 5.3.1c) highlights the irregular edges of terraced shelves, which are present down to depths of 50–80 m. The slope map also reveals numerous mounds, which may be related to the presence of coral habitats. Below the shelves, the seabed is moderately sloping (< 30°), although the low-rugosity, smooth slopes are punctuated by large blocks of material, often indicative of mass wasting. Southwest of Puntan Pona, the high-resolution data reveal a broad ridge that is a submarine continuation of the coastal feature. The high-resolution multibeam bathymetry and slope map (Figs. 5.3.1b and c) reveal a fairly complex topography with lumpy, closely terraced shelves present down to a depth of ~ 70 m and then another steeply sided ridge below this depth.

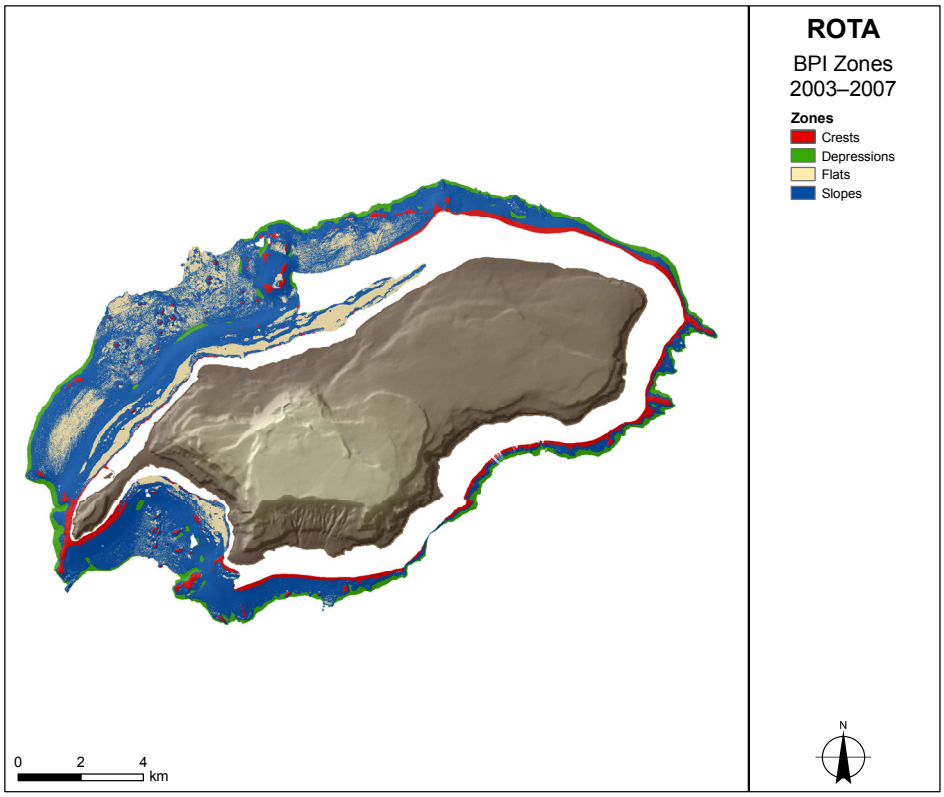


Figure 5.3.1e. BPI zones of 5-m bathymetric grid around Rota derived from data collected between 2003 and 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

The slope map derived from the low-resolution multibeam bathymetry highlights the markedly different seabed character northwest of Rota versus southeast. North and west of Rota, high slopes of up to 50° were revealed along the edges of the linear scarps (Fig. 5.3.1f) described from the bathymetry data earlier in this section. Aside from these scarp edges, the seabed is relatively flat, with slopes generally < 10°, and characterized by low rugosity (Fig. 5.3.1g). This abundance of flat areas is highlighted in the BPI analysis (Fig. 5.3.1h). In contrast, southeast of Rota, the BPI terrain analysis reveals a distinct region dominated by slopes, crests and depressions with no flat areas. This region is narrowest south of Rota, where it extends to a depth of ~ 1000 m, and widest east of this island where the zone of slopes, crests and depressions continues to ~ 1600 m. Below this region, the seabed was characterized almost entirely as a flat zone, with very low rugosity and slopes recorded.

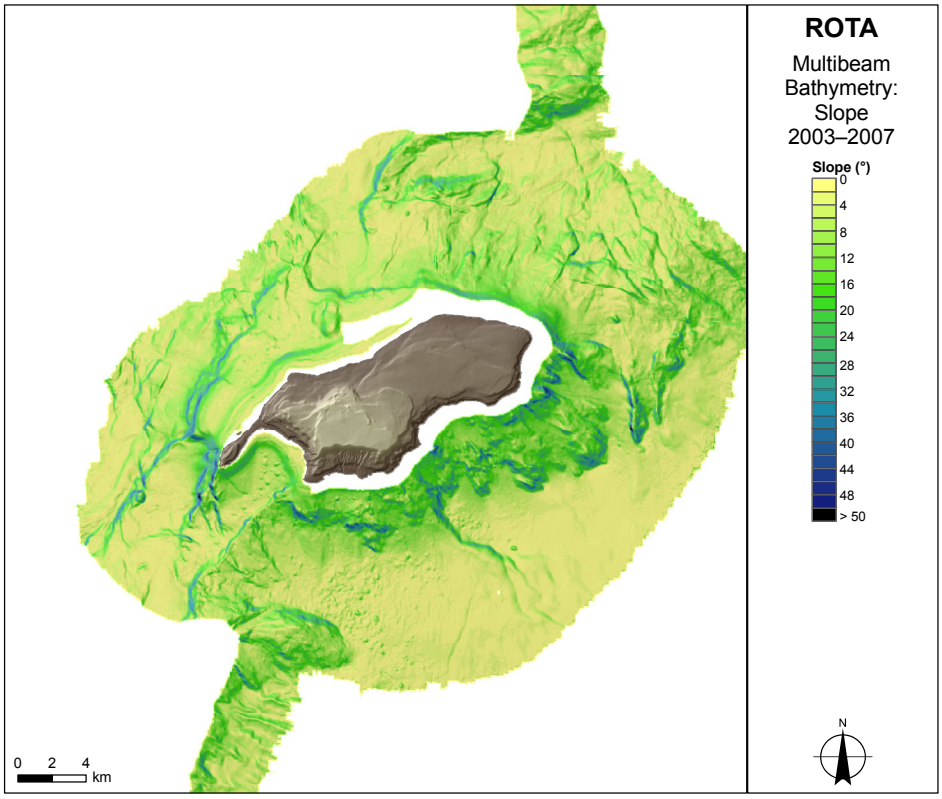


Figure 5.3.1f. Slope (°) of 60-m bathymetric grid around Rota. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades.

In the shallowest waters surveyed, the BPI analysis identifies reef crests (Fig, 5.3.1h). However, this classification is likely an artifact of the methodology, since no data are available for immediately inshore areas and no comparison can be made to the innermost cells of the grid. Instead, these areas probably should be characterized as slopes.

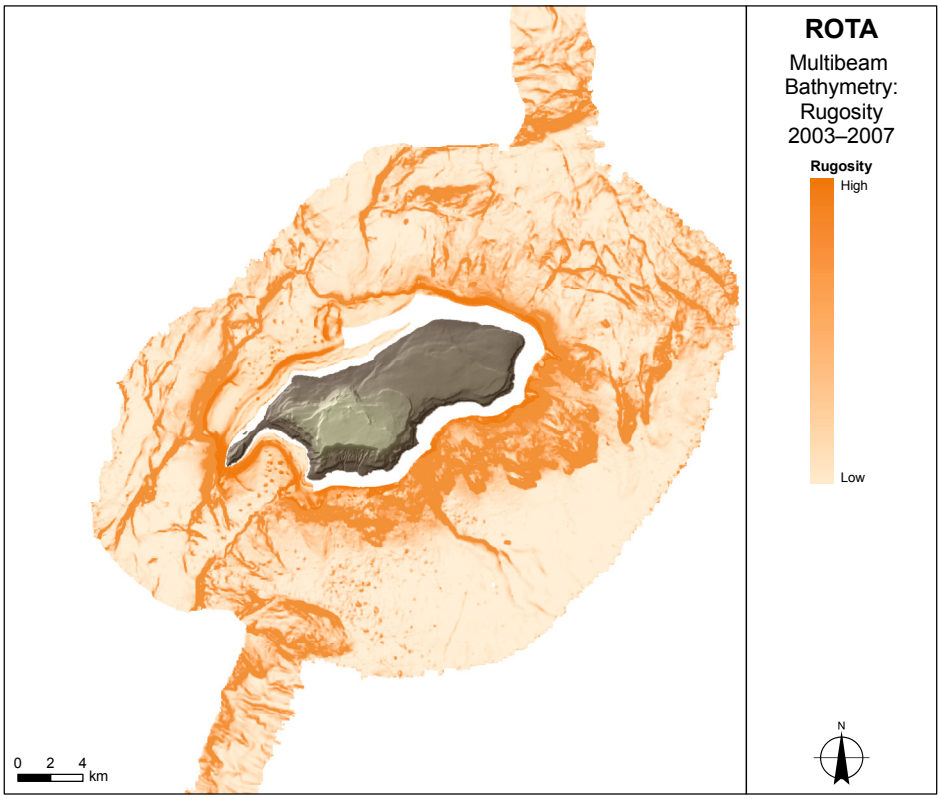


Figure 5.3.1g. Rugosity of 60-m bathymetric grid around Rota. Derived from data collected between 2003 and 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

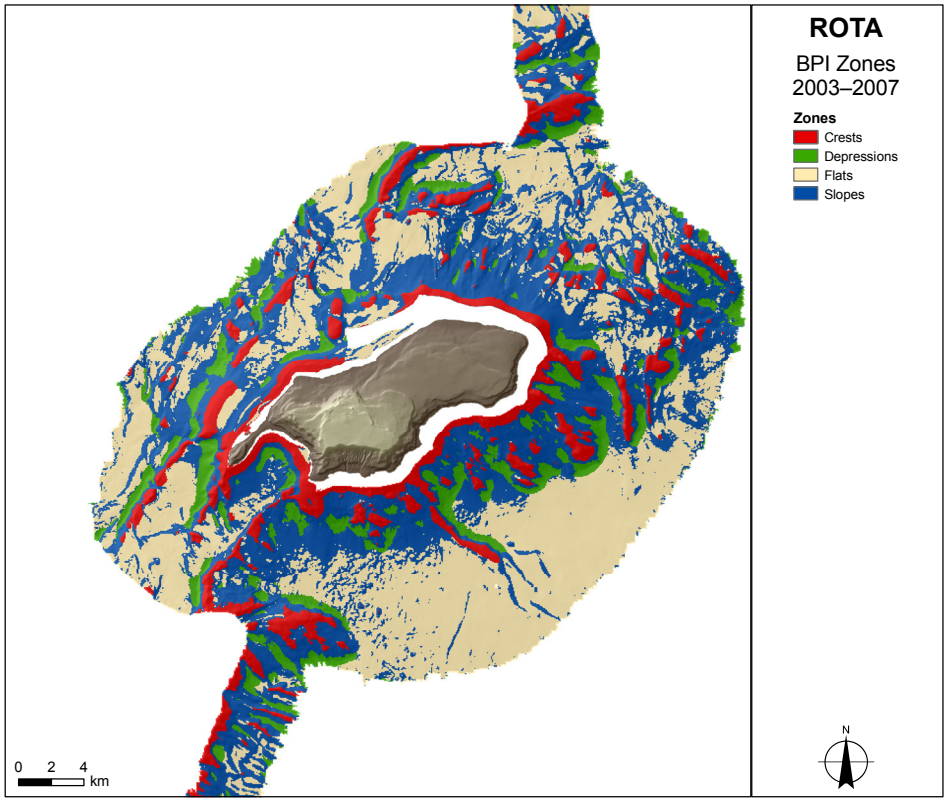


Figure 5.3.1h. BPI zones of 60-m bathymetric grid around Rota derived from data collected between 2003 and 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

High-resolution Multibeam Backscatter and Derivatives

High-resolution backscatter data were acquired around the western half of Rota using a 240-kHz Reson SeaBat 8101 ER sonar. Because of the limited extent of these data, substrate analysis was not carried out; therefore, no hard–soft substrate map is presented here.

The limited coverage of the shallow backscatter data acquired around Rota makes interpretation somewhat complex. This complexity is further exacerbated by some artifacts present in the data, such as the distinct line at the ship's nadir; in particular west of Rota where crisscrossing tracks make it impossible to see any clear patterns in the backscatter intensity. The area of greatest coverage is south of Rota, within Sasanhaya Bay, and here it is possible to draw some conclusions about the distribution of backscatter values. High-intensity backscatter was recorded along the shelf areas, in particular those characterized by the bumpy topography described from the slope map. These data suggest that these shelves are likely to be characterized by the presence of hard substrates at or near the seabed surface. In contrast, the smoother areas shown on the slope map at greater depths and within the 2 corners of the bay are characterized by lower backscatter values, indicative of softer sediments (Fig. 5.3.1i).

Northwest and west of Rota, the shallow shelves also appear to be characterized by high-intensity backscatter, with lower backscatter values present on the slopes below, but the problems highlighted above make these data more difficult to interpret.

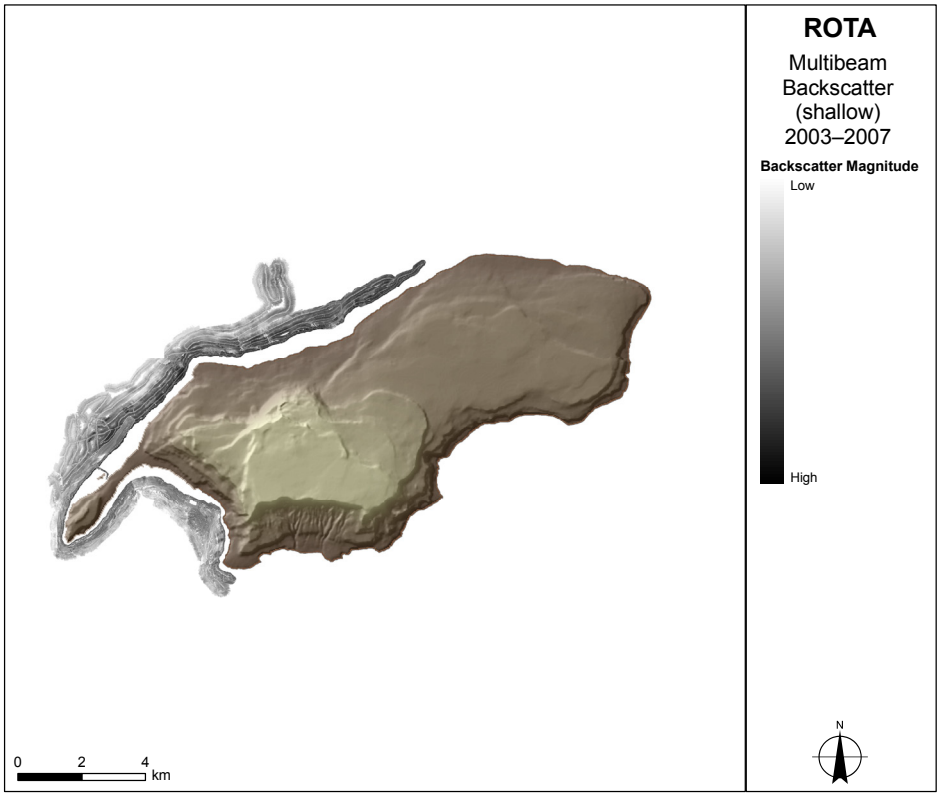


Figure 5.3.1i. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) collected at Rota during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

5.3.2 Optical Validation

During MARAMP 2003, 10 TOAD optical-validation surveys were conducted around Rota at depths of 53–188 m. Subsequent analysis of video acquired from these surveys provided estimates of the percentages of sand cover and live-hard-coral cover.

Covering a distance of 71 km at depths of 6–24 m, 33 towed-diver optical-validation surveys of forereef habitats were conducted around Rota during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

5.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Rota are discussed in this section. These descriptions are discussed with reference to the 6 geographic regions around Rota, beginning with the north and east regions and moving clockwise. Towed-diver observations during MARAMP 2003, 2005, and 2007 revealed that the shallow-water habitats around Rota, in general, were characterized by hard substrates supporting fairly low levels of live coral cover. In contrast, TOAD surveys conducted in deeper waters showed habitats characterized by soft substrates with scarce occurrence of live corals.

In the north and east regions, sand cover observed by towed divers was 5.1%–20%, suggesting that these habitats were predominantly characterized by hard substrates (Fig. 5.3.3a). In these regions, towed divers classified the observed habitats as moderate-relief spur-and-groove areas and pavement reef flats of predominantly low to medium-low complexity (Fig. 5.3.3b). These areas also were characterized by having low cover of live corals (interpolated live coral cover < 5%; Fig. 5.3.3c). TOAD surveys of habitats in deeper waters (53–86 m) suggested variable sand cover of 20%–100%, and no live corals were recorded.

Habitats in the southeast region varied in complexity from low to high. These changes in complexity did not occur with changes in the sand cover, which was fairly low (1.1%–20%) throughout this region; however, complexity did relate to variations in live coral cover. Patches of habitats of medium-high to high complexity were associated with moderately

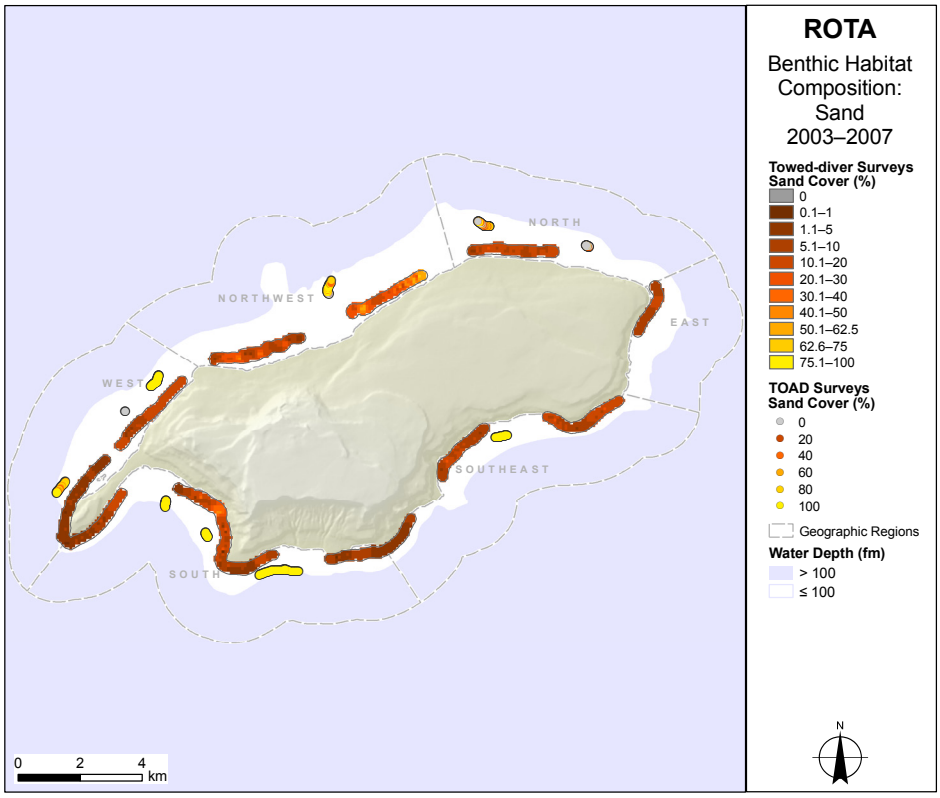


Figure 5.3.3a. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Rota during MARAMP 2003, 2005, and 2007.

high live coral cover (5.1%–20%); whereas, elsewhere within this region, cover of live corals was 1.1%–10%. The highest complexity habitats were described by towed divers as high-relief spur-and-groove areas with overhangs, caves, and large boulders. One TOAD survey conducted at depths of 86–100 m suggested substrate of 100% sand cover. No live corals were observed in analyses of video footage from TOAD surveys.

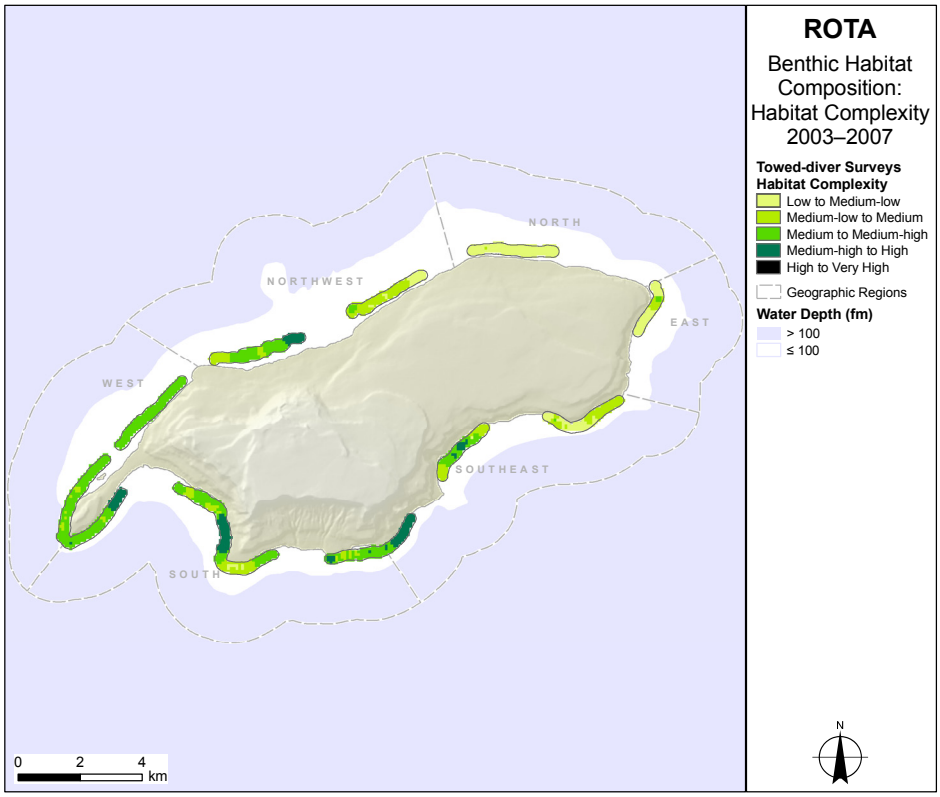


Figure 5.3.3b. Observations of benthic habitat complexity from towed-diver surveys of forereef habitats conducted around Rota during MARAMP 2003, 2005, and 2007.

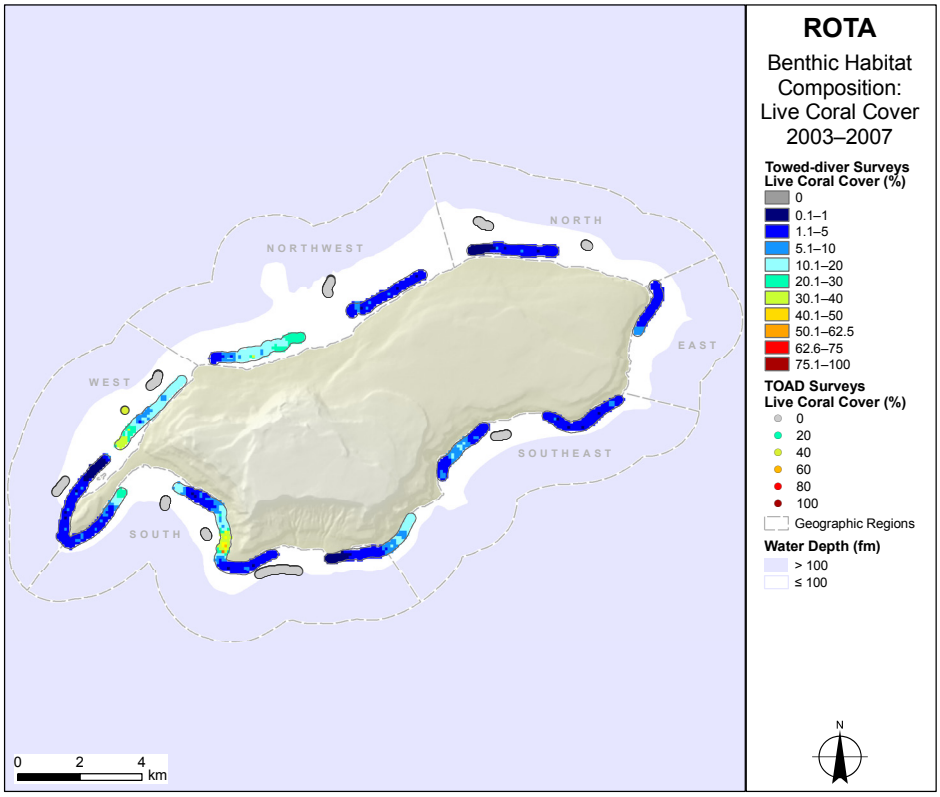


Figure 5.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Rota during MARAMP 2003, 2005, and 2007.

In the south region, towed divers recorded habitat complexity between medium-low and high. Areas of high-complexity habitat observed within Sasanhaya Bay were associated with the highest levels of live coral cover, with a small patch of cover of 10.1%–20% observed on the west side of the bay and an area of live coral cover of up to 75% recorded on the east side of the bay. This latter area, within Coral Gardens in the Sasanhaya Fish Reserve, had the highest cover of live corals recorded by towed divers around Rota. Elsewhere within the south region, cover of live corals was generally < 20%. Habitats within this region were predominantly characterized by hard substrates, with sand cover mainly < 20%, although interpolated sand cover of up to 50% was recorded within one small patch on the east side of the bay. These hard-substrate habitats were described by towed divers as including pavement reef, boulders, and spur-and-groove habitats, with occasional patch reefs in sand. Three TOAD surveys were conducted at depths or 61–188 m south of Rota. In all 3 surveys, the substrate encountered was 100% sand, with no live corals observed.

In the northwest and west regions of Rota, on either side of Puntan Sailigai, moderately high cover of live corals was observed by towed divers, with interpolated cover within a range of 5.1%–40%. In this same area, habitat complexity ranged from low to high, and observed sand cover was generally 5.1%–20%. In the eastern section of the northwest region, interpolated sand cover of 10.1%–75% was recorded by towed divers. This area had the highest levels of sand observed in any of the shallow waters surveyed by towed divers around Rota. In the adjacent, deeper (83–100 m) waters, TOAD surveys recorded predominantly sandy substrate with sand cover of 20.1%–100%.

Three additional TOAD surveys were conducted in the west region at depths of 70–180 m. One of these surveys was very short, with only 2 video frames analyzed, because the TOAD was too high in the water to allow the habitat characteristics to be classified. Live coral cover of 40% was observed in 1 of these 2 frames. The remaining 2 surveys were longer in duration and were both characterized by predominantly sandy habitats with sand cover of 20.1%–100% and no live corals observed.

5.4 Oceanography and Water Quality

5.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 21 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the island of Rota over the period of September 18–20 (Fig. 5.4.1a). Temperature, salinity, and density values from these casts varied both spatially and vertically (Figs. 5.4.1a and b). Spatial comparisons of water properties at a depth of 10 m suggest warm (> 29.95°C) waters around most of this island; however, the west and south regions were generally warmer than all other regions. Salinity and density values showed spatial patterns similar to those seen in temperature values. Levels of both salinity and density generally were lower in the south and west regions than in other regions. The highest density value was recorded at a single location (cast 9) in the north region, and the highest salinity values were recorded at locations in the north and southeast regions (casts 9 and 13). Vertical comparisons of CTD profiles (Fig. 5.4.1b) reveal mostly well-mixed and warm waters around much of this island, except at one location (cast 9) in the north region where differences in values show waters that were much cooler (1.7°C), more saline (0.4 psu), and more dense (0.9 kg m^{-3}) than waters at other cast locations. Also, similarly high salinity levels were found at a single location in the southeast region (cast 13).

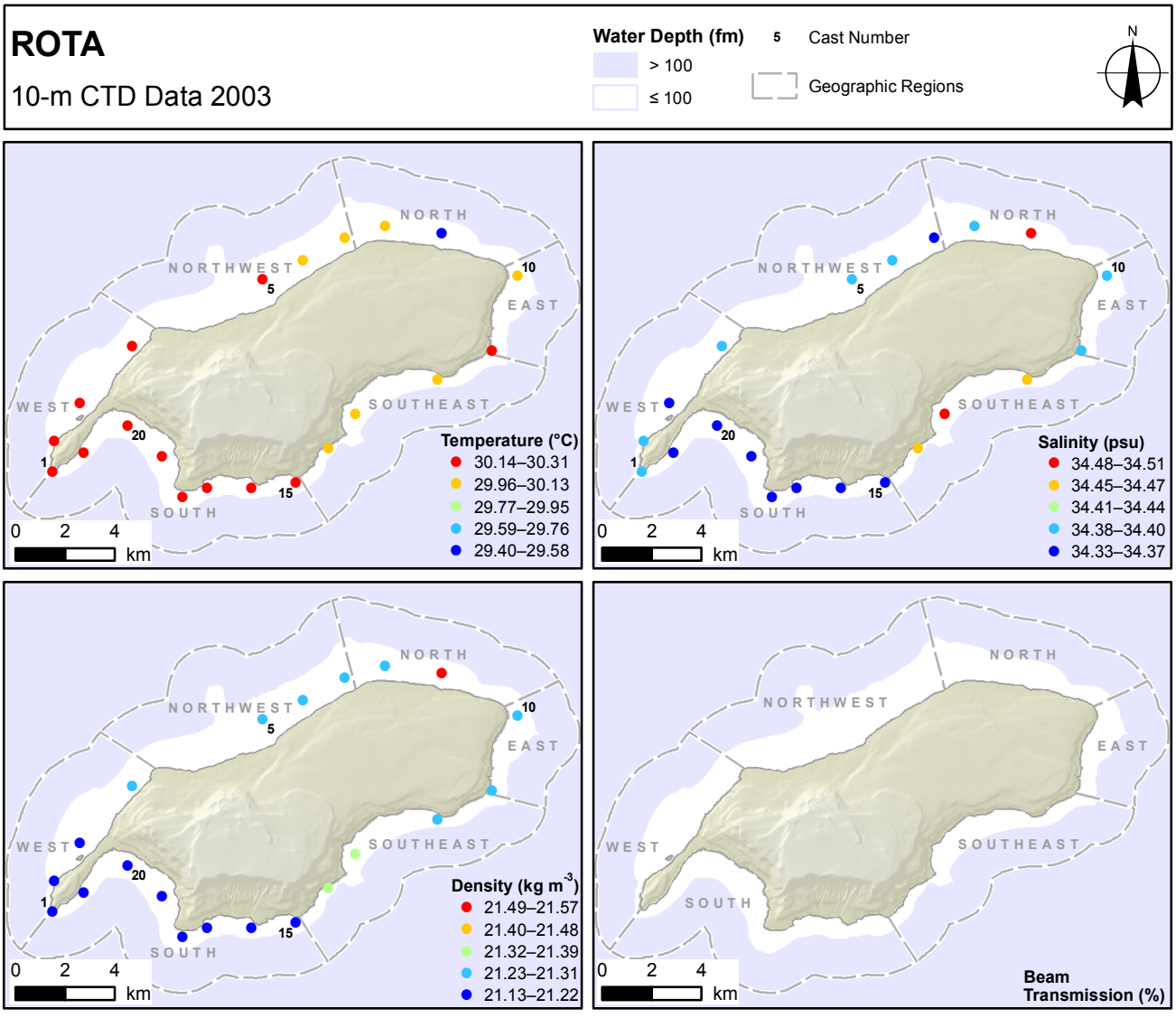


Figure 5.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts around Rota on September 18–20 during MARAMP 2003.

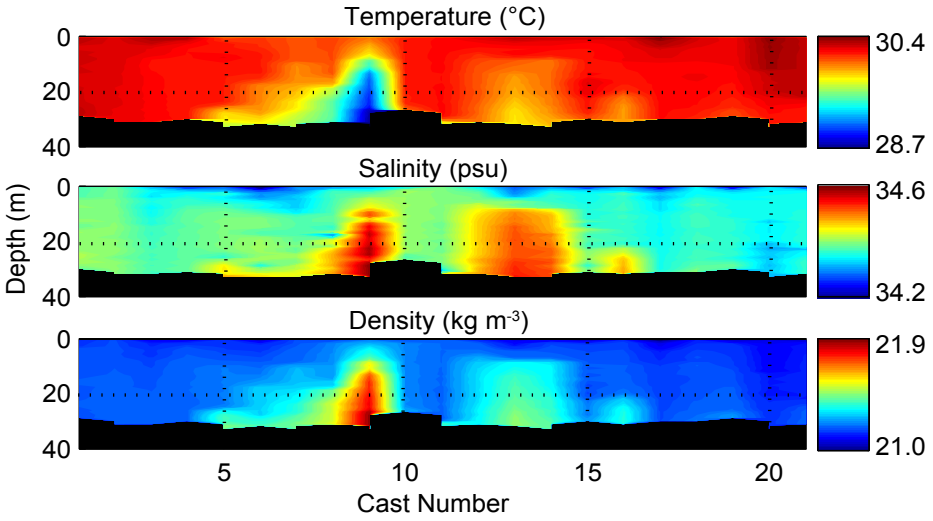


Figure 5.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Rota on September 18–20 during MARAMP 2003, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–21 in a clockwise direction around Rota. For cast locations and numbers around this island in 2003, see Figure 5.4.1a.

2005 Spatial Surveys

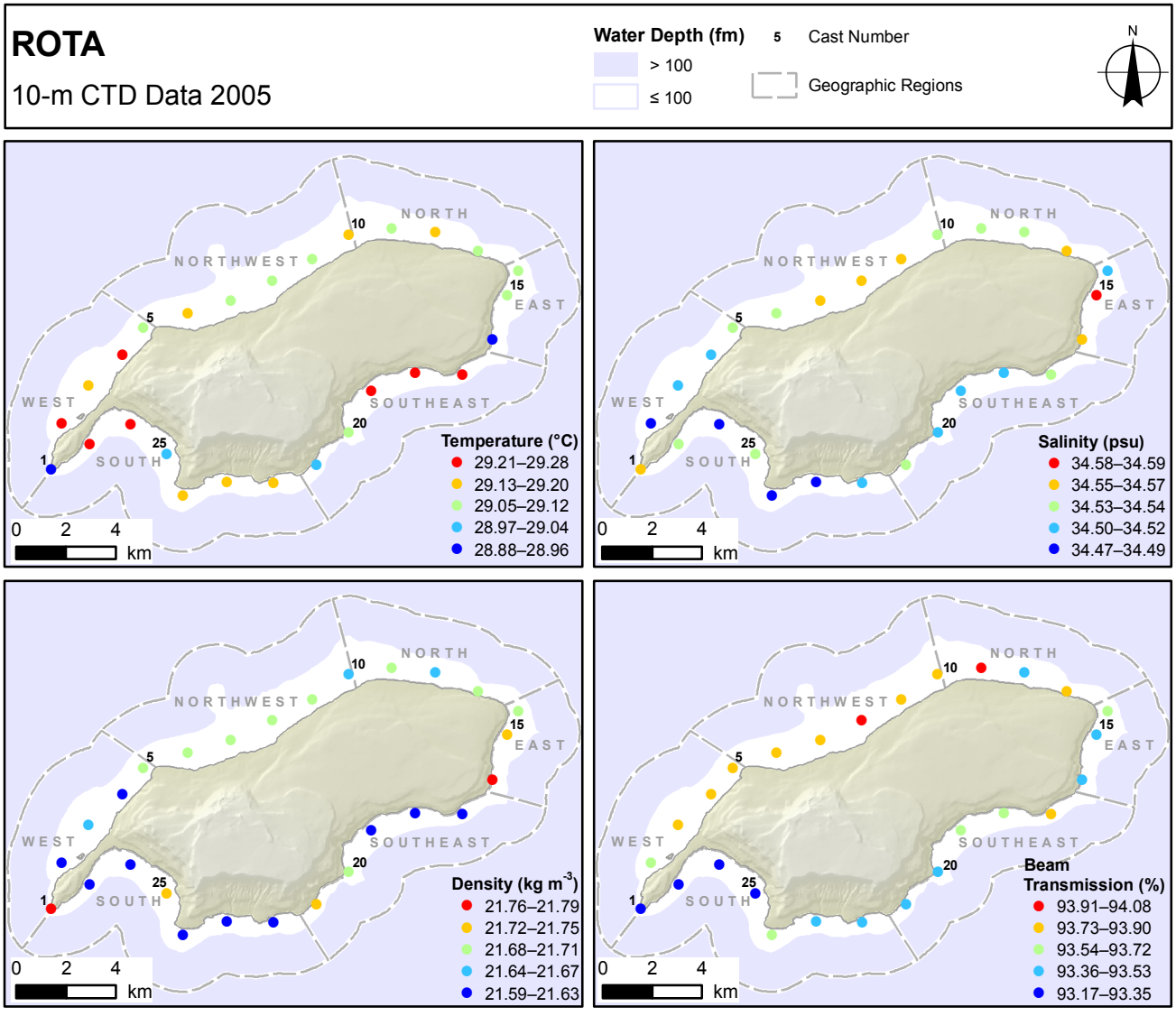


Figure 5.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Rota on September 29–October 1 during MARAMP 2005.

During MARAMP 2005, shallow-water CTD casts were conducted in nearshore waters around Rota over the period of September 29–October 1 (Fig. 5.4.1c). Temperature, salinity, density, and beam transmission values from 27 of these casts varied both spatially and vertically (Figs. 5.4.1c and d). Spatial comparisons of water properties at a depth of 10 m suggest slight ranges in all parameters measured. Temperature differences were as large as 0.4°C, although cast locations in the southeast, south, and west regions showed greater heterogeneity compared to the northwest, north, and east regions. Similar variability was seen in recorded density values. Salinity and beam transmission values generally were lower in the southeast, south, and west regions than in the other regions, differences likely associated with subsurface mixing or ground water input. Vertical comparisons of CTD profiles (Fig. 5.4.1d) reveal a complex oceanographic structure around Rota with a broad range in temperature (1.6°C) values, moderate ranges in salinity (0.3 psu) and density (0.5 kg m^{-3}) values, and a small range in beam transmission (1.4%) values. A series of intrusions of cold and high-salinity water were recorded in the north and east regions (casts 13 and 16) and to a lesser extent in the south region (casts 23–27). Beam transmission values suggest a less turbid environment in the west, northwest, and north regions (casts 1–15), while, in contrast, the generally lower values recorded along the other half of this island suggest a more turbid environment.

Water samples were collected in concert with shallow-water CTD casts at 4 select locations at Rota in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.15–1.46 µg L^{-1}; total nitrogen (TN), 0.181–0.311 µM; nitrate (NO_3^-), 0.168–0.284 µM; nitrite (NO_2^-), 0.011–0.026 µM; phosphate (PO_4^{3-}), 0.002–0.03 µM; and silicate [$Si(OH)_4$], 0.685–0.781 µM. Based on data from these sample locations, nearly all parameters were lower in the west region than in other regions, except for Chl-*a*, which was an order of magnitude greater in concentration than the lowest value recorded at Rota (Fig. 5.4.1e). All nutrient parameters measured, except Chl-*a,* were greatest in the south region.

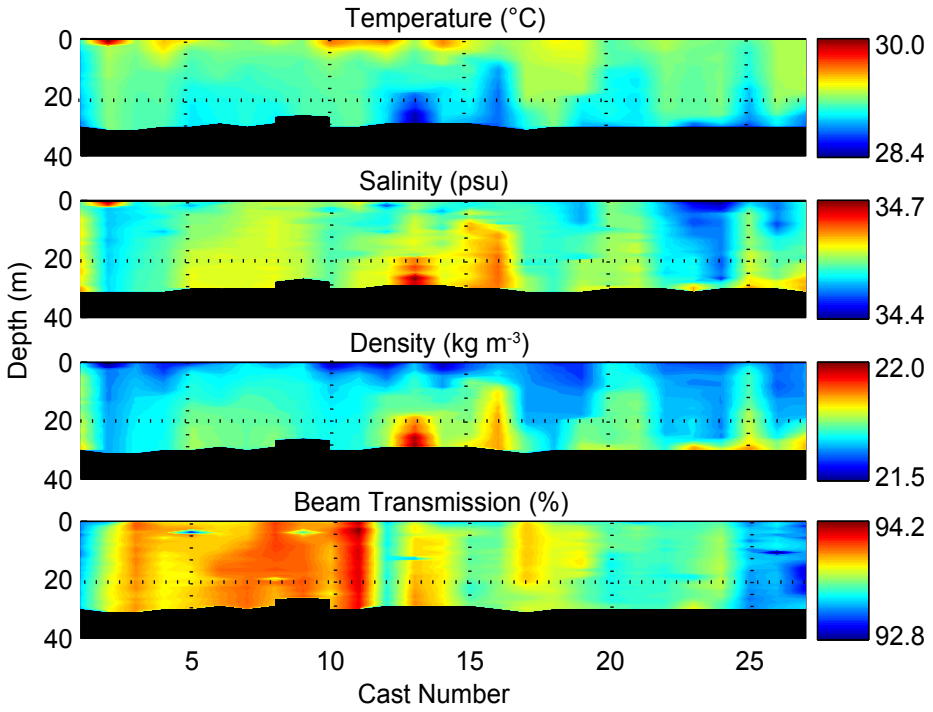


Figure 5.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Rota on September 29–October 1 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–27 in a clockwise direction around Rota. For cast locations and numbers around this island in 2005, see Figure 5.4.1c.

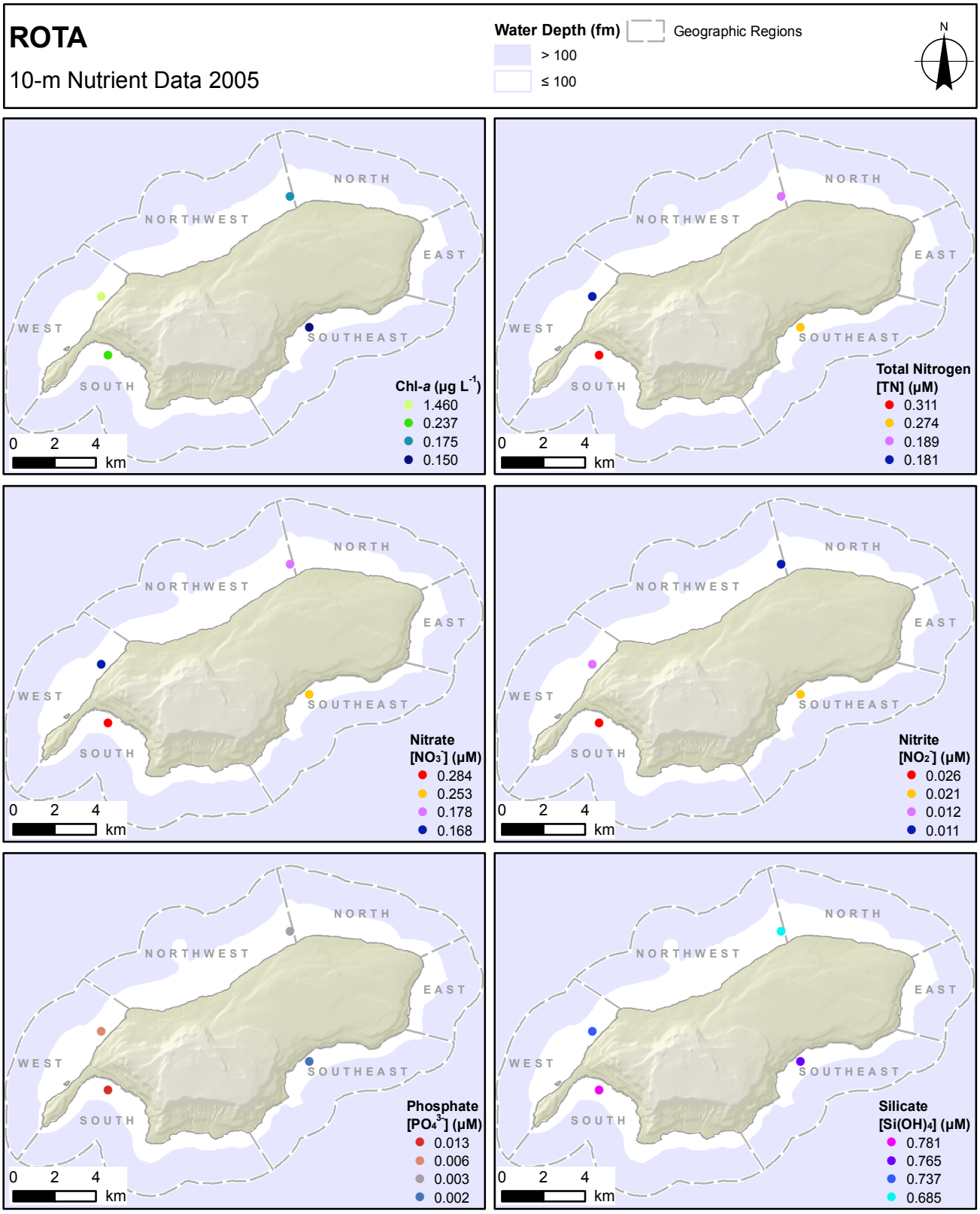


Figure 5.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate and (*bottom right*) silicate at a 10-m depth, from water samples collected at Rota on September 29–October 1 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, shallow-water CTD casts were conducted in nearshore waters around Rota over the period of May 16–17 (Fig. 5.4.1f). Temperature, salinity, density, and beam transmission values from 27 of these casts varied both spatially and vertically (Figs. 5.4.1f and g). Spatial comparisons of water properties at a depth of 10 m suggest small ranges around this island with temperature differences as large as 0.35°C. In general, waters were cooler, more saline, more dense, and less turbid in the west, northwest, and north regions than in the south, southeast, and east regions. Vertical comparisons of CTD profiles (Fig. 5.4.1g) reveal distinct variability around Rota. In the west, northwest, and north regions (casts 1–13) waters from a depth of 30 m to the surface were well mixed and, compared to waters around the rest of this island, were cooler, more dense, and more saline. In the east, southeast, and south regions (casts 14–27) waters were much warmer, less saline, and less dense than in other regions; however, waters at these cast locations exhibited greater stratification and vertical complexity. Beam transmission was generally high around Rota, compared to data collected at other islands, with values around one half of Rota (casts 2–15) slightly higher than around the other half (casts 1 and 16–27).

Water samples were collected in concert with shallow-water CTD casts at 5 select locations around Rota in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: Chl-*a*, 0.013–0.135 µg L^{-1}; total nitrogen (TN), 0.022–0.185 µM; nitrate (NO_3^-), 0.007–0.158 µM; nitrite (NO_2^-), 0.016–0.027 µM; phosphate (PO_4^{3-}), 0.129–0.154 µM; and silicate [$Si(OH)_4$], 0.721–0.992 µM. Based on data from these sample locations, nearly all parameters were low in the east region and high in the southeast region, compared to results in other regions (Fig. 5.4.1h). In

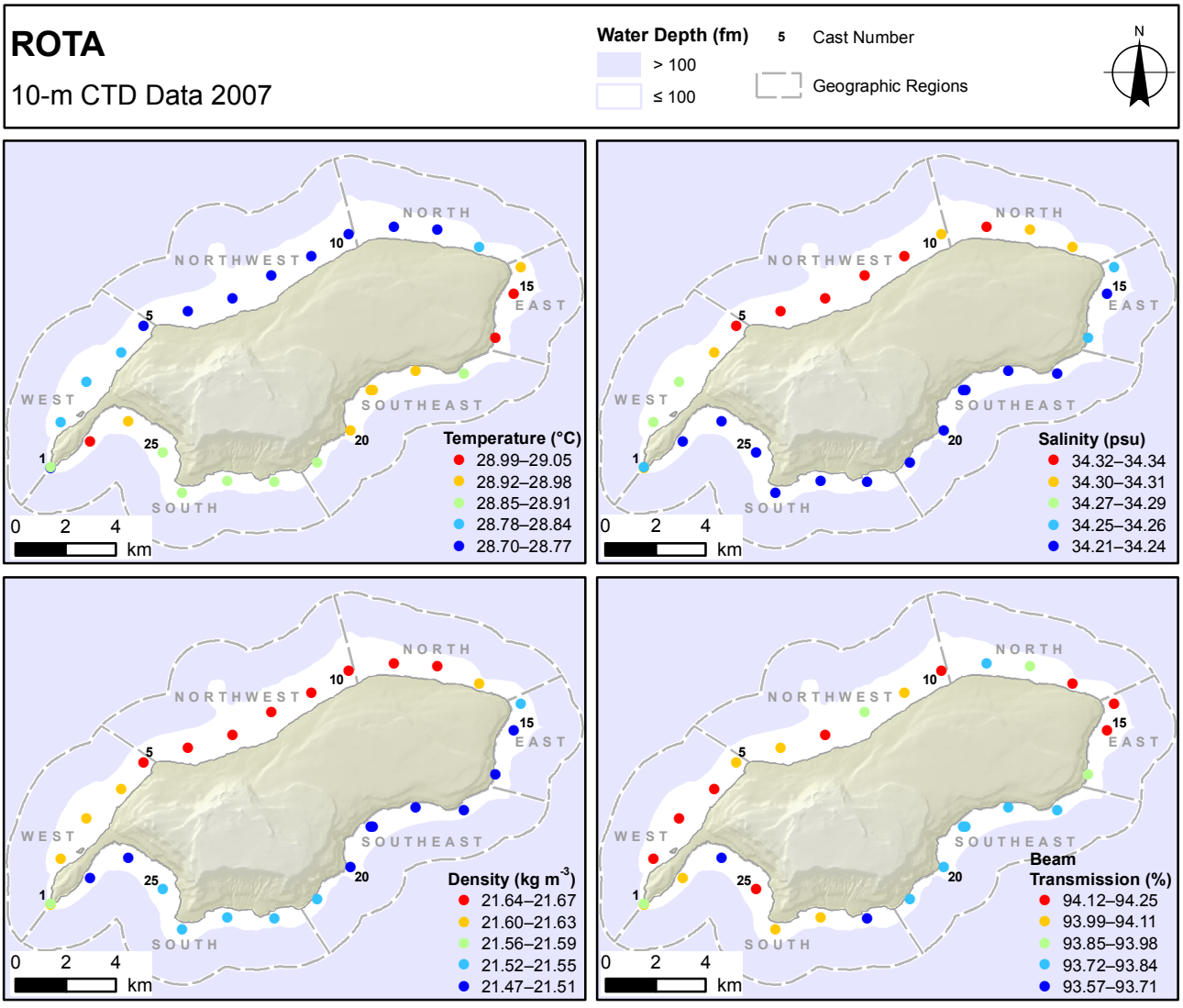


Figure 5.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Rota on May 16–17 during MARAMP 2007.

the northwest region, nutrient concentrations were low, but the level of Chl-*a* was an order of magnitude higher than the lowest level found in the east region.

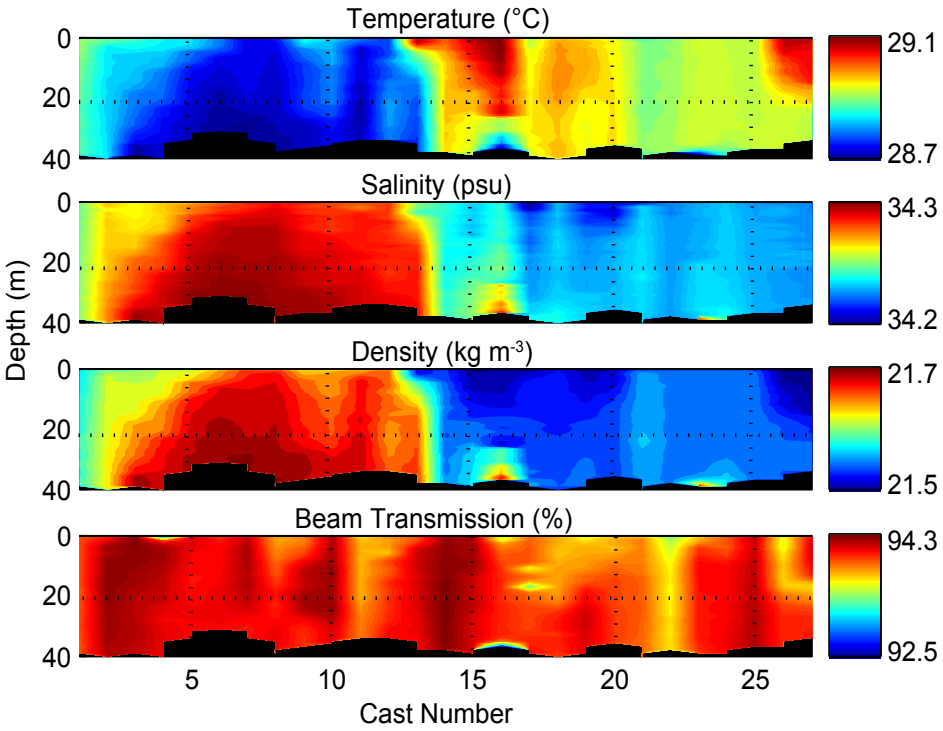


Figure 5.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Rota on May 16–17 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–27 in a clockwise direction around Rota. For cast locations and numbers around this island in 2007, see Figure 5.4.1f.

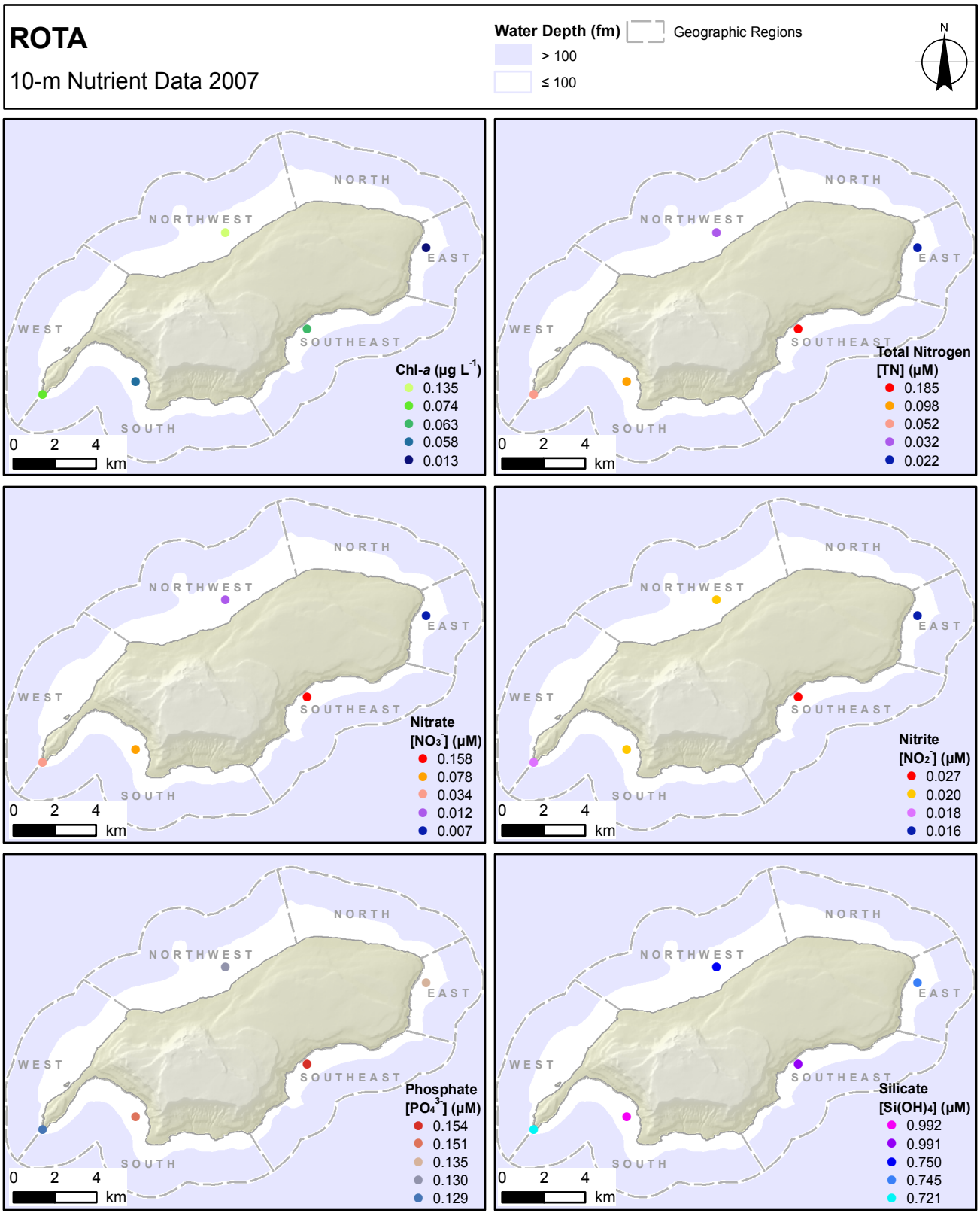


Figure 5.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate and (*bottom right*) silicate, at a 10-m depth, from water samples collected at Rota on May 16–17 during MARAMP 2007.

Temporal Comparison

Shallow-water CTD casts conducted during MARAMP 2003, 2005, and 2007 show very different spatial and vertical hydrographic structure around Rota. Intrusions of cold water originating from 30 m below the ocean surface were recorded during MARAMP 2003 and 2005: cold-water intrusions were prevalent at multiple locations in 2005, but waters were mostly well mixed and warm in 2003 with the exception of a single location (cast 9) in the north region. In contrast, a strong east–west gradient in water properties was documented during MARAMP 2007, with waters cooler and more saline along the west- and north-facing shorelines than along the south- and east-facing shores. Beam transmission was high in 2005 and 2007, although a prominent east–west gradient was recorded in 2005 with transmission values higher on the western shorelines than elsewhere around Rota. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May, and MARAMP 2003 and 2005 occurred in September and October. This change was made to avoid the typhoon season and reduce the probability of weather disruptions. Wind and wave conditions are generally higher during the wet season (July–December) than during the rest of the year, with stronger trade winds prominent on the east side of Rota. Higher winds and waves likely caused more mixing during MARAMP 2003 and 2005, and calmer weather potentially allowed for the east–west gradient recorded in 2007. Further investigation will help make these particular results and patterns more apparent.

Some differences in water-quality conditions between MARAMP 2005 and 2007 were observed. Total nitrogen and nitrate concentrations were greater and Chl-*a* levels were an order of magnitude greater in 2005 than in 2007. In contrast, phosphate concentrations were an order of magnitude greater in 2007 than in 2005, and silicate concentrations also were greater. The highest Chl-*a* value was recorded along the northwestern shoreline (north or northwest region) of Rota in both MARAMP survey years, while all nutrient concentrations were greatest along the southern shoreline (south or southeast region). The differences in nitrogen and Chl-*a* concentrations between years could be linked to seasonal weather patterns, terrigenous runoff, or nutrient limitation. Precipitation data show that MARAMP 2005 occurred during a period of seasonally high precipitation, while MARAMP 2007 occurred during a period of seasonally low precipitation (for precipitation information, see Chapter 3: "Archipelagic Comparisons," Section 3.3.1: "Oceanography and Water Quality: Seasonal Climatologies").

5.4.2 Time-series Observations

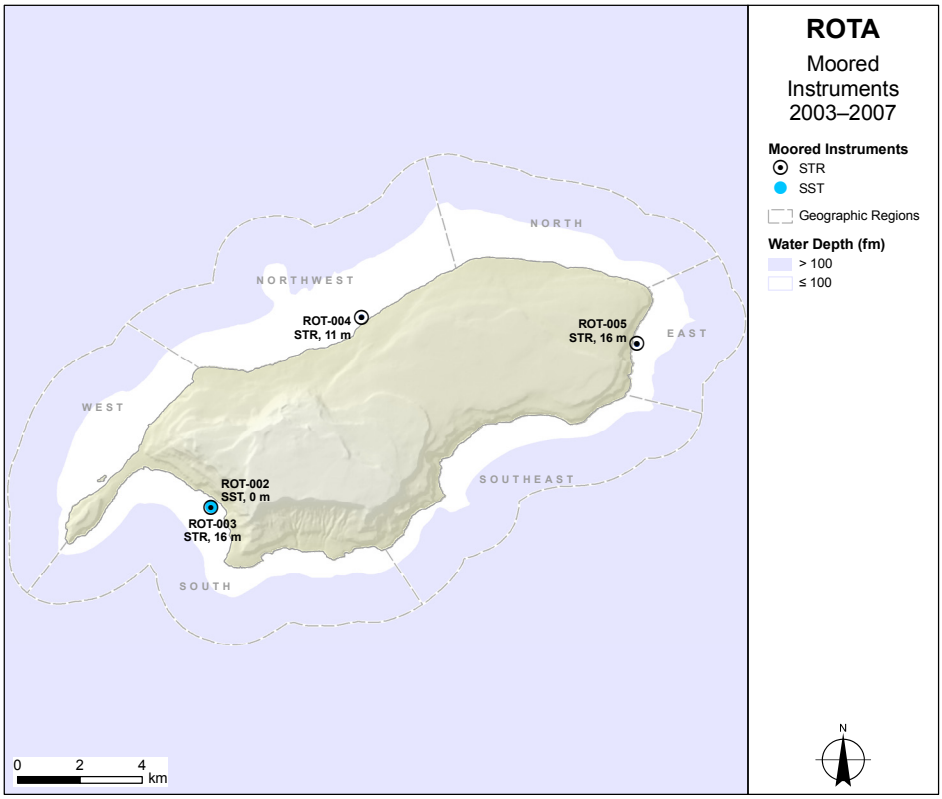


Figure 5.4.2a. Locations, depths, and types of oceanographic instrument moorings deployed at Rota during MARAMP 2003, 2005, and 2007. Two types of instruments were moored at Rota: sea-surface temperature (SST) buoy and subsurface temperature recorder (STR).

Between 2003 and 2007, 2 types of moored instruments were deployed at Rota to collect time-series observations of temperature, a key oceanographic parameter. The locations, depths, time frames, and other details about these deployments are provided in Figures 5.4.2a and b.

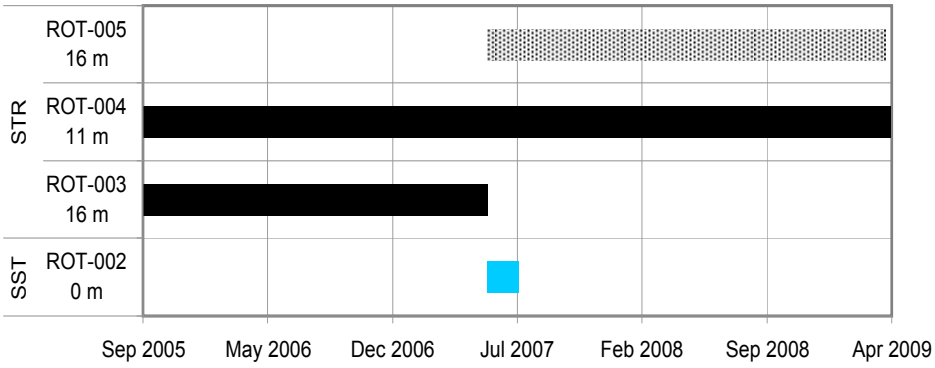


Figure 5.4.2b. Deployment timelines and depths of oceanographic instruments moored at Rota during the period from September 2005 to April 2009. A solid bar indicates the period for which temperature data were collected by a single instrument or a series of them deployed and retrieved at a mooring site. A stippled bar indicates that the STR at mooring site ROT-005 and the data it collected were not yet retrieved. The time period shown above for data stored on and collected from an SST buoy may differ from the periods for which telemetered SST data, shown in Figure 5.4.2c, was available.

Satellite-derived (Pathfinder) sea-surface temperature (SST) and in situ temperature observations around Rota reveal that the seasonal maxima for water temperatures around Rota are typically reached in late August or September. The monthly maximum climatological mean from Pathfinder SST was 29.2°C (Fig. 5.4.2c[a]). Winter minima occurred in February with a monthly minimum climatological mean of 27.2°C. Data from the SST buoy deployed in the south region in the Sasanhaya Fish Reserve show that nearshore SST throughout this time series was 0.1°C–1.5°C greater than SST measured via satellite. In situ SST surpassed the bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean, multiple times during the summer months of 2003–2006, with a particularly warm episode of 1.2°C above the bleaching threshold recorded in September 2006. Recorded at a location highly sheltered from prevailing trade winds and associated swell, the high SST values measured via this SST buoy are not an accurate representation of temperatures from around this entire island. However, these data are accurate for this location and show the importance of prevailing oceanographic phenomena for nearshore thermal dynamics. It's important to note that satellite-derived SST represents the upper few millimeters of oceanographic temperatures within the region of an island, as opposed to site- or reef-specific temperatures.

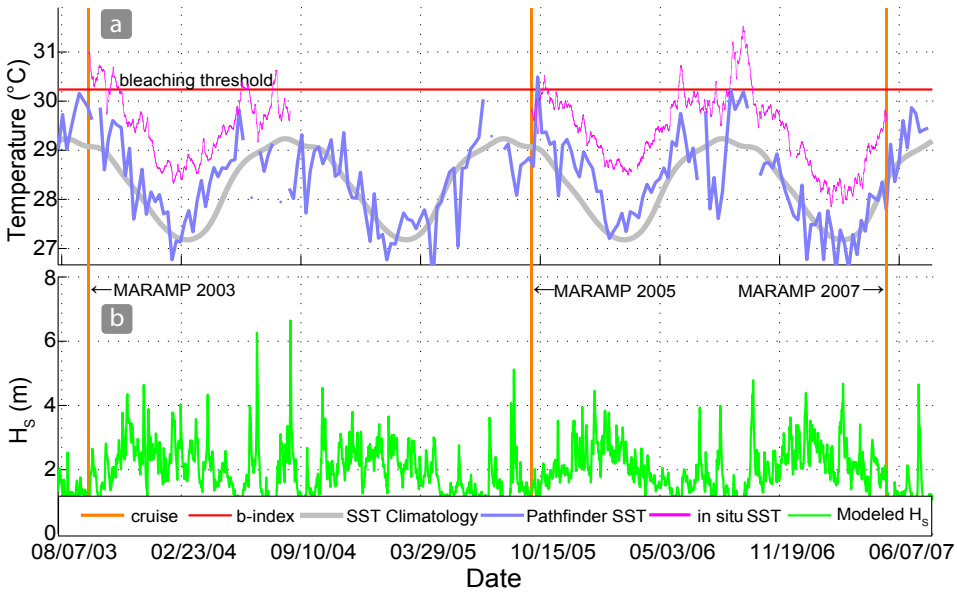


Figure 5.4.2c. Time-series observations of (*a*) SST and (*b*) wave height around Rota for the period between August 2003 and June 2007. Remotely sensed data (SST climatology and weekly Pathfinder-derived SST) and modeled significant wave height (Hs) derived from Wave Watch III are shown with CRED in situ temperature data from SST buoys (see Figure 5.4.2a for buoy location). The 2 high points in the modeled wave height in the summer of 2004 show the occurrences of Typhoons Tingting and Chaba. The horizontal red and vertical orange bars represent the bleaching threshold and the MARAMP research cruise dates, respectively.

Periods of elevated mean wave heights of 3–4 m were usually more frequent during winter (Fig. 5.4.2c[b]). The largest episodic events of wave heights > 4 m, however, tended to happen during periods of warm temperatures. Warm temperatures typically occurred during the period of August–December when wave heights > 4 m were generally associated with typhoons. This pattern was especially noticeable during the summer of 2004 with the passages of Typhoons Tingting and Chaba.

Subsurface temperature recorders (STRs) were deployed at 2 locations at depths of 11 and 16 m in the south and northwest regions of Rota beginning in October 2005. Data from these STRs show seasonal temperature variability of 2°C–3°C (Fig. 5.4.2d). Water temperatures reached ~ 30.5°C during the months of June–October and fell to a low of ~ 27.5°C during the months of January–May. Temperature at these 2 locations reached the coral bleaching threshold for the region in September 2006, with the temperature at the shallower sensor reaching 0.5°C higher than the bleaching threshold of 30.5°C. Both STRs showed high-frequency (return periods of 12–24 h) temperature fluctuations of 0.5°C–1°C that were likely associated with the vertical uplift of a stratified water column.

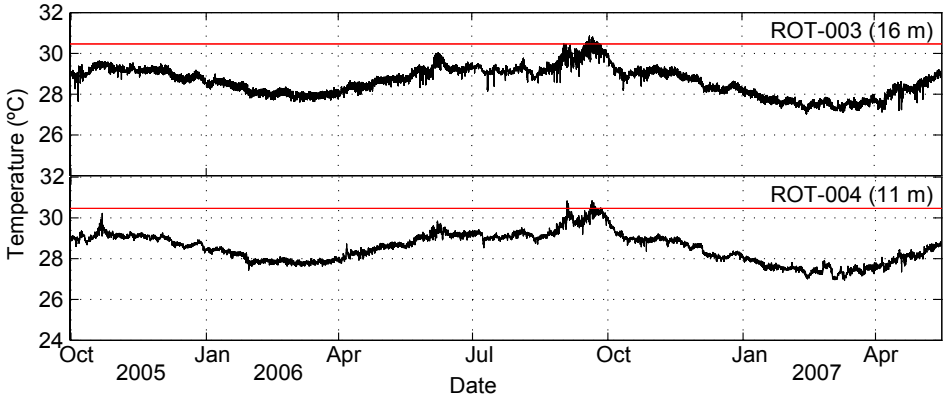


Figure 5.4.2d. Time-series observations of temperature over the period between October 2005 and May 2007 collected from 2 STR mooring sites at different locations and depths at Rota (see Figure 5.4.2a for mooring locations). The red lines indicate the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

5.4.3 Wave Watch III Climatology

Seasonal wave climatology for Rota was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008 (Fig. 5.4.3a), and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (~ 70°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the east-southeast (120°), although they could originate from a broad directional source (110°–200°). These large, episodic waves primarily were generated via typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from the west and southwest (240°–270°) and probably were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) was also characterized by frequent (> 30 d per season), short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season), long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this time and originated from the southwest (~ 240°).

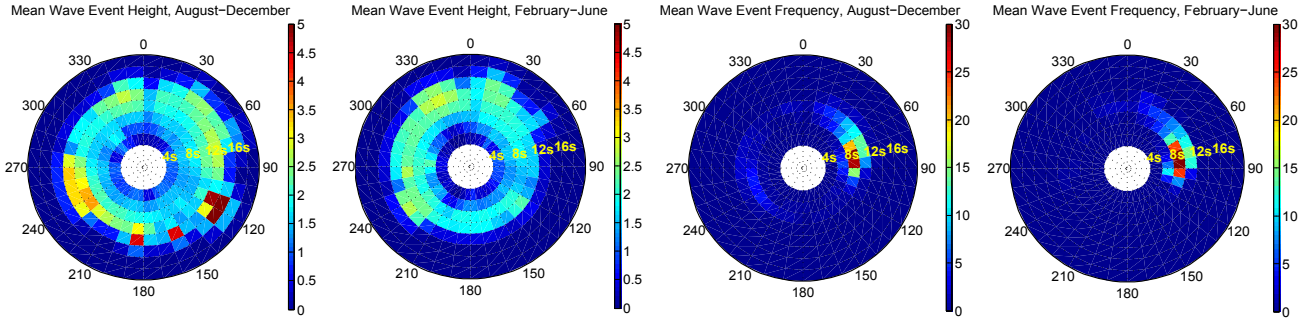


Figure 5.4.3a. NOAA Wave Watch III directional wave climatology for Rota from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Rota (13° N, 145° E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 out of 150 days of that season.

5.5 Corals and Coral Disease

5.5.1 Coral Surveys

Coral Cover and Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Rota was 9% (SE 1). Coral cover was lowest over the 5 surveys conducted around the eastern half of Rota, with < 10% coral cover recorded for 49 of 50 survey segments (Fig. 5.5.1a): the easternmost survey in the northwest region, the survey near Asuzudo and Mochon Points in the north region, the survey near Puntan Fina`atkos in the east region, and the 2 surveys nearest to Puntan Sagua`gahga in the southeast region (for place-names and their locations, see Figure 5.2a in Section 5.2: "Survey Effort"). Coral cover was highest for the survey conducted just east of Puntan Sailigai in the northwest region with a mean of 25% for 10 segments. Localized areas of high coral cover were also found in the south region in Coral Gardens, which is in the Sasanhaya Fish Reserve, with a mean of 24% over 7 segments.

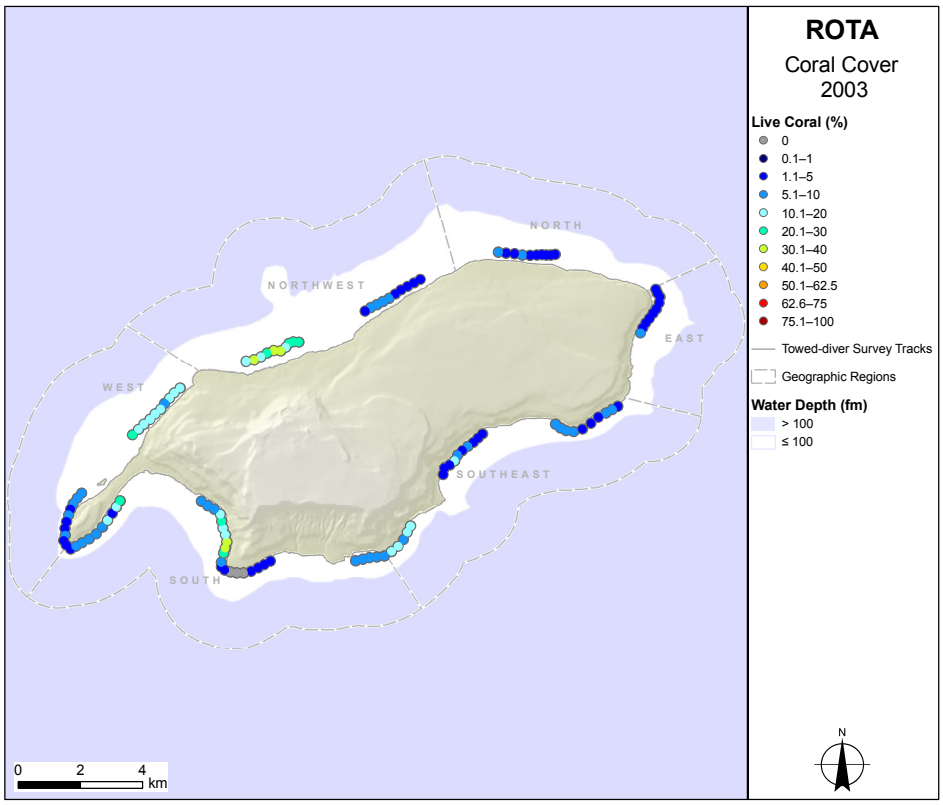


Figure 5.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted around Rota during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 x 10 m (~ 2000 m^2).

During MARAMP 2003, 5 REA benthic surveys using the quadrat method on forereef habitats at Rota documented 364 coral colonies within a total survey area of 18.75 m^2. Site-specific colony densities ranged from 6.9 to 37.1 colonies m^{-2} with an overall sample mean of 19.4 colonies m^{-2} (SE 5.7). The highest colony density was observed in the west region at REA site ROT-06 southwest of Puntan Sailigai, and the lowest colony density was recorded in the north region at ROT-04 near Mochon Point (Fig. 5.5.1b).

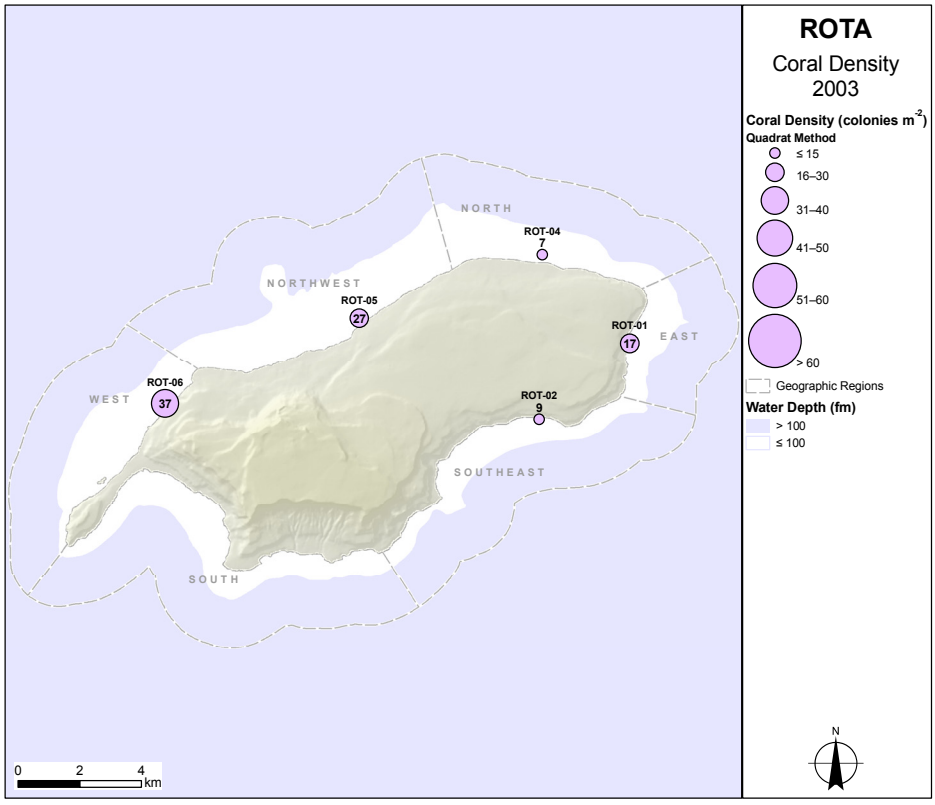


Figure 5.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2003. Values are provided within or above each symbol. The quadrat method was used in 2003 to assess coral-colony density.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats at Rota was 6% (SE 1). Coral cover was < 10% in the majority (87%) of the 108 segments surveyed at Rota. Coral cover was highest in the south region in Coral Gardens with a mean of 49% over 3 segments (Fig. 5.5.1c). A localized area of high coral cover, relative to other areas surveyed at Rota, was also found in the west region near Sasanlagu (West) Harbor, where cover was estimated at 29% over 5 segments.

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 2% (SE 1) of coral cover observed on forereef habitats at Rota appeared stressed in 2005. Low values of stressed-coral cover were seen during the majority of segments. Stressed-coral cover was highest, within a range of 40.1%–50% for 2 segments and a range of 10.1%–20% for a third segment, in the southeast region near Puntan Sagua`gahga (Fig. 5.5.1c). An additional area of stressed-coral cover, within a range of 10.1%–20% for 3 segments, was observed in the northwest region near Puntan Sailigai.

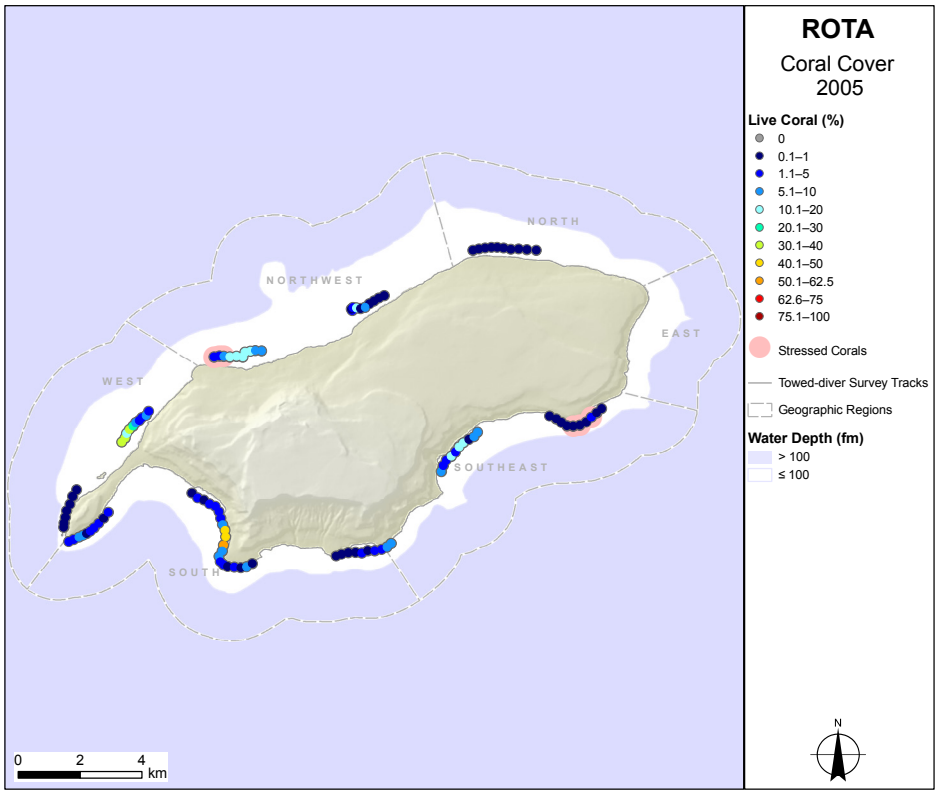


Figure 5.5.1c. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2005. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 x 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005.

During MARAMP 2005, 5 REA benthic surveys using the quadrat method on forereef habitats at Rota documented 599 coral colonies within a total survey area of 20 m^2. Site-specific colony densities ranged from 9.5 to 52.4 colonies m^{-2} with an overall sample mean of 30 colonies m^{-2} (SE 8.1). Similar to results from MARAMP 2003 surveys, the highest colony density was observed at ROT-06 in the west region (Fig. 5.5.1d). ROT-04, where the lowest colony density was found in 2003, was not surveyed in 2005; however, the lowest colony density in 2005 was recorded in the southeast region at ROT-02, the REA site with the second-lowest colony density in 2003.

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats at Rota was 4% (SE 1). Coral cover was < 10% in the majority (93%) of the 100 segments surveyed at Rota (Fig. 5.5.1e). Coral cover was highest in the south region in Coral Gardens with a mean of 58% over 3 segments.

Overall, 1% (SE 0) of coral cover observed on forereef habitats at Rota appeared stressed in 2007. Low values of stressed-coral cover were observed during the majority of segments (Fig. 5.5.1e). Stressed-coral cover was highest, within a range of 10.1%–20%, for 1 segment in the southeast region midway between Puntans Sagua`gahga and Ha`ina.

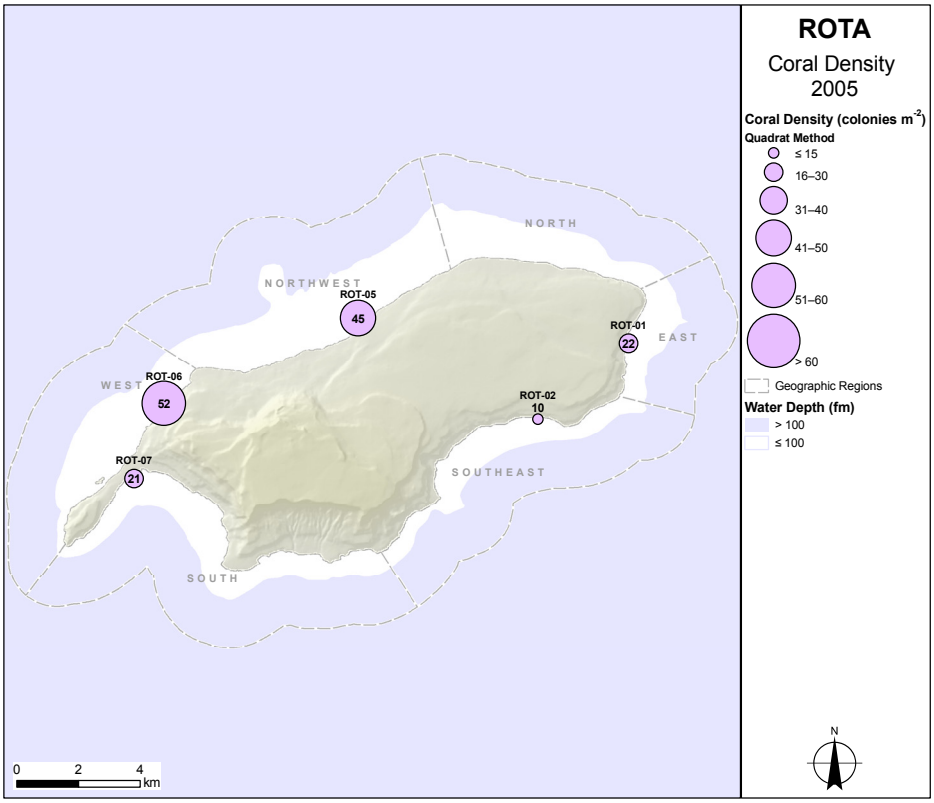


Figure 5.5.1d. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2005. Values are provided within or above each symbol. The quadrat method was used in 2005 to assess coral-colony density.

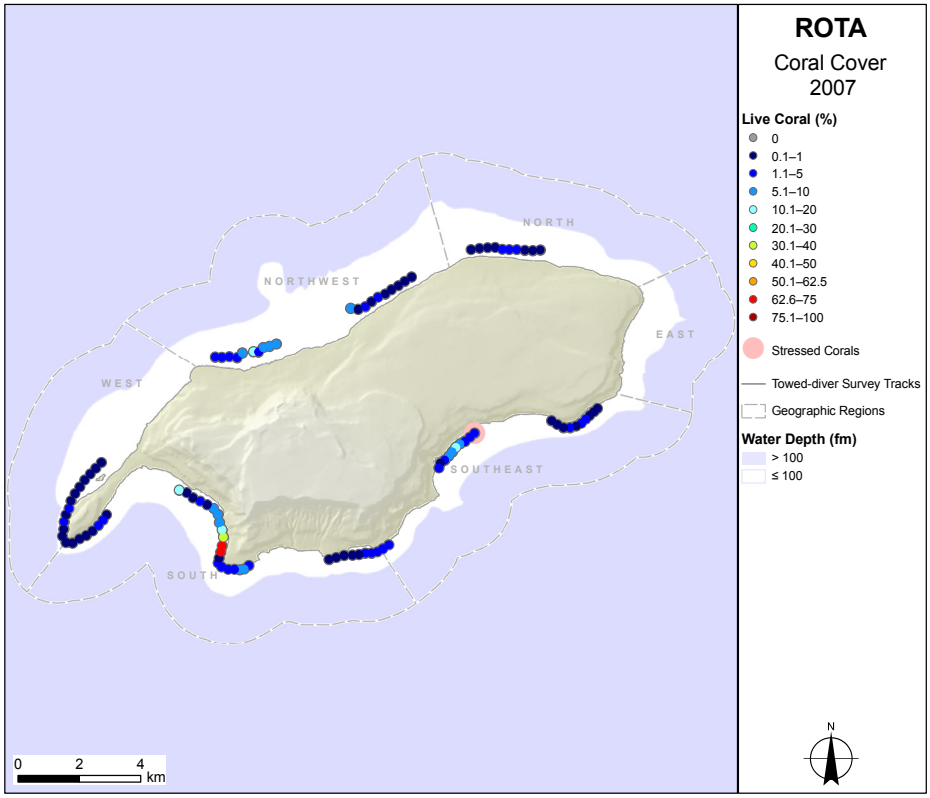


Figure 5.5.1e. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 x 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover.

During MARAMP 2007, 6 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Rota. Site-specific estimates of live-hard-coral cover from these surveys ranged from 2% to 34.3% with an overall sample mean of 12.4% (SE 5.4). The highest coral cover was observed at ROT-03 in the south region near Puntan Pona, and the lowest coral cover was recorded west of Puntan Sagua`gahga at ROT-02 in the southeast region (Fig. 5.5.1.f).

During MARAMP 2007, 6 REA benthic surveys using the belt-transect method on forereef habitats at Rota documented 1307 coral colonies within a total survey area of 300 m^2. Site-specific colony densities ranged from 2.3 to 6.8 colonies m^{-2} with an overall sample mean of 4.4 colonies m^{-2} (SE 0.6). Similar to results from MARAMP 2005 surveys, the highest colony density was observed at ROT-06 in the west region, and the lowest colony density was recorded at ROT-02 in the southeast region (Fig. 5.5.1.f).

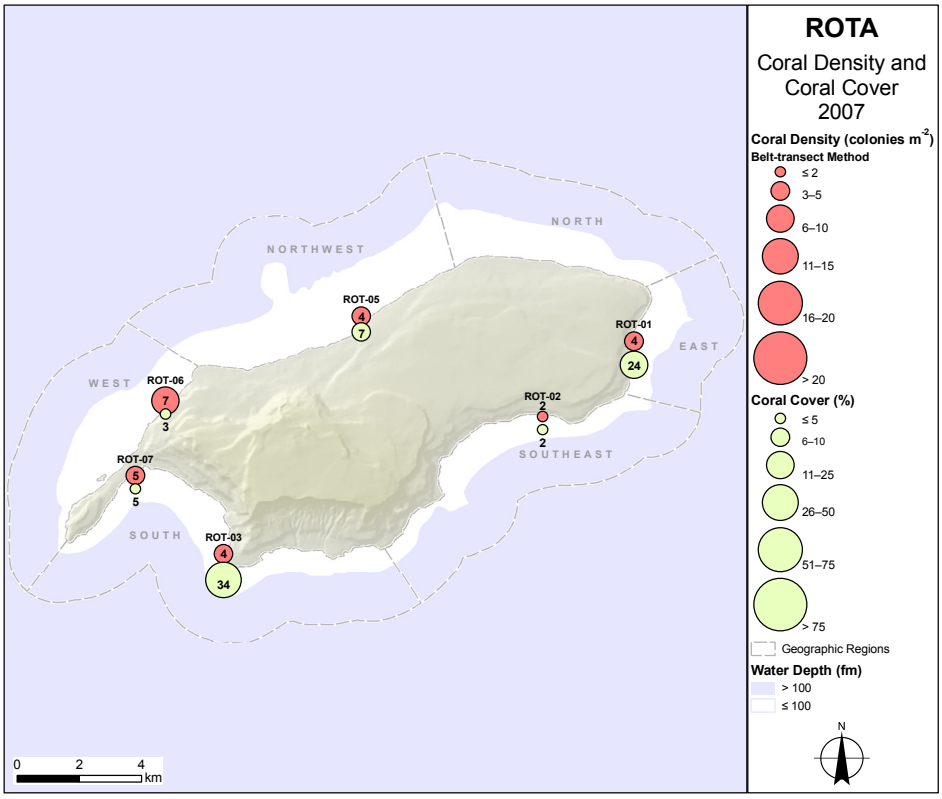


Figure 5.5.1f. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2007. Values are provided within of below each symbol. The belt-transect method was used in 2007 to assess coral-colony density.

Islandwide mean cover of live corals, estimated from towed-diver surveys of forereef habitats, varied slightly between survey years, falling from 9% (SE 1) in 2003 to 6% (SE 1) in 2005 and 4% (SE 1) in 2007 (Fig. 5.5.1g). This variation in overall mean values of live coral cover between MARAMP survey years is not necessarily indicative of actual changes in overall coral cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Estimates of live coral cover from REA surveys generally exceeded levels recorded in towed-diver surveys; REA surveys target hard-bottom communities, whereas towed-diver surveys include a wider array of substrate types. Site-specific estimates of coral cover averaged 12.4% (SE 5.4) for the 6 REA sites surveyed in 2007 (Rota was not surveyed for coral cover using the line-point-intercept method in 2003 and 2005).

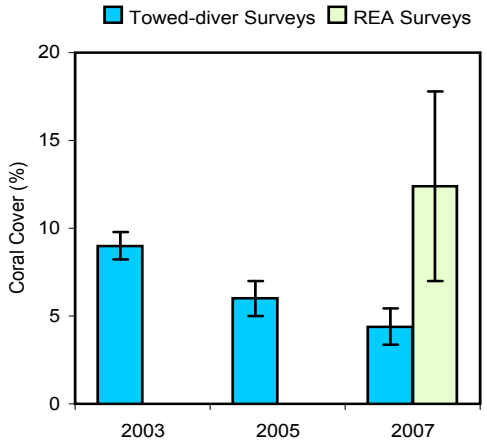


Figure 5.5.1g. Temporal comparison of mean live-coral-cover (%) values from REA and towed-diver benthic surveys conducted on forereef habitats around Rota during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted around Rota in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

The decrease in live coral cover near Puntan Sailigai in the northwest region, from a mean of 25% in 2003 to means of 10% in 2005 and 6% in 2007 over 10 segments, may also result from spatial variation in track locations and depths between survey years (Fig. 5.5.1g). However, elevated levels of stressed-coral cover recorded in 2005 may hint at additional reasons for the decline near this point.

During the 3 MARAMP survey periods, high levels of coral cover were recorded in the survey area in Coral Gardens in the south region, com-

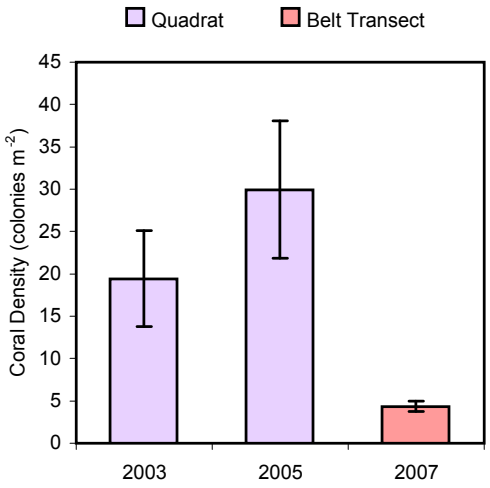


Figure 5.5.1h. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Rota during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to measure coral-colony density, but the belt-transect method was used in 2007. Error bars indicate standard error (± 1 SE) of the mean.

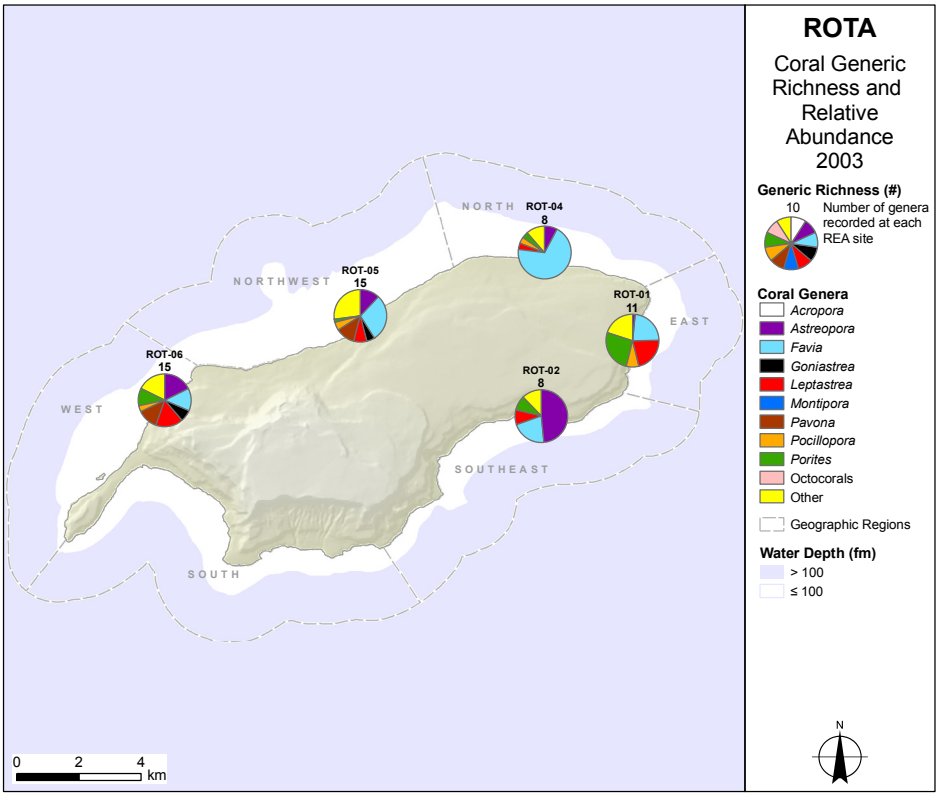
pared to results from other towed-diver-survey areas at Rota. Observed coral cover in this area varied between survey years: 24% for 7 segments in 2003, 49% for 3 segments in 2005 and 58% for 3 segments in 2007.

Overall mean coral-colony density from REA benthic surveys of forereef habitats at Rota did not change significantly between MARAMP 2003 and 2005, when the quadrat method was used, with 19.4 colonies m^{-2} (SE 5.7) and 30 colonies m^{-2} (SE 8.1), respectively (Fig. 5.5.1h). At each of the 4 sites surveyed in both years (ROT-01, ROT-02, ROT-05, and ROT-06), observed colony density increased between 2003 and 2005. This increase could result from recruitment, fragmentation of existing colonies, or both. Site-specific coral-colony densities and overall mean density were substantially lower in 2007 than in 2003 and 2005. However, this decline is likely an artifact of the use of a different method, the belt-transect method, to assess colony density in 2007. The method of placing quadrats used in 2003 and 2005 was highly biased towards surveying hard-bottom substrate where corals were present, whereas the belt-transect method used in 2007 assessed benthos that fell within transect belts regardless of the nature of the substrate.

Coral Generic Richness and Relative Abundance

Five REA benthic surveys of forereef habitats were conducted using the quadrat method at Rota during MARAMP 2003. At least 18 coral genera were observed at Rota. Generic richness ranged from 8 to 15 with a mean of 11.4 (SE 1.6) coral genera per site. The highest generic diversity was seen at both ROT-05 and ROT-06 in the northwest and west regions, and the lowest generic diversity was recorded at both ROT-02 and ROT-04 in the southeast and north regions (Fig. 5.5.1i).

Figure 5.5.1i. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2003. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to assess generic richness.



Favia, *Astreopora, Leptastrea*, and *Porites* were the most numerically abundant genera, contributing 31.2%, 17.4%, 11.8%, and 10.4% of the total number of colonies enumerated at Rota during MARAMP 2003. All other genera individually contributed < 10% of the total number of colonies. *Favia* dominated the coral fauna at ROT-04 and ROT-05 in the north and northwest regions, contributing 69.2% and 28.7% of the total number of colonies (Fig. 5.5.1i). *Porites* and *Favia* co-dominated at ROT-01 in the east region, contributing 26.2% and 23.1% of the total number of colonies. *Astreopora* dominated at ROT-02 in the southeast region, contributing 48.5% of the total number of colonies.

Five REA benthic surveys of forereef habitats were conducted using the quadrat method at Rota during MARAMP 2005. At least 24 coral genera were observed at Rota. Generic richness ranged from 7 to 17 with a mean of 12.8 (SE 1.7) coral genera per site. The highest generic diversity was seen at ROT-05 in the northwest region, and the lowest generic diversity was recorded at ROT-02 in the southeast region (Fig. 5.5.1j).

Favia, *Porites*, *Leptastrea*, and *Astreopora* were the most numerically abundant genera, contributing 19.9%, 21.8%, 13.9%, and 11.4% of the total number of colonies enumerated at Rota during MARAMP 2005. All other genera individually contributed < 10% to the total number of colonies. *Favia* dominated the coral fauna at ROT-02 and ROT-05 in the southeast and northwest regions, contributing 44.7% and 18.2% of the total number of colonies (Fig. 5.5.1j). *Favia*, *Porites*, and *Leptastrea* were found at similar abundance levels at ROT-07 in East Harbor in the south region, contributing 19%, 21.4%, and 23.8% of the total number of colonies. *Porites* dominated at ROT-01 in the east region, contributing 57% of the total number of colonies.

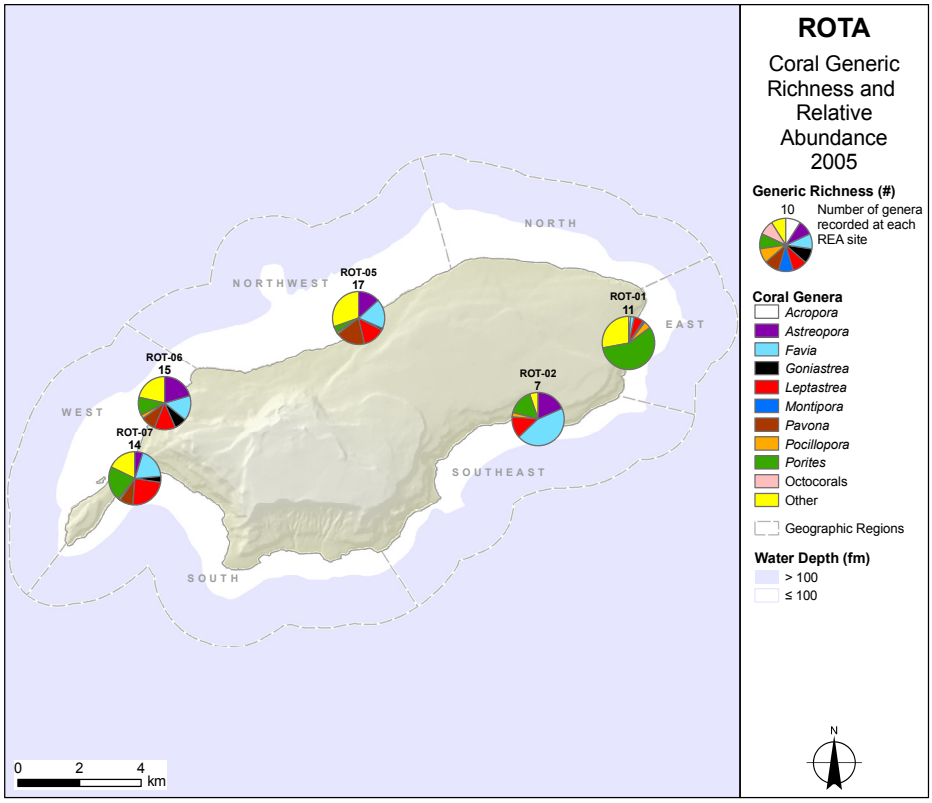


Figure 5.5.1j. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2005. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2005 to assess generic richness.

Six REA benthic surveys of forereef habitats were conducted using the belt-transect method at Rota during MARAMP 2007. At least 28 coral genera were observed at Rota, including the following 5 genera that had not been previously recorded at Rota in 2003 and 2005: *Cycloseris*, *Lobophytum*, *Palythoa*, *Sarcophyton*, and *Sinularia*. Generic richness ranged from 7 to 21 with a mean of 16.5 (SE 2.1) coral genera per site. The highest generic diversity was seen at ROT-07 in the south region, and the lowest generic diversity was recorded at ROT-03, also in the south region (Fig. 5.5.1k).

Porites and *Astreopora* were the most numerically abundant genera, contributing 35.4% and 11.2% of the total number of colonies enumerated at Rota during MARAMP 2007. All other genera individually contributed < 10% of the total number of colonies. *Porites* dominated the coral fauna at ROT-01, ROT-03, ROT-06, and ROT-07 in the east, south, and west regions, contributing 50.5%, 88.6%, 22.1%, and 40.3% of the total number of colonies (Fig. 5.5.1k). *Astreopora* dominated at ROT-02 and ROT-05 in the southeast and northwest regions, contributing 18.6% and 37.2% of the total number of colonies.

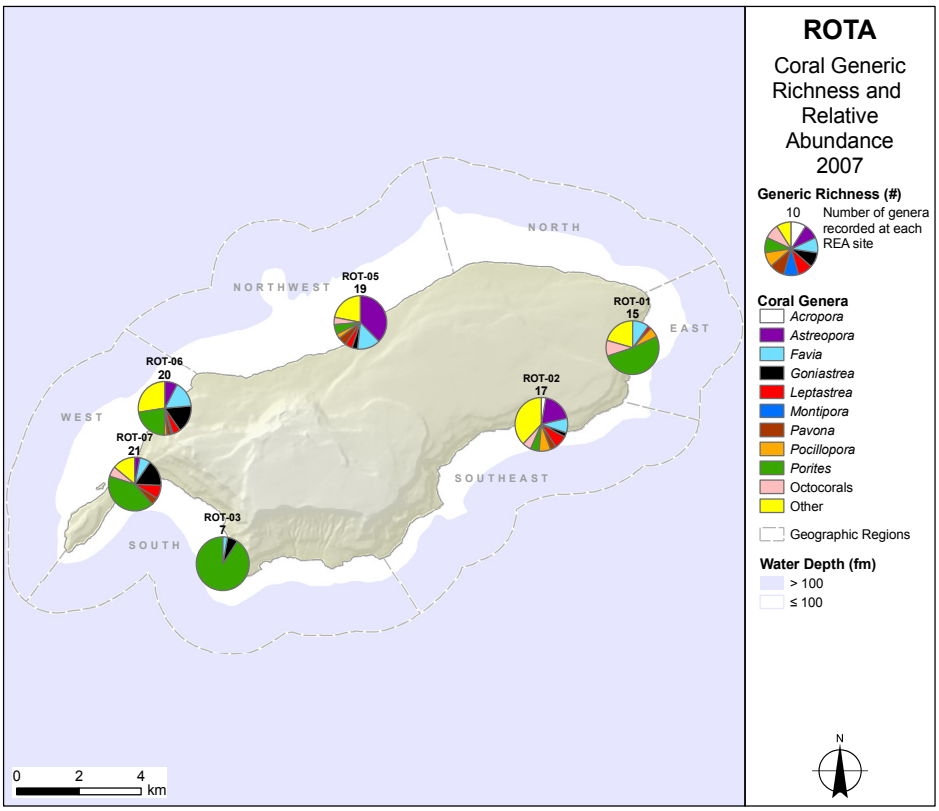


Figure 5.5.1k. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2007. The pie charts indicate percentages of relative abundance of key coral genera. The belt-transect method was used in 2007 to assess generic richness.

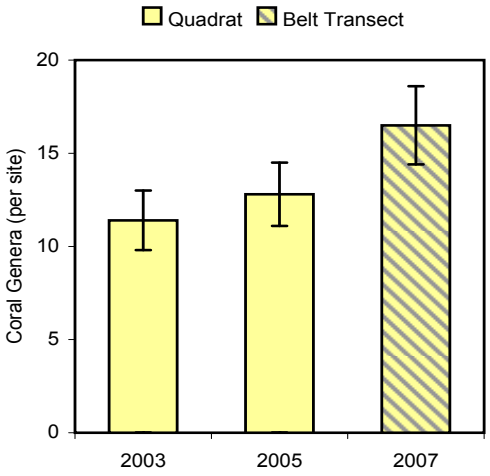


Figure 5.5.1l. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Rota during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to survey coral genera, but the belt-transect method was used in 2007. Error bars indicate standard error (± 1 SE) of the mean.

Site-specific estimates of generic richness across the 3 MARAMP survey years ranged from 7 to 21 on forereef habitats at Rota. Site-specific and overall mean values of generic richness were higher in 2007 than in previous survey years (Fig. 5.5.1l). The overall mean was 16.5 (SE 2.1) coral genera per site in 2007 and 11.4 (SE 1.6) and 12.8 (SE 1.7) coral genera per site in 2003 and 2005. This increase is likely a result of the difference in the size of the areas in which corals were censused: the survey area in 2007 was 50 m^2 per site, much larger than the 3.75–4 m^2 per site surveyed in 2003 and 2005 (see Chapter 2: "Methods and Operational Background," Section 2.4.5: "Corals and Coral Disease"). Additionally, the only octocoral genus assessed in 2003 and 2005 was *Heliopora*, whereas all octocoral genera were assessed in 2007.

Across the 3 MARAMP survey periods, 31 coral genera were observed on forereef habitats at Rota. *Favia*, *Porites*, *Astreopora*, and *Leptastrea* were important components of the coral fauna. *Favia* was the most numerically abundant taxon in 2003 and 2005, contributing 31.2% and 19.9% of the total number of colonies enumerated at Rota. *Porites* was the most numerically abundant taxon in 2007, contributing 35.4% of the total number of colonies. *Astreopora* was the second-most numerically abundant taxon in 2003 and 2007, contributing 17.4% and 11.2% of the total number of colonies. *Leptastrea* was the third-most numerically abundant taxon in 2003 and 2005, contributing 11.8% and 13.9% of the total number of colonies.

Coral Size-class Distribution

During MARAMP 2003, 5 REA benthic surveys of forereef habitats were conducted at Rota using the quadrat method. The coral size-class distribution from these surveys shows that the majority (75.5%) of corals had maximum diameters ≤ 5 cm (Fig. 5.5.1m). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 18.1%, 4.5%, and 1.9% of colonies recorded. No colonies with a maximum diameter > 40 cm were recorded. At each of the 5 REA sites, the majority (63%) of corals were in the smallest (≤ 5 cm) size class.

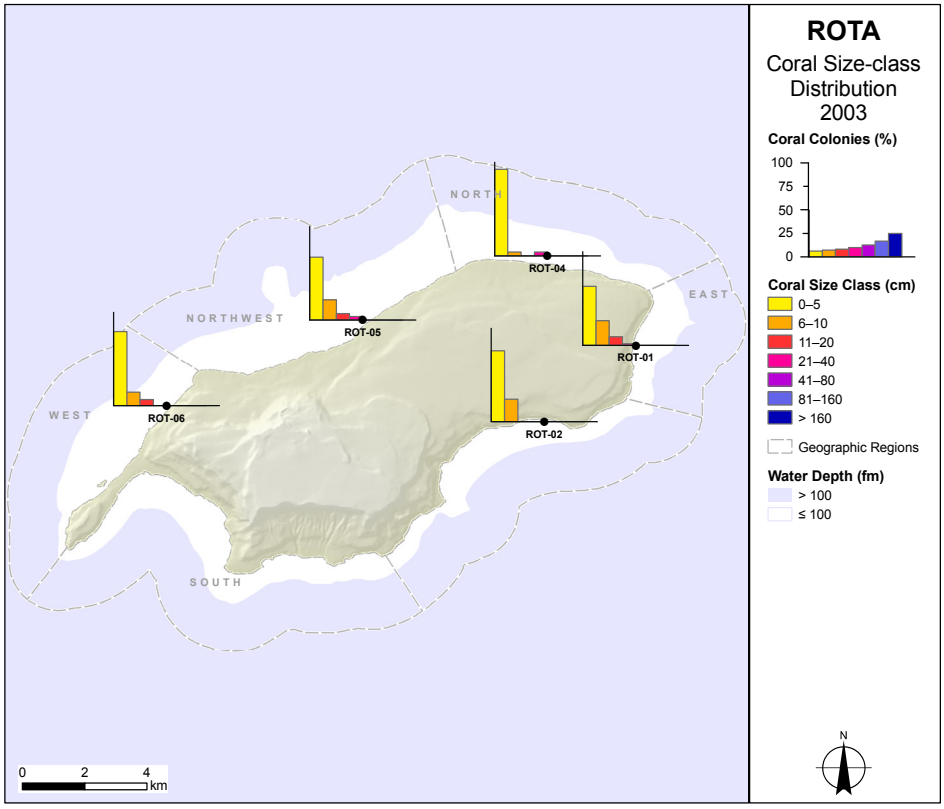


Figure 5.5.1m. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.

During MARAMP 2005, 5 REA benthic surveys of forereef habitats were conducted at Rota using the quadrat method. The coral size-class distribution from these surveys shows that the majority (86%) of corals had maximum diameters ≤ 5 cm (Fig. 5.5.1n). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 9%, 3.6%, and 1.4% of colonies recorded. No colonies with a maximum diameter > 40 cm were recorded. At each of the 5 REA sites, the majority (> 69%) of corals were in the smallest (≤ 5 cm) size class.

During MARAMP 2007, 6 REA benthic surveys of forereef habitats were conducted at Rota using the belt-transect method. The coral size-class distribution from these surveys shows that the majority (76.9%) of corals had maximum diameters ≤ 10 cm (Fig. 5.5.1o). The first 5 size classes (0–5, 6–10, 11–20, 21–40, and 41–80) accounted for 35.2%, 41.7%, 14.8 %, 6.2%, and 1.6% of colonies recorded. Only 0.6% of corals had a maximum diameter > 80 cm. The highest proportions of midsize (11–40 cm) and large (> 40 cm) colonies combined were found at ROT-01 and ROT-05 in the east and northwest regions, contributing 43.2% and 34.3% of colonies recorded, respectively. The highest proportion of small (≤ 10 cm) colonies was found at ROT-02 and ROT-06 in the southeast and west regions, accounting for 99.1% and 91.1% of colonies recorded.

Site-specific and overall distributions of estimated coral size classes on forereef habitats at Rota are affected by inherent biases in the methods used to census and size corals. During MARAMP 2003 and 2005, corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. During MARAMP 2007, corals whose center fell within a belt transect (1 × 25 m) were tallied and binned into 1 of 7 size classes based on visual estimates of maximum colony diameter. This method

is better suited to capturing large colonies, but the larger census area likely reduces the number of very small colonies (≤ 5 cm) that are observed and recorded. For more on these survey methods, see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease."

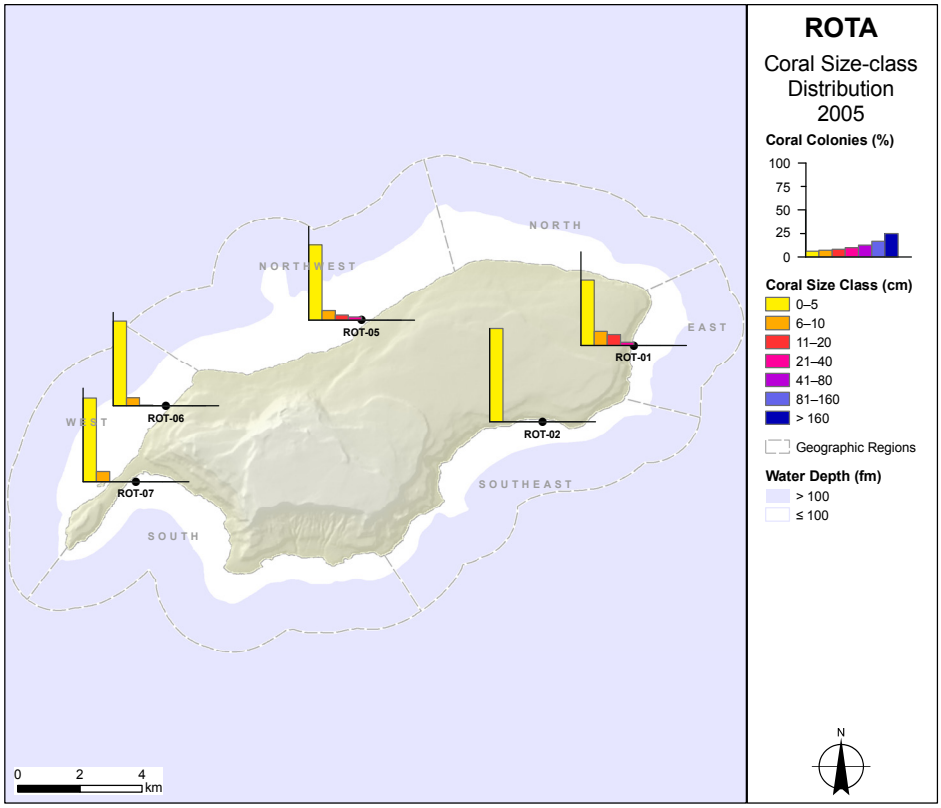


Figure 5.5.1n. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2005. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2005 to size corals.

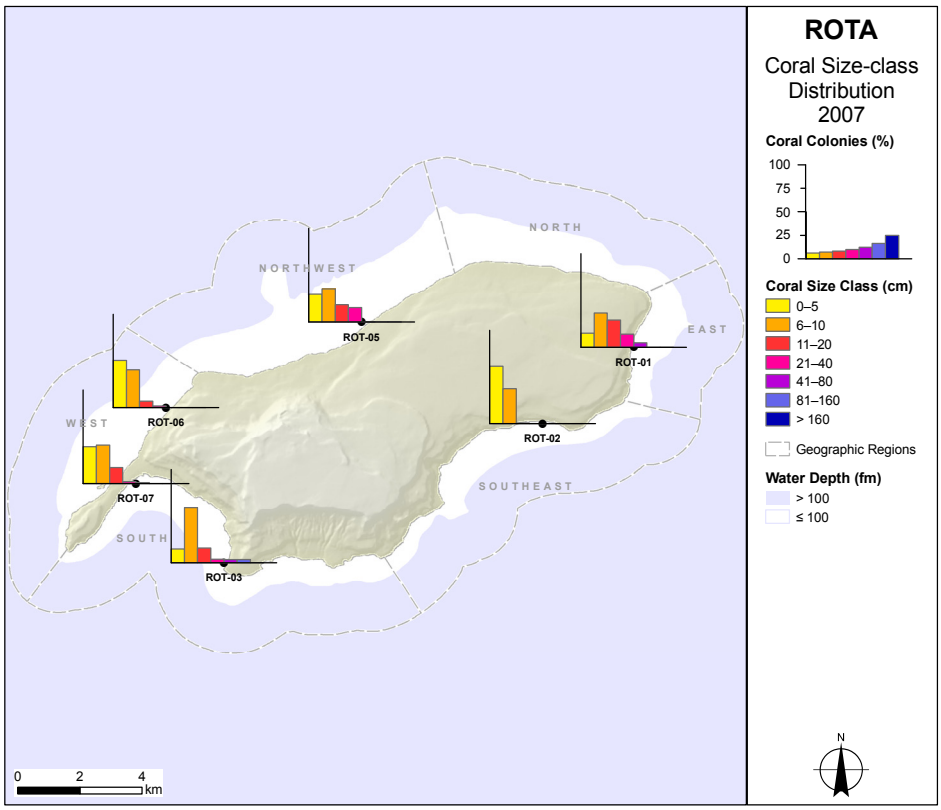


Figure 5.5.1o. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The belt-transect method was used in 2007 to size corals.

These methodological biases are reflected in the size-class data by survey year. Observed colony densities were higher in in 2003 and 2005 than in 2007 (Fig. 5.5.1p). In 2003 and 2005, more than three-quarters (75.5% and 86.2%) of all colonies censused on forereef habitats at Rota had a maximum diameter ≤ 5 cm, but in 2007 only 35.2% of colonies fell into this smallest size class (Fig. 5.5.1p). Comparing size-class data between survey years when different methods were used is, therefore, inappropriate. Only ROT-01, ROT-02, ROT-05, and ROT-06 in the east, southeast, northwest, and west regions were surveyed with the same quadrat method in 2003 and 2005. At all 4 REA sites, between these 2 survey periods, the proportion of colonies in the smallest size class (≤ 5 cm) increased substantially and the proportion of colonies in other size classes decreased, suggesting that either increased recruitment, colony fragmentation, or both occurred during this period.

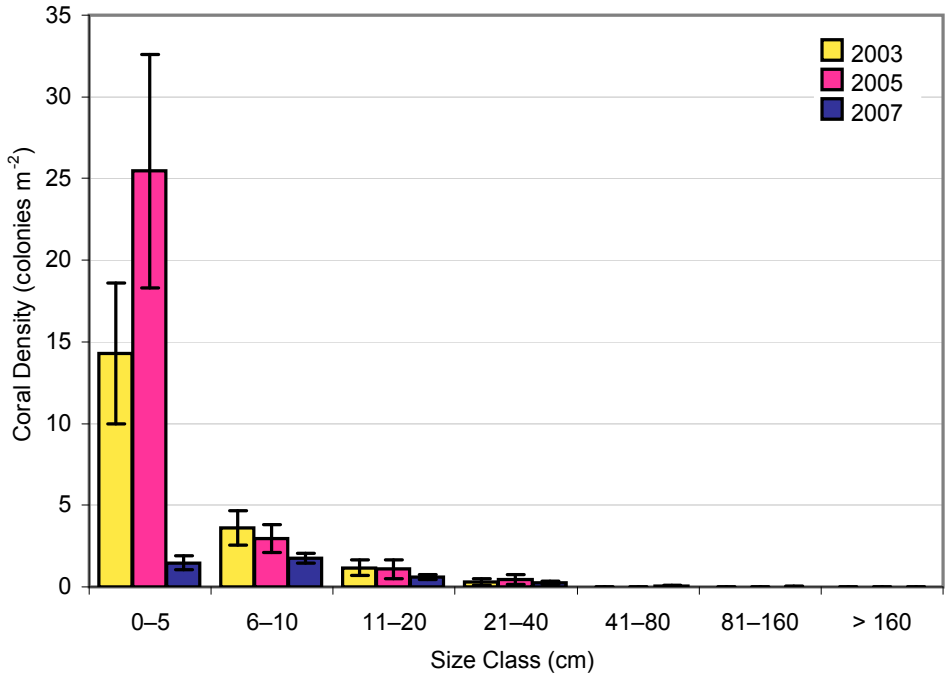


Figure 5.5.1p. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to size corals, but the belt-transect method was used in 2007. Error bars indicate standard error (± 1 SE) of the mean.

5.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted on forereef habitats using the belt-transect method at 6 sites at Rota, covering a total area of over 1700 m^2. Surveys detected 5 cases of coral disease, translating to an overall mean prevalence of 0.06% (SE 0.03), excluding predation. Bleaching was the only disease state observed at Rota, detected at ROT-01, ROT-05, and ROT-06 in the east, west, and northwest regions. Relative to colony density, the highest value of disease prevalence was 0.17%, observed at ROT-05 (Fig. 5.5.2a; the values of overall prevalence shown in this figure include predation). All cases of bleaching at Rota were recorded on corals of the genus *Astreopora*.

Cases of coral predation attributable to crown-of-thorns seastars (*Acanthaster planci)* or corallivorous snails, such as snails from the genus *Drupella*, were also observed at Rota, particularly at ROT-03 near Puntan Pona in the south region and at ROT-06 southwest of Puntan Sailigai in the west region (Fig. 5.5.2b). A variety of coral genera were the main prey of crown-of-thorns seastars (COTS) and snails, including *Pavona*, *Stylophora*, *Goniastrea*, *Pocillopora*, *Astreopora*, and *Porites*, with the greatest number of cases (40%) detected on *Astreopora* corals. For more information about COTS at Rota, see Section 5.7.1: "Benthic Macroinvertebrate Surveys".

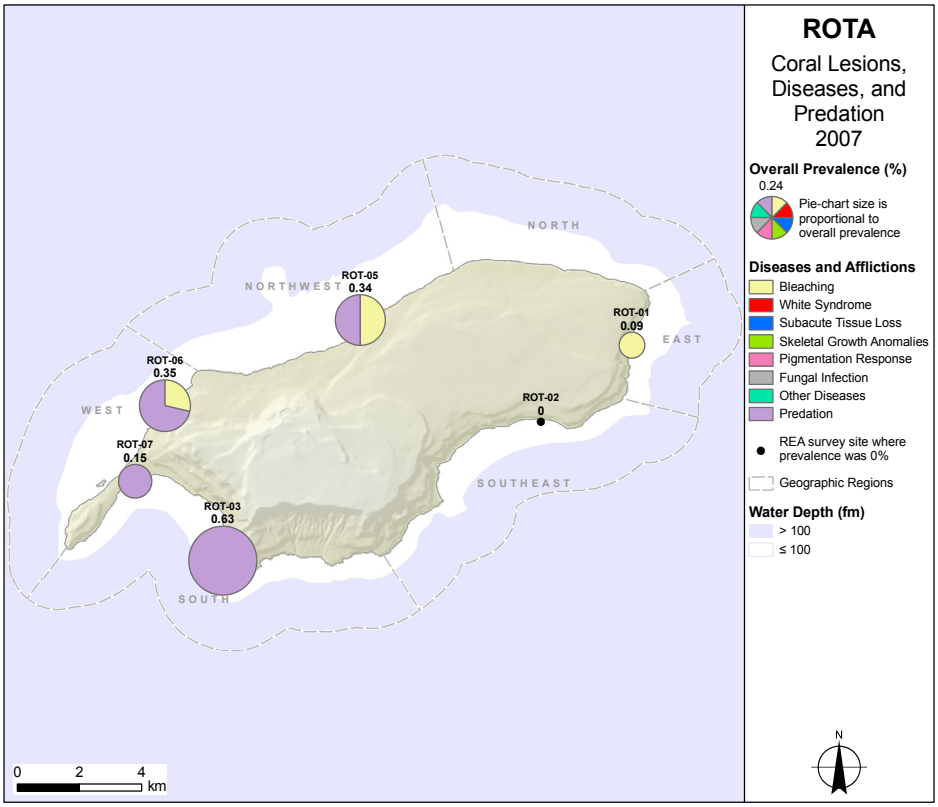


Figure 5.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie charts indicate disease-specific prevalence.

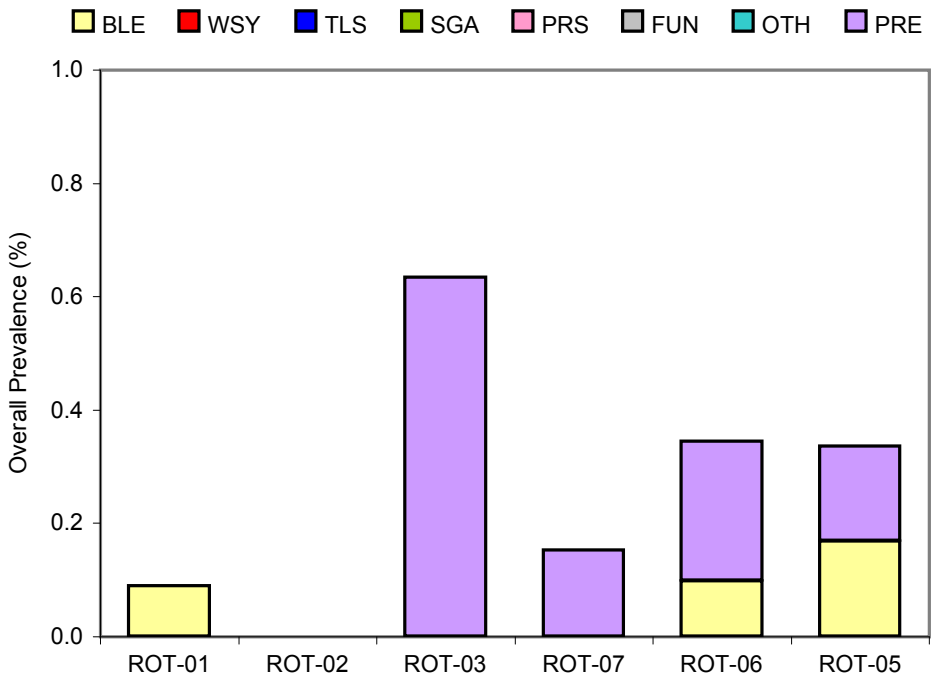


Figure 5.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesions of unknown etiology; PRE: predation by COTS or corallivorous snails.

5.6 Algae and Algal Disease

5.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Rota was 54% (SE 1.6). Observations of macroalgal cover in 2003 included both macroalgae and turf algae (see Chapter 2: "Methods and Operational Background"). The survey with the highest mean macroalgal cover of 77%, within a range of 50.1%–100%, occurred in the east region (Fig. 5.6.1a, top left panel). In this area, pavement was the dominant habitat type, with low complexity observed over 6 segments. The second-greatest mean macroalgal cover of 76%, within a range of 62.6%–100%, was recorded during a survey in the north region, where the dominant habitat was pavement for all segments; low complexity was observed for the majority of segments. The survey with the lowest macroalgal cover of 30%, within a range of 20.1%–40%, occurred in the northwest region in a mostly continuous-reef habitat of medium to high complexity, with half of the observations characterizing complexity at medium-high.

TOAD surveys completed at Rota during MARAMP 2003 were conducted at depths of 53–188 m. Analyses of TOAD video footage obtained from 7 surveys in the west, south, and southeast regions suggest that macroalgal cover was generally low in these areas (Fig. 5.6.1a, top left panel). In some small sections, these surveys recorded macroalgal cover up to 100%, but no macroalgae were observed in the majority of images. In contrast, analyses of TOAD video footage obtained from 2 surveys in the north region suggest sections with consistent macroalgal cover of 20.1–100%. Similarly, 1 survey in the northwest region recorded, over the southern end of its track, consistent macroalgal cover of 40.1%–100% at depths of 83–100 m.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats at Rota was 56% (SE 2). The survey with the highest mean macroalgal cover of 71%, within a range of 40.1%–100%, occurred in the northwest region over a low-complexity habitat (Fig. 5.6.1a, middle left panel). No data were recorded on the dominant habitat type during towed-diver surveys conducted in 2005. The survey with the lowest mean macroalgal cover of 37%, within a range of 10.1%–50%, occurred in the south region in Sasanhaya Bay near REA site ROT-03 over habitat of mixed complexity that ranged from medium-low to high (for place-names and their locations, see Figure 5.2a in Section 5.2: "Survey Effort").

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats at Rota was 39% (SE 2). The survey with the highest mean macroalgal cover of 69%, within a range of 40.1%–100%, occurred in the southeast region west of Puntan Sagua`gahaga (Fig. 5.6.1a, bottom left panel). Habitat in this area was primarily of medium-low complexity, and species of the green algal genera *Halimeda* and *Microdictyon* were observed during all survey segments, with *Microdictyon* the dominant genera for 6 of the 10 segments. The survey with the lowest mean macroalgal cover of 13%, within a range of 1.1%–30%, occurred in the south region near Puntan Pona. In this area, habitat complexity ranged from medium-low to high, and an abundance of turf, brown, and red cyanobacteria was observed over the first 6 segments.

During MARAMP 2007, 6 REA benthic surveys of forereef habitats at Rota were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 0% to 49% with an overall mean of 20% (SE 7.2). The survey with the highest macroalgal cover occurred in the southeast region at ROT-02 (Fig. 5.6.1b). All other surveys recorded macroalgal cover ≤ 27.5%. No macroalgae were found at ROT-07 in the south region in East Harbor.

Turf-algal cover from these REA benthic surveys ranged from 28.4% to 77.5% with an overall mean of 56% (SE 6.9). The highest turf-algal cover was observed at ROT-07 (Fig. 5.6.1b). High levels of turf-algal cover were also found in the northwest region at ROT-05, with a value of 62.7%, and in the west region at ROT-06. The lowest turf-algal cover was recorded in the southeast region at ROT-02.

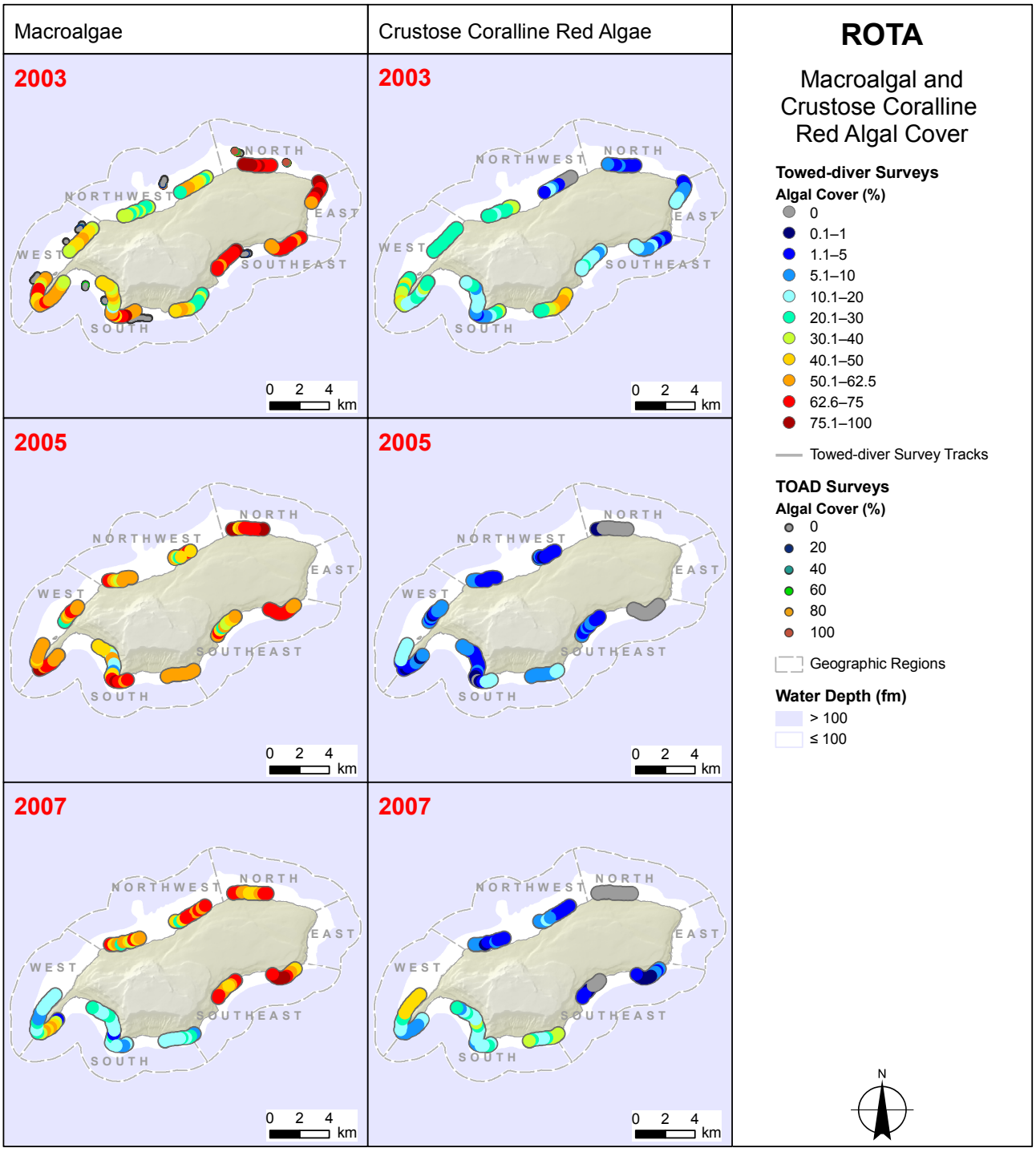


Figure 5.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Rota was 18% (SE 1). The survey with the highest mean cover of crustose coralline red algae of 34%, within a range of 20.1%–50%, occurred in the west region (Fig. 5.6.1a, top right panel), where pavement was the dominant habitat and complexity was predominantly medium-high with 1 segment of high and 2 segments of medium complexity. The survey with the lowest mean crustose-coralline-red-algal cover of 4%, within a range of 1.1%–10%, occurred in the north region near Mochon Point over habitat that was primarily low complexity pavement.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats at Rota was 5% (SE 0.44). The survey with the highest cover of 13%, within a range of 1.1%–20%, occurred in the west region over habitat of medium to medium-low complexity (Fig. 5.6.1a, middle right panel). Surveys with no crustose coralline red algae occurred over predominantly low-complexity habitat in the north region west of Mochon Point and in the southeast region near Puntan Sagua`gahga. During the survey conducted in the southeast region, the diver noted "a grey cylindrical sponge everywhere" for the first 6 segments.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats at Rota was 12% (SE 1). The survey with the highest mean cover of crustose coralline red algae of 38%, within a range of 10.1%–50%, occurred in the west region (Fig. 5.6.1a, bottom right panel), where habitat was primarily of medium-high complexity and a variety of habitat types were encountered, including continuous reef, steep wall, moderate slope with boulders at the bottom, spur and groove, and pavement. In the north region near Mochon Point, a survey found no crustose coralline red algae. Habitat in this area was predominantly flat continuous reef of medium-low complexity, except for the first 2 segments where pavement was the dominant habitat and species of the green algal genus *Halimeda* and the brown algal genus *Padina* were recorded.

During MARAMP 2007, REA benthic surveys of forereef habitats at Rota were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 9.8% with an overall mean of 5% (SE 1.6). The REA survey with the highest crustose-coralline-red-algal cover occurred in the east region at ROT-01 (Fig. 5.6.1b). No crustose coralline red algae were recorded in the southeast region at ROT-02.

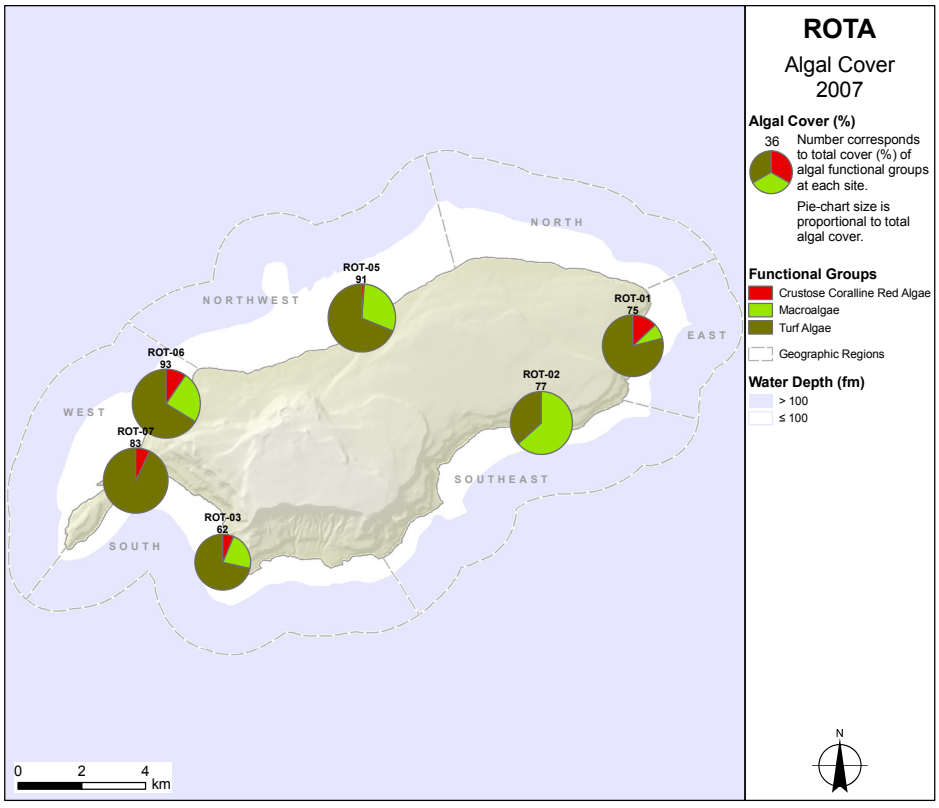


Figure 5.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method at Rota during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Algal Cover: Temporal Comparison

Islandwide mean cover of macroalgal populations around Rota, based on towed-diver surveys of forereef habitats, was nearly identical in 2003 and 2005 (Fig. 5.6.1c) with 54% (SE 2) and 56% (SE 2) and was lower in 2007 at 39% (SE 2). When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

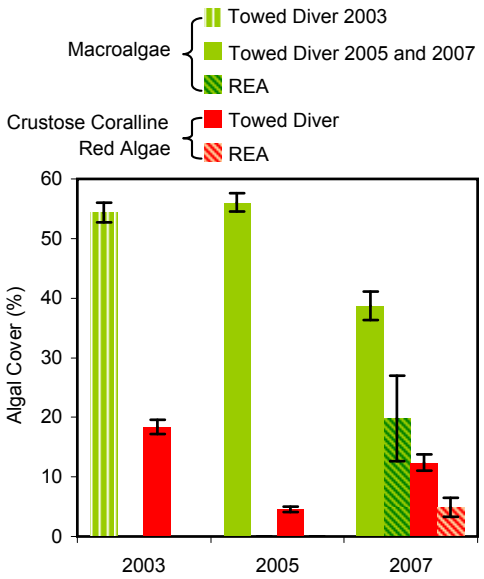


Figure 5.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Rota during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted at Rota in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Across the 3 MARAMP survey years, high macroalgal cover was consistently recorded in the north and east regions during towed-diver surveys. The lowest levels of macroalgal cover were not quite as consistent but were observed in the south region in 2005 and 2007. In 2003, the lowest macroalgal cover occurred in the northwest region.

The observed overall mean cover of crustose coralline red algae on forereef habitats at Rota decreased from 18% (SE 1) in 2003 to 5% (SE 0.44) in 2005 and increased to 12% (SE 1) in 2007. The locations of the lowest and highest values in cover of crustose coralline red algae were consistent for the 3 MARAMP survey years. The towed-diver survey with the highest crustose-coralline-red-algal cover was always at the western tip of Rota. The survey with the lowest cover was always in the north region near Mochon Point, although, in 2005, no crustose coralline red algae were recorded in the southeast region near Puntan Sagua`gahga.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites has not been undertaken yet for the southern islands of the Mariana Archipelago. Ultimately, based on microscopic analysis that may be done in the future, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 5 sites on forereef habitats at Rota. In the field, 22 macroalgal genera (8 red, 3 brown, and 11 green), containing at least 29 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, cyanophytes, and branched calcified red algae—were observed. ROT-05 in the northwest region had the highest macroalgal generic diversity with 15 genera, containing 18 species, documented in the field. The lowest macroalgal generic diversity was found in the south region at ROT-03 near Puntan Pona and the Sasanhaya Fish Reserve with 3 species representing 3 genera recorded.

Chlorophytes were the most widely distributed algal taxa at every site surveyed at Rota in 2003. Species of the genus *Halimeda* were the most common component of macroalgal communities, occurring in 63.3% of sampled photoquadrats, and this green algal genus was the only genus recorded at all sites surveyed at Rota in 2003 (Fig. 5.6.1d). Species of the

green algal genera *Microdictyon* and *Dictyosphaeria* were also common, occurring in 36.7% and 33.3% of sampled photoquadrats. Species of the green algal genus *Neomeris* were observed in 20% of sampled photoquadrats. Species of the green algal genus *Caulerpa* and the red algal genus *Laurencia* were equally numerous, each occurring in 16.7% of photoquadrats sampled at Rota. Species of the brown algal genus *Dictyota* occurred in 15% of sampled photoquadrats. Other observed genera occurred in < 10% of sampled photoquadrats. Green algal genera dominated at ROT-01 in the east region. Of the 12 species recorded in the field at this REA site, all but 1 was a green alga, and the genera *Halimeda, Dictyosphaeria, Microdictyon*, and *Neomeris* were very abundant. A similar pattern of high green algal abundance was observed near Puntan Sagua`gahga in the southeast region at ROT-02, where an additional green algal genus, *Bornetell*, was observed in 41.7% of sampled photoquadrats. Some genera were recorded with high frequency at a single site (for example, species of the genus *Laurencia* were found in 75% of photoquadrats sampled at ROT-02) but occurred in very few or none of the photoquadrats sampled at other sites, thus, greatly reducing their overall occurrence when considered on an islandwide scale. In addition to the diverse representation of green algae, species of red algal genera, such as *Dichotomaria*, *Galaxaura*, and *Portiera*, were observed frequently in ~ 25% of photoquadrats sampled at ROT-05 in the northwest region.

Turf algae, crustose coralline red algae, and cyanophytes were all common in 2003, occurring in 100%, 36.7%, and 48.3% of photoquadrats sampled at Rota. Recorded in all photoquadrats sampled at all sites, turf-algal communities were ubiquitous. Crustose coralline red algae were commonly observed at all sites except ROT-02 in the southeast region and typically varied in occurrence within a range of 25%–91.7%; however, branched coralline red algae were recorded in 8.3% of photoquadrats sampled at ROT-02. Cyanobacteria were found in 16.7%–83.3% of sampled photoquadrats.

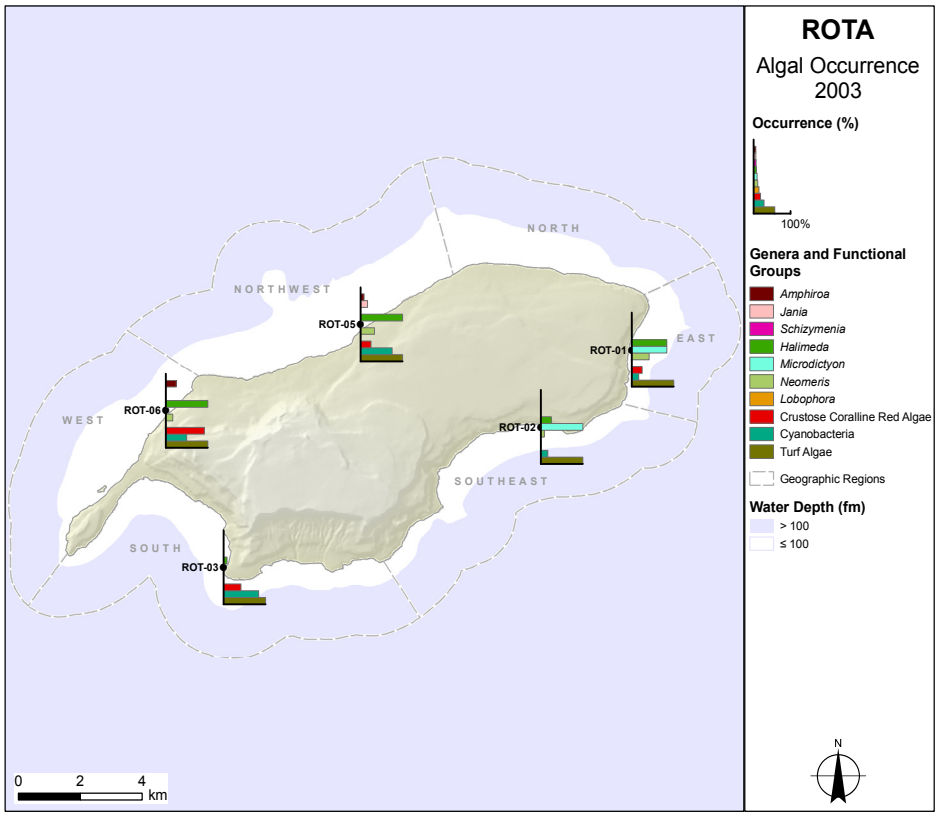


Figure 5.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Rota during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2005, REA benthic surveys were conducted at 6 sites on forereef habitats at Rota. In the field, 23 macroalgal genera (7 red, 12 green, and 4 brown), containing at least 23 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. ROT-01 in the east region had the highest macroalgal generic diversity with 12 genera, each containing 1 species, documented in the field. The lowest macroalgal generic diversity was found in the southeast region at ROT-02 with 8 species representing 8 genera recorded.

No macroalgal genus was recorded at every site in 2005; however, species of the genus *Halimeda* were observed at all but one site and were the most widely distributed algae at Rota (Fig. 5.6.1e), occurring in 66.7% of sampled photoquadrats. Species of the genera *Dictyota* and *Dictyosphaeria* and the calcified red algal genera *Amphiroa* and *Jania* were all common, occurring in 38.9%, 34.7%, 29.2%, and 27.8% of sampled photoquadrats. Species of *Microdictyon* were recorded

with frequent occurrence at 2 sites, ROT-01 (33.3%) and ROT-02 (75%), both of which also contained a high number of other green algal genera. Two thirds of the 12 genera recorded at ROT-01 were chlorophytes and were the only algal genera recorded in > 35% of sampled photoquadrats. At ROT-02, all 8 genera observed in the field were green algae. Since ROT-01 and ROT-02 are near each other in the east and southeast regions, it's reasonable to speculate that environmental conditions favor the growth of green algae in this region over brown or red algae. Furthermore, these sites supported a higher diversity and greater occurrence of green algae than was observed at nearby islands. Species of *Neomeris* were also fairly common, occurring in ≥ 25% of sampled photoquadrats at 5 of the 6 sites surveyed at Rota and in 26.4% of photoquadrats sampled overall at Rota. Other genera commonly encountered at Rota included *Galaxaura*, which occurred in 19.4% of photoquadrats sampled, largely resulting from its presence in 100% of photoquadrats sampled at ROT-05, and *Dictyota*, which occurred in 66.6%, 58.3%, 83.3%, and 25% of sampled photoquadrats at ROT-03, ROT-05, ROT-06, ROT-07.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2005, occurring in 97.2%, 48.6%, and 88.9% of photoquadrats sampled at Rota. Turf-algal communities, ubiquitous at all sites, were found in 75%–100% of photoquadrats sampled at any given site. Recorded at every site, crustose coralline red algae were observed in 8.3%–100% of sampled photoquadrats, and cyanobacteria were a prominent component of the algal community at all sites, occurring in 66.7%–100% of sampled photoquadrats.

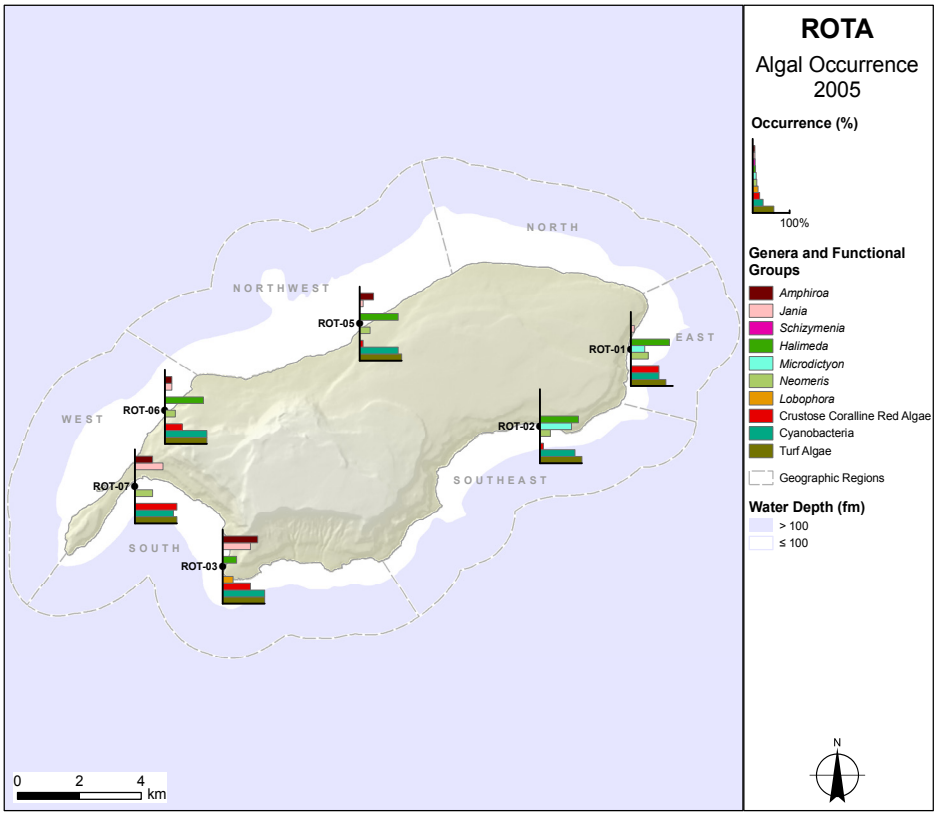


Figure 5.6.1e. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats at Rota during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2007, REA benthic surveys were conducted at 6 sites on forereef habitats at Rota. In the field, 19 macroalgal genera (7 red, 10 green, and 2 brown), containing at least 28 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. ROT-05 in the northwest region had the highest macroalgal generic diversity with 11 genera, containing 13 species, documented in the field. The lowest macroalgal generic diversity was found in the south region at ROT-03 near Puntan Pona and Coral Gardens in the Sasanhaya Fish Reserve, with 5 species representing 5 genera recorded.

Species of the genus *Halimeda* were common at every site surveyed at Rota in 2007, except at ROT-07 in the south region in East Harbor, occurring in 72.2% of sampled photoquadrats at Rota (Fig. 5.6.1f). Of the 20 macroalgal species tentatively identified in the field, only a select few showed any spatial pattern of distribution, with no genus occurring at all sites. Species of the green alga genera *Halimeda*, *Neomeris*, and *Chlorodesmis* were each recorded at 4 of the 6 sites surveyed. Green algae dominated at ROT-01 and ROT-02 with only occasional observations of species of the brown algal genus *Padina*, the green algal genus *Rhipiliopsis*, and the red algal genera *Jania* and *Galaxaura*. Species of the genus *Amphiroa* were very

common at ROT-03, near Puntan Pona in the south region, and ROT-05 in the northwest region, occurring in 91.7% and 75% of sampled photoquadrats, but far less common in East Harbor at ROT-07, where it occurred in only 25% of sampled photoquadrats. Despite the low occurrence of *Amphiroa* at ROT-07, this genus was the most frequently observed taxon because of the low abundance of the 5 other genera recorded at this site. Species of the genus *Microdictyon* was abundant at ROT-01 and ROT-02 in the east and southeast regions, occurring in 50% and 100% of sampled photoquadrats at these sites; but were absent from all other sites. The green algae *Caulerpa* and *Avrainvillea* were the next-most frequently recorded genera, occurring in 65.3% and 19.4% of sampled photoquadrats.

Turf algae, crustose coralline red algae, and cyanobacteria were all fairly common in 2007, occurring in 47.2%, 30.6%, and 54.2% of photoquadrats sampled at Rota. Turf algae were not recorded at ROT-01 in the east region; however, this functional group occurred in 25%–91.7% of photoquadrats sampled at the other sites surveyed at Rota. Recorded at all sites, cyanobacteria were ubiquitous and represented a prominent component of the algal community, occurring in 33.3%–75% of sampled photoquadrats.

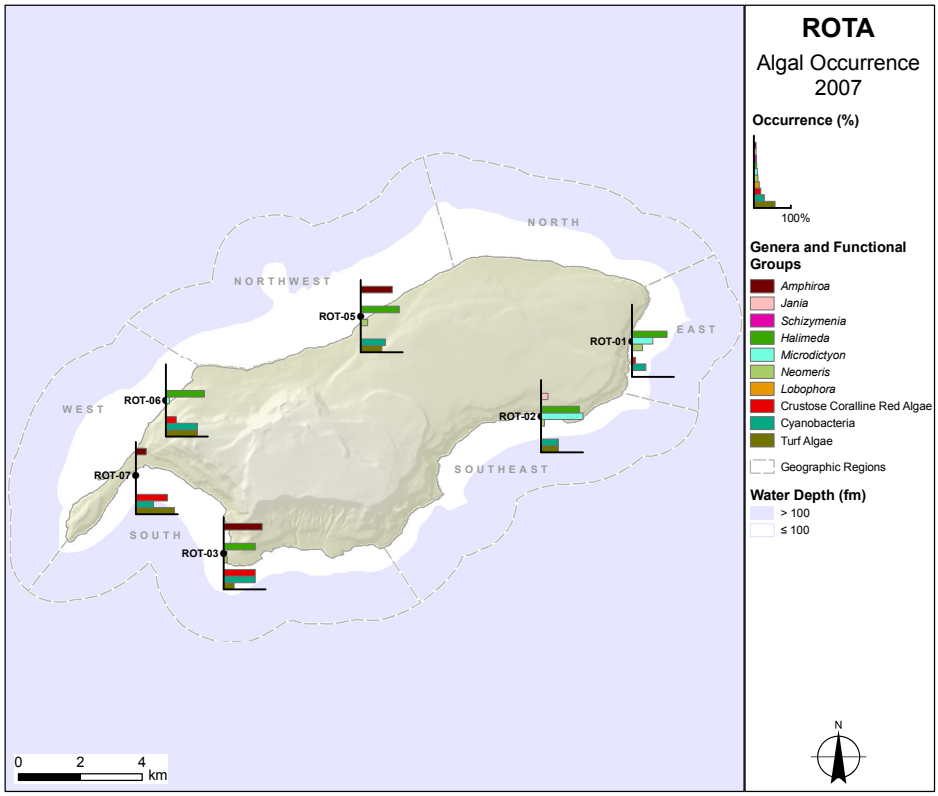


Figure 5.6.1f. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats at Rota during MARAMP 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

The number of macroalgal genera recorded on forereef habitats at Rota was 22 and 23 during MARAMP 2003 and 2005 but decreased to 19 during MARAMP 2007. Such a small reduction in generic diversity is not enough to suggest environmental or benthic compositional change, since seasonal variability can affect greatly algal abundance and MARAMP 2007 took place during a different season than did MARAMP 2003 and 2005 (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). The overall occurrence of macroalgal genera did not fluctuate greatly between MARAMP survey periods. Species of the genus *Halimeda* consistently exhibited the highest occurrence during the 3 survey years, occurring in 63.3%–72.2% of sampled photoquadrats (Fig. 5.6.1g). The occurrence of species of the genus *Amphiroa* was low in 2003, when it was only recorded in 6.7% of sampled photoquadrats; however, it was found in 29.1% and 31.9% of sampled photoquadrats in 2005 and 2007. ROT-01 and ROT-02 remained dominated by green algae across MARAMP survey periods, and *Jania*, *Porteria*, and *Padina* were the only brown or red algal genera recorded at these sites.

Turf algae occurred in 100%, 97.2%, and 47.2% of photoquadrats sampled on forereef habitats at Rota during MARAMP 2003, 2005, and 2007. Observed occurrence of turf-algae declined by 50% between 2003 and 2007. Crustose coralline red algae occurred in 30.6%–48.6% of photoquadrats sampled across survey years, while cyanobacteria occurred in 48.3%–88.9% of sampled photoquadrats. No clear patterns of increasing or decreasing abundance of these functional groups were observed.

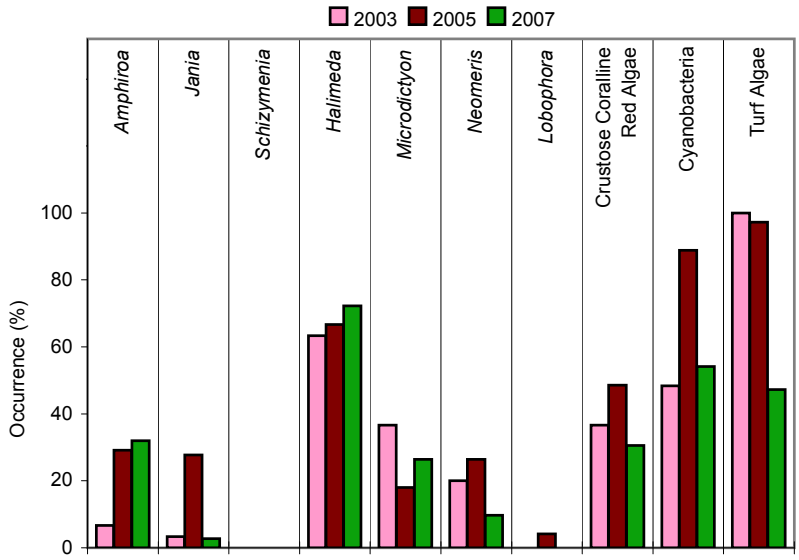


Figure 5.6.1g. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Rota during MARAMP 2003, 2005, and 2007.

5.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 6 sites on forereef habitat at Rota. These surveys covered a total reef area of more than 1700 m^2 and detected 13 cases. These numbers translate to an overall mean density of 0.8 cases 100 m^{-2} (SE 0.4). Disease of coralline algae was found on reefs in all regions surveyed, although no disease was recorded at 1 of 2 sites surveyed in the south region, ROT-3 near Puntan Pona (Fig. 5.6.2a). Only 1 major type of coralline-algal disease was observed at Rota: coralline lethal orange disease, present at 5 of the 6 sites surveyed. The greatest density of 2.7 cases 100 m^{-2} was found at ROT-01 in the east region. At ROT-02 and ROT-05 in the southeast and northwest regions, a much lower density of 0.7 cases 100 m^{-2} was recorded.

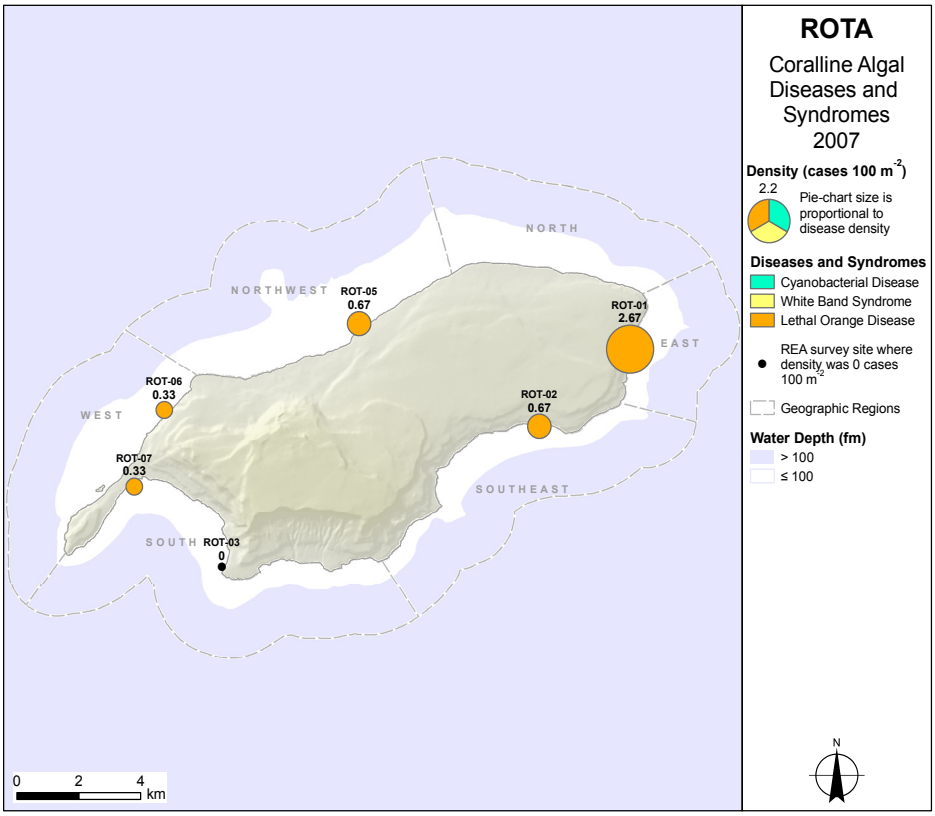


Figure 5.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats at Rota during MARAMP 2007. The color-coded portions of the pie charts indicate disease-specific density.

5.7 Benthic Macroinvertebrates

5.7.1 Benthic Macroinvertebrates Surveys

Four groups of organisms—sea urchins, sea cucumbers, giant clams, and crown-of-thorn seastars (COTS)—were monitored on forereef habitats around the island of Rota through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that have been sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 5 REA surveys and 12 towed-diver benthic surveys were conducted, and in 2005, 6 REA surveys and 11 towed-diver benthic surveys were performed around Rota. In 2007, because of the lack of a scientific diver with expertise in invertebrates, no REA surveys were conducted; however, 10 towed-diver benthic surveys were completed. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Minor fluctuations in observed macroinvertebrate densities on forereef habitats between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density around Rota—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 5.7.1d, h, l, and p). Because of differences in survey methodology and in REA survey effort, with 5 surveys in 2003, 6 surveys in 2005, and no surveys in 2007, temporal comparisons of REA data are not presented (see Chapter 2: "Methods and Operational Background, Section 2.4.7: "Benthic Macroinvertebrates").

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at 3 of the 5 REA sites surveyed and in 9 of the 12 towed-diver surveys conducted around Rota (Fig. 5.7.1a). The overall mean density of giant clams from REA surveys was 1.2 organisms 100 m^{-2} (SE 0.58), and the islandwide mean density from towed-diver surveys was 0.03 organisms 100 m^{-2} (SE 0.005). Results from REA surveys suggest that giant clams were most abundant at REA site ROT-03, near Puntan Pona with a mean density of 3 organisms 100 m^{-2} (for place-names and their locations, see Figure 5.2a in Section 5.2: "Survey Effort"). Among all towed-diver surveys around Rota, the survey completed between Angyuta Island and Puntan Taipingot had the highest mean density of giant clams with 0.09 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.31 organisms 100 m^{-2}.

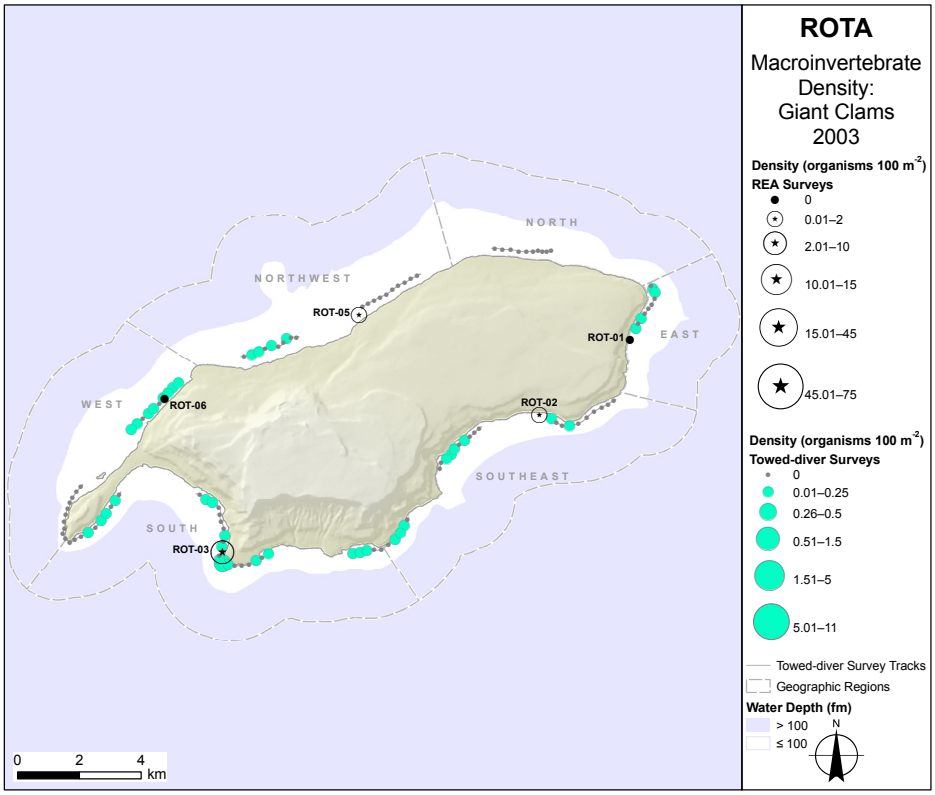


Figure 5.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Rota during MARAMP 2003.

During MARAMP 2005, giant clams were observed at 1 of the 6 REA sites surveyed and in 7 of the 11 towed-diver surveys conducted at Rota (Fig. 5.7.1b). REA site ROT-07 had a density of 2 organisms 100 m^{-2}. The overall mean density of giant clams from towed-diver surveys was 0.01 organisms 100 m^{-2} (SE 0.003). The towed-diver survey in the southeast region from Puntan As Fani past Puntan Sagua'gahga had the highest mean density of giant clams with 0.024 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.138 organisms 100 m^{-2}.

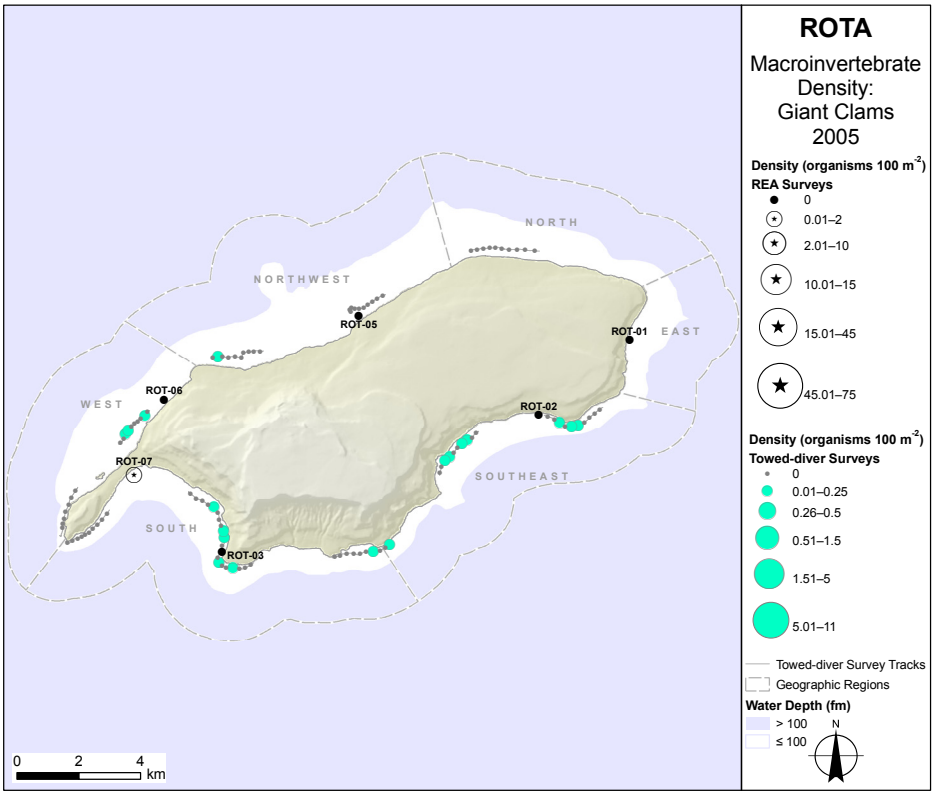


Figure 5.7.1b. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2005

During MARAMP 2007, giant clams were observed in 6 of the 10 towed-diver surveys conducted at Rota (Fig. 5.7.1c) with an overall mean density of 0.008 organisms 100 m^{-2} (SE 0.002). Among all towed-diver surveys at this island, the towed-diver survey completed between Afuefuniya Point and Puntan Malilok on the southern coast had the highest mean density of giant clams with 0.024 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.051 organisms 100 m^{-2}.

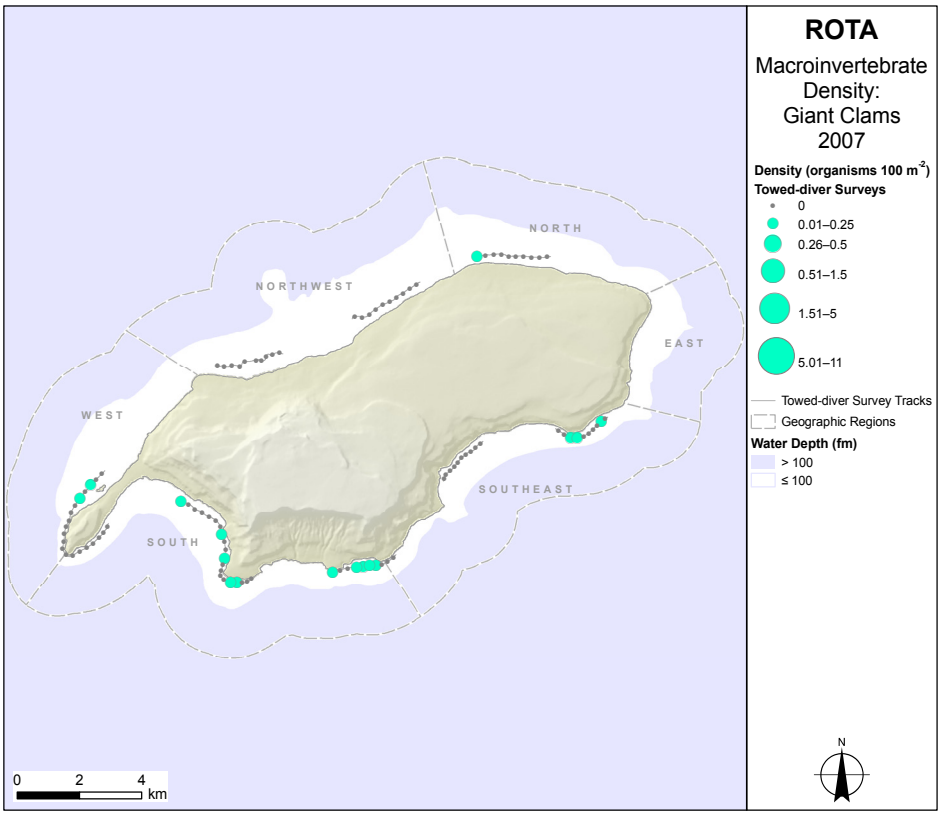


Figure 5.7.1c. Densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2007.

Towed-diver benthic surveys suggested low giant clam abundance at Rota during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago. In the 3 survey years, densities of giant clams were low in the north and northwest regions. The overall observed mean density of giant clams was higher in 2003 than in 2005 and 2007 (Fig. 5.7.1d). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

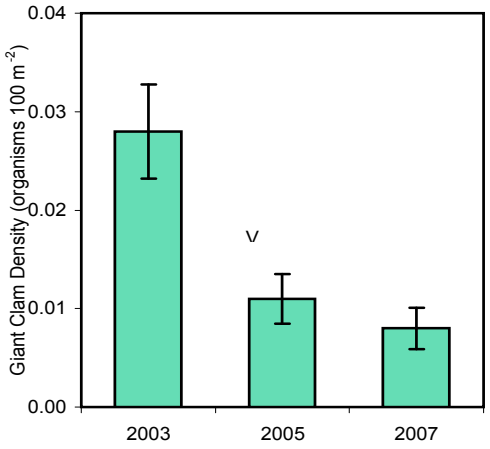


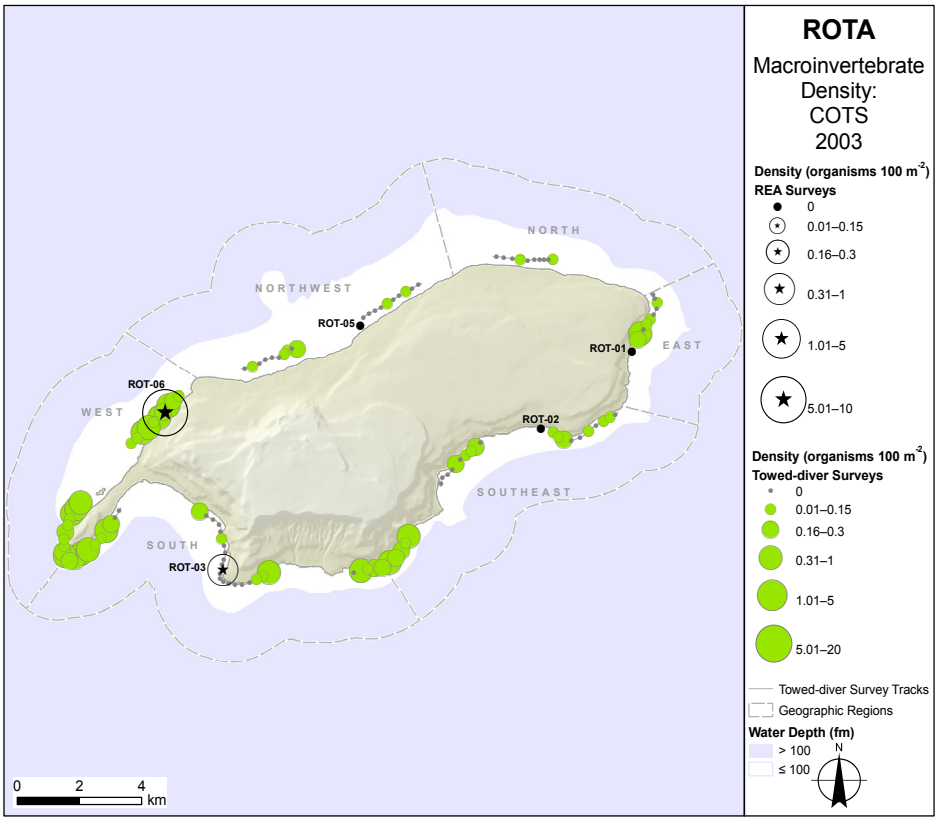
Figure 5.7.1d. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Rota during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Crown-of-thorns Seastars

During MARAMP 2003, crown-of-thorn seastars (*Acanthaster planci*) were observed at 2 of the 5 REA sites surveyed and in all 12 towed-diver surveys conducted around Rota (Fig. 5.7.1e). The overall mean density from REA surveys was 1.4 organisms 100 m^{-2} (SE 1.16), and the islandwide mean density from towed-diver surveys was 0.11 organisms 100 m^{-2} (SE 0.01). Results from REA surveys suggest that COTS were most abundant at ROT-06 in the west region with 6 organisms 100 m^{-2}.

Among all towed-diver surveys around Rota in 2003, 4 surveys had mean densities of COTS > 0.20 organisms 100 m^{-2}. The towed-diver survey completed just south of Puntan Sailigai in the west region had the highest mean density of 0.25 organisms 100 m^{-2}; segment densities from this survey ranged from 0.08 to 0.47 organisms 100 m^{-2}. The 2 towed-diver surveys conducted around Puntan Taipingot had mean densities of 0.22 and 0.24 organisms 100 m^{-2}; segment densities for these 2 surveys ranged from 0 to 0.5 organisms 100 m^{-2}. The towed-diver survey around Puntan Malilok had a mean density of 0.23 organisms 100 m^{-2}; segment densities ranged from 0 to 0.55 organisms 100 m^{-2}.

Figure 5.7.1e. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Rota during MARAMP 2003.



During MARAMP 2005, no COTS were observed at the 6 REA sites surveyed at Rota, but 9 of the 11 towed-diver surveys had recordings of COTS (Fig. 5.7.1f), with an overall mean density of 0.04 organisms 100 m^{-2} (SE 0.01). Among all towed-diver surveys at Rota, the 2 towed-diver surveys completed in the south and west regions from Puntan Taipingot past Puntan Senhanom toward West Harbor had the greatest COTS density, each with 0.11 organisms 100 m^{-2}; segment densities from both surveys ranged from 0 to 0.26 organisms 100 m^{-2}.

During MARAMP 2007, COTS were observed in low densities in 5 of the 10 towed-diver surveys conducted at Rota (Fig. 5.7.1g), compared to estimates made at other islands, with an overall mean density of 0.11 organisms 100 m^{-2} (SE 0.01). These 5 surveys were in the south, west, and northwest regions only. Among these 5 towed-diver surveys along the western half of Rota, the survey completed between Puntan Taipingot and West Harbor had the highest mean density with 0.034 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.09 organisms 100 m^{-2}.

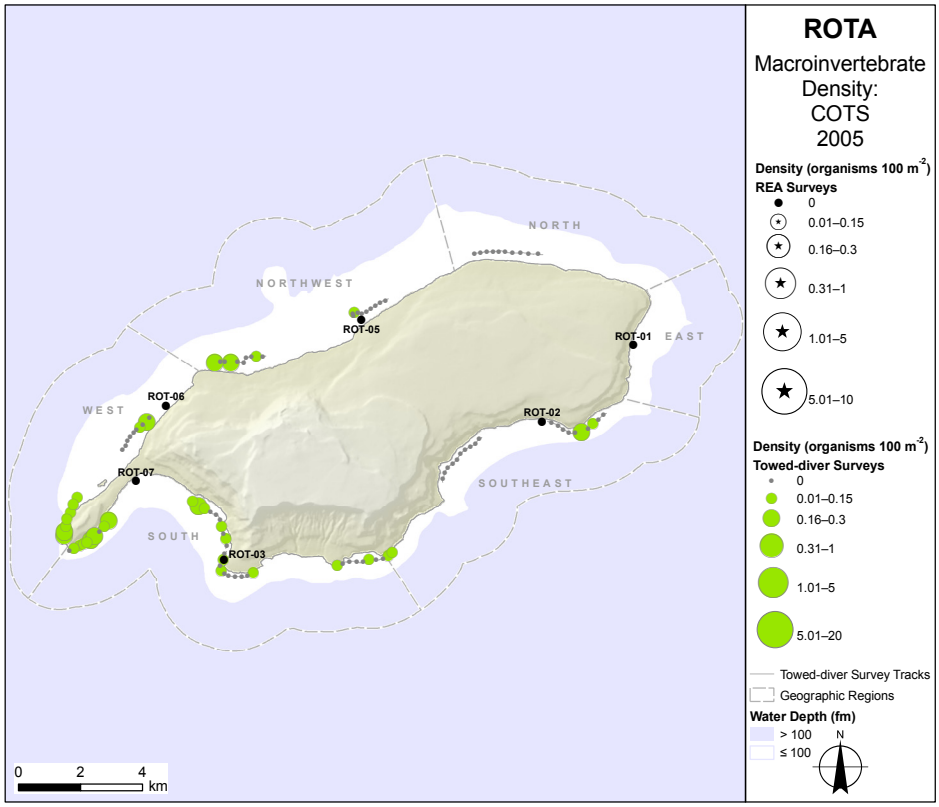


Figure 5.7.1f. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2005.

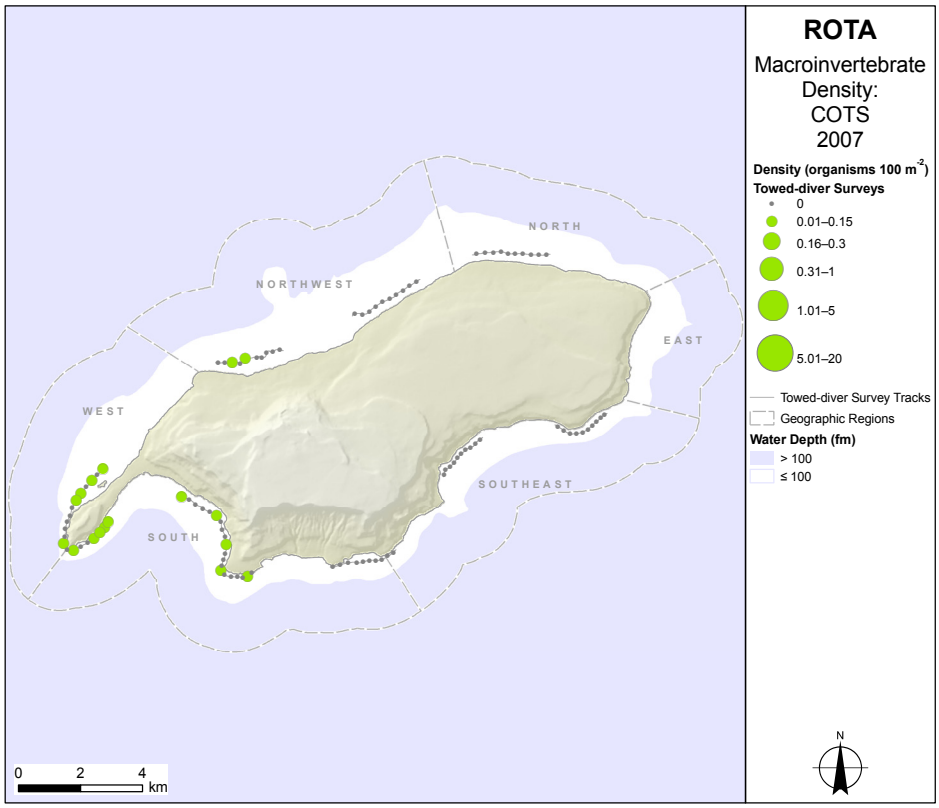


Figure 5.7.1g. Densities (organisms 100 m^{-2}) of COTS from towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2007.

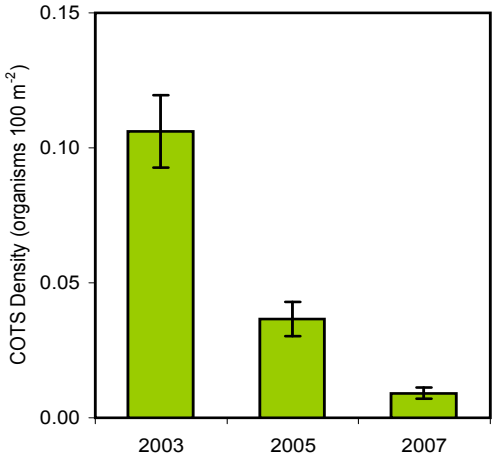


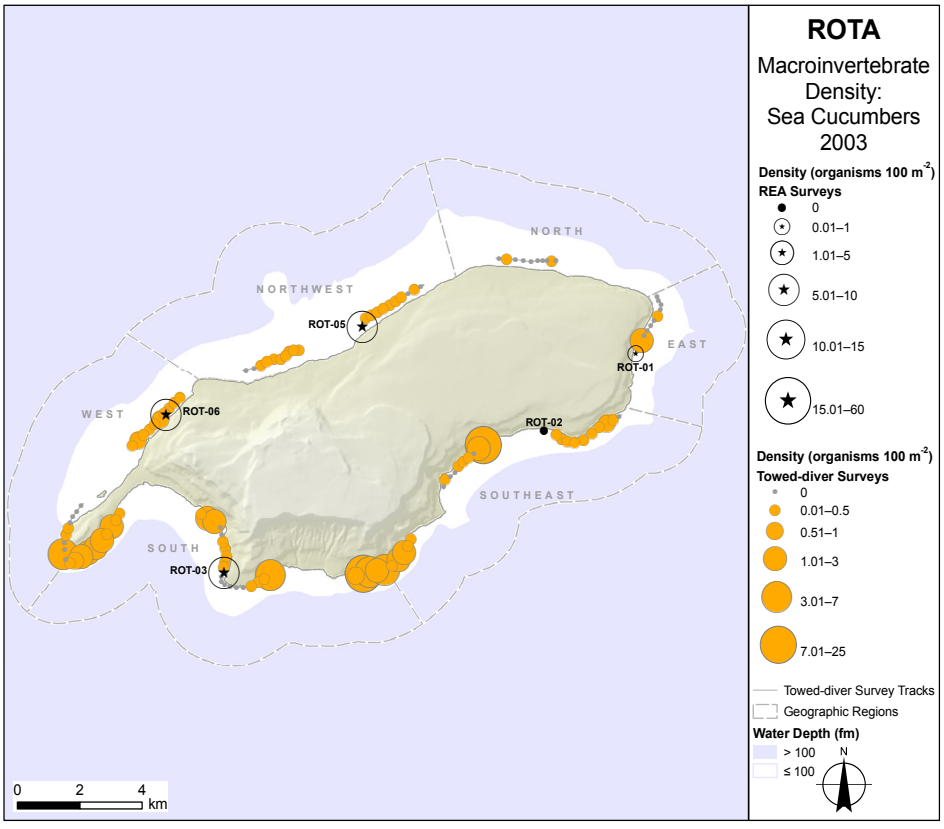
Figure 5.7.1h. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Rota during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver benthic surveys suggested relatively high daytime densities of COTS around Rota during MARAMP 2003, compared to the rest of the Mariana Archipelago, a sharp decline in 2005 and then again in 2007 (Fig. 5.7.1h). Given that these corallivorous seastars can decimate a reef, understanding whether their observed densities signify an outbreak is important. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure established for using scuba divers to conduct MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms km^{-2} (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of density and considering each towed-diver survey as an individual reef area, localized areas with relatively high densities that suggest that they were undergoing an outbreak were found during MARAMP 2003: south of Puntan Sailigai, around Puntan Taipingot, and around Puntan Malilok with COTS densities of 0.25, 0.24, and 0.23 organisms 100 m^{-2}. By 2005, densities from Puntan Sailigai to Puntan Taipingot and around this island's peninsula toward East Harbor were still relatively high, although not above the aforementioned density criterion. Around the rest of Rota, COTS populations were substantially smaller in 2005 than in 2003. By 2007, these populations had dwindled. COTS density naturally fluctuates with food availability and variation in recruitment success (Birkeland and Lucas 1990; Fabricius et al. 2010; and Yamaguchi 1987).

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at 4 of the 5 REA sites surveyed and in all 12 towed-diver surveys conducted around Rota. The overall mean density of sea cucumbers from REA surveys was 4.6 organisms 100 m^{-2}

Figure 5.7.1i. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Rota during MARAMP 2003.



(SE 1.75), and the islandwide mean density from towed-diver surveys was 0.65 organisms 100 m^{-2} (SE 0.18). Survey results suggest that sea cucumbers were most abundant at ROT-06 just south of Puntan Sailigai in the west region with 9 organisms 100 m^{-2} (Fig. 5.7.1i). These sea cucumbers were from the genera *Holothuria, Stichopus*, and *Actinopyga.*

Among all towed-diver surveys around Rota, the survey completed just north of Puntan Ha`ina in the southeast region had the highest mean density with 2.19 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 18.88 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 2.03 organisms 100 m^{-2}, recorded along the coast near Puntan Malilok at the border of the southeast and south regions; segment densities ranged from 0.08 to 8 organisms 100 m^{-2}.

During MARAMP 2005, sea cucumbers were observed at 3 of the 6 REA sites surveyed and in 10 of the 11 towed-diver surveys conducted at Rota. The sample mean density of sea cucumbers from REA sites was 0.5 organisms 100 m^{-2} (SE 0.22), and the overall mean density from towed-diver surveys was 0.27 organisms 100 m^{-2} (SE 0.05). Among all towed-diver surveys at Rota, the survey completed along the coast near Puntan Malilok in the south region had the highest mean density with 1.22 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 3.56 organisms 100 m^{-2} (Fig. 5.7.1j).

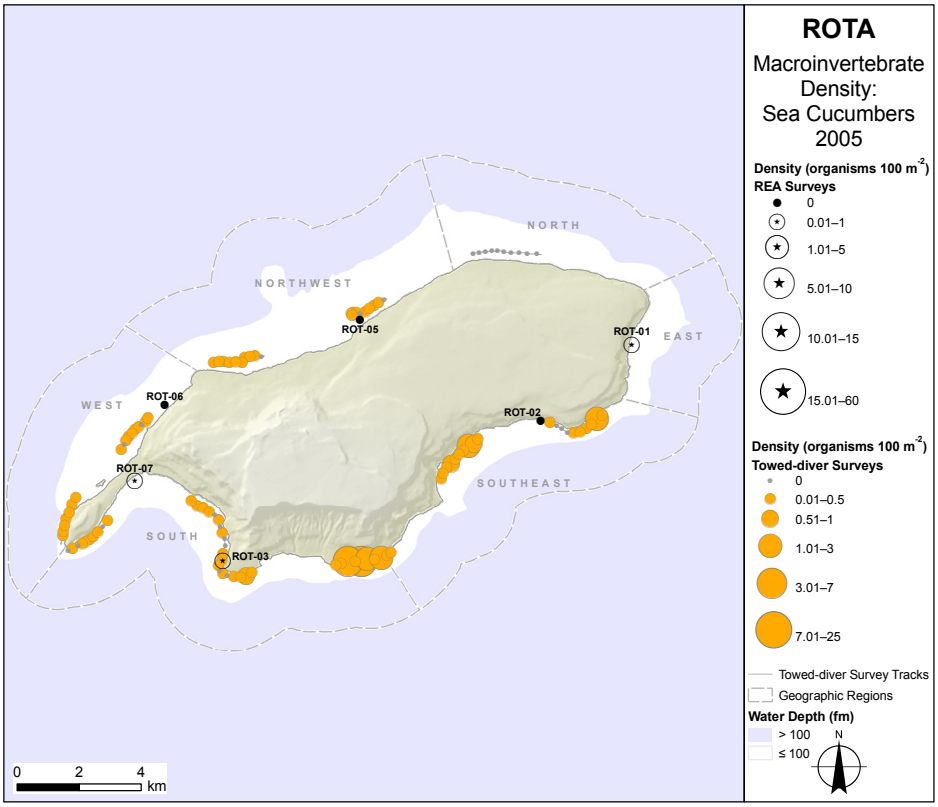


Figure 5.7.1j. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2005.

During MARAMP 2007, sea cucumbers were observed in all 10 towed-diver surveys conducted at Rota. The overall mean density of sea cucumbers from towed-diver surveys was 0.24 organisms 100 m^{-2} (SE 0.04). Among all towed-diver surveys at Rota, the survey completed between Puntan Taipingot and West Harbor had the highest mean density with 0.45 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.77 organisms 100 m^{-2} (Fig. 5.7.1k).

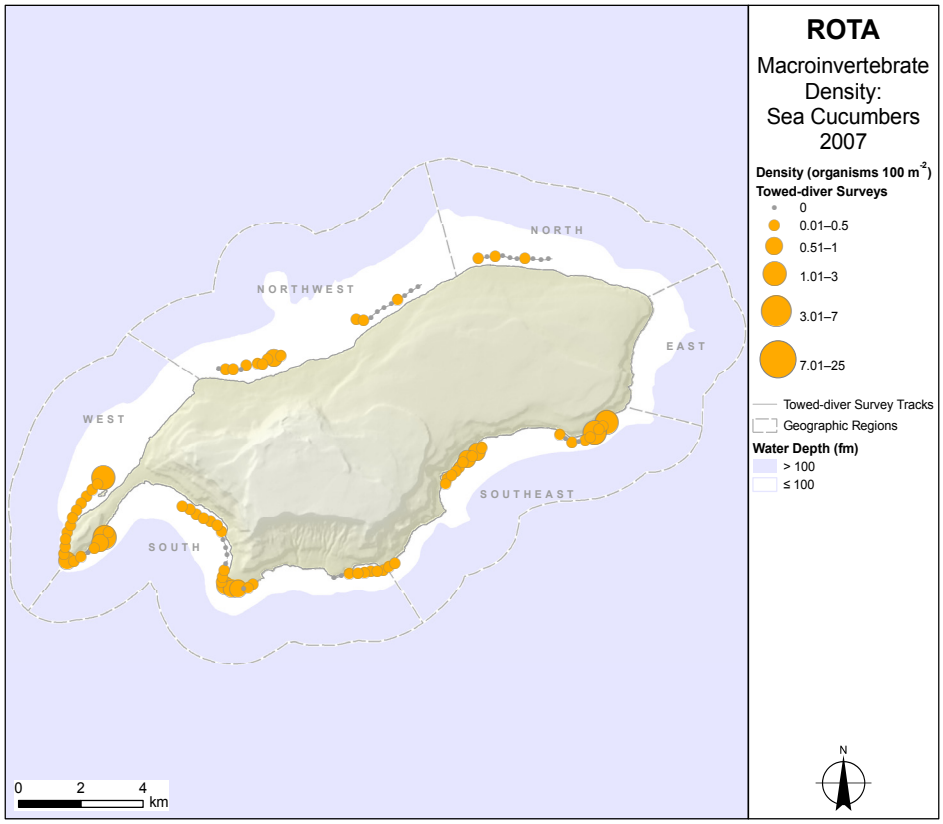


Figure 5.7.1k. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2007.

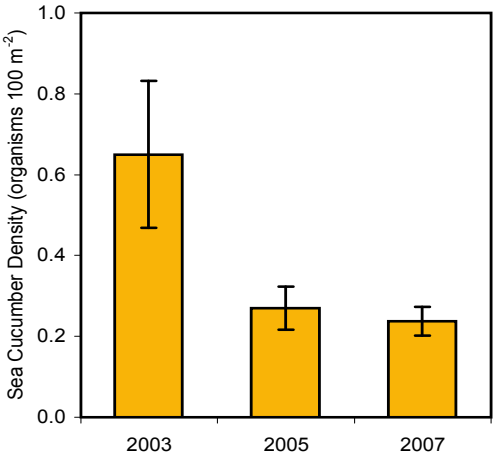


Figure 5.7.1l. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Rota during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested higher daytime abundance of sea cucumbers in the south and southeast regions, relative to the other regions around Rota, during the 3 MARAMP survey periods. The overall observed mean density of sea cucumbers was higher in 2003 than in 2005 and 2007 (Fig. 5.7.1l). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Sea Urchins

During MARAMP 2003, sea urchins were observed at all 5 REA sites surveyed and in 11 of the 12 towed-diver surveys conducted around Rota (Fig. 5.7.1m). The overall mean density of sea urchins from REA surveys was 165.4 organisms 100 m^{-2} (SE 48.27), and the islandwide mean density from towed-diver surveys was 4.64 organisms 100 m^{-2} (SE 0.55). Results from REA surveys suggest that ROT-06, just south of Puntan Sailigai in the west region, had the highest density of sea urchins with 309 organisms 100 m^{-2}. All sea urchins observed at this site were from the genus *Echinostephus*. The second-greatest density of 243 organisms 100 m^{-2} was recorded in the east region at ROT-01, where the rock-boring urchin *Echinostrephus* was again the dominant urchin genus at this site, accounting for 82% of recorded urchins. Sea urchins from the genera *Echinometra* and *Echinothrix* were also present at both sites, accounting for 4% and 14% of sea urchins recorded.

Among all towed-diver surveys around Rota in 2003, the survey completed in the southeast region in Aratsu-wan had the highest mean density of sea urchins with 11.53 organisms 100 m^{-2}; segment densities from this survey ranged from 3.66 to 18.90 organisms 100 m^{-2}. The second-greatest mean density of sea urchins was 9.46 organisms 100 m^{-2}, recorded just south of Puntan Sailigai in the west region; segment densities ranged from 0 to 30.52 organisms 100 m^{-2}.

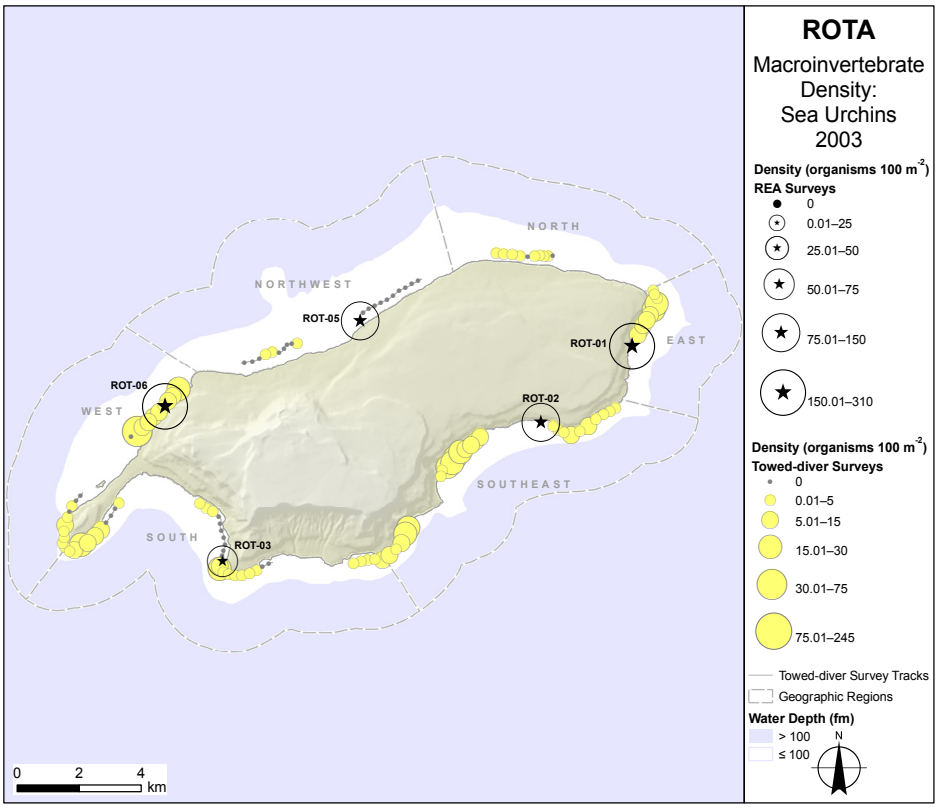


Figure 5.7.1m. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Rota during MARAMP 2003.

During MARAMP 2005, sea urchins were observed at 2 of the 6 REA sites surveyed and in 10 of the 11 towed-diver surveys conducted at Rota (Fig. 5.7.1n). The sample mean density of sea urchins from REA surveys was 7.16 organisms 100 m^{-2} (SE 6.77), and the overall mean density from towed-diver surveys was 6.8 organisms 100 m^{-2} (SE 1.14). Among all towed-diver surveys at Rota, the survey completed south of Angyuta Island to Puntan Taipingot in the south region had the greatest mean density with 18.43 organisms 100 m^{-2}; segment densities from this survey ranged from 3.17 to 38.68 organisms 100 m^{-2}. The second-greatest mean density of sea urchins was 13.79 organisms 100 m^{-2}, recorded between Puntans As Fani and Sagua`gahga in the southeast region; segment densities ranged from 0 to 50.17 organisms 100 m^{-2}.

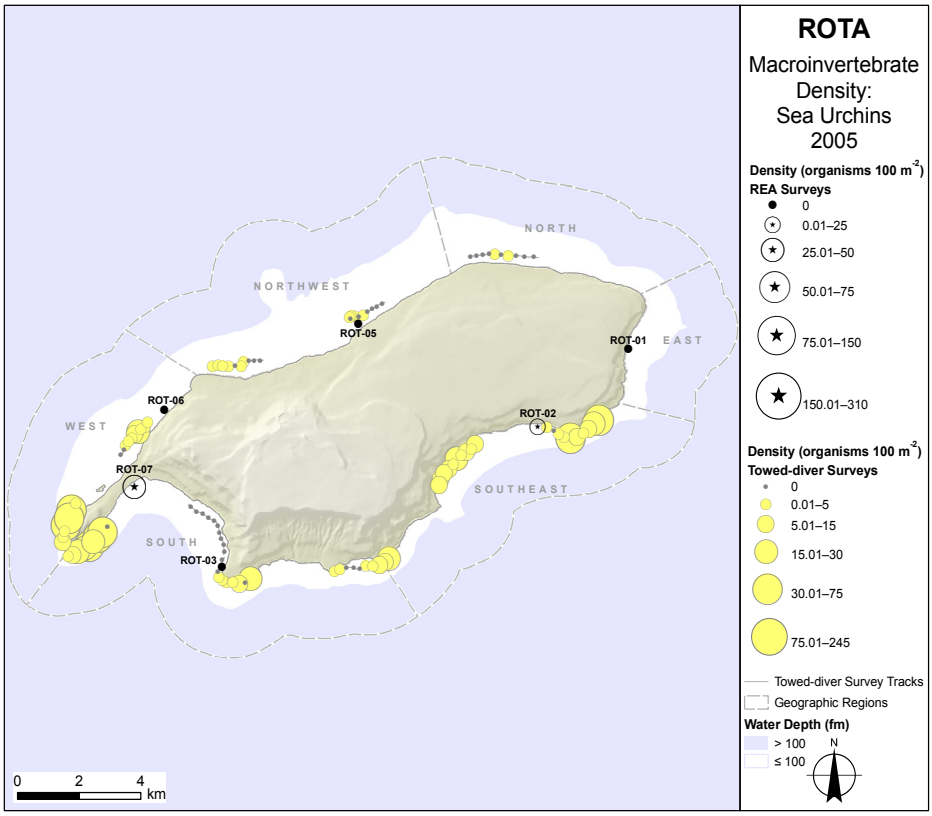


Figure 5.7.1n. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2005.

During MARAMP 2007, sea urchins were observed in 8 of the 10 towed-diver surveys conducted at Rota (Fig. 5.7.1o) with an overall mean density of 4.79 organisms 100 m^{-2} (SE 0.70). Among all towed-diver surveys at this island, the survey conducted south of Angyuta Island to Puntan Taipingot in the south region had the highest mean density with

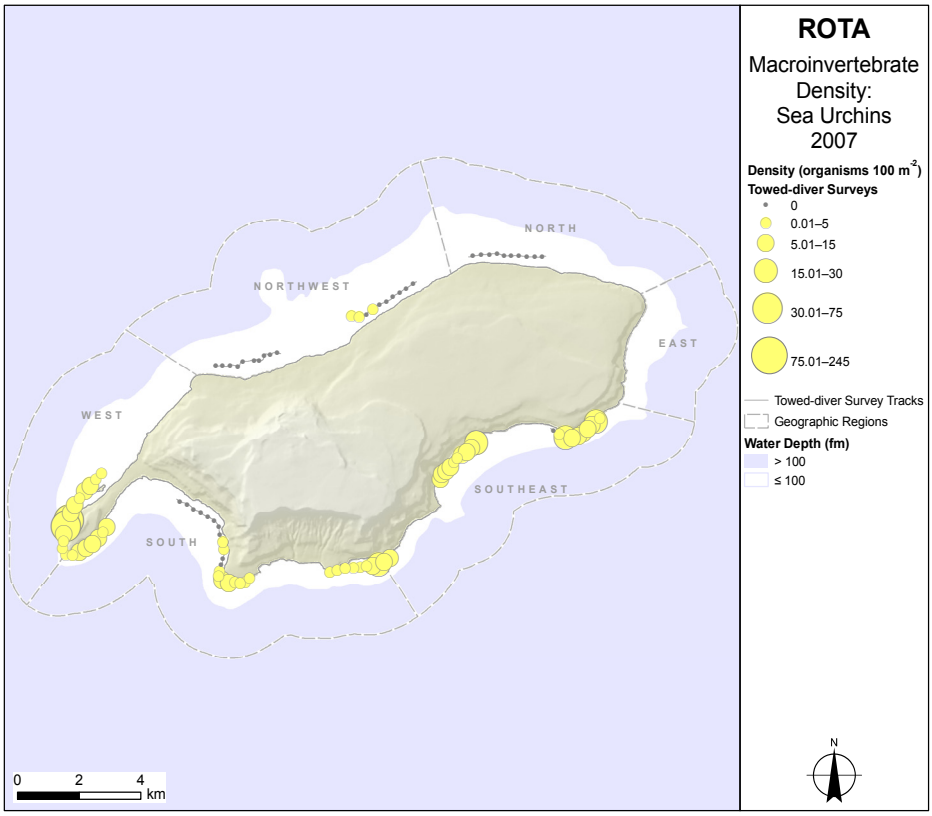


Figure 5.7.1o. Densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2007.

14.07 organisms 100 m^{-2}; segment densities from this survey ranged from 2.91 to 43.28 organisms 100 m^{-2}.

The overall observed mean density of sea urchins was slightly higher in 2005 than in 2003 and 2007 (Fig. 5.7.1p). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

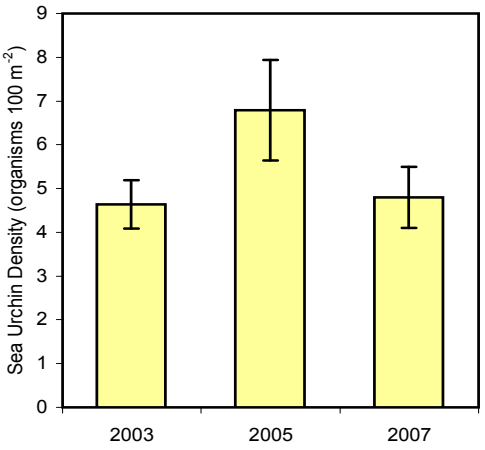


Figure 5.7.1p. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Rota during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

5.8 Reef Fishes

5.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 12 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Rota. The islandwide estimated mean biomass of large fishes, calculated as weight per unit area, was 0.49 kg 100 m^{-2} (SE 0.14). Observed biomass values for large fishes were highest in the southwest region, where

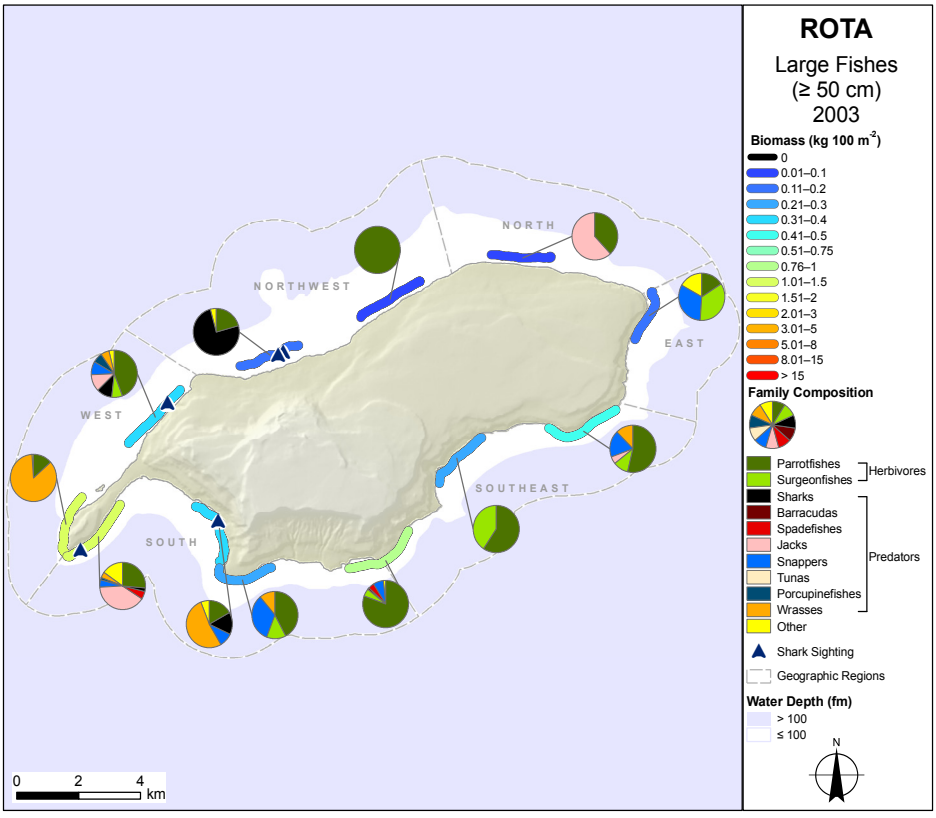


Figure 5.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted around Rota during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside the survey area over which it is shown.

a school of bigeye trevally (*Caranx sexfaciatus*) and multiple humphead wrasse (*Cheilinus undulatus*) were observed (Fig. 5.8.1a). Parrotfishes (Scaridae) and wrasses (Labridae) together accounted for 63% of the overall mean biomass of large fishes. Parrotfishes accounted for the greatest proportion of large-fish biomass, with the filament-finned parrotfish (*Scarus altipinnis*) contributing 38% of parrotfish biomass. The humphead wrasse accounted for the majority of wrasse biomass with 12 individuals observed in 2003. Jacks (Carangidae) were also common, contributing 11% of islandwide large-fish biomass. The bigeye trevally contributed 0.05 kg 100 m^{-2} to overall large-fish biomass and accounted for 84% of jack biomass. Five reef sharks (Carcharhinidae) were observed around Rota: 3 blacktip reef shark (*Carcharhinus melanopterus*) and 2 whitetip reef shark (*Triaenodon obesus*).

During MARAMP 2005, 11 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats at Rota. The overall estimated mean biomass of large fishes at this island was 0.48 kg 100 m^{-2} (SE 0.23). Observed biomass values for large fishes were highest in the west region, where a large school of blackfin barracuda (*Sphyraena qenie*) was observed (Fig. 5.8.1b). Barracudas (Sphyraenidae) and wrasses made up the majority of the overall biomass, together accounting for 56% or 0.27 kg 100 m^{-2} of the overall mean large-fish biomass. The blackfin barracuda was the most abundant barracuda species, accounting for 24% of overall biomass of large fishes. Consistent with observations made in 2003, the humphead wrasse was the dominant wrasse species by weight with 8 individuals recorded. Batfishes (Ephippidae) and parrotfishes were also common, and the teira batfish (*Platax teira*) and ember parrotfish (*Scarus rubroviolaceus*) were the most abundant batfish and parrotfish species, contributing 0.06 kg 100 m^{-2} and 0.02 kg 100 m^{-2} to overall large-fish biomass. Two reef sharks were observed at Rota: 1 whitetip reef shark and 1 blacktip reef shark.

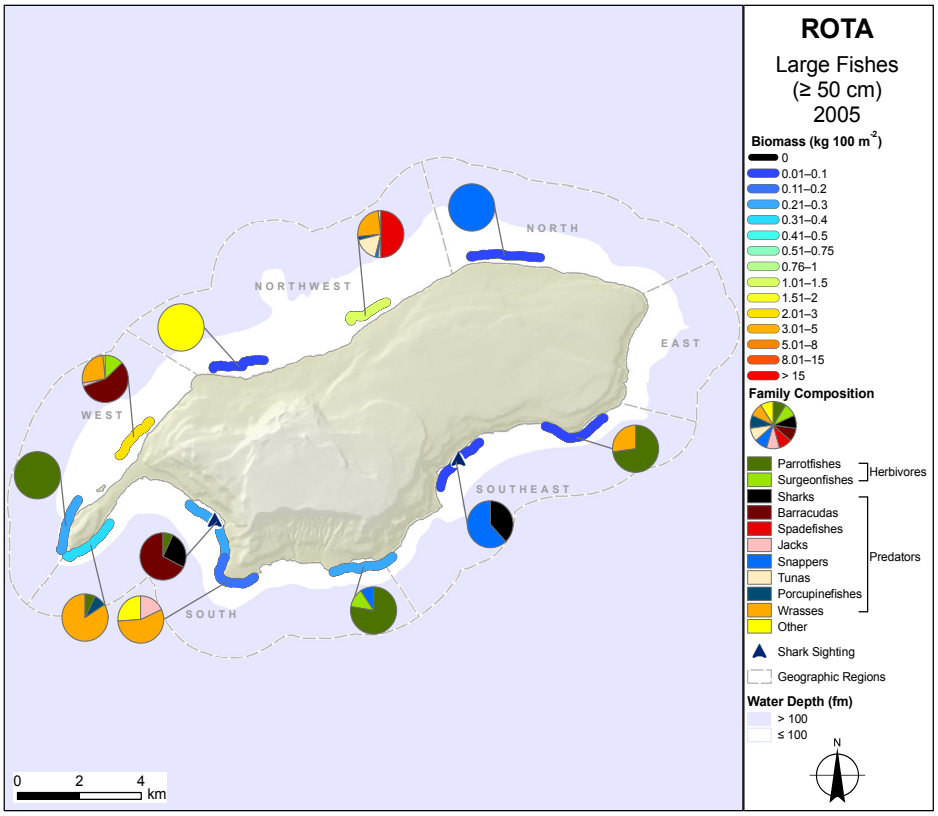


Figure 5.8.1b. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted at Rota during MARAMP 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside the survey area over which it is shown.

During MARAMP 2007, 10 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats at Rota. The overall estimated mean biomass of large fishes at this island was 0.14 kg 100 m^{-2} (SE 0.05), lower than biomass estimates made in 2005 and 2003. Observed biomass values for large fishes were highest in the south region, where dogtooth tuna (*Gymnosarda unicolor*) and surgeonfishes (Acanthuridae) were common (Fig. 5.8.1c). Surgeonfishes and tunas (Scombridae) together contributed 32% or 0.03 kg 100 m^{-2} of overall large-fish biomass. The bulbnose unicornfish (*Naso tonganus*) dominated surgeonfish biomass and accounted for 10% of the overall mean biomass of large fishes. Dogtooth tuna was the most abundant tuna species, contributing 11% of overall large-fish biomass. A single whitetip reef shark was observed at Rota, but, unlike in 2003 and 2005, no humphead wrasse were recorded.

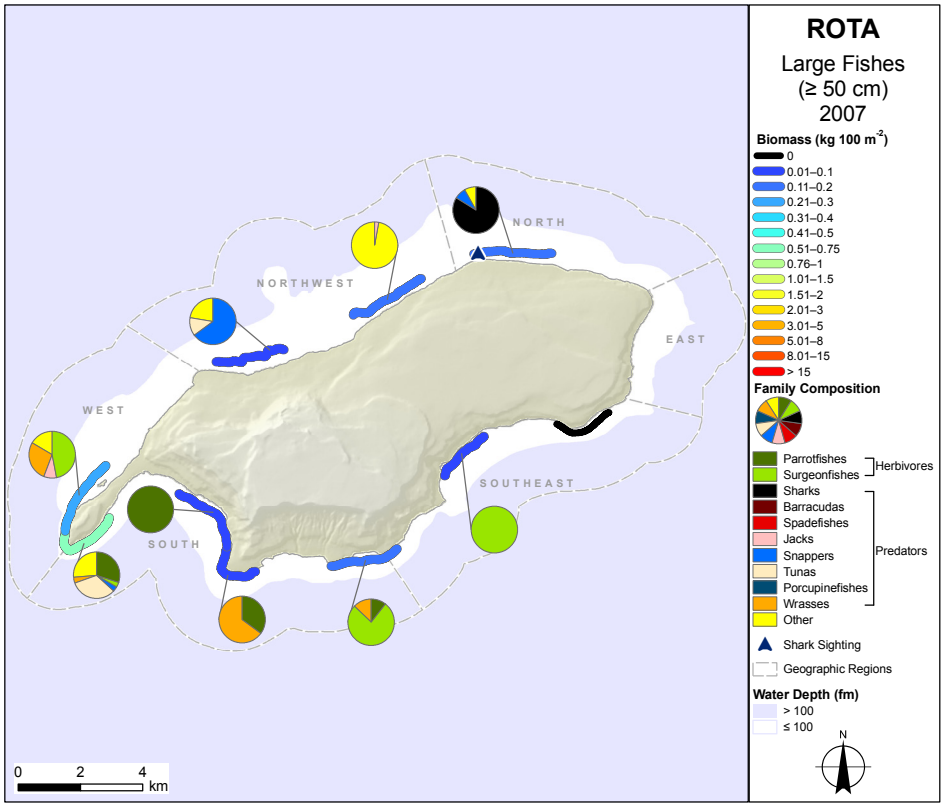


Figure 5.8.1c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted at Rota during MARAMP 2007. Each blue triangle represents a shark sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

Overall large-fish biomass from towed-diver surveys of forereef habitats at Rota was moderately low in 2003 and 2005, compared to the rest of the Mariana Archipelago, and was lower still in 2007 (Fig. 5.8.1d). No single species consistently dominated large-fish biomass, and no consistent spatial pattern was observed during the 3 MARAMP survey periods. One observation that stands out is the sighting in 2003 of a large school of bigeye trevally in the southwest region. Also notable were sightings of humphead wrasse with 12 individuals observed in 2003, 8 individuals seen in 2005, and none recorded in 2007.

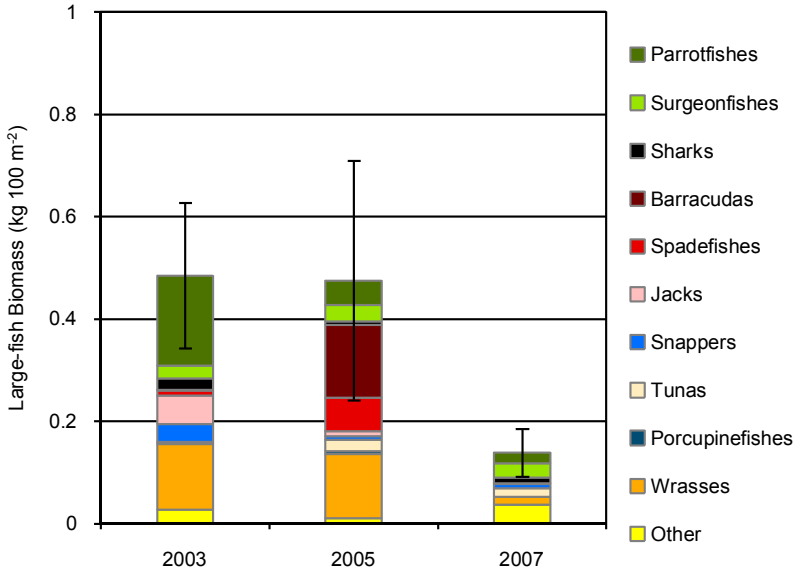


Figure 5.8.1d. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Rota during MARAMP 2003, 2005 and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Total fish biomass for the 5 REA sites surveyed using belt transects in forereef habitats at Rota during MARAMP 2003 was moderately low compared to other sites in the Mariana Archipelago with an overall sample mean of 4.00 kg 100 m^{-2} (SE 0.93). The highest mean biomass of 7.49 kg 100 m^{-2} was observed at ROT-05 in the northwest region, and the lowest biomass of 1.95 kg 100 m^{-2} was found at ROT-02 in the southeast region (Fig. 5.8.1e). Emperors (Lethrinidae) and surgeonfishes were the dominant families in terms of biomass, contributing 30% (1.21 kg 100 m^{-2}) and 21% (0.85 kg 100 m^{-2}) of overall total fish biomass. The striped large-eye bream (*Gnathodentex aureolineatus*) was the major emperor species, accounting for 40% of emperor biomass, while the orangespot surgeonfish (*Acanthurus olivaceus*) was the major surgeonfish species, contributing 37% of surgeonfish biomass. No reef sharks were observed during these site-specific fish surveys.

Based on REA surveys conducted during MARAMP 2003, species richness at Rota ranged from 21 to 41 species 100 m^{-2}. The highest species richness was found at both ROT-06 in the west region and ROT-05 in the northwest region. Wrasses were the most diverse family with 23 species recorded at Rota in 2003. The fivestripe wrasse (*Thalassoma quinquevittatum*) and the blunthead wrasse (*Thalassoma amblycephalum*) were the most abundant wrasse species. Triggerfishes (Balistidae) were the most abundant fish taxa overall, and the redtoothed triggerfish (*Odonus niger*) dominated counts with 179 individuals 100 m^{-2} observed. All of these triggerfishes were < 10 cm in TL; hence, they likely were very recently recruited.

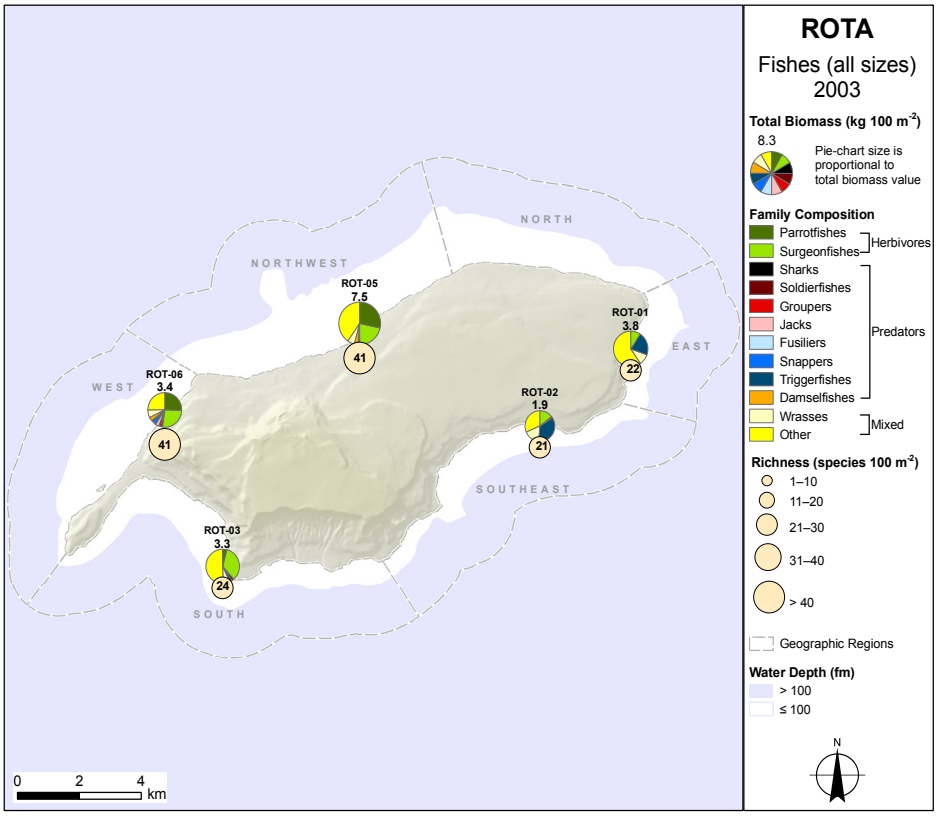


Figure 5.8.1e. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Rota during MARAMP 2003.

Mean total fish biomass for the 6 REA sites surveyed in forereef habitats at Rota during MARAMP 2005 was 5.73 kg 100 m^{-2} (SE 1.54). The highest fish biomass of 12.64 kg 100 m^{-2} was observed at ROT-02 in the southeast region (Fig. 5.8.1f), and the lowest fish biomass of 2.62 kg 100 m^{-2} was found at ROT-05 in the northwest region. Surgeonfishes accounted for the largest proportion of (39%) or 2.25 kg 100 m^{-2} of total fish biomass for Rota. Consistent with the observations made in 2003, the orangespot surgeonfish was the major surgeonfish species, contributing 35% or 0.80 kg 100 m^{-2} of surgeonfish biomass. Parrotfishes contributed 19% of the overall total fish biomass. The bullethead parrotfish (*Chlorurus sordidus*) accounted for 61% or 0.65 kg 100 m^{-2} of parrotfish biomass. No sharks were observed during these site-specific fish surveys.

Based on REA surveys conducted during MARAMP 2005, species richness at Rota was heterogeneous among REA sites with a range of 16–38 fish species 100 m^{-2}. The highest species richness was observed at ROT-03 in the south region near Puntan Pona in the Sasanhaya Fish Reserve. Wrasses and surgeonfishes were the 2 most diverse families with 29 and 20

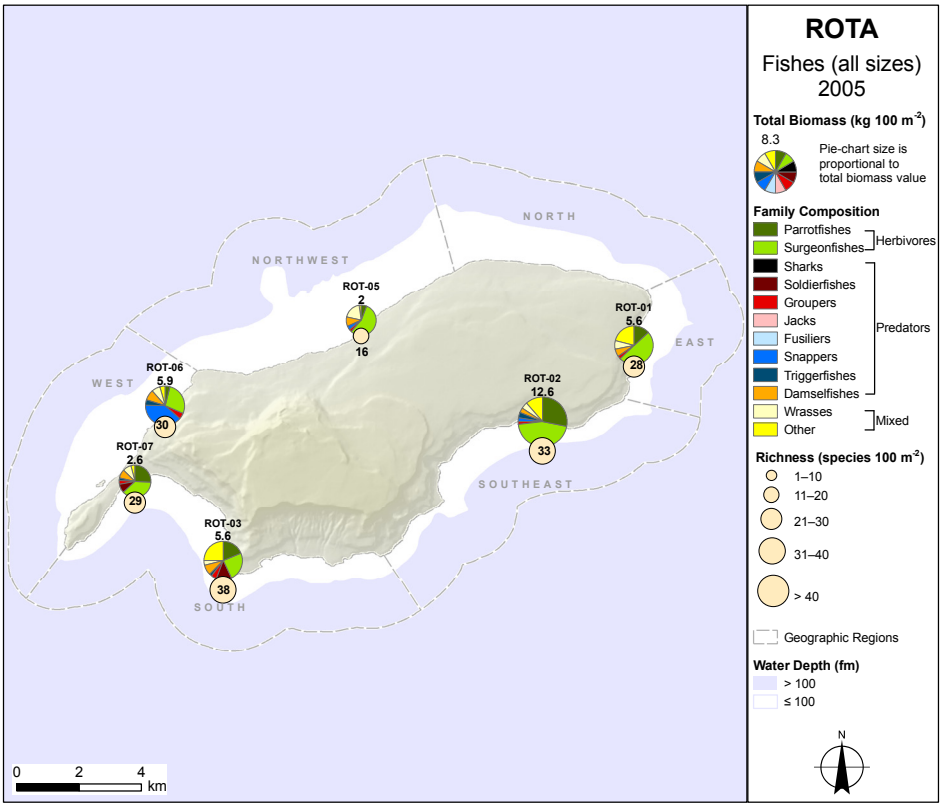


Figure 5.8.1f. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Rota during MARAMP 2005

species recorded. The ornate wrasse (*Halichoeres ornatissimus*) was the most abundant wrasse species, and the brown surgeonfish (*Acanthurus nigrofuscus*) was the most abundant surgeonfish species. Damselfishes (Pomacentridae) were the most abundant fish taxa overall, and the midget chromis (*Chromis acares*) was the most common species with 44 individuals 100 m^{-2} observed.

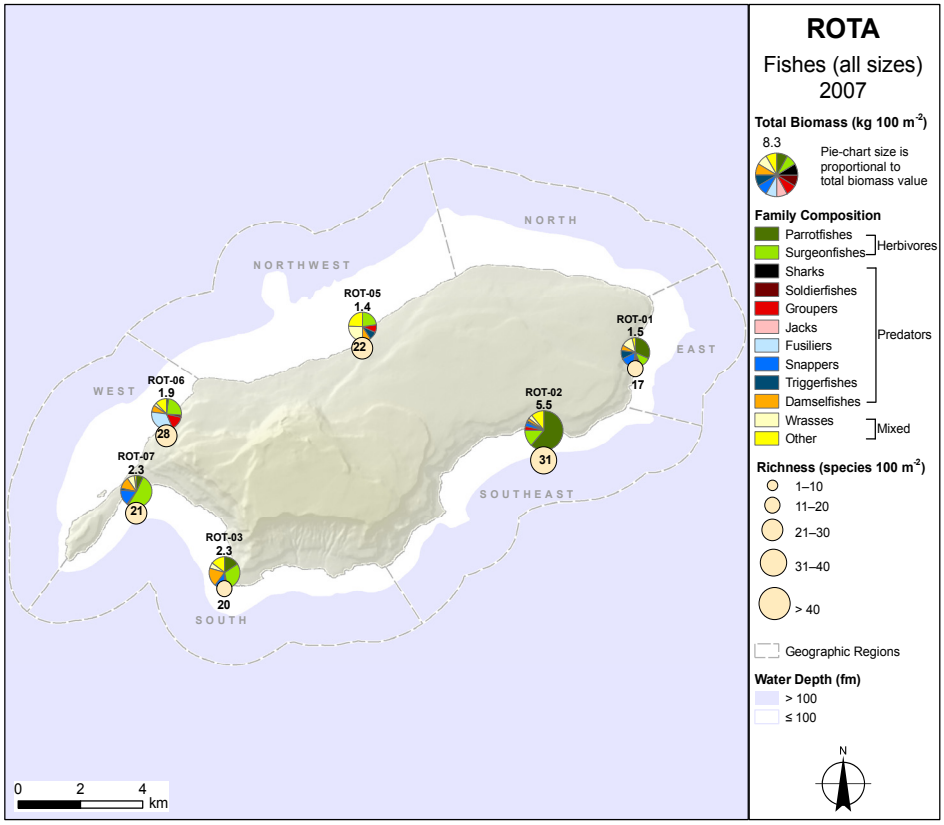
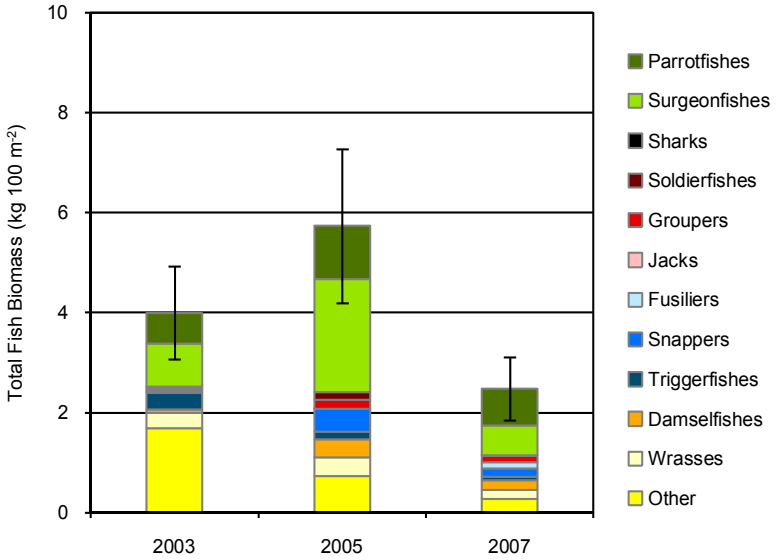


Figure 5.8.1g. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Rota during MARAMP 2007.

Total fish biomass for the 6 REA sites surveyed in forereef habitats at Rota during MARAMP 2007 was low, compared to other sites in the Mariana Archipelago, with an overall sample mean of 2.48 kg 100 m^{-2} (SE 0.63). The highest biomass of 5.93 kg 100 m^{-2} was observed at ROT-02 in the southeast region (Fig. 5.8.1g). Parrotfishes accounted for the largest proportion (30%) or 0.74 kg 100 m^{-2} of overall total fish biomass. Surgeonfishes were the second-most dominant family, contributing 24% of total fish biomass for Rota. The bullethead parrotfish was the major parrotfish species by weight, and the striated surgeonfish (*Ctenochaetus striatus*) was the major surgeonfish species by weight. No sharks were observed during these site-specific fish surveys.

Based on REA surveys conducted during MARAMP 2007, species richness at Rota ranged from 17 to 31 species 100 m^{-2}. The highest species richness was observed at ROT-02 in the southeast region (Fig. 5.8.1g). Wrasses, surgeonfishes, and damselfishes were the 3 most diverse families with 29, 15, and 15 species recorded, respectively. The red-lined wrasse (*Halichoeres biocellatus*) was the most abundant wrasse species, and the brown surgeonfish was the most abundant surgeonfish species. Damselfishes again were the most abundant fish taxa overall, and the ocellate damselfish (*Pomacentrus vaiuli*) was the most common species with more than 20 individuals 100 m^{-2} recorded at Rota.

Figure 5.8.1h. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Rota during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.



No persistent spatial pattern was observed for total fish biomass in forereef habitats at Rota between the 3 MARAMP survey periods; however, the highest mean value of total fish biomass was found at ROT-02 in the southeast region in both 2003 and 2005. Across the 3 MARAMP survey years combined, the overall mean total fish biomass for Rota was 4.07 kg 100 m^{-2} (Fig. 5.8.1h), a low value relative to the rest of the Mariana Archipelago. The highest fish biomass of 12.64 kg 100 m^{-2} was recorded at ROT-02 in 2005, and the lowest fish biomass of 1.37 kg 100 m^{-2} was observed at ROT-05 in the northwest region in 2007. No single species accounted for the greatest proportion of total fish biomass for the 3 survey periods; however, surgeonfishes were one of the 2 the most dominant families in each year, accounting for 21%–39% of overall total fish biomass. The orangespot surgeonfish, brown surgeonfish, and striated surgeonfish collectively made up more than 50% of surgeonfish biomass recorded in 2003, 2005, and 2007. No sharks were observed in sight-specific surveys during any of the 3 MARAMP survey periods.

Species richness at Rota was recorded within a range of 23.3–29.7 species 100 m^{-2} during the 3 MARAMP survey years, with no clear spatial pattern observed. Wrasses, surgeonfishes, and damselfishes were the 3 most diverse families overall, with an average of 27, 16, and 14 species recorded. Damselfishes were the most abundant taxa of fishes; however, no single species consistently dominated counts in the 3 MARAMP survey periods.

5.9 Marine Debris

5.9.1 Marine Debris Surveys

During MARAMP 2003, 3 sightings of derelict fishing gear and 2 sightings of wrecks were recorded in the 12 towed-diver surveys conducted on forereef habitats around the island of Rota (Fig. 5.9.1a). The 2 wreck sightings, which included a propeller, blade, anchor, and chain, were made in the south region and were probably 2 of 5 known wrecks in Sasanhaya Bay in the south region (for place-names and their locations, see Figure 5.2a in Section 5.2: "Survey Effort"): 3 wooden Japanese subchasers were sunk during or after WWII, and 2 steel Chinese smuggling ships were impounded and sunk intentionally in 1999 as artificial dive sites. Two fishing lines were recorded, 1 in the south region and 1 in the west region. The third sighting of derelict fishing gear was noted in the northwest region, but no additional descriptive information was recorded. No munitions or other man-made objects were identified.

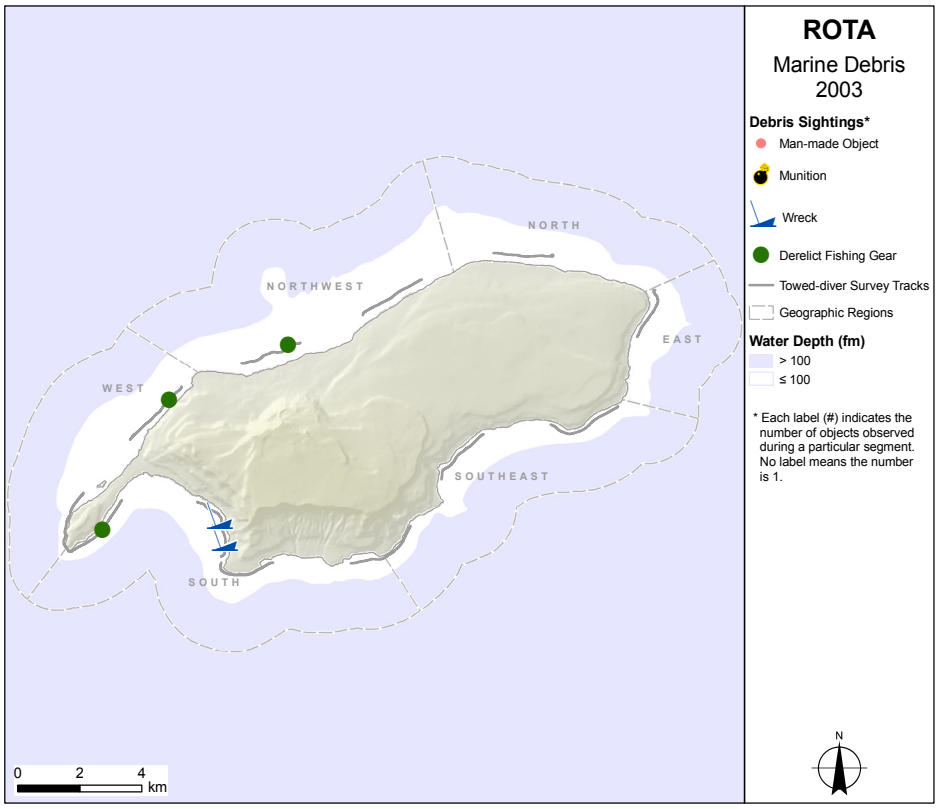
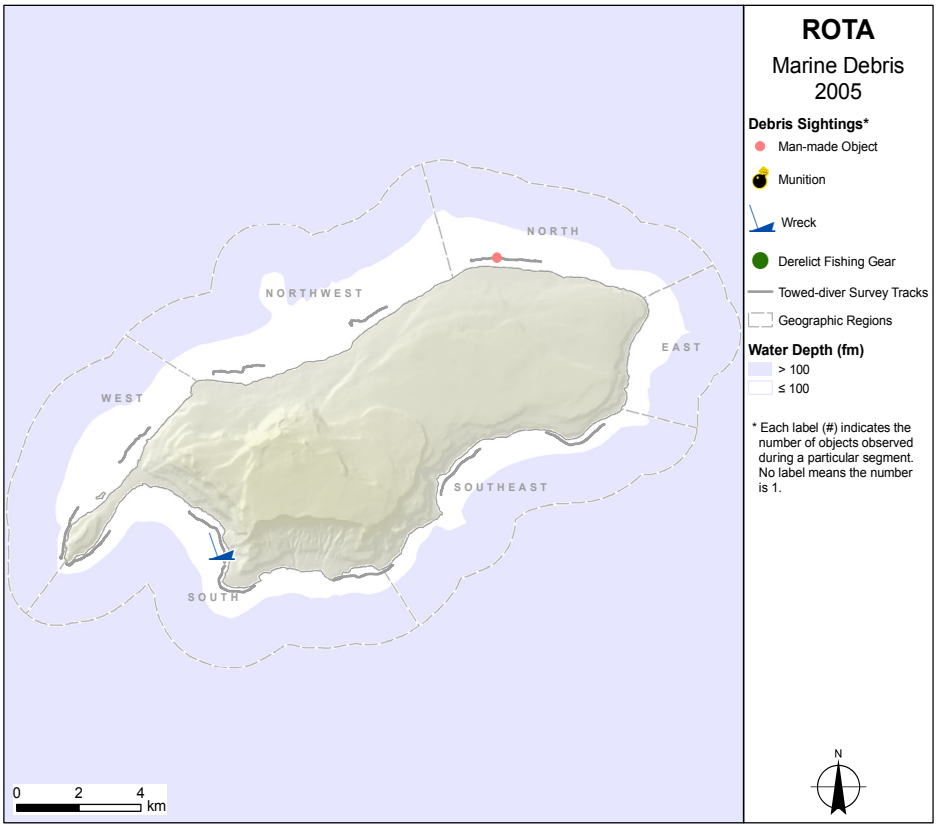


Figure 5.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Rota during MARAMP 2003. Symbols indicate the presence of specific debris types.

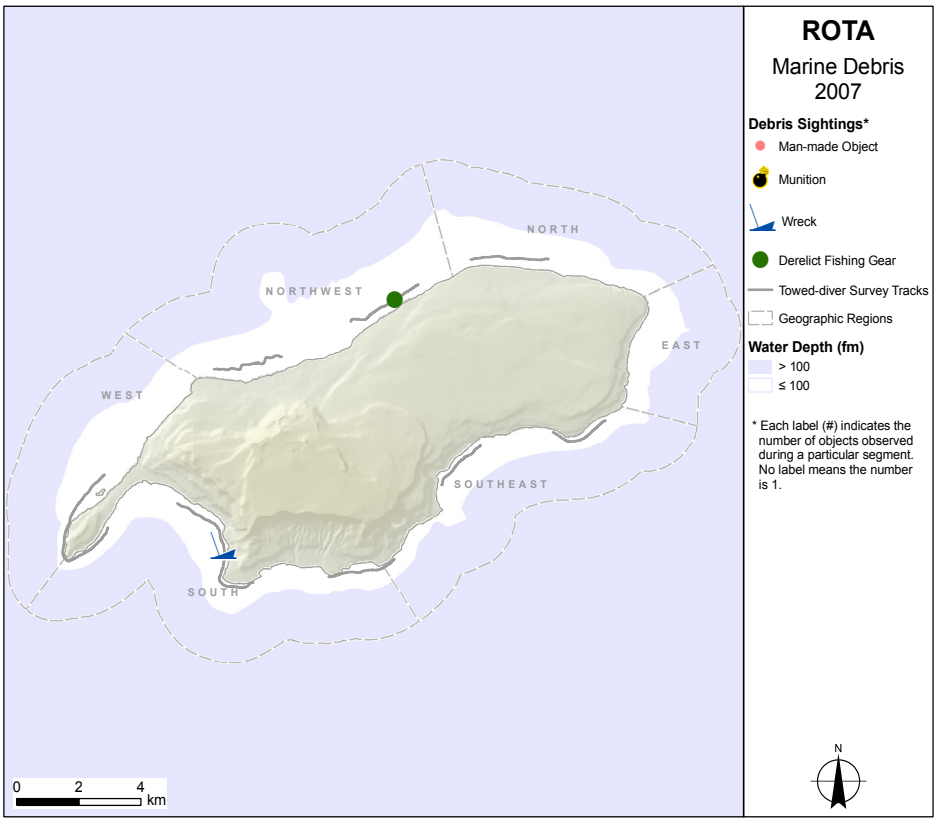
During MARAMP 2005, sightings of 1 wreck and 1 man-made object were recorded in the 11 towed-diver surveys conducted on forereef habitats at Rota (Fig. 5.9.1b). The wreck was observed in the south region, and the man-made object was identified as an anchor in the north region. No sightings of munitions or derelict fishing gear were recorded.

Figure 5.9.1b. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2005. Symbols indicate the presence of specific debris types.



During MARAMP 2007, 1 wreck sighting and 1 sighting of derelict fishing gear were recorded in the 10 towed-diver surveys conducted on forereef habitats at Rota (Fig. 5.9.1c). The wreck was noted in the south region. A fishing line was observed in the northwest region. No munitions or other man-made objects were identified.

Figure 5.9.1c. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted at Rota during MARAMP 2007. Symbols indicate the presence of specific debris types.



Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments. One constant between the 3 survey periods is worth mentioning: the presence of 1 or more shipwrecks in Sasanhaya Bay in the south region.

5.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Rota are discussed in the individual, discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. Biological information from towed-diver surveys was integrated to derive 3 composite indices that provide assessments of the relative ecological conditions of forereef habitats in the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan.

The *Benthic Condition Index for Guam, Rota, Tinian, and Saipan* was derived by equally weighting observations of the following 5 parameters from towed-diver benthic surveys around these 4 islands: cover of live hard corals, stressed corals, macroalgae, and crustose coralline red algae and density of COTS. *The Fish Condition Index for Guam, Rota, Tinian, and Saipan* was derived from 2 equally weighted parameters from towed-diver fish surveys: density and biomass of large fishes (≥ 50 cm in TL). The overall *Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan* was derived from an equal weighting of these benthic and fish indices. These condition indices were calculated using ranks assigned to the biological variables from towed-diver surveys conducted around Rota, relative to all surveys around the 4 populated, southern islands for each survey year. To indicate changes in these ranks between survey years, these indices were visualized on a map within survey areas, which are represented by color-coded and irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007 (towed-diver-survey tracks were often similar but not exactly the same in each survey year). For more details about the methodology behind these indices, see Chapter 2: "Methods and Operational Background," Section 2.5: "Ecosystem Integration." Each of these 3 condition indices for Rota is presented on a map in Figure 5.10b. Reef condition indices for the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," providing ranks for Rota as well as the other 13 islands of the Mariana Archipelago covered in this report.

MARAMP surveys notably have revealed low levels of live-hard-coral cover at Rota (Fig. 5.10a), relative to values observed around the other populated, southern islands. For example, in 2005, overall mean live coral cover for Rota was 6% (SE 1) from towed-diver surveys, compared to 9% (SE 1.1) for Tinian, 11% (SE 1) for Saipan, and 23% (SE 1.2) for Guam. Similarly, in 2007, overall mean live coral cover for Rota was 4% (SE 1), compared to values > 8% for the other 3 islands. A number of factors can influence abundance of corals; however, none of the data obtained by the CRED provide a clear explanation for the differences observed between Rota and Tinian, Guam, and Saipan.

All of the towed-diver surveys conducted at Rota recorded areas dominated by macroalgae (as seen in a photograph of a shipwreck in Sasanhaya Bay, Fig. 5.10c), with some soft corals and sponges and extensive cyanobacteria in the south and west regions. The most commonly observed macroalgal genera at Rota were *Padina*, *Halimeda*, and *Microdictyon.* Despite this apparent algal dominance, the overall mean cover of macroalgae or turf algae was no higher at Rota than at Guam, Tinian, or Saipan.

Documented anthropogenic impacts known to negatively affect abundance of live corals are less severe at Rota than at Saipan and Guam, and Rota has less pressure from human population and associated activities than do those two islands. Although watershed issues are known to reduce water quality in some locations at Rota, such as Talakhaya Bay, and impaired water quality has been documented at several sites (Fig. 5.10a), overall water quality around Rota is considered excellent (Bearden et al. 2008). Monitoring by the CNMI Division of Environmental Quality (DEQ) revealed that examined reefs were broadly healthy (Bearden et al. 2008). Similarly, although high densities of COTS in 2003 and areas of stressed coral have been recorded in some locations at Rota, these observations appear no more numerous than at the other southern islands.

Subtle differences between the geomorphology of the shallow habitats around Rota versus around Guam and Tinian may exist, but they are not discernable from CRED acoustic data, since benthic habitat mapping is not yet complete around Rota. Riegl and Dodge (2008) noted the absence of substantial modern deposition in some areas around Rota and described shallow habitats as small massive corals occurring directly on Pleistocene (2.6 million to 11,550 years ago) limestone and

the size of framework building corals as limited by environmental factors. Such environments tend to naturally support relatively low levels of live coral cover because of the morphology of the corals present.

Since there is no obvious present-day cause, the low coral cover observed at Rota may be a result of past events. For example, an extensive outbreak of COTS occurred around the southern islands of the Mariana Archipelago in 1968, resulting in extensive coral mortality (Tsuda 1972; Quinn and Kojis 2003). While Saipan and Guam had control programs to remove COTS, such management measures historically have not been implemented at Rota, Tinian, or Aguijan.

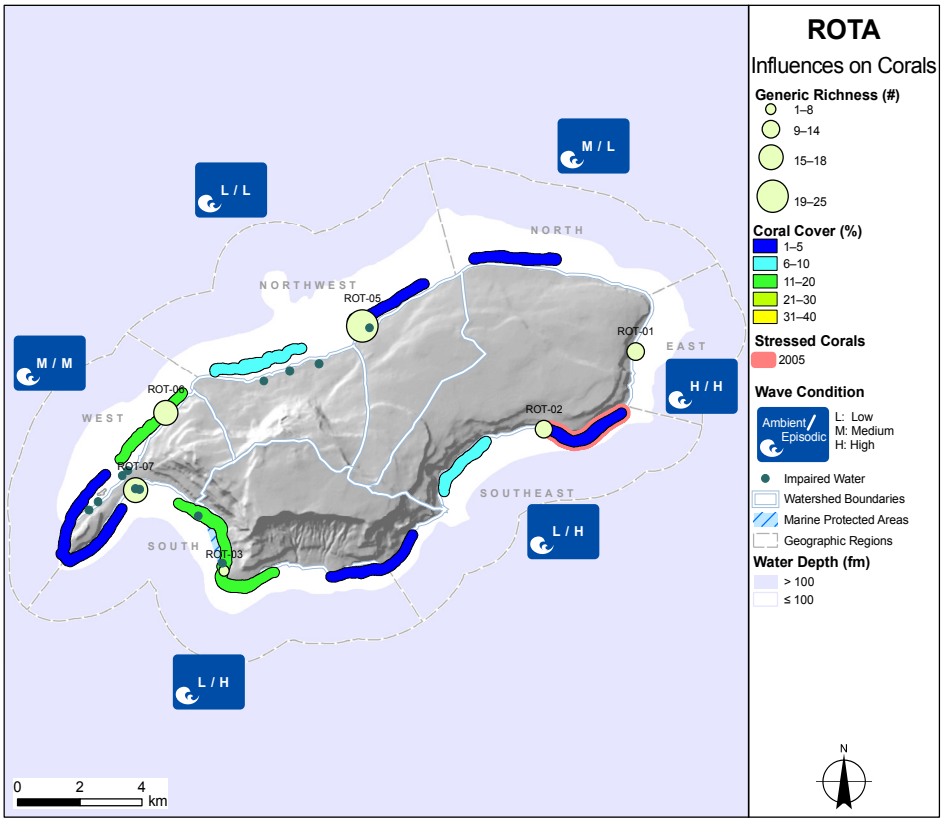


Figure 5.10a. Cover (%) observations of live and stressed corals from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats at Rota during MARAMP 2005 and 2007, presented with watersheds and impaired water sites (M Pangelinan, CNMI Department of Land and Natural Resources, pers. comm.; Bearden et al. 2008). Values of coral cover and generic richness represent averages of data from both survey years, where available; otherwise values represent data from the single year surveyed. Towed-diver-survey areas combine overlapping survey tracks for both MARAMP survey years. Colored outlines represent areas where estimates of stressed-coral cover were > 10%. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.

In addition to likely impacts from COTS, Rota has been subject to a number of episodes of coral bleaching, including one episode in 2002 when bleaching was observed in corals at depths of up to 18 m (Richmond et al. 2002). The coral bleaching threshold is defined as 1°C above the monthly maximum climatological mean. In situ data from an SST buoy deployed at mooring site ROT-002 in Sasanhaya Bay in the south region shows that SST there surpassed the bleaching threshold multiple times during the summer months of 2003–2006, with a particularly warm episode in September 2006 (see Figure 5.4.2c in Section 5.4: "Oceanography and Water Quality;" for place-names and their locations, see Figure 5.2a in Section 5.2: "Survey Effort"). This evidence suggests that the reefs there experience considerable thermal stress on a variety of time scales, although this area in Sasanhaya Bay is highly sheltered from prevailing trade winds and their associated swell and, therefore, is likely to have temperatures that are warmer than at other locations at Rota. This thermal stress may have been a potential cause of observed differences in coral cover between MARAMP survey periods. Bleaching was observed during REA surveys conducted at Rota in 2007.

Overall, the ranks for reefs at Rota in the calculated *Benthic Condition Index for Guam, Rota, Tinian, and Saipan* (Fig. 5.10b) ranged from low to high in both 2005 and 2007. For most surveyed locations at Rota, ranks in the *Benthic Condition Index* were the same or higher in 2007 compared to ranks in 2005. In some cases, this pattern was a result of a change in one or more of the index parameters, such as increased cover of crustose coralline red algae or decreased COTS density. At many locations, however, one or more index components changed in a direction that would suggest a decline in actual benthic condition; for example, lower values of live coral cover and higher levels of stressed-coral cover were observed. Still, in these instances where observations suggest that the overall benthic conditions at a specific location has dropped, it declined to a lesser extent than at other locations around the populated, southern islands.

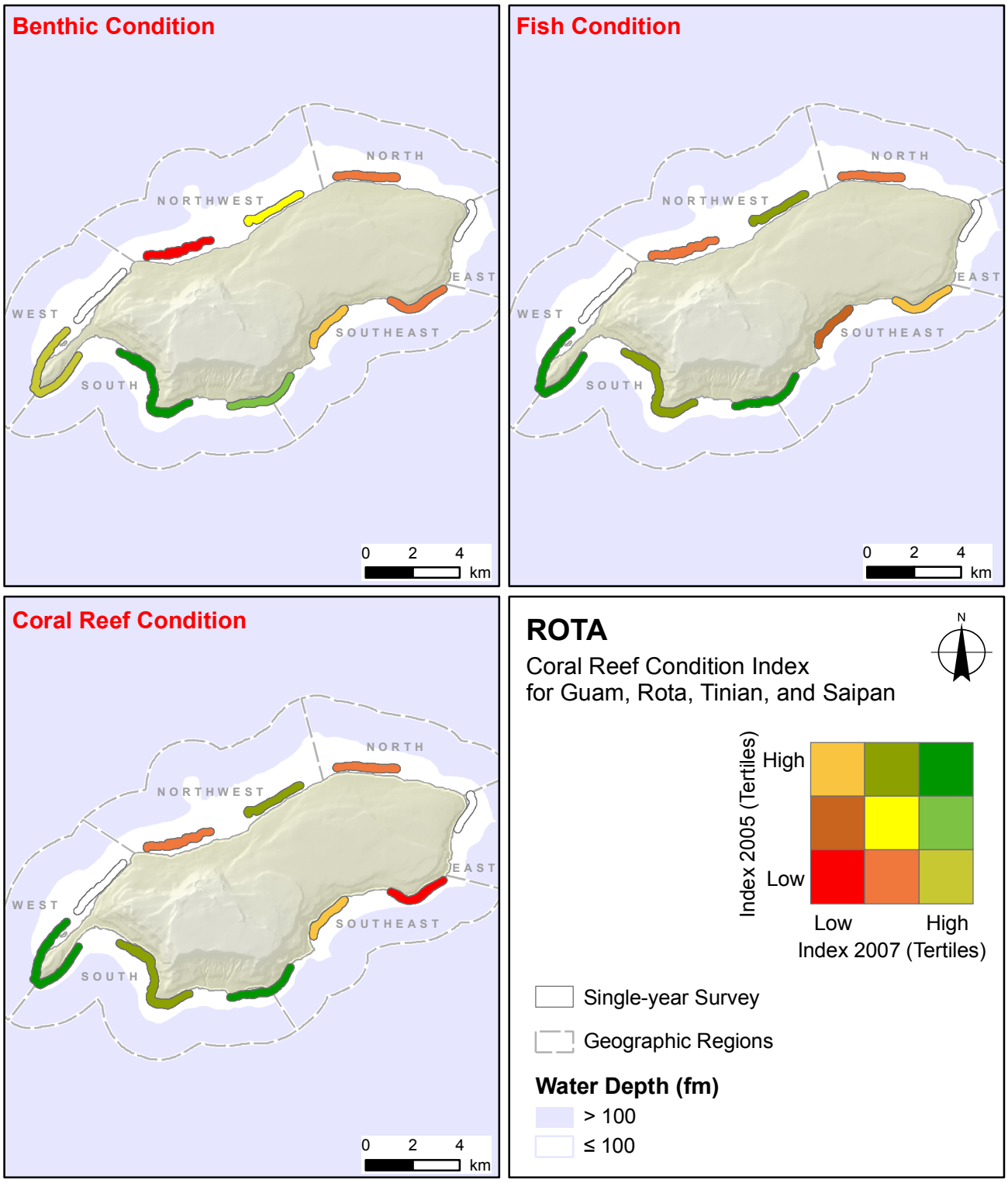


Figure 5.10b. The *Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan*, as well as the associated *Benthic Condition Index* and *Fish Condition Index*, reflects the condition of the benthic and fish communities and their integrated ecosystem for each towed-diver-survey area, *relative to other survey areas around the 4 populated, southern islands*. These maps indicate changes in index ranks between MARAMP 2005 and 2007 for towed-diver-survey areas at Rota. Survey areas are represented by irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007. No index value is calculated for areas with only one year of survey data. A high rank means superior condition relative to other survey areas around the 4 populated, southern islands. The survey area around this island's peninsula in the west and south regions, for example, has a high rank for both 2005 (y-axis) and 2007 (x-axis) and, thus, is assigned the bright-green color that corresponds to the top-right square in the legend. The position of the horizontal bar above the midline in this square also reflects that this survey area maintained a high rank in both years.

Sasanhaya Bay

Although the overall abundance of live corals was low at Rota, high levels of coral cover were observed along the eastern edge of Sasanhaya Bay within the Sasanhaya Fish Reserve, an MPA that includes Coral Gardens. Estimates of live coral cover from towed-diver surveys conducted in this area were consistently high through the 3 MARAMP survey years, compared to other areas at Rota. In 2003, the highest mean live coral cover in this survey area was 24% over 7 segments, which included 32% for 3 of those consecutive segments, compared to an islandwide mean of 9% (SE 1). Similarly, in 2005 and 2007, the highest mean cover values recorded for 3 consecutive segments were 49% and 58%, and the overall means were 6% (SE 1) and 4% (SE 1). In 2007, the single year when the line-point-intercept method was used to assess live coral cover at REA sites at Rota, the highest coral cover of 34% was observed at ROT-03, also located in Coral Gardens. This survey location was the only area at Rota that showed high coral cover during each of the 3 MARAMP survey periods, although the extent of the area of high coral cover was very restricted, covering less than 1 km of surveyed distance. This area is well sheltered from trade wind waves, allowing for coral cover that was higher there than at more exposed locations along the southeastern and eastern sides of Rota. Although high coral cover was observed at ROT-03, the generic richness recorded at this site in 2007 was only 7, the lowest number of genera per site observed at Rota. This sampled coral community was dominated by corals of the genus *Porites*, predominantly *P. rus* and *P. lichen* and occasionally *P. lobata*. Coral colonies of this genus formed large pillars, extending upward ~ 6 m from the bottom of the seafloor and creating a highly complex habitat with numerous overhangs and crevices.

This well-developed coral community at Coral Gardens sits within a wider reef area observed to have low to moderate levels of coral cover, compared to other areas surveyed around the 4 populated, southern islands. High ranks in the *Benthic Condition Index* were calculated for this area in both 2005 and 2007 (Fig. 5.10b). These high ranks are attributable to the relatively low stressed-coral cover, low COTS density, and moderate abundance of crustose coralline red algae observed in this area, despite the low to moderate coral cover recorded there.

The low coral-cover values found outside of the Coral Gardens area in Sasanhaya Bay and the low generic richness at ROT-03 both likely result from a number of different factors over the past 50 years. As discussed previously, similar to reefs around Saipan and Tinian, reefs at Rota were affected by an outbreak of COTS in 1968 that significantly affected coral communities and greatly reduced live coral cover there. Observers shortly after that outbreak noted that "luxuriant reefs that had previously thrived in [Sasanhaya] Bay…were just drab foundations" (Tsuda et al. 1971, cited in Quinn and Kojis 2003). About 32 years later, during MARAMP 2003, divers reported the continued presence of large areas of upstanding but dead coral in Sasanhaya Bay. Tsuda et al. (1971, cited in Quinn and Kojis 2003) also reported that the species *P. rus* appeared unaffected by the COTS outbreak. This apparent resistance to COTS predation had been previously noted by Goreau (1972). This major COTS outbreak, along with subsequent COTS outbreaks, may have permanently altered the reef composition in this area, resulting in observations there of high coral cover in limited areas and low-diversity, *Porites*-dominated reefs during subsequent MARAMP and other surveys. As noted in the previous section, oceanographic data suggests that reefs in Sasanhaya Bay have experienced considerable thermal stress on a variety of time scales.

Another factor that may affect coral communities in Sasanhaya Bay is the presence of at least 5 shipwrecks (Fig. 5.10c). The direct physical impact of shipwrecks can damage reefs as can the leaching of foreign compounds from wrecks into the surrounding environment, as has been documented at Rose Atoll in American Samoa, where rust from a steel shipwreck caused cyanobacteria blooms and changes in the coral reef environment (Schroeder et al. 2008). Three of the Sasanhaya Bay wrecks are wooden Japanese submarine chasers from WWII, one of which lies in Coral Gardens. Significant damage to the coral reef community in Sasanhaya Bay occurred in 1996, as a result of a powerful detonation of the wreck in Coral Gardens performed by the U.S. Navy at the request of the CNMI Emergency Management Office (Starmer 2005). Aside from direct effects from the explosion, subsequent sediment plumes reportedly caused considerable damage that was further exacerbated by the passage of 2 typhoons, which together affected an area of some 29,000 m^2 (Starmer 2005). In central Sasanhaya Bay, 2 steel Chinese smuggling vessels, one of which has 7 propellers, were sunk in 1999 in a sandy area as dive targets to take recreational diving stress off Coral Gardens.

Although this bay includes the Sasanhaya Fish Reserve and a high-quality benthic community relative to the other populated, southern islands of the Mariana Archipelago, the rank for this area in the Fish Condition Index for Guam, Rota, Tinian, and Saipan was not the highest one observed for Rota (Fig. 5.10b). The Fish Condition Index rank for this survey area in 2005 was high, a result of large-fish biomass and density estimates that were higher than levels observed at the other 3 islands in the index, but the rank in 2007 declined to medium because this area's fish biomass and density dropped while estimates for other survey areas around the populated, southern islands improved. Biomass of large fishes (≥ 50 cm in TL), based on towed-diver surveys, was low in this area and overall at Rota in both 2005 and 2007, compared to results at other islands in the Mariana Archipelago, and dominated by parrotfishes (Scaridae) and barracudas (Sphyraenidae). In both 2003 and 2005, a shark was sighted in this area. The highest mean values of large-fish biomass were observed in the west and northwest regions (Fig. 5.10d). Meanwhile, results from the REA site in Sasanhaya Bay, ROT-03, in the 3 MARAMP survey years suggested that fish biomass was not higher there than at other REA sites surveyed at Rota that did not benefit from fisheries protection in an MPA. Other studies have reported some recovery of fish communities within this reserve (Starmer et al. 2008). Note that the southern coast of Rota is readily accessible from both the West and East Harbors, is relatively well protected from prevailing winds, and has one of the higher human population densities on this island.

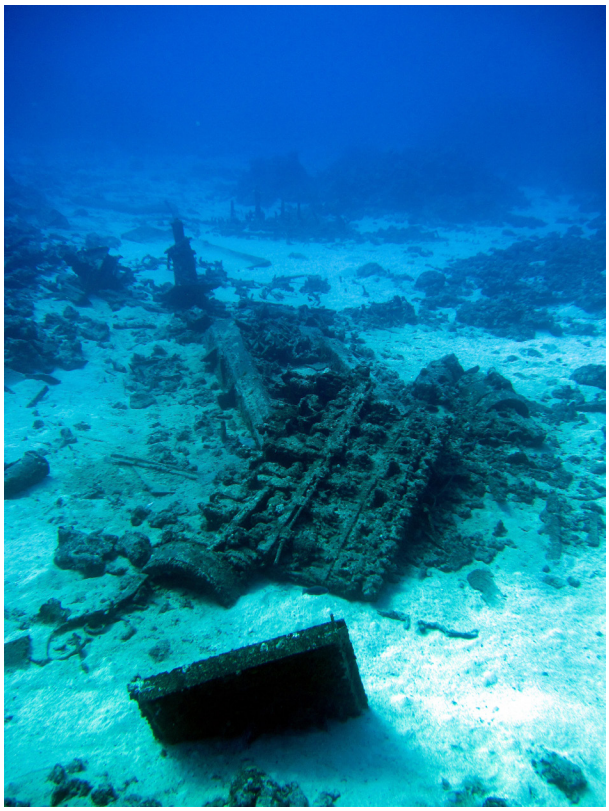


Figure 5.10c. Shipwreck within Sasanhaya Bay. *NOAA photo by Kevin Lino*

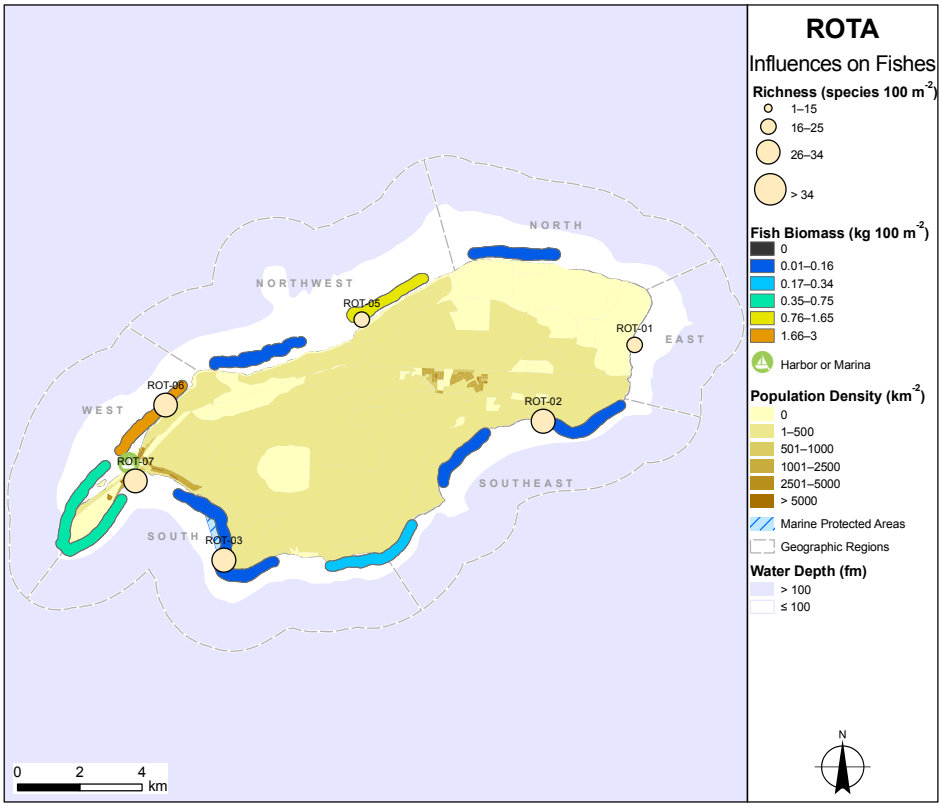


Figure 5.10d. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver surveys and species richness from REA surveys conducted on forereef habitats at Rota during MARAMP 2005 and 2007, presented over a human population density map (U.S. Bureau of the Census 2003, 2008). Biomass and richness values represent averages of data from both survey years, but, if surveys were conducted during one year only, values represent data from that single year. Towed-diver-survey areas combine overlapping survey tracks for both MARAMP survey years; survey tracks are often similar but not necessarily the same between survey years.

5.11 Summary

This section presents an overview of the status of coral reef ecosystems around the island of Rota as well as some of the key natural processes and anthropogenic activities influencing coral reefs around this island. MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Rota. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Rota chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter.

To simplify interpretation of ecosystem conditions around Rota, a *Benthic Condition Index*, a *Fish Condition Index*, and an integrated *Coral Reef Condition Index* were developed to reflect ecosystem conditions at specific locations around Rota, relative to locations around the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan and based on MARAMP 2005 and 2007 surveys only (see Section 5.10: "Ecosystem Integration"). By synthesizing large amounts of complex, interdisciplinary information, these reef condition indices assist resource managers in identifying potential relationships between various ecosystem components. The conditions of the fish and benthic communities and the overall ecosystem around Rota, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

The following summary highlights the key attributes of the coral reef ecosystems around Rota (for place-names and their locations, see Figure 5.2a in Section 5.2: "Survey Effort"):

- Rota is the fourth largest island in the Mariana Archipelago but in 2000 contained only 1.5% of the total human population of the Mariana Archipelago.
- Popular beaches are located mainly in the northwest region, and most dive sites are located in the south, west, and northwest regions. Steep cliffs on the southern and southeastern coasts reduce accessibility there.
- Rota is surrounded by narrow fringing reefs and shelves. The shallowest waters mapped around Rota reveal a series of narrow shelves, likely related to previous sea level stands. Northwest and west of Rota, shelves are narrow, but in Sasanhaya Bay wider shelves are present. Mounds distinguishable in the map of seabed slope at depths up to 50–80 m may be interpreted as coral mounds.
- Wave model output shows ambient trade wind swells impacting the north and east and to a lesser extent the southeast. Episodic wave energy from storm tracks impacts the south and southeast and to a lesser extent the east and west.
- SST in the south and northwest regions surpassed the bleaching threshold in September 2006.
- Overall abundance of live corals for Rota was low from both towed-diver and REA surveys, compared to the rest of the Mariana Archipelago. The overall sample mean for coral cover from REA surveys was 12.4% in 2007. Overall mean for cover of live hard corals from towed-diver surveys was 9% in 2003, 6% in 2005, and 4% in 2007.
- Current levels of affects from human activities or other stressors did not appear to explain the low live coral cover observed at Rota, compared to Guam, Saipan, and Tinian. The low cover of live corals may result from subtle differences in geomorphology or historic impacts, such as COTS outbreaks, coral bleaching, and typhoons.
- On the eastern edge of Sasanhaya Bay, towed-diver surveys suggested consistently high coral cover in Coral Gardens, a marine protected area, with mean coral cover over 3 consecutive segments estimated at 32%, 49%, and 58% in 2003, 2005, and 2007.
- Bleaching was the only disease state observed at Rota in 2007, the only year in which disease surveys were conducted, and was found on *Astreopora* colonies. Five cases of bleaching were documented, translating to a mean prevalence of coral disease of 0.05%. Additionally, predation attributable to COTS or *Drupella* snails was observed, and 40% of predation cases occurred on *Astreopora* colonies.
- Overall mean macroalgal cover, from towed-diver surveys conducted at Rota, was nearly identical in 2003 and 2005 but slightly lower in 2007. This difference may result from seasonal shifts of algal populations. High macroalgal cover was consistently recorded during surveys in the north and east regions in the 3 MARAMP survey years.

- The highest cover value for crustose coralline red algae was consistently recorded during the towed-diver survey completed at the western tip of this island. The survey with the lowest cover level was consistently located in the north region, near Asuzudo and Mochon Points, although, in 2005, no crustose coralline red algae were observed during the survey conducted in the southeast region west of Puntan Sagua`gahga.

- Only one type of coralline-algal disease was documented at Rota: coralline lethal orange disease, which was present at 5 of the 6 REA sites surveyed.

- Overall large-fish (≥ 50 cm in TL) biomass, from towed-diver surveys, declined to 0.14 kg 100 m^{-2} in 2007 from 0.49 kg 100 m^{-2} and 0.48 kg 100 m^{-2} in 2003 and 2005. REA fish surveys conducted during the 3 MARAMP survey periods showed no clear spatial pattern at Rota; however, the highest mean total fish biomass in 2005 and 2007 was seen at ROT-02, located west of Puntan Sagua`gahga in the southeast region. Fish biomass at Rota was low, relative to the rest of the Mariana Archipelago, with mean total fish biomass of 4.07 kg 100 m^{-2} for the 3 MARAMP survey years.

- A low abundance of giant clams was recorded around Rota during the 3 MARAMP survey periods, compared to the rest of the Mariana Archipelago.

- In 2003, towed-diver benthic surveys found that COTS were ubiquitous around Rota. However, COTS were most abundant in the southeast, south, and west regions. Localized areas where potential COTS outbreaks may have been occurring were observed near Puntans Taipingot, Sailigai, and Malilok. Observed COTS densities suggest that the COTS population around Rota was much smaller in 2005 than in 2003, and densities were greatest around Puntan Taipingot in 2005. By 2007, this COTS population appears to have declined further.

- Towed-diver benthic surveys revealed higher sea cucumber abundance in the south and southeast regions than in other regions around Rota during the 3 MARAMP survey periods.

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6 AGUIJAN

6.1 Introduction

Aguijan, also called Aguiguan, is a small, uninhabited island of the Commonwealth of the Northern Mariana Islands (CNMI) and is located 8 km southwest of Tinian at 17°36′ N, 145°50′ E. The highest elevation of this low-lying island is only 57 m. Oriented northeast–southwest, Aguijan has a land area of 7.01 km^2 and an elongated shape that is ~ 4.8 km long and 1.6 km wide (Fig. 6.1a). Like the adjacent islands of Tinian and Saipan, Aguijan is composed of a series of uplifted carbonate terraces overlying an older volcanic structure and surrounded by steep sea cliffs (Fig. 6.1b).



Figure 6.1a. Satellite image of Aguijan (IKONOS Carterra Geo Data, 2003).



Figure 6.1b. Aguijan is surrounded by steep cliffs, as seen from a small boat during MARAMP 2007. *NOAA photo*

6.1.1 History and Demographics

Archaeological evidence of Chamorro culture on Aguijan has been found in the form of pottery shards and latte sets, and an old village was located on the top of this island. However, it is not certain how much of the time Aguijan was permanently inhabited or whether it was mainly used for temporary fishing camps (Rogers 1995; Rainbird 2004). Aguijan has significant historical importance as the stage of the last battle between Spain and the Chamorro of the Mariana Archipelago. In 1695, Chamorro on Tinian sent women and children to Aguijan for safety, subsequently leaving for Aguijan themselves to join them while Spain was defeating Chamorro on Saipan. Surviving Chamorro were taken to Guam for resettlement (Rogers 1995). After the period of control by Spain, Aguijan, like Tinian and Saipan, came under control by Germany, until the period of Japanese administration that followed World War I (WWI). During WWII, the Japanese maintained a garrison on Aguijan, which was surrendered to the U.S. Coast Guard in 1944. Since 1945, this island has remained uninhabited (Cruz et al. 2000). Currently, Aguijan is administered by the municipality of Tinian. Tinian residents visit periodically for hunting, although access to Aguijan is limited because of the steep cliffs that surround it (Cruz et al. 2000). South of Aguijan, a small islet called Naftan Rock has been used by the U.S. Navy for bombing practice, which has resulted in the presence of unexploded ordnance in surrounding waters (Starmer 2005).

6.1.2 Geography

Aguijan, like the neighboring islands of Guam, Rota, Tinian, and Saipan, is composed of a series of coralline limestone terraces that lie on top of a volcanic core. These terraces are very flat and separated by steep slopes (Fig. 6.1.2a). No beaches are found around Aguijan, which is instead surrounded by sea cliffs.

Although Aguijan is completely vegetated, human activities and feral ungulates have affected its natural vegetation (Fig. 6.1.2b). Extensive areas of level land were cleared on Aguijan for Japanese sugarcane plantations, and *Casuarina* trees were planted as windbreaks on the upper terraces (Mueller-Dombois and Fosberg 1998). The areas that weren't cleared have retained native limestone forest, similar in composition to forests on Tinian but dominated by a relatively small number of species (Esselstyn et al. 2003).

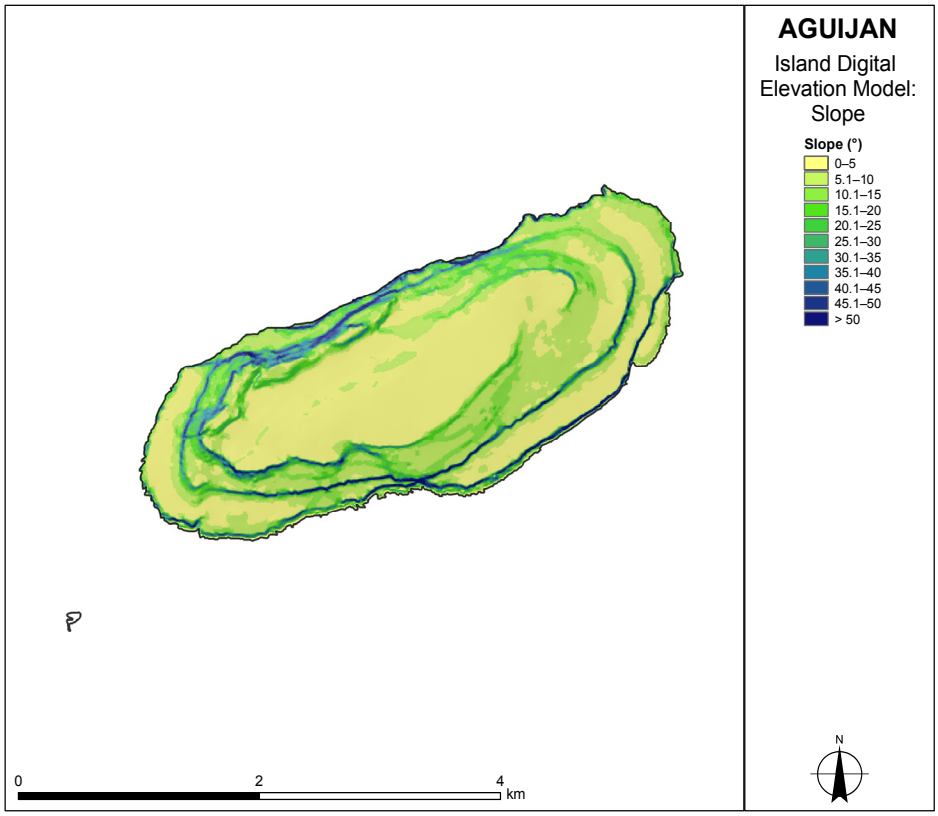


Figure 6.1.2a. Slope map using the digital elevation model (grid cell size: 10 m) for Aguijan.

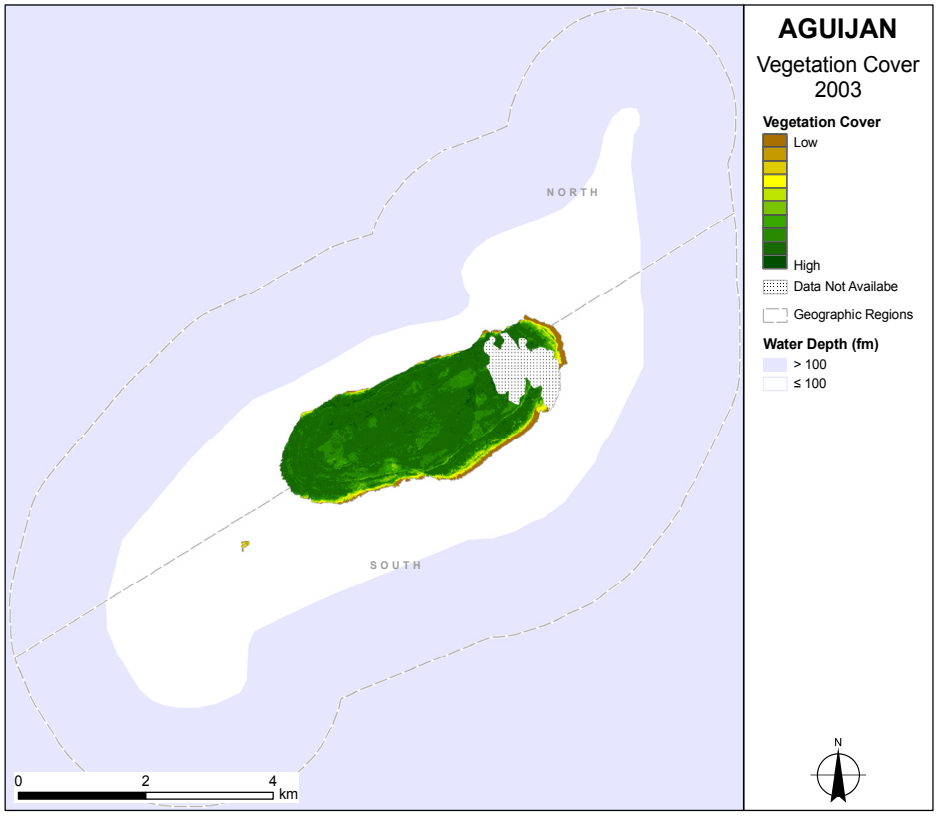


Figure 6.1.2b. Vegetation cover on Aguijan, derived using the Normalized Difference Vegetation Index from a satellite image (grid cell size: 4 m; IKONOS Carterra Geo Data, 2001). Hatched lines display areas where data are not available because cloud cover obscures the satellite image.

6.1.3 Environmental Issues on Aguijan

The main environmental issues of concern on Aguijan are the effects of feral ungulates on native flora and the spread of the invasive weed *Lantana camara*. Feral goats have affected severely this island's native forests. An eradication program conducted in 1990 was only partially successful (Campbell and Donlan 2005), and the goat population on Aguijan in 1998 remained at an estimated 1500 animals (Atkinson and Atkinson 2000). Goats affect this island's native forest by causing severe erosion and removing the understory, which is becoming dominated by the aggressively invasive weed *Lantana camara* (Esselstyn et al. 2003).

Maintenance of native forest is of key importance for the support of associated fauna. Aguijan supports a number of native bird species, including ~ 10% of the archipelago-wide population of the Mariana grey swiftlet (*Aerodramus vanikorensis bartschi*), also known as the Guam swiftlet and listed both Federally as endangered and locally as threatened or endangered; Micronesian megapode (*Megapodius laperouse*), also listed Federally as endangered and locally as threatened or endangered; and golden white-eye (*Cleptornis marchei*), also found on Guam (U.S. Fish and Wildlife Service; Berger et al. 2005; Cruz et al. 2000; Esselstyn et al. 2003).

Aguijan has a small population of the Mariana fruit bat (*Pteropus mariannus mariannus*), which is listed Federally as endangered and locally as threatened or endangered (U.S. Fish and Wildlife Service; Berger et al. 2005). Estimates made in 2002 put this bat population at 30–50 individuals, considerably lower than estimates of 150–200 from surveys in 2000, a drop that could be a result of periodic poaching (Esselstyn et al. 2003).

Another issue for Aguijan is the proposed development of ecotourism (Esselstyn et al. 2003). Ecotourism providers would need to develop landing areas or piers to allow safe access to Aguijan, since access to this island is very limited because of steep sea cliffs.

6.2 Survey Effort

Biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing coral reef ecosystems around the island of Aguijan since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. Different areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 2 geographic regions around Aguijan are delineated in Figure 6.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Aguijan. Potential reef habitat around this island is represented by a 100-fm contour shown in white on this map.

Benthic habitat mapping data were collected around Aguijan using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around Aguijan, Tinian, Tatsumi Reef, Saipan, and Marpi Bank with multibeam sonar covered a total area of 213.4 km^2 in 2003 and 1800 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live-hard-coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 6.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Aguijan was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 6.5–6.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 6.2a, along with their mean depths and total areas or length.

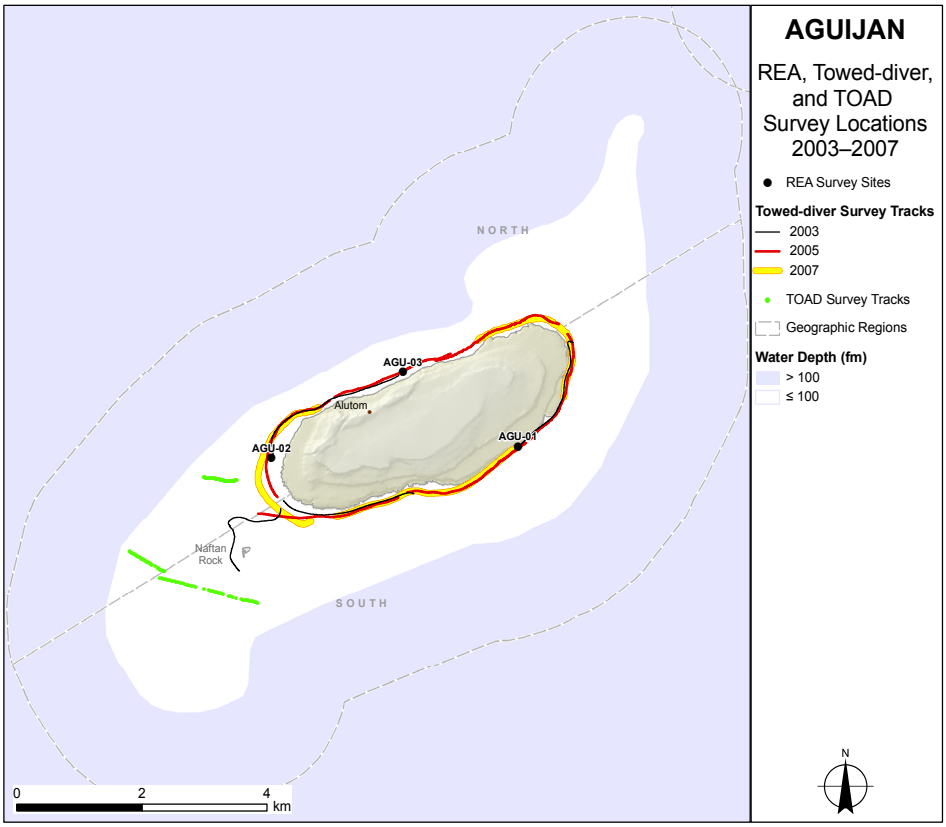


Figure 6.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Aguijan during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 2 geographic regions: north and south.

Table 6.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Aguijan during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	2	3	1
	Mean Depth (m)	14 (SD 1.4)	13.8 (SD 1)	13.5
Benthic	Number of Surveys	2	3	2
	Mean Depth (m)	14 (SD 1.4)	13.8 (SD 1)	13.3 (SD 0.4)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	4	6	3
	Total Survey Area (ha)	8.7	12.6	8.5
	Mean Depth (m)	13.6 (SD 0.5)	17.1 (SD 1.7)	15.2 (SD 0.6)
TOAD		**2003**		
	Number of Surveys	3		
	Total Length (km)	2.71		

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Aguijan were collected using (1) subsurface temperature recorders (STR) designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007. Results for some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 6.2b, and results are discussed in Section: 6.4: "Oceanography and Water Quality."

Table 6.2b. Numbers of STRs deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Aguijan during MARAMP 2003, 2005, and 2007. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Additional deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
STR	1	–	1	1	1	1	1
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	12	21		19			52
Deepwater Casts	–	4		1			5
Water Samples		**2005**		**2007**			**Total**
		3		3			6

Towed-diver Surveys: Depths

Figures 6.2b and c illustrate the locations and depths of towed-diver-survey tracks around Aguijan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

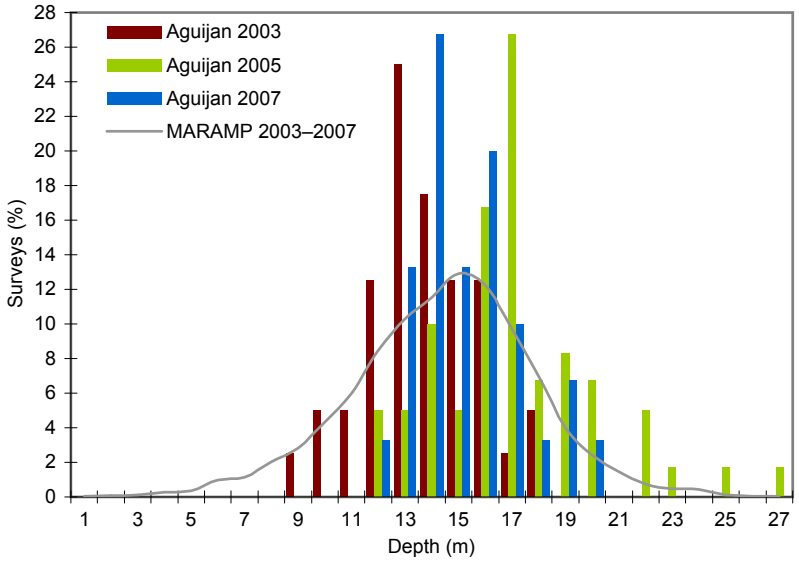


Figure 6.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

During MARAMP 2003, 4 towed-diver surveys were conducted along parts of the forereef slopes of Aguijan (Figs. 6.2b and c top panel). The mean depth of all survey segments was 13.6 m (SD 2.6), and the mean depths of individual surveys ranged from 13.3 m (SD 2.8) to 14.4 m (SD 2.3).

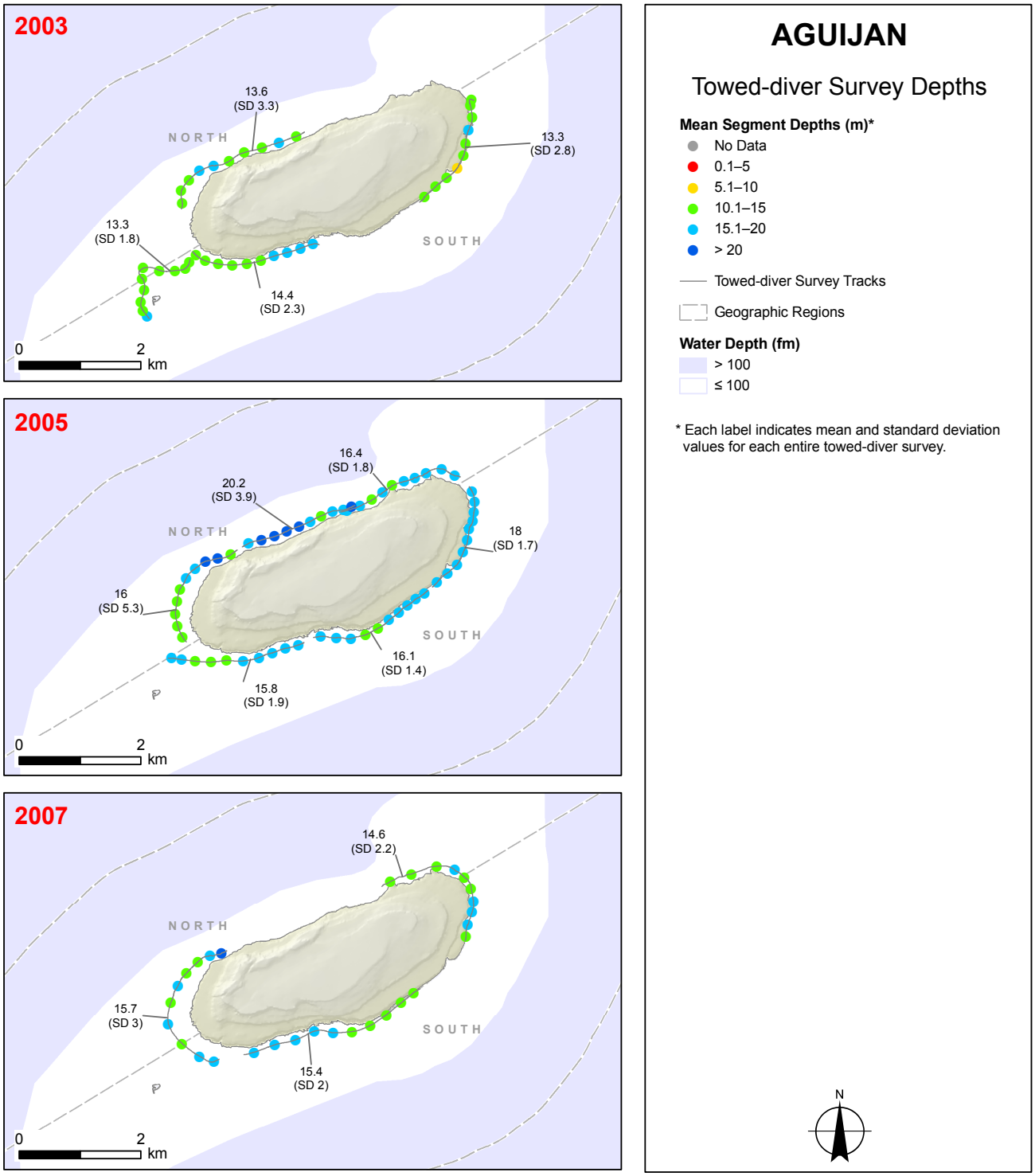


Figure 6.2c. Depths and tracks of towed-diver surveys conducted on forereef slopes around Aguijan during MARAMP 2003, 2005, and 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

During MARAMP 2005, 6 towed-diver surveys were conducted along the forereef slopes of Aguijan (Figs. 6.2b and c middle panel). The mean depth of all survey segments was 17.1 m (SD 3.4), and the mean depths of individual surveys ranged from 15.8 m (SD 1.9) to 20.2 m (SD 3.9).

During MARAMP 2007, 3 towed-diver surveys were conducted along parts of the forereef slopes of Aguijan (Figs. 6.2b and c bottom panel). The mean depth of all survey segments was 15.2 m (SD 2.5), and the mean depths of individual surveys ranged from 14.6 m (SD 2.2) to 15.7 m (SD 3).

6.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Aguijan were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 200–1500 m. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of ~ 15–100 m.

6.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 6.3.1a) collected by the Coral Reef Ecosystem Division around Aguijan, Tinian, Tatsumi Reef, Saipan, and Marpi Bank in 2007 encompassed an area of 2013.4 km^2. Multibeam data acquisition was limited to the single pass completed by the NOAA Ship *Hi`ialakai* around this island in 2007 cover-

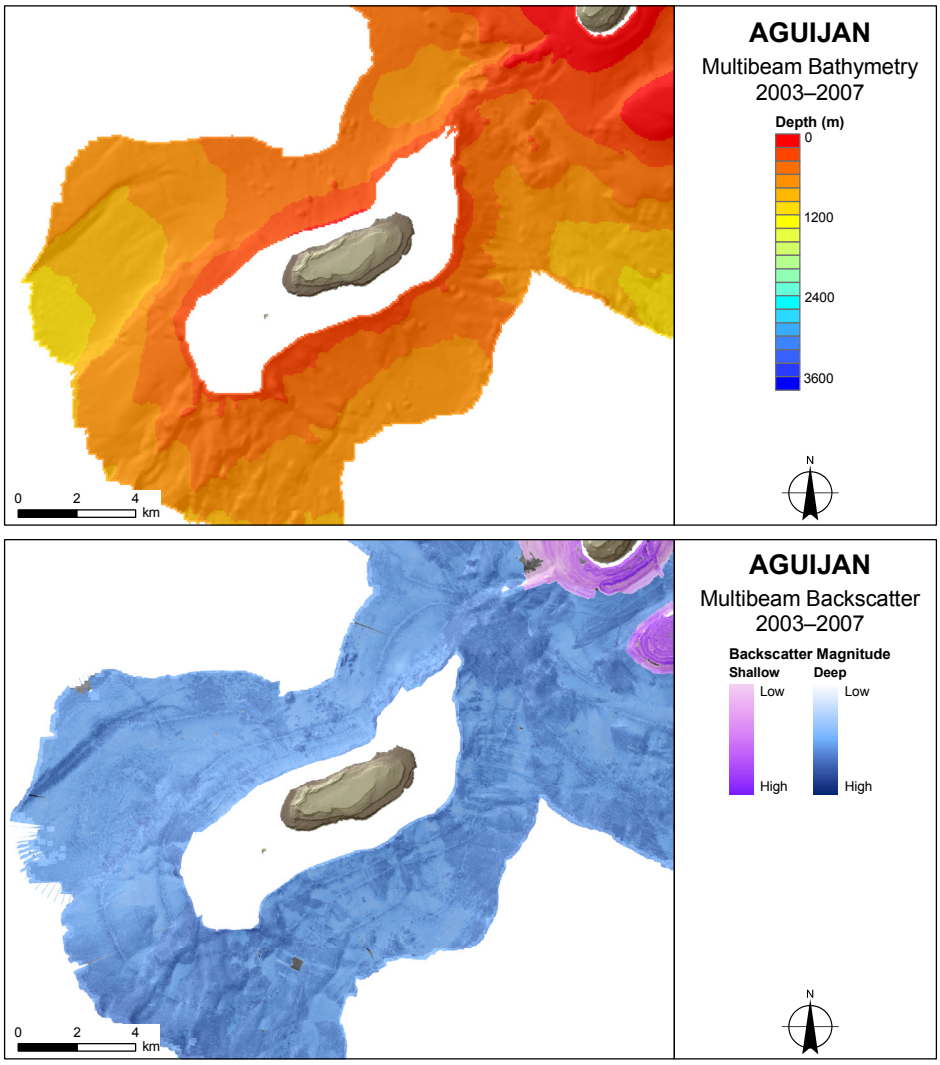


Figure 6.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Aguijan during MARAMP 2007 at depths of 200–1500 m. Backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades of blue represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

ing depths of ~ 200 to ~ 1000 m. Additional data were acquired by the *Hi'ialakai* to depths of ~ 1500 m during transits between Aguijan and adjacent islands.

Multibeam bathymetry acquired during MARAMP 2007 reveals a sloping bank around Aguijan (Fig. 6.3.1a, top panel). East of Aguijan, the flanks of the bank descend to a depth of 400 m within ~ 2 km of this island's coast. North of Aguijan, a broad submerged ridge connects the bank to Tinian at a depth of ~ 380 m. Northeast of Aguijan, bathymetry data suggest a series of narrow, parallel ridges, the tops of which gradually deepen to depths of ~ 650 m. South of this island, bathymetry show rugged topography with 2 steep-sided ridges. West of Aguijan, a major bathymetric feature is an ~ 3-km-wide depression that reaches a depth of 1000 m at the edge of the multibeam survey area.

The limited amount of backscatter data acquired around Aguijan show some variability. Higher backscatter values, relative to other surveyed areas, suggest that harder substrates may be present along the tops of the ridges, described above, northeast, north, and south of Aguijan (Fig. 6.3.1a, bottom panel). Multibeam data collected around Aguijan also reveal that flatter areas of the seabed are generally associated with lower backscatter values, suggesting that these areas may be characterized by softer sediments.

6.3.2 Optical Validation

During MARAMP 2003, 3 TOAD optical-validation surveys were conducted at Aguijan at depths of ~ 15–100 m (for survey locations, see Figure 6.2a in Section 6.2: "Survey Effort"). Subsequent analysis of video acquired from these surveys provided estimates of the percentages of sand cover and live-hard-coral cover (Fig. 6.3.3a).

Covering a distance of 30 km at depths of 9–27 m, 13 towed-diver optical-validation surveys were conducted on forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

6.3.3 Habitat Characterization

Both towed-diver observations and analyses of TOAD video footage showed low sand cover at most of the areas surveyed at Aguijan (< 20% in most areas), suggesting that the seabed in these areas was predominantly composed of hard substrates (Fig. 6.3.3a, top panel). The distribution of sand cover also showed an east–west gradient, with sand cover higher to the west of Aguijan than to the east. The greatest level of sand cover, recorded during towed-diver surveys within a range of 20.1%–50%, was observed in an area south of this island, and the seabed there was characterized by sand with patch reefs. Analyses of video footage from TOAD surveys suggest that 100% sand cover occurred in slightly deeper (50–100 m) waters surveyed to the west of Naftan Rock (for place-names and their locations, see Figure 6.2a in Section 6.2: "Survey Effort"). Otherwise, sand cover was predominantly low for the areas surveyed with the TOAD, with a few smaller patches of sand recorded to the south of Naftan Rock. No general conclusions about the distribution of sand in shallow versus deeper waters can be drawn from these data, since the area of seabed surveyed by the TOAD is much less than the area covered by towed-diver surveys.

Observations from towed-diver surveys conducted at depths of 9–27 m showed that habitat complexity generally was higher on the north side of this island than on the south side (Fig. 6.3.3a, middle panel). Distribution of live corals at Aguijan from on towed-diver surveys suggests a similar pattern: higher live coral cover was observed on the north side, where habitat complexity was also highest, and lower live coral cover was seen on the less complex south side (Fig. 6.3.3a, bottom panel). Around northern Aguijan, live coral cover was generally 10.1%–40% and divers observed a mixture of carbonate pavement, reef slopes, and spur-and-groove habitat. Around southern Aguijan, live coral cover was generally < 10%, with estimates higher on the southwest coast, where coral cover of 10.1%–20% was recorded. Observed habitats included hard pavement, boulders, and rubble. No live corals were observed in the analyses of TOAD video footage.

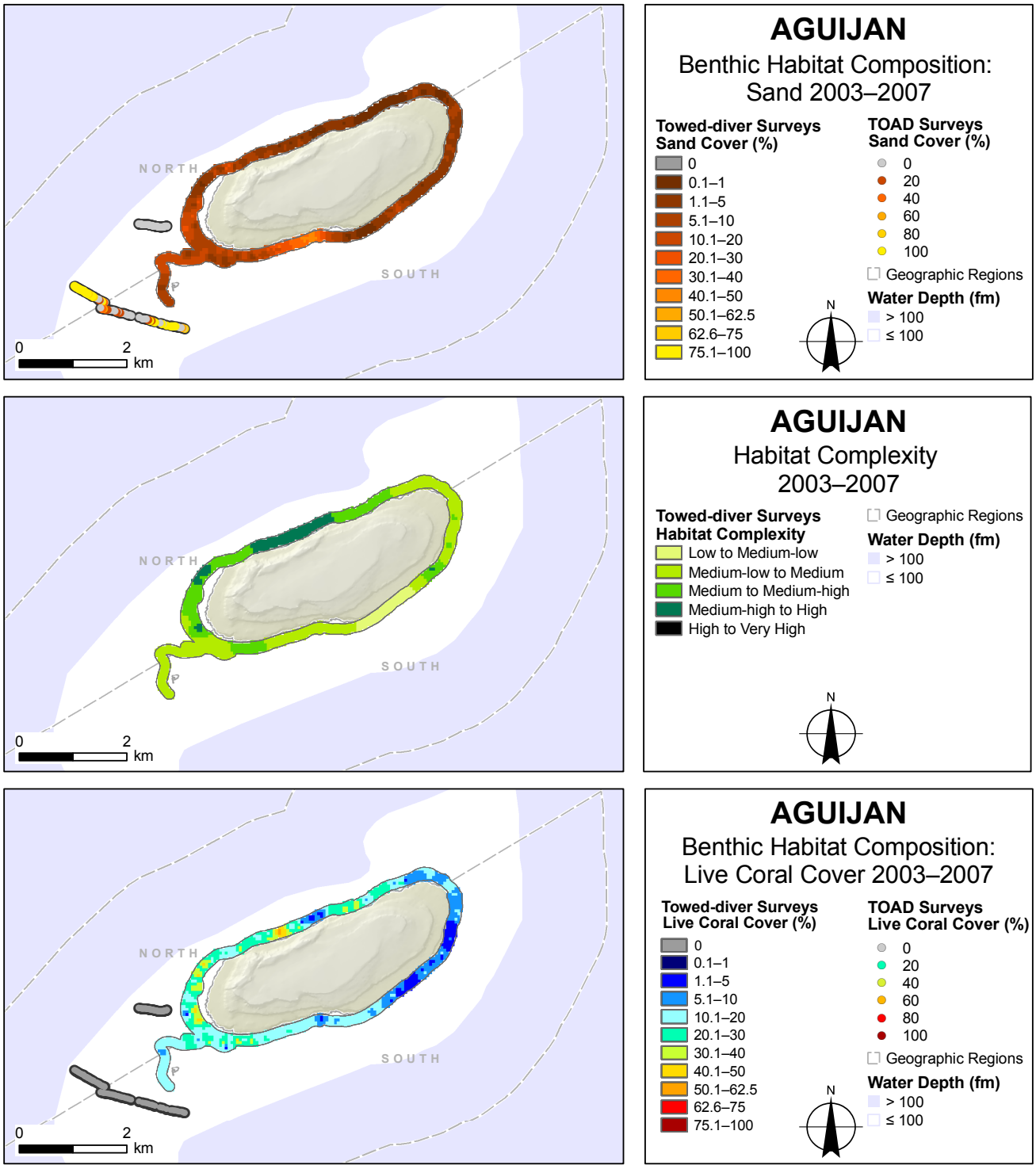


Figure 6.3.3a. Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) cover (%) of live hard corals from towed-diver surveys of forereef habitat conducted and analysis of TOAD video collected around Aguijan during MARAMP 2003, 2005, and 2007.

6.4 Oceanography and Water Quality

6.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 12 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the island of Aguijan on September 17. Temperature, salinity, and density values from these casts varied both spatially and vertically around Aguijan. Spatial comparisons of water properties at a depth of 10 m suggest low variability around Aguijan with recorded temperature differences up to 0.4°C. The coldest temperature (29.52°C) in the north region (cast 1) coincided with the highest salinity (34.35 psu) and greatest density (21.4 kg m^{-3}) values (Fig. 6.4.1a). Vertical comparisons of CTD profiles reveal water properties with a broad range in temperature (1.1°C) values and a moderate range in salinity (0.3 psu) values (Fig. 6.4.1b). The greatest range in vertical water properties was recorded on the west side of the south region. The high stratification of the water column in this area may have been caused by the combined effects of solar heating on surface waters and topography-related tidal mixing below the depth of 15 m.

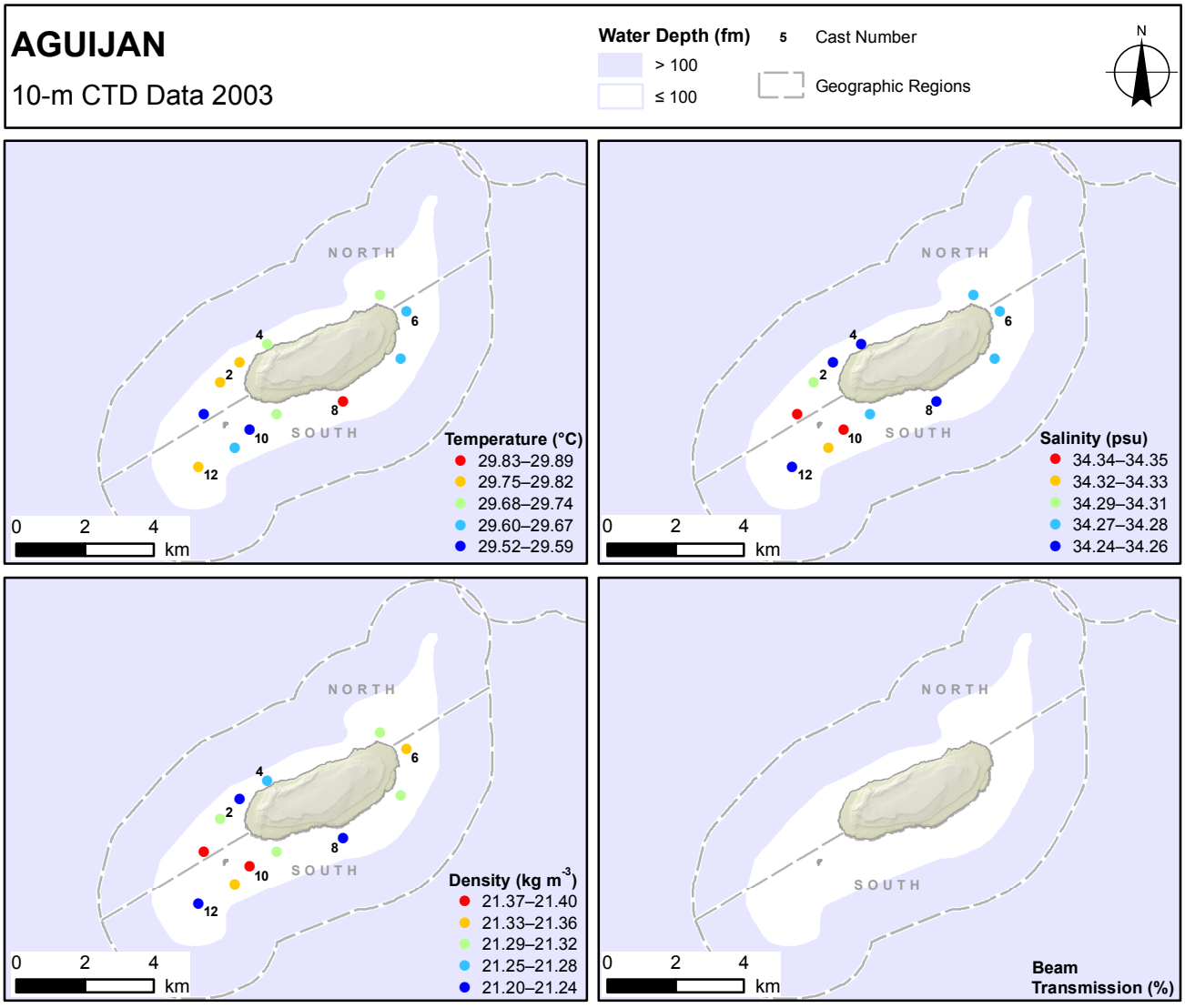


Figure 6.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts around Aguijan on September 17 during MARAMP 2003.

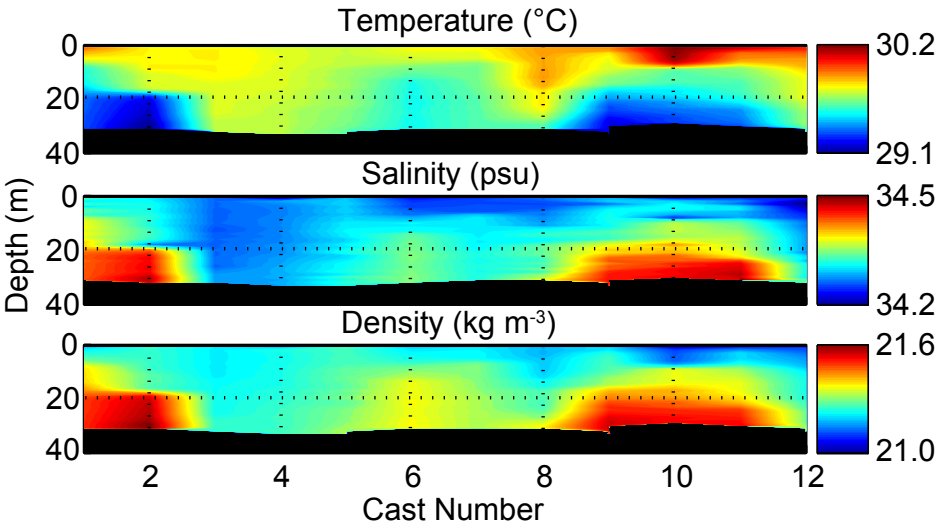


Figure 6.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Aguijan on September 17 during MARAMP 2003, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–12 in a clockwise direction around Aguijan. For cast locations and numbers around this island in 2003, see Figure 6.4.1a.

2005 Spatial Surveys

During MARAMP 2005, shallow-water CTD casts were conducted in nearshore waters around Aguijan over the period of September 27–28. Temperature, salinity, density, and beam transmission values from 20 of these casts varied both spatially and vertically around Aguijan. Spatial comparisons of water properties at a depth of 10 m show no clear spatial pattern around this island; however, a moderate range in temperature (0.8°C) was recorded (Fig. 6.4.1c). Vertical comparisons of CTD profiles reveal a series (casts 10–14, 17) of cold-water intrusions (Fig. 6.4.1d). Variation of salinity (0.2 psu) and density (1.1 kg m^{-3}) values occurred concurrently with these drops in temperature (1°C) values, suggesting enhanced mixing with deeper waters relative to other areas around this island. Beam transmission was generally high (~ 94%) at all cast locations.

Water samples were collected in conjunction with shallow-water CTD casts at 3 select locations at Aguijan in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.15–0.97 µg L^{-1}; total nitrogen (TN), 0.29–0.34 µM; nitrate (NO_3^-), 0.27–0.32 µM; nitrite (NO_2^-), 0.023–0.025. µM; phosphate (PO_4^{3-}), 0.013–0.016 µM; and silicate [$Si(OH)_4$], 0.73–0.85 µM. All parameters measured around Aguijan were similar at the east end of the south and north regions (Fig. 6.4.1e). In contrast, one location southwest of this island in the south region showed dissimilar water properties. Chl-*a* concentration was greater, total nitrogen and nitrate concentrations were lower, and nitrite, phosphate, and silicate concentrations were similar at this location relative to the other cast locations at Aguijan.

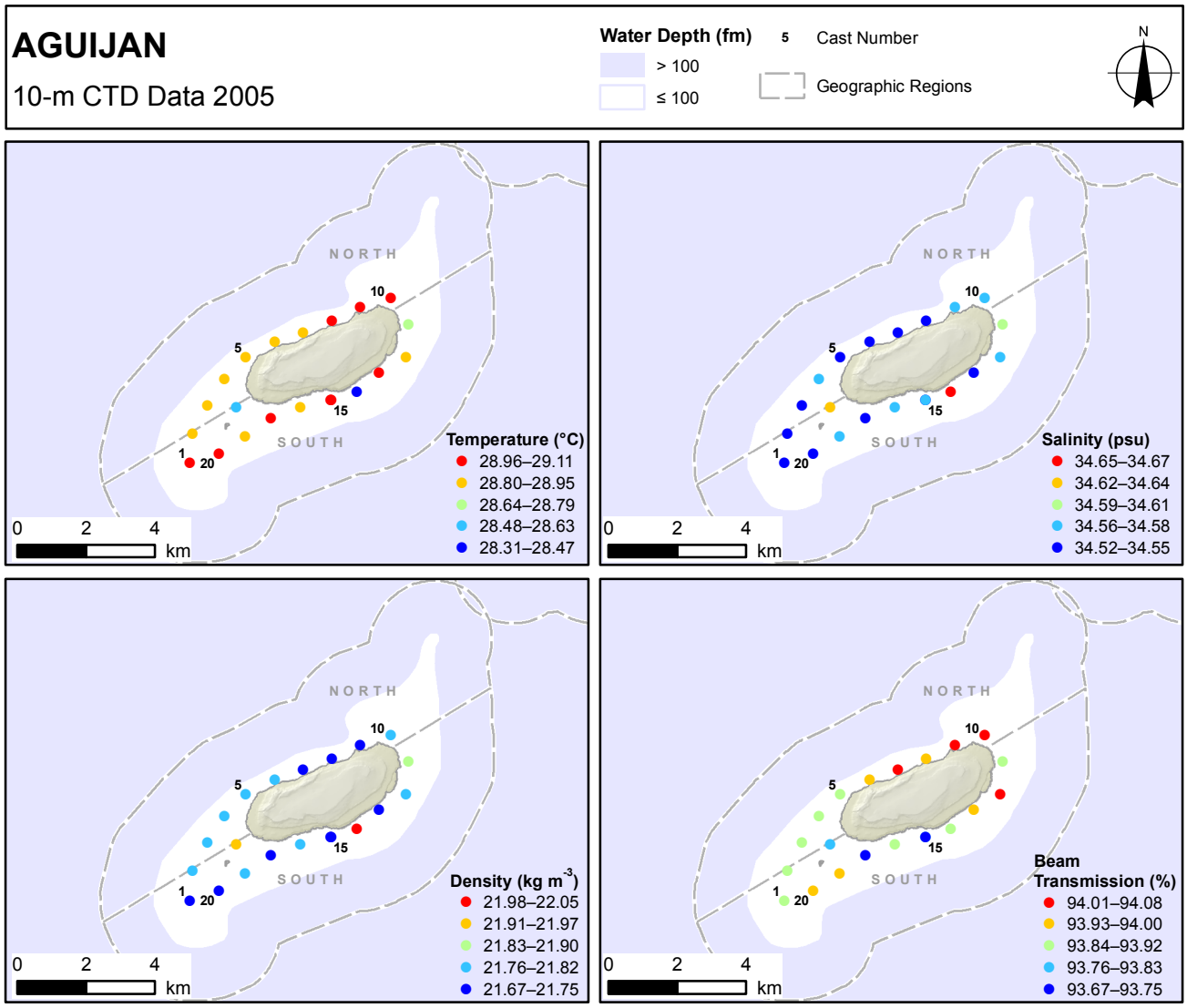


Figure 6.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Aguijan on September 27–28 during MARAMP 2005.

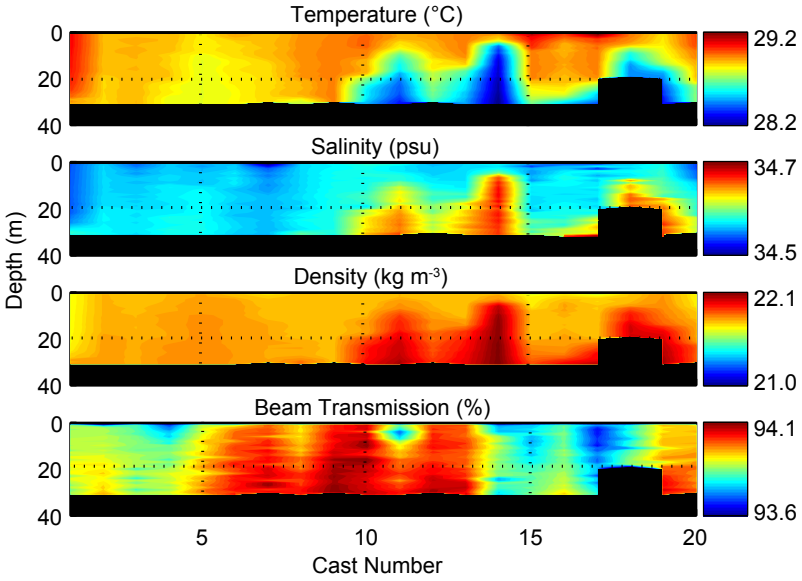


Figure 6.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Aguijan on September 27–28 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–20 in a clockwise direction around Aguijan. For cast locations and numbers around this island in 2005, see Figure 6.4.1c.

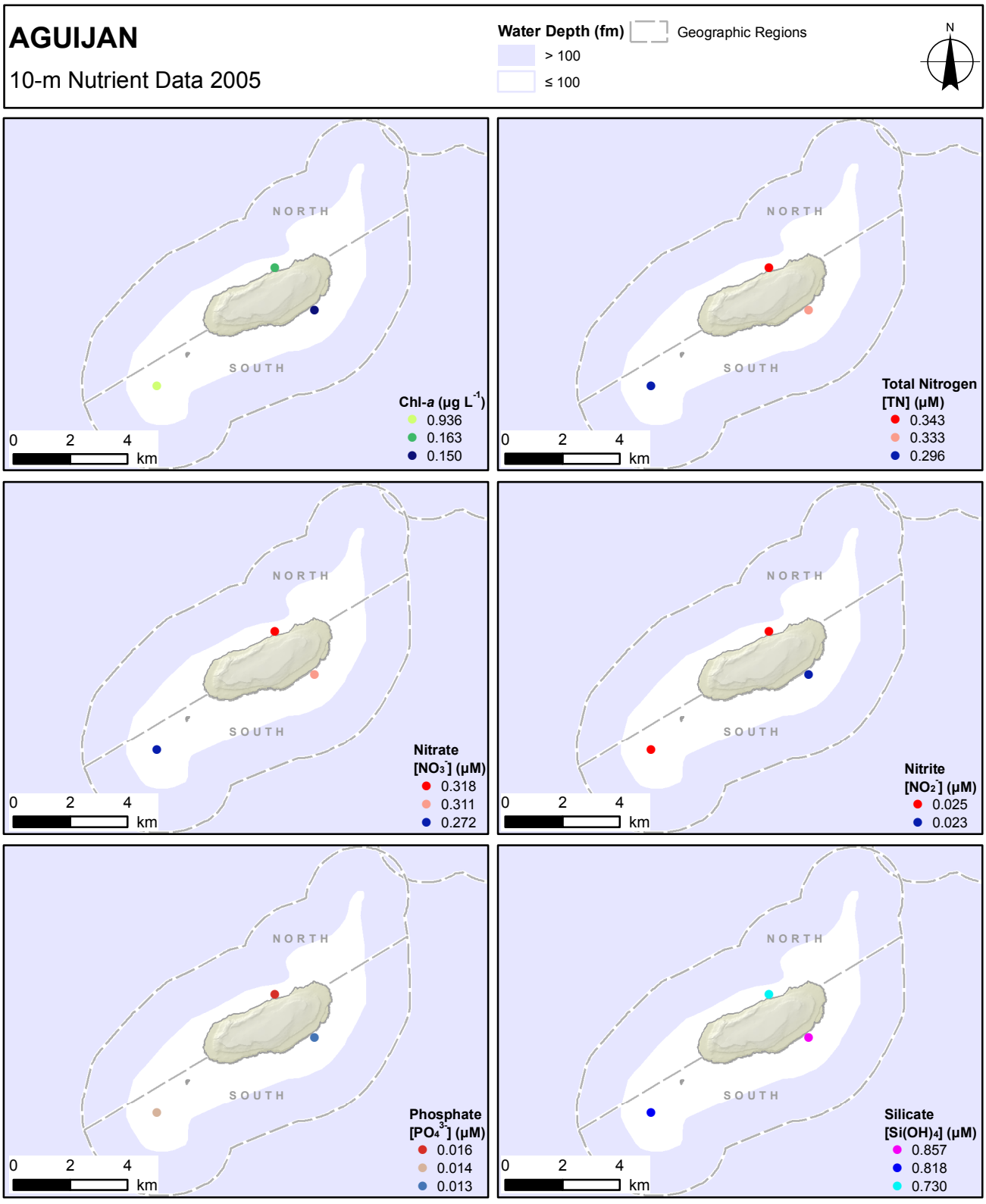


Figure 6.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Aguijan on September 27–28 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, shallow-water CTD casts were conducted in nearshore waters around Aguijan on May 18. Temperature, salinity, density, and beam transmission values from 18 of these casts varied both spatially and vertically around Aguijan. Spatial comparisons of water properties at a depth of 10 m show no clear spatial pattern around this island; the coldest (cast 16) and warmest (casts 1, 12) temperatures were recorded in the south region within 2 km of each other (Fig. 6.4.1f). Vertical comparisons of CTD profiles (Fig. 6.4.1g) reveal a large range in temperature (1°C) values and a series of disparate cold-water intrusions to the west, north, and south of this island (casts 1, 9, 16). Moderate variation of salinity (0.2 psu) and density (0.5 kg m^{-3}) values occurred concurrently with these drops in temperature values, suggesting enhanced mixing with deeper waters or localized upwelling relative to other areas of this island. Beam transmission was generally high (~ 94%) at all cast locations; all temperature, salinity, and water-clarity data show little, if any, sign of terrestrial runoff.

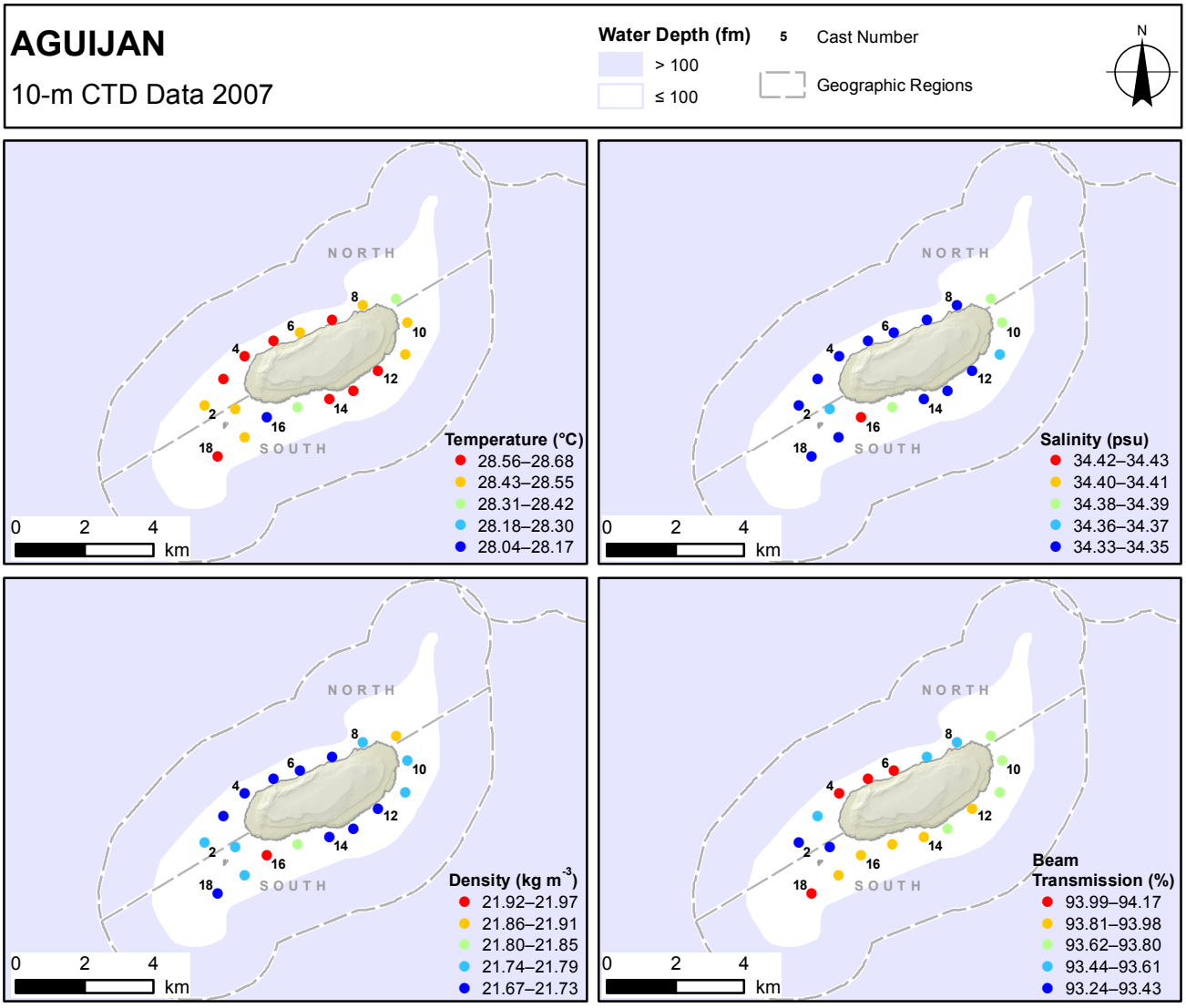


Figure 6.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, (*bottom right*) and beam transmission at a 10-m depth from shallow-water CTD casts around Aguijan on May 18 during MARAMP 2007.

Water samples were collected in concert with shallow-water CTD casts at 3 select locations at Aguijan in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: Chl-*a*, 0.03–0.05 µg L^{-1}; total nitrogen (TN), 0.01–0.03 µM; nitrate (NO_3^-), 0.01–0.02 µM; nitrite (NO_2^-), 0.001–0.005 µM; phosphate (PO_4^{3-}), 0.05–0.054 µM; and silicate [$Si(OH)_4$], 0.49–0.61 µM. Comparisons of all parameters measured around Aguijan suggest homogeneity among locations (Fig. 6.4.1h).

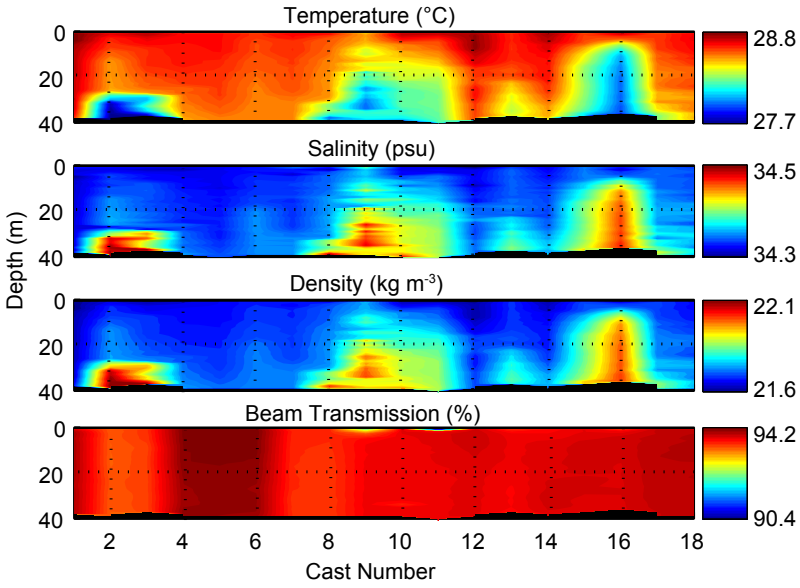


Figure 6.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Aguijan on May 18 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–18 in a clockwise direction around Aguijan. For cast locations and numbers around this island in 2007, see Figure 6.4.1f.

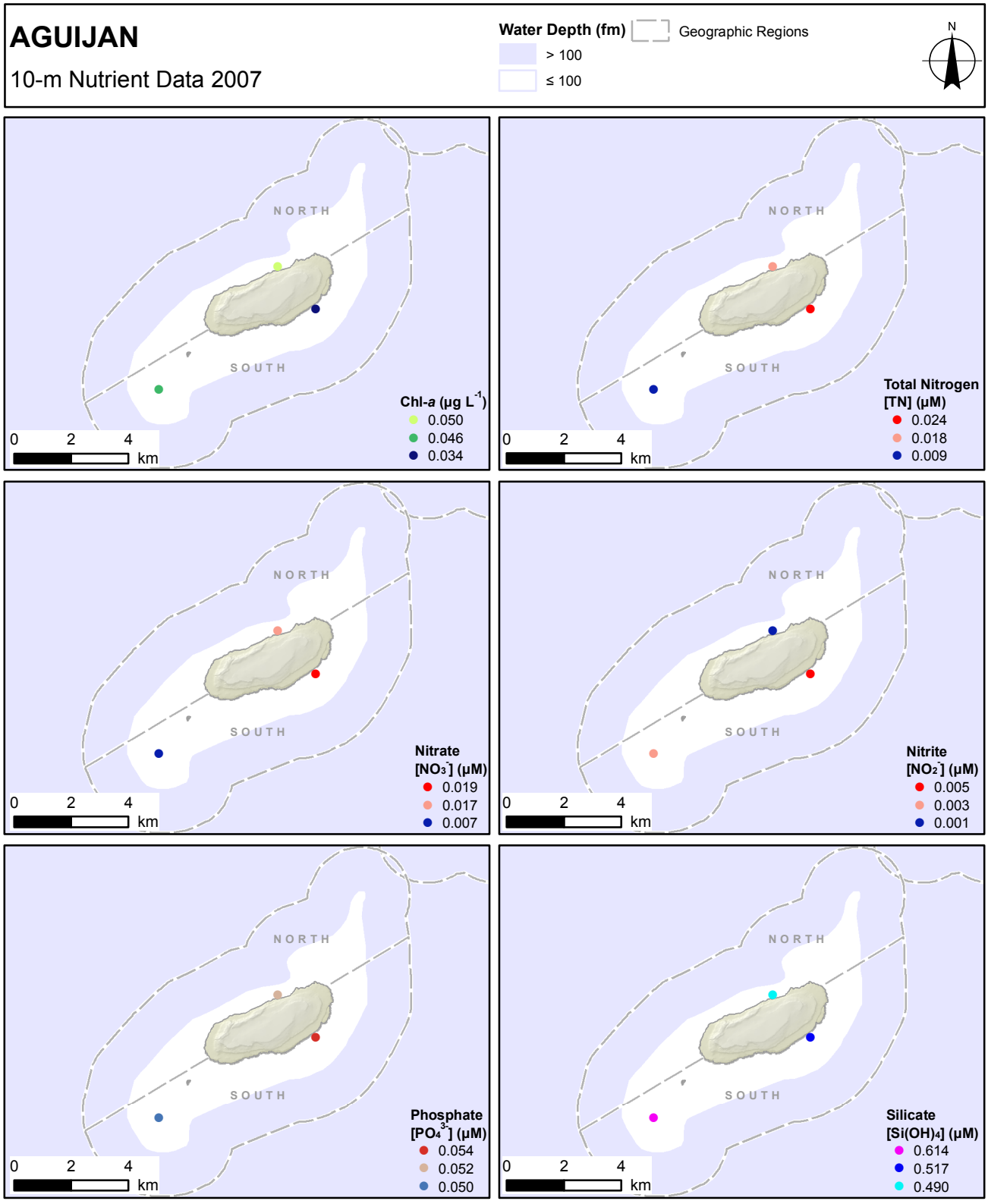


Figure 6.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Aguijan May 18 during MARAMP 2007.

Temporal Comparison

Data from shallow-water CTD casts performed around Aguijan during MARAMP 2003, 2005, and 2007 show temperature ranges > 1°C within these survey periods. Cold-water intrusions, with associated higher salinities and higher densities, were observed during each MARAMP survey year. The mechanism behind these intrusions is unknown, since there is no clear spatial pattern and they occurred at variable depths. Beam transmission was relatively high (93.36%–97.06%) in the 3 survey years, suggesting that terrestrial runoff was low in the vicinity of Aguijan during MARAMP surveys.

Water-quality data obtained during MARAMP 2005 and 2007 indicate that Chl-*a*, total nitrogen, nitrate, nitrite, and silicate concentrations were much lower in 2007 than in 2005, while phosphorus was slightly higher. Whether a reduction in the majority of nutrient levels was the result of a seasonal effect or some other process is unknown at this time. MARAMP 2005 occurred during a period of seasonally high precipitation, while MARAMP 2007 occurred during a period of seasonally low precipitation (see Chapter 3: "Archipelagic Comparisons," Section 3.3.1: "Seasonal Climatologies" for precipitation information).

6.4.2 Time-series Observations

Between 2003 and 2007, a subsurface temperature recorder (STR) was deployed at a single mooring site at Aguijan at a depth of 8 m to collect time-series observations of a key oceanographic parameter (Figs. 6.4.2a and b). The location, depth, time frame, and other details about deployments at this site are provided in Figures 6.4.2a and b.

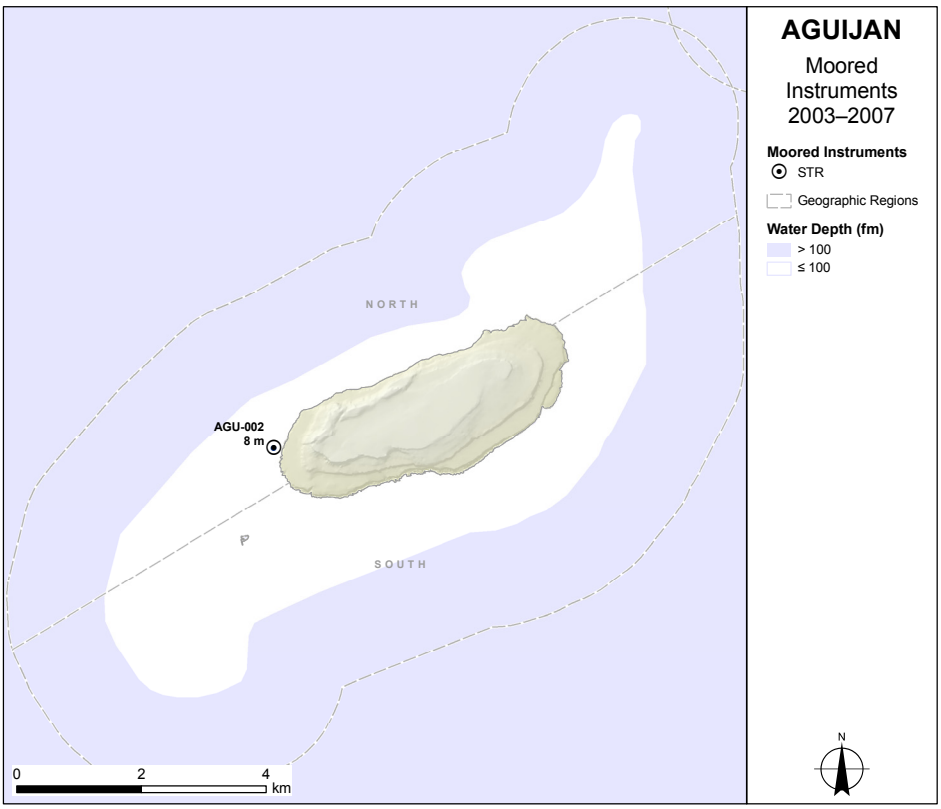


Figure 6.4.2a. Location and depth of the subsurface temperature recorder (STR) deployed at Aguijan during MARAMP 2003, 2005, and 2007.

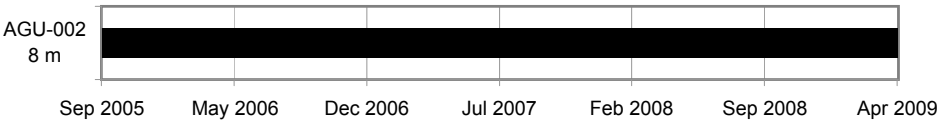


Figure 6.4.2b. Deployment timeline and depth of the STR moored at Aguijan during the period from September 2005 to April 2009. A solid bar indicates the period for which temperature data were collected by the STR deployed and retrieved at the mooring site.

Temperature data from the STR at this mooring site showed predominantly seasonal temperature variability of 3°C–3.5°C (Fig. 6.4.2c). Water temperatures reached ~ 31°C during the period of June–October and fell to a low of ~ 27°C during the period of January–May. Temperatures in September 2006 reached and surpassed the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean. Diurnal temperature fluctuation was consistently ~ 0.3°C during this time series.

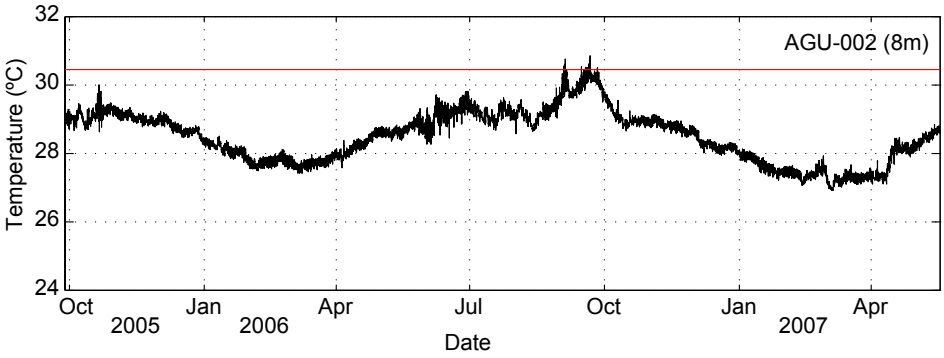


Figure 6.4.2c. Time-series observations of temperature over the period between October 2005 and June 2007 collected from 1 STR mooring site at Aguijan at a depth of 8 m (see Figure 6.4.2a for the mooring location). The red line indicates the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

6.5 Corals and Coral Disease

6.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats at the island of Aguijan and the reef area at Naftan Rock was 18% (SE 1.9). Coral cover was lowest in the south region of Aguijan and at Naftan Rock with a mean of 12% for 30 survey segments; only 1 segment there had an estimate of coral cover > 20% (Fig. 6.5.1a, top panel). Coral cover was highest along the northwestern coast of Aguijan with a mean of 34% for 10 segments.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Aguijan was 17% (SE 1.8). Coral cover was highest along the west coast of Aguijan with a mean of 35% for 11 segments (Fig. 6.5.1a, middle panel). High levels of coral cover, relative to other areas surveyed at Aguijan, also were noted in the north region with a mean of 42% for 3 segments. Coral cover was lowest along the southeastern coast of Aguijan with a mean of 7% for 20 segments. Towed divers recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 0.6% (SE 0.1) of coral cover observed on forereef habitats around Aguijan appeared stressed. Stressed-coral cover recorded at Aguijan never exceeded 5%.

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats at Aguijan was 12% (SE 1.2). Only 3 surveys were conducted at Aguijan in 2007 with low coral cover observed in all survey areas except for a single area along the northeastern coast with a mean of 25% for 2 segments (Fig. 6.5.1a, bottom panel). Overall, 7.5% (SE 1.1) of coral cover observed on forereef habitats at Aguijan appeared stressed. Stressed-coral cover was highest for the 2 surveys conducted along the western and southern shores, each with a mean of 10.8% for 20 segments (Fig. 6.5.1a, bottom panel). Stressed-coral cover was considerably higher in these areas in 2007 than in 2005; however, no additional observations were collected by towed divers that would explain the higher level in 2007. Values were lowest around the east coast, where no segment had stressed-coral cover exceeding 5%.

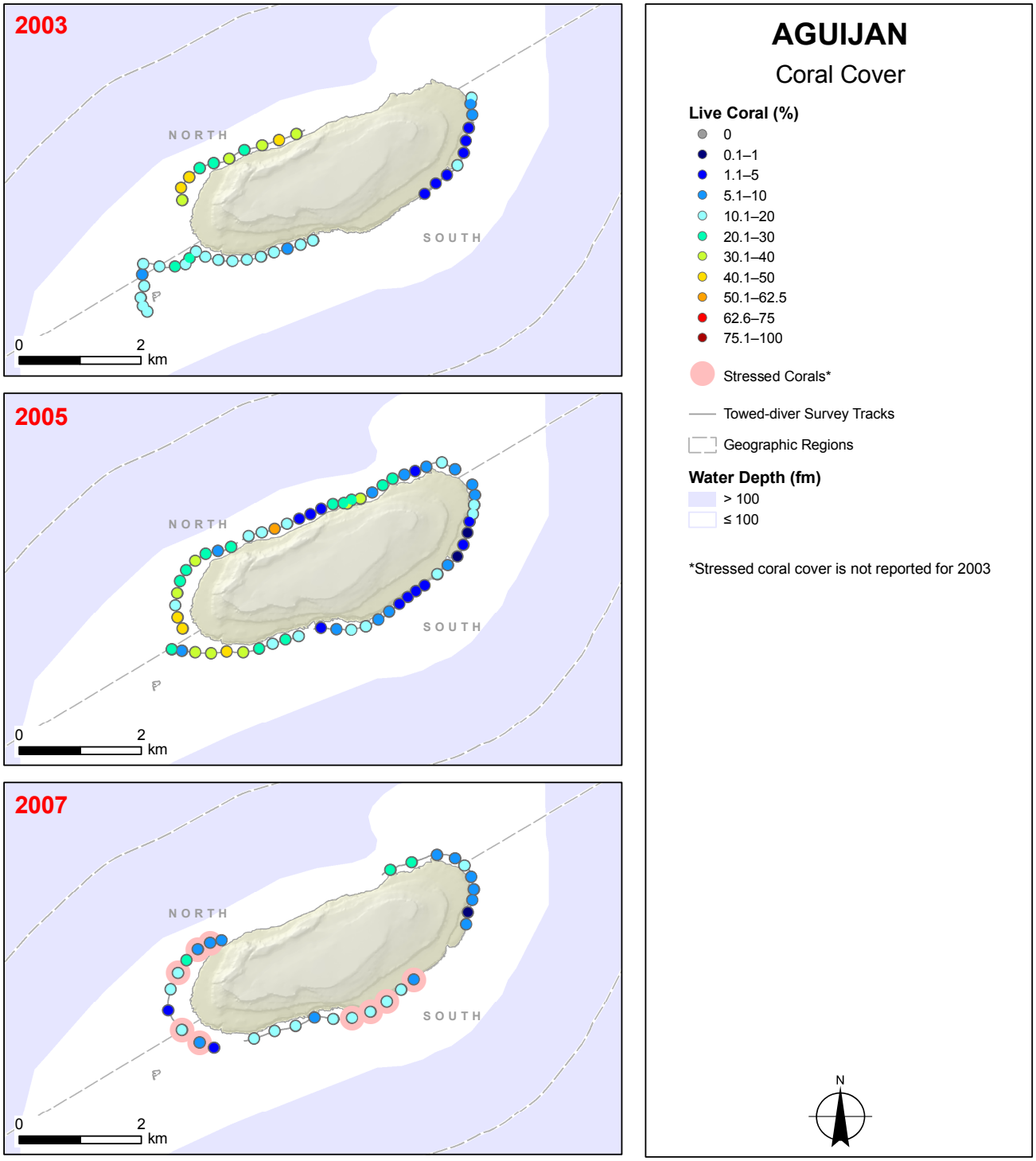


Figure 6.5.1a. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Aguijan during MARAMP 2003, 2005, and 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 x 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005 and 2007.

During MARAMP 2003, 2 REA benthic surveys using the quadrat method on forereef habitats at Aguijan documented 204 coral colonies within a total survey area of 7.5 m^2. Site-specific colony density ranged from 21.9 to 32.5 colonies m^{-2} with an overall sample mean of 27.2 colonies m^{-2} (SE 5.3). The highest colony density was recorded at AGU-02 on the northwestern coast, and the lowest colony density was observed at AGU-01 on the southeastern coast (Fig. 6.5.1b, top panel).

During MARAMP 2005, 3 REA benthic surveys using the quadrat method on forereef habitats at Aguijan documented 470 coral colonies within a total survey area of 12 m^2. Site-specific colony density ranged from 27.5 to 47.8 colonies m^{-2} with an overall sample mean of 39.2 colonies m^{-2} (SE 6.1). The highest colony density was recorded at AGU-03 in the north region. Similar to estimates from MARAMP 2003 surveys, the lowest colony density was observed at AGU-01 in the south region (Fig. 6.5.1b, middle panel).

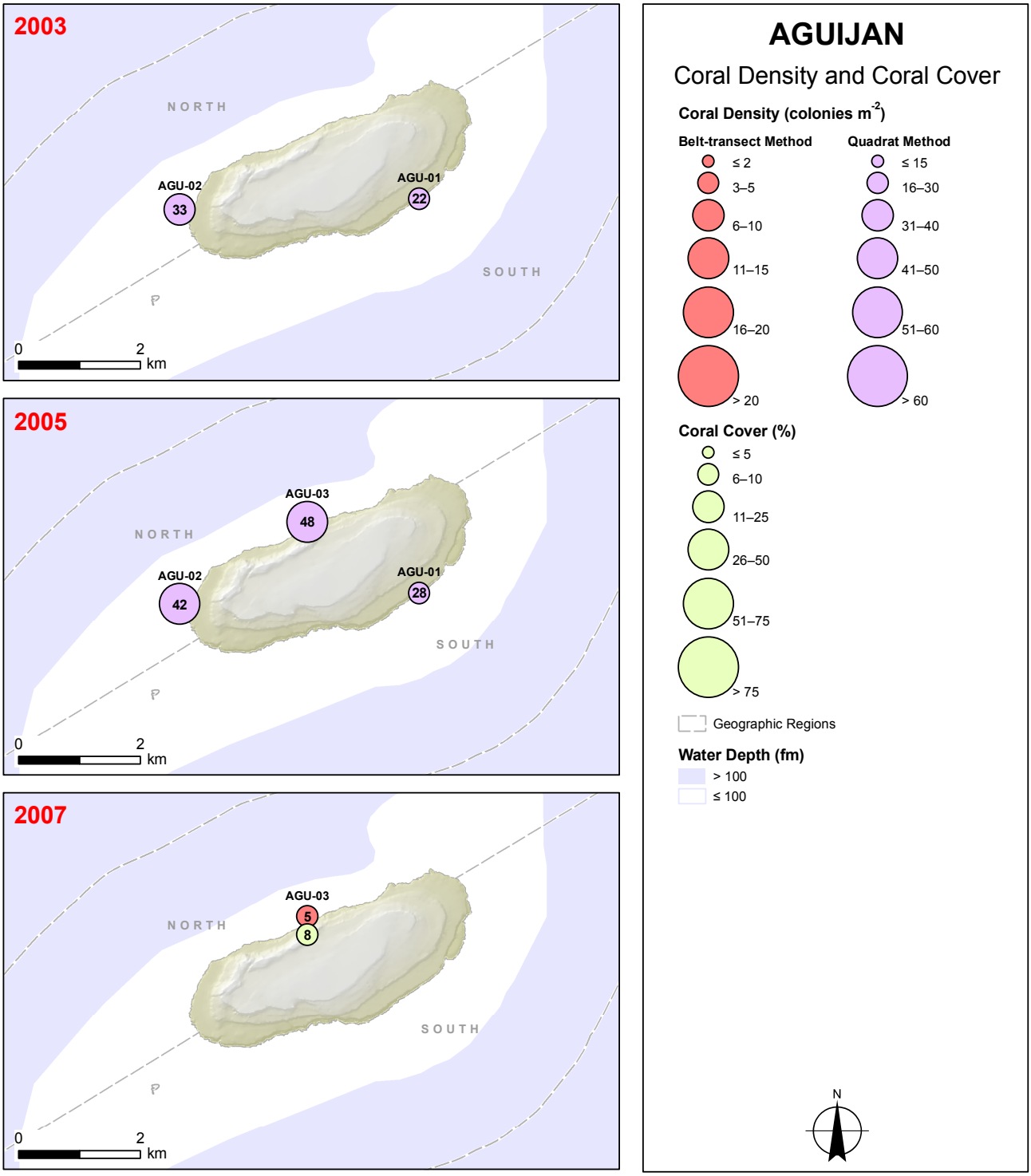


Figure 6.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Aguijan during MARAMP 2003, 2005, and 2007, and cover (%) observations of live corals from REA benthic surveys during MARAMP 2007. Values are provided within each symbol. The quadrat method was used in 2003 and 2005 to assess coral-colony density, but the belt-transect method was used in 2007.

During MARAMP 2007, 1 REA benthic survey using the line-point-intercept method was conducted on a forereef habitat at Aguijan. The estimate of live-hard-coral cover at AGU-03 in the north region was low at 7.8% (Fig. 6.5.1b, bottom panel).

During MARAMP 2007, 1 REA benthic survey using the belt-transect method on a forereef habitat at Aguijan documented 226 coral colonies within a total survey area of 50 m^2. Colony density was 4.5 colonies m^{-2} at AGU-03 (Fig. 6.5.1b, bottom panel).

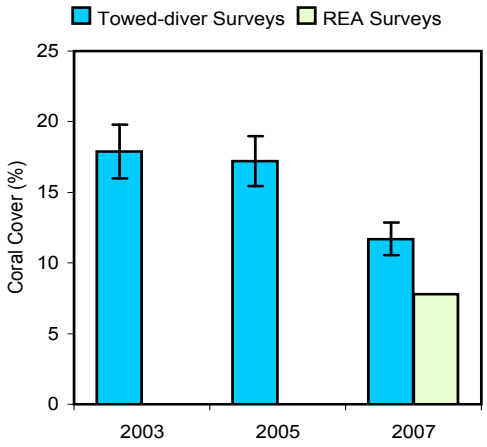


Figure 6.5.1c. Temporal comparison of mean live coral cover (%) from REA and towed-diver benthic surveys conducted on forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted around Aguijan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

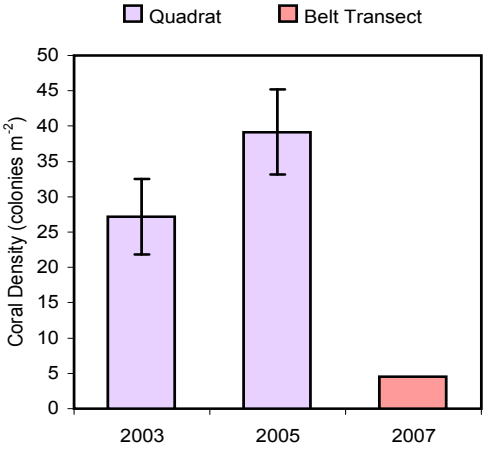


Figure 6.5.1d. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Aguijan during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to measure coral-colony density, but the belt-transect method was used in 2007. Error bars indicate standard error (± 1 SE) of the mean.

Islandwide mean cover of live corals, estimated from towed-diver surveys of forereef habitats, was nearly the same in 2003 and 2005 at 18% (SE 1.9) and 17% (SE 1.8) but lower in 2007 at 12% (SE 1.2) in 2007 (Fig. 6.5.1c). This relatively small variation in overall mean values of live coral cover between MARAMP survey years does not necessarily reflect actual changes in overall coral cover (For information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Coral cover was 7.8% at the 1 REA site surveyed in 2007, AGU-03, a value that is congruent with estimates from towed-diver surveys conducted in this area in 2005 (towed-diver surveys in 2007 were not conducted along the north central coast, where AGU-03 was located. Aguijan was not surveyed for coral cover using the line-point-intercept method in 2003 or 2005).

During MARAMP 2003 and 2005, REA benthic surveys of forereef habitats were conducted using the quadrat method at Aguijan. Overall mean coral-colony density from REA benthic surveys of forereef habitats at Aguijan varied from 27.2 (SE 5.3) colonies m^{-2} in 2003 to 39.2 (SE 6.1) colonies m^{-2} in 2005 (Fig. 6.5.1d). The higher mean value in 2005 primarily results from a high colony density of 47.8 colonies m^{-2} at AGU-03, which was surveyed in 2005 but not in 2003. At AGU-03, the only site surveyed during MARAMP 2007, coral-colony density appeared substantially lower, with 4.5 colonies m^{-2}, than the overall density observed in 2005. This difference, however, is likely a result of the use of different methods to assess colony density. The method of placing quadrats used in 2003 and 2005 was highly biased towards surveying hard-bottom substrate where coral was present, whereas the belt-transect method used in 2007 assessed benthos that fell within the transect belt regardless of the nature of the substrate.

Coral Generic Richness and Relative Abundance

Two REA benthic surveys of forereef habitats were conducted using the quadrat method at Aguijan during MARAMP 2003. At least 30 coral genera were observed at Aguijan. Generic richness was 15 at AGU-01 in the south region and 17 at AGU-02 on the west coast in the north region with a mean of 16 (SE 1) coral genera per site (Fig. 6.5.1e, top panel). *Leptastrea*, *Favia*, and *Pocillopora* were the most numerically abundant genera, contributing 25.1%, 14.5%, and 13.3% of the total number of colonies enumerated at Aguijan. All other genera individually contributed < 10% of the total number of colonies. *Leptastrea* dominated the coral fauna at both sites, contributing 32.9% of the total number of colonies at AGU-01 and 17.2% of the colonies at AGU-02. *Porites* and *Astreopora,* in addition to *Favia* and *Pocillopora,* contributed > 10% to the total number of colonies at AGU-02.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Aguijan during MARAMP 2005. At least 24 coral genera were observed at Aguijan. Generic richness ranged from 13 to 19 with a mean of 16 (SE 1.7) coral genera per site (Fig. 6.5.1e, middle panel). The highest generic diversity was seen at AGU-02 in the north region, and the lowest diversity was recorded at AGU-01 on the southeastern coast. *Leptastrea, Favia*, and *Pavona* were the most numerically abundant genera, contributing 18.5%, 14.0%, and 14.1% of the total number of colonies enumerated at Aguijan. All other genera individually contributed < 10% to the total number of colonies. Site-specific dominance patterns,

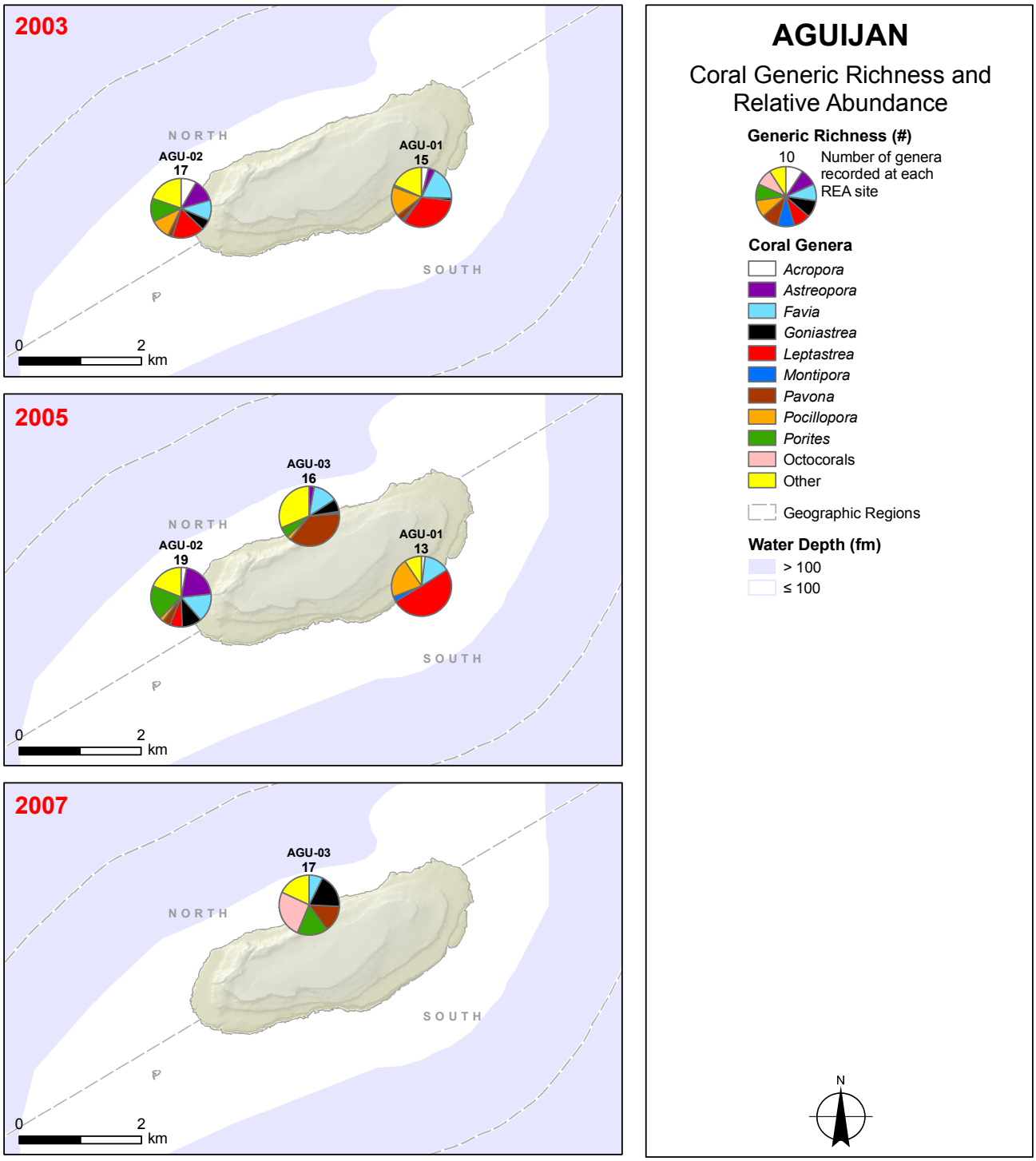


Figure 6.5.1e. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Aguijan during MARAMP 2003, 2005, and 2007. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2003 and 2005 to survey coral genera, but the belt-transect method was used in 2007.

however, varied somewhat from the overall average. *Leptastrea* dominated the coral fauna at AGU-01, contributing 49.1% of the total number of colonies recorded. *Astreopora* and *Porites* dominated at AGU-02, contributing 20.1% and 18.3% of the total number of colonies. *Pavona* dominated at AGU-03 in the north region, contributing 37.2% of the total number of colonies, while *Leptastrea* was not recorded at AGU-03.

One REA benthic survey of a forereef habitat was conducted using the belt-transect method at Aguijan during MARAMP 2007. At least 17 coral genera were observed at AGU-03 on the north central shore (Fig. 6.5.1e, bottom panel), including 3 genera that had not been recorded at Aguijan in 2003 or 2005: *Coscinaraea*, *Lobophytum*, and *Sinularia*. Octocorals (*Lobophytum* and *Sinularia*), *Goniastrea*, *Porites*, and *Pavona* were the most numerically abundant taxa, contributing 25.2% (octocorals combined), 18.1%, 15.9%, and 14.2% of the total number of colonies enumerated. All other genera individually contributed < 10% to the total number of colonies.

Site-specific estimates of generic richness across the 3 MARAMP survey years ranged from 13 to 19 on forereef habitats at Aguijan (Fig. 6.5.1f). All 3 REA sites were surveyed twice, at a biennial interval, and at each site the number of genera did not vary substantially between survey years. Overall mean generic richness values were quite consistent between survey years with 16–17 genera per site. The number of genera recorded in the north region at AGU-03 was similar in both 2005 and 2007 (16 and 17 genera). This consistency in generic diversity was observed despite differences in the survey methods used. The only octocoral genus assessed in 2003 and 2005 was *Heliopora*, whereas all octocoral genera were assessed in 2007. The size of the areas in which corals were censused were different between methods: the survey area in 2007 was 50 m^2 per site, much larger than the 3.75–4 m^2 per site surveyed in 2003 and 2005 (see Chapter 2: "Methods," Section 2.4.5: "Corals and Coral Disease").

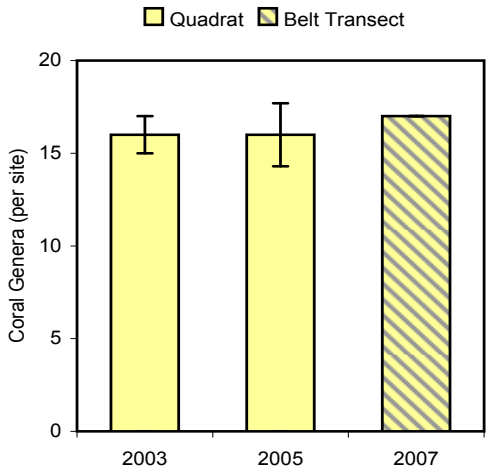


Figure 6.5.1f. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Aguijan during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to survey coral genera, but the belt-transect method was used in 2007. Error bars indicate standard error (± 1 SE) of the mean.

During the 3 survey years, 32 coral genera were observed on forereef habitats at Aguijan. *Leptastrea*, *Favia*, *Pavona*, *Pocillopora*, *Astreopora*, and *Porites* were important components of the coral fauna. As determined from the 3 sites surveyed in 2005, *Leptastrea*, *Favia*, and *Pavona* dominated the coral fauna, accounting for 18.5%, 14.2%, and 14.1% of the total number of colonies enumerated at Aguijan. However, considerable variability between sites was observed. For example, *Leptastrea* was particularly abundant at AGU-01 in the south region, accounting for 49.1% of the number of colonies, but was absent from AGU-03 in the north region, where *Pavona* dominated the coral fauna. At AGU-01, surveyed in 2003 and 2005, *Leptastrea*, *Pocillopora*, and *Favia* were the 3 most numerically abundant taxa. On the northwestern coast at AGU-02, also surveyed in 2003 and 2005, *Leptastrea*, A*strepora*, and *Porites* were the 3 most numerically abundant taxa in 2003, but *Favia* replaced *Leptastrea* as 1 of the 3 most abundant taxa in 2005. At AGU-03, surveyed in 2005 and 2007, *Pavona*, *Favia*, and *Goniastrea* were the most numerically abundant taxa in 2005, but octocorals replaced *Favia* as 1 of the 3 most abundant taxa in 2007.

Coral Size-class Distribution

During MARAMP 2003, 2 REA benthic surveys of forereef habitats were conducted at Aguijan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (56.3%) of corals had maximum diameters ≤ 5 cm (Fig. 6.5.1g, top panel). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 25.5%, 6.9%, and 11.2% of colonies recorded at Aguijan. No colonies measuring > 40 cm in maximum diameter were recorded. At both AGU-01, in the south region, and AGU-02, in the north region, high proportions (89% and 74.6%) of colonies enumerated were small (≤ 10 cm) and correspondingly low proportions (11% and 25.4%) of observed colonies were midsize (11–40 cm).

During MARAMP 2005, 3 REA benthic surveys of forereef habitats were conducted at Aguijan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (73.6%) of corals had maximum diameters ≤ 5 cm (Fig. 6.5.1g, middle panel). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 18.8%, 5.7%, and 1.8% of colonies recorded at Aguijan, and size classes > 40 cm accounted for 0.2% of colonies recorded. High proportions of colonies found at all 3 REA sites fell into the 2 smallest size classes (≤ 10 cm): 95.5% for AGU-01, in the south region, as well as 85.8% and 95.8% for AGU-02 and AGU-03 in the north region. Correspondingly low proportions (4.5%, 13.6%, and 4.2%) of observed colonies were midsize (11–40 cm) at these 3 sites.

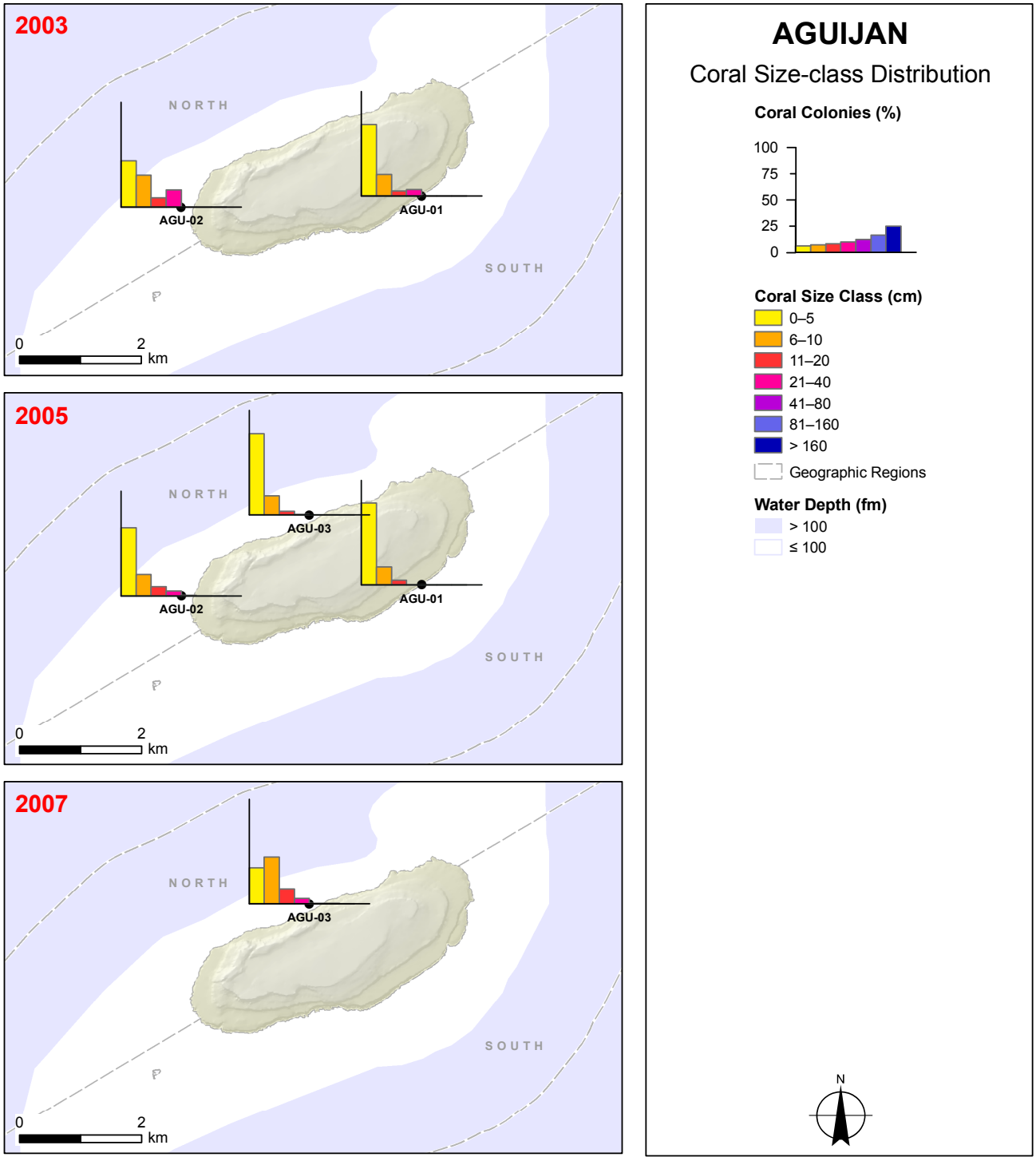


Figure 6.5.1g. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Aguijan during MARAMP 2003, 2005, and 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 and 2005 to size corals, but the belt-transect method was used in 2007.

During MARAMP 2007, 1 REA benthic survey of a forereef habitat was conducted at Aguijan using the belt-transect method. The coral size-class distribution from this survey shows that the majority (79.2%) of corals had maximum diameters ≤ 10 cm (Fig. 6.5.1g, bottom panel). The next 4 size classes (0–5, 6–10, 11–20, and 21–40 cm) accounted for 34.5%, 44.6%, 14.3%, and 5.4% of colonies recorded, and size classes > 40 cm accounted for 1.2% of colonies recorded.

Site-specific and overall distributions of estimated coral size classes on forereef habitats at Aguijan are affected by inherent biases in the methods used to census and size corals. During MARAMP 2003 and 2005, corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling the observer to closely inspect and record each coral colony within the quadrat. During MARAMP 2007, corals whose center fell within a belt transect (1 × 25 m) were tallied and binned into 1 of 7 size classes based on visual estimates of maximum colony diameter. This method is better suited to capturing large colonies, but the larger census area likely reduces the number of very small colonies (≤ 5 cm) that are observed and recorded. For more on these survey methods, see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease."

These methodological biases are reflected in the size-class data by survey year. Estimates of coral densities on forereef habitats were much higher in the first 2 MARAMP survey years compared to 2007 (Fig. 6.5.1h). In 2003 and 2005, more than half (56.3% and 73.6%) of all colonies censused at Aguijan had a maximum diameter ≤ 5 cm, but in 2007 only 34.5% of the observed colonies were in this smallest size class. Comparing size-class data between survey years when different methods were used is, therefore, inappropriate. Only REA sites AGU-01 in the south region and AGU-02 in the north region were surveyed with the same quadrat method in 2 different survey years (2003 and 2005). At these sites, the changes in size-class distributions between survey years likely results from chance variation in the placement of individual quadrats.

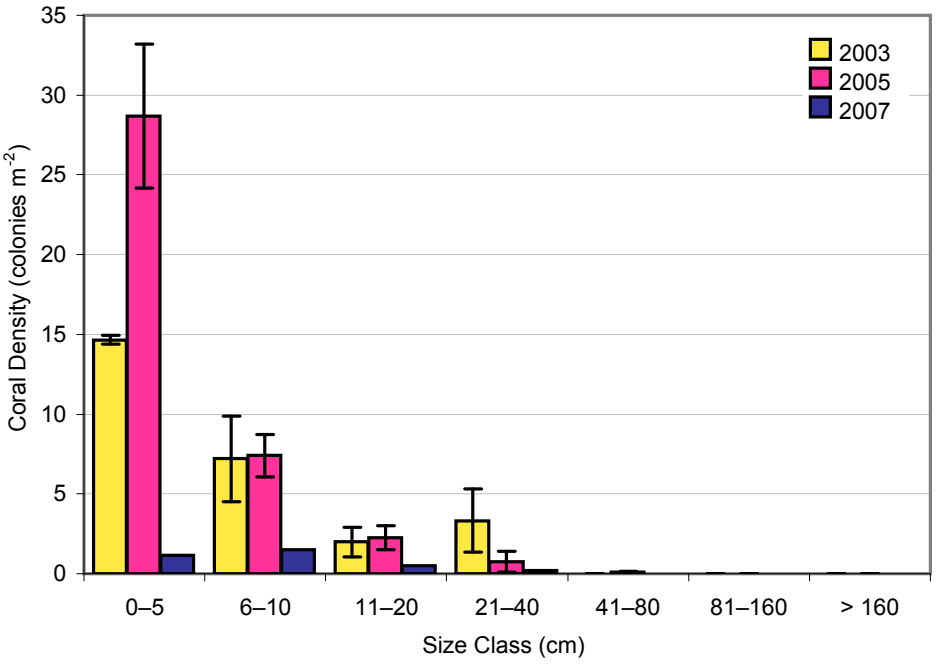


Figure 6.5.1h. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Aguijan during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to size corals, but the belt-transect method was used in 2007. Error bars indicate standard error (± 1 SE) of the mean.

6.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, a REA benthic survey for coral disease and predation was conducted using the belt-transect method at 1 site on a forereef habitat at Aguijan, covering a total area of 200 m^2. Overall prevalence of disease at AGU-03 was 0.5%. This site contained 2 cases of white syndrome on *Gardineroseris planulata*, amounting to a site-specific prevalence value of 0.3% (Fig. 6.5.2a). Additionally, one case of cyanophyte infection was detected at AGU-03 with a prevalence of 0.2%. No cases of coral predation were observed.

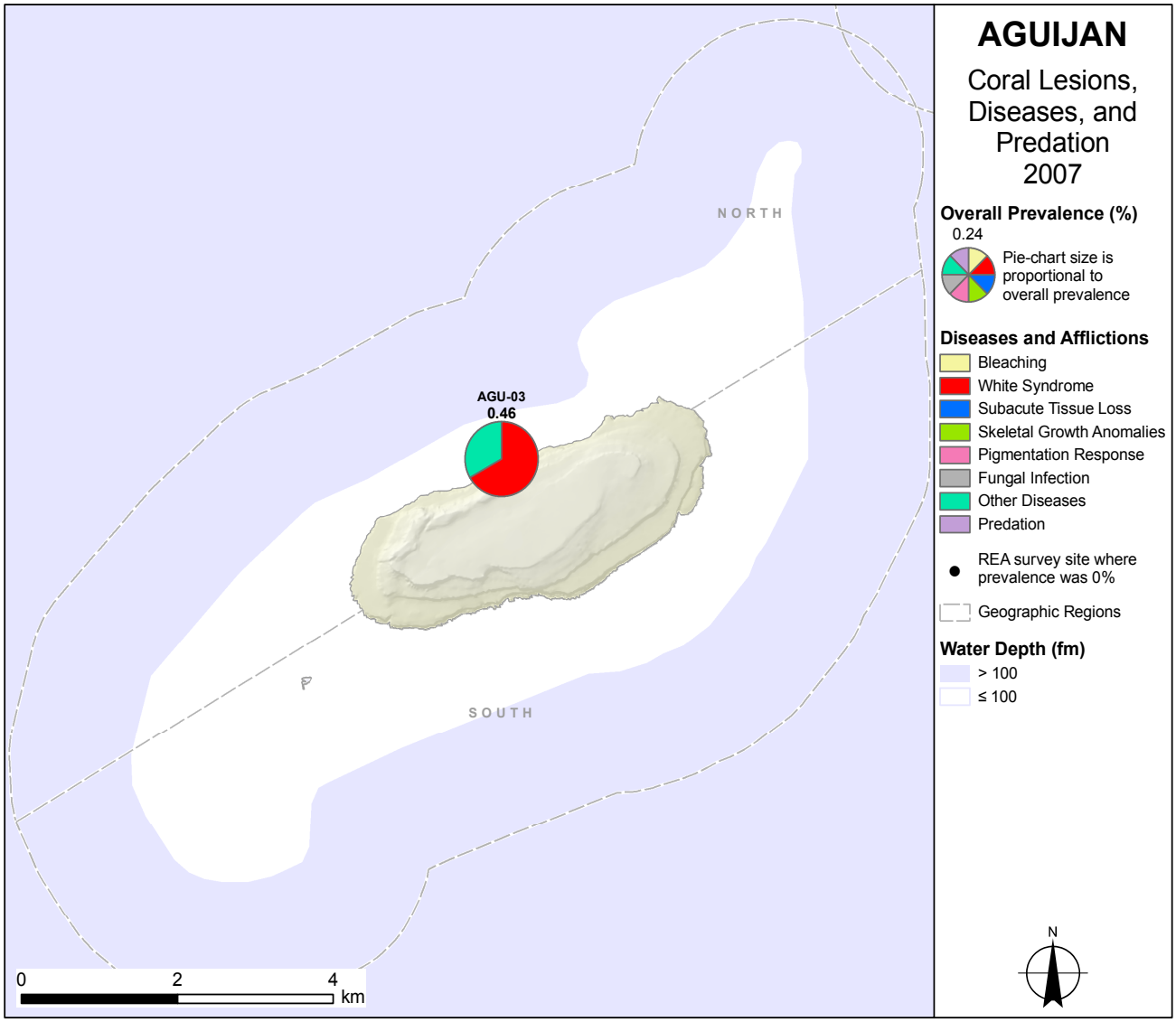


Figure 6.5.2a. Overall prevalence (%) observations of coral diseases and predation from a REA benthic survey of a forereef habitat conducted at Aguijan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at the REA site. The color-coded portions of the pie chart indicate disease-specific prevalence.

6.6 Algae and Algal Disease

6.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats at the island of Aguijan was 45% (SE 3). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 66%, within a range of 30.1%–100%, occurred along the southeastern, where pavement and rock boulders of medium complexity were the predominant types of habitat (Fig. 6.6.1a, top left panel). Two surveys, primarily in the south region, between Aguijan and Naftan Rock recorded a mean macroalgal cover of 44%, within a range of 20.1%–75%, where the habitat consisted predominantly of medium-low to medium complexity pavement. The lowest macroalgal cover was observed during 1 survey conducted in the north region with a mean of 24%, within a range 10.1%–30%, where spur-and-groove habitat, with sections of continuous reef, had medium-high to high complexity.

TOAD surveys completed south of Aguijan during MARAMP 2003 were conducted at depths of 15–100 m. Analyses of TOAD video footage obtained from 3 surveys suggests that little or no macroalgae existed in these areas (Fig 6.6.1a, top left panel). In some small sections, these surveys recorded macroalgal cover up to 80%, but no macroalgae were observed in the majority of images.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Aguijan was 39% (SE 2.3). The survey with the highest mean macroalgal cover of 64%, within a range of 40.1%–100%, occurred along the southeastern coast, in an area of pavement and rock boulder habitat of medium-low to medium complexity (Fig. 6.6.1a, middle left panel). Species of the calcified, green macroalga *Halimeda* dominated the benthos in this area. Similarly, an adjacent survey to the southwest reported relatively high values of macroalgal cover with a mean of 52%, within a range of 30.1%–75%, in comparison to other surveys at Aguijan. The remaining surveys reported little variation with one exception: mean macroalgal cover was 38%, 34%, and 30%, within a range of 10.1%–62.5%, for 3 surveys, but a survey along the north central coast recorded macroalgal cover of 11%, within a range of 1.1%–20. Habitat complexity from these remaining surveys ranged primarily from medium-high to high.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats at Aguijan was 28% (SE 3.5). As in 2003 and 2005, the survey with the highest macroalgal cover occurred along the southeastern coast (Fig. 6.6.1a, bottom left panel), with a mean of 36% within a range of 5.1%–75%. This area was characterized by cliffs, coral pavement and continuous reef, wide spur-and-groove formations, and moderate or steep slopes. Increases in cover of the green macroalgae genera *Halimeda* and *Microdictyon* were recorded in areas of continuous-reef habitat.

During MARAMP 2007, 1 REA benthic survey of forereef habitats was conducted using the line-point-intercept method at Aguijan. Mean macroalgal cover was 5.9% and mean turf-algal cover was 50% from this survey at AGU-03, the REA site located on the north central coast (Fig. 6.6.1b).

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats at Aguijan was 15% (SE 1.5). The survey with highest mean crustose-coralline-red-algal cover of 27%, within a range of 10.1%–40%, occurred along the continuous-reef and spur-and-groove habitat on the northwestern coast (Fig. 6.6.1a, top right panel). Habitat complexity ranged from medium-high to high, and hard corals dominated this area. The remaining 3 surveys recorded means of 8%, 10%, and 11% for cover of crustose coralline red algae. These surveys occurred in areas with less complex habitat, composed of pavement and rock boulders, which are less prone to development of crustose coralline red algae. No crustose coralline red algae were observed in the analyses of the video footage collected during TOAD surveys in 2003.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Aguijan was 11% (SE 2.4). For most towed-diver surveys, mean cover was < 6%. The clear exception to this pattern, a survey with a mean cover of 43%, within a range of 10.1%–75%, occurred along the north central shore, where habitat complexity ranged from medium-high to high and several observations of orange band disease were noted on crustose coralline red algae (Figs. 6.6.1a, middle right panel, and 6.6.2a).

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats at Aguijan was 13% (SE 1.4). The survey with the highest mean cover of 15% occurred along the northwestern coast, in continuous-reef and spur-and-groove habitats of medium complexity (Fig. 6.6.1a, bottom right panel).

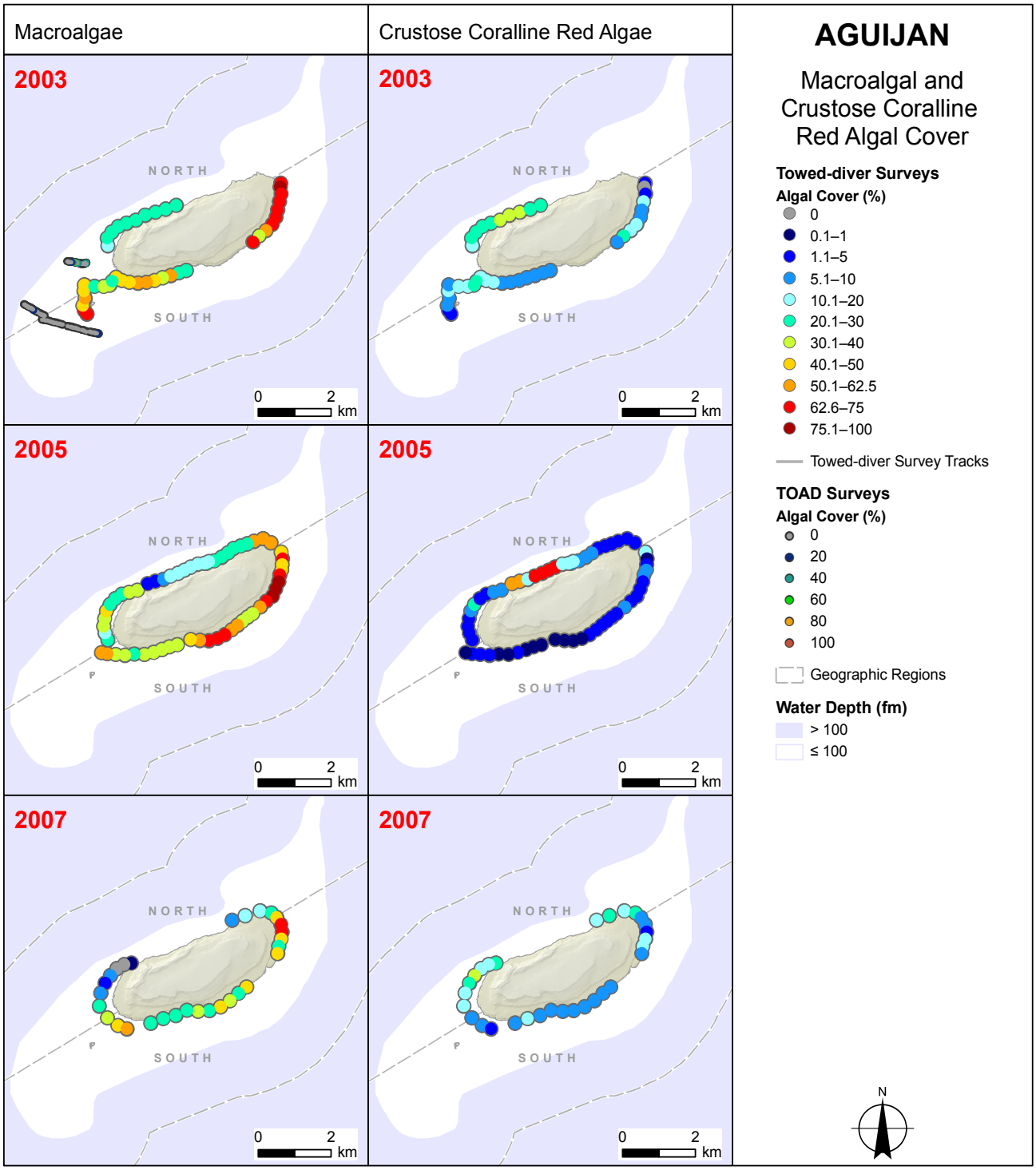


Figure 6.6.1a. Cover (%) observations of macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Aguijan during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

At the single REA site surveyed in 2007, AGU-03, mean crustose-coralline-red-algal cover was 32.4% (Fig. 6.6.1b).

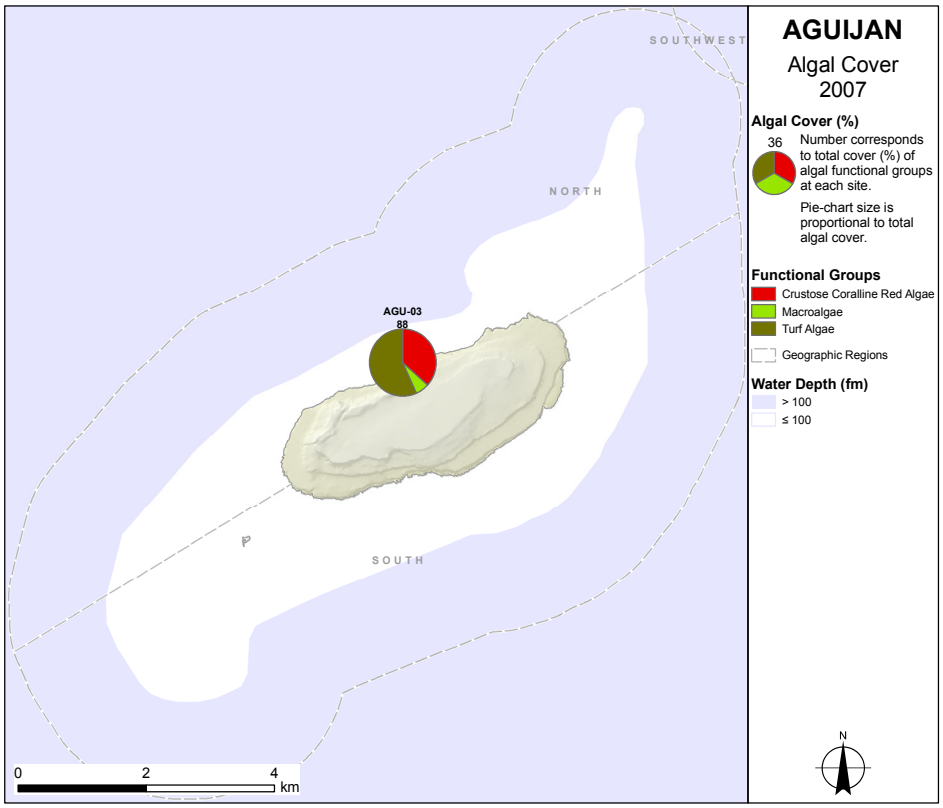


Figure 6.6.1b. Observations of algal cover (%) from REA benthic survey of forereef habitats conducted using the line-point-intercept method at Aguijan during MARAMP 2007. The pie chart indicates algal cover by functional group, and the value of total algal cover is provided above the symbol.

Algal Cover: Temporal Comparison

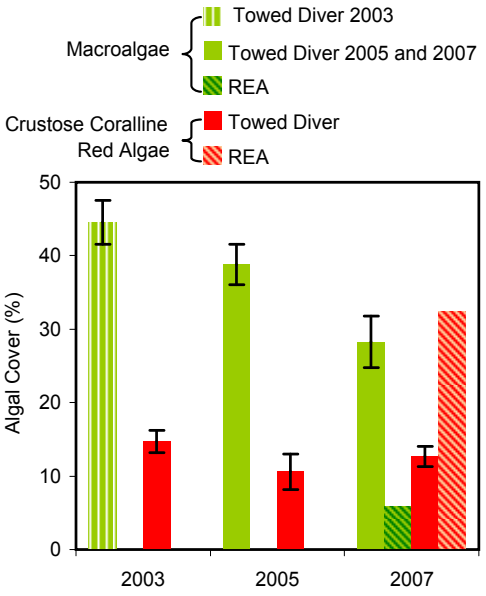


Figure 6.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted at Aguijan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Between MARAMP 2005 and 2007, islandwide mean cover of macroalgal populations around Aguijan, based on towed-diver surveys of forereef habitats, varied by 11% (Fig. 6.6.1c). In general, macroalgae most commonly inhabited pavement habitats, which had lower levels of complexity relative to other areas surveyed at Aguijan. The green algae *Halimeda* and *Microdictyon* were the most frequently observed genera. When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in macroalgal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Macroalgal cover from towed-diver surveys was lower in 2005 than in 2003 in nearly all areas surveyed at Aguijan, likely a result of including turf algae in the macroalgae category in 2003, although a small number of localized areas where macroalgal cover was higher were noted. During MARAMP 2005, 2 additional surveys were added to compliment the data set from MARAMP 2003, and this greater area of survey coverage reconfirmed that macroalgal cover was highest along reefs on the southeastern coast. For all survey areas, observed macroalgal cover appeared lower in 2007 than in 2005, but this result is uncertain because fewer surveys were conducted in 2007. The most noticeable decrease in macroalgal cover between these survey periods occurred along the northwestern coast.

Populations of crustose coralline red algae on forereef habitats around Aguijan, based on towed-diver surveys, essentially remained the same in islandwide mean cover of the benthos between MARAMP survey years. Crustose-coralline-red-algal cover was higher in continuous reef and spur-and-groove habitats of medium to medium-high complexity than in other types of habitats, while macroalgal cover appeared more prevalent in pavement and rock boulder habitats of medium-low to medium complexity.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites has not been undertaken yet for the southern islands of the Mariana Archipelago. Ultimately, based on microscopic analysis that may be done in the future, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 2 sites on forereef habitats at Aguijan. In the field, 10 macroalgal genera (3 red and 7 green), containing at least 12 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. AGU-01 on the southeastern coast had the greater macroalgal generic diversity with 8 genera, containing 11 species, documented in the field. At AGU-02 on the northwestern coast, 2 species representing 2 genera were recorded (Fig. 6.6.1d, top panel).

The green macroalga *Halimeda* was the most common genus at both sites surveyed at Aguijan in 2003, occurring in 42% and 25% of sampled photoquadrats. The majority of the 12 algal species tentatively identified occurred only at AGU-01. The green algae *Dictyosphaeria* and *Caulerpa*, found in 25% and 33% of sampled photoquadrats, were the second- and third-most common genera at AGU-01. The remaining 5 genera observed at AGU-01 were equally abundant, all occurring in 8.33% of sampled photoquadrats. The only genus to occur at AGU-02 but not at AGU-01 was the green alga *Ventricaria*.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2003, occurring in 96%, 75%, and 37.5% of photoquadrats sampled at Aguijan. Turf algae were abundant at both sites, where they were found in > 92% of sampled photoquadrats. Crustose coralline red algae were observed in 66%–83% of sampled photoquadrats. Cyanobacteria were less common at both sites with individuals found in 25% of sampled photoquadrats at AGU-01 and in 50% at AGU-02.

During MARAMP 2005, REA benthic surveys were conducted at 3 sites on forereef habitats at Aguijan. In the field, 12 macroalgal genera (3 red, 6 green, and 3 brown), containing at least 12 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, branched nongeniculate coralline red algae, and cyanophytes—were observed. AGU-03 on the north central coast had the highest macroalgal generic diversity with 11 genera, containing 11 species, documented in the field. The lowest macroalgal generic diversity was found at AGU-02 on the northwestern coast with 5 species representing 5 genera recorded.

At all 3 REA sites surveyed at Aguijan in 2005, 5 algal genera were observeved (Fig. 6.6.1d, middle panel). Species of the genera *Halimeda* and *Dictyosphaeria* occurred in 42% and 25% of sampled photoquadrats at AGU-02 and 42% and 58% of the photoquadrats at AGU-03. At AGU-01 in the south region, species of *Halimeda* occurred in only 8% of sampled photoquadrats, but species of *Dictyosphaeria* were abundant and occurred in 33% of sampled photoquadrats. Broad ranges of abundance were observed for both the brown macroalgal genus *Dictyota* and the calcified, red algal genus *Jania*, occurring in 8%–58% and 8%–50% of the photoquadrats sampled at Aguijan, depending on the location of the survey sites. For the majority of the 29 algal species tentatively identified in the field, no distinctive spatial patterns of distribution were observed at Aguijan. However, 5 of the 6 algal genera observed at AGU-01 on the southeastern coast also occurred at both of the other sites surveyed in 2005. The exception, the green algal genus *Microdictyon*, occurred in 50% of photoquatrats sampled at AGU-01 but was not seen elsewhere at this island. The second- and third-most abundant genera at AGU-01 were the chlorophytes *Dictyosphaeria* and *Caulerpa*, occurring in 33% and 58% of sampled photoquadrats, suggesting that conditions on the southeastern shore may favor green algal growth. Species of *Jania* were quite abundant at AGU-02 and AGU-03, occurring in 33% and 50% of sampled photoquadrats. In contrast, at AGU-01, where green algae were dominant, species in this genus were recorded less frequently, occurring in only 8% of sampled photoquadrats.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2005, occurring in 100%, 89%, and 61% of photoquadrats sampled at Aguijan. Communities of both turf algae and crustose coralline red algae were prevalent at all

survey sites. Cyanobacteria were less abundant, with occurrence values ranging from 100% at AGU-02 down to 33% at AGU-03, the site on the north central coast where green algae were dominant.

During MARAMP 2007, REA benthic surveys were conducted at only 1 site on a forereef habitat at Aguijan: AGU-02 on the northwestern coast. In the field, 4 macroalgal genera (2 red and 2 green), containing at least 4 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. *Halimeda* was the most abundant genus, occurring in 33% of photoquadrats sampled at Aguijan in 2007 (Fig. 6.6.1d, bottom panel). The

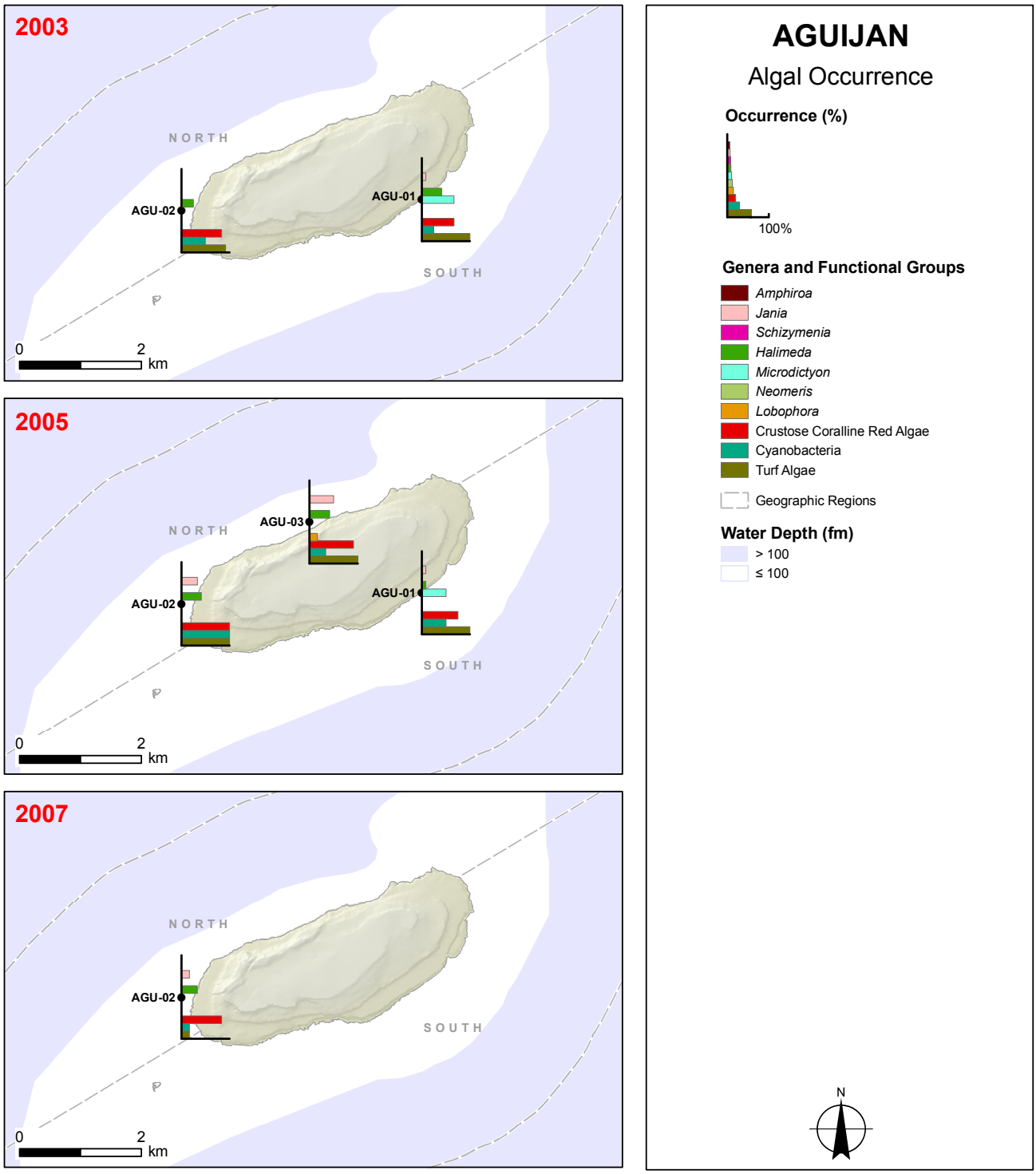


Figure 6.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys on forereef habitats conducted at Aguijan during MARAMP 2003, 2005, and 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

red algal genera *Jania* and *Portiera*, equally abundant, were recorded in 17% of sampled photoquadrats. The only other genus recorded, *Dictyosphaeria* was found in only 8% of sampled photoquadrats.

Crustose coralline red algae were very common at AGU-02 in 2007, occurring in 83% of sampled photoquadrats. Turf algae and cyanobacteria were equally abundant, occurring in 17% of sampled photoquadrats. Inferences about the spatial distribution of these different functional groups or particular genera are susceptible to error with such a low sampling resolution, and they should be treated with caution.

The number of macroalgal genera recorded on forereef habitats at Aguijan corresponded with the number of sites surveyed within a given MARAMP survey year. The maximum number of distinct genera observed in any given survey year was 12 in 2005, when 3 REA sites were surveyed (for information on data limitations, see hapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Between MARAMP 2003 and 2005, a marginal decrease in the diversity of macroalgal genera was observed at AGU-01 on the southeastern coast accompanied by an equivalent increase in generic diversity at AGU-02 on the northwestern shore. With the addition in 2005 of AGU-03, a novel site on the north central coast, the number of unique genera observed at Aguijan increased by 2 to a total of 12. The only site sampled in 2007, AGU-02 had the lowest diversity in 2003 and 2005.

Crustose coralline red algae, recorded in 75%–89% of sampled photoquadrats, were extremely abundant at Aguijan in the 3 MARAMP survey years. However, this dominance was not observed among co-occurring cyanobacterial or turf-algal communities (Fig. 6.6.1d). Cyanobacteria were recorded in 17%–38% of sampled photoquadrats from 2003 to 2007, and the inconsistency in the occurrence of turf algae was more dramatic. Turf algae were encountered in 96% and 100% of the photoquadrats sampled at Aguijan in 2003 and 2005 but present in only 17% of photoquadrats in 2007.

During MARAMP 2003, the green algal genera *Halimeda* and *Microdictyon* were equally abundant, occurring in 33% of photoquadrats sampled at Aguijan. The overall occurrence of *Halimeda* was consistent throughout the 3 survey years (Fig. 6.6.1e). However, a severe reduction in abundance of this genus was observed at AGU-02 from 42% in 2003 to 8% in 2007, while increases in observed abundance occurred at AGU-01 and AGU-03 between 2003 and 2005. The overall occurrence of *Microdictyon* decreased by one-half to 17% in 2005 and then to 0% in 2007. Since AGU-02 was the only site sampled in 2007 and *Microdictyon* had not been observed there in 2003 or 2005, it is not surprising that this genus was not observed in 2007.

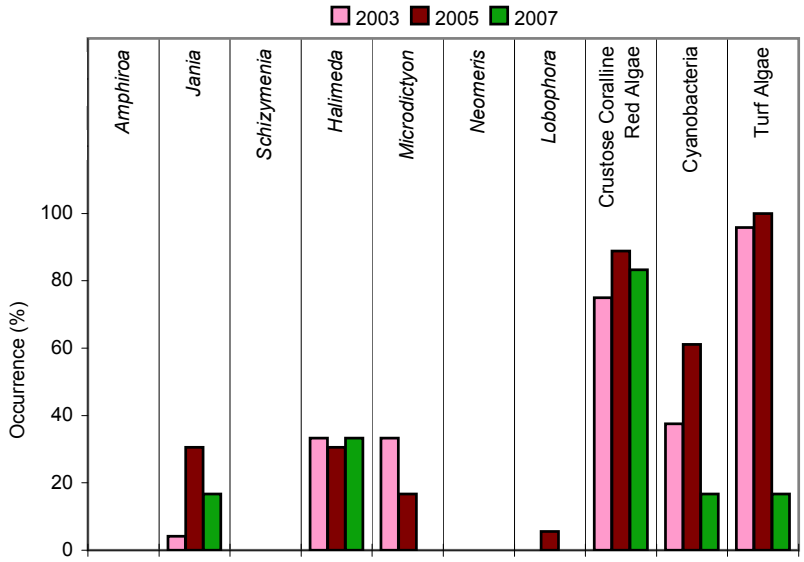


Figure 6.6.1e. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Aguijan during MARAMP 2003, 2005, and 2007.

6.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 1 site on a forereef habitat at Aguijan. At AGU-03, density of disease was 15.4 cases 100 m^{-2} (Fig. 6.6.2a), a high level relative to survey results for other sites in the Marina Archipelago. All cases recorded at this site in the north region corresponded to the coralline lethal orange disease.

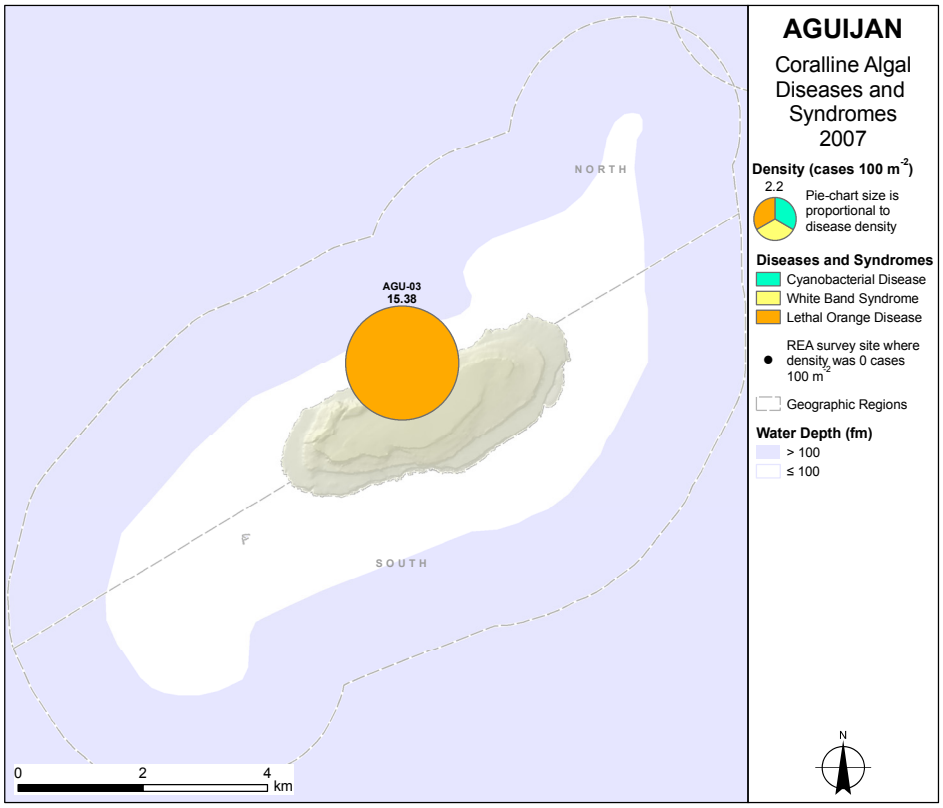


Figure 6.6.2a. Density (cases 100 m^{-2}) of the coralline lethal orange disease found in the REA benthic survey conducted on a forereef habitat at Aguijan during MARAMP 2007.

6.7 Benthic Macroinvertebrates

6.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and the crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Aguijan through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 2 REA surveys and 4 towed-diver benthic surveys were conducted at Aguijan. In 2005, 3 REA surveys and 6 towed-diver benthic surveys were performed around Aguijan. In 2007, because of the lack of an invertebrate scientific diver, no REA surveys were conducted; however, 3 towed-diver benthic surveys were completed. Also, when considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, both REA and towed-diver surveys suggested low daytime macroinvertebrate abundance on forereef habitats at Aguijan compared to the rest of the Mariana Archipelago. Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density around Aguijan—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 7.1b, d, f, and h). Because of differences in survey methodology and in REA survey effort, with 2 surveys in 2003, 3 in 2005, and 0 in 2007, temporal comparisons of REA data are not presented (see Chapter 2: "Methods and Operational Background," Section 2.4.7: "Benthic Macroinvertebrates").

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at both of the REA sites surveyed and in 3 of the 4 towed-diver surveys conducted at Aguijan (Fig. 6.7.1a, top panel). The sample mean density of giant clams from REA surveys was 4 organisms 100 m^{-2} (SE 1), and the overall mean density from towed-diver surveys was 0.05 organisms 100 m^{-2} (SE 0.01). Survey results suggest that giant clams were most abundant at AGU-02 off the northwest coast with 5 organisms 100 m^{-2}. Among all towed-diver surveys around this island, the survey completed along the northwest coast had the highest mean density of giant clams with 0.15 organisms 100 m^{-2}; segment densities from this survey ranged from 0.03 to 0.39 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.05 organisms 100 m^{-2}, recorded around the southwestern shore; segment densities ranged from 0 to 0.18 organisms 100 m^{-2}.

During MARAMP 2005, giant clams were observed at 1 of the 3 REA sites surveyed and in all 6 towed-diver surveys conducted around Aguijan (Fig. 6.7.1a, middle panel). AGU-03 in the north region had a density of 3 organisms 100 m^{-2}, and the islandwide mean density of giant clams from towed-diver surveys was 0.05 organisms 100 m^{-2} (SE 0.01). Among all towed-diver surveys around this island, the survey completed along the northwestern coast had the highest mean density of giant clams with 0.11 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.75 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.1 organisms 100 m^{-2}, recorded along the southeastern and south central coast; segment densities ranged from 0 to 0.22 organisms 100 m^{-2}.

During MARAMP 2007, giant clams were observed in all 3 towed-diver surveys conducted at Aguijan (Fig. 6.7.1a, bottom panel) with an overall mean density of 0.06 organisms 100 m^{-2} (SE 0.01). Among all towed-diver surveys around this island, the survey completed along the southern coast had the highest mean density of giant clams with 0.1 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.26 organisms 100 m^{-2}. The second-greatest mean density of giant clams was 0.05 organisms 100 m^{-2}, recorded around the west coast; segment densities ranged from 0 to 0.28 organisms 100 m^{-2}.

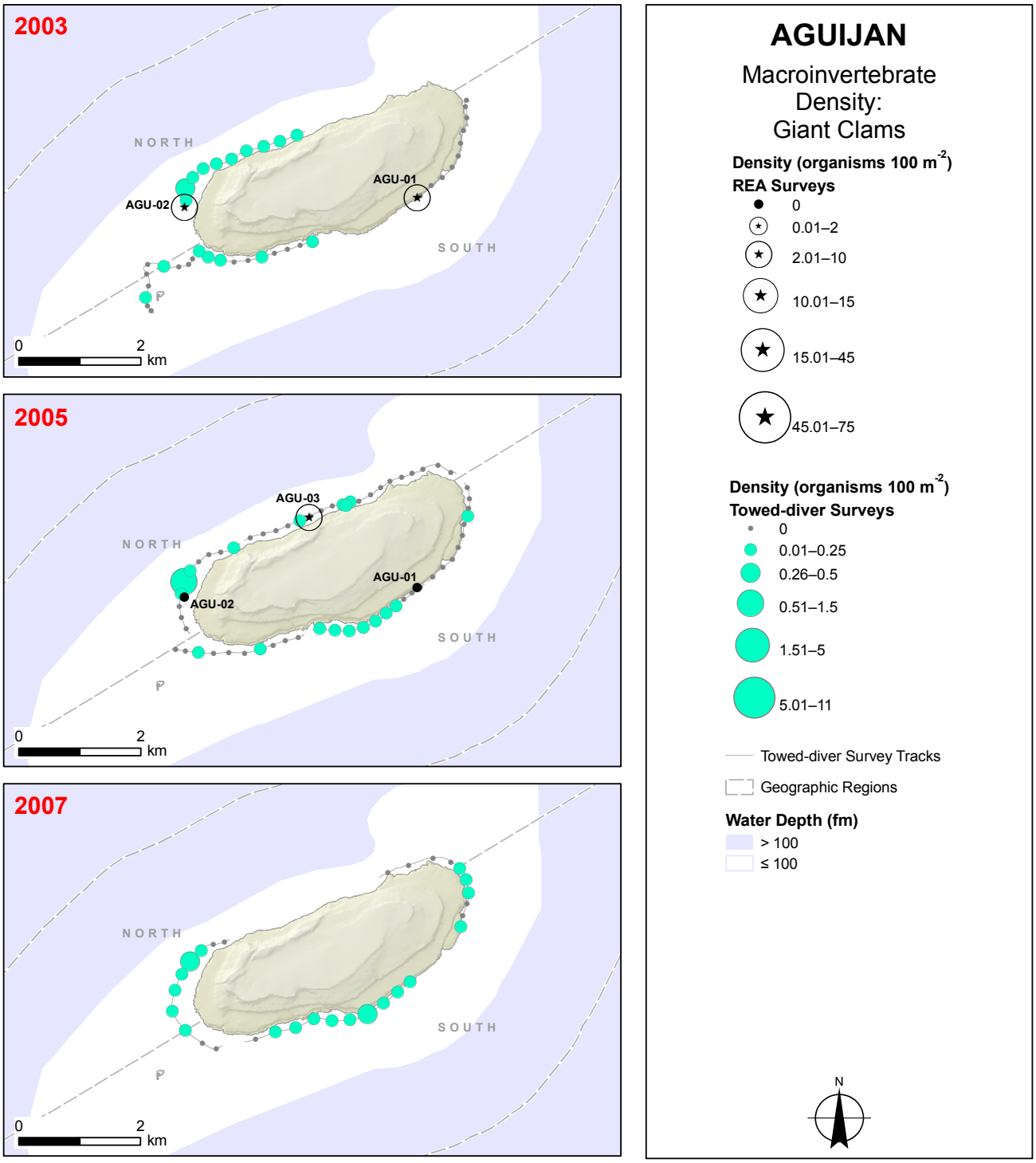


Figure 6.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Aguijan during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggested low abundance of giant clams at Aguijan during the 3 MARAMP survey periods relative to the rest of the Mariana Archipelago (Fig. 6.7.1b). Minor fluctuations in density were observed, but this variation is not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

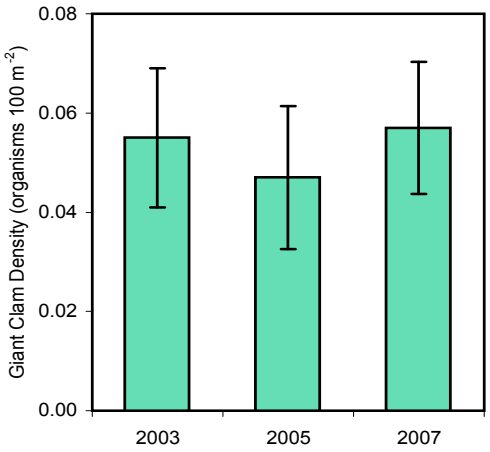


Figure 6.7.1b. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Crown-of-thorns Seastars

During MARAMP 2003, no crown-of-thorns seastars (*Acanthaster planci*) were observed at either of the 2 REA sites surveyed at Aguijan, but COTS were recorded in 2 of the 4 towed-diver surveys conducted (Fig. 6.7.1c, top panel). The overall mean density of COTS from towed-diver surveys was 0.06 organisms 100 m^{-2} (SE 0.04). The survey completed along the southwestern coast had the greatest mean density of COTS with 0.17 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.49 organisms 100 m^{-2}. The other survey area where COTS were seen, performed along the northwestern coast, recorded a mean density of COTS of 0.08 organisms 100 m^{-2}; segment densities ranged from 0 to 0.29 organisms 100 m^{-2}.

During MARAMP 2005, COTS were observed at 1 of the 3 REA sites surveyed and in 5 of the 6 towed-diver surveys conducted around Aguijan (Fig. 6.7.1c, middle panel). AGU-03 had a COTS density of 3 organisms 100 m^{-2}, and the islandwide mean density of COTS from towed-diver surveys was 0.06 organisms 100 m^{-2} (SE 0.02). The majority of COTS recorded during towed-diver surveys were observed in the north region. Among all towed-diver surveys around this island, the survey completed along the north central coast had the greatest mean density of COTS with 0.20 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.47 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.11 organisms 100 m^{-2}, recorded along the northwestern coast; segment densities ranged from 0 to 0.50 organisms 100 m^{-2} The survey completed along the northeast coast had a mean density of 0.07 organisms 100 m^{-2}; segment densities ranged from 0 to 0.25 organisms 100 m^{-2}.

During MARAMP 2007, COTS were observed in all 3 towed-diver surveys conducted at Aguijan (Fig. 6.7.1c, bottom panel) with an overall mean density 0.01 organisms 100 m^{-2} (SE 0.004). Among all towed-diver surveys around this island, the survey completed around the west coast had the greatest mean density with 0.03 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.07 organisms 100 m^{-2}.

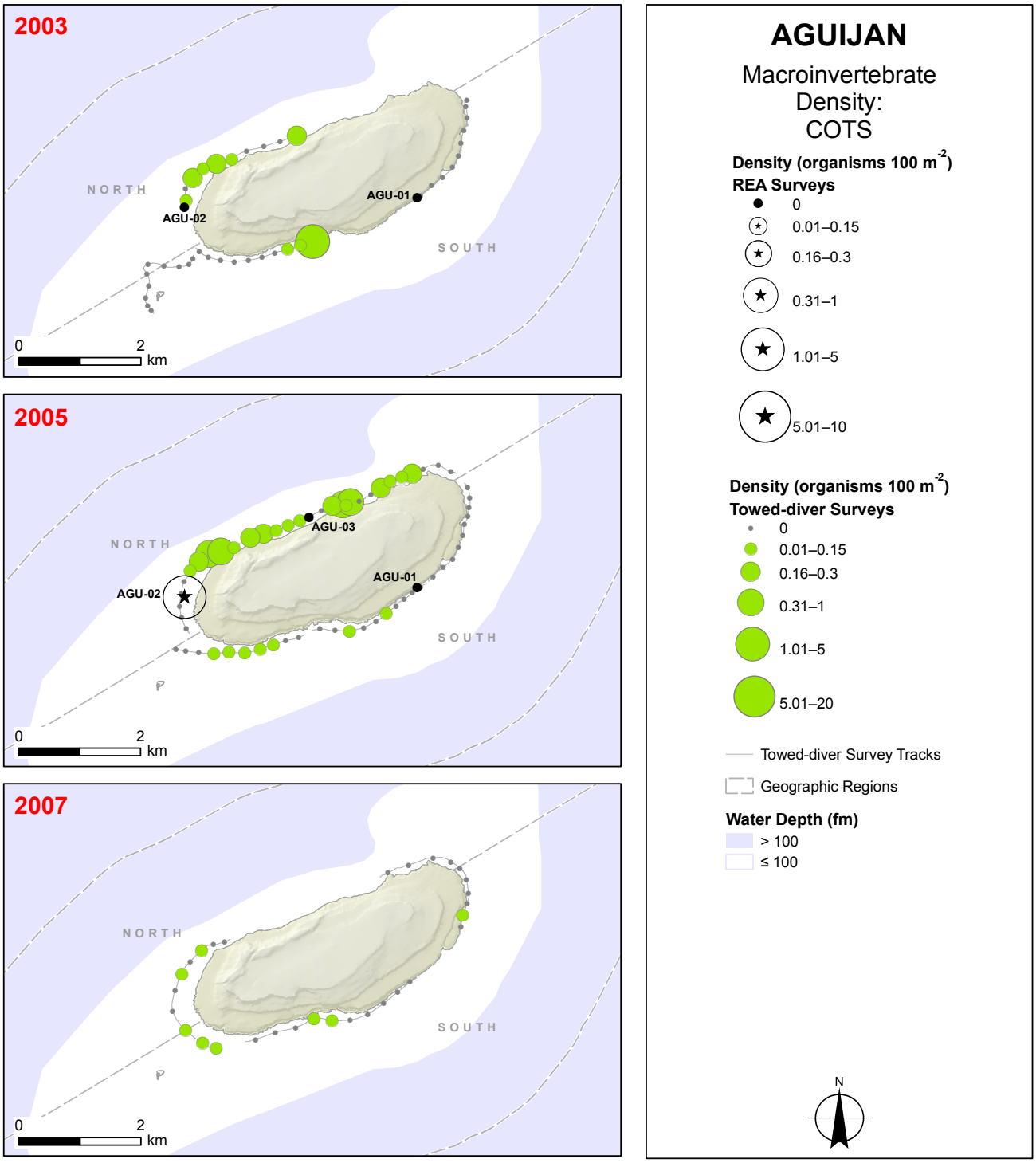


Figure 6.7.1c. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Aguijan during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggested high daytime densities of COTS at Aguijan during MARAMP 2003 and 2005, compared to the rest of the Mariana Archipelago. Overall observed mean values, and particularly results for individual towed-diver surveys, suggested that daytime densities of COTS at Aguijan were higher during MARAMP 2003 and 2005 than during MARAMP 2007 (Fig. 6.7.1d). Given that COTS can decimate a reef, understanding whether their observed densities signify an outbreak is important. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure established for using scuba divers to conduct MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms per km² (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of COTS density and considering each towed-diver survey as an individual reef area, localized areas with relatively high densities that suggest that they were undergoing an outbreak were found during MARAMP 2003 and 2005. In 2003, a towed-diver survey along the southwestern shore met this criterion with a COTS density of 0.17 organisms 100 m^{-2}, and, in 2005, a survey along the north central coast did so with a density of 0.20 organisms 100 m^{-2}.

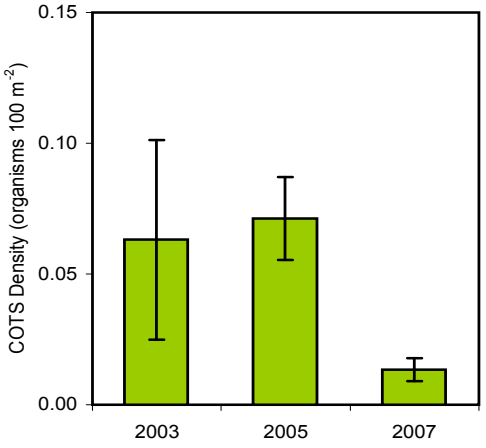


Figure 6.7.1d. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Cucumbers

During MARAMP 2003, no sea cucumbers were observed at either of the 2 REA sites surveyed at Aguijan, but 2 of the 3 towed-diver surveys had recordings of sea cucumbers (Fig. 6.7.1e, top panel), with an overall mean density of 0.32 organisms 100 m^{-2} (SE 0.08). The survey completed southwest of Aguijan at Naftan Rock (for place-names and their locations, see Fig. 6.2a in Section 6.2: "Survey Effort") had the highest mean density of sea cucumbers with 0.81 organisms 100 m^{-2}; segment densities from this survey ranged from 0.05 to 1.76 organisms 100 m^{-2}.

During MARAMP 2005, sea cucumbers were observed at 1 of the 3 REA sites and in 4 of the 6 towed-diver surveys conducted around Aguijan (Fig. 6.7.1e, middle panel). AGU-03 in the north region had a density of 3 organisms 100 m^{-2}, and the islandwide mean density of sea cucumbers from towed-diver surveys was 0.05 organisms 100 m^{-2} (SE 0.01). Of the organisms observed at AGU-03, one was from the genus *Holothuria*, and the others were unknown. Among all towed-diver surveys around this island, the survey completed along the northwestern coast had the highest mean density of sea cucumbers with 0.14 organisms 100 m^{-2}; segment densities from this survey ranged from 0.04 to 0.38 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.11 organisms 100 m^{-2}, recorded along the southwestern coast; segment densities ranged from 0 to 0.38 organisms 100 m^{-2}.

During MARAMP 2007, sea cucumbers were observed in all 3 towed-diver surveys conducted at Aguijan (Fig. 6.7.1e, bottom panel) with an overall mean density of 2.53 organisms 100 m^{-2} (SE 1.1). Among all towed-diver surveys around this island, the survey completed along the northeastern coast had the highest mean density of sea cucumbers with 7.4 organisms 100 m^{-2}; segment densities from this survey ranged from 0.07 to 24.07 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers was 0.15 organisms 100 m^{-2}, recorded around the west coast; segment densities ranged from 0.02 to 0.37 organisms 100 m^{-2}.

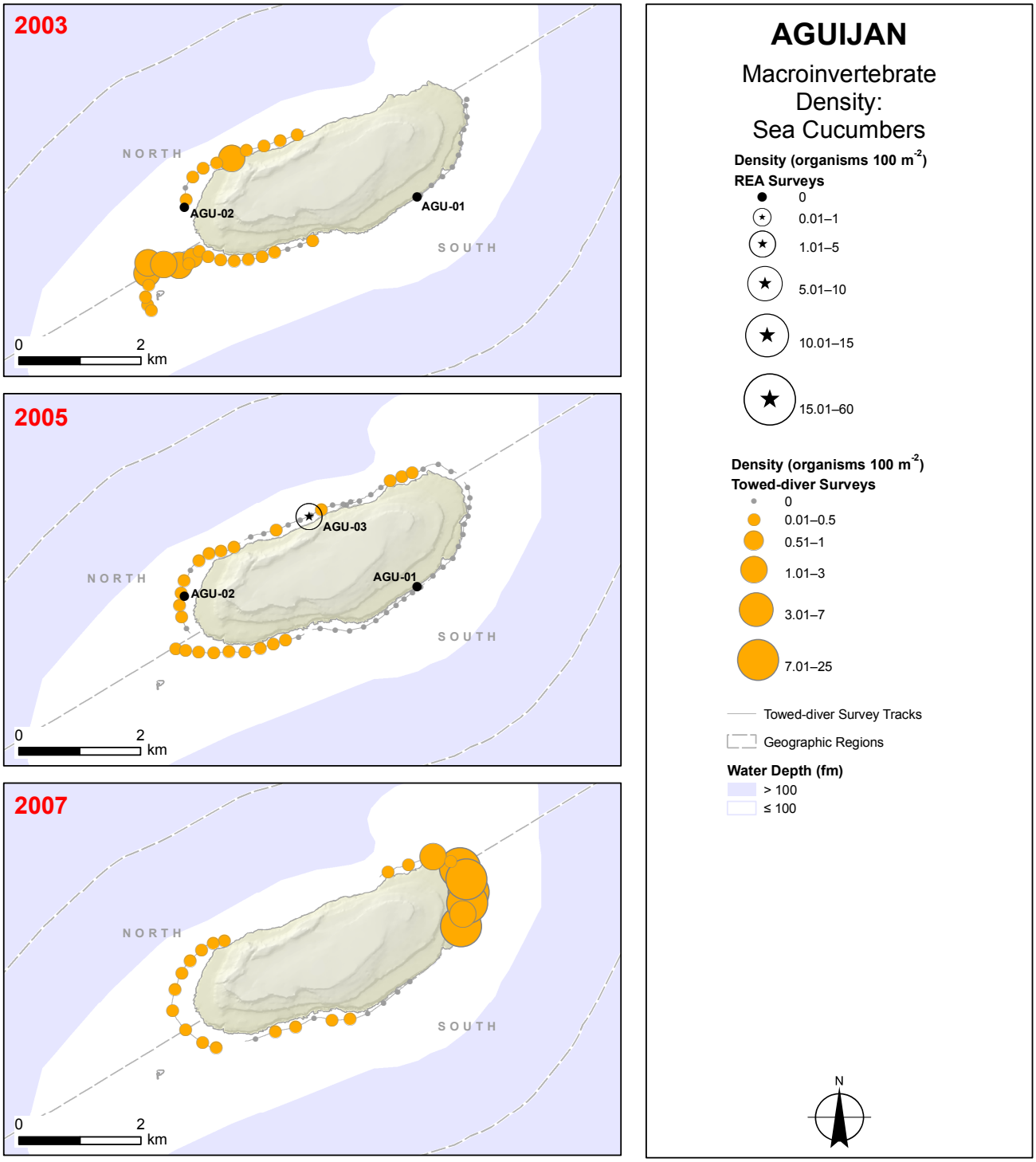


Figure 6.7.1e. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Aguijan during MARAMP 2003, 2005, and 2007.

With the exception of an individual towed-diver survey conducted around the northeastern coast of Aguijan during MARAMP 2007, daytime abundance of sea cucumbers was low around Aguijan relative to the rest of the Mariana Archipelago. The overall observed mean density of sea cucumbers around Aguijan was higher in 2007 than in 2003 and 2005 (Fig. 6.7.1f). Survey results suggest that a recruitment event may have occurred along the northeastern shore, since no sea cucumbers were seen there in 2003 and 2005 but in 2007 a mean density of 7.39 organisms 100 m^{-2} was recorded. Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

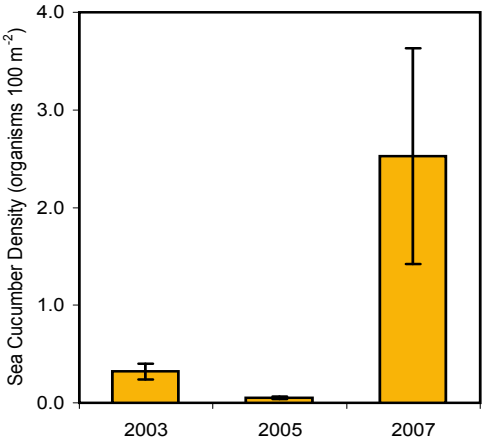


Figure 6.7.1f. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Urchins

During MARAMP 2003, sea urchins were observed at both of the REA sites surveyed and in all 4 of the towed-diver surveys conducted at Aguijan (Fig. 6.7.1g, top panel). The sample mean density of sea urchins from REA surveys was 40.5 organisms 100 m^{-2} (SE 4.5), and the overall mean density from towed-diver surveys was 1.77 organisms 100 m^{-2} (SE 0.35). Survey results suggest that sea urchins were most abundant at AGU-01 on the southeastern coast with 45 organisms 100 m^{-2}. During these REA surveys, 3 genera were observed: *Echinostrephus*, *Echinometra*, and *Echinothrix*. The rock-boring urchin *Echinostrephus* was the dominant macroinvertebrate genus at both sites, accounting for 63% of recorded urchins. Among all towed-diver surveys around this island, the survey completed along the northeastern shore had the highest mean density of sea urchins with 3.47 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 7.53 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was very similar with 3.37 organisms 100 m^{-2}, recorded at Naftan Rock; segment densities ranged from 0 to 7.4 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed at 1 of the 3 REA sites surveyed and in all 3 of the towed-diver surveys conducted around Aguijan (Fig 6.7.1g, middle panel). AGU-01 in the south region had a density of 54 organisms 100 m^{-2}, and the islandwide mean density of sea urchins from towed-diver surveys was 5.37 organisms 100 m^{-2} (SE 0.56). Only rock-boring urchins of the genus *Echinostrephus* were observed at AGU-01. Among all towed-diver surveys around this island, the survey completed along the northeastern coast had the highest mean density of sea urchins with 9.12 organisms 100 m^{-2}; segment densities from this survey ranged from 3.47 to 23.48 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 3.39 organisms 100 m^{-2}, recorded along the south central shore; segment densities ranged from 1.44 to 4.55 organisms 100 m^{-2}.

During MARAMP 2007, sea urchins were observed during all 3 of the towed-diver surveys conducted at Aguijan (Fig. 6.7.1g, bottom panel) with an overall mean density of 0.57 organisms 100 m^{-2} (SE 0.17). Among all towed-diver surveys around this island, the survey completed along the south central coast had the highest mean density of sea urchins with 1.44 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 3.04 organisms 100 m^{-2}.

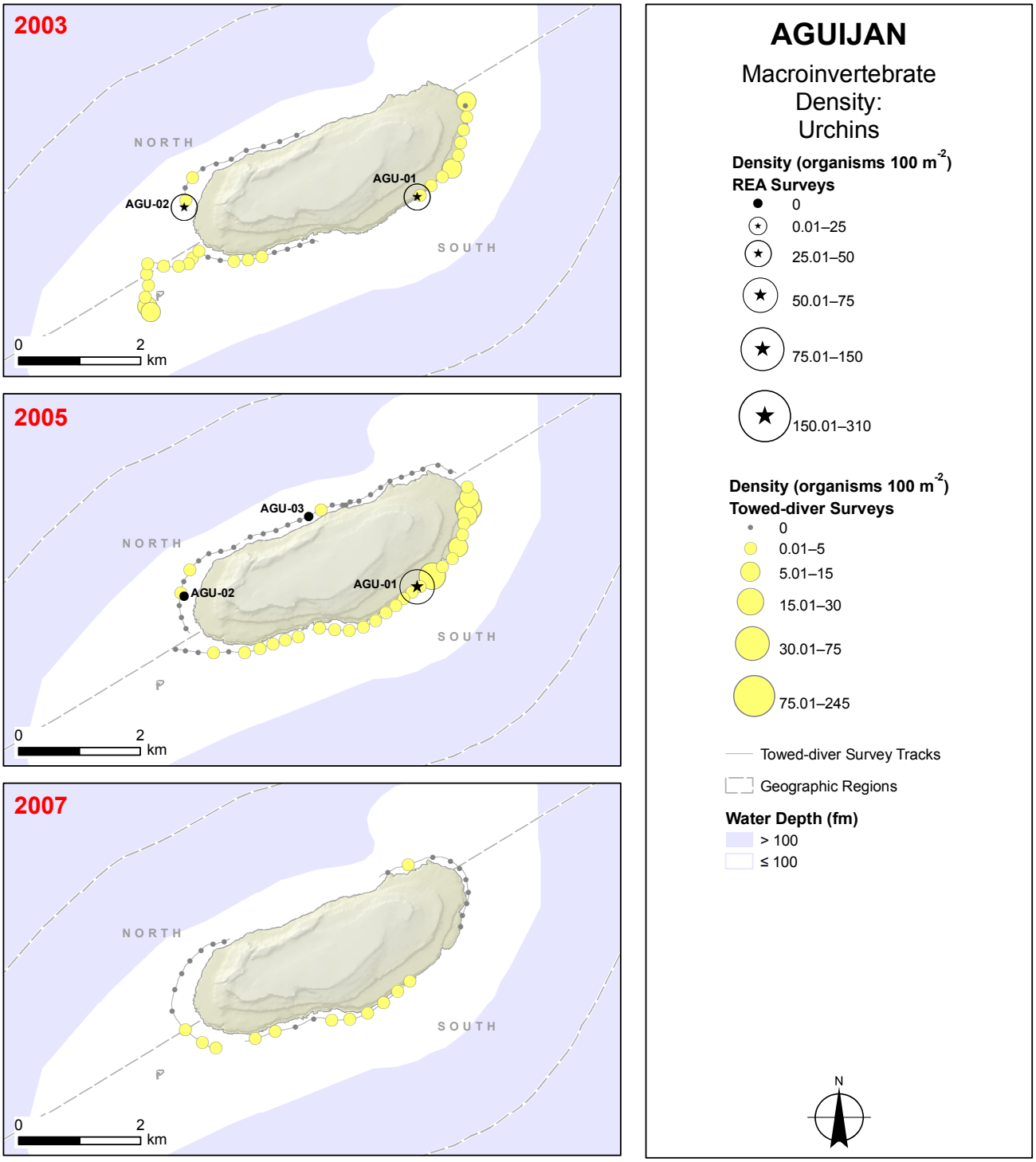


Figure 6.7.1g. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Aguijan during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggested low daytime abundance of sea urchins around Aguijan during MARAMP 2003, 2005 and 2007, compared to the rest of the Mariana Archipelago. The overall observed mean density of sea urchins around Aguijan was higher in 2003 and 2005 than in 2007 (Fig. 6.7.1h). This variation may be a result of differences between survey years in the number of surveys conducted and other factors and is not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys")

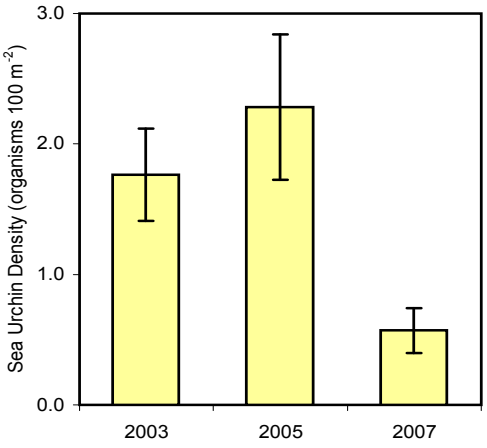


Figure 6.7.1h. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

6.8 Reef Fishes

6.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 3 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats at the island of Aguijan with a fourth survey completed near Naftan Rock southwest of this island. The overall estimated mean biomass of large fishes at Aguijan, calculated as weight per unit area, was 0.16 kg 100 m^{-2} (SE 0.03), a low value and 7 times less than the archipelago-wide mean biomass of large fishes observed for this survey period. With only 4 surveys conducted, no clear spatial patterns were apparent in the distribution of large-fish biomass (Fig. 6.8.1a, top panel). Reef sharks (Carcharhinidae) and parrotfishes (Scaridae) contributed the largest proportions to overall mean large-fish biomass. Two reef sharks were recorded at Aguijan during in 2003. Both sharks were blacktip reef shark (*Carcharhinus melanopterus*), and both were observed in the south region with 1 on the west side and 1 on the east side.

During MARAMP 2005, 6 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Aguijan. The islandwide estimated mean biomass of large fishes was 0.21 kg 100 m^{-2} (SE 0.08), a value similar to the level observed in 2003. Biomass values for large fishes were highest along the northwestern coast, where 2 whitetip reef shark (*Triaenodon obesus*) were observed during a single survey (Fig. 6.8.1a, middle panel). Reef sharks and surgeonfishes (Acanthuridae) contributed the largest proportions to islandwide mean large-fish biomass. Five sharks were observed in total, all of them in the north region.

During MARAMP 2007, 3 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats at Aguijan. The overall estimated mean biomass of large fishes at this island was 0.15 kg 100 m^{-2} (SE 0.11), a level similar to results from previous MARAMP survey years (Fig. 6.8.1a, bottom panel). Biomass values for large fishes were highest around the east side of this island. Reef sharks and snappers (Lutjanidae) contributed the largest proportions to overall mean large-fish biomass. Three sharks were observed, all along the southeastern coast.

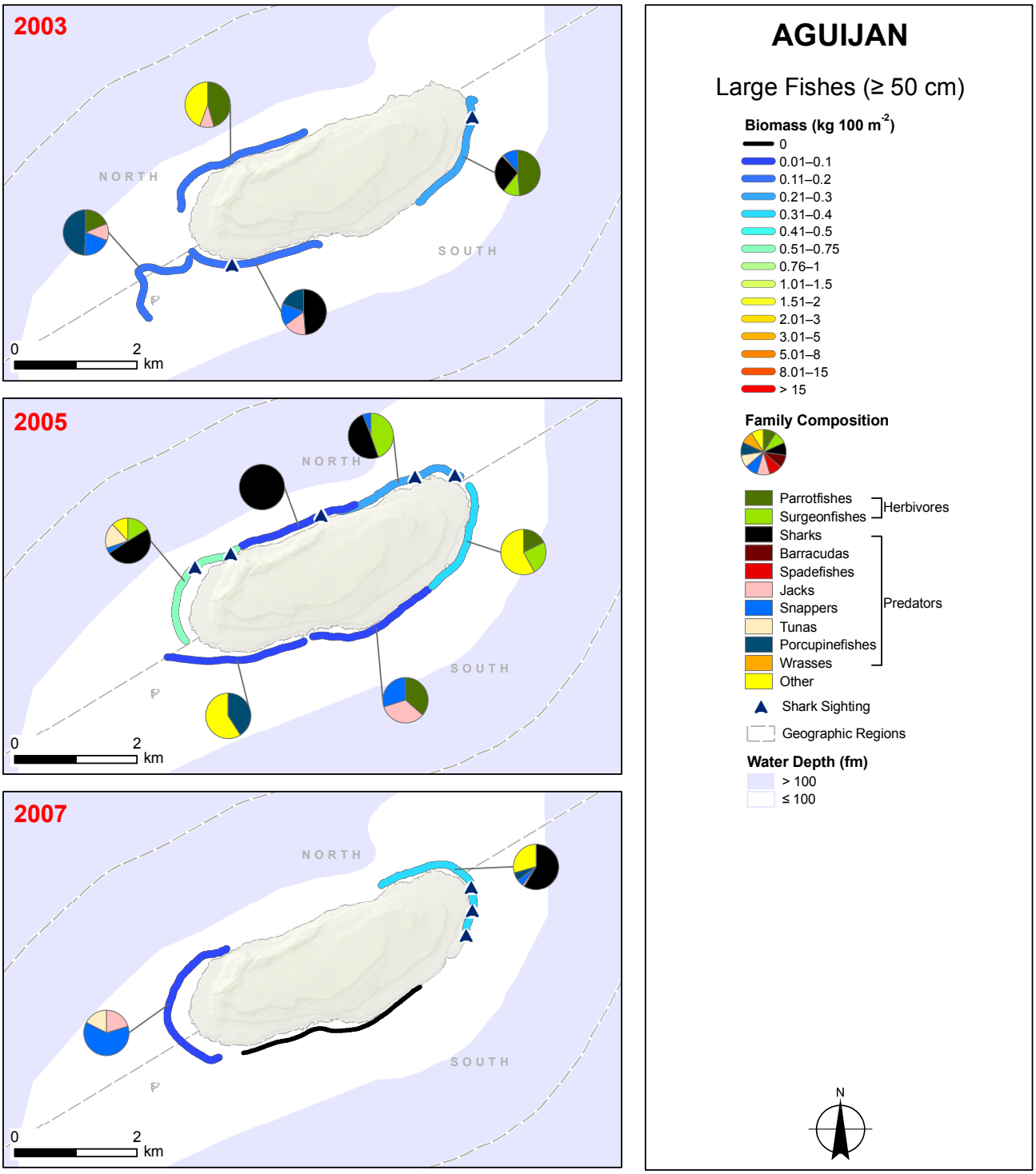


Figure 6.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted around Aguijan during MARAMP 2003, 2005, and 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

Large-fish biomass from towed-diver surveys of forereef habitats was similar across the 3 MARAMP survey years (Fig. 6.8.1b). Temporal comparisons are confounded by the inconsistent survey effort between years. The number of shark sightings recorded was higher in 2005 than in 2003 and 2007: 5 versus 2–3 sightings. For the 3 MARAMP survey periods combined, mean large-fish biomass at Aguijan was 0.17 kg 100 m^{-2} (SE 0.02). Although this level of large-fish biomass is low compared to the archipelago-wide average, this overall mean estimate for Aguijan is similar to values recorded at other southern islands.

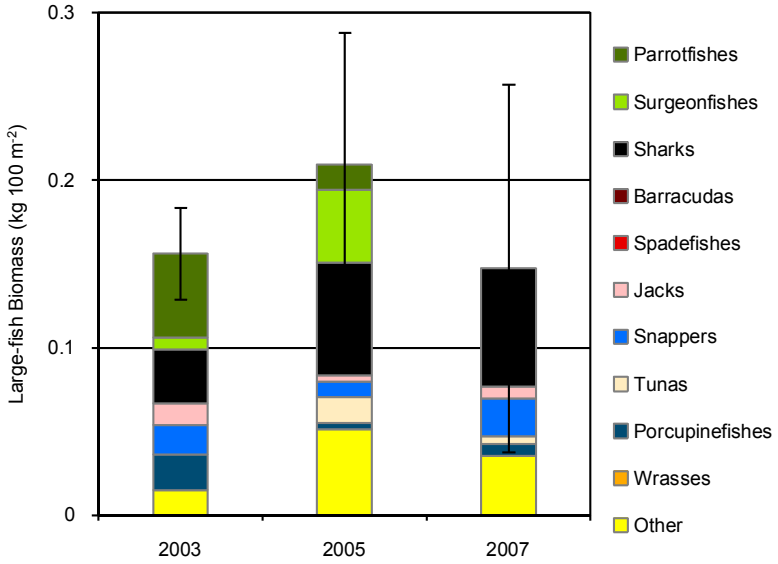


Figure 6.8.1b. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Aguijan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Total fish biomass for the 2 REA sites surveyed in forereef habitats at Aguijan during MARAMP 2003 was moderate, compared to other sites in the Mariana Archipelago, with an overall sample mean of 4.69 kg 100 m^{-2} (SE 1.67). Fish biomass was higher at AGU-01 (Fig. 6.8.1c, top panel), mainly because of fusiliers (Caesionidae), herring (Clupeidae), and emperors (*Lethrinus* spp.). Other families commonly observed at AGU-01 were surgeonfishes and triggerfishes (Balistidae). Surgeonfishes accounted for 47% of total fish biomass at AGU-02. Species richness at Aguijan, based on REA surveys conducted during MARAMP 2003, was 34 and 38 species 100 m^{-2} at AGU-01 and AGU-02, values similar to the archipelago-wide mean of 31.1 species 100 m^{-2}.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Aguijan during MARAMP 2005 was moderate, compared to other sites in the Mariana Archipelago, with an overall sample mean of 6.50 kg 100 m^{-2} (SE 0.73). Surgeonfishes accounted for 35%–56% of the total fish biomass per site (Fig. 6.8.1c, middle panel). Parrotfishes and damselfishes (Pomacentridae) were also common. The most common species was the bullethead parrotfish (*Chlorurus sordidus*).

Based on REA surveys conducted during MARAMP 2005, species richness at Aguijan, with a range of 31–33 species 100 m^{-2}, was high relative to results from other islands in the Marina Archipelago and similar to the diversity seen at this island in 2003. Species observed at Aguijan but rarely seen elsewhere in the Mariana Archipelago included the leopard blenny (*Exallis brevis*), mackerel scad (*Decapterus macarellus*), tomato clownfish (*Amphiprion frenatus*), sixblotch hind (*Cephalopholis sexmaculata*), and bronzespot razorfish (*Iniistius celebicus*).

Total fish biomass during MARAMP 2007 was 4.52 kg 100 m^{-2} at AGU-03, the single REA site surveyed at Aguijan. Surgeonfishes composed about two-thirds of total fish biomass (Fig. 6.8.1c, bottom panel). Species richness at AGU-03, based on REA surveys conducted during MARAMP 2007, was 22 species seen 100 m^{-2}, a value lower than the diversity recorded at Aguijan during previous MARAMP survey years.

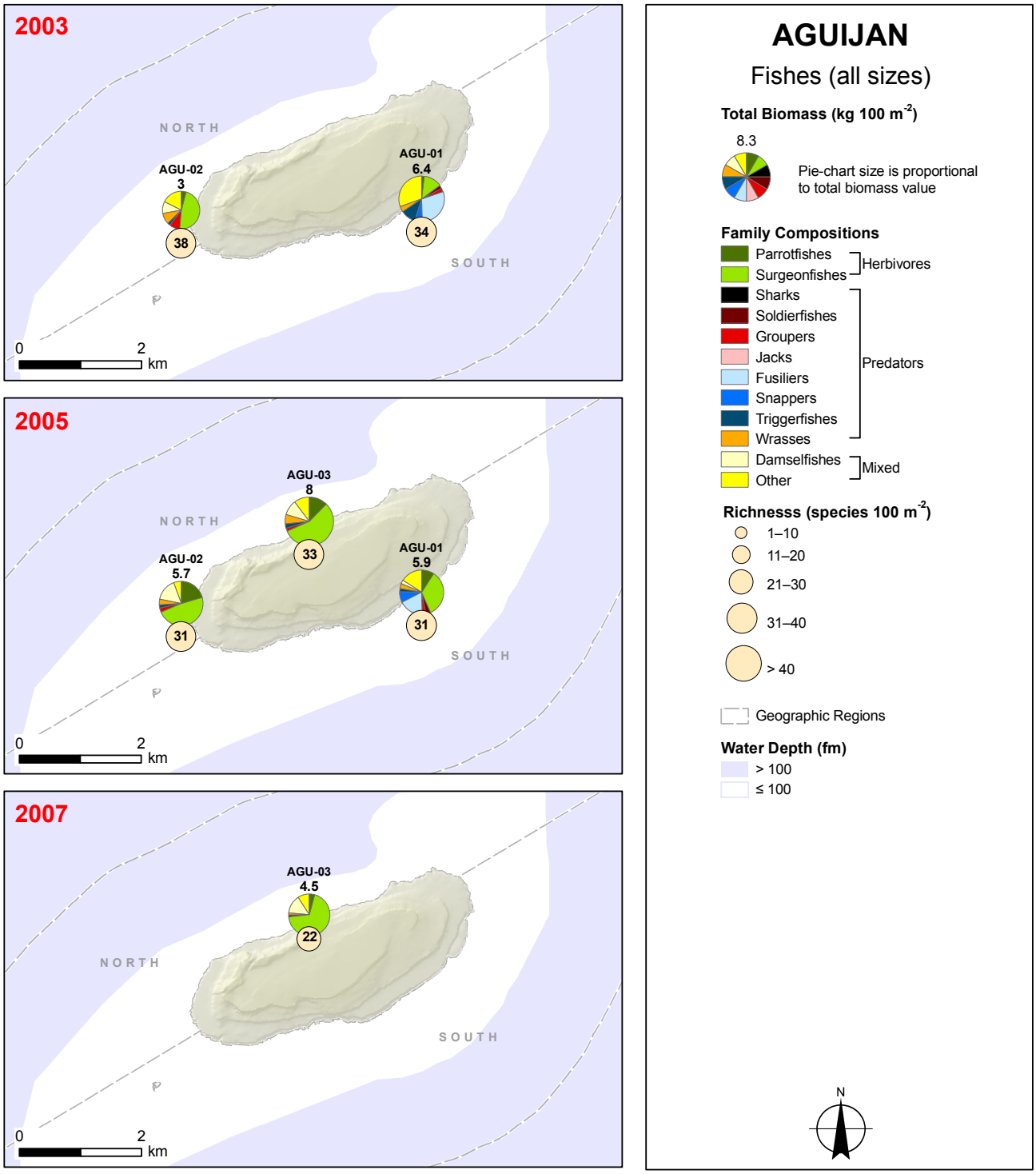


Figure 6.8.1c. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007.

Because of this island's small size, only 1–3 REA sites were surveyed at Aguijan during MARAMP 2003, 2005, and 2007. The low number of surveys makes assessing spatial patterns around this island difficult. Nearly half of the total fish biomass recorded at REA sites at Aguijan was composed of surgeonfishes. Estimates of total fish biomass at Aguijan were similar between the 3 MARAMP survey years (Fig. 6.8.1d), with few observations of medium- and large-sized fishes, and slightly higher than the overall mean values of total fish biomass recorded at other islands on the southern end of the Mariana Archipelago.

Overall species richness varied among sites from year to year with no clear spatial or temporal trend in diversity observed. The average fish species richness at Aguijan was 30 species 100 m^{-2} (SE 2) across all REA surveys conducted during MARAMP 2003, 2005, and 2007. Exactly the same as the average observed at Tinian, this level of diversity was moderate for the Mariana Archipelago but 50% higher than the average found around Guam, an unexpected difference given Aguijan's size and homogenous habitat.

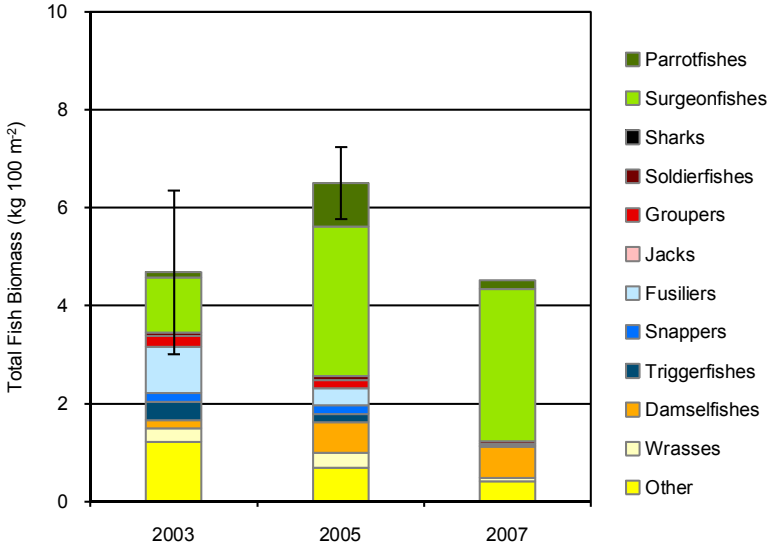


Figure 6.8.1d. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted around Aguijan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

6.9 Marine Debris

6.9.1 Marine Debris Surveys

During MARAMP 2003, 2 sightings of derelict fishing gear and 18 sightings of other man-made objects were recorded in the 4 towed-diver surveys conducted on forereef habitats at the island of Aguijan. Off the northwestern coast, 1 fishing line and 1 anchor with a chain were observed (Fig. 6.9.1a, top panel). The remaining sightings were all noted during the single towed-diver survey that occurred off the west coast of Aguijan and at Naftan Rock. One trawl net and 17 unidentified man-made objects were observed during this survey. No munitions or wrecks were identified.

During MARAMP 2005 and 2007, no sightings of marine debris were recorded in the towed-diver surveys conducted on forereef habitats around Aguijan (Fig. 6.9.1a).

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments. Still, in both 2005 and 2007, no marine debris was observed.

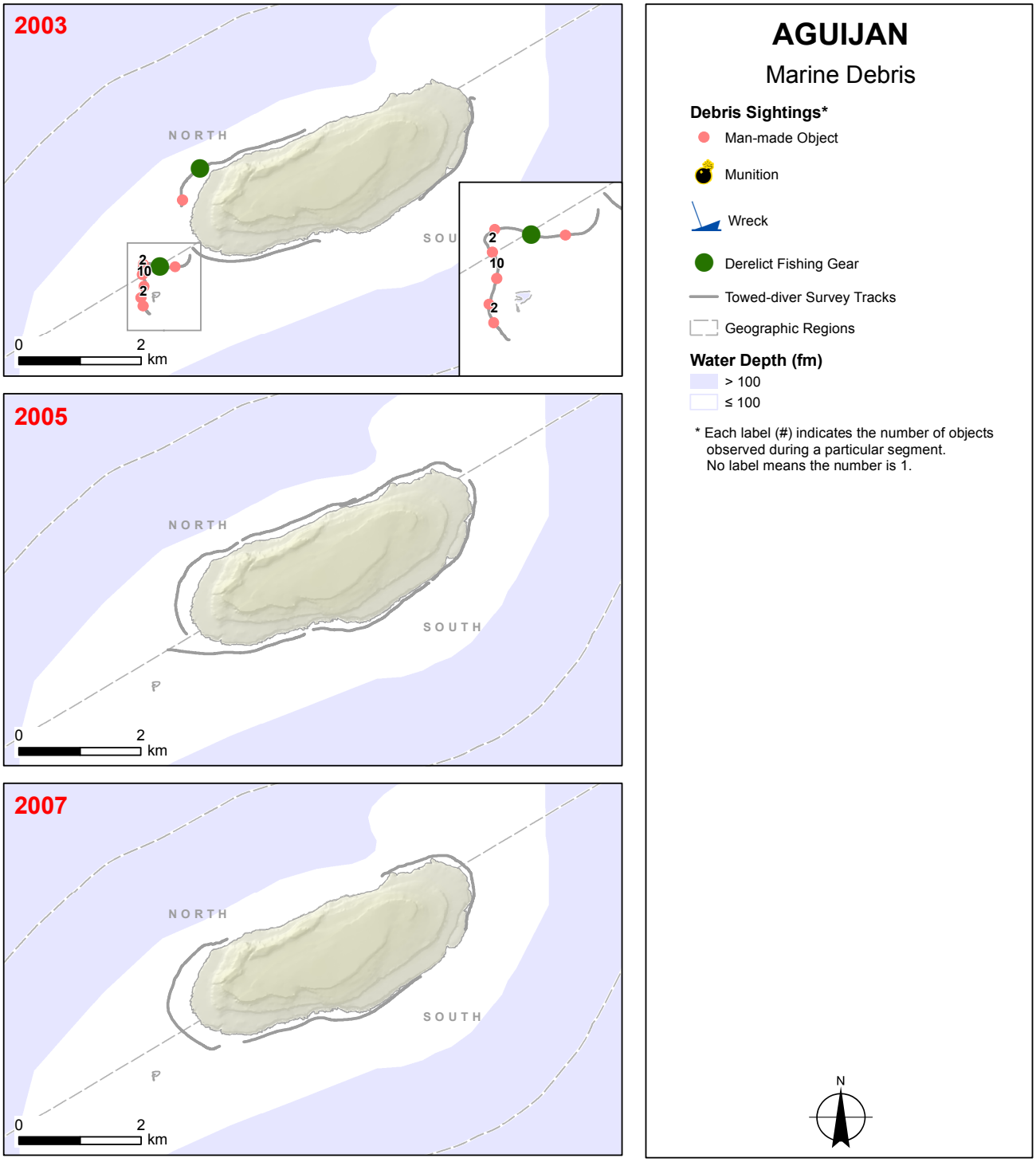


Figure 6.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Aguijan during MARAMP 2003. No debris sightings were recorded in 2005 and 2007. Symbols indicate the presence of specific debris types.

6.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Aguijan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. Few conclusions can be drawn from the sparse data collected at this small island; however, if data describing individual reef components are considered in tandem, some patterns are revealed. The predominant pattern is the difference between benthic communities north and south of Aguijan. In addition to this island-level analysis, evaluations across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Aguijan as well as the other 13 islands covered in this report.

Aguijan is the smallest of the southern islands in the Mariana Archipelago. It is low-lying and flat-topped, formed of a series of carbonate terraces overlying a volcanic core. Located only 9 km southwest of Tinian, Aguijan is surrounded by a sloping bank that descends to ~ 400 m within ~ 2 km of the coast (Fig. 6.3.1a in Section 6.3.1: "Acoustic Mapping"). The limited coverage of multibeam mapping at shallow depths leaves the nature of the nearshore submarine topography unknown. This island is currently uninhabited, partly as a result of the steep onshore slopes and lack of viable land areas.

The highest cover of live hard corals was observed along the northwestern coast (Fig. 6.10a), in an area of spur-and-groove habitat (Fig. 6.10b). This reef area had the highest live coral cover recorded during towed-diver surveys in both 2003 and 2005 with an estimated mean cover of ~ 34%, within a range of 5.1%—62.5% (Fig. 6.5.1a in Section 6.5.1: "Coral Surveys"). Live coral cover in this area and overall at Aguijan was lower in 2007 than in previous MARAMP survey years. Based on towed-diver surveys, estimated cover of live corals was lower on the reef pavement flats observed south of Aguijan than on the habitats surveyed north of this island (Figs. 6.10a and c).

Results from fine-scale REA surveys conducted at Aguijan suggest that coral-colony density at Aguijan was higher at REA sites AGU-02 and AGU-03 in the north region than at AGU-01 in the south region (Fig. 6.5.1b in Section 6.5.1: "Coral Surveys" and Fig. 6.10a). Habitat complexity, estimated during towed-diver surveys, was also higher north of Aguijan compared to the south (Fig. 6.3.3a in Section 6.3.3: "Habitat Characterization"). The highest habitat complexity was observed off the north central coast, in an area characterized by high (20%–75%) cover of crustose coralline algae in both 2003 and 2005. In contrast to the higher cover of live corals and crustose coralline red algae, estimates of macroalgal cover were lower along the northern shores than off the southern coast, with values typically < 30% during each of the 3 MARAMP survey years (Fig. 6.6.1a in Section 6.6.1: "Algal Surveys"). The highest levels of macroalgal cover were observed on the southeastern shore, along the most exposed coast of this island.

Overall, the coral reef ecosystems observed during MARAMP surveys appear to be comparable to the ecosystems surveyed at the other southern islands of Guam, Rota, Tinian, and Saipan, with similar relative cover of live corals, macroalgae, and crustose coralline red algae and similar coral generic richness. No specific spatial pattern in distribution of biomass of large (≥ 50 cm TL) fishes was observed (Fig. 6.8.1a in Section 6.8.1: "Reef Fish Surveys"), and fish biomass estimates for Aguijan were similar to survey results for the other southern islands.

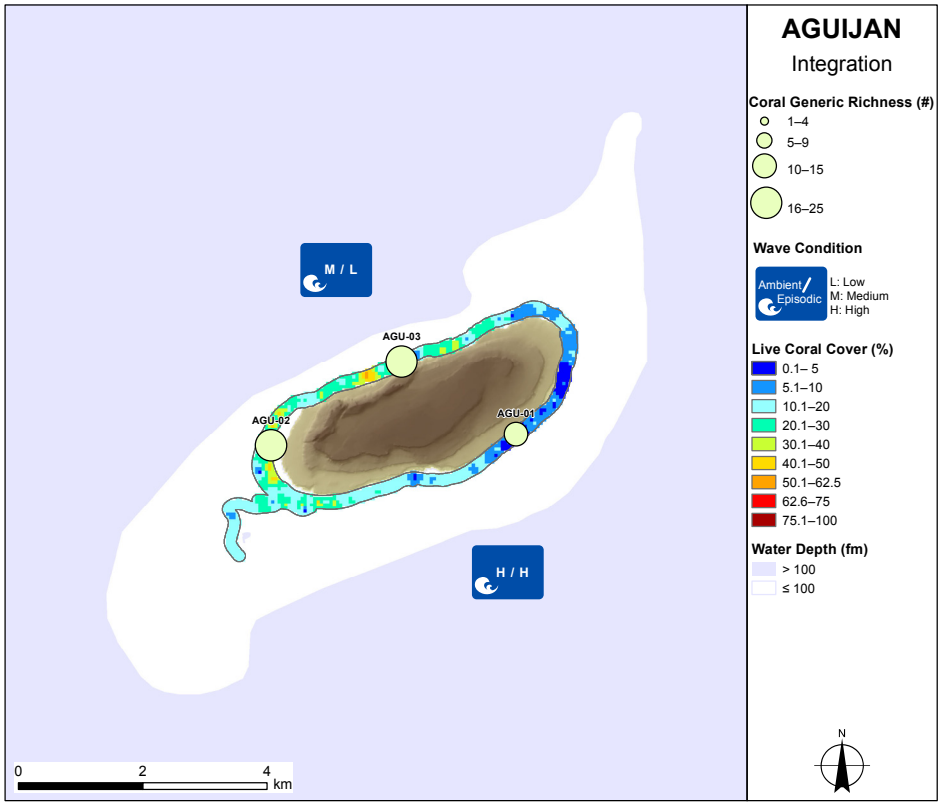


Figure 6.10a. Observations of cover (%) of live hard corals from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Aguijan during MARAMP 2003, 2005, and 2007. Values of coral cover represent interpolated values from the 3 MARAMP survey years, and values of coral generic richness represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.



Figure 6.10b. Northern reef of Aguijan with spur-and-groove habitat. *NOAA photo by Edmund Coccagna*

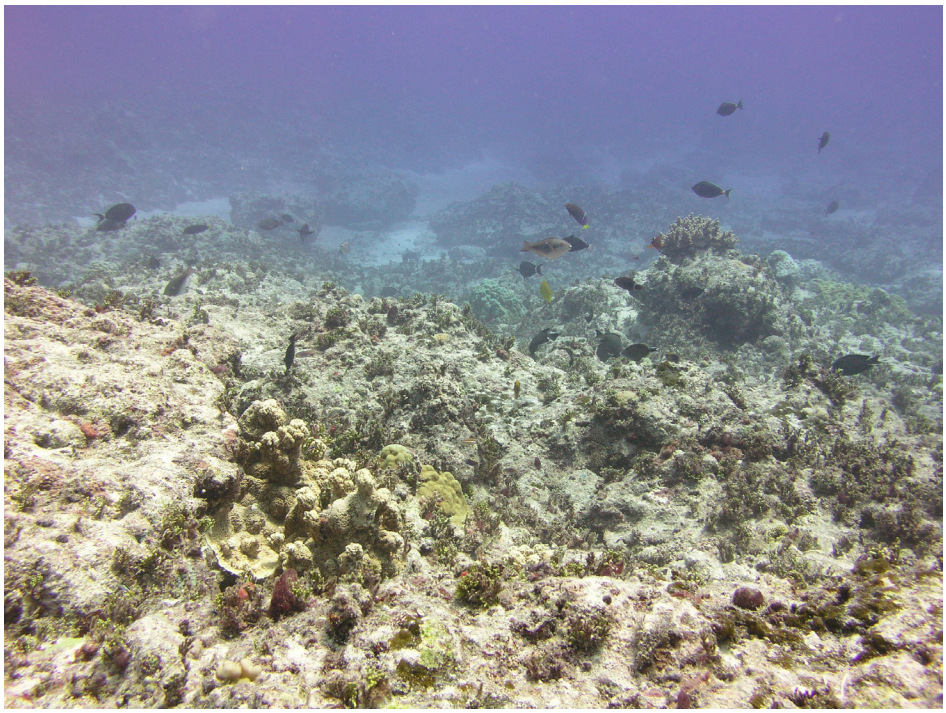


Figure 6.10c. Pavement reef south of Aguijan. *NOAA photo by Robert Schroeder*

6.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around the island of Aguijan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Aguijan chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Aguijan, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around Aguijan as well as some of the key natural processes and anthropogenic activities influencing these ecosystems:

- Aguijan, with a land area of 7.3 km^2, is the smallest island in the southern portion of the Mariana Archipelago.
- Aguijan has been uninhabited since 1945, but because of its proximity to Tinian, it is still visited by hunting parties.
- Surrounded by steep sea-cliffs, this low-lying island is composed of a series of uplifted, carbonate terraces overlying an older volcanic structure.
- Offshore, Aguijan is surrounded by a sloping bank, the flanks of which descend to a depth of 400 m within ~ 2 km of the coast. It is connected to Tinian by a broad, submerged ridge at a depth of ~ 380 m.
- An east–west gradient was observed in the distribution of sand cover estimated from towed-diver surveys, with the west having more sand than the east, especially in a survey area on the southwestern coast. The seabed in this area was characterized as sand with patch reefs.
- Wave model output shows ambient trade wind swells impacting the south, and to a lesser extent, the north. Episodic wave energy from storm tracks impact the south.
- Water clarity was relatively high (93.4%–97.1%) at Aguijan during MARAMP 2005 and 2007, suggesting that terrestrial runoff is low in the vicinity of Aguijan.

- STR data show that temperatures during September 2006 reached and surpassed the coral bleaching threshold, which is defined as 1˚C above the monthly maximum climatological mean.

- Estimates of live coral cover from towed-diver surveys were congruent with the mean of 7.8% at AGU-03, the only REA site surveyed in 2007, the only year in which coral cover was assessed using the line-point-intercept method. Overall mean coral cover from towed-diver surveys was 12% in 2007, a lower value than the overall means from previous MARAMP survey years. Observed densities of coral colonies from REA surveys were higher along the northern coast of Aguijan than along the southern shore.

- Overall prevalence of coral disease was 0.46% at AGU-03, the only site surveyed for coral disease in 2007. Two types of coral disease were observed: white syndrome (0.31%) and cyanophyte infection (0.15%). Surveys for coralline-algal disease at AGU-03 found cases of coralline lethal orange disease.

- The overall mean cover of crustose coralline red algae essentially remained the same between the 3 MARAMP survey years.

- Estimated biomass of large fishes at Aguijan, based on towed-diver surveys, was comparable to results from other southern islands of the Mariana Archipelago, such as Guam and Tinian. Sharks were seen in each of the 3 MARAMP survey years.

- The average fish species richness at Aguijan was 30 species 100 m^{-2} across all REA surveys conducted during MARAMP 2003, 2005, and 2007. The same estimate made at Tinian, this level of diversity was moderate for the Mariana Archipelago but 50% higher than the average observed at Guam, an unexpected difference given Aguijan's size and homogenous habitat. Nearly half of the total fish biomass recorded at REA sites around Aguijan was composed of surgeonfishes.

- COTS densities were high in 2003 and 2005, compared to the rest of the Mariana Archipelago, with a localized area of high density suggesting that an outbreak was underway observed on the southwestern coast in 2003 and on the north central coast in 2005.

- With the exception of the northeastern shore in 2007, densities of sea cucumbers were low at Aguijan relative to the rest of the Mariana Archipelago. The overall observed densities of giant clams and sea urchins were low at Aguijan in each of the 3 MARAMP survey years.

7 TINIAN

7.1 Introduction

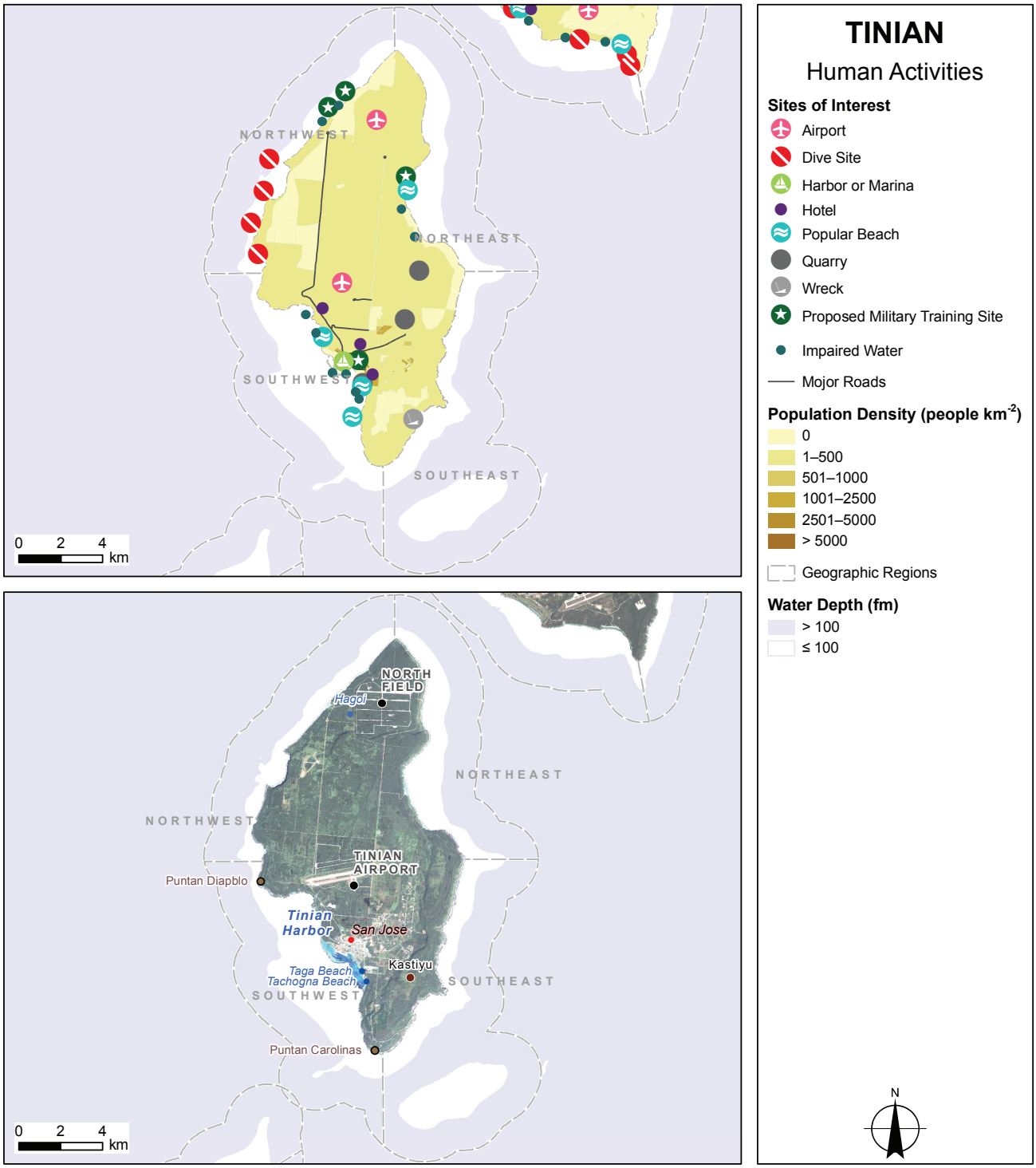


Figure 7.1a. Major locations of human activities (*top*) on Tinian that have the potential to affect the marine environment (Placenames.com; Bearden 2008; U.S. Geological Survey 2005b) are represented over a population-density map (U.S. Bureau of the Census 2003, 2008). Satellite imagery of Tinian (*bottom*, includes material © 2006 DigitalGlobe Inc. All rights reserved), labeled with places of interest (U.S. Geological Survey).

The island of Tinian and Tatsumi Reef are adjacent volcanic structures that mostly are overlain by uplifted carbonate rock. Tinian, 6 km south of Saipan, is one of the 14 islands that compose the Commonwealth of the Northern Mariana Islands (CNMI) and, together with Aguijan 8 km to the southwest, forms Tinian County. Located between 15°7′ and 14°53′ N latitude and 145°33′ and 145°43′ E longitude, Tinian is the third largest island in the Mariana Archipelago with a land area of 101.22 km^2, 52 km of coastline, and a maximum elevation of 187 m. The village of San Jose, located near Tinian Harbor on the southwest coast (Fig. 7.1a), is the principal population center. A casino and hotel in San Jose are the major tourist facilities on this island. In the later part of World War II (WWII), a major U.S. airfield was located on Tinian, and 65% of the land on Tinian is still leased by the U.S. military.

7.1.1 History and Demographics

Tinian was ruled by Spain and Germany before World War I (WWI) and became a major sugarcane growing and processing center while under Japanese control between WWI and WWII. In mid-1944, this island was captured by U.S. forces, who built on the flat terraces of Tinian what were then the world's longest runways. These runways were used to launch U.S. planes for attacks on Japan, including the B-29 bombers that dropped atomic bombs on Hiroshima and Nagasaki. North Field, which encompasses these runways, is a National Historic Landmark maintained by the U.S. Department of Defense.

In 2010, Tinian was the second-most populated island in the CNMI, with a population of 3136, an 11% decrease from 3540 in 2000 but a 262% increase from 866 in 1980 (Fig. 7.1.1a; U.S. Bureau of the Census 2011a; CNMI Department of Commerce 2002a).

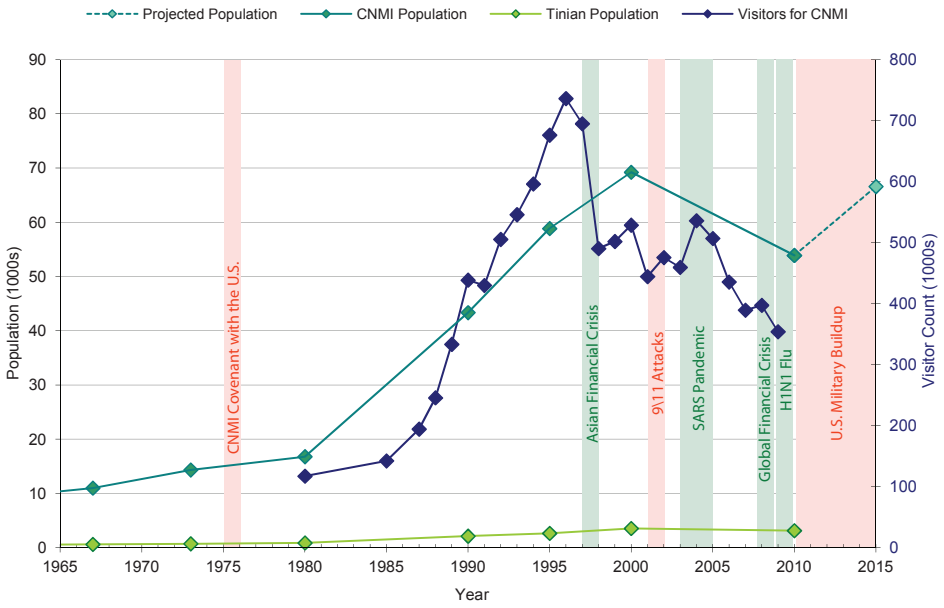


Figure 7.1.1a. Population growth (U.S. Bureau of the Census 1983, 2003, 2011a; CNMI Department of Commerce 2002a; Secretariat of the Pacific Community 2011) and visitor count (Bank of Hawaii 1995; Lucas 1990; U.S. Department of the Interior 1996; CNMI Department of Commerce 2002b; Marianas Visitors Authority) trends on Tinian and in the CNMI for the period of 1965–2015.

7.1.2 Geography

The primary type of rock on Tinian and the other southern islands in the Mariana Archipelago consists of raised limestone (Fig. 7.1.2a) with relatively flat surrounding terraces and steep sea cliffs (Fig. 7.1.2b) that make up more than half of the Tinian coastline. These features are caused by episodic tectonic uplift associated with the subduction of seamounts in the

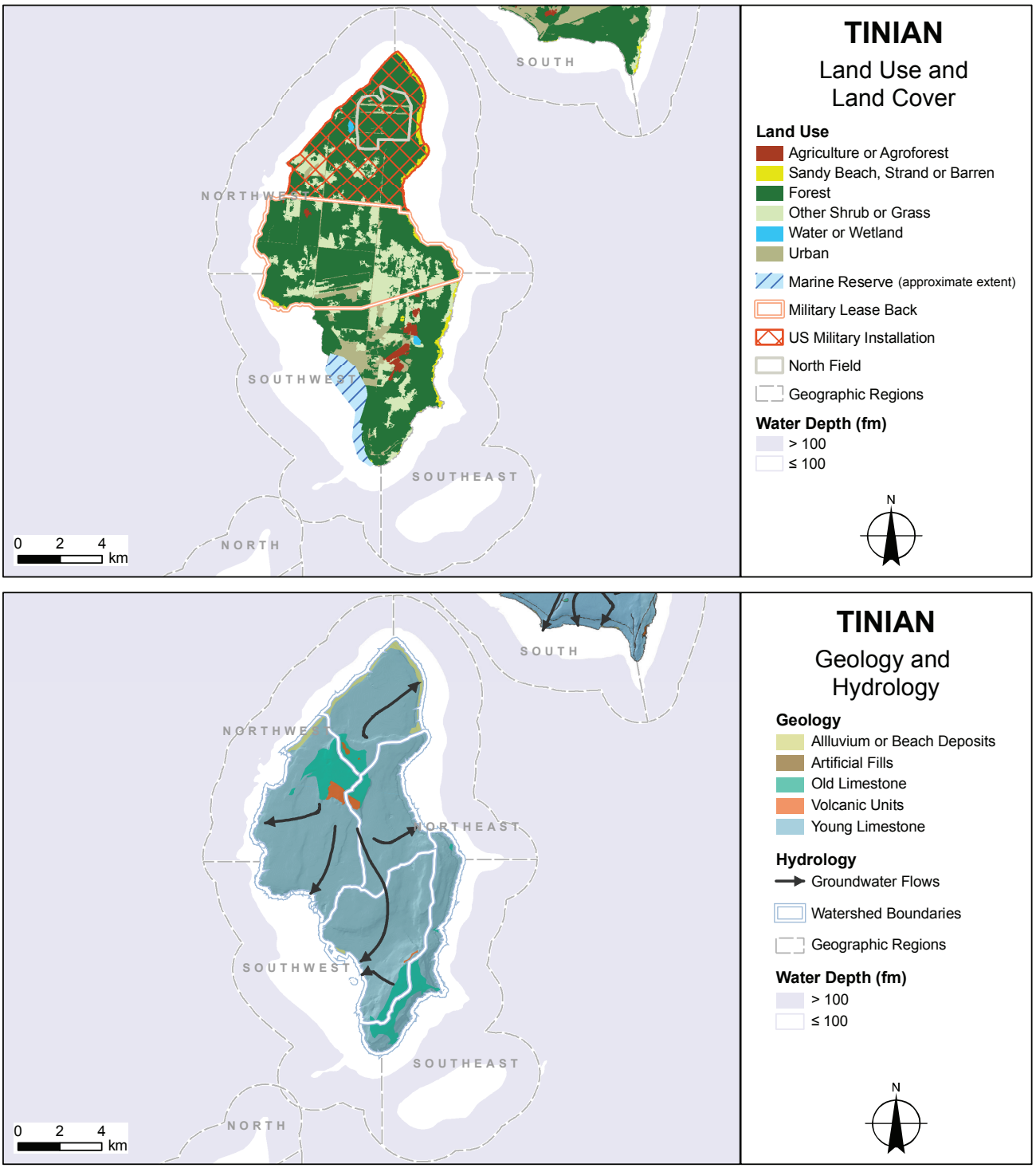


Figure 7.1.2a. Land use (U.S. Department of Agriculture Forest Service 2006b), a military installation and lease back area (U.S. Geological Survey 2005a; K Herrmann, CNMI Division of Environmental Quality, pers. comm.), a historic site (National Park Service 2001), and a marine protected area (CNMI Public Law 17-14; K Herrmann, pers. comm.) on Tinian are represented over a vegetation cover map (*top*, Liu and Fischer 2006). Geology, watersheds, and groundwater flows on Tinian (*bottom*, Gingerich 2002; M Pangelinan, CNMI Department of Land and Natural Resources, pers. comm.).

Isu-Bonin Mariana arc system (Fryer et al. 1992). Much of the limestone on Tinian is covered by thin to moderately thick soils, but some limestone areas exhibit karst topography, which is formed by dissolution of carbonate rocks and characterized by sinkholes, caves, and subterranean passages. Volcanic basement rocks are exposed in only a few areas and cover < 3 km^2 (Stafford et al. 2005).

Most water consumed on Tinian comes from shallow wells in the karst aquifer (Stafford et. al. 2005); Tinian has no perennial streams and very little surface water. Groundwater collects in a subsurface "Ghyben-Herzberg lens" of water and springs, and frequent freshwater seeps occur along the beaches (Gingerich 2002). Groundwater drainage patterns on Tinian are shown as arrows in Figure 7.1.2a. Although an estimated 88%–94% of the rainfall is absorbed into the limestone, effects from runoff into coastal waters still would be expected during periods of heavy rainfall and storms (Gingerich 2002). Severe storm events can cause erosion and pollution, events that are especially problematic for coral reef environments. The major observed source of sediment into nearshore waters has been runoff from unpaved secondary roads (Starmer et al. 2005).

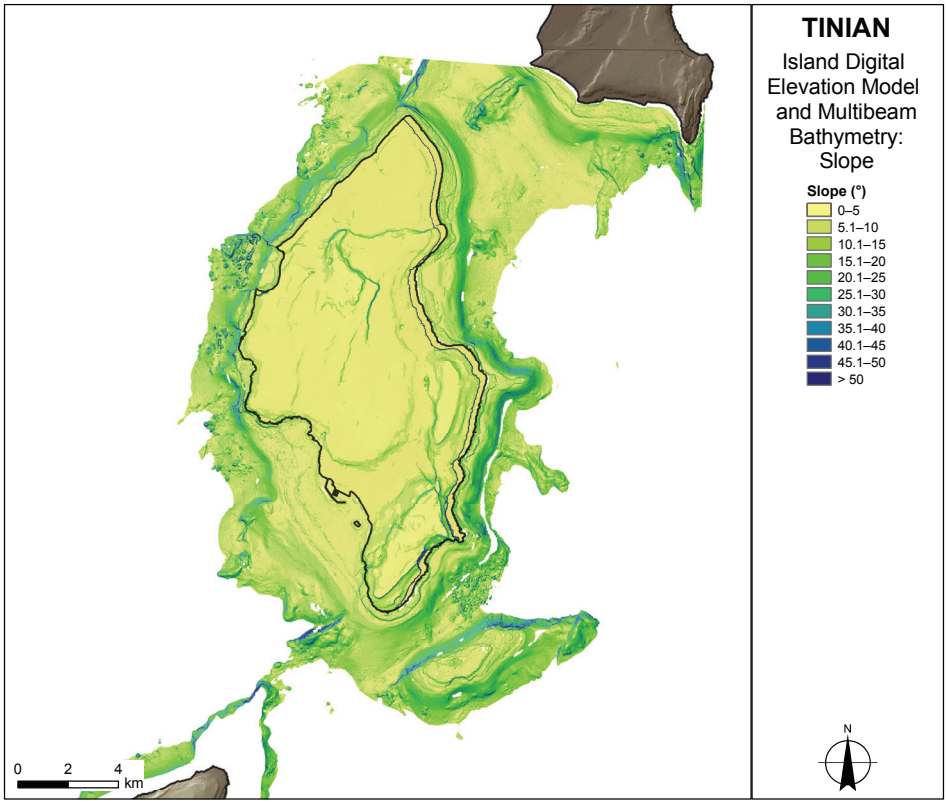


Figure 7.1.2b. Combined slope map using the digital elevation model and multibeam bathymetric data for Tinian.

7.1.3 Economy

The service sector and local government make up the largest components of Tinian's resident workforce. Agriculture, tourism, and military spending also contribute to the local economy (Fig. 7.1.3a). Commercial agriculture on Tinian consists of small-scale vegetable and fruit cultivation on the southern part of this island (Fig. 7.1.2a). Produce from these farms is marketed locally and also shipped to Saipan. Commercial cattle grazing on Tinian involves a few small, family-owned ranches.

Under an agreement signed in 1983, the northern two-thirds of Tinian—more than 65 km^2 or 16,000 acres—was leased to the U.S. military for a period of 50 years (Fig. 7.1.2a). U.S. military training operations are conducted regularly in this area. Any nonmilitary uses within this area, including visits to the North Field National Historic Landmark, must be approved by the Department of Defense. Much of the southern portion of this military-controlled area has been leased back to the CNMI for uses judged to be compatible with the long-term needs of the Department of Defense, uses that primarily include grazing and agriculture (National Park Service 2001). Under this agreement, the leased-back area may be used for training activities that would not be detrimental to ongoing CNMI economic and agricultural activities. The Department of Defense currently is proposing expansion of military training activities on Tinian because of the projected move of 8000 marines to Guam within the next decade (Kan 2012).

In 1997, a casino was constructed adjacent to Tachogna and Taga Beaches near San Jose, Tinian's only major settlement. A major source of revenue for Tinian comes from tourists who visit on day trips from Saipan via boat or air, although the tourist trade has diminished since flights from Japan to Saipan were reduced in 2005. As shown in Figure 7.1.1a, CNMI visitor trends fluctuate with external events, such as economic downturns and disease outbreaks.

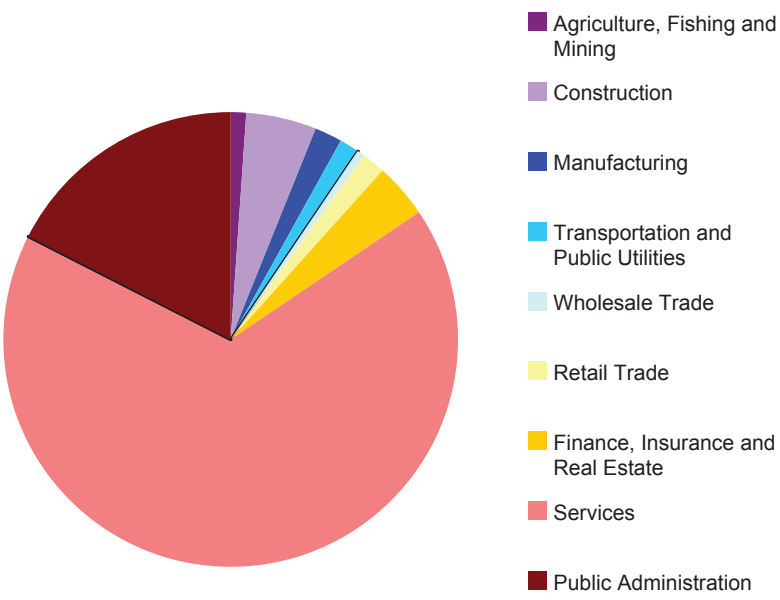


Figure 7.1.3a. Employment by sector on Tinian in 2005 (CNMI Department of Commerce 2008).

7.1.4 Environmental Issues on Tinian

The native vegetation of Tinian has been highly disturbed, and only small remnants now remain. In the 1920s, the Japanese cleared much of the native limestone forest, which was believed to have covered this island in the late 1700s and 1800s, to plant sugar cane. During WWII, sugar cane plantations were abandoned, and bombing, fires, and military reconstruction further reduced the native limestone forest. Currently, the introduced, weedy tangantangan (*Leucaena leucocephala*), a shrub-like tree also called *haole koa* in Hawai`i that can form dense monospecific thickets and is difficult to eradicate, has replaced both the sugar cane fields and native limestone forest areas. Tangantangan stands dominate most of the level and moderately sloping portions of this island, except for in the few, interspersed non-carbonate regions where guinea grass (*Panicum maximum*) is dominant (Stafford et al. 2005). The remnants of the native limestone forest are now restricted to cliff lines and escarpments around the plateau on the southeast side of Tinian and in a corridor on the central escarpment (National Park Service 2001).

There are 3 wetland areas on Tinian. The largest includes Hagoi, a lake on the northwest part of this island, and the 2 smaller areas are farther south (Fig.7.1a). At present, these wetlands are effectively protected by both Federal and local laws. In 2007, the CNMI legislature designated a marine reserve area on the southwest side of Tinian through CNMI Public Law 15-90. This area, which CNMI Public Law 17-14 revised in 2010, is bounded from Puntan Carolinas to Tinian Harbor (Fig. 7.1.2a); however, the exact geographic coordinates of the reserve boundary are still undefined. All fishing activities—with the exception of aquaculture and fishing for the seasonal species *atulai* or bigeye scad (*Selar crumenophthalmus*), *i`e* or juvenile jacks (Carangidae), and *ti`ao* or juvenile goatfish (Mullidae)—are prohibited in this reserve for an initial period of 5 years that began in 2007 when Public Law 15-90 became effective. Tinian's wetlands are essential to the survival of the Mariana common moorhen (*Gallinula chloropus guami*), a bird listed both as an endangered species Federally (U.S. Fish and Wildlife Service) and as a threatened or endangered species locally (Berger et al. 2005). Small, remnant populations of the Mariana megapode, a pigeon-sized bird of the forest floor, persist on both Tinian and Aguijan.

Current activities to mitigate environmental issues on Tinian (CNMI Department of Commerce 2009):

- Resurfacing of secondary roads to reduce pollution and danger
- Examining alternate energy resources
- Rehabilitating Tinian Harbor, which is in very poor repair
- Upgrading Tinian Airport, including an instrument-landing system and improved fuel storage
- Constructing a wastewater treatment plant (currently septic tanks are used)
- Relocating the sanitary landfill currently located just south of the airport
- Studying impacts of increased military training activities

Projects and proposals for economic improvements and revenue generation on Tinian:

- Creating an interisland super ferry
- Completing Natibu Park
- Building Kastiyu Wildlife Park for ecotourism
- Implementing a Tinian public market
- Creating an aquaculture industry
- Beginning Tangantangan charcoal export
- Building Taga House Museum
- Creating Tinian Botanical Garden

7.2 Survey Effort

Extensive biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and the processes influencing coral reef ecosystems around the island of Tinian and Tatsumi Reef since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around Tinian were delineated in Figure 7.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of Rapid Ecological Assessment (REA) and towed-diver surveys conducted around Tinian. Potential reef habitat around this island is represented by a 100-fm contour shown in white on this map.

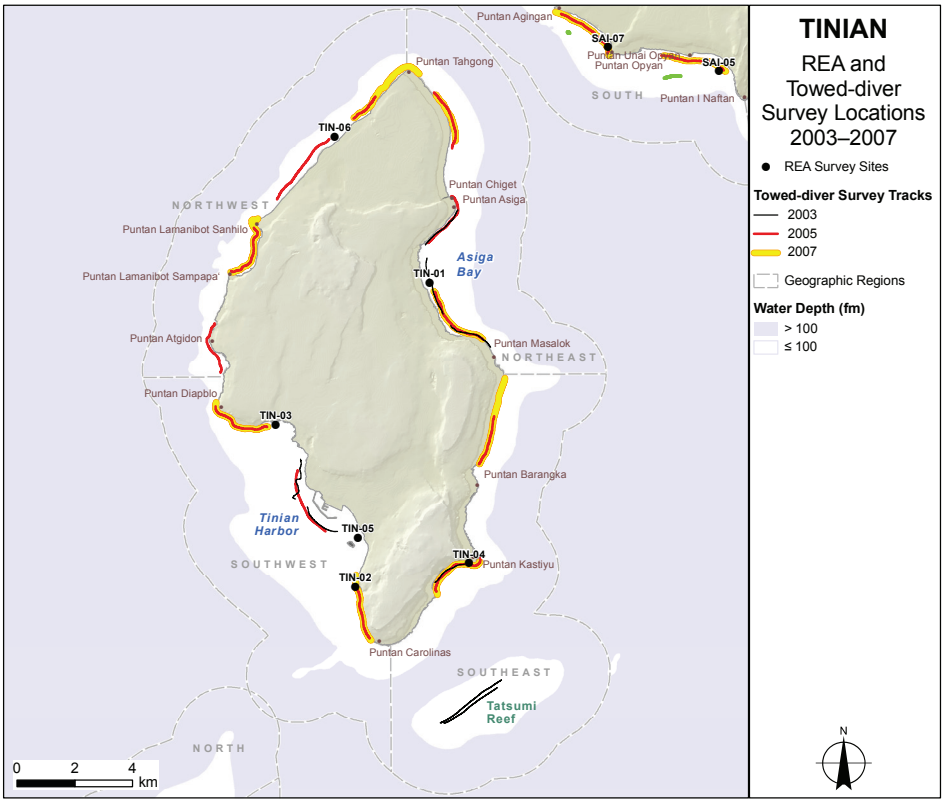


Figure 7.2a. Locations of REA and towed-diver benthic surveys conducted around Tinian Island and Tatsumi Reef during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 4 geographic regions: northeast, southeast, southwest, and northwest

Benthic habitat mapping data were collected around Tinian using a combination of acoustic and optical survey methods. MARAMP benthic habitat surveys conducted with multibeam sonar around Tinian, Tatsumi Reef, Aguijan, Saipan, and Marpi Bank covered a total area of 210 km^2 in 2003 and 1800 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 7.3: Benthic Habitat Mapping and Characterization.

Information on the condition, abundance, diversity, and distribution of biological communities around Tinian was collected using REA and towed-diver surveys. The results of these surveys are reported in Sections 7.5–7.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The number of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 7.2a, along with their mean depths and total areas.

Table 7.2a. Numbers, mean depths (m), and total areas (ha) of REA and towed-diver surveys conducted around Tinian Island and Tatsumi Reef during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates. REA surveys were conducted only around Tinian.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	3	6	5
	Mean Depth (m)	11.2 (SD 0.6)	10.8 (SD 2.3)	11.7 (SD 0.9)
Benthic	Number of Surveys	3	6	5
	Mean Depth (m)	11.2 (SD 0.6)	10.8 (SD 2.3)	11.7 (SD 0.9)
Towed Diver		**2003**	**2005**	**2007**
TINIAN	Number of Surveys	6	12	8
	Total Survey Area (ha)	9.8	25.5	20.2
	Mean Depth (m)	12.9 (SD 2.1)	15.8 (SD 1.2)	14.7 (SD 1.6)
TATSUMI	Number of Surveys	2	–	–
	Total Survey Area (ha)	4.8	–	–
	Mean Depth (m)	16.4 (SD 2.6)	–	–

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Tinian were collected using (1) subsurface temperature recorders (STR) designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007. Results for some casts and water samples are not presented in this report because either the data were redundant or errone-

Table 7.2b. Numbers of oceanographic instruments deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Tinian during MARAMP 2003, 2005, and 2007. One type of instrument, a subsurface temperature recorder (STR), was installed on the seafloor. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Additional deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

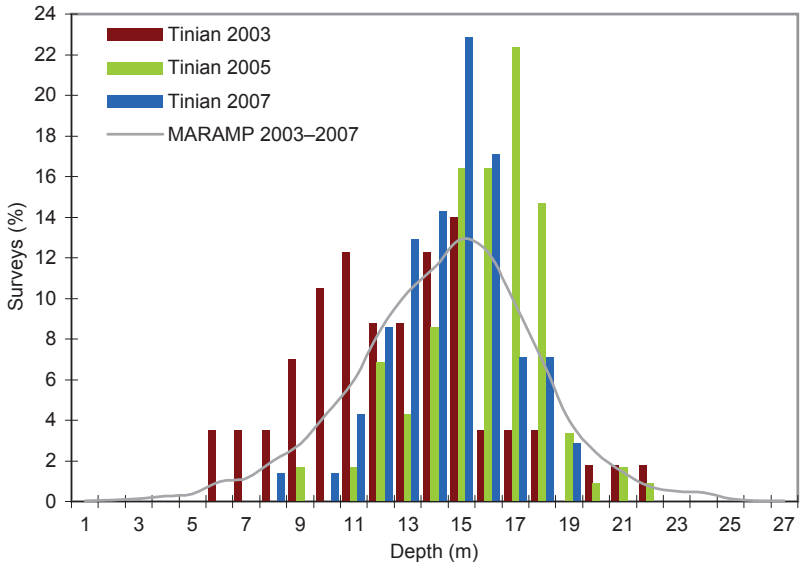
Observation Type	Year						
Instruments	**2003**	**2005**		**2007**		**2009**	**Lost**
	Deployed	**Retrieved**	**Deployed**	**Retrieved**	**Deployed**	**Retrieved**	
STR	–	–	1	1	2	2	–
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	9	31		26			66
Deepwater Casts	–	2		2			4
Water Samples		**2005**		**2007**			**Total**
		6		5			11

ous or no data were produced (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 7.2b, and results are discussed in Section: 7.4: "Oceanography and Water Quality."

Towed-diver Surveys: Depths

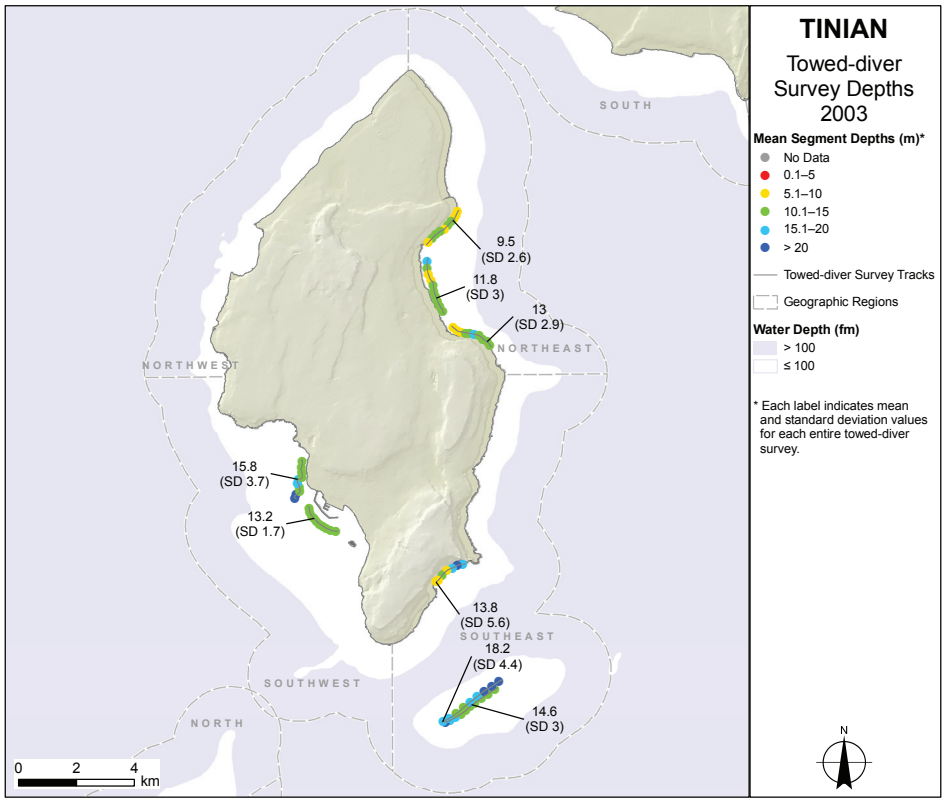
Figures 7.2b–e illustrate the locations and depths of towed-diver-survey tracks around Tinian and Tatsumi Reef and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

Figure 7.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Tinian and Tatsumi Reef during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.



During MARAMP 2003, 6 towed-diver surveys were conducted along parts of the forereef slopes in the northeast and south regions of Tinian; two additional towed-diver surveys were conducted at Tatsumi Reef off the southeast coast of Tinian (Figs. 7.2b and c). The mean depth for all survey segments around Tinian and Tatsumi Reef was 12.8 m (SD 3.7), and the mean depths of individual surveys ranged from 9.5 m (SD 2.6) to 18.2 m (SD 4.4).

Figure 7.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Tinian and Tatsumi Reef during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.



During MARAMP 2005, 12 towed-diver surveys were conducted along the forereef slopes around most of Tinian (Figs. 7.2b and d). The mean depth of all survey segments was 15.9 m (SD 2.7), and the mean depths of individual surveys ranged from 12.7 m (SD 1.5) to 17.1 m (SD 2.1).

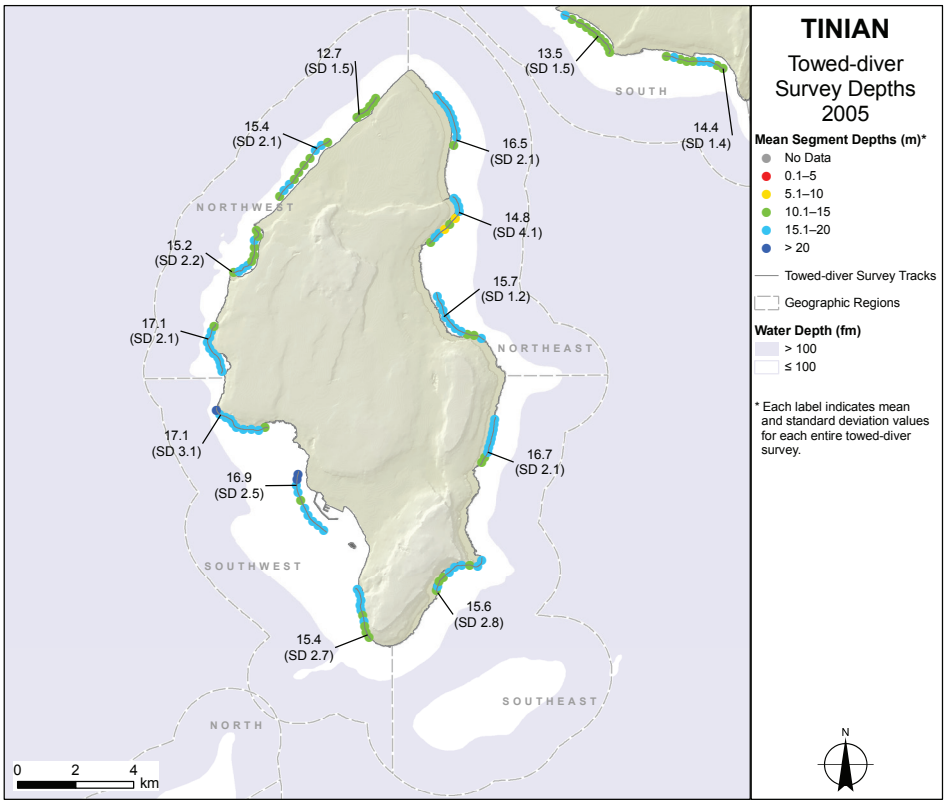


Figure 7.2d. Depths and tracks of towed-diver surveys conducted on forereef habitats around Tinian during MARAMP 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

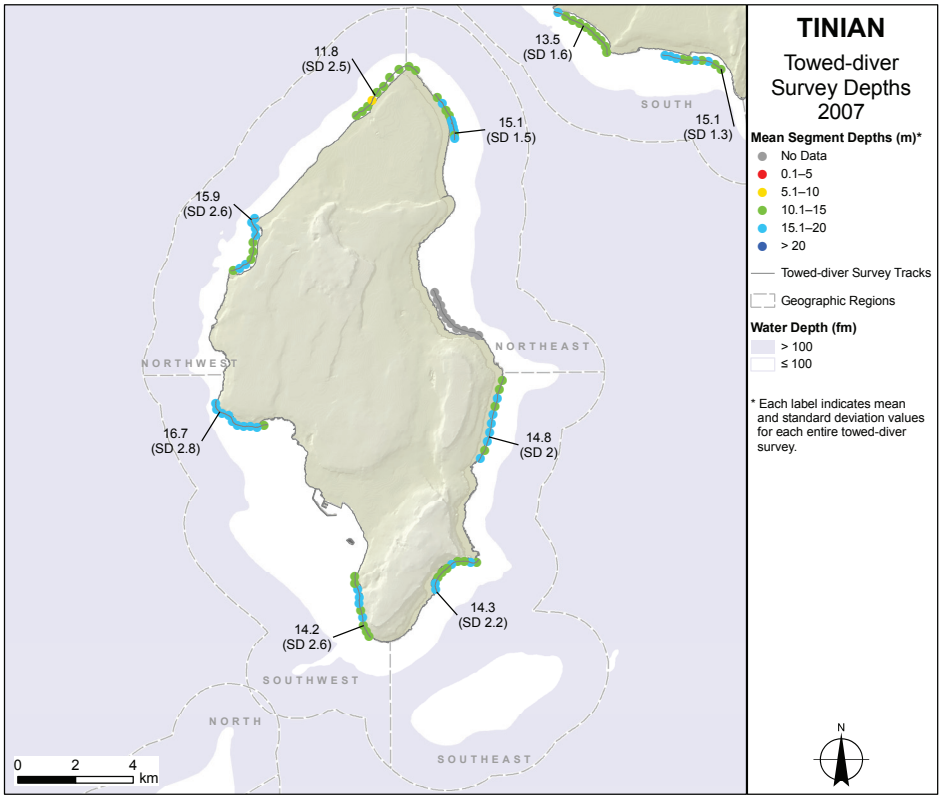


Figure 7.2e. Depths and tracks of towed-diver surveys conducted on forereef habitats around Tinian during MARAMP 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

During MARAMP 2007, 8 towed-diver surveys were conducted along parts of the forereef slopes around Tinian (Figs. 7.2b and e). The mean depth of all survey segments was 14.7 m (SD 2.8), and the mean depths of individual surveys ranged from 11.8 m (SD 2.5) to 16.7 m (SD 2.8).

7.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Tinian and Tatsumi Reef were conducted during MARAMP 2003, 2005, and 2007 using multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 2–1700 m with almost complete coverage around Tinian and Tatsumi Reef. Optical validation and benthic characterization via diver observations and both video and still underwater imagery were performed using towed-diver surveys conducted at depths < 25 m.

7.3.1 Acoustic Mapping

Multibeam bathymetry and backscatter imagery (Fig. 7.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around Tinian, Tatsumi Reef, Saipan, Marpi Bank, and Aguijan during MARAMP 2003 and 2007 encompassed an area of 2013.4 km^2. The primary multibeam bathymetry was collected by CRED using sonars aboard the NOAA R/V *AHI* and the NOAA Ship *Hi`ialakai*. The second data set includes both lidar data and, in waters deeper than ~ 40 m, multibeam bathymetric data collected by the U.S. Naval Ship *Sumner*; all of these data were collected in 2001 by the Naval Oceanographic Office (2004). The lidar data were used in areas where no CRED multibeam data were available, primarily in waters shallower than ~ 20 m. Finally, in shallow areas where neither multibeam nor lidar data were available, "estimated depths" or "derived depths" were calculated from IKONOS imagery data using a modified Lyzenga (1985) method (Hochberg et al. 2007; Hogrefe 2009).

Multibeam bathymetry acquired around Tinian reveals a steeply sloping bank, the flanks of which descend to depths > 200 m within 1–2 km of the shore (Fig. 7.3.1a, top panel). This steep slope runs along the east side of Tinian before extending 1.5 km east of Puntan Masalok to form a submerged peninsula (for place-names and their locations, see Figure 7.2a in Section 7.2: Survey Effort). The bathymetry at the base of this slope shows a number of areas of complex topography offshore from southeast Tinian; this topography is caused by erosion and mass wasting (movement of soil and surface materials by gravity) and coincides with onshore margin failure (Stafford et al. 2005). To the south-southeast of Tinian, a shallow bank known as Tatsumi Reef with a minimum depth of ~ 7 m, is separated from Tinian by a channel nearly 350 m deep. A major feature southwest of Tinian, the anchorage area is composed of a series of 4–6 carbonate platforms forming progressively deeper platforms that extend up to 4 km offshore. The seabed northwest of Tinian, within 1 km of the shore, again slopes steeply to depths of more than 200 m. At the base of this slope, frequently complex topography provides further evidence of mass wasting. An additional feature of note is a series of narrow submerged ridges that extend from the north of Tinian toward Saipan.

Backscatter data reflect signal form and strength and are affected by 3 primary seafloor characteristics—roughness, hardness, and slope. In general, "high" backscatter values usually suggest a hard or rocky seafloor, while "low" backscatter values suggest a soft or sediment-covered seafloor. Backscatter values, however, are also influenced by methodological factors, such as sonar settings and vessel speed. In the case of Tinian, it is important to note that shallow multibeam data collected during MARAMP 2003 were collected at high survey speeds, and this circumstance may also influence results. Thus, it is not possible to directly interpret backscatter into a specific type of seafloor (e.g., hard versus soft); instead backscatter data must be combined with bathymetry derivatives, such as slope or rugosity, to provide an understanding of seafloor characteristics. Nevertheless, backscatter imagery around Tinian does help to elucidate interrelationships between onshore and offshore geology (Fig. 7.3.1a, bottom panel). Maps of groundwater flow patterns and beaches show that carbonate beaches are often located in areas of groundwater discharge. Likewise, considering the offshore backscatter imagery in relationship to these and other factors reveals that areas of low backscatter often associate with the locations of beaches, groundwater discharge, and flow of surface water.

Data acquired around Tinian show high backscatter values in areas where mass wasting has occurred and along the top of many of the ridges around this island. High-intensity backscatter is also observed north of Tinian within the Saipan Channel. High backscatter values around Tinian may suggest hard substrates, but this interpretation must be viewed with caution because of the steep slopes surrounding most of this island.

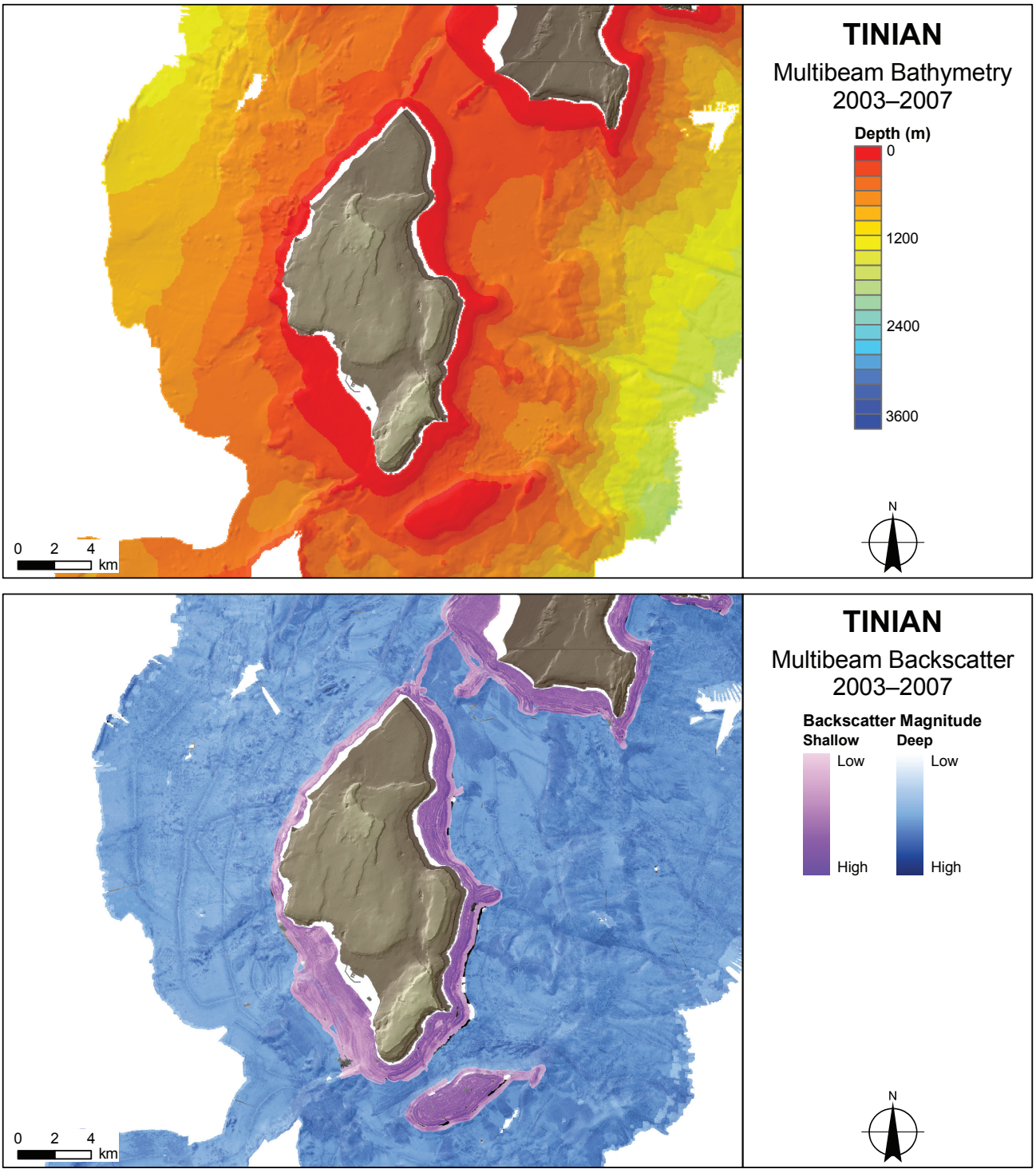


Figure 7.3.1a. Gridded multibeam bathymetry (*top*, grid cell size: 60 m) and backscatter (*bottom*, grid cell size: 5 m) collected around Tinian during MARAMP 2003 and 2007 at depths of 2–1700 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and backscatter data (shown in blue) were collected in deeper depths using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

High-resolution Bathymetry and Derivatives

The final Tinian high-resolution depth map is a mosaic with 3 different depth inputs: multibeam sonar, airborne lidar, and estimated depths derived from IKONOS satellite imagery (Fig. 7.3.1b).

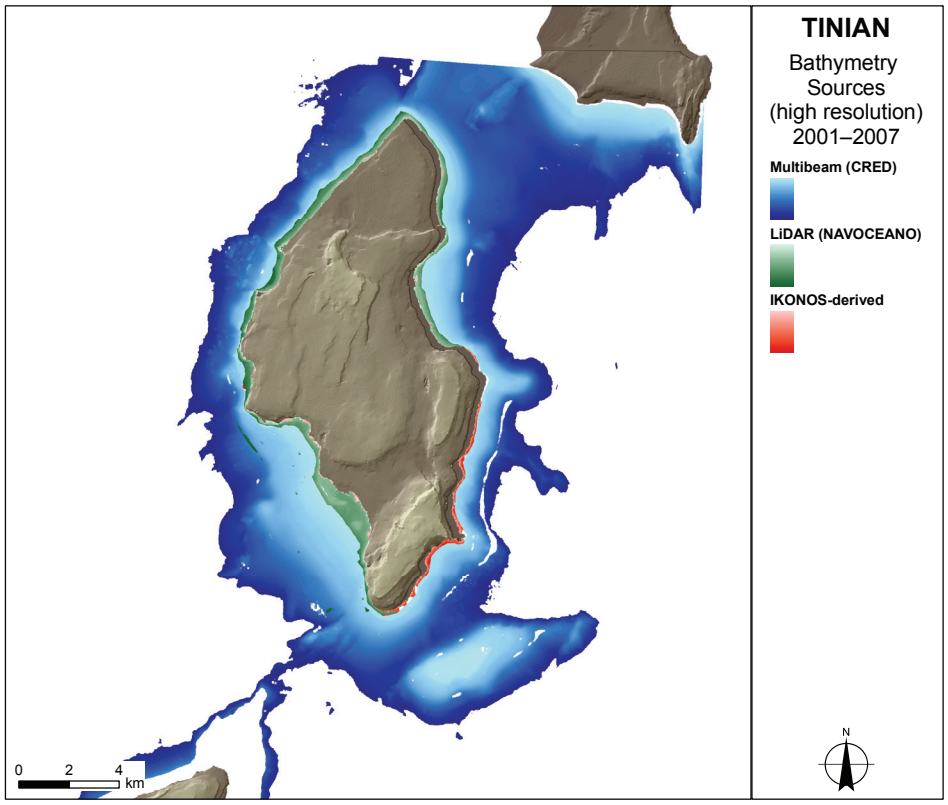


Figure 7.3.1b. Location of multibeam data collected by CRED (shown in blue), lidar and multibeam data obtained by the National Oceanographic Office (NAVOCEANO, shown in green), and depths derived from IKONOS satellite imagery (shown in red).

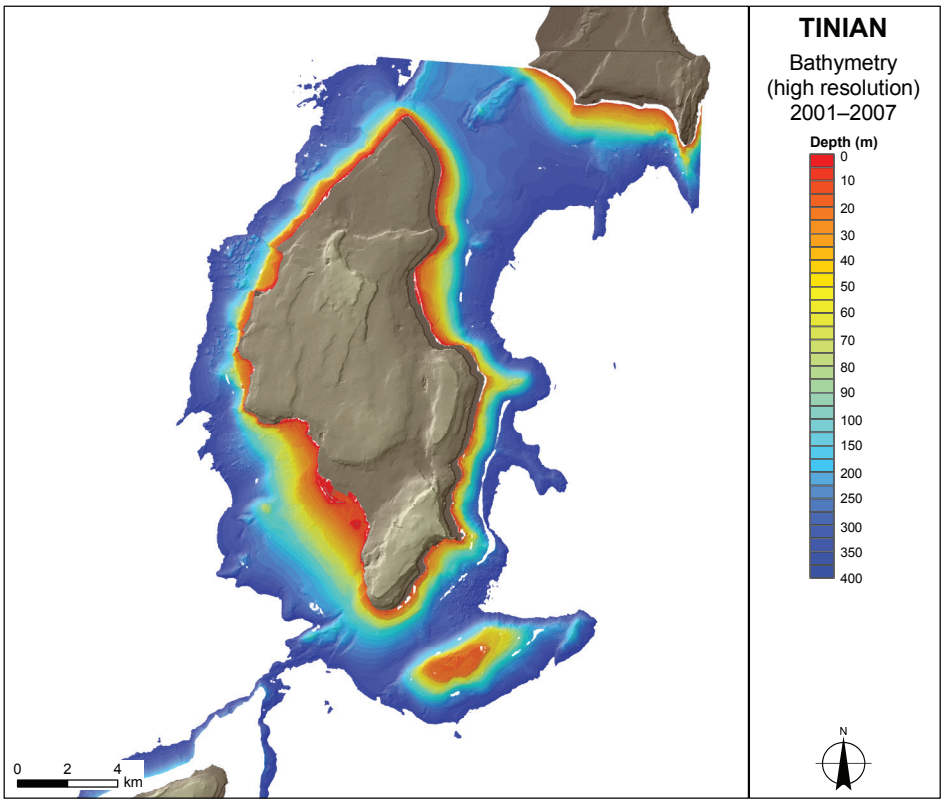


Figure 7.3.1c. High-resolution multibeam bathymetry collected around Tinian during MARAMP 2003 and 2007 combined with NAVOCEANO lidar bathymetry and depths derived from IKONOS satellite imagery. This 5-m bathymetry grid, clipped at 400 m, is used as the basis for slope, rugosity, and BPI derivatives.

Bathymetric data collected in nearshore (depths of 0–400 m) waters around Tinian were combined into a grid at 5-m resolution to allow for the identification of fine-scale features (Fig. 7.3.1c). Because error estimates for the derived depths around Tinian (Hogrefe 2009) are similar in magnitude to the error estimates for both shallow multibeam depths and lidar depths, it is also justifiable to use all 3 of the depth sources (multibeam, lidar, and estimated depths from IKONOS imagery) to derive meaningful slope (Fig. 7.3.1d), rugosity (Fig. 7.3.1e), and bathymetric position index (BPI) zones (Fig. 7.3.1f). Together, these maps provide layers of information to characterize the benthic habitats and describe features of interest around Tinian.

The high-resolution bathymetry further emphasizes the numerous areas of complex topography found around this island, highlighting individual ridges and mounds. In the shallowest areas surveyed, high-resolution bathymetry data also reveal intricate topographic patterns that may represent coral reef formations.

Northeast of Tinian, the slope map (Fig. 7.3.1d) highlights steps in the bathymetry that are not conspicuous in the map of bathymetry (Fig. 7.3.1c) alone and where steep slopes of up to 70° are recorded. Below this steep slope, the seabed continues to deepen but does so more gradually until it reaches a plateau in the Saipan Channel at a depth of ~ 250 m. This plateau is identified as a "flat" zone through the BPI analysis. The highest rugosity values around Tinian are associated with the slopes, suggesting a convoluted and rugged terrain.

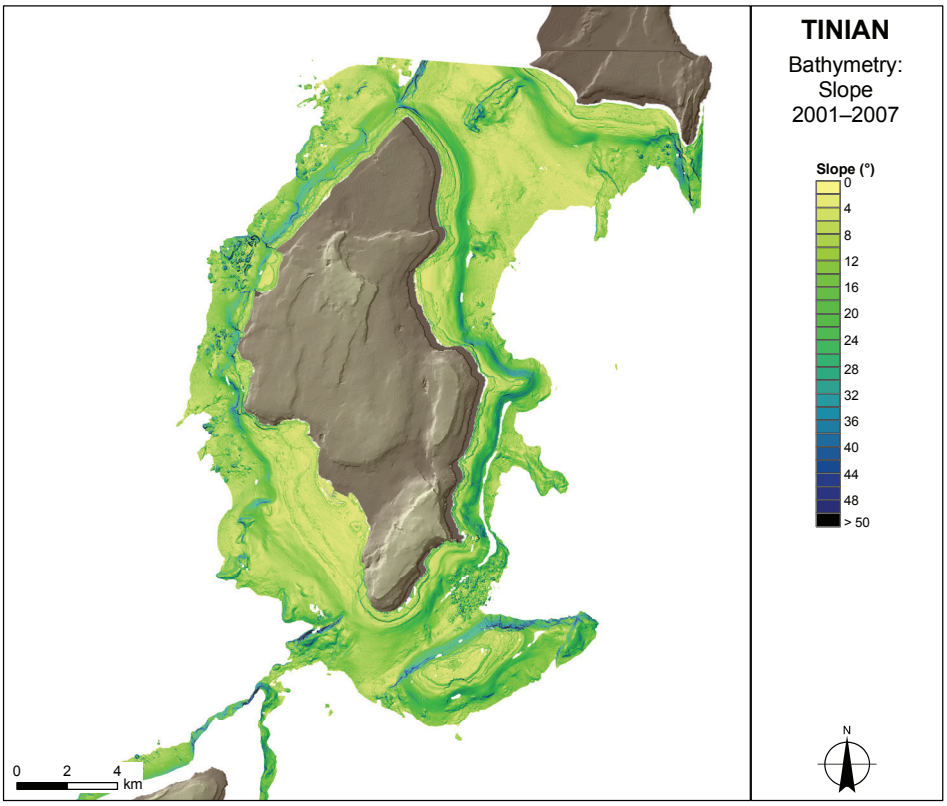


Figure 7.3.1d. Slope (°) of 5-m bathymetric grid around Tinian. Derived from data collected between 2001 and 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in shades of yellow.

East of Puntan Asiga, at depths of 200–300 m, high-resolution bathymetric data and derived slope and rugosity clearly show an area of more complex topography. These slope and rugosity maps (Figs. 7.3.1d and e) show that Asiga Bay has a generally flat bottom with low rugosity, an observation further supported by BPI analysis (Fig. 7.3.1f).

A distinct pattern is shown in the high-resolution bathymetry map (Fig. 7.3.1c) in the shallowest waters, generally < 40 m deep, along the east coast of Tinian: the appearance of linear ridges and mounds that may suggest the presence of spur and groove topography. The slope and rugosity maps also outline these features and help to further elucidate their topography. On the submerged ridge east of Puntan Masalok, this rough topographic character continues to a depth of 80 m (see inset in Figure 7.3.1e), and additional investigation of this area is recommended.

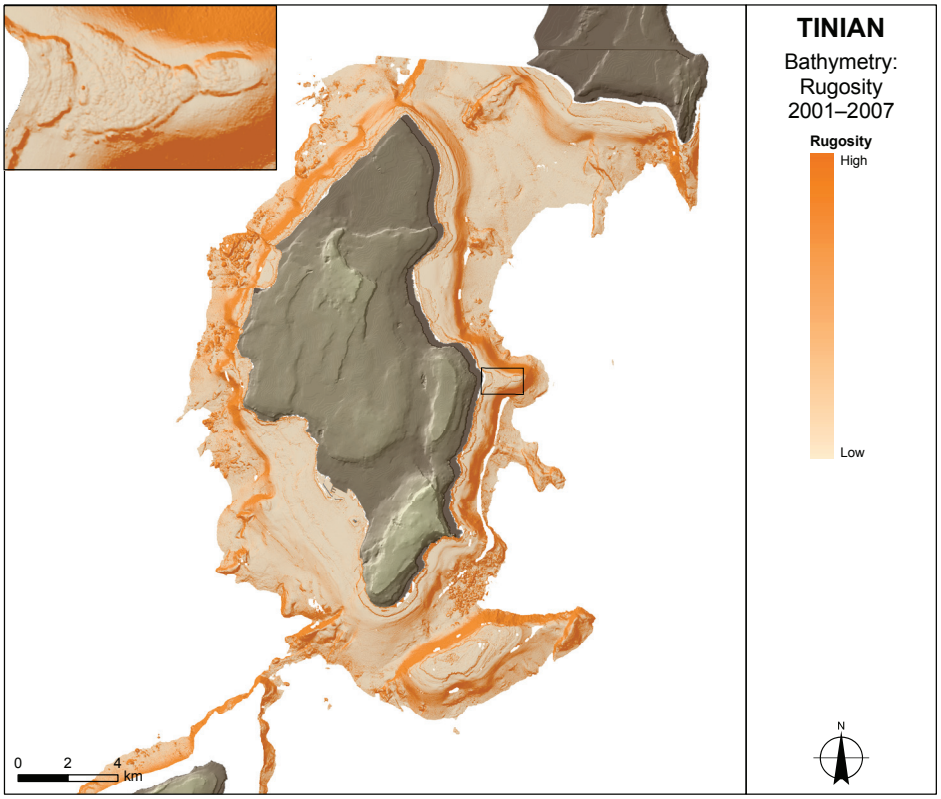


Figure 7.3.1e. Rugosity of 5-m bathymetric grid around Tinian. Derived from data collected between 2001 and 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness. Inset map shows complex bathymetry at depths of 20–80 m in the featured area east of Puntan Masalok.

Southeast of Tinian, the slope map reveals steps in the bathymetry similar to those steps found farther north. Very little flat seabed is found in this area, apart from within the small bay south of Puntan Kastiyu. Again, the steepest slopes are associated with the highest rugosity values. The submerged bank Tatsumi Reef, a major bathymetric feature south-southeast of Tinian, has a similar topography to the seabed around Tinian itself, which is composed of a series of platforms. The top of

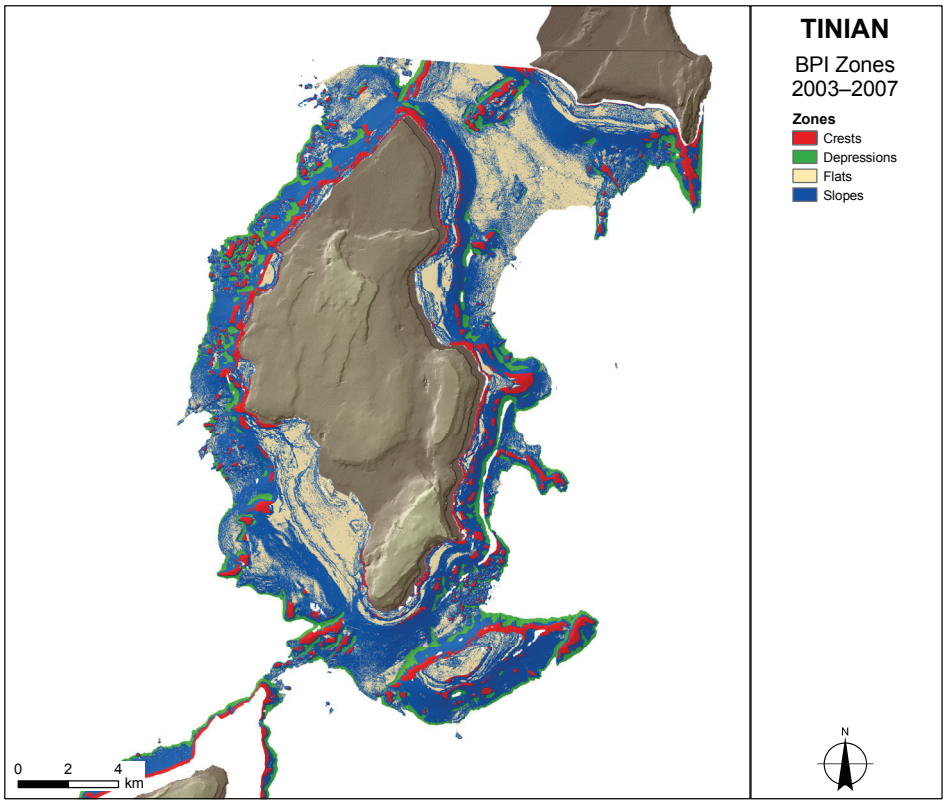


Figure 7.3.1f. BPI zones of 5-m bathymetric grid around Tinian derived from data collected between 2003 and 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

the reef has low slope values and is identified from the BPI analysis as being a flat zone with correspondingly low rugosity values. This reef descends steeply, with slope values up to 60º, into the deep channel that separates it from Tinian.

A major feature off the southwest coast is the anchorage area surrounding Tinian Harbor. Here, the seabed is generally flat with low rugosity values. BPI terrain analysis highlights the slopes that separate the successively deeper shelf flats. Three of these platforms are shown clearly in the slope and rugosity maps (Figs. 7.3.1d and e). Such offshore platforms usually indicate previous sea level stands but could also be expressions of faults like those that are seen onshore in the dynamic tectonics of the Mariana Archipelago. This anchorage is one of the few large areas of flats revealed by the BPI terrain analysis, which otherwise shows a seascape dominated by a complex pattern of crests, depressions, and slopes. Within the very shallow waters of Tinian Harbor, rugosity, slope, and bathymetry data also reveal numerous small mounds.

From Puntan Diapblo to the northern tip of Tinian, the seabed is characterized by very steep slopes of up to 70° running parallel to the shore at a distance of less than 500 m. These slopes are associated with high rugosity values, suggesting a relatively rough and convoluted seafloor. BPI terrain analysis (Fig. 7.3.1f) for this region also shows the topographic complexity of a mixture of crests, depressions, and slopes.

High-resolution Multibeam Backscatter and Derivatives

High-resolution backscatter data were acquired around Tinian using a 240-kHz Reson SeaBat 8101 ER multibeam echosounder and a 30-kHz Kongsberg EM 300 sonar. As discussed in Chapter 2: "Methods and Operational Background," Section 2.2.2: "Acoustic Mapping", because sonars of different frequencies have different backscatter signatures, only data from the SeaBat 8101 ER sonar were used for hard–soft analyses. Also, the backscatter and hard–soft maps in this section use only SeaBat 8101 ER backscatter data because no backscatter was available from either the lidar or IKONOS sensors, although additional bathymetric data were acquired from lidar and IKONOS satellite imagery.

A number of factors aside from substrate characteristics can also affect the measured backscatter intensity, including sonar frequency, settings, and slope (see Chapter 2: "Methods and Operational Background"). In some of the steep nearshore areas, where the depth was close to the maximum range of the 240-kHz sonar (~ 300 m), sonar settings were modified in

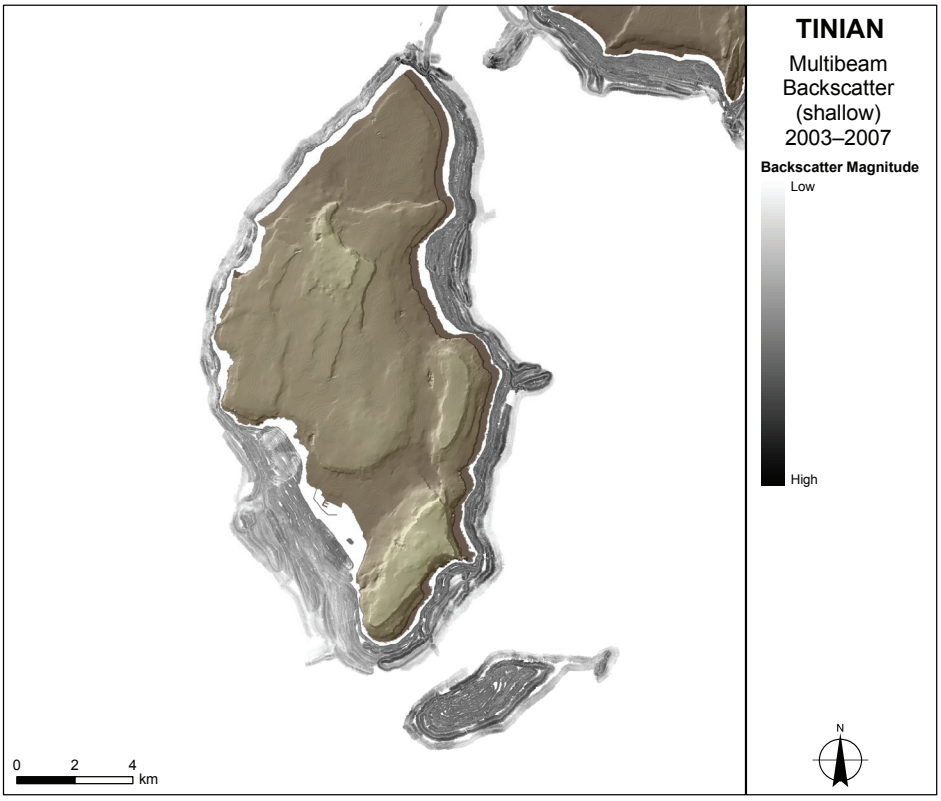


Figure 7.3.1g. Gridded, high-resolution, multibeam backscatter data (grid cell size: 5 m) collected around Tinian during MARAMP 2003 and 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

order to obtain these deep data. These different settings, and the steep slopes themselves, resulted in noticeably different characteristics between the deepest swath collected with the SeaBat 8101 ER sonar and the shallower swaths surveyed with the same sonar (Fig. 7.3.1g). To exclude these artifacts, the backscatter data were clipped to a depth of 150 m prior to deriving the hard–soft substrate map (Fig. 7.3.1h).

The backscatter and hard–soft substrate maps both show a clear pattern of predominantly hard substrate on the east (windward) side of Tinian with soft substrate more common on the west (leeward) side. Tatsumi Reef is almost entirely classified as hard substrate and may be composed of hard carbonate pavement that supports coral reef growth.

A number of interesting exceptions to this general trend are observed. The small bay southwest of Puntan Kastiyu, for example, is both characterized as an area of soft substrate by backscatter data and defined as a flat area by BPI terrain analysis (Fig. 7.3.1f). The anchorage area at Tinian is characterized by a mixture of hard and soft substrate. Two clearly defined patches of soft substrate in the north of this anchorage correspond to areas of low slope and rugosity as shown in Figures 7.3.1d and e. Northwest of Tinian, a narrow band of hard substrate runs close inshore with softer substrate farther offshore. This band coincides with the flat, low-rugosity crests shown in the bathymetry derivatives (Figs. 7.3.1d, e, and f).

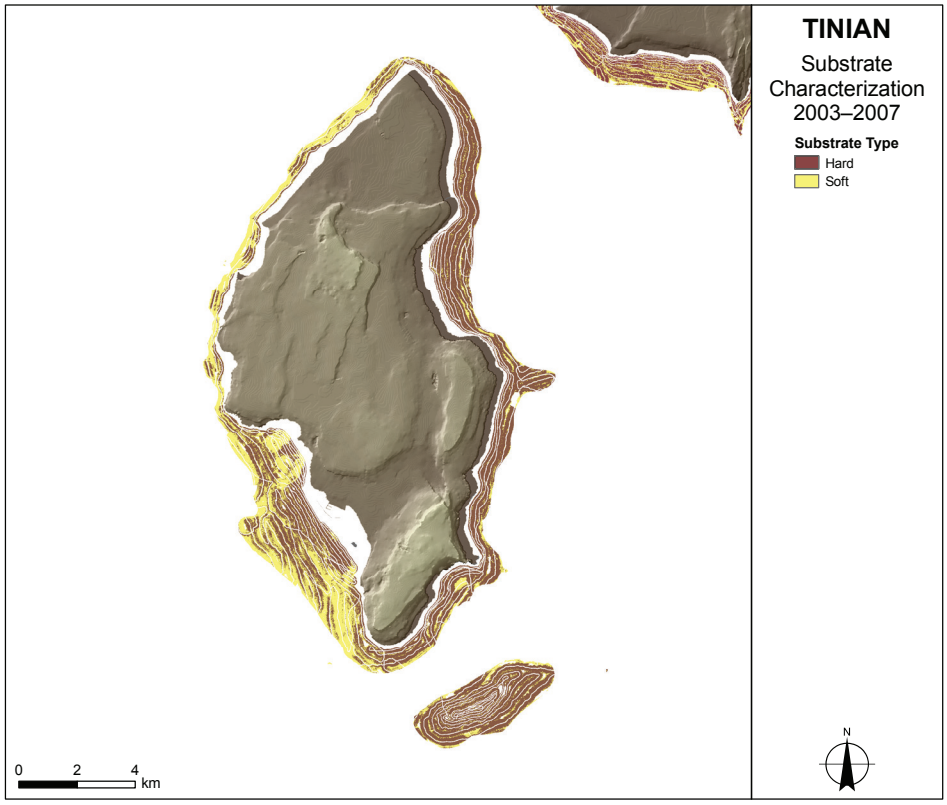


Figure 7.3.1h. Hard and soft substrates (grid cell size: 5 m) at depths < 150 m based upon an unsupervised classification of multibeam bathymetry and backscatter data acquired around Tinian between 2003 and 2007. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

7.3.2 Optical Validation

Covering a distance of 55 km at depths of 6–26 m, 28 towed-diver optical-validation surveys of forereef habitats were conducted around Tinian and Tatsumi Reef during MARAMP 2003, 2005, and 2007 (Fig. 7.3.2a). At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

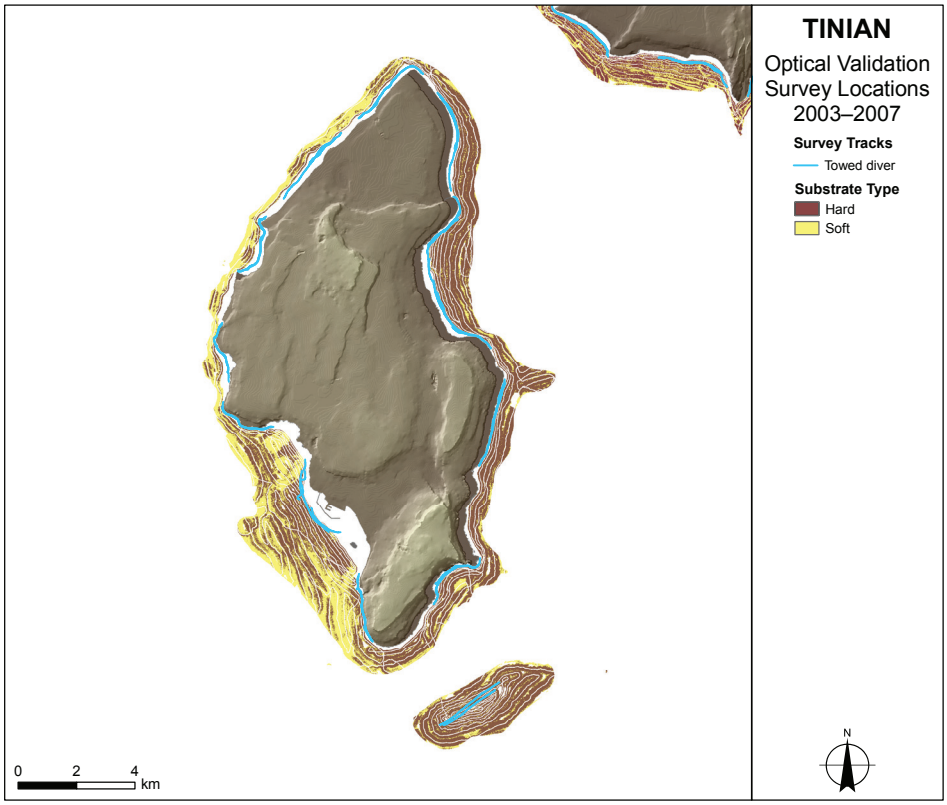


Figure 7.3.2a. Towed-diver tracks from surveys of forereef habitats conducted around Tinian during MARAMP 2003, 2005, and 2007. Survey tracks are displayed over multibeam hard–soft substrate maps. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

7.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Tinian are discussed in this section. These descriptions are organized by the 4 geographic regions around Tinian, beginning with the northeast region and moving clockwise. Towed-

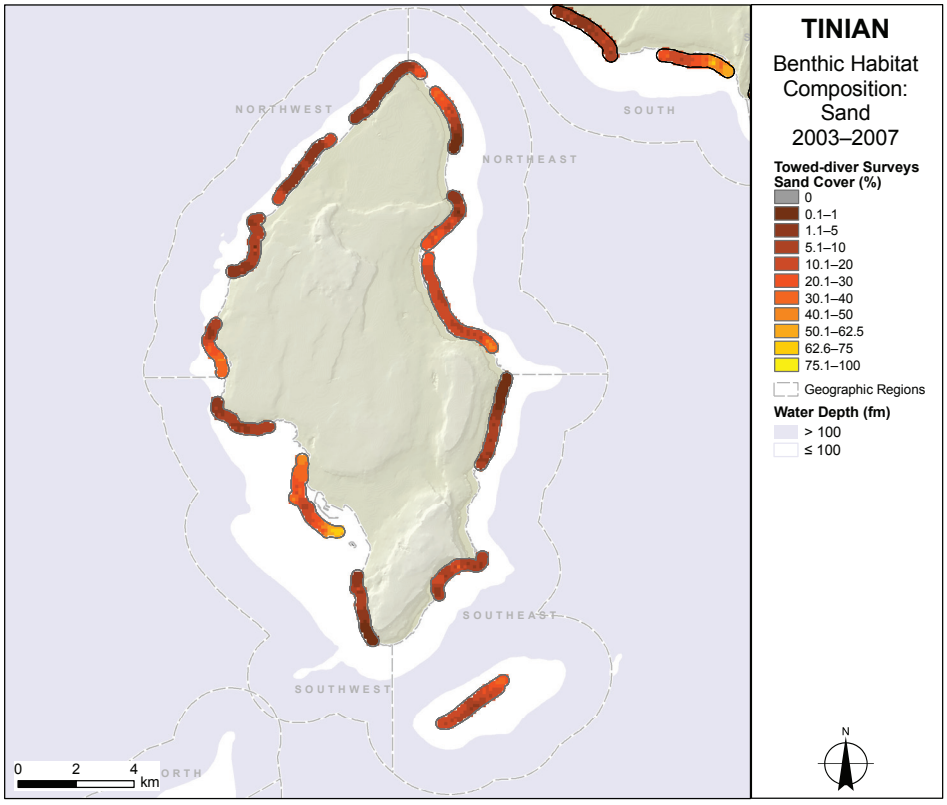


Figure 7.3.3a. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted around Tinian during MARAMP 2003, 2005, and 2007.

diver surveys conducted during MARAMP 2003, 2005, and 2007 recorded moderately low sand cover around Tinian (Fig. 7.3.3a), suggesting that the substrate around this island is predominantly hard. This towed-diver finding corresponds well to the prediction of predominance of hard substrate close inshore by the hard–soft analyses (Fig. 7.3.2a). The distribution of habitat complexity (Fig. 7.3.3b) and live coral cover (Fig. 7.3.3c) around Tinian were both varied and in some areas appeared to associate well with each other. Areas with the highest coral cover also had habitat complexity ranging from medium to high, although some areas where medium habitat complexity was recorded, such as south of Puntan Masalok and east of Puntan Diapblo, did not support high coral cover. Other regional distribution patterns were observed, and they are described in relation to the other benthic substrate categories in more detail in the rest of this section.

Towed-diver observations of sand cover (Fig. 7.3.3a) suggest that habitats northeast of Tinian were characterized by predominantly hard substrate with high sand cover recorded only at a small area close to Puntan Tahgong in the northeast region. North of Puntan Asiga, habitat complexity was low, and live coral cover was correspondingly low at < 5%. However, within Asiga Bay, the hard substrate supported a relatively high cover of live corals, particularly in the north part of the bay where interpolated mean cover was observed at 30%–40%. In Asiga Bay, a similarly high level of habitat complexity was also recorded, reflecting the mixture of spur-and-groove formations, boulder fields, and pinnacles observed by divers in this area.

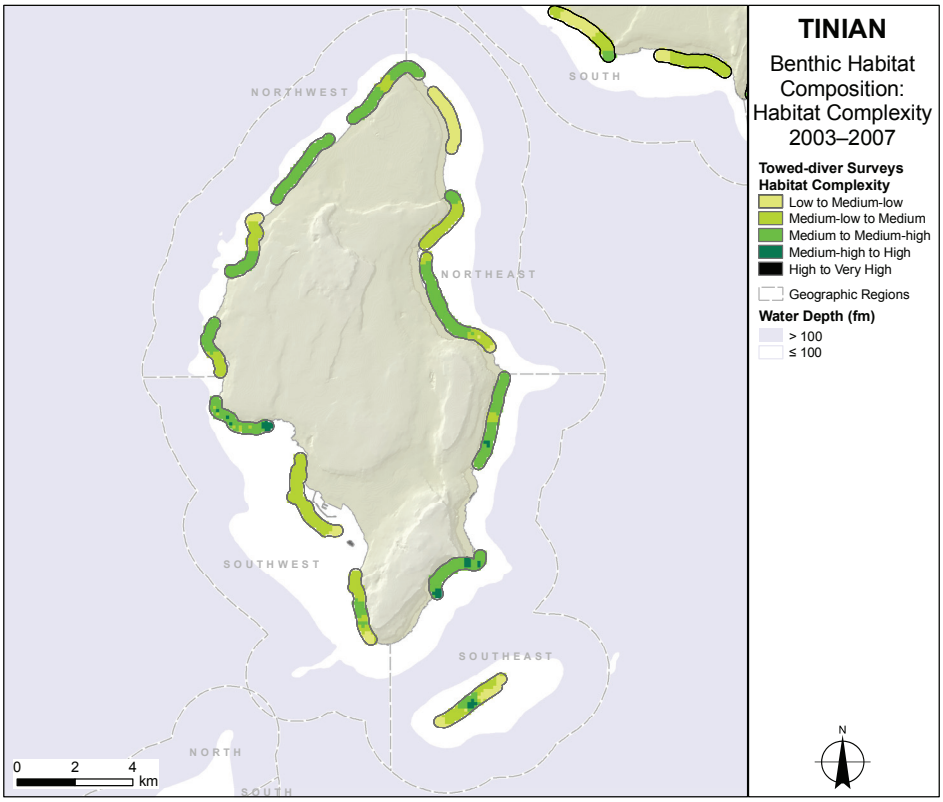


Figure 7.3.3b. Observations of benthic habitat complexity from towed-diver surveys of forereef habitats conducted around Tinian during MARAMP 2003, 2005, and 2007.

In the southeast region, towed-diver surveys conducted south of Puntan Masalok and in the bay south of Puntan Kastiyu revealed differences in these 2 areas. Sand cover south of Puntan Masalok was low, and this hard substrate supported a low cover of live corals. Habitats observed in this area included rubble flats, rocks and crags, and reef slopes. In contrast, habitats south of Puntan Kastiyu included high-relief, spur-and-groove formations, boulders, and rocky crags. Habitats encountered were characterized by low sand cover of 0%–10% and a high live coral cover of up to 40.1%–50%.

Tatsumi Reef showed a gradient of habitat complexity and live coral cover with complexity and coral cover highest at its shallowest point and decreasing with depth. The maximum observed live coral cover of 20.1%–30% was recorded at the center of this reef.

Tinian anchorage in the southwest region was observed to have a relatively low habitat complexity and support low (< 10%) cover of live corals. Areas of high and low sand cover were seen, suggesting a mixed substrate. This area was described by towed divers as consisting of rock flats with rocks and boulders.

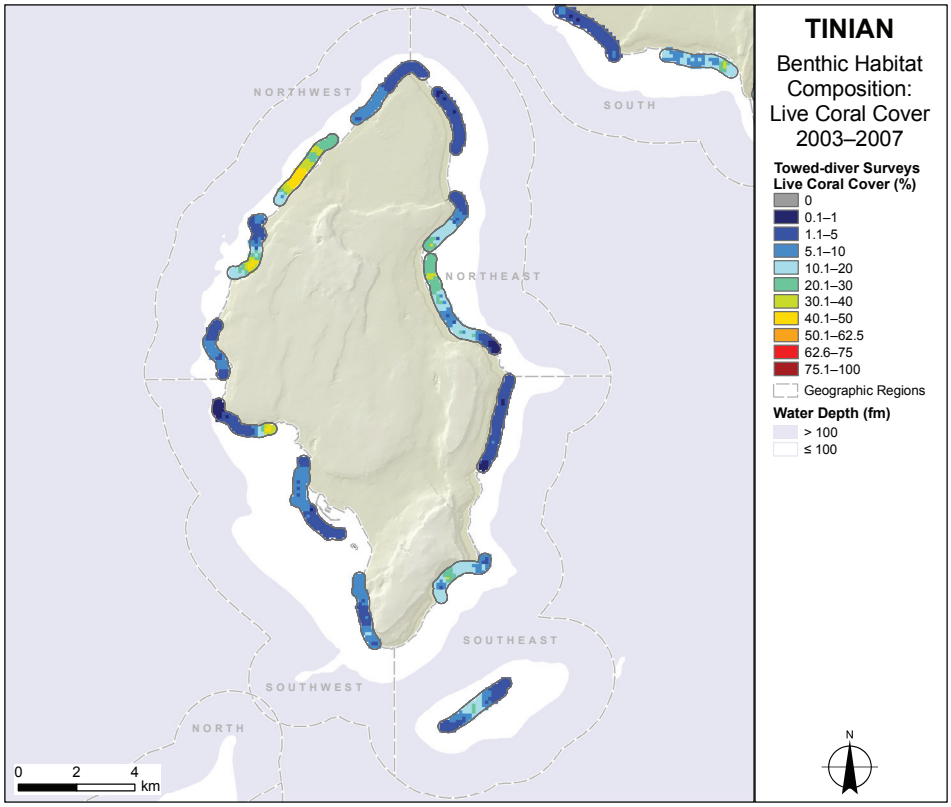


Figure 7.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted around Tinian during MARAMP 2003, 2005, and 2007.

Southeast of Puntan Diapblo in the north of the anchorage, relatively high levels of habitat complexity were observed during towed-diver surveys. Sand cover was low, representing a predominantly hard-bottom substrate that supported high coral cover of 40.1%–50%, relative to other areas surveyed around Tinian. Towed divers encountered a range of habitat types, including reef with sand channels, rubble fields, and rocky walls, crags, and boulders.

In the northwest region, medium to medium-high habitat complexity was observed, and, similarly, high mean coral cover was recorded at several locations. Between Puntans Lamanibot Sampapa` and Lamanibot Sanhilo, high coral cover of 40.1%–50% was found in an area characterized as spur-and-groove habitat of medium complexity. The remainder of this survey was characterized by pavement flats, and low sand cover was recorded there. Northeast of Puntan Lamanibot Sanhilo, along the northwestern coast, high coral cover of 40.1%–50% also was recorded. Although the hard–soft map shows numerous soft substrate patches in this area (Fig. 7.3.2a), towed divers saw very low sand cover. This observation could result from this survey running closer inshore and missing the sand patches; divers were probably towed along the top of the carbonate shelf, the edge of which is shown in the combined bathymetry (Fig. 7.3.1b).

7.4 Oceanography and Water Quality

7.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the island of Tinian over the period of August 22–23. Temperature, salinity, and density values from 8 of these casts varied both spatially and vertically (Figs. 7.4.1a and b). Spatial comparisons of water properties at a depth of 10 m suggest a moderate range in temperature (0.43°C) and a small range in salinity (0.08 psu) values (Fig. 7.4.1a). Cooler temperatures and higher salinities, and associated higher densities were recorded around the northeast end of Tinian (casts 3 and 4) relative to other areas of this island. Vertical comparisons of CTD profiles (Fig. 7.4.1b) reveal a prominent north–south gradient. To the south of Tinian (casts 6–8), water temperatures were warmer and profiles show higher stratification compared to those obtained in the north, where waters were cool and well mixed. This observation is likely because of mixing of deep waters or localized upwelling, which may be caused by vigorous tidal flows around the north tip of this island.

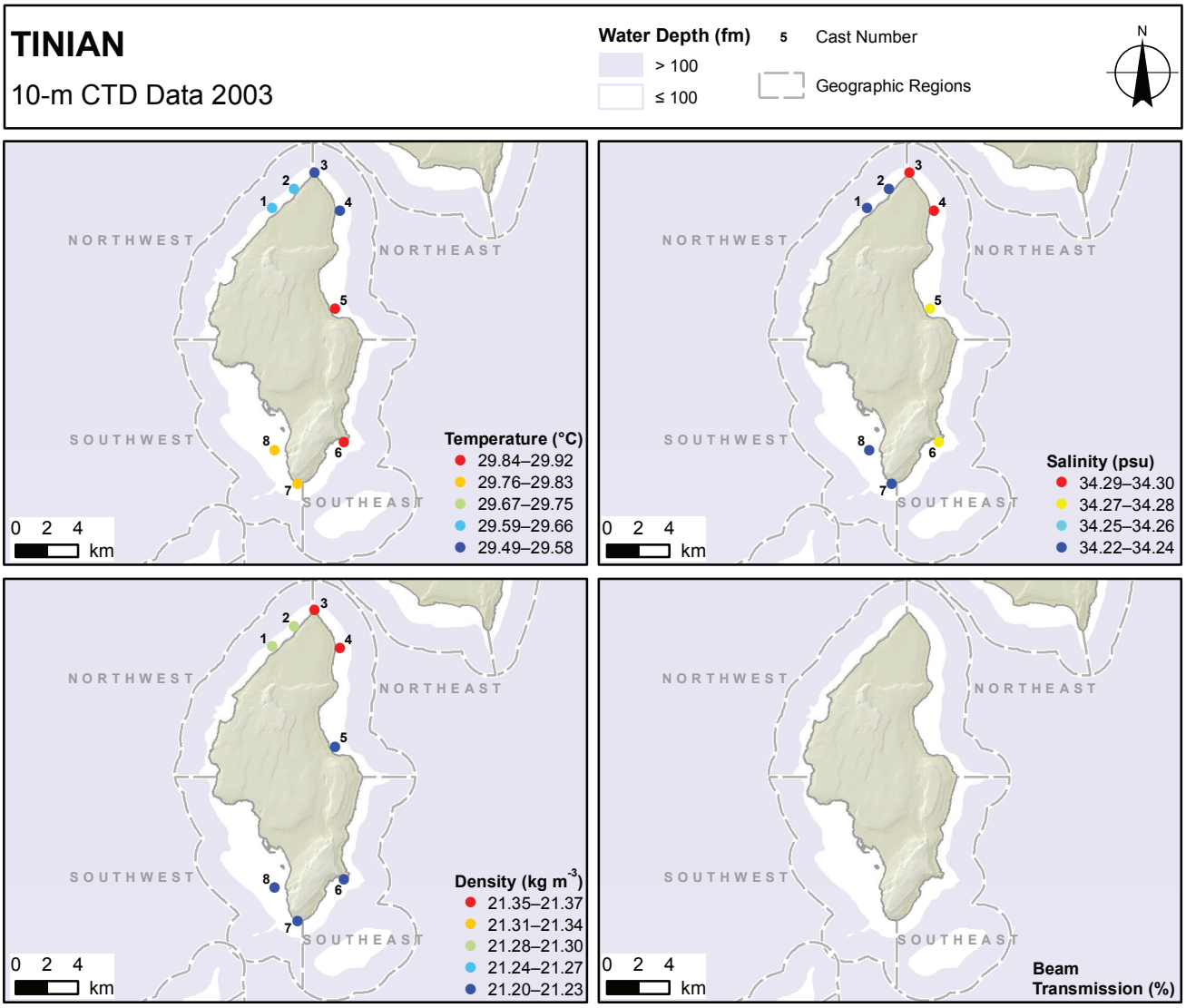
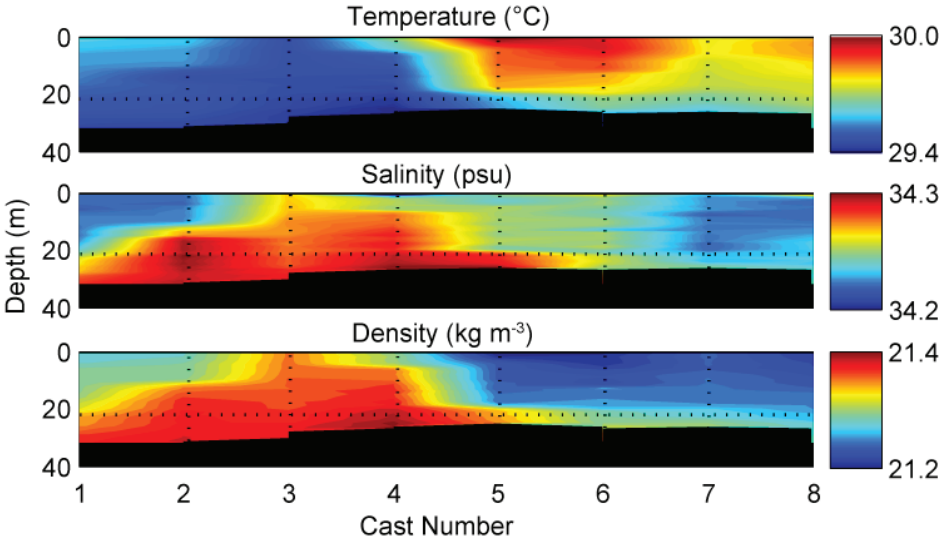


Figure 7.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts around Tinian on August 22–23 during MARAMP 2003.

Figure 7.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Tinian on August 22–23 during MARAMP 2003, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–8 in a clockwise direction around Tinian. For cast locations and numbers around this island in 2003, see Figure 7.4.1a.



2005 Spatial Surveys

During MARAMP 2005, shallow-water CTD casts were conducted in nearshore waters around Tinian over the period of September 25–27. Temperature, salinity, density, and beam transmission values from 28 of these casts varied both spatially and vertically around this island (Figs. 7.4.1c and d). Spatial comparisons of water properties at a depth of 10 m suggest an east–west gradient in water properties, with warmer, more saline, less dense, and less turbid waters along the western half of the island compared to the eastern half (Fig. 7.4.1c). Vertical comparisons of CTD profiles (Fig. 7.4.1d) reveal well-mixed waters with a broad range in water properties with temperature differences as large as 1.6°C at the southeast side close to the channel between Tinian and Tatsumi Reef. The east side of Tinian (casts 10–21) exhibited slightly lower temperatures, slightly higher salinities, and associated higher densities compared to the west side of Tinian (casts 21–28; 1–7). This difference may be caused by greater wind and wave mixing with deep waters compared to the west (leeward) side of this island. Two profiles (casts 19 and 20) on the southeast end of this island suggest enhanced mixing with deep waters or localized upwelling, relative to other areas of this island. Turbidity was low with beam transmission > 93% at all cast locations; all temperature, salinity, and water-clarity data show no obvious signs of terrestrial runoff.

Water samples were collected in concert with shallow-water CTD casts at 6 select locations around Tinian in 2005 to assess water-quality conditions (Fig. 7.4.1e). Three successive samples were obtained at the northern site in the southwest region. The following ranges of measured parameters were recorded around Tinian during MARAMP 2005: chlorophyll-*a*

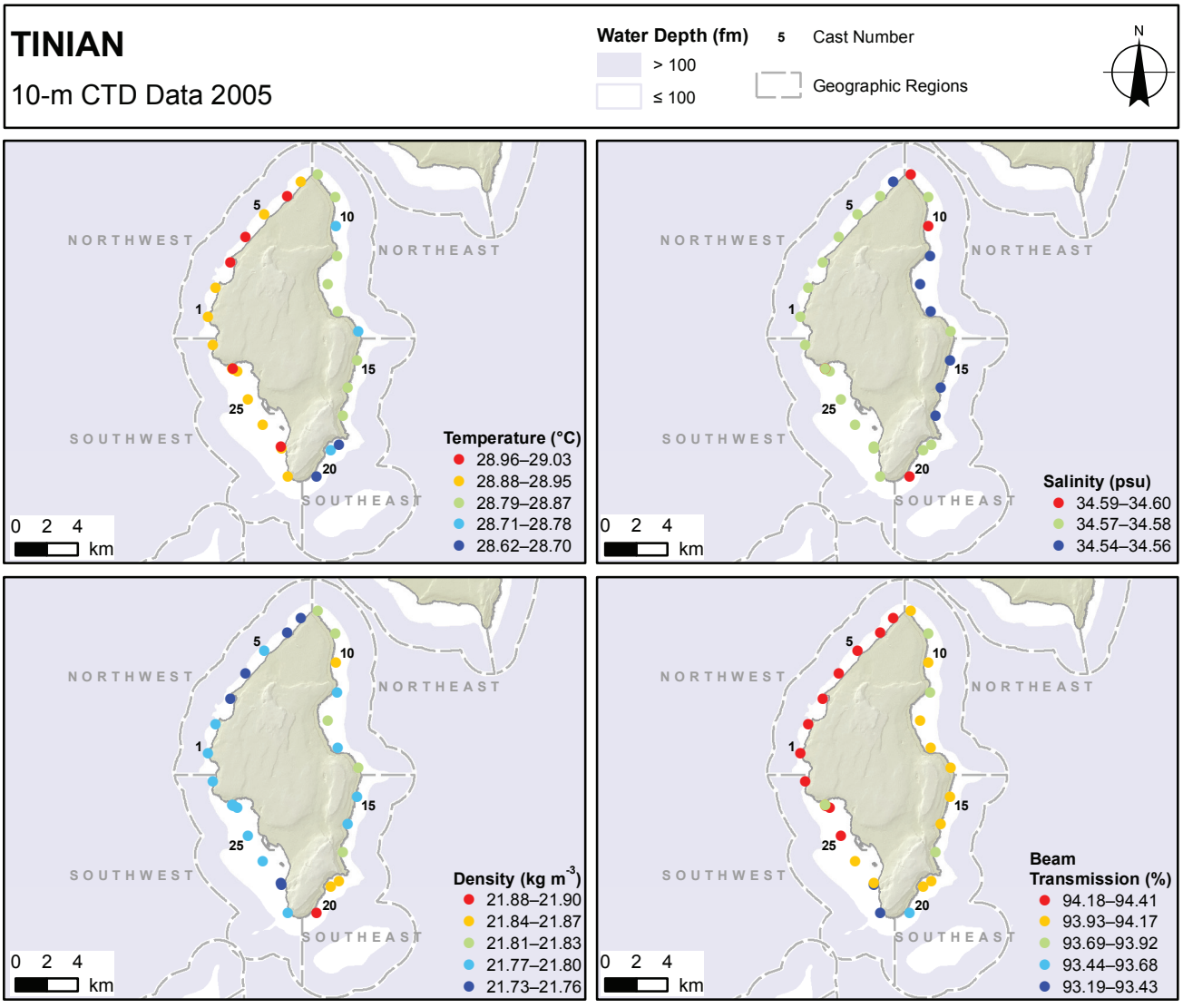


Figure 7.4.1c. Values of (*top left*) water temperature, (*top right)* salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Tinian on September 25–27 during MARAMP 2005.

(Chl-*a*), 0.163–0.387 µg L^{-1}; total nitrogen (TN), 0.213–1.046 µM; nitrate (NO_3^-), 0.198–0.990 µM; nitrite (NO_2^-), 0.015–0.056 µM; phosphate (PO_4^{3-}), 0.011–0.040 µM; and silicate ($Si(OH)_4$), 0.692–0.937 µM. Based on data from the 6 sample locations, all parameters measured showed higher concentrations at the southern sample site in the southwest region; total nitrogen was 4 times higher at this site compared to all other locations from around this island. Chl-*a* and nutrient concentrations were lower in the northwest region compared to other regions. The succession of 3 samples at the northern site in the southwest region exhibited a wide range of values, suggesting a dynamic oceanographic environment.

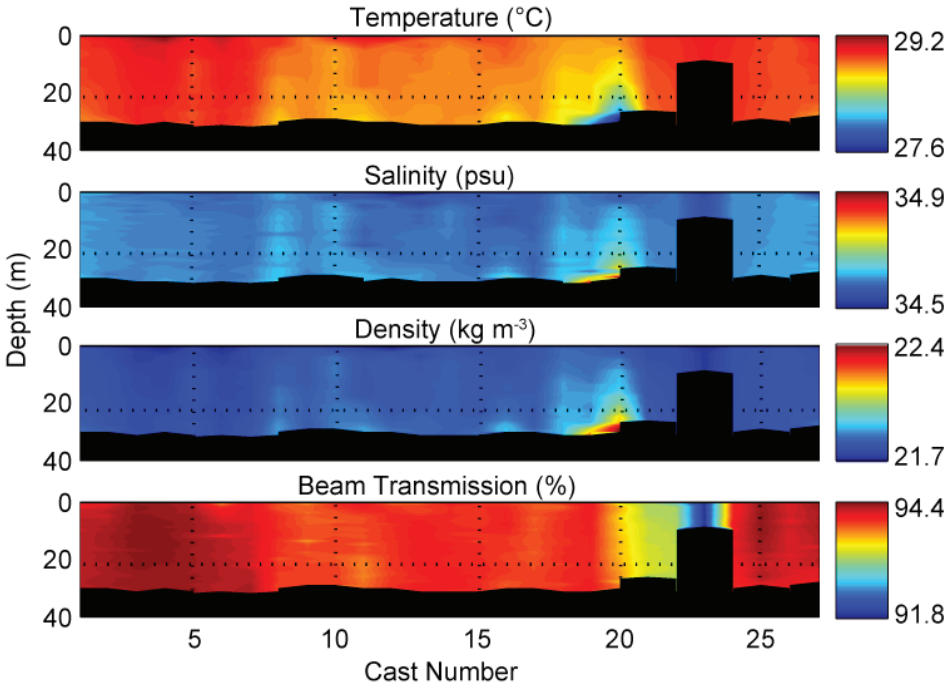


Figure 7.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Tinian on September 25–27 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–27 in a clockwise direction around Tinian. In the southwest region, 2 casts were performed at essentially the same location, but only 1 vertical profile is shown in this graph. For cast locations and numbers around this island in 2005, see Figure 7.4.1c.

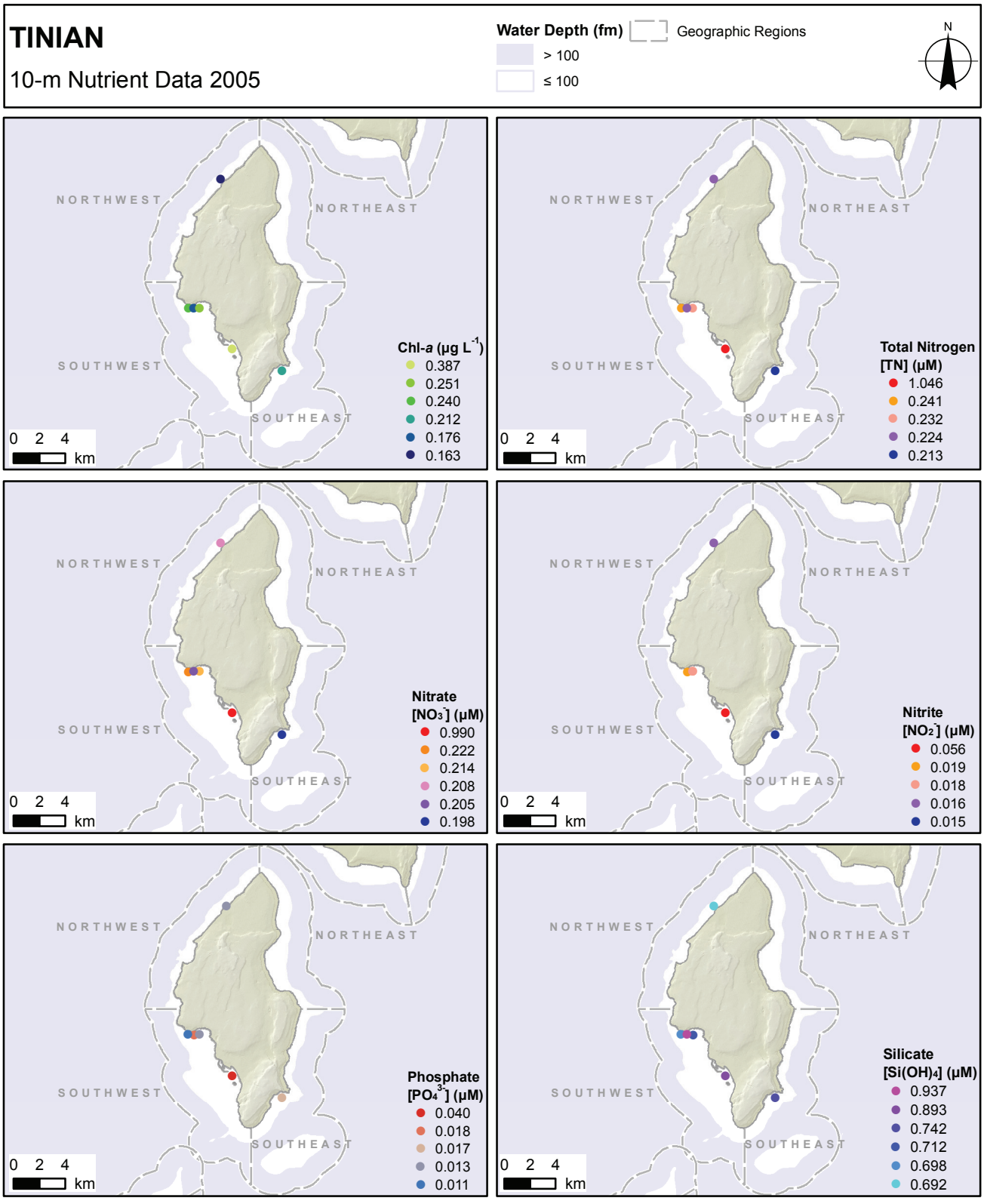


Figure 7.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected around Tinian on September 25–27 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, 26 shallow-water CTD casts were conducted in nearshore waters around Tinian over the period of May 18–19 (Fig. 7.4.1f). Temperature, salinity, density, and beam transmission values varied both spatially and vertically around this island (Figs. 7.4.1f and g). Spatial comparisons of water properties at a depth of 10 m suggest an east–west gradient in oceanographic conditions, with warmer, slightly less saline, less dense waters along the western half of this island compared to the eastern half. Beam transmission values were low at select sites (cast 17 and 21), but were generally homogenous around much of this island (Fig. 7.4.1f). Vertical comparisons of CTD profiles (Fig. 7.4.1g) reveal distinct intraisland variability. Greater cold-water intrusions were found along the east coast of Tinian with generally lower temperatures, higher salinities, and associated higher densities than in other areas around this island. This interpretation may result from greater wind and wave mixing with deep waters compared to the west (leeward) side of this island. Both the northeast (casts 7–10) and southeast (casts 13–17) corners of Tinian, relative to other areas of this island, show signs of greater mixing with deep waters or localized upwelling. These areas were potentially influenced by strong tidal flows across the Marianas Ridge, and between the islands on the ridge. Another area of cooler, more saline water, similar to the areas at the northeast and southeast corners of this island, can be seen near the harbor (cast 25).

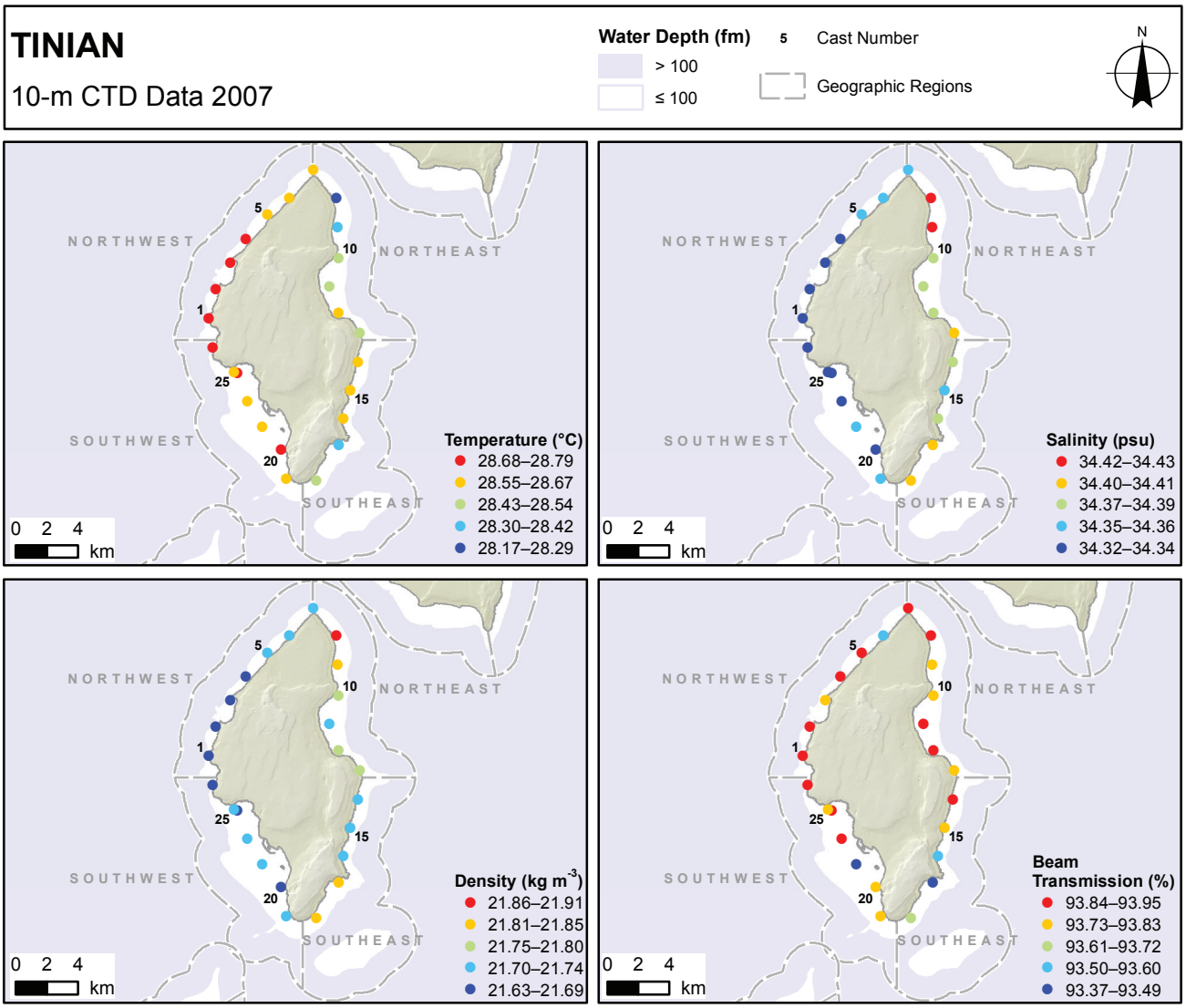


Figure 7.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Tinian on May 18–19 during MARAMP 2007.

Water samples were collected in concert with shallow-water CTD casts at 5 select locations around Tinian in 2007 to assess water-quality conditions (Fig. 7.4.1h). The following ranges of measured parameters of 4 out of 5 water samples were recorded around Tinian during MARAMP 2007: Chl-*a*, 0.059–0.123 µg L^{-1}; total nitrogen (TN), 0.009–0.044 µM; nitrate (NO_3^-), 0.002–0.035 µM; nitrite (NO_2^-), 0.006–0.010 µM; phosphate (PO_4^{3-}), 0.050–0.056 µM; and silicate ($Si(OH)_4$), 0.792–1.198 µM. Based on data from the 4 sample locations, the highest concentrations of nutrients were in found in the northeast and northwest regions, while the highest Chl-*a* values were in the southwest region.

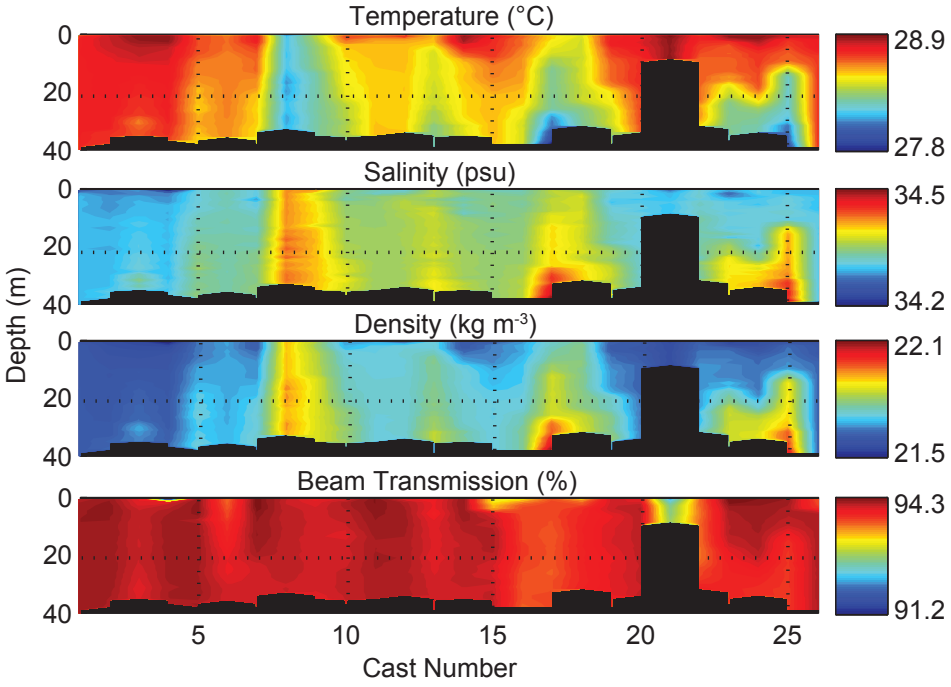


Figure 7.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Tinian on May 18–19 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–26 in a clockwise direction around Tinian. For cast locations and numbers around this island in 2005, see Figure 7.4.1f.

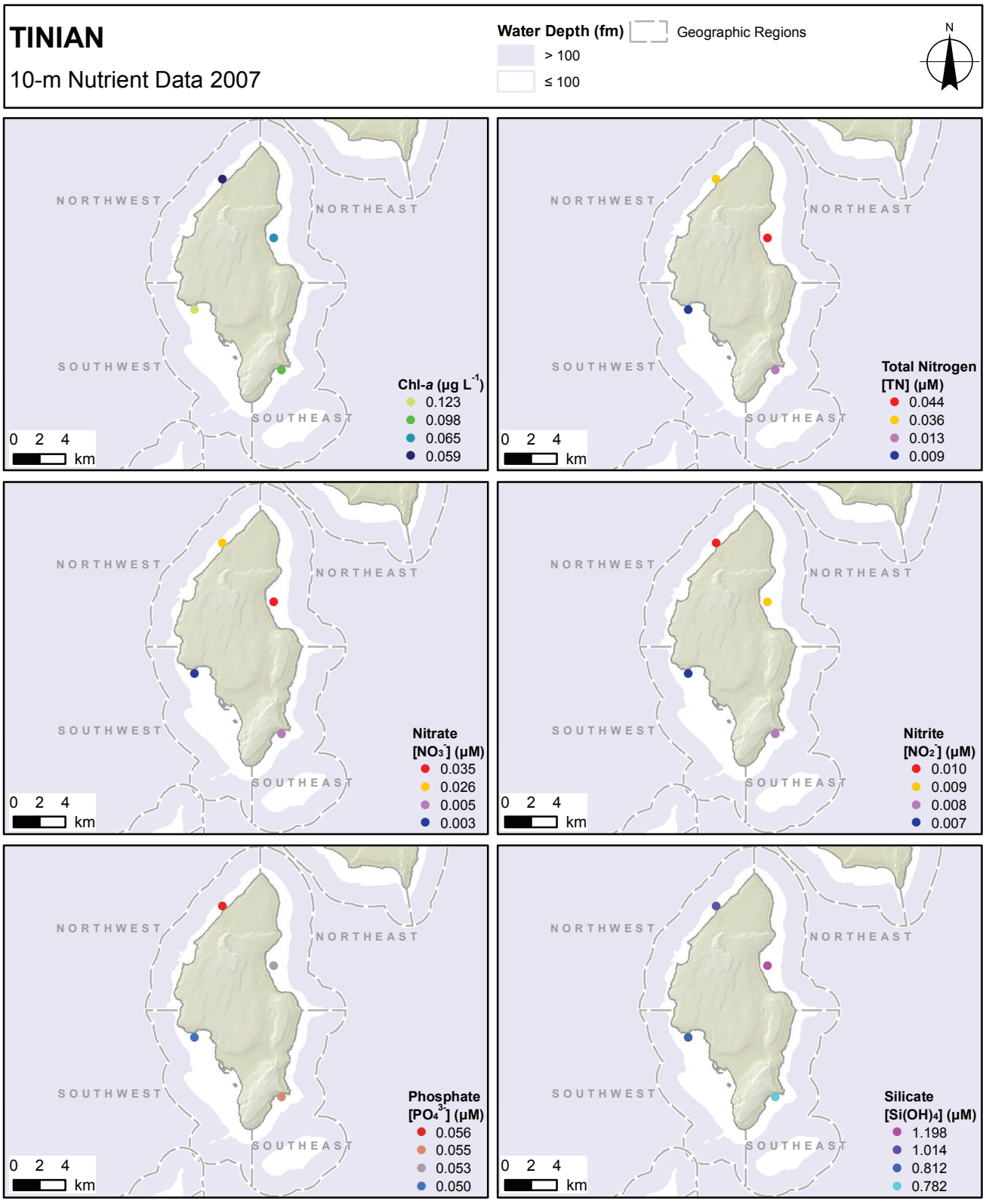


Figure 7.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected around Tinian on May 18–19 during MARAMP 2007.

Temporal Comparison

Results from shallow-water CTD casts taken during MARAMP 2003, 2005, and 2007 suggest a complex oceanographic environment around Tinian. Intersurvey comparisons show a similarity in the 3 MARAMP survey years of high water clarity or low turbidity with > 93% beam transmission for all profiles for the 3 survey years. Maximum water temperature decreased with each subsequent MARAMP survey period, while the greatest range in temperature (1.6°C) values was observed in 2005. Spatial and vertical variability was greatest during the 2007 survey, when pronounced, localized, deepwater mixing tongues were observed. A similar pattern of cooler temperatures and higher salinities on the east side (windward) of Tinian compared to the west (leeward) existed in both 2005 and 2007 surveys. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May, and MARAMP 2003 and 2005 occurred in August and September. This change was made to avoid the typhoon season and reduce the probability of weather disruptions. Wind and waves conditions are generally higher during the wet season (July–December), with stronger trade winds prominent on the east side. This seasonal variation could explain some of the differences seen between survey years, with higher winds and waves causing more mixing during MARAMP 2003 and 2005, and calmer weather potentially allowing for the east-west gradient recorded in 2007. Further investigation will help make these particular results and patterns more apparent.

Water-quality data obtained during MARAMP 2005 and 2007 suggest that chl-*a*, total nitrogen, nitrate, and nitrite concentrations were much lower in 2007 than in 2005, while phosphorus and silicate concentrations were much higher. Differences between the two survey years are likely because of seasonal effects. Precipitation data show that MARAMP 2005 occurred during a period of seasonally high precipitation, while MARAMP 2007 occurred during a period of seasonally low precipitation (Fig. 7.4.2d). The comparatively high nitrogen and chl-*a* concentrations measured in 2005 versus 2007 are likely related to an increase in terrigenous run-off associated with increased precipitation during the sampling period. Future water sampling efforts will help constrain what appears to be a dynamic coastal environment.

7.4.2 Time-series Observations

Between MARAMP 2003 and 2007, subsurface temperature recorders (STRs) were deployed at 2 mooring locations at Tinian to collect time-series observations a key oceanographic parameter. The locations, depths, time frames, and other details about these deployments are provided in Figures 7.4.2a and b.

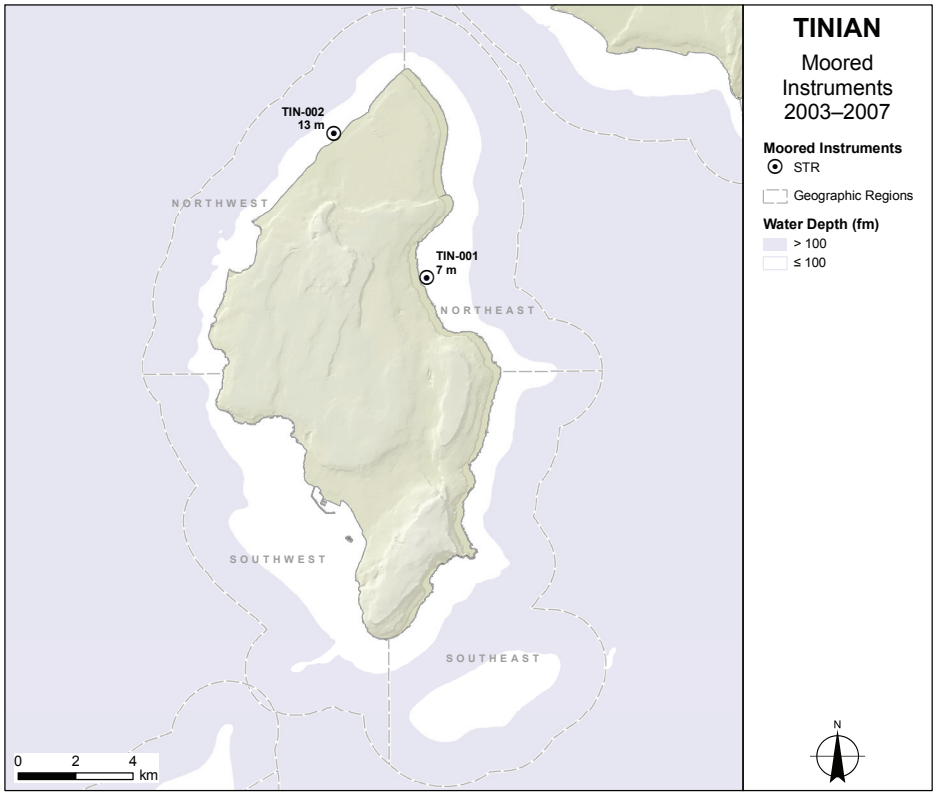


Figure 7.4.2a. Locations and depths of the STRs deployed at Tinian during MARAMP 2003, 2005, and 2007. For information about deployments and retrievals, see Figure 7.4.2b in this section and Table 7.2b in Section 7.2: "Surve Effort."

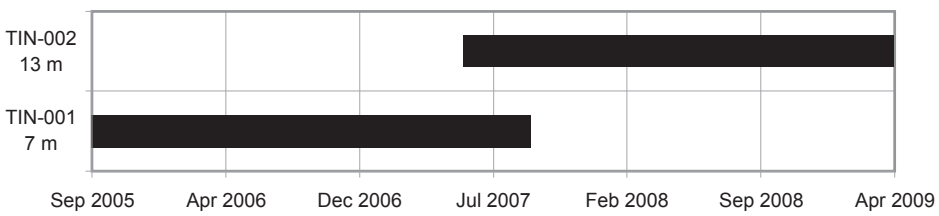


Figure 7.4.2b. Deployment timelines and depths of the STRs installed at Tinian during the period from September 2005 to April 2009. A solid bar indicates the period for which temperature data were collected by a series of STRs that were deployed and retrieved at a mooring site.

An STR mooring site was established in 2005 at Tinian (Fig. 7.4.2a). Data from the STRs deployed at a depth of 7 m at this site in the northeast region show seasonal temperature variability of 3°C–4°C (Fig. 7.4.2c). Water temperatures reached ~ 30.5°C during the months of June–October and fell to a low of ~ 27°C during the months of January–May. Temperatures briefly exceeded the coral bleaching threshold of 30.5°C in September 2006. Diurnal temperature fluctuation was ~ 0.3°C throughout this time series.

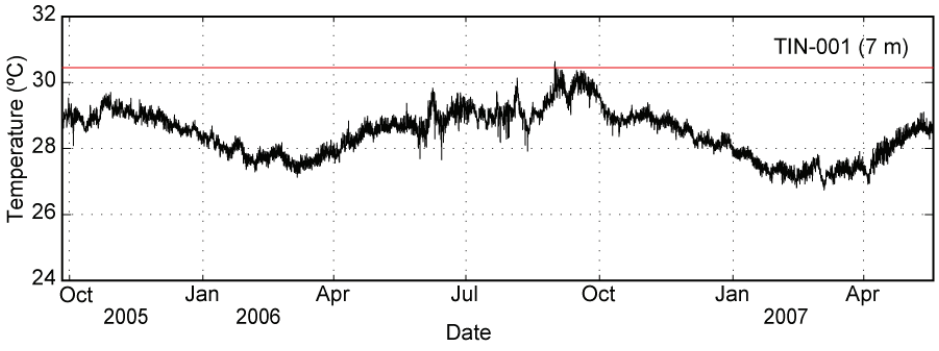


Figure 7.4.2c. Time-series observations of temperature over the period between September 2005 and May 2007 collected from 1 STR mooring site on the east side of Tinian at depth of 7 m. The red line indicates the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean (see Figure 7.4.2a for mooring locations).

Precipitation at Tinian from 2002 to the middle of 2008 was highly seasonal with the greatest rainfall occurring in the months of July–September and the lowest occurring in the months of February–April (Fig. 7.4.2d). MARAMP 2003 and 2005 cruises were conducted in September and October, which are months characterized by seasonally high precipitation. In contrast, MARAMP 2007 was conducted in May when rainfall was seasonally low.

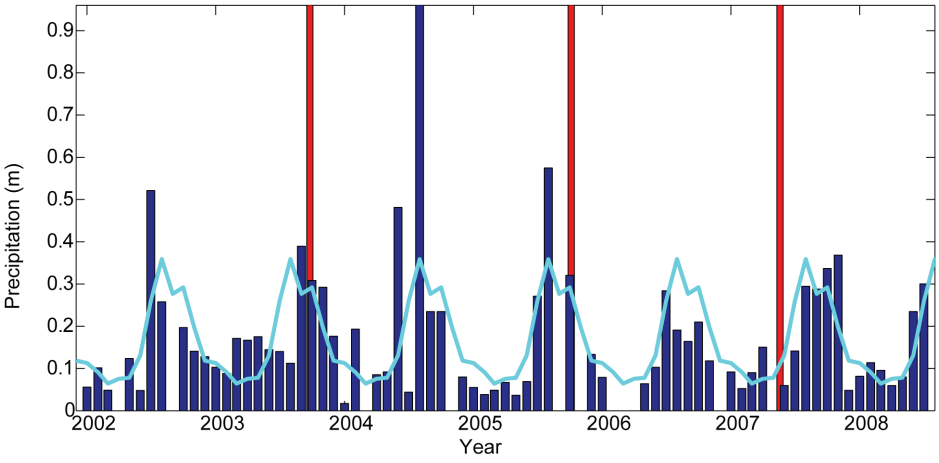


Figure 7.4.2d. Average monthly rainfall (m) from the Tinian Airport from January 2002 to July 2008. They cyan line indicates precipitation climatology (1987–2008) and vertical red bars indicate MARAMP cruise periods. Source: National Weather Service, Honolulu, Hawaii (http://www.prh.noaa.gov/hnl/).

7.4.3 Wave Watch III Climatology

Seasonal wave climatology for Tinian was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008 (Fig. 7.4.3a), and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (~ 75°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the southeast (135°), although they could originate from a broad directional source (90°–200°). These large, episodic waves primarily were generated via typhoons and occurred on annual to interannual time scales. Also, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from the southwest (~ 240°) and were likely associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) also was characterized by frequent (> 30 d per season) and short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 days per season) and long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this time and originated from the southwest (~ 240°).

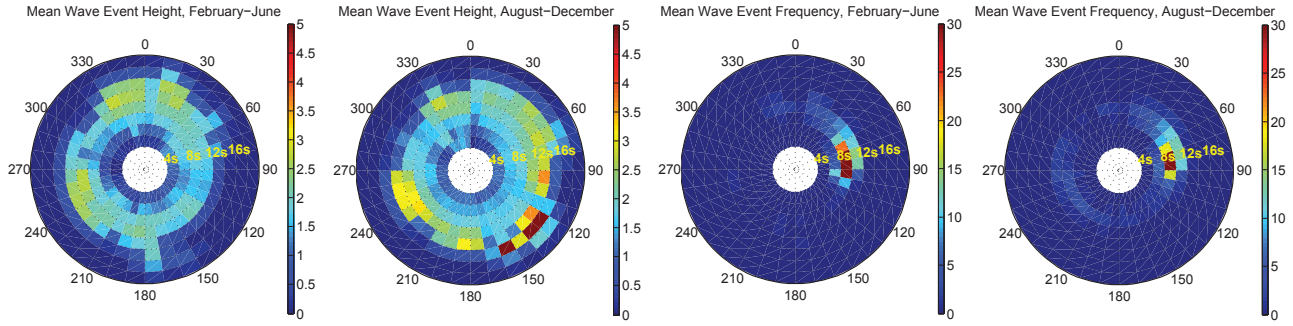


Figure 7.4.3a. NOAA Wave Watch III directional wave climatology for Tinian from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Tinian (15° N, 145°35′ E). Mean significant wave height (*top*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*bottom*) that conditions in each directional and frequency bin occur in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 out of 150 days of that season.

7.5 Coral and Coral Disease

7.5.1 Coral Surveys

Coral Cover and Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats was 13% (SE 1.4) at the island of Tinian and 8% (SE 1.8) at Tatsumi Reef. The spatial coverage of surveys was limited, but, among the areas surveyed, coral cover was lowest within Tinian Harbor, with a mean of 5% for 20 survey segments, and highest within Asiga Bay, with a mean of 28% for 15 segments (Fig. 7.5.1a; for place-names and their locations, see Figure 7.2a in Section 7.2: Survey Effort). The 2 parallel towed-diver surveys conducted at Tatsumi Reef recorded relatively low coral cover (0%–10%) along the ends of this reef with an area of higher coral cover (10%–30%) within 4 segments in the center of this reef.

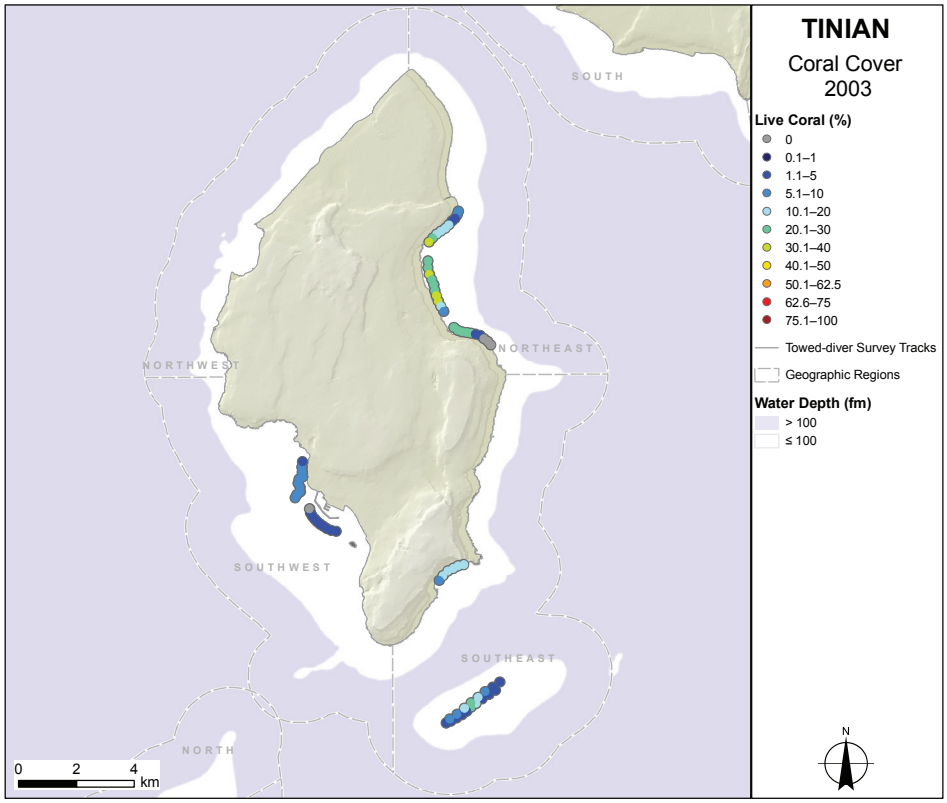


Figure 7.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted at Tinian and Tatsumi Reef during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2).

During MARAMP 2003, the 2 REA benthic surveys using the quadrat method on forereef habitats at Tinian documented 234 coral colonies within a total survey area of 7.5 m^2. Colony density was 25.6 colonies m^{-2} at REA site TIN-02 in the southwest region and 36.8 colonies m^{-2} and TIN-01 in Asiga Bay (Fig. 7.5.1b) with a mean of 31.2 colonies m^{-2} (SE 5.6).

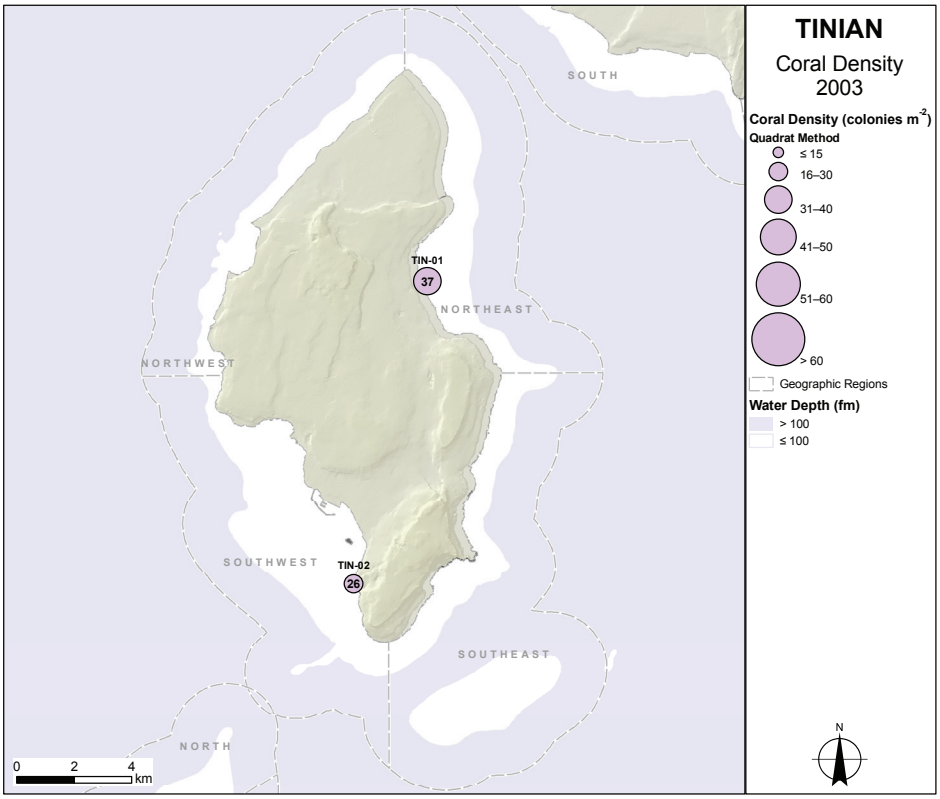


Figure 7.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003. Values are provided within each symbol. The quadrat method was used in 2003 to assess coral-colony density.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Tinian was 9% (SE 1.1). Coral cover was < 10% for the majority (78%) of the 115 segments surveyed around Tinian (Fig. 7.5.1c). A long, continuous stretch of high coral cover, compared to other areas surveyed at Tinian, was observed in the northwest region over 9 segments with a mean of 35%. Localized areas of high coral cover were observed south of Puntan Diapblo for 1 segment with 45%, near Puntan Kastiyu with a mean of 35% for 2 segments, and in the northwest region between Puntans Lamanibot Sanhilo and Lamanibot Sampapa` with a mean of 35% for 4 segments.

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 0.6% (SE 0.1) of coral cover observed on forereef habitats around Tinian appeared stressed in 2005, with very low values of stressed-coral cover recorded in most survey segments (Fig. 7.5.1c). However, levels of stressed-coral cover for 2 segments in the northeast region fell in the range of 5%–10%.

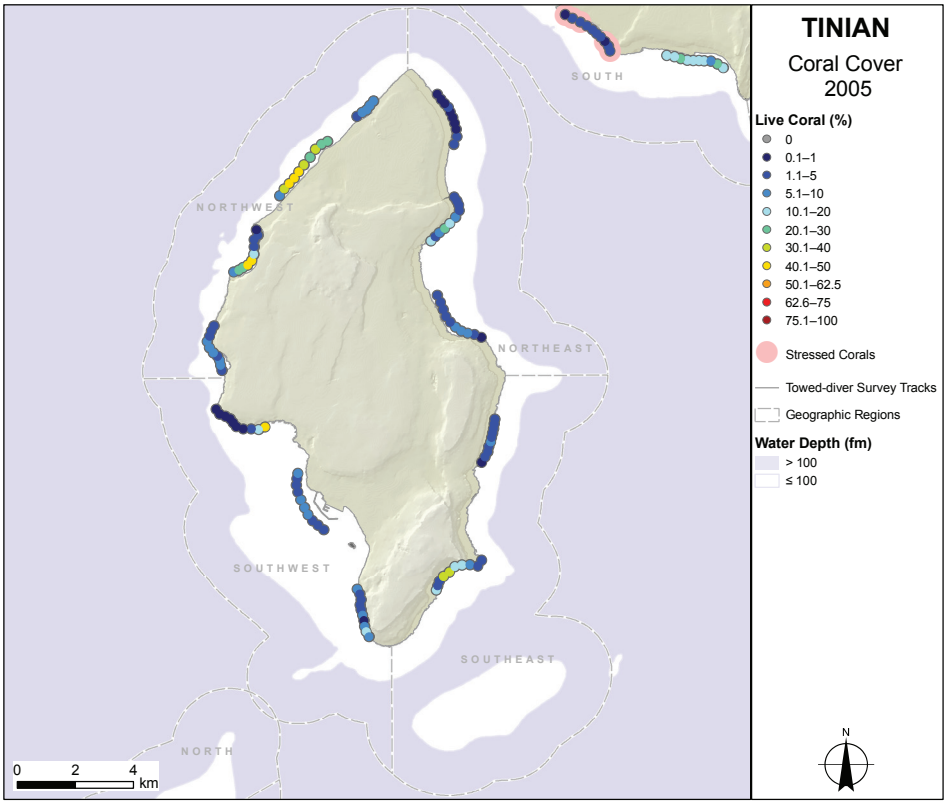


Figure 7.5.1c. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2005. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols are shown only for segments with stressed-coral cover > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005.

During MARAMP 2005, the 5 REA benthic surveys using the quadrat method on forereef habitats at Tinian documented 638 coral colonies within a total survey area of 20 m^2. Site-specific colony density ranged from 28.5 to 38.3 colonies m^{-2} with an overall sample mean of 32 colonies m^{-2} (SE 1.8). The highest colony density was recorded at TIN-02 in the southwest region, and the lowest colony densities were recorded at TIN-03, east of Puntan Diapblo in the southwest region, and at TIN-06 in the northwest region (Fig. 7.5.1d).

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Tinian was 8% (SE 1.1). The spatial coverage for surveys was more limited in 2007 than in 2005, with 4 fewer surveys. No towed-diver surveys were conducted in the area that had the longest stretch of continuous high coral cover in 2005. Coral cover in 2007 was < 10% within the majority (80%) of 80 segments. Similar to results from MARAMP 2005, localized areas of high coral cover were observed within the northwest region between Puntans Lamanibot Sanhilo and Lamanibot Sampapa` over 3 segments with a mean of 38%, south of Puntan Diapblo with 45% for 1 segment, and near Puntan Kastiyu over 5 segments with a mean of 23% (Fig.7.5.1e).

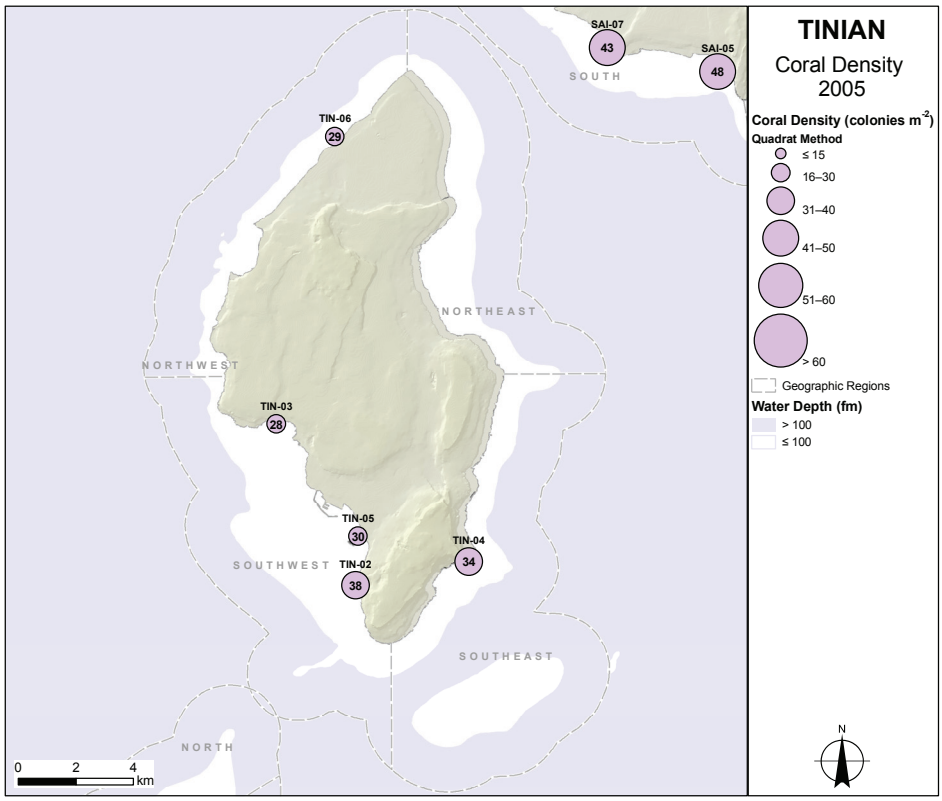


Figure 7.5.1d. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Tinian during MARAMP 2005. Values are provided within each symbol. The quadrat method was used in 2005 to assess coral-colony density.

Overall, 3% (SE 0.6) of coral cover observed on forereef habitats around Tinian appeared stressed in 2007 (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Stressed-coral cover was highest south of Tinian Harbor over 9 segments with a mean of 12% (Fig. 7.5.1e). Stressed-coral cover was also noted in the northwest region between Puntans Lamanibot Sanhilo and Lamanibot Sampapa` with a mean of 5% over 9 segments and in the northeast region with a mean of 6% over 7 segments.

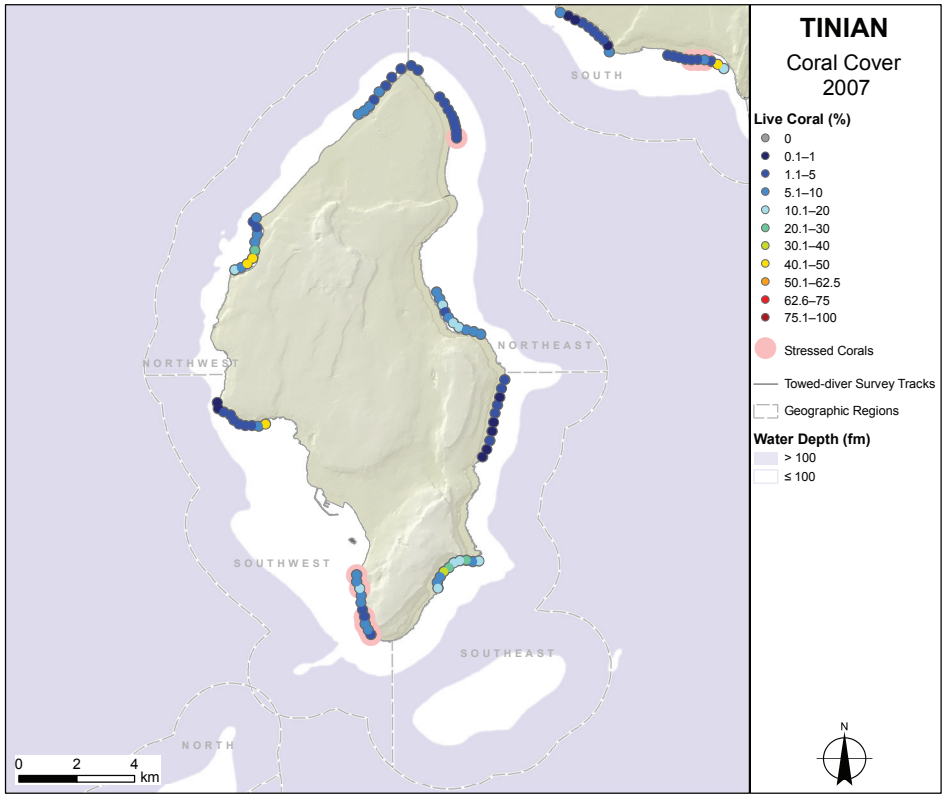


Figure 7.5.1e. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2007.

During MARAMP 2007, 5 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats around Tinian. Site-specific estimates of live-hard-coral cover from these surveys ranged from 5.9% to 31.4% with an overall sample mean of 13.3% (SE 4.7). The highest coral cover was observed at TIN-03 in the southwest region, and the lowest level was found at TIN-04 in the southeast region (Fig. 7.5.1f).

During MARAMP 2007, 5 REA benthic surveys using the belt-transect or quadrat method on forereef habitats around Tinian documented 1464 coral colonies within a total survey area of 204 m^{-2}. For the 4 REA sites surveyed using the belt-transect method, site-specific densities ranged from 4.5 to 9 colonies m^{-2} with an overall sample mean of 6.7 colonies m^{-2} (SE 1); a colony density of 28.8 colonies m^{-2} was recorded near Puntan Kastiyu at TIN-04, which was surveyed with the quadrat method (Fig. 7.5.1f).

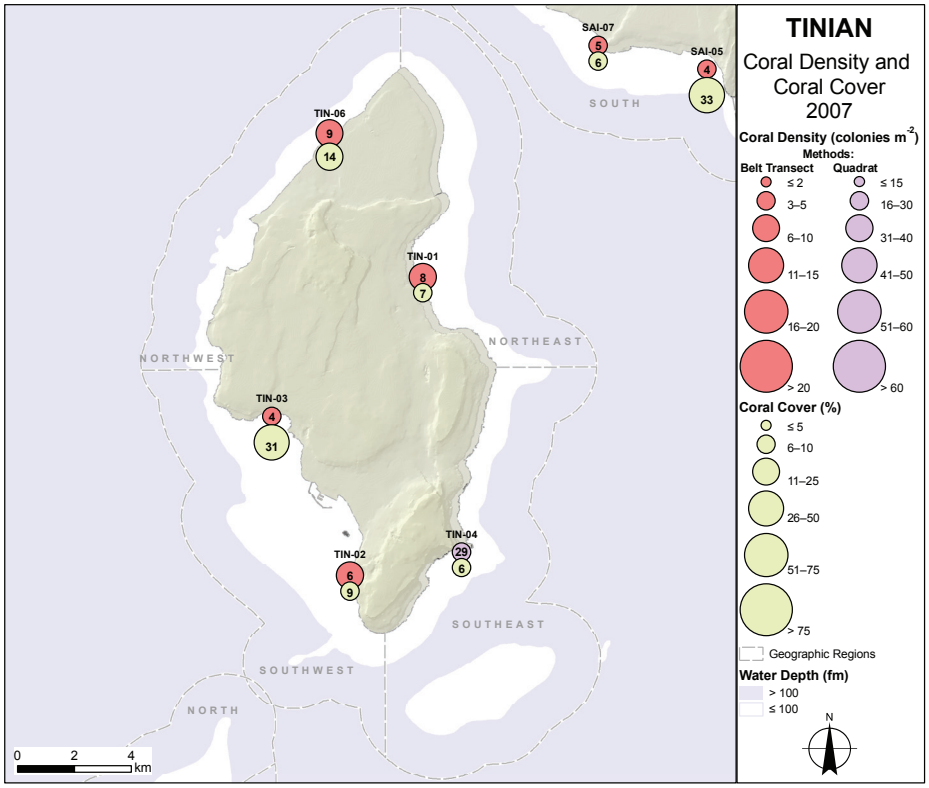


Figure 7.5.1f. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007. Values are provided within each symbol. In 2007, the quadrat method was used only at TIN-04, and the belt-transect method was used to assess coral-colony density at the other 4 of the 5 REA sites surveyed.

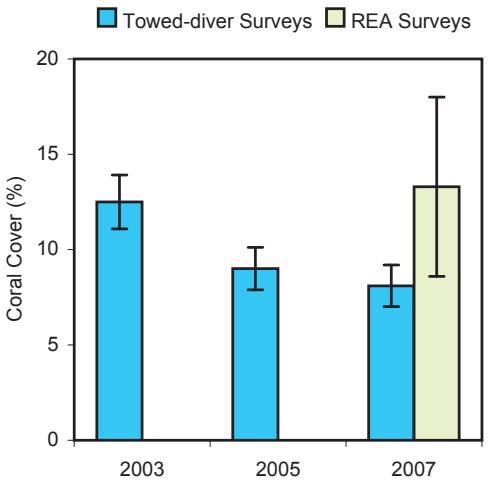


Figure 7.5.1g. Temporal comparison of mean live coral cover (%) from REA and towed-diver benthic surveys conducted on forereef habitats around Tinian during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted around Tinian in 2003 or 2005. Error bars indicate standard error (± 1 SE) of the mean.

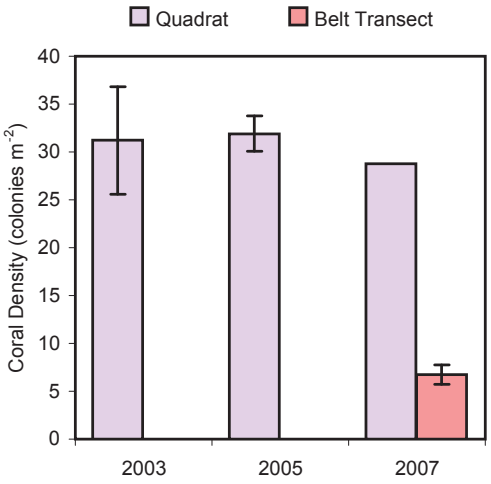


Figure 7.5.1h. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Tinian during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to measure coral-colony density, but in 2007 the belt-transect method was used at 4 of 5 survey sites and the quadrat method at 1 site. Error bars indicate standard error (± 1 SE) of the mean.

Islandwide mean cover of live corals, estimated from towed-diver surveys of forereef habitats, was 13% (SE 1.4) in 2003, 9% (SE 1.1) in 2005, and 8% (SE 1.1) in 2007 (Fig. 7.5.1g). This variation in overall mean values of live coral cover between MARAMP survey years does not necessarily reflect actual changes in overall coral cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Estimates of live coral cover from REA surveys generally exceeded levels recorded in towed-diver surveys; REA surveys target hard-bottom communities, whereas towed-diver surveys include a wider array of substrate types. Site-specific estimates of coral cover averaged 13.3% (SE 4.7) for the 3 REA sites surveyed in 2007 (Tinian was not surveyed for coral cover using the line-point-intercept method in 2003 or 2005).

Overall mean coral-colony density from REA surveys conducted on forereef habitats at Tinian were similar during MARAMP 2003 and 2005, when the quadrat method was used, with 31.2 colonies m^{-2} (SE 5.6) and 31.9 colonies m^{-2} (SE 1.8, Fig. 7.5.1h). Site-specific coral-colony densities appeared substantially lower in 2007, as did the overall mean density with 6.7 colonies m^{-2} (SE 1), excluding TIN-04 in the southeast region. However, this apparent decline is likely an artifact of the use of a different method to assess colony density during MARAMP 2007. The placement of quadrats used in 2003 and 2005 was highly biased towards surveying hard-bottom substrate where coral was present, whereas the belt-transect method used at 4 of the 5 sites in 2007 sampled benthos that fell within the transect belt regardless of the nature of the substrate. TIN-04, the fifth REA site surveyed in 2007, was assessed with the quadrat method. At this site near Puntan Kastiyu, observed colony density was 28.8 colonies m^{-2}, nearly 4 times greater than the density recorded at other sites surveyed with the belt-transect method. This considerable difference strengthens the supposition that the quadrat method yielded higher density values than the belt-transect method.

Coral Generic Richness and Relative Abundance

Two REA benthic surveys of forereef habitats were conducted using the quadrat method at Tinian during MARAMP 2003. At least 21 coral genera were observed at Tinian. Generic richness was 15 at TIN-02 in the southwest region and 20 at TIN-01 in Asiga Bay in the northeast region with a mean of 17.5 (SE 2.5) coral genera per site (Fig. 7.5.1i).

Leptastrea, *Favia*, and *Astreopora* were the most numerically abundant genera, contributing 18.5%, 14.6%, and 13.3% of the total number of colonies enumerated at Tinian during MARAMP 2003. All other genera individually accounted for < 10% of the total number of observed colonies. *Leptastrea* dominated the coral fauna at TIN-02, accounting for 31.3% of the total number of colonies, while *Favia* dominated at TIN-01, accounting for 16.7% of the total number of colonies. *Porites*, in addition to *Leptastrea*, *Favia*, and *Astreopora*, accounted for more than 10% of the total number of colonies at TIN-02.

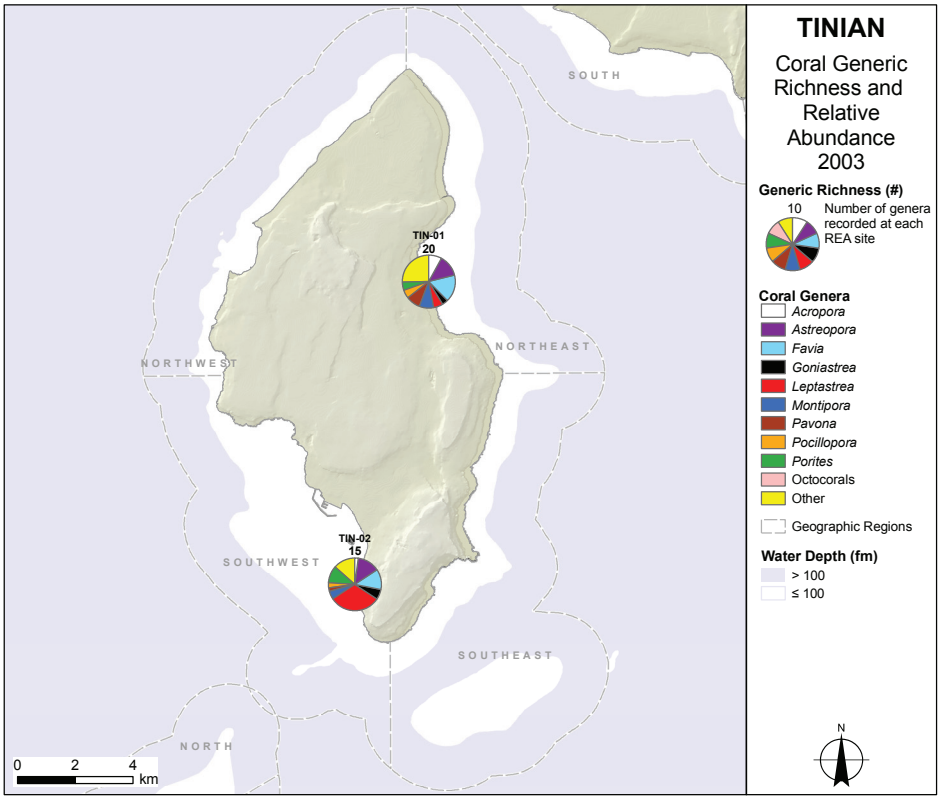


Figure 7.5.1i. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to survey coral genera.

Five REA benthic surveys of forereef habitats were conducted using the quadrat method at Tinian during MARAMP 2005. At least 22 coral genera were observed at Tinian. Generic richness ranged from 10 to 19 with a mean of 14.2 (SE 1.4) coral genera per site (Fig. 7.5.1j). The highest generic diversity was seen at TIN-06 in the northwest region, and the lowest generic diversity was recorded at TIN-03 in the southwest region near Puntan Diapblo.

Porites, Favia, Leptastrea, and Montipora were the most numerically abundant genera, contributing 23.8%, 13.5%, 12.8%, and 10.5% of the total number of colonies enumerated at Tinian during MARAMP 2005. All other genera individually accounted for < 10% of the total number of colonies. *Porites* dominated the coral fauna at TIN-03 and TIN-05 in the southwest region, accounting for 71.9% and 29.8% of the total number of colonies enumerated at those sites. *Favia* dominated at TIN-04 near Puntan Kastiyu and at TIN-06 in the northwest region, accounting for 21.5% and 30.4% of the total number of colonies at those sites. *Montipora* dominated at TIN-02 in the southwest region, accounting for 32% of the total number of colonies.

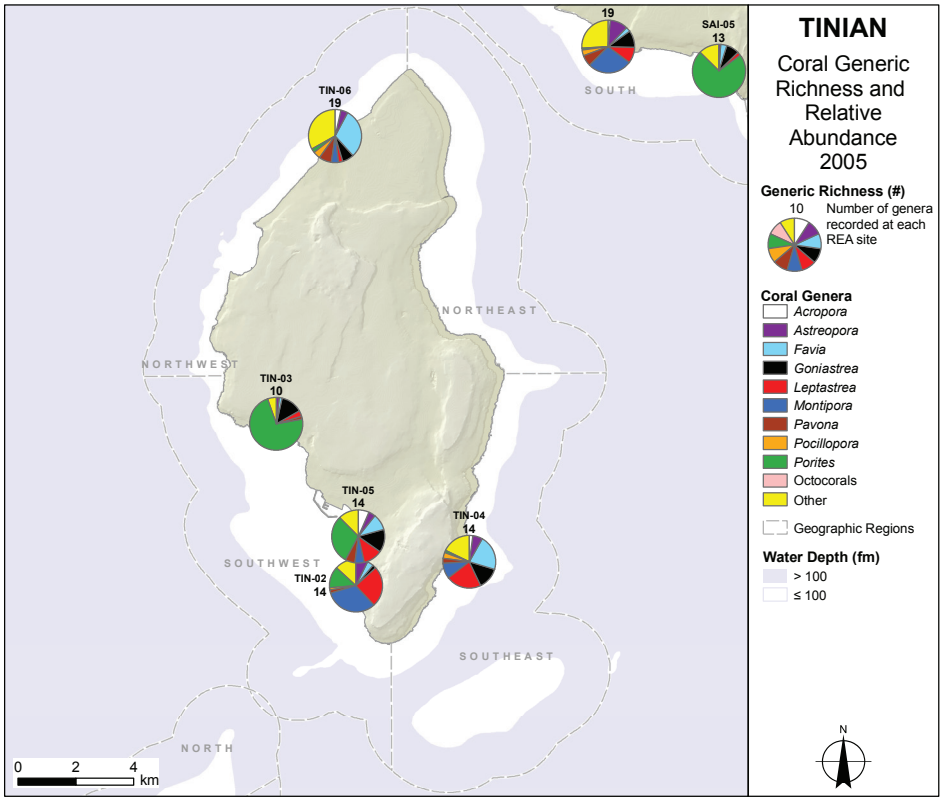


Figure 7.5.1j. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Tinian during MARAMP 2005. The pie charts indicate the percentages of relative abundance of key coral genera. The quadrat method was used in 2005 to survey coral genera.

Five REA benthic surveys of forereef habitats were conducted around Tinian during MARAMP 2007. The belt-transect method was used to survey 4 sites, while the quadrat method was used at TIN-04 in the southeast region near Puntan Kastiyu. At least 29 coral genera were observed, including the following 11 genera that had not been recorded at Tinian in 2003 and 2005: *Coscinaraea, Cycloseris, Goniopora, Heliopora, Lobophyllia, Lobophytum, Montastrea*, *Plesiastrea*,

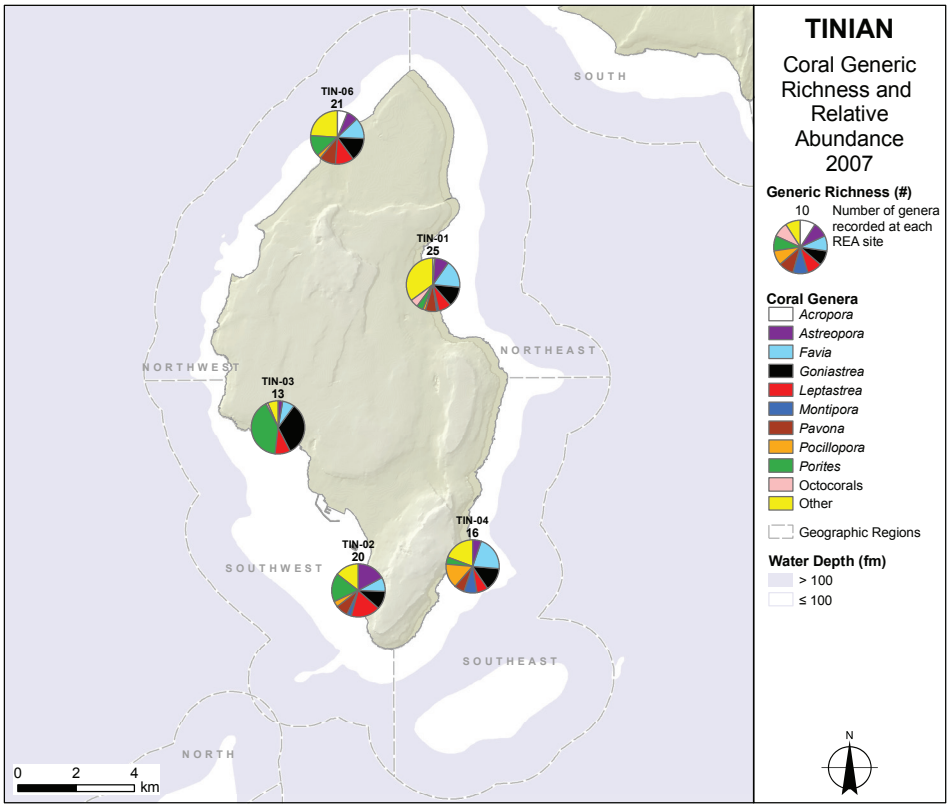


Figure 7.5.1k. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007. The pie charts indicate the percentages of relative abundance of key coral genera. In 2007, the quadrat method was used only at TIN-04, and the belt-transect method was used to assess coral-colony density at the other 4 of the 5 REA sites surveyed.

Sinularia, *Turbinaria*, and *Zoanthus*. Generic richness ranged from 16 to 25 with a mean of 19 (SE 1.6) coral genera per site (Fig. 7.5.1k). The highest generic diversity was seen at TIN-01 in the northeast region, and the lowest generic diversity was recorded at TIN-03 in the southwest region near Puntan Diapblo.

Goniastrea, *Porites*, *Favia*, and *Leptastrea* were the most numerically abundant genera, contributing 16.5%, 15.6%, 13.2, and 10.6 % of the total number of colonies enumerated around Tinian during MARAMP 2007. All other genera individually accounted for < 10% of the total number of colonies. *Porites* dominated the coral fauna at TIN-03 in the southwest region, contributing 39.7% of the total number of colonies enumerated at that site, and co-dominated farther south at TIN-02 with *Leptastrea* and *Astreopora*, each genus accounting for 17.3%, 17.7%, and 17%, respectively, of the total number of colonies. *Favia* dominated at TIN-01 and TIN-04 on the east side, accounting for 16.8% and 20.9% of the total number of colonies observed at those sites, and co-dominated with *Goniastrea* and *Porites* at TIN-06 in the northwest region, with each genus accounting for 12.7%, 13.8%, and 12.4%, respectively, of the total number of colonies.

Site-specific estimates of generic richness across the 3 MARAMP survey years ranged from 10 to 25 on forereef habitats at Tinian. Site-specific and overall mean generic-richness values in 2007 with a mean of 19 genera per site (SE 1.6) were higher than estimates in 2005 with a mean of 14.2 genera per site (SE 1.4) and were comparable to values in 2003 with a mean of 17.5 (SE 2.5) genera per site (Fig. 7.5.1l). Note the difference in the size of the area in which corals were censused: the survey area at 4 of the 5 sites surveyed in 2007 was 50 m^2 per site, an area much larger than the 3.75 m^2 and 4 m^2 per site surveyed at TIN-04 in 2003 and 2005 (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Additionally, the only octocoral genus assessed in 2003 and 2005 was *Heliopora*, whereas all octocoral genera were assessed at 4 of the 5 sites surveyed in 2007.

Across the 3 MARAMP survey years, 36 coral genera were observed on forereef habitats at Tinian. *Porites, Favia, Leptastrea, Astreopora, Montipora*, and *Goniastrea* were important components of the coral fauna. *Porites* was the most numerically abundant taxon in 2005 and the second-most abundant in 2007, accounting for 23.8% and 15.6% of the total number of colonies enumerated at Tinian. *Favia* and *Leptastrea* were also important components of the coral fauna, accounting for > 10% of the total number of colonies enumerated in the 3 MARAMP survey years. *Astreopora, Montipora*, and *Goniastrea* accounted for > 10% of the total number of colonies in 2003, 2005, and 2007, respectively.

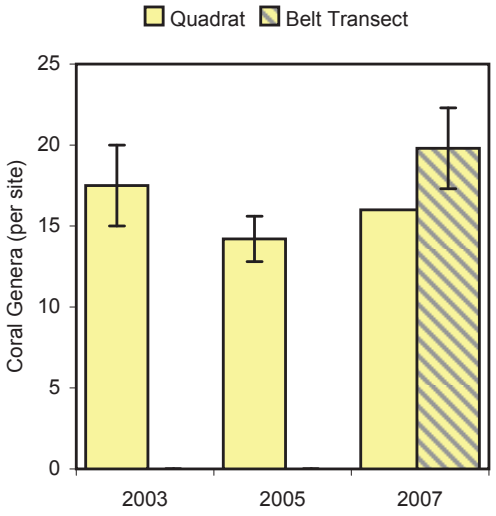


Figure 7.5.1l. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Tinian during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to survey coral genera, but in 2007 the belt-transect method was used at 4 of 5 survey sites and the quadrat method at 1 site. Error bars indicate standard error (± 1 SE) of the mean.

Coral Size-class Distribution

During MARAMP 2003, 2 REA benthic surveys of forereef habitats were conducted at Tinian using the quadrat method. The coral size-class distribution from these surveys shows that the majority (68.8%) of corals had maximum diameters ≤ 5 cm (Fig. 7.5.1m). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 19.6%, 8.2%, 2.5%, and 0.9% of colonies recorded. At both TIN-01 in Asiga Bay and TIN-02 in the southwest region, high proportions (86.2% and 90.6%) of colonies were small (≤ 10 cm) and low proportions (13% and 8.3%) of colonies were midsize (11–40 cm).

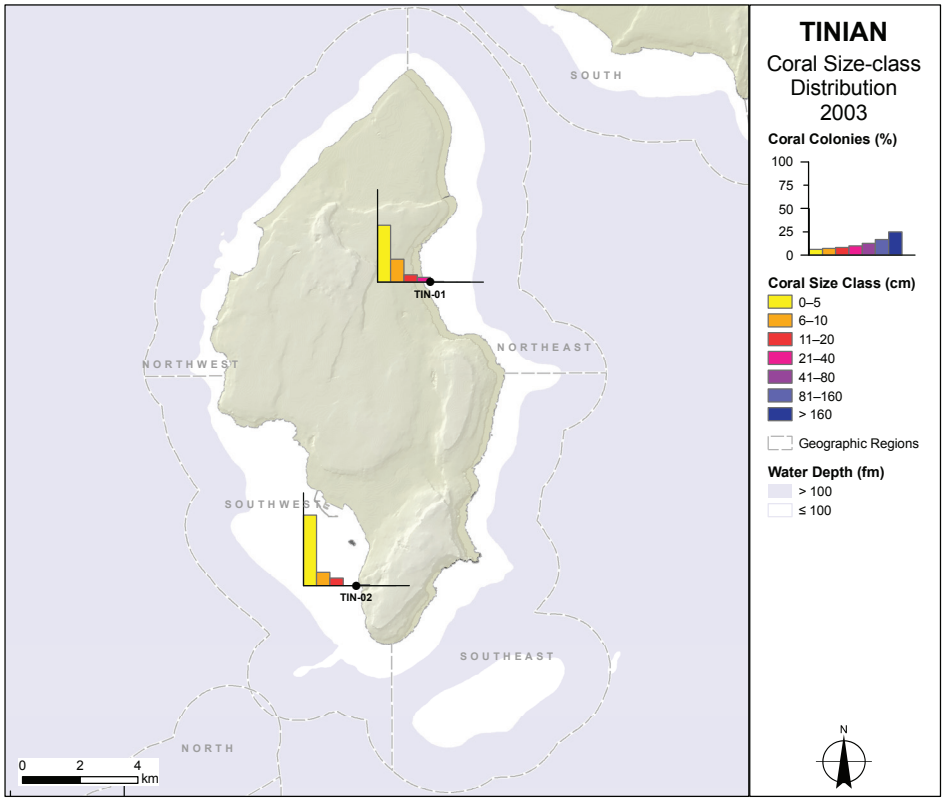


Figure 7.5.1m. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.

During MARAMP 2005, 5 REA benthic surveys of forereef habitats were conducted at Tinian using the quadrat method. The coral size-class distribution from these surveys shows that the majority of corals (72.1%) had maximum diameters ≤ 5 cm (Fig. 7.5.1n). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 19.2%, 5.3%, and 2.3% of colonies recorded, and colonies with maximum diameters > 40 cm accounted for only 1% of colonies recorded. A high proportion (> 80%) of small (≤ 10 cm) colonies was found at all sites and a low proportion (< 17%) of colonies was midsize (11–40 cm).

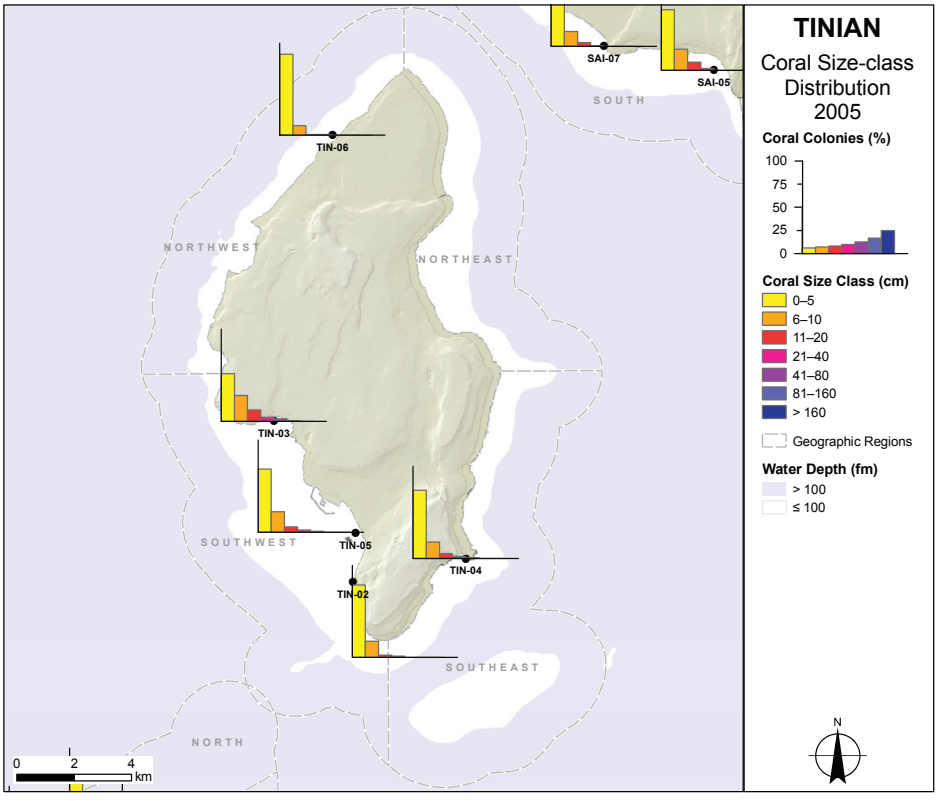


Figure 7.5.1n. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Tinian during MARAMP 2005. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2005 to size corals.

During MARAMP 2007, 4 REA benthic surveys of forereef habitats were conducted around Tinian using the belt-transect method. The coral size-class distribution from these surveys shows that the majority (81.3%) of corals had maximum diameters ≤ 10 cm (Fig. 7.5.1o). The first 4 size classes (0–5, 6–10, 11–20, and 21–40 cm) accounted for 37.9%, 43.4%, 10.5%, and 5.4% of colonies recorded, and colonies with maximum diameters > 40 cm accounted for only 2.7% of colonies observed. At TIN-04 near Puntan Kastiyu, the only site surveyed with the quadrat method, 79.1% of colonies had maximum diameters ≤ 5 cm, 16.5% occurred in the next size class (6–10 cm), and only 4.3% had maximum diameters > 10 cm.

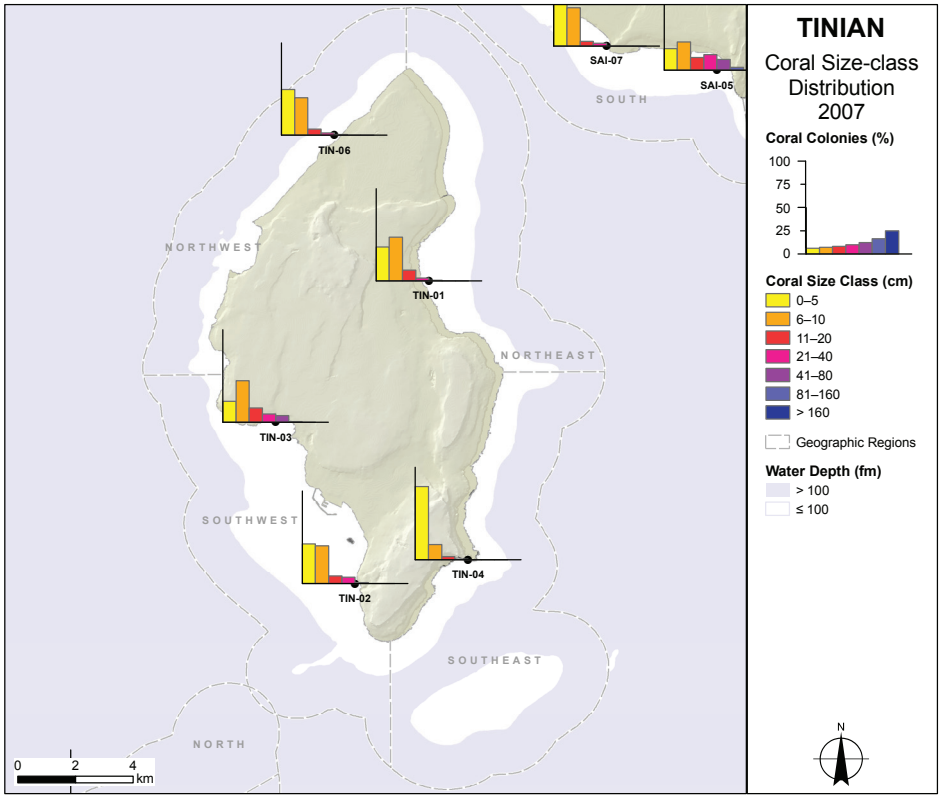


Figure 7.5.1o. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007. The observed size classes are color coded in a size-frequency chart at each REA site. In 2007, the quadrat method was used only at TIN-04, and the belt-transect method was used to size corals at the other 4 of the 5 REA sites surveyed.

Site-specific and overall distributions of estimated coral size classes on forereef habitats at Tinian are affected by inherent biases in the methods used to census and size corals. During MARAMP 2003 and 2005, corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. During MARAMP 2007, corals whose center fell within a belt transect (1 × 25 m) were tallied and binned into 1 of 7 size classes based on visual estimates of maximum colony diameter. This method is better suited to capturing large colonies, but the larger census area likely reduces the number of very small colonies (≤ 5 cm) that are observed and recorded. For more on these survey methods, see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease."

These methodological biases are reflected in the size-class data by survey year. During MARAMP 2003 and 2005, a high number of coral colonies (> 20 colonies m^{-2}) observed at Tinian were in the smallest size class (Fig. 7.5.1p). In 2003 and 2005, more than half (68.8% and 72.1%) of all colonies censused at Tinian had maximum diameters ≤ 5 cm, but in 2007 only 37.9% of colonies were in this smallest size class, excluding TIN-04 in the southeast region, the one site where the quadrat method was used in 2007. Comparing size-class data between survey years when different methods were used is, therefore, inappropriate. Only TIN-02 in the southwest region was surveyed with the same quadrat method in 2 different survey years (2003 and 2005). At this site, the minor changes in size-class distribution between years likely reflect chance variation in the placement of individual quadrats.

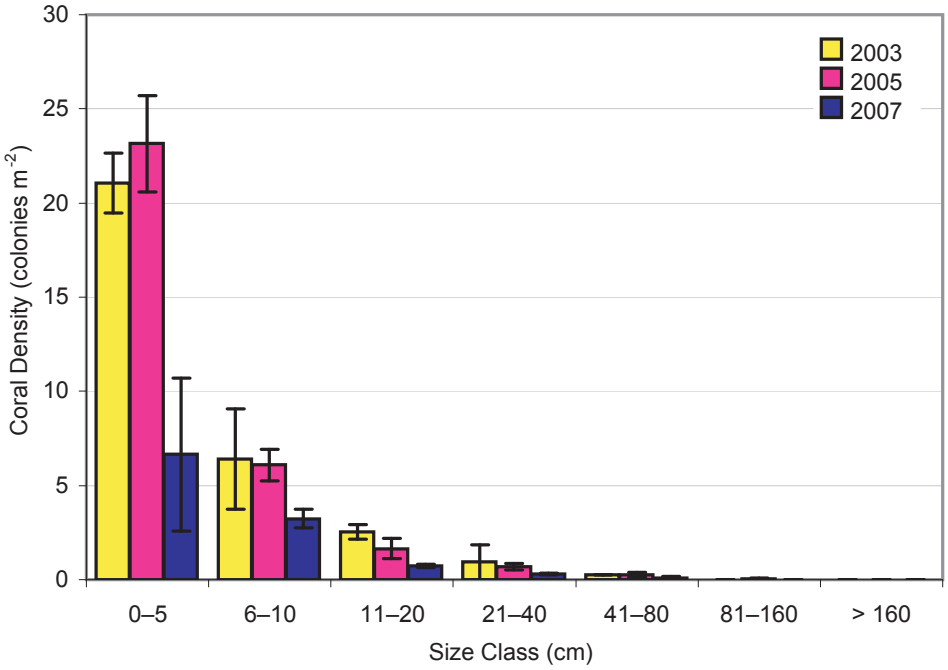


Figure 7.5.1p. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to size corals, but in 2007 the belt-transect method was used at 4 of 5 survey sites and the quadrat method at 1 site. Error bars indicate standard error (± 1 SE) of the mean.

7.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted using the belt-transect and quadrat methods at 5 sites on forereef habitats around Tinian, covering a total area of 1430 m^2. Surveys detected 20 cases of disease. Two different methods were used to collect coral-colony counts: 2 belt transects (1 × 25 m), at TIN-01, TIN-02, TIN-03, and TIN-06, and 16 haphazardly placed quadrats (50 × 50 cm) at TIN-04 (see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease). The biases of each method are reflected in colony-density and disease-prevalence estimates: the quadrat method resulted in higher coral-colony densities and, therefore, lower-than-expected disease-prevalence values. For the purpose of this report, however, site-specific overall prevalence values obtained using differing methods are combined to produce mean overall disease prevalence. As such, the mean overall disease prevalence for Tinian was low, amounting to 0.2% (SE 0.1). Four major disease conditions were observed at Tinian—bleaching, subacute tissue loss, skeletal growth anomalies, and pigmentation response—all of which were recorded at TIN-03 north of Tinian Harbor in the southwest region. This site also had the greatest number of cases (50% of total) and overall disease prevalence (0.7%) of all sites. Overall prevalence of disease at the other 4 REA survey sites was quite low with a range of 0.01%–0.17% (Fig. 7.5.2a; the values of overall prevalence shown in this figure include predation).

Lesions involving pigmentation response were the most common disease condition encountered, accounting for 60% of disease cases. Bleaching contributed 20% of disease cases, and subacute tissue loss and skeletal growth anomalies combined accounted for 15% of cases. Overall, pigmentation response was the most prevalent disease condition with 0.13% (SE 0.08) of the surveyed population at Tinian affected (Fig. 7.5.2b). Bleaching was uncommon and, when present, mild and focal (i.e., concentrated in one area of an affected colony); overall prevalence of bleaching only amounted to 0.06% (SE 0.02). Cases of bleaching were observed on the genera *Goniastrea* and *Astreopora*. Corals of the genus *Porites* hosted all other disease states recorded at Tinian.

Cases of coral predation attributable to crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails, such as snails from the genus *Drupella*, were observed at all sites except for TIN-02 in the southwest region. Active predation and predation scars were most numerous and prevalent at TIN-03 north of Tinian Harbor. The genera *Porites, Astreopora*, *Goniastrea*, and *Montipora* were the main prey of crown-of-thorns seastars (COTS) and snails. For more about COTS around Tinian, see Section 7.7.1: "Benthic Macroinvertebrates Surveys."

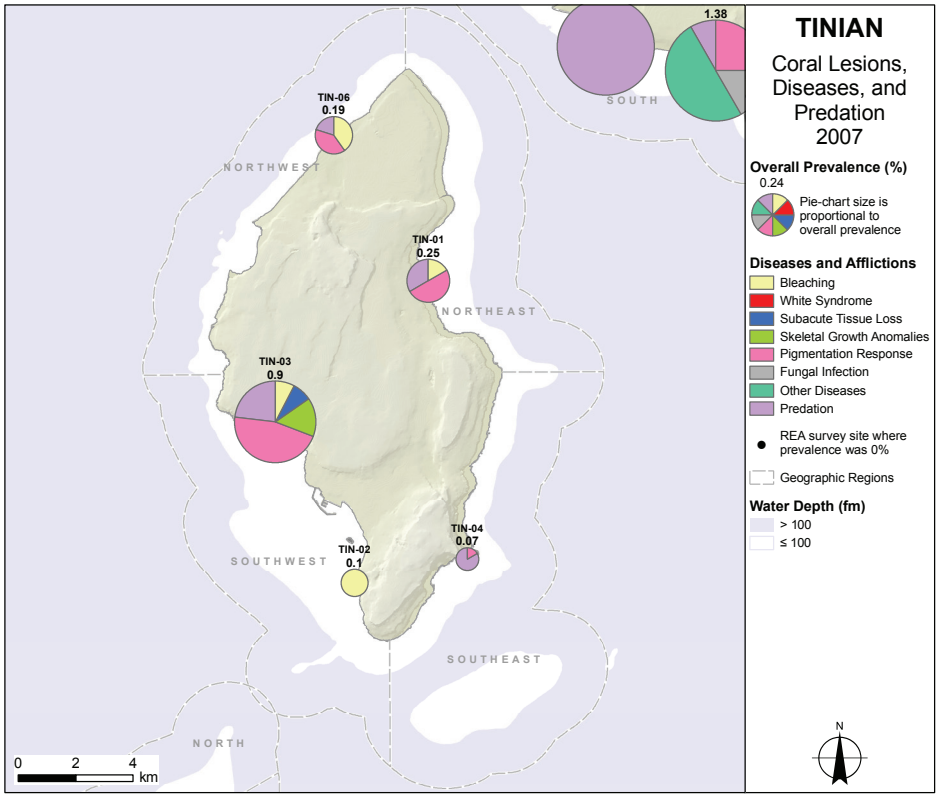


Figure 7.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie charts indicate disease-specific prevalence. In 2007, the quadrat method was used only at TIN-04, and the belt-transect method was used to estimate colony density and disease prevalence at the other 4 of the 5 REA sites surveyed.

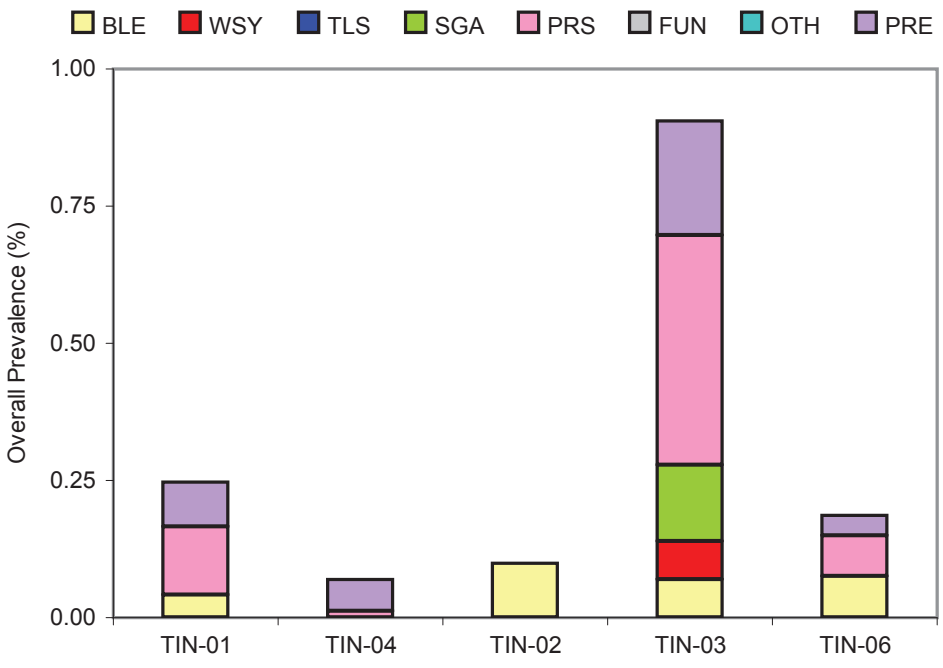


Figure 7.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. In 2007, the quadrat method was used only at TIN-04, and the belt-transect method was used to estimate colony density and disease prevalence at the other 4 of the 5 REA sites surveyed. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infections; OTH: algal and cyanophyte infections and other lesions of unknown etiology; and PRE: predation by COTS or coralli-vorous snails.

7.6 Algae and Algal Disease

7.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats at the island of Tinian and Tatsumi Reef was 47% (SE 1). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 78%, within a range of 40.1%–100%, occurred on Tatsumi Reef, offshore of the southeast region of Tinian and where pavement habitat of low to medium-low complexity was the dominant structural feature (Fig.7.6.1a, top left panel). Other moderately dense areas of macroalgal cover were found along Tinian Harbor in the southwest region and the area between Puntans Chiget and Asiga in the northeast region (for place-names and their locations, see Figure 7.2a in Section 7.2: Survey Effort). Pavement or boulder habitats of medium to medium-low complexity were the dominant observed habitats.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Tinian was 56% (SE 1.5). Macroalgae were abundant islandwide, but estimates of cover were especially high in the northeast region between Puntans Asiga and Masalok and in the southwest region in the vicinity of Tinian Harbor (Fig. 7.6.1a, middle left panel). Species of *Halimeda,* a calcified, jointed green alga, were recorded covering extensive areas in low to medium-low complexity habitats along the coast near Puntan Tahgong in the northeast region.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats around Tinian was 40% (SE 2.5). The survey with the highest mean macroalgal cover of 76%, within a range of 62.6%–100%, occurred along a 3.2-km towed-diver survey that ended near Puntan Masalok in the northeast region (Fig. 7.6.1a, bottom left panel). This area was characterized by continuous, moderately sloping reef areas that contained occasional rubble flats, rock slabs, clefts, crags, and pillars. Species of the siphonous alga *Halimeda*, the brown alga *Padina*, and the red alga *Liagora* dominated the benthos with several survey segments exhibiting macroalgal cover of 75.1%–100%. Species of the red alga *Asparagopsis* and the green alga *Microdictyon* were also recorded as lesser benthic components.

During MARAMP 2007, 5 REA benthic surveys of forereef habitats around Tinian were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 7.8% to 23.5% with an overall mean of 15% (SE 2.7). The survey with the highest macroalgal cover occurred in the northeast region at TIN-01 (Fig. 7.6.1b). Macroalgal cover was also high, compared to other sites surveyed at Tinian, in the northwest region at TIN-06 and in the southwest region at TIN-02: 17.6% and 16.7%. The lowest macroalgal cover was recorded in the southwest region at TIN-03.

Turf-algal cover from these REA surveys in 2007 ranged from 44.1% to 57.8% with an overall mean of 52% (SE 2.9). The highest turf-algal cover was found at 2 sites, both with 57.8%: TIN-01 in the northeast region and TIN-02 in the southwest region (Fig. 7.6.1b). The survey with the lowest turf-algal cover occurred in the southwest region at TIN-03.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats at Tinian was 6% (SE 0.7). The survey with the highest mean crustose-coralline-red-algal cover of 13.3%, within a range of 0%–30%, occurred in the vicinity of Punatan Chiget in the northeast region on spur-and-groove habitat of medium to medium-high complexity (Fig. 7.6.1a, top right panel). All other surveys reported relatively low cover values for crustose coralline red algae.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats at Tinian was 5% (SE 0.4). Crustose coralline red algae appeared to favor boulder and pavement habitats of medium to medium-high complexity near Puntans Chiget and Asiga in the northeast region, where its cover was 10.1%–20% over 4 survey segments (Fig. 7.6.1a, middle right panel).

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Tinian was 16% (SE 1.1). The survey with the highest mean cover of crustose coralline red algae of 25%, within a range of 20.1%–40%, occurred along the northwest corner of Tinian, rounding Puntan Tahgong (Fig. 7.6.1a, bottom right panel).

Areas near Puntans Kastiyu and Diapblo also exhibited high cover averages. All survey areas were characterized habitats of medium-high to high complexity.

During MARAMP 2007, 5 REA benthic surveys of forereef habitats around Tinian were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 2.9% to 12.7% with an overall mean of 6.7% (SE 1.7). The survey with the highest crustose-coralline-red-algal cover occurred in the southeast region at TIN-04 (Fig. 7.6.1b). The lowest crustose-coralline-red-algal cover was recorded in the southwest region at TIN-02.

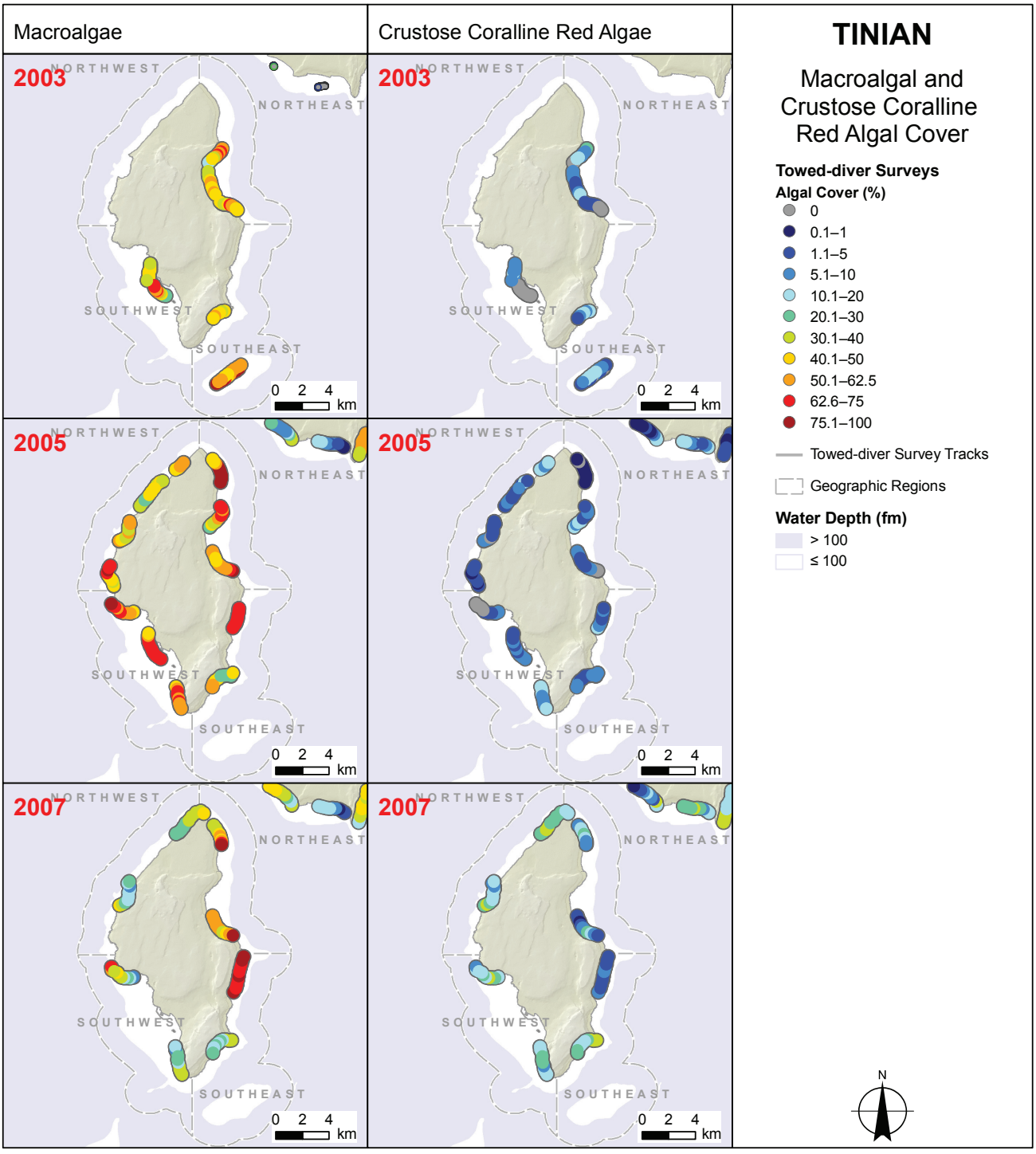


Figure 7.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2003, 2005, and 2007. Each colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003).

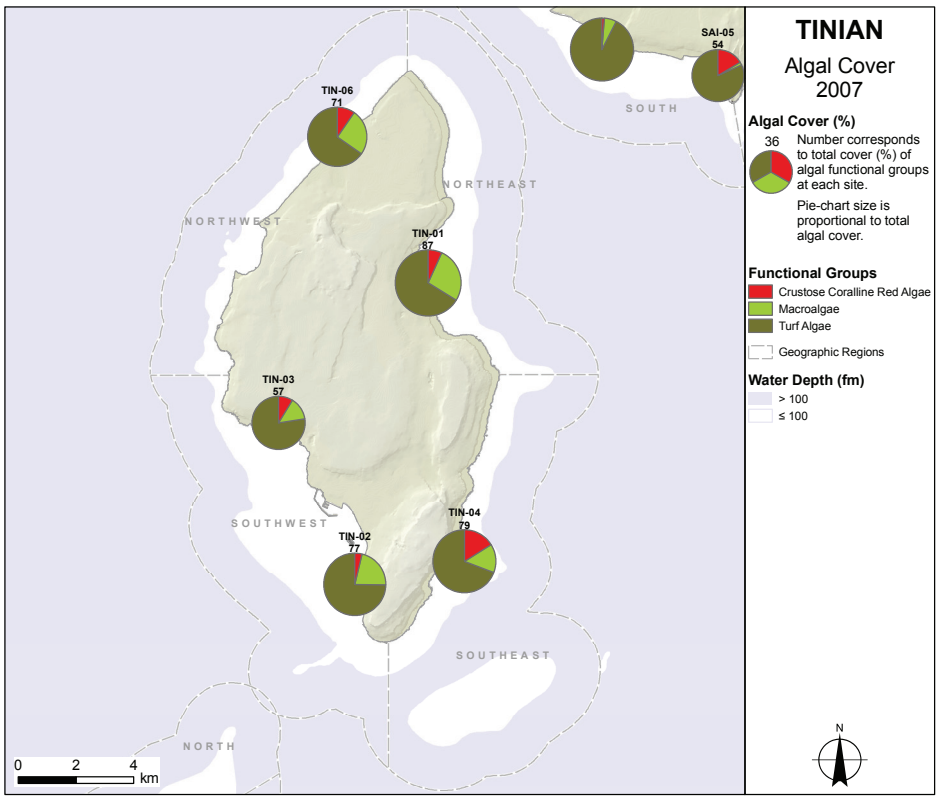


Figure 7.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method around Tinian during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, islandwide mean cover of macroalgal populations around Tinian, based on towed-diver surveys of forereef habitats, varied by 16.4% (Fig. 7.6.1c). The most common habitat for macroalgae was low-to-medium complexity pavement. When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Macroalgal cover near Tinian Harbor in the southwest region and north of Puntan Masalok in the northeast region was higher in 2005 than in 2003. Surveys recorded lower macroalgal cover in 2007 than in 2005 for several survey areas around the island, particularly for west-facing reefs. The greatest changes between MARAMP 2005 and 2007 occurred in survey areas north of Puntan Carolinas, the southernmost tip; south of Puntan Diapblo in the southwest region; and south of Puntan Lamanibot Sanhilo in the northwest region.

Populations of crustose coralline red algae around Tinian, based on towed-diver surveys on forereef habitats, varied as much as 11% in average cover of the benthos between MARAMP survey years. The greatest changes in cover of crustose coralline red algae between surveys in 2003 and 2005 were observed along the east side of Tinian, where cover was lower near Puntans Asiga and Kastiyu. Cover was higher in 2007 than in 2005 in the majority of surveys, except along

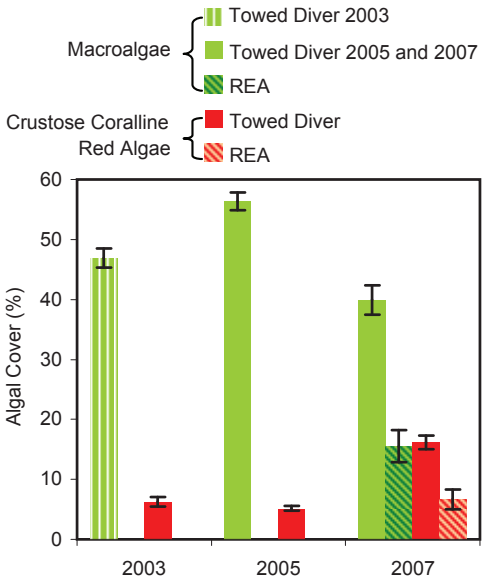


Figure 7.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Tinian during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted at Tinian in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

the central portion of the east side of this island. The greatest differences between MARAMP 2005 and 2007 occurred in surveys southwest of Puntan Tahgong in the northwest region, south of Puntan Kastiyu in the southeast region, and south of Puntan Diapblo in the southwest region.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae are lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites has not been undertaken yet for the southern islands of the Mariana Archipelago. Ultimately, based on microscopic analysis that may be done in the future, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA algal surveys were conducted at 3 sites on forereef habitats at Tinian. In the field, 8 macroalgal genera (4 red and 4 green), containing at least 11 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. TIN-01, located in Asiga Bay in the northeast region, had the highest macroalgal generic diversity with 7 genera, containing 10 species, documented in the field. The lowest macroalgal generic diversity was found in the southwest region at TIN-02 with 2 species representing 2 genera recorded.

Species of *Halimeda* were some of the most common components of algal communities at Tinian in 2003 (Fig. 7.6.1d), occurring in 66.7% of sampled photoquadrats. Species of the calcified, red algal genus *Amphiroa* were also extremely common, although these algae were seen more often in the southwest region at TIN-02 and TIN-03, where they were found in 41.7% and 50% of sampled photoquadrats, than in the northeast region at TIN-01, where they were seen in 16.7% of sampled photoquadrats. At the species level, most of the remaining 7 taxa tentatively identified were observed only at 1 or 2 sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Tinian.

Turf algae and crustose coralline red algae were exceptionally common in 2003, occurring in 88.9% and 47.2% of photoquadrats sampled at Tinian in 2003. Turf-algal communities were ubiquitous at each site. Although crustose coralline red algae were recorded at all sites, the occurrence of this functional group at individual sites varied between 8% and 100%. Cyanobacteria, found in 8%–17% of sampled photoquadrats, were less common.

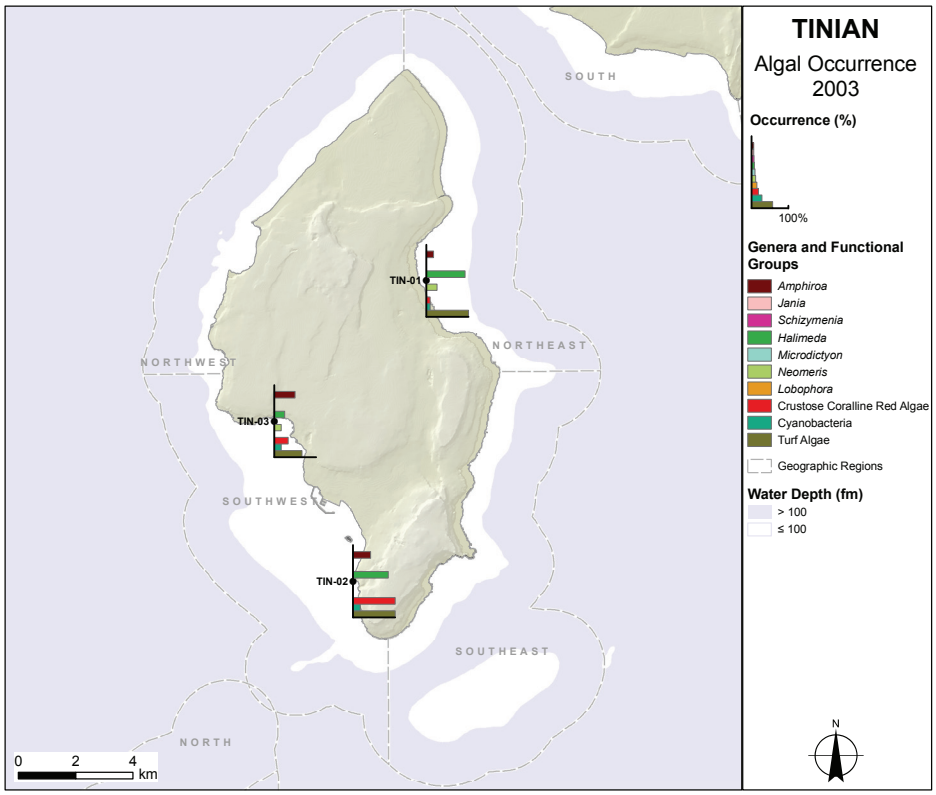


Figure 7.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2005, REA algal surveys were conducted at 6 sites on forereef habitats around Tinian. In the field, 23 macroalgal genera (9 red, 10 green, and 4 brown), containing at least 23 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, nongeniculate coralline red algae, and cyanophytes—were observed. TIN-01 in Asiga Bay, TIN-03 in the southwest region north of Tinian Harbor, and TIN-06 in the northwest region had the highest macroalgal generic diversity with 12 genera, each containing 1 species, documented in the field at each site. The lowest macroalgal generic diversity was found at TIN-02, the southernmost site in the southwest region, with 8 species representing 8 genera recorded.

Species of the green algae *Halimeda* and *Neomeris*, the red algae *Amphiroa* and *Jania*, and the brown alga *Dictyota* were common at every site surveyed around Tinian in 2005 (Fig. 7.6.1e), occurring in 59.7%, 33.3%, 40.3%, 30.6%, and 30.6% of sampled photoquadrats. At the genus level, most of the 23 taxa tentatively identified occurred only at 1 or 2 sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Tinian. However, species of the red alga *Peyssonnelia* were a major component of 3 sites on the west side of this island: TIN-03, TIN-05, and TIN-06, where they were observed in 83%, 50%, and 67% of sampled photoquadrats. A species of *Padina* commonly occurred at TIN-01 in Asiga Bay and on the southern coasts at TIN-02, TIN-05, and TIN-04, and species of both the red alga *Galaxaura* and green alga *Caulerpa* were common at TIN-01, TIN-03, TIN-04, and TIN-06. Species of *Amphiroa* were found along the west side at TIN-02, TIN-03, TIN-05, and TIN-06 but were missing from both of the sites on the east side.

Turf algae, crustose coralline red algae, and cyanobacteria were all exceptionally common in 2005, occurring in 97.2%, 50%, and 65.3% of photoquadrats sampled around Tinian. Turf-algal communities were found in 83%–100% of sampled photoquadrats, and crustose coralline red algae were observed in 25%–83% of sampled photoquadrats. Cyanobacteria were a prominent component of the algal community at all sites, excluding TIN-06 in the northwest region, occurring in 58%–83% of sampled photoquadrats. At TIN-06, located southwest of Puntan Tahgong, the northernmost point of Tinian, cyanobacteria were seen in 8% of sampled photoquadrats. Nongeniculate, calcified, branched red algae were a minor component of the algal community at 4 of the 6 sites surveyed, occurring in 8%–33% of photoquadrats sampled at TIN-01 in the northeast region and on the west side at TIN-03, TIN-05, and TIN-06.

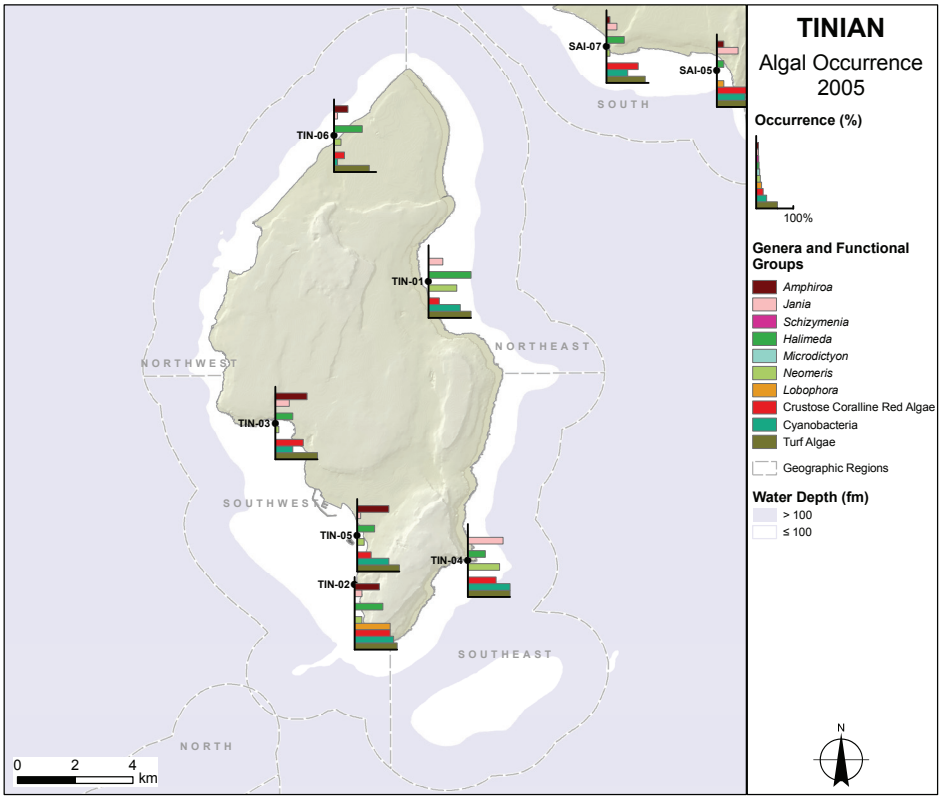


Figure 7.6.1e. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted around Tinian during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2007, REA benthic surveys were conducted at 5 sites on forereef habitats around Tinian. In the field, 20 macroalgal genera (12 red, 6 green, and 2 brown), containing at least 28 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed in the field. TIN-01 in Asiga Bay had

the highest macroalgal generic diversity with 13 genera, containing 15 species, documented in the field. The lowest macroalgal generic diversity was found in the southwest region at TIN-02 with 5 species representing 5 genera recorded.

Species of *Halimeda*, seen in 68.3% of sampled photoquadrats overall, were common at every site surveyed around Tinian in 2007 (Fig. 7.6.1f), occurring in 42%–100% of photoquadrats sampled at individual sites. At the genus level, most of the 20 taxa tentatively identified only occurred at 1 or 2 sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae around Tinian. However, species of *Jania* occurred as a minor component of the algal community with 8%–17% occurrence at TIN-01 in Asiga Bay, TIN-02 in the southwest region, TIN-04 near Puntan Kastiyu, and TIN-06 in the northwest region. Except for TIN-01, species of *Amphiroa* were observed at all sites, where they exhibited 17%–100% occurrence.

Turf algae, crustose coralline red algae, and cyanobacteria were all exceptionally common in 2007, occurring in 43.8%, 45.8%, and 75% of photoquadrats sampled around Tinian. Communities of crustose coralline red algae were ubiquitous at all sites. Although turf algae were observed at all sites, the occurrence of this functional group at individual sites varied between 17% and 67%. Cyanobacteria were a prominent component of algal communities around Tinian, occurring at all sites and in 58%–83% of sampled photoquadrats.

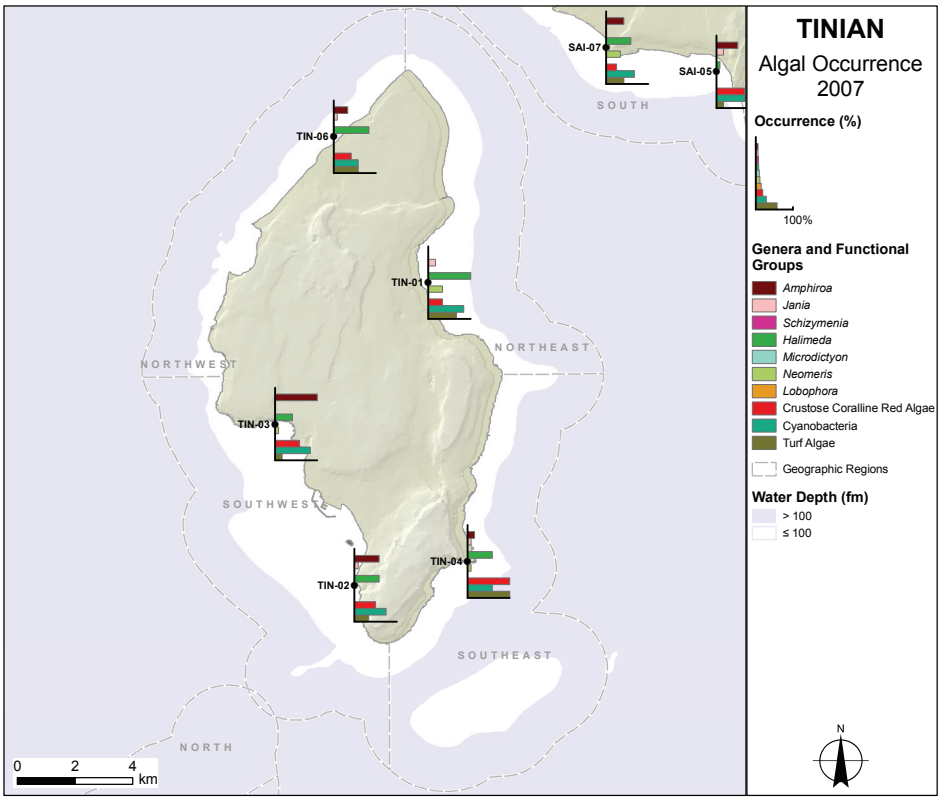


Figure 7.6.1f. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

The number of macroalgal genera recorded on forereef habitats around Tinian increased from 7 to 23 between MARAMP 2003 and 2005 but decreased to 20 during MARAMP 2007. Estimates of macroalgal biodiversity may have been higher in 2005 and 2007 than in 2003 because of the increased number of REA sites surveyed (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). The overall occurrence of macroalgal genera did not fluctuate greatly between 2003, 2005, and 2007. Species of *Halimeda* consistently exhibited the highest occurrence during the 3 MARAMP survey years, ranging from 59.7% to 68.3% (Fig. 7.6.1g). Species of *Amphiroa*, with occurrence of 36.1%–41.7%, were the second-most prevalent components of algal communities, steadily increasing in occurrence between survey years. Other common genera included the green algae *Neomeris* and *Caulerpa*; the red algae *Dichotomaria*, *Tricleocarpa, Galaxaura*, *Gelidiella*, and *Jania*; and the brown alga *Dictyota.* Species of *Jania* exhibited greater variation in occurrence between survey years than did other species. Not recorded at all in 2003, species of *Jania* occurred in 30.6% and only 8.3% of photoquadrats sampled in 2005 and 2007.

Turf algae and crustose coralline red algae occurred in 16.7%–100% and 8.3%–100% of photoquadrats sampled at sites around Tinian during MARAMP 2003, 2005, and 2007. No patterns in abundance of these functional groups were obvious in survey results.

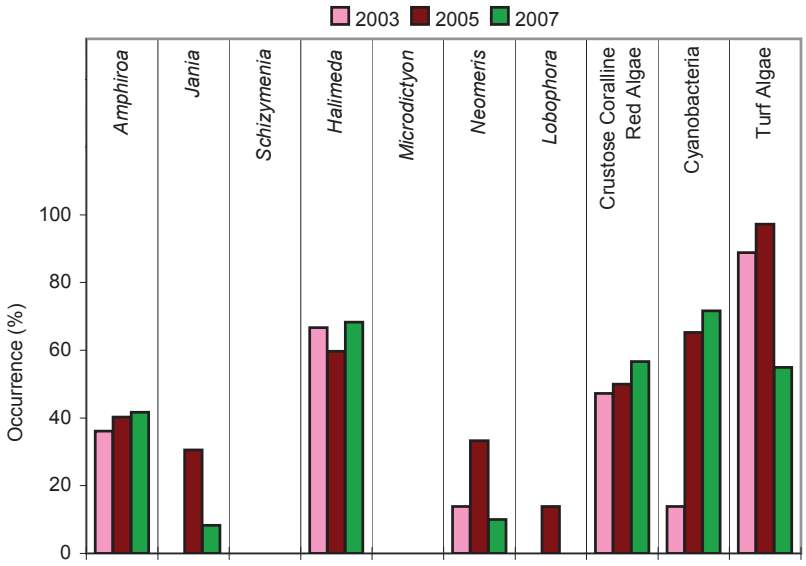


Figure 7.6.1g. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats around Tinian during MARAMP 2003, 2005 and 2007.

7.6.2 Coralline-algae-disease Surveys

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 5 sites on forereef habitats around Tinian. These surveys covered a total reef area of 1430 m^2 and detected 33 cases. These numbers translate to a high overall mean density of 2.8 cases 100 m^{-2} (SE 1.7), compared to other areas surveyed in the Mariana Archipelago. Disease in coralline algae was found at 4 sites, and 2 major types of diseases were observed: coralline lethal orange disease and coralline white band syndrome. Cases of coralline lethal orange disease represented nearly 60% of all cases recorded at Tinian. Site-specific density of disease was the highest with 8.3 cases 100 m^{-2} at TIN-02 in the southwest region; the other sites registered much lower disease densities (Figs. 7.6.2a and b).

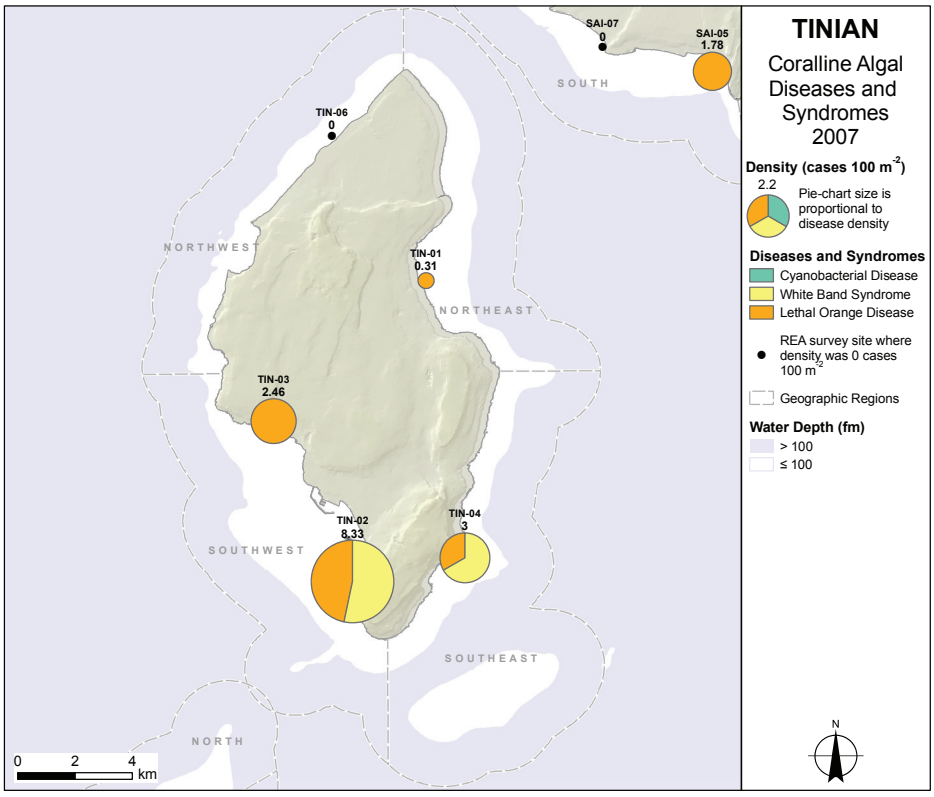


Figure 7.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats around Tinian during MARAMP 2007. The color-coded portions of the pie charts indicate disease-specific density.

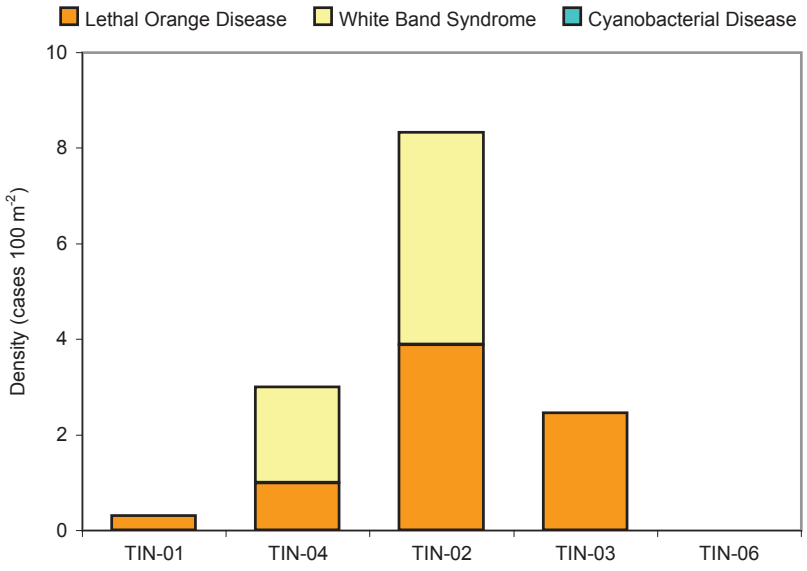


Figure 7.6.2b. Densities (cases 100 m^{-2}) of coral-line-algal diseases from REA benthic surveys conducted on forereef habitats around Tinian during MARAMP 2007.

7.7 Benthic Macroinvertebrates

7.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Tinian through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 3 REA surveys and 6 towed-diver benthic surveys were conducted around Tinian. Also, 2 towed-diver surveys were performed along Tatsumi Reef, located ~ 4 km southeast of Tinian. In 2005, 6 REA surveys and 12 towed-diver benthic surveys were completed. In 2007, 1 REA survey and 12 towed-diver benthic surveys were conducted around Tinian. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may underrepresent the number of individuals present.

Overall, both the REA and towed-diver surveys suggested low daytime macroinvertebrate abundance on forereef habitats around Tinian compared to the rest of the Mariana Archipelago. Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. For each target organism, temporal patterns of islandwide mean macroinvertebrate density around Tinian—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 7.7.1d, h, l, and p). Because of the variable REA survey effort, with 3 surveys in 2003, 6 in 2005, and 1 in 2007, temporal comparisons of REA data are not presented.

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at 2 of the 3 REA sites surveyed and in 4 of the 6 towed-diver surveys conducted at Tinian (Fig. 7.7.1a). The sample mean density of giant clams from REA surveys was 1.66 organisms 100 m^{-2} (SE 1.2), and the overall mean density from towed-diver surveys was 0.013 organisms 100 m^{-2} (SE 0.004). Results from REA surveys suggest giant clams were most abundant in the northeast region between Puntans Asiga and Masalok (Fig. 7.7.1a; for place-names and their locations, see Figure 7.2a in Section 7.2: Survey Effort). TIN-01, the

only REA site in the northeast region, had the highest density with 4 organisms 100 m^{-2}. Also recorded in the northeast region, the second-greatest mean density of giant clams from a towed-diver survey was 0.028 organisms 100 m^{-2} along Puntan Asiga; segment densities from this survey ranged from 0 to 0.16 organisms 100 m^{-2}. Among all towed-diver surveys at Tinian, the survey completed just south of Puntan Kastiyu in the southeast region had the highest mean density of giant clams with 0.03 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.11 organisms 100 m^{-2}.

As part of MARAMP 2003, 2 towed-diver surveys were conducted along Tatsumi Reef. The overall mean density of giant clams on this reef was extremely low at 0.005 organisms 100 m^{-2}, compared to the rest of the Mariana Archipelago. Giant clams were observed during only 1 survey and occurred in only 2 of 18 segments in this survey. The densities from these 2 segments were 0.07 and 0.03 organisms 100 m^{-2}.

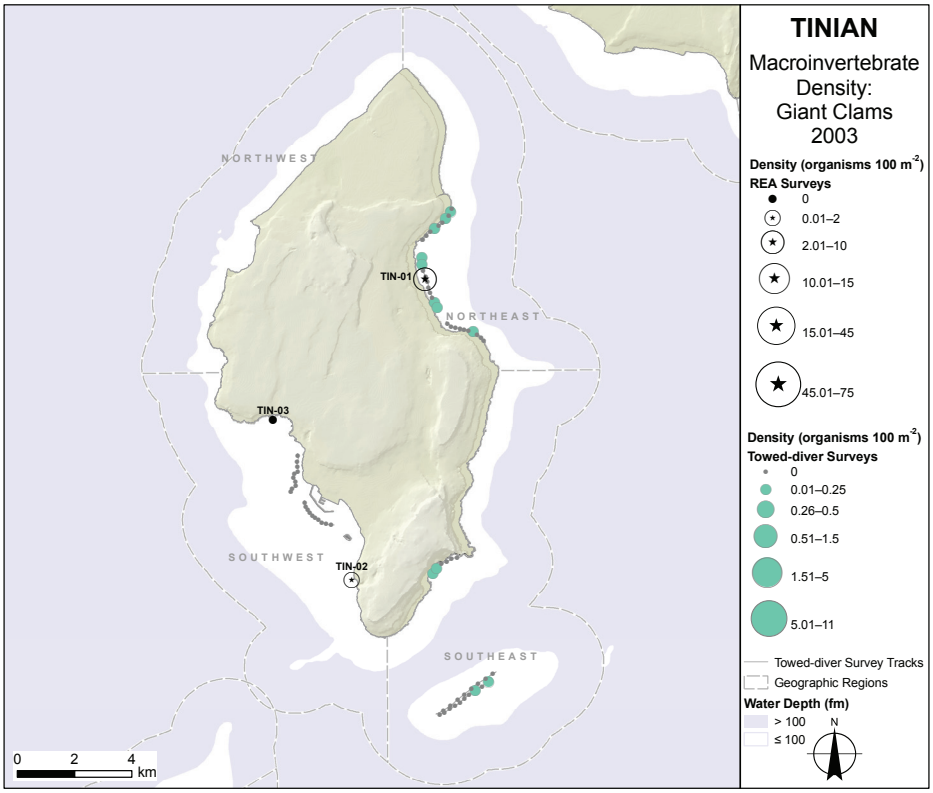


Figure 7.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003.

During MARAMP 2005, giant clams were observed at 3 of the 6 REA sites and in 8 of the 12 towed-diver surveys conducted around Tinian (Fig. 7.7.1b). With the increase in coverage by towed-diver surveys in 2005, giant clams were detected sporadically around much of Tinian but not in the southwest region. Also in this region, no giant clams were observed at the 3 REA sites surveyed there. The overall mean density of giant clams from REA surveys was 0.5 organisms 100 m^{-2} (SE 1.2), and the islandwide mean density from towed-diver surveys was 0.02 organisms 100 m^{-2} (SE 0.004). Among all towed-diver surveys around Tinian, the survey completed just south of Puntan Kastiyu in the southeast region had the highest mean density of giant clams with 0.11 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.26 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.04 organisms 100 m^{-2}, recorded in the northeast region just north of Puntan Masalok; segment densities ranged from 0 to 0.19 organisms 100 m^{-2}.

During MARAMP 2007, giant clams were observed at the 1 REA site surveyed and in 6 of the 8 towed-diver surveys conducted around Tinian (Fig. 7.7.1c). Density of giant clams at TIN-04, the single REA site surveyed in 2007, was 1.33 organisms 100 m^{-2}, and the overall mean density of giant clams from towed-diver surveys was 0.008 organisms 100 m^{-2} (SE 0.002). Among all towed-diver surveys around Tinian, the survey completed just north of Puntan Masalok in the northeast region had the highest mean density of giant clams with 0.02 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.09 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.015 organisms 100 m^{-2}, recorded in the northwest region between Puntans Lamanibot Sampapa` and Lamanibot Sanhilo; segment densities ranged from 0 and 0.11 organisms 100 m^{-2}.

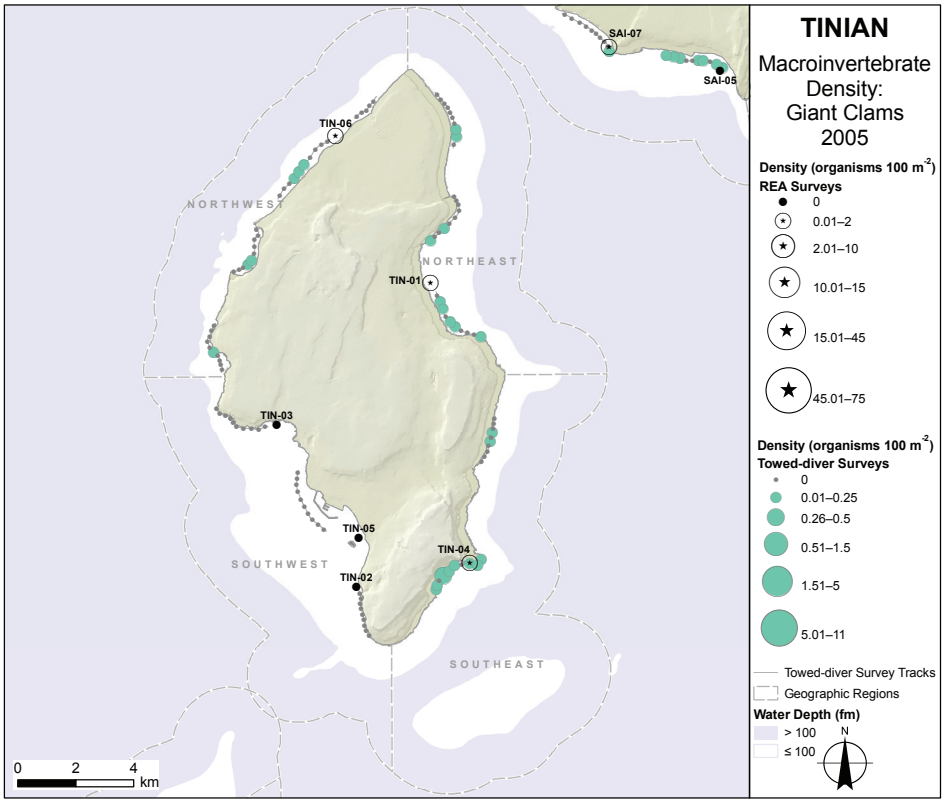


Figure 7.7.1b. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2005.

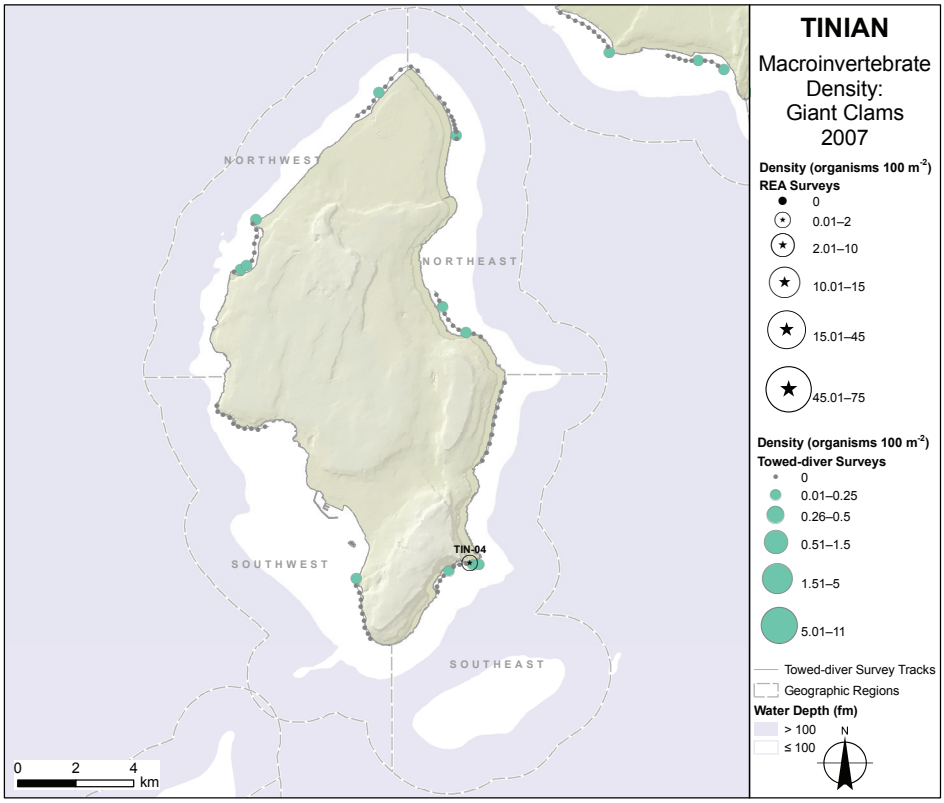


Figure 7.7.1c. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007.

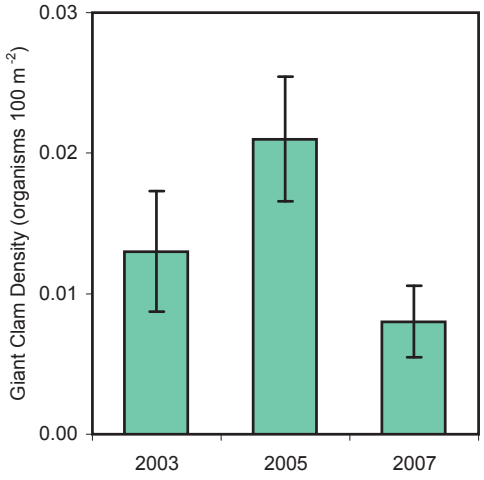


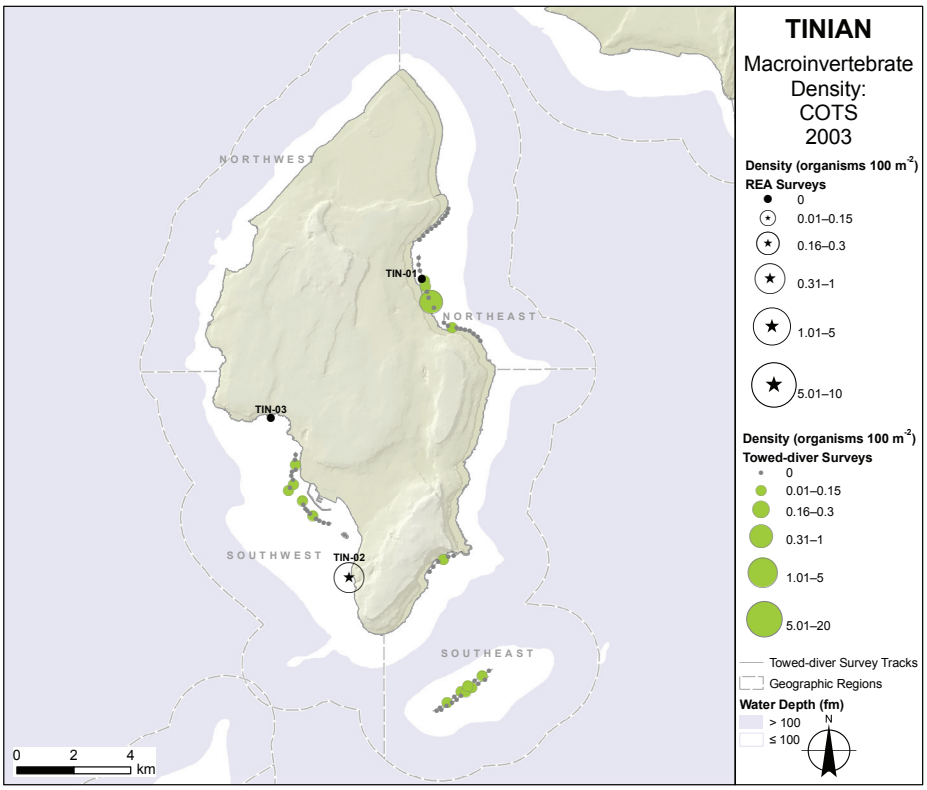
Figure 7.7.1d. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Tinian during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver benthic surveys suggested low abundance of giant clams around Tinian during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago. The overall observed mean density of giant clams was lower in 2007 than in 2005 (Fig. 7.7.1d). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Crown-of-thorns Seastars

During MARAMP 2003, COTS (*Acanthaster planci*) were observed at 1 of the 3 REA sites surveyed and in 5 of the 6 towed-diver surveys conducted at Tinian (Fig. 7.7.1e). COTS density at TIN-02 was 0.33 organisms 100 m^{-2}, and the overall mean density from towed-diver surveys was 0.018 organisms 100 m^{-2} (SE 0.007). Among all towed-diver surveys at Tinian, the survey completed in the northeast between Puntans Asiga and Masalok had the highest mean density of COTS with 0.04 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.31 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.03 organisms 100 m^{-2}, recorded just north of Tinian Harbor in the southwest region; segment densities ranged from 0 to 0.14 organisms 100 m^{-2}.

Figure 7.7.1e. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003.



The 2 towed-diver surveys conducted on Tatsumi Reef in 2003 recorded COTS densities with an overall mean density of 0.02 organisms 100 m^{-2}. The second survey, moving southwest, had the greater mean density at 0.03 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.15 organisms 100 m^{-2}.

During MARAMP 2005, COTS were observed at 1 of the 6 REA sites surveyed and in 7 of 12 towed-diver surveys conducted around Tinian (Fig. 7.7.1f). COTS density at TIN-01 was 0.33 organisms 100 m^{-2}, and islandwide mean density from towed-diver surveys was 0.02 organisms 100 m^{-2} (SE 0.005). The majority of COTS recorded during towed-diver surveys were observed in the northeast region between Puntans Asiga and Masalok. Among all towed-diver surveys around Tinian, the survey heading north around Puntan Asiga had the highest mean density of COTS with 0.13 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.39 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.06 organisms 100 m^{-2}, recorded just north of Puntan Masalok; segment densities ranged from 0 to 0.19 organisms 100 m^{-2}.

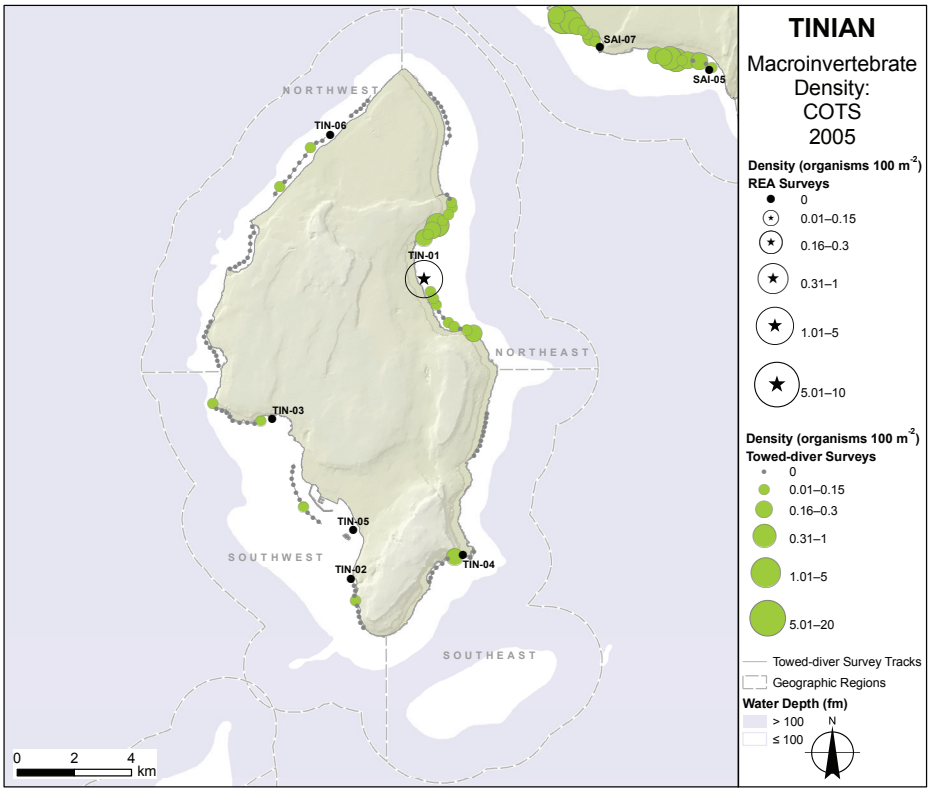


Figure 7.7.1f. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2005.

During MARAMP 2007, COTS were observed at the 1 REA site surveyed and in 4 of the 8 towed-diver surveys conducted around Tinian (Fig. 7.7.1g). COTS density at TIN-04, the single REA site surveyed in 2007, was 0.33 organisms 100 m^{-2}, and the islandwide mean density from towed-diver surveys was 0.008 organisms 100 m^{-2} (SE 0.004). Among all towed-diver surveys around Tinian, the survey completed in the southeast region near and around Puntan Kastiyu had the highest mean density of COTS with 0.05 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.22 organisms 100 m^{-2}.

Towed-diver surveys suggested low daytime densities of COTS around Tinian during MARAMP 2003, 2005, and 2007, relative to the rest of the Mariana Archipelago. The overall observed mean density of COTS was lower in 2007 than in 2003 and 2005 (Fig. 7.7.1h). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of COTS (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). The density of this corallivorous seastar naturally fluctuates with food availability and variation in recruitment success.

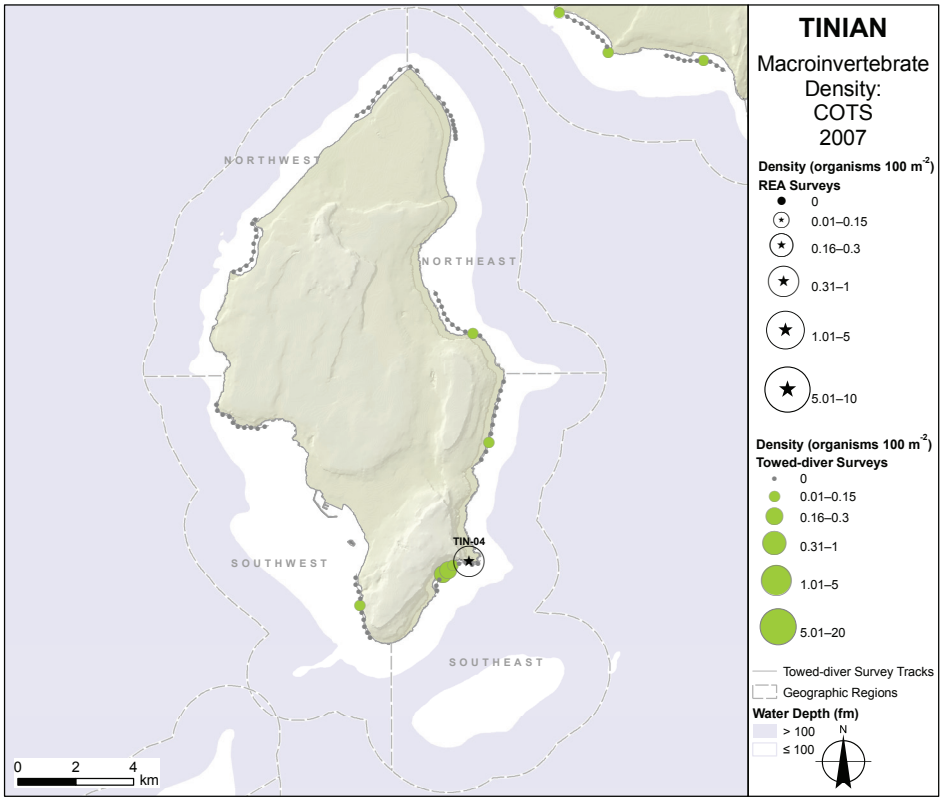


Figure 7.7.1g. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007.

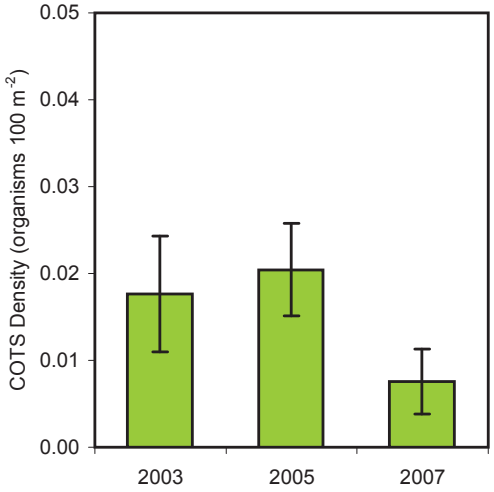


Figure 7.7.1h. Temporal comparison of COTS mean densities (organisms m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Tinian during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

During MARAMP 2003 and 2005, the greatest mean density of COTS from a towed-diver survey was recorded in the northeast region between Puntans Asiga and Masalok. The overall mean density of COTS in this region was 0.017 organisms 100 m^{-2} from 3 surveys in 2003, 0.096 organisms 100 m^{-2} from 2 surveys in 2005, and 0.003 organisms 100 m^{-2} from 1 survey in 2007. The observed density in this area increased fivefold between 2003 and 2005 even though fewer surveys were conducted there in 2005. The sharp reduction in observed density in 2007 was more likely a result of a population die off or exodus to shallower or deeper depths in search of food rather than a result of lower survey effort.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at 2 of the 3 REA sites surveyed and in all 6 towed-diver surveys conducted at Tinian (Fig. 7.7.1i). The sample mean density of sea cucumbers from REA surveys was 1 organism 100 m^{-2} (SE 0.58), and the overall mean density from towed-diver surveys was 0.73 organisms 100 m^{-2} (SE 0.201). Species from 3 genera were observed during REA surveys: *Pearsonothuria*, *Stichopus*, and *Holothuria*. Among all towed-diver surveys at Tinian, the survey performed to the north of Puntan Masalok had the highest mean density of sea cucumbers with 2.38 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 5.05 organisms 100 m^{-2}. Just a little farther north, the

towed-diver survey completed between Puntans Masalok and Asiga had the second-greatest mean density of sea cucumbers from a towed-diver survey with 1.44 organisms 100 m^{-2}; segment densities ranged from 0 to 3.87 organisms 100 m^{-2}.

The 2 towed-diver surveys conducted on Tatsumi Reef in 2003 recorded densities of sea cucumbers with an overall mean density of 0.41 organisms 100 m^{-2}. The second survey, moving southwest, had the greater mean density with 0.79 organisms 100 m^{-2}; segment densities from this survey ranged from 0.37 to 1.34 organisms 100 m^{-2}.

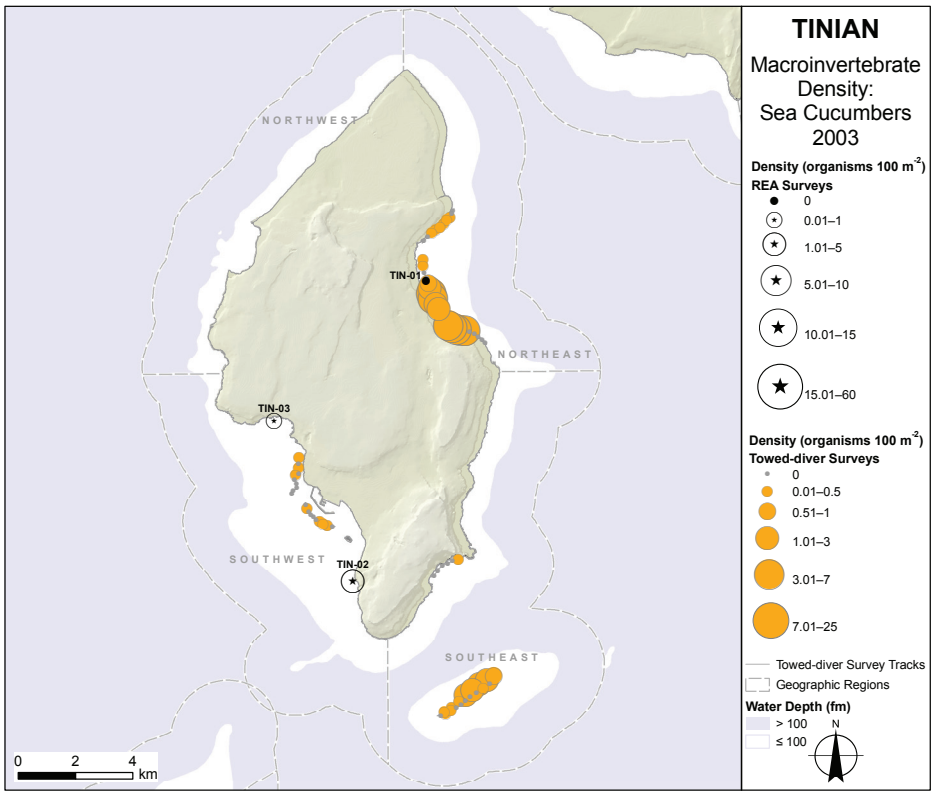


Figure 7.7.1i. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003.

During MARAMP 2005, sea cucumbers were observed at 3 of the 6 REA sites surveyed and in all 12 towed-diver surveys conducted around Tinian (Fig. 7.7.1j). The overall mean density of sea cucumbers from REA surveys was 1.66 organisms 100 m^{-2} (SE 1.12), and the islandwide mean density from towed-diver surveys was 0.16 organisms 100 m^{-2} (SE 0.03). Survey results suggest that sea cucumbers were most abundant at TIN-06 in the northwest region with a mean density of 7 organisms 100 m^{-2}—all of which consisted of animals from the genus *Stichopus*. During REA surveys at Tinian, *Stichopus* and *Holothuria* were the only 2 genera observed.

Overall, sea cucumbers were seen predominantly along the shores of the northern half of this island during towed-diver surveys in 2005. As in the REA surveys, the towed-diver survey that had the highest density, with a mean of 0.9 organisms 100 m^{-2}, was completed in the northwest region, specifically just south of Puntan Tahgong; segment densities from this survey ranged from 0.26 to 2.07 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.66 organisms 100 m^{-2}, recorded just north of Puntan Masalok in the northeast region; segment densities ranged from 0 to 1.64 organisms 100 m^{-2}.

During MARAMP 2007, no sea cucumbers were observed at the 1 REA site surveyed at Tinian, but sea cucumbers were recorded in all 8 of the towed-diver surveys conducted (Fig. 7.7.1k), with an islandwide mean density of 0.14 organisms 100 m^{-2} (SE 0.029). Among all towed-diver surveys around Tinian, the survey completed to the north of Puntan Masalok in the northeast region had the highest mean density of sea cucumbers with 0.61 organisms 100 m^{-2}; segment densities from this survey ranged from 0.08 to 1.49 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.13 organisms 100 m^{-2}, recorded just south of Puntan Tahgong in the northwest region; segment densities ranged from 0 to 0.41 organisms 100 m^{-2}.

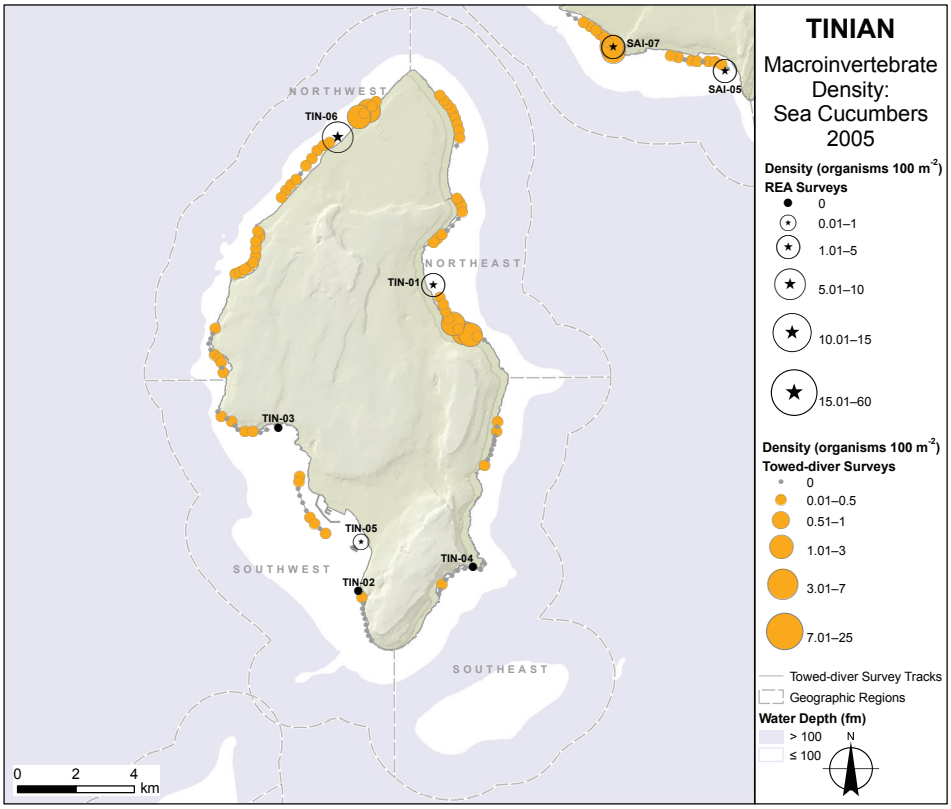


Figure 7.7.1j. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2005.

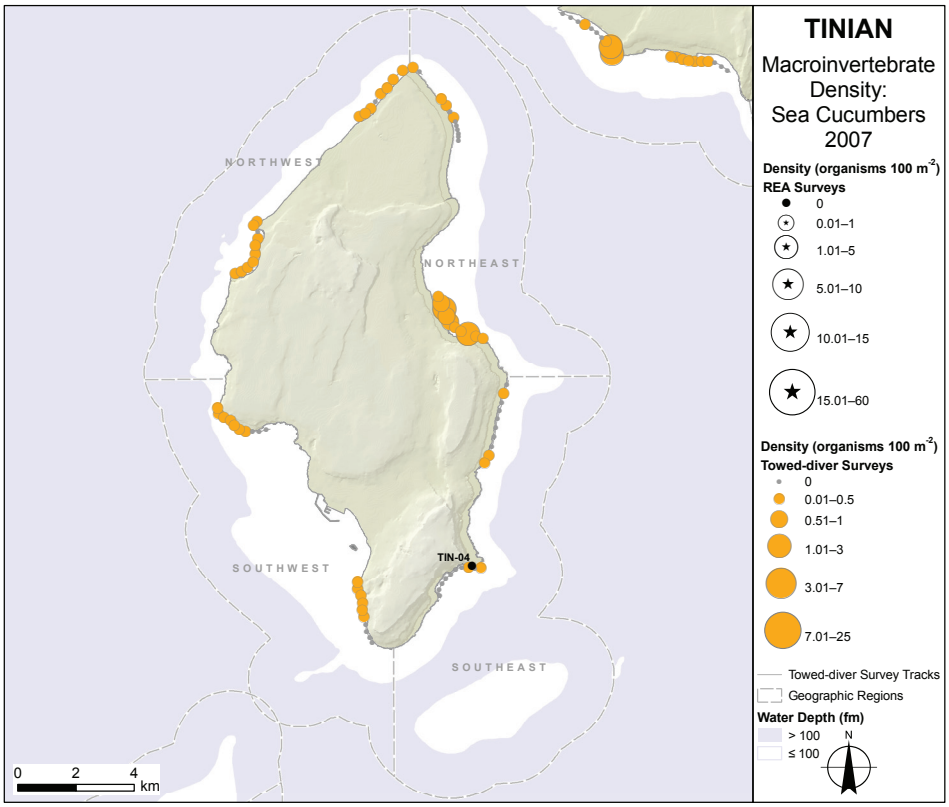


Figure 7.7.1k. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007.

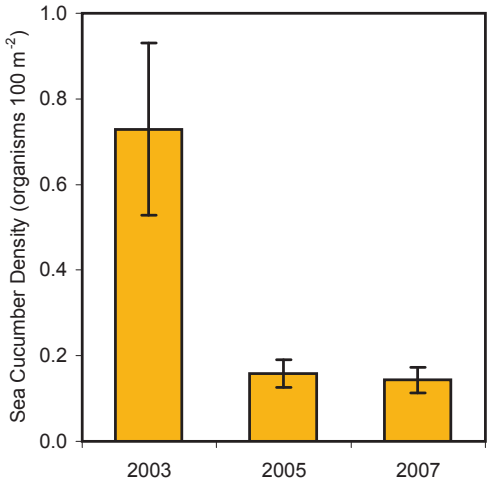


Figure 7.7.1l. Temporal comparison of mean densities (organisms m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Tinian during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested low daytime abundance of sea cucumbers around Tinian during MARAMP 2003, 2005, and 2007, relative to the rest of the Mariana Archipelago. The overall observed mean density of sea cucumbers was much lower in 2005 and 2007 than in 2003 (Fig. 7.7.1l). Although the overall number of surveys increased around Tinian during MARAMP 2005 and 2007, the number of surveys conducted in the area that had the greatest density of sea cucumbers in 2003—between Puntans Asiga and Masalok in the northeast region—decreased to 2 surveys in 2005 and 1 survey in 2007 from 3 surveys in 2003 (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Sea Urchins

During MARAMP 2003, sea urchins were observed at all 3 of the REA sites surveyed and in 4 of the 6 towed-diver surveys conducted at Tinian (Fig. 7.7.1m). The sample mean density of sea urchins from REA surveys was 11.67 organisms 100 m^{-2} (SE 5.17), and the overall mean density from towed-diver surveys was 2.05 organisms 100 m^{-2} (SE 0.43). Survey results suggest that sea urchins were most abundant at TIN-02, in the southwest region north of Puntan Carolinas, with a mean density of 22 organisms 100 m^{-2}. Four genera were observed overall during REA surveys at Tinian: *Echinostrephus*, *Echinometra*, *Echinothrix*, and *Diadema.* The rock-boring urchins *Echinostrephus* and *Echinometra* were the dominant macroinvertebrate taxa at all sites; together, they accounted for 91% of recorded urchins, and the genus *Echinostrephus* alone composed 84% of boring urchins. TIN-03, east of Puntan Diapblo, had the greatest species diversity with representatives from the genera *Echinostrephus*, *Echinometra*, and *Diadema.*

Among all towed-diver surveys conducted at Tinian in 2003, the survey completed just north of Puntan Masalok in the northeast region had the highest mean density of sea urchins in 20037 with 4.69 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 11.34 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 3.5 organisms 100 m^{-2}, recorded during the survey completed around Puntan Asiga in the northeast region; segment densities ranged from 0 to 5.31 organisms 100 m^{-2}. The next-highest mean density of 3.2 organisms 100 m^{-2} was from the towed-diver survey performed in the southeast region near Puntan Kastiyu; segment densities ranged from 0 to 9.9 organisms 100 m^{-2}. No sea urchins were recorded during the 2 surveys conducted near Tinian Harbor.

The 2 towed-diver surveys conducted on Tatsumi Reef in 2003 recorded densities of sea urchins with an overall mean density of 2.13 organisms 100 m^{-2}. The first towed-diver survey, moving southwest, had the greater mean density with 6.55 organisms 100 m^{-2}; segment densities from this survey ranged from 3.61 to 9.25 organisms 100 m^{-2}. The second towed-diver survey had a mean density of 3.92 organisms 100 m^{-2}; segment densities ranged from 2.37 to 6.44 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed at all 6 of the REA sites surveyed and in 10 of the 12 towed-diver surveys conducted around Tinian (Fig. 7.7.1n). The overall mean density of sea urchins from REA surveys was 10.22 organisms 100 m^{-2} (SE 3.78), and the islandwide mean density from towed-diver surveys was 4.48 organisms 100 m^{-2} (SE 1.05). Survey results suggest that sea urchins were most abundant at TIN-04 near Puntan Kastiyu with a mean density of 22 organisms 100 m^{-2}. The second-greatest density, recorded at TIN-01 in Asiga Bay, was 20 organisms 100 m. Species from 2 genera were observed during REA surveys: *Echinometra* and *Diadema*.

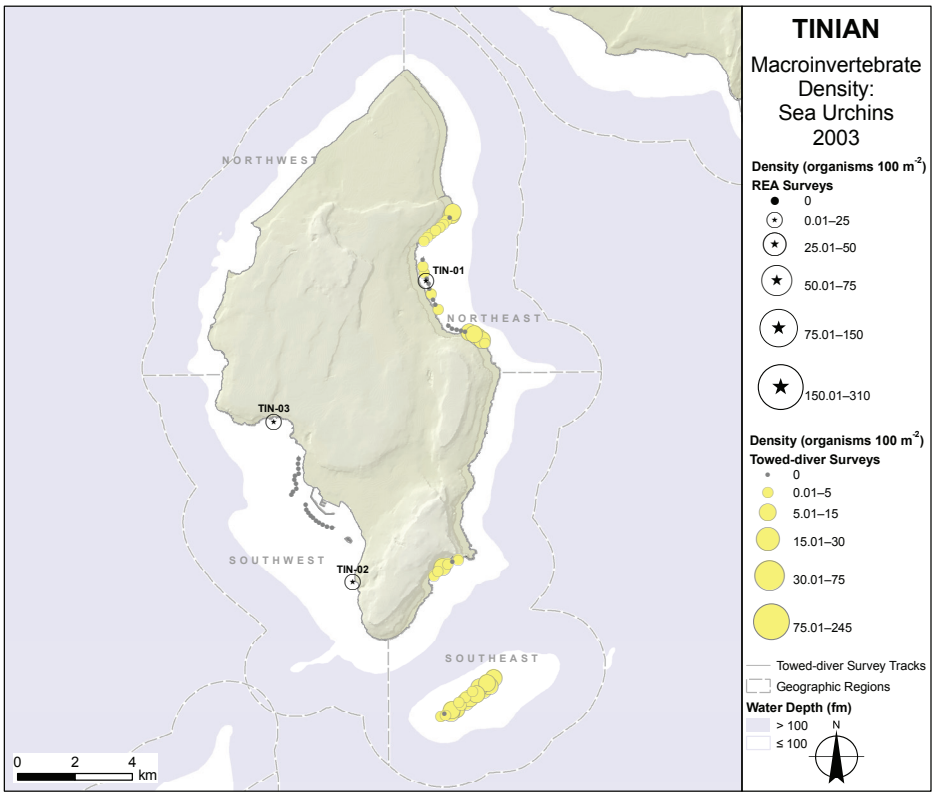


Figure 7.7.1m. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003.

Sea urchins were most abundant along the western shore, around Puntan Atgidon and east of Puntan Diapblo, as well as in the southeast region around Puntan Kastiyu during towed-diver surveys in 2005. Among all towed-diver surveys around Tinian, the survey completed near Puntan Diapblo had the highest mean density of sea urchins with 23.38 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 57.13 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 8.3 organisms 100 m^{-2}, recorded near Puntan Kastiyu; segment densities ranged from 0 to 47.5 organisms 100 m^{-2}.

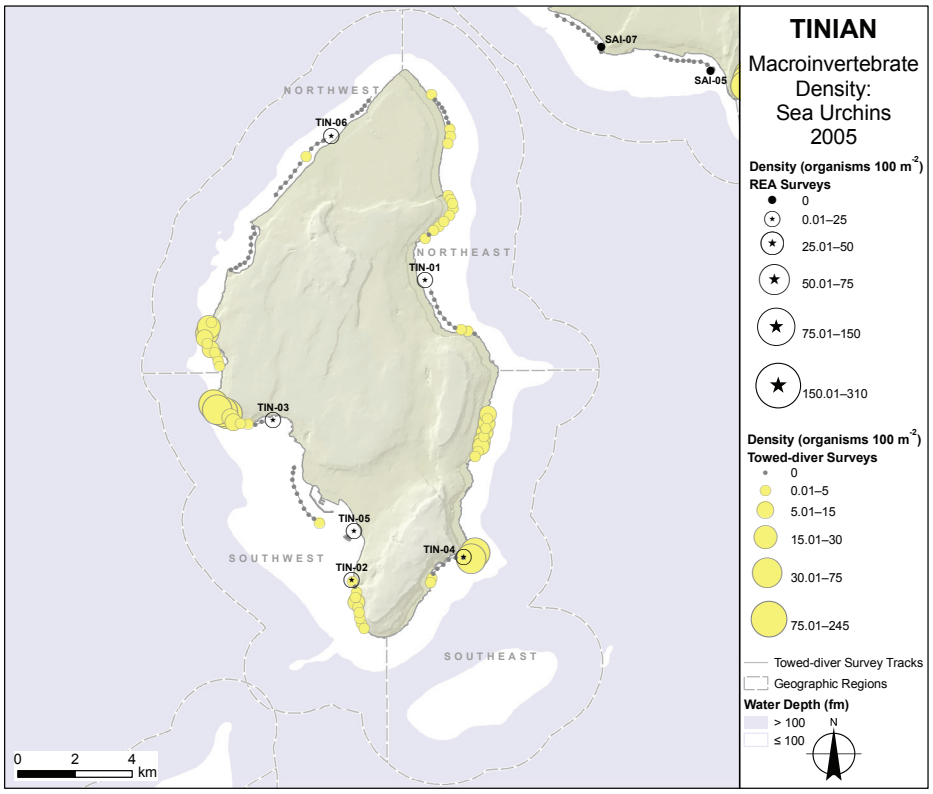


Figure 7.7.1n. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2005.

During MARAMP 2007, sea urchins were observed at the 1 REA site surveyed and in all 8 of the towed-diver surveys conducted around Tinian (Fig. 7.7.1o). The density of sea urchins at TIN-04, the single REA site surveyed in 2007, was 20.33 organisms 100 m^{-2}, and the islandwide mean density from towed-diver surveys was 6.37 organisms 100 m^{-2} (SE 1.20). Only the rock-boring urchins, *Echinostrephus* and *Echinometra*, were observed during the REA survey, with 98% of observations belonging to the genus *Echinostrephus.* Among all towed-diver surveys around Tinian, the survey completed near Puntan Diapblo had the highest mean density of sea urchins with 19.91 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 48.58 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 10.12 organisms 100 m^{-2}, recorded south of Puntan Masalok in the southeast region; segment densities ranged from 2.55 to 23.28 organisms 100 m^{-2}.

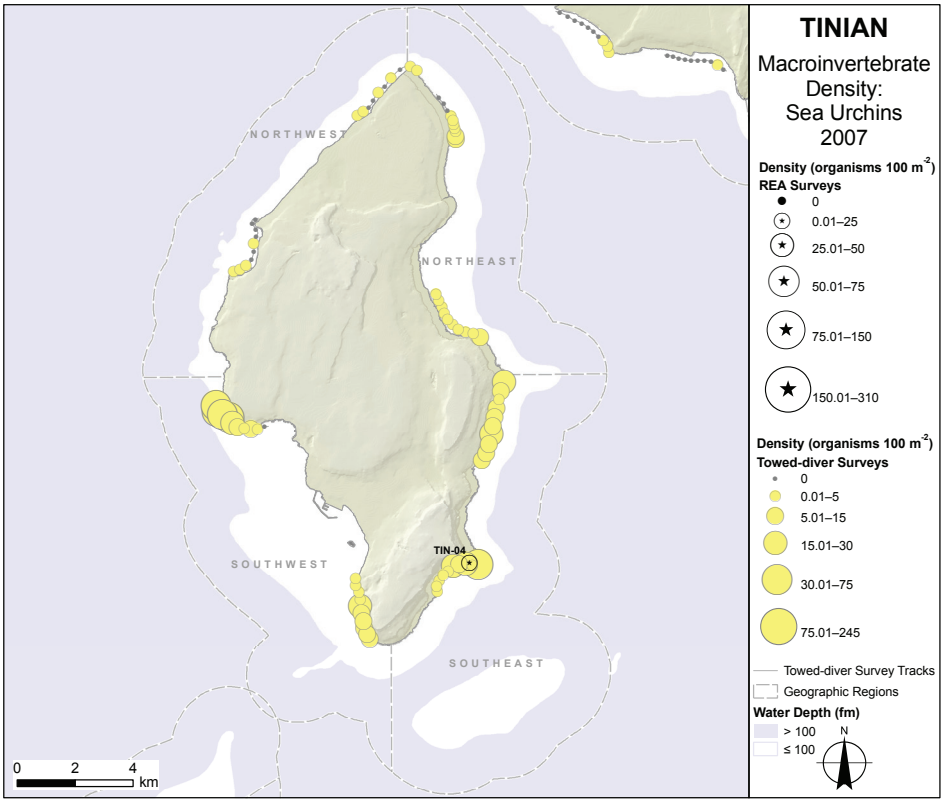


Figure 7.7.1o. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007.

With the exceptions of the surveys near Puntans Diapblo and Kastiyu, towed-diver surveys suggested low daytime abundance of sea urchins around Tinian, compared to the rest of the Mariana Archipelago. The overall observed mean density of sea urchins was lower in 2003 than in 2005 and 2007 (Fig. 7.7.1p). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). During both MARAMP 2005 and 2007, the greatest mean density of sea urchins from towed-diver surveys was recorded on the west side of Tinian in areas that were not surveyed in 2003.

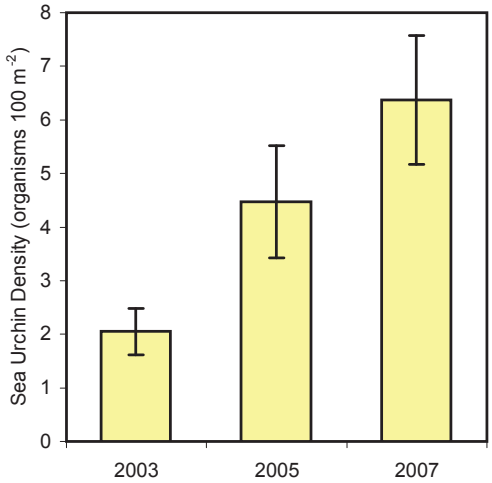


Figure 7.7.1p. Temporal comparison of mean densities (organisms m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Tinian during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

7.8 Reef Fishes

7.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 6 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats at the island of Tinian, primarily in the southwest and northeast regions; 2 additional surveys were completed near Tatsumi Reef. The overall estimated mean biomass of large fishes at Tinian, calculated as weight per unit area, was 0.20 kg 100 m^{-2} (SE 0.09), a low value compared to other survey areas in the Mariana Archipelago. Reef sharks (Carcharhinidae) accounted for the greatest proportion (50%) or 0.10 kg 100 m^{-2} of overall mean large-fish biomass. Three reef sharks, all of them whitetip reef sharks (*Triaenodon obesus*), were observed at Tinian, 1 near Puntan Masalok in the northeast region and 2 south of Puntan Kastiyu in the southeast region (Fig. 7.8.1a; for place-names and their locations, see Figure 7.2a in Section 7.2: Survey Effort).

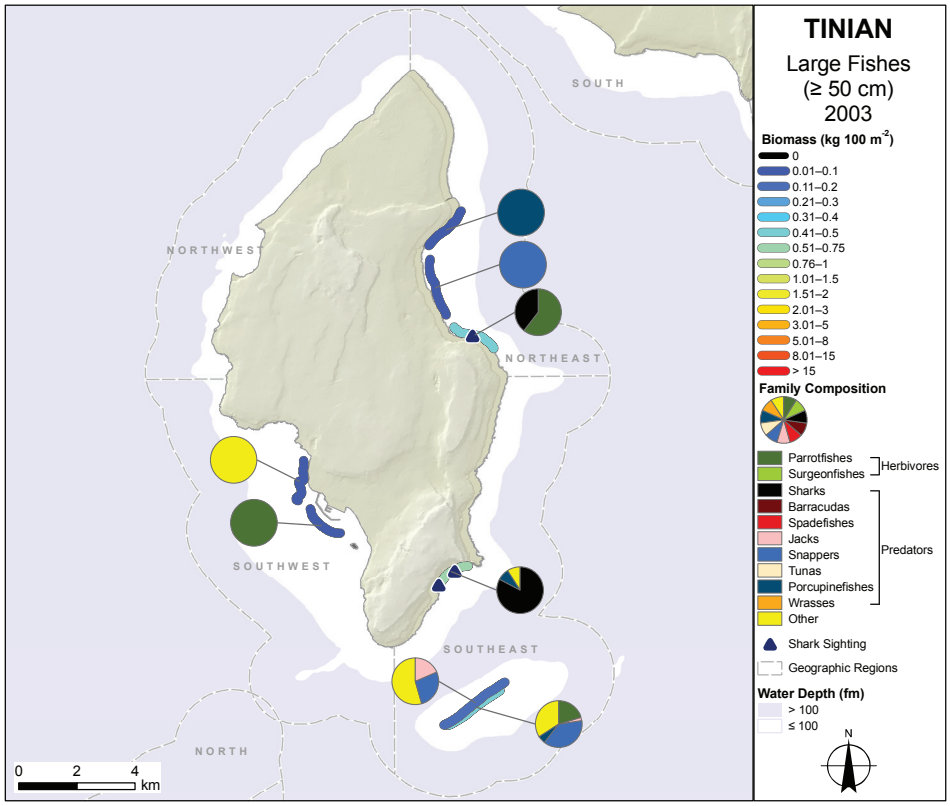


Figure 7.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted at Tinian during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

During MARAMP 2005, 12 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Tinian. The islandwide estimated mean biomass of large fishes was 0.17 kg 100 m^{-2} (SE 0.07). Stingrays (Dasyatidae) contributed the greatest proportion (45%) of islandwide mean large-fish biomass. No clear spatial patterns in the distribution of large-fish biomass or families were evident in 2005. One reef shark, a whitetip reef shark, was observed near Puntan Kastiyu in the southeast region (Fig. 7.8.1b).

During MARAMP 2007, 8 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Tinian. The overall estimated mean biomass of large fishes around this island was 0.31 kg 100 m^{-2} (SE 0.15), a level higher than the islandwide values observed in the previous MARAMP survey years. Barracudas (Sphyraenidae) and sharks accounted for the largest proportion of islandwide large-fish biomass, contributing 0.11 and 0.07 kg 100 m^{-2} of overall mean biomass. Mean large-fish biomass was somewhat higher along the east side of this island, compared to other areas surveyed at Tinian (Fig. 7.8.1c). In 2007, 11 sharks were observed. Whitetip reef sharks were the most common with 8 individuals encountered. The remaining sharks were 2 black tip reef sharks (*Carcharhinus melanopterus*) and 1 tawny nurse shark (*Nebrius ferrugineus*). A majority of these sharks were seen along the east coast, 3 of them north of Puntan Barangka.

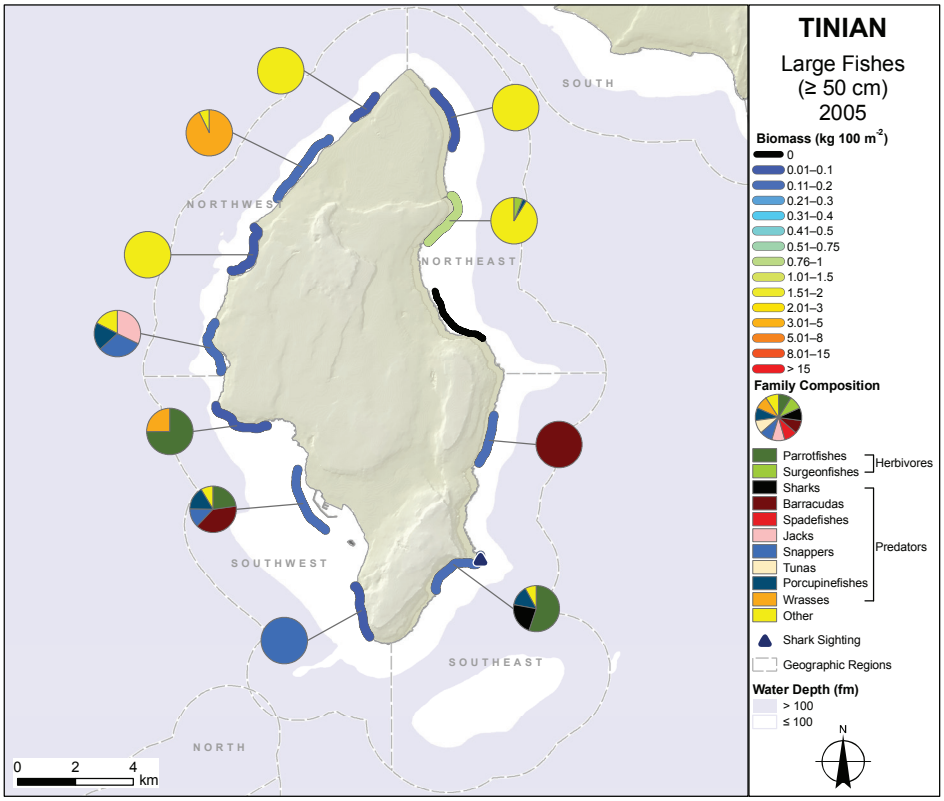


Figure 7.8.1b. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Tinian during MARAMP 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

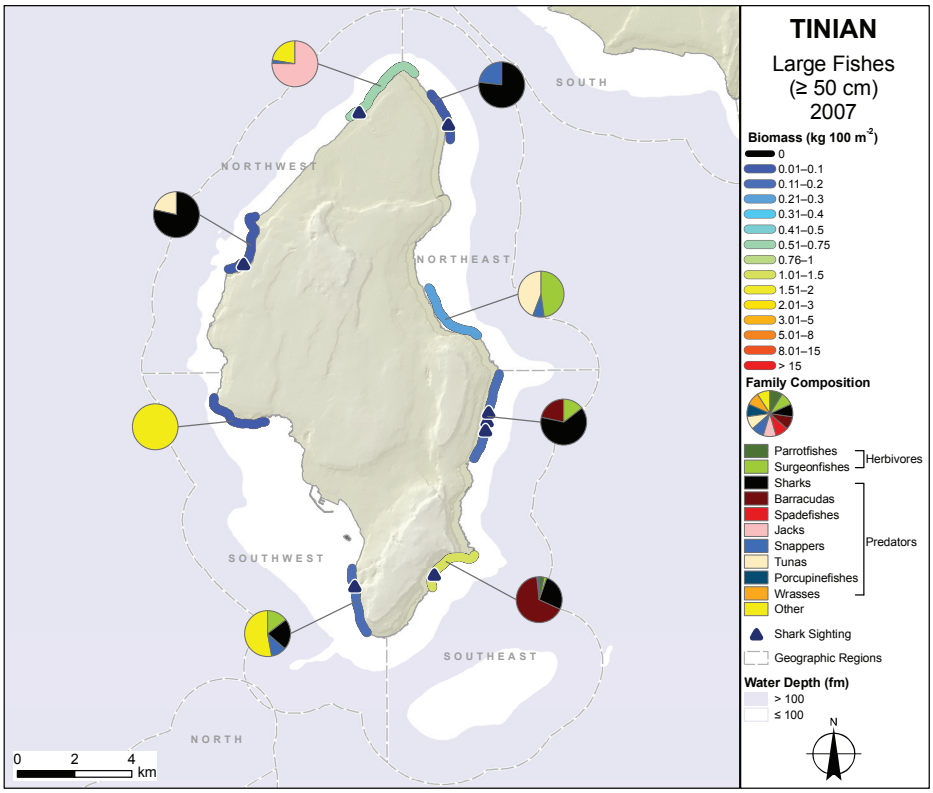
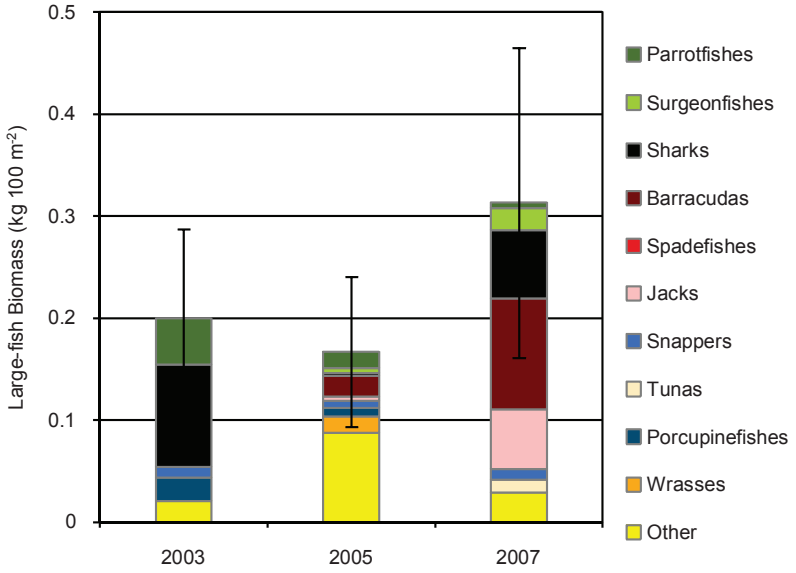


Figure 7.8.1c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Tinian during MARAMP 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

Islandwide mean biomass of large fishes from towed-diver surveys of forereef habitats around Tinian ranged from 0.17 kg 100 m^{-2} (SE 0.07) in 2005 to 0.31 kg 100 m^{-2} (SE 0.15) in 2007 (Fig. 7.8.1d). Sharks were sighted more frequently on the east side of Tinian, with the fewest sharks observed during MARAMP 2005, when only one shark was sighted. Large-fish biomass from towed-diver surveys was higher on the east side of Tinian in 2007.

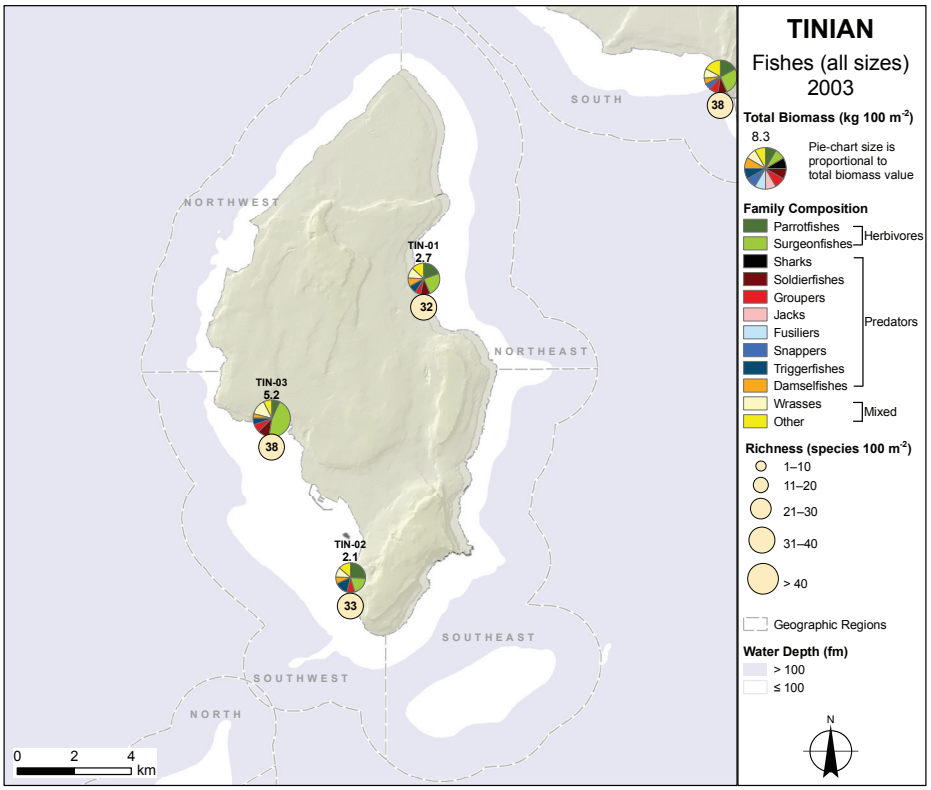
Figure 7.8.1d. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Tinian during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.



Total Fish Biomass and Species Richness

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Tinian during MARAMP 2003 was low compared to other sites in the Mariana Archipelago, with an overall sample mean of 3.33 kg 100 m^{-2} (0.96 SE). The highest biomass of 5.22 kg 100 m^{-2} was observed at TIN-03 in the southwest region, and the lowest biomass of 2.09 kg 100 m^{-2} was found at TIN-02 farther south along the southwest coast (Fig. 7.8.1e). Surgeonfishes (Acanthuridae) and parrotfishes (Scaridae) together accounted for about half of the total mean biomass, contributing 1.14 and 0.47 kg 100 m^{-2} of biomass.

Figure 7.8.1e. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Tinian during MARAMP 2003.



Based on REA surveys conducted during MARAMP 2003, species richness at Tinian did not vary much with a small range of 32–38 species 100 m^{-2}. Damselfishes (Pomacentridae), surgeonfishes (Acanthuridae) and wrasses (Labridae) were common. No large fishes (≥ 50 cm TL) were recorded during REA surveys.

Total fish biomass for the 6 REA sites surveyed in forereef habitats around Tinian during MARAMP 2005 remained low with an overall sample mean of 4.04 kg 100 m^{-2} (SE 0.88). The highest biomass of 6.27 kg 100 m^{-2} was observed in the southeast region at TIN-04 near Puntan Kastiyu, and the lowest biomass (1.22 kg 100 m^{-2}) again was found in the southern part of the southwest region, this time at TIN-05 just south of Tinian Harbor (Fig. 7.8.1f). Surgeonfishes and parrotfishes together accounted for 64% of the total mean biomass, a proportion that was dominated by the striated surgeonfish (*Ctenochetus striatus*) and the orange-spine unicornfish (*Naso lituratus*).

Based on REA surveys conducted during MARAMP 2005, species richness around Tinian, with a range of 24–37 species 100 m^{-2}, was broadly similar to data recorded in 2003. Damselfishes, most of them juveniles, composed the most abundant family with 3 species that were particularly common: princess damsel (*Pomacentrus vaiuli*), jewel damsel (*Plectroglyphidodon lacrymatus*), and midget chromis (*Chromis acares*). Wrasses and surgeonfishes were also common.

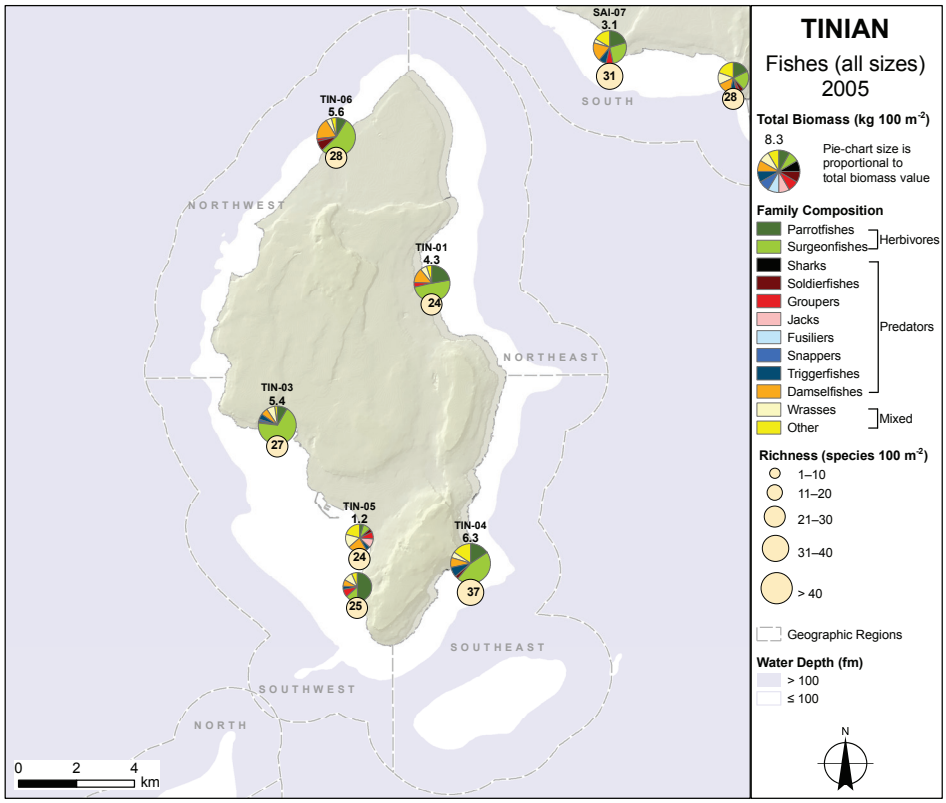


Figure 7.8.1f. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats around Tinian during MARAMP 2005.

Total fish biomass at the 5 REA sites surveyed in forereef habitats around Tinian during MARAMP 2007, with an overall sample mean of 4.16 kg 100 m^{-2} (0.73 SE), was above the average observed at the southern islands but moderately low compared to survey results from other islands in the Mariana Archipelago. The highest biomass of 5.68 kg 100 m^{-2} was observed at TIN-04 in the southeast region, and the lowest biomass of 2.04 kg 100 m^{-2} was found in the northwest region at TIN-06 southwest of Puntan Tahgong (Fig. 7.8.1g). Parrotfishes and surgeonfishes together accounted for the largest proportion (62%) of total fish biomass around Tinian, contributing 1.58 and 0.99 kg 100 m^{-2} of biomass.

Based on REA surveys conducted during MARAMP 2007, species richness around Tinian was similar to results from previous survey years with a range of 21–36 species 100 m^{-2}. The highest diversity was observed at TIN-02 in the southwest region.

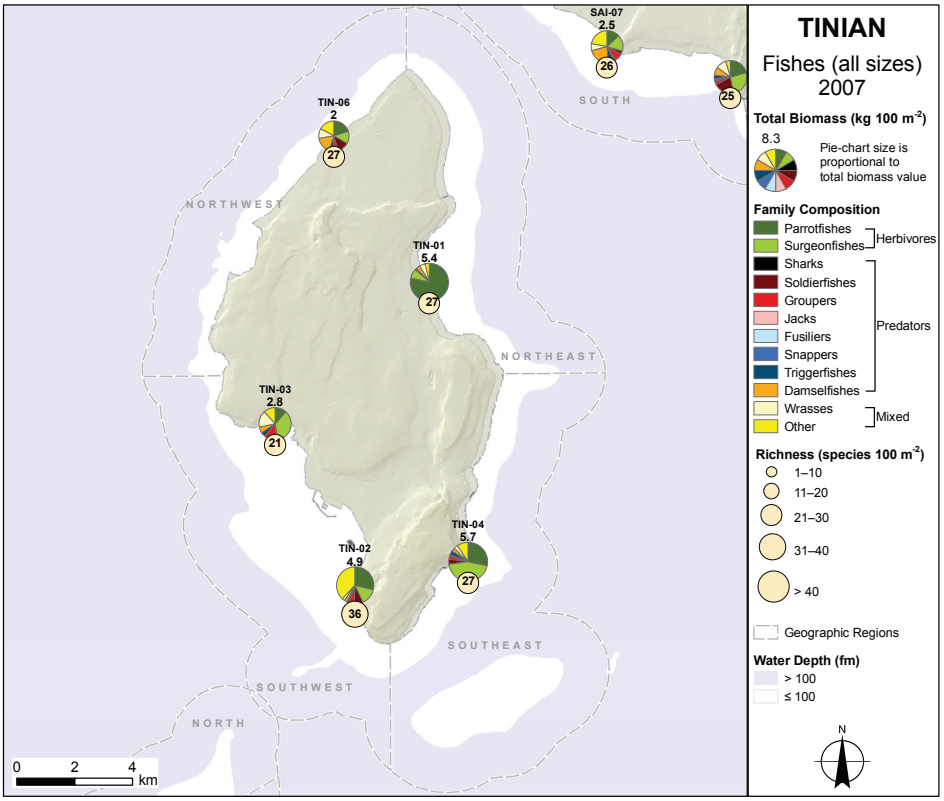


Figure 7.8.1g. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats around Tinian during MARAMP 2007.

The lack of consistent survey effort made it difficult to identify clear spatial patterns for total fish biomass in forereef habitats around Tinian between the 3 MARAMP survey periods. During the 3 survey years, parrotfishes and surgeonfishes were major contributors to biomass. Overall mean values of total fish biomass from REA surveys conducted at Tinian varied from 3.33 kg 100 m^{-2} in 2003 to 4.16 kg 100 m^{-2} in 2007 (Fig. 7.8.1h). Across the 3 MARAMP survey years combined, mean total fish biomass around Tinian was 3.85 kg 100 m^{-2} (SE 0.26).

No clear patterns for species richness were seen between sites or MARAMP survey years. The average diversity of fish species around Tinian was 29.9 species 100 m^{-2} (SE 2.3) across all REA surveys conducted during MARAMP 2003, 2005, and 2007.

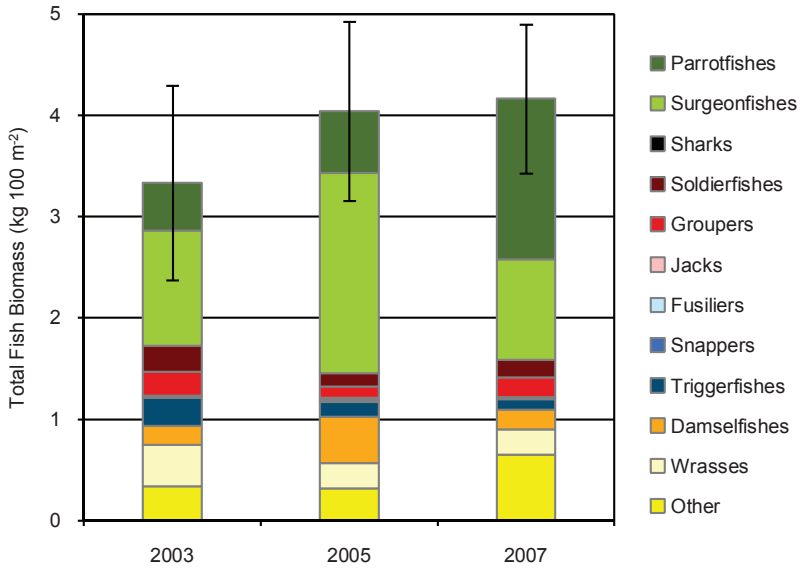


Figure 7.8.1h. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted around Tinian during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

7.9 Marine Debris

7.9.1 Marine Debris Surveys

During MARAMP 2003, 15 man-made objects were recorded in the 6 towed-diver surveys conducted on forereef habitats at the island of Tinian. Debris sightings were recorded only in the southwest region (Fig. 7.9.1a). Outside of the Tinian Harbor break-wall, 2 anchors, 2 pipes, and 4 cables were identified (for place-names and their locations, see Figure 7.2a in Section 7.2: Survey Effort). No additional descriptive information was recorded during towed-diver surveys, and no derelict fishing gear, munitions, or wrecks were identified.

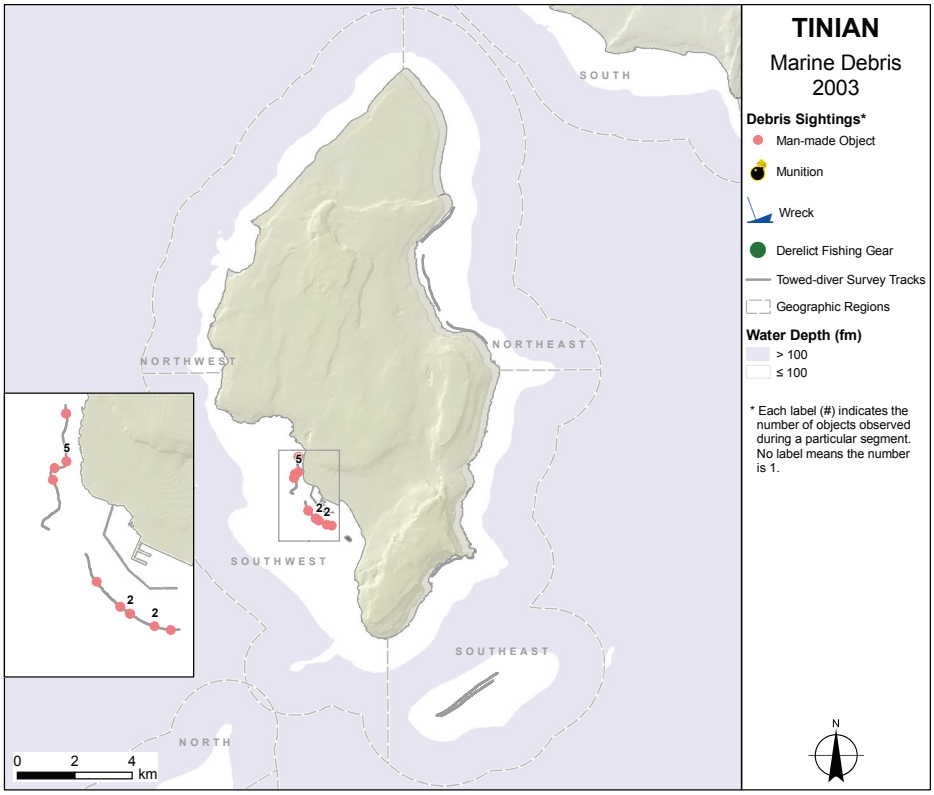


Figure 7.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted at Tinian during MARAMP 2003. Symbols indicate the presence of specific debris types.

During MARAMP 2005, 3 sightings of derelict fishing gear and 2 sightings of other man-made objects were recorded in the12 towed-diver surveys conducted on forereef habitats around Tinian (Fig. 7.9.1b). In the southwest region near Puntan Carolinas, one of the sighting of derelict fishing gear consisted of lost lines and weights at a depth of 14–15 m. In the northwest region, a trawl or seine net was observed at a depth of 16–18 m in the vicinity of Puntan Atgidon, and a small net was noted north of Puntan Lamanibot Sanhilo. Finally, a dump site that included helicopter components and wheels was recorded just off Puntan Lamanibot Sanhilo. No munitions or wrecks were identified.

During MARAMP 2007, 1 sighting of derelict fishing gear, 15 sightings of munitions, 1 wreck, and 35 other man-made objects were recorded in the 8 towed-diver surveys conducted on forereef habitats around Tinian (Fig. 7.9.1c). No additional descriptive information was recorded for the derelict fishing gear, which was located in the northeast region near Puntan Masalok. In the southeast region South of Puntan Kastiyu, an estimated 15 bombs (unexploded ordinances), each ~ 110 kg, were noted at 14°56′ N, 145°39′ E, and a possible airplane wheel strut was observed during the same survey. As in observations made in 2005, a dump site was recorded in the northwest region near Puntan Lamanibot Sanhilo. This time at that site, 35 man-made objects were counted within the survey swath, including helicopter components, airplane and vehicle parts, and many unidentifiable metal objects.

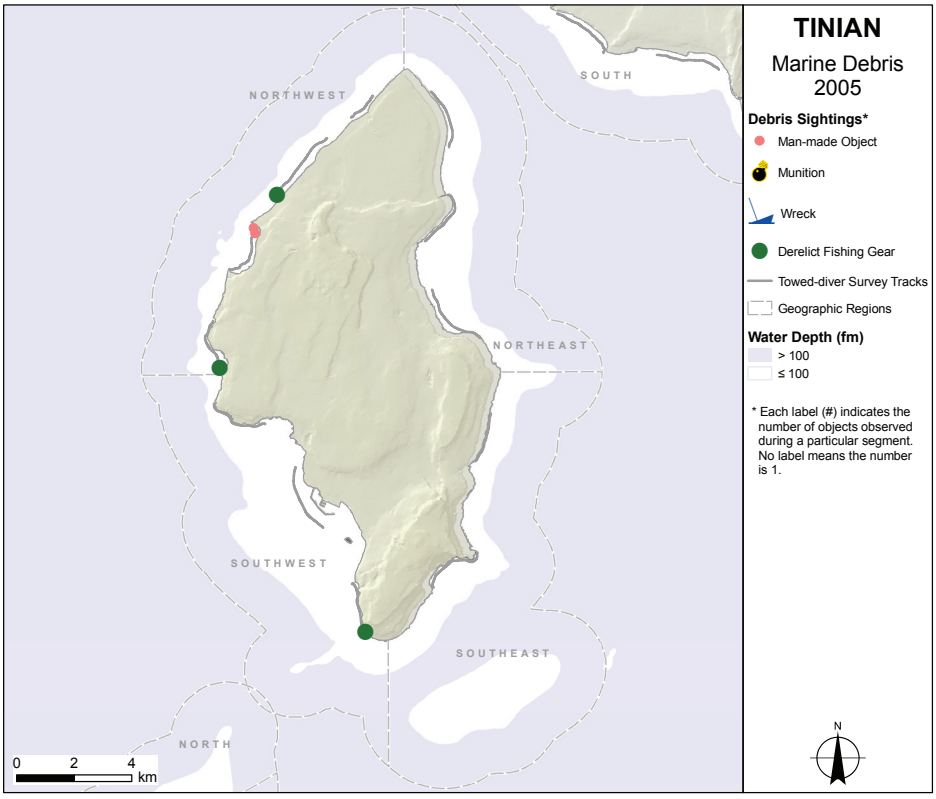


Figure 7.9.1b. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2005. Symbols indicate the presence of specific debris types.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments. Still, the location of an apparent dump site in the vicinity of Puntan Lamanibot Sanhilo was the same in 2005 and 2007.

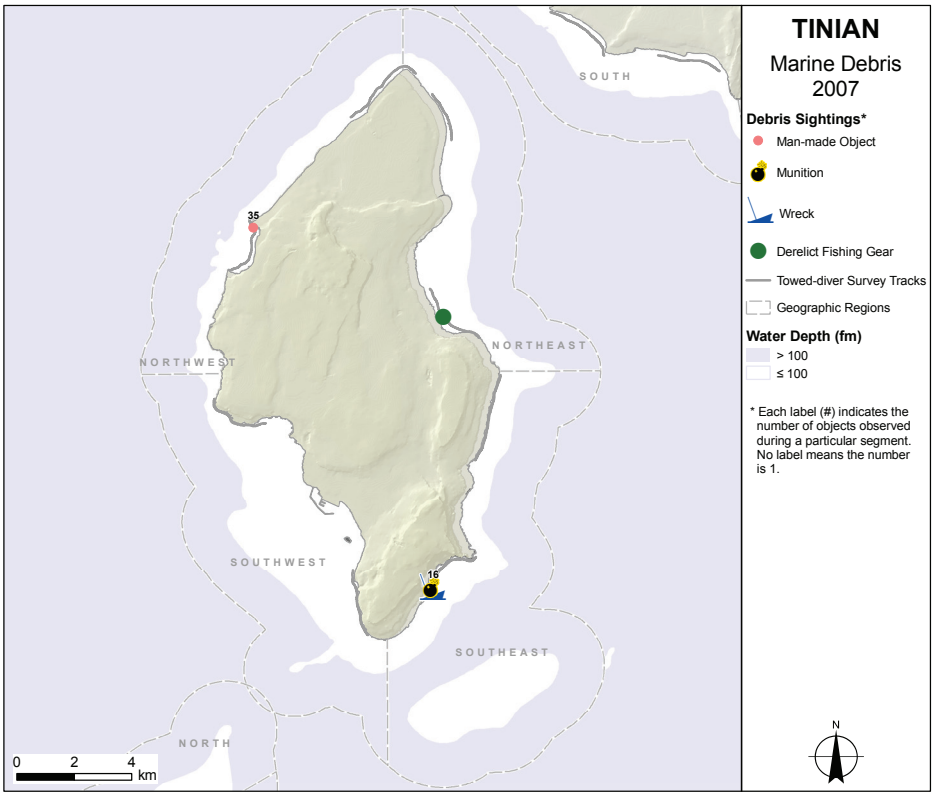


Figure 7.9.1c. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Tinian during MARAMP 2007. Symbols indicate the presence of specific debris types.

7.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Tinian are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. Biological information from towed-diver surveys was integrated to derive 3 composite indices that provide assessments of the relative ecological conditions of forereef habitats in the 4 populated, southern islands of Tinian, Saipan, Rota, and Guam.

The *Benthic Condition Index for Guam, Rota, Tinian, and Saipan* was derived by equally weighting observations of the following 5 parameters from towed-diver benthic surveys around these 4 islands: cover of live hard corals, stressed corals, macroalgae, and crustose coralline red algae and density of crown-of-thorns seastars (COTS). The *Fish Condition Index for Guam, Rota, Tinian, and Saipan* was derived from 2 equally weighted parameters from towed-diver fish surveys: density and biomass of large fishes (≥ 50 cm in TL). The overall *Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan* was derived from an equal weighting of these benthic and fish indices. These condition indices were calculated using ranks assigned to the biological variables from towed-diver surveys conducted around Tinian, relative to all surveys performed around the 4 populated, southern islands of Tinian, Saipan, Rota, and Guam for each survey year. To indicate changes in these ranks between survey years, these indices were visualized on a map within survey areas, which are represented by color-coded and irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007 (towed-diver-survey tracks were often similar but not exactly the same in each survey year). For more details about the methodology behind these indices, see Chapter 2: "Methods and Operational Background," Section 2.5: "Ecosystem Integration." Each of these 3 condition indices for Tinian is presented on a map in Figure 7.10a. Reef condition indices for the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," providing ranks for Tinian as well as the other 13 islands covered in this report.

Tinian sits atop a steeply sloping bank that is primarily composed of carbonate terraces that overlie a volcanic core. Hard–soft analysis and towed-diver observations suggest that the substrate on these terraces is predominantly hard. West of Tinian, areas of softer sediment were observed, mainly associated with sand patches within shallow bays and the anchorage and on the shelf slope. At various points around this island, the submarine bank extends away from the coast, forming ridges. Tatsumi Reef, a popular fishing bank, lies ~ 2 km south-southeast of Tinian, and the uninhabited island of Aguijan is located ~ 5 km to the southwest.

Immediately offshore in the southwest region of Tinian, the anchorage area is formed by 4–6 carbonate platforms of progressively deeper shelves and characterized by a mixture of hard and soft substrate. The anchorage area, which extends 2 km offshore, was one of the few areas of flats around Tinian suggested by BPI terrain analysis. Based on towed-divers surveys of forereef habitats, estimates of habitat complexity and live coral cover were low in the 3 MARAMP survey years in this area, relative to other areas surveyed around Tinian. High levels of macroalgal cover were observed near Tinian Harbor compared to most other areas surveyed around this island (for place-names and their locations, see Figure 7.2a in Section 7.2: Survey Effort). From the anchorage area south to Puntan Carolinas, towed divers characterized habitat complexity as high to medium. The rank for this area in the Benthic Condition Index for Guam, Rota, Tinian and Saipan was high in 2005 and medium in 2007 (Fig. 7.10a). Observed coral cover was low there in 2005 and 2007 compared to other areas surveyed around Tinian, and stressed-coral cover was > 10% for several survey segments in 2007 (Fig. 7.10b), suggesting some level of declining condition in this area.

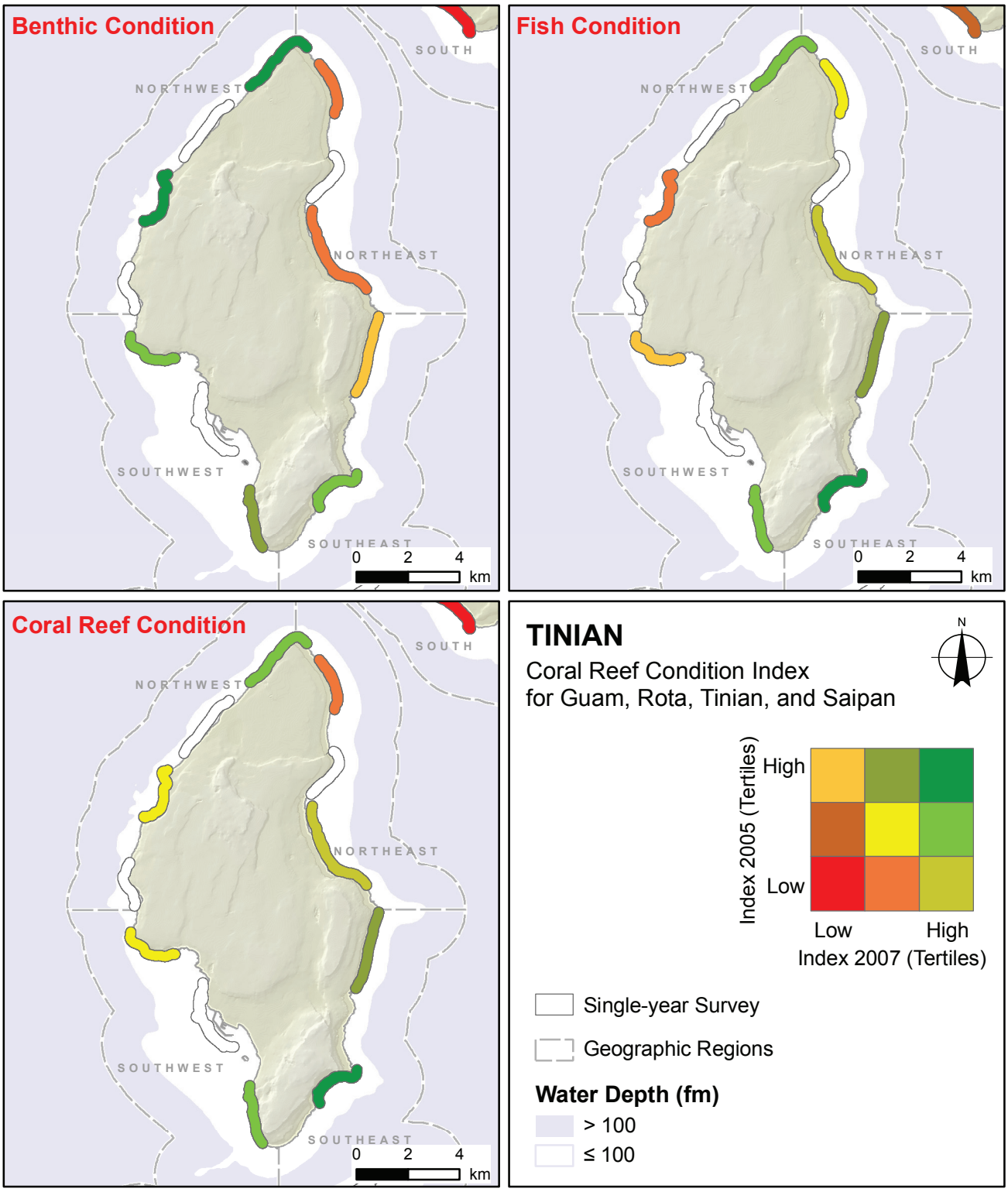


Figure 7.10a. The Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan, as well as the associated Benthic Condition Index and Fish Condition Index, reflects the condition of the benthic and fish communities and their integrated ecosystem for each towed-diver-survey area, *relative to other survey areas around the 4 populated, southern islands*. These maps indicate changes in index ranks between MARAMP 2005 and 2007 for towed-diver-survey areas around Tinian. Survey areas are represented by irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007. No index value is calculated for areas with only one year of survey data. A high rank means superior condition relative to other survey areas around the 4 populated, southern islands. The survey area in the southeast region south of Puntan Kastiyu, for example, has a high rank for both 2005 (y-axis) and 2007 (x-axis) and, thus, is assigned the bright-green color that corresponds to the top-right square in the legend. The position of the horizontal bar above the midline in this square also reflects that this survey area maintained a high rank in both years.

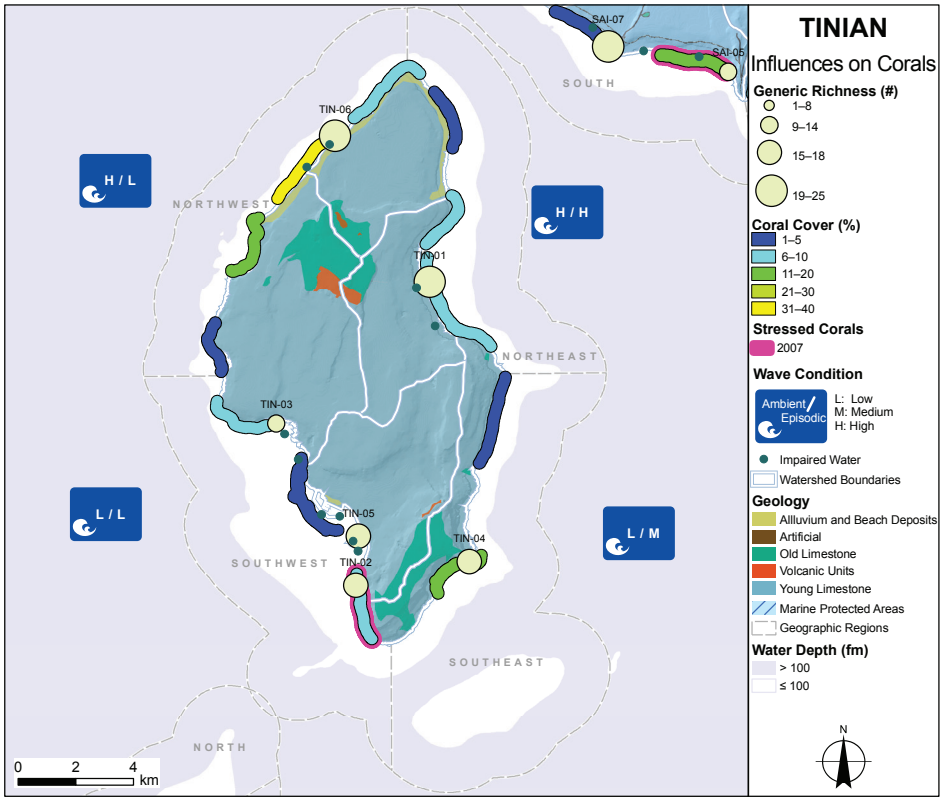


Figure 7.10b. Cover (%) observations of live and stressed corals from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Tinian during MARAMP 2005 and 2007, presented with geology, watersheds, impaired water sites and other factors (Gingerich 2002; M Pangelinan, pers. comm; Bearden et al. 2008). Values of coral cover and generic richness represent averages of data from both survey years, where available; otherwise values represent data from the single year surveyed. Towed-diver-survey areas combine overlapping survey tracks for both MARAMP survey years. Colored outlines represent areas where estimates of stressed-coral cover were > 10%. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.

The northwest region of Tinian was characterized by a steep sloping bank with high habitat complexity composed of hard and soft substrates interspersed with channels and sharp ridges. This region is popular for recreational scuba diving, a status that can be attributed to the dynamic habitat and greater amount of corals there relative to other regions of this island. A large dump site with military debris was observed off Puntan Lamanibot Sanhilo in this region during towed-diver surveys in both 2005 and 2007 (Fig. 7.10c); 35 man-made objects were counted within the survey swath in 2007, including helicopter components, airplane and vehicle parts, and many unidentifiable metal objects. The survey area around and south of Puntan Lamanibot Sanhilo stands out with benthic conditions that are among the best when compared in the Benthic Condition Index to other areas surveyed around the populated, southern islands.



Figure 7.10c. A dump site observed at Tinian off Puntan Lamanibot Sanhilo in the northwest region. *NOAA photo by Ben Richards*

Waters east of Tinian were cooler and more saline than waters west of this island. This interpretation may result from the greater wind and wave mixing with deep waters that occur on the east side of Tinian. This difference, combined with varying habitat along the eastern coast of Tinian, results in a variety of reef conditions. East of Puntan Masalok, a submerged ridge was characterized by a rough and complex topography to a depth of 80 m, suggesting that coral reefs may exist in this area (no benthic surveys were conducted there). South of Puntan Masalok, habitat complexity varied from high to low, but coral cover in this forereef area was moderate compared to other forereef habitats surveyed at Tinian. Farther south, the survey area between Puntans Kastiyu and Carolinas, had a high rank in the Coral Reef Condition Index in both 2005 and 2007, suggesting reef conditions there are among the best of the areas surveyed around the populated, southern islands. During towed-diver surveys in this area, moderate levels of coral cover were recorded and no indications of stressed corals were recorded, including COTS predation, coral bleaching, or coral disease. In addition to these benthic observations, during the 3 MARAMP survey years, high levels of large-fish biomass were observed in this area compared to other areas surveyed around Tinian (Fig. 7.10d), and shark sightings were more common on the east side. The single REA site surveyed in the southeast region, TIN-04, had the largest biomass of reef fishes of all sizes, among all sites surveyed at Tinian, in both 2005 and 2007.

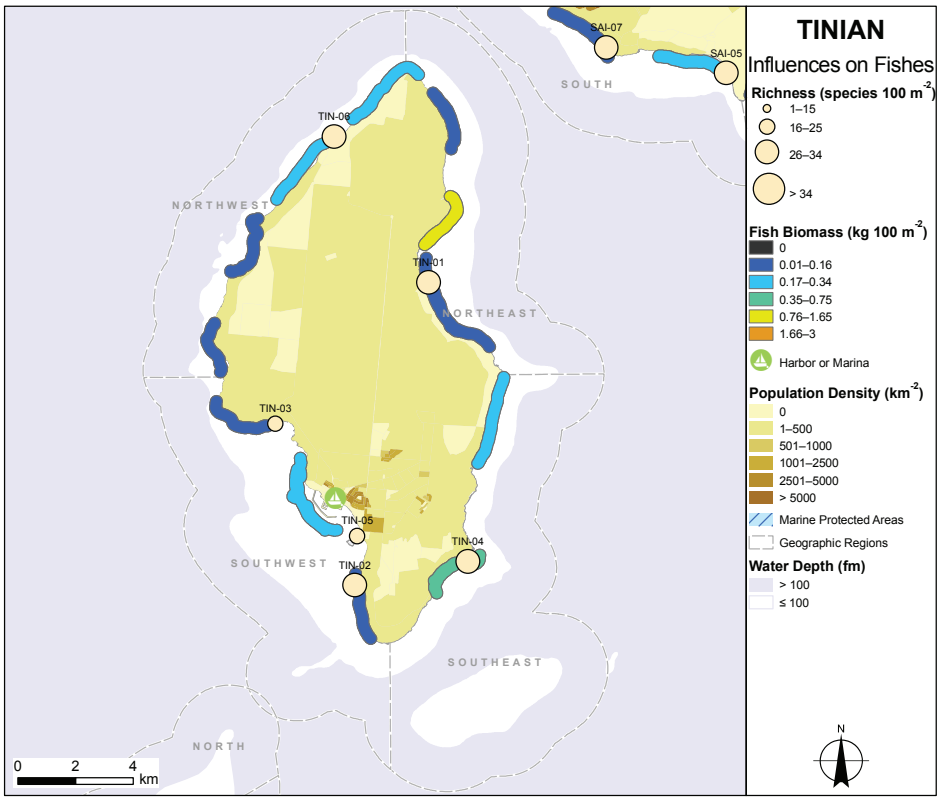


Figure 7.10d. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver surveys and species richness from REA fish surveys conducted on forereef habitats around Tinian during MARAMP 2005 and 2007, presented over a map of human population density (U.S. Bureau of the Census 2003, 2008). Biomass and richness values represent averages of data from both survey years, but, if surveys were conducted during one year only, then values represent data from that single year. Towed-diver-survey areas combine overlapping survey tracks for both MARAMP survey years; survey tracks are often similar but not necessarily the same between survey years.

7.11 Summary

This section presents an overview of the status of coral reef ecosystems around the island of Tinian and some of the key natural processes and anthropogenic activities influencing them. MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Tinian. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Tinian chapter are included in the appropriate discipline sections. One noteworthy limitation, for example, is the focus of MARAMP observations on forereef habitats to the exclusion of the shallow backreef flats around Tinian. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter.

To simplify interpretation of ecosystem conditions around Tinian, a Benthic Condition Index, a Fish Condition Index, and an integrated Coral Reef Condition Index were developed to reflect ecosystem conditions at specific locations around Tinian, relative to locations around the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan and based on MARAMP 2005 and 2007 surveys only (see Section 7.10: "Ecosystem Integration"). By synthesizing large amounts of complex, interdisciplinary information, these reef condition indices assist resource managers in identifying potential relationships between various ecosystem components The conditions of the fish and benthic communities and the overall ecosystem around Tinian, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

The following summary highlights key attributes of the coral reef ecosystems around Tinian (for place-names and their locations, see Figure 7.2a in Section 7.2: "Survey Effort"):

- With a land area of 102 km^2, Tinian is the second-largest island in the CNMI. After Saipan, Tinian has the second-highest human population in the CNMI with 3540 or ~ 5% of the total CNMI population in 2000.
- The topography of Tinian is formed by a series of uplifted carbonate platforms bounded by steep faults. Although this island has no streams, during periods of heavy rainfall, runoff into the ocean from unpaved secondary roads on Tinian has been reported.
- Wave model output shows trade wind swells from the east and high wave energy from storm tracks from the southeast and, to a lesser extent, the southwest.
- A similar pattern of cooler temperatures and higher salinities on the east (windward) side of Tinian compared to the west (leeward) side existed during both MARAMP 2005 and 2007. This interpretation may result from greater wind and wave mixing with deep waters on the east side compared to the west side of this island. The northeast (in 2007 only) and southeast (in 2005 and 2007) corners of Tinian, relative to other areas of this island, show signs of greater mixing with deep waters or localized upwelling. These areas were potentially influenced by strong tidal flows across the Mariana Ridge and between the islands on the ridge.
- Temperature data from the STRs deployed at a depth of 7 m in the northeast region briefly exceeded the coral bleaching threshold of 30.5˚C in September 2006.
- This island sits atop a steeply sloping bank that in many places is composed of carbonate terraces. Hard–soft analysis and observations from towed-diver surveys suggest that the substrate on these terraces is predominantly hard. At various points around Tinian, the submarine bank extends away from the coast, forming ridges. East of Puntan Masalok, a submerged ridge was characterized by a rough and complex topography to a depth of 80 m, suggesting that coral reefs possibly exist there.
- In the southwest region, the anchorage area at Tinian is composed of 4-6 carbonate platforms forming progressively deeper shelves and is characterized by a mixture of hard and soft substrate. The anchorage area was one of the few areas of flats suggested by BPI terrain analysis.
- Site-specific estimates of cover of live hard corals from REA surveys conducted at 5 sites during MARAMP 2007 ranged from 5.9% to 31.4%. The overall mean from these surveys was 13.3%, a level similar to survey results at the other populated, southern islands of Guam, Rota, and Saipan. The islandwide means for coral cover from towed-diver surveys of forereef habitats varied from 13% in 2003 to 9% in 2005 and 8% in 2007.
- In 2007, the mean overall prevalence of coral disease at Tinian was low (0.22%). Four major disease states were observed around Tinian: pigmentation response (60% of cases), bleaching (20% of cases), and subacute tissue loss and skeletal growth anomalies (15% of cases combined). Lesions involving pigmentation response were the most prevalent disease state with 0.13% of the surveyed population at Tinian affected.
- Mean macroalgal cover around Tinian varied as much as 16.4% between MARAMP survey years. Near Tinian Harbor and north of Puntan Masalok, observed macroalgal cover was higher in 2005 than in 2003. For several survey areas around this island, particularly for west-facing reefs, macroalgal cover was lower in 2007 than in 2005.
- Mean cover of crustose coralline red algae varied as much as 11% between MARAMP survey years. The greatest differences in observed cover between 2003 and 2005 were along the east coast, where cover was lower near Puntans Asiga and Kastiyu. Observed cover was higher in 2007 than in 2005 with the greatest differences occurring southwest of Puntan Tahgong in the northwest region, south of Puntan Kastiyu in the southeast region, and south of Puntan Diapblo in the southwest region.

- Two major types of coralline-algal diseases were observed around Tinian: coralline lethal orange disease and coralline white band syndrome. Cases of coralline lethal orange disease represented nearly 60% of all cases recorded at Tinian.
- Large-fish biomass, from towed-diver surveys conducted on forereef habitats during MARAMP 2007, tended to be higher on the east side than on the west side of Tinian. Sharks were sighted more frequently on the east side of Tinian in 2007.
- Total fish biomass was moderately low at the REA sites surveyed at Tinian with an overall mean of 3.85 kg 100 m^{-2} across the 3 MARAMP survey years, a level close to the average for the populated, southern islands. TIN-04, near Puntan Kastiyu in the southeast region, had the highest mean biomass observed at Tinian in both of the years in which it was surveyed (2005 and 2007), but biomass levels were only marginally higher there than at other sites.
- Abundance of giant clams from towed-diver surveys conducted around Tinian was low during the 3 MARAMP survey years, relative to the rest of the Mariana Archipelago. Estimates of daytime abundance of crown-of-thorns seastars (COTS), sea cucumbers, and sea urchins also were low.
- In the northwest region, the survey area around and south of Puntan Lamanibot Sanhilo stands out with benthic conditions that are among the best when compared to other areas surveyed using the Benthic Condition Index for Guam, Rota, Tinian, and Saipan.
- The survey area between Puntans Kastiyu and Carolinas in the southeast region had high ranks in the overall Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan in both 2005 and 2007. The highest biomass of large fishes at Tinian in 2007 was recorded during this survey, and the rank for this survey area was high in the Fish Condition Index in both 2005 and 2007.
- At Tatsumi Reef, a popular fishing spot, a gradient of habitat complexity and coral cover was observed. Complexity and coral cover were highest at this reef's shallowest point at its center and decrease with depth.

8 SAIPAN

8.1 Introduction

The island of Saipan is centered at 15°12′ N, 45°45′ E to the north-northeast of Guam, Rota, Aguijan, and Tinian. With a total area of 118.98 km² and a coastline of 75 km, Saipan is the largest of the 14 islands of the Commonwealth of the Northern Mariana Islands (CNMI). The highest point on Saipan is 474 m at Okso` Tagpochau (for place-names and their locations, see Figure 8.1.2a, bottom panel in this section and Figure 8.2a in Section 8.2: "Survey Effort"). Nearly 90% of the human population of the CNMI resides on Saipan (U.S. Bureau of the Census 2011a), with 60% of this island's total population concentrated within 20% of the available landmass around the villages of Garapan, Chalan Laolao, Susupe, Chalan Kanoa, and San Antonio (Castro et al. 2006). Beaches, dive sites, and golf courses are scattered around Saipan, and the most easily accessed of these sites are located along the west coast with the majority of the hotel and tourist facilities on this island. All major boating access points are in the general Lagunan Garapan area. Isleta Managaha, a small island off the central west coast near the entrance to Saipan Harbor, is one of the most popular tourist destinations and is surrounded by a marine protected area (MPA). A large, flat bank extends ~ 10 km offshore from the west side of Saipan, and another bank extends from the northern area of Garapan Anchorage towards the southern shore. These 2 banks are used as the primary anchorage sites for commercial and military vessels operating in the CNMI.

8.1.1 History and Demographics

A brief summary of Saipan's history and political structure is presented here. The history of the Mariana Archipelago and the political structure of Saipan and the CNMI are discussed further in Chapter 1: "Introduction."

Saipan was first populated with the arrival of the Chamorro people, presumably from the Malaysian and Philippine region (Spoehr 1957), about 3500 years ago (Rogers 1995). Following European contact, the Mariana Islands were ruled by Spain from 1521 to 1899. Prolonged contact with newly introduced diseases and increased conflicts between the Chamorro and Spanish resulted in an archipelagic-wide decrease in the Chamorro population from estimates as much as 100,000 in 1668 to less than 4000 in 1710 (Rogers 1995; Underwood 1973). Chamorros remaining on Saipan and other islands were removed and resettled to Guam and Rota in 1698 (Rogers 1995). Saipan became largely uninhabited for more than 100 years until 1815. Carolinian islanders were relocated to Saipan from Lamotrek and Satawal around 1815 to provide labor, and Chamorros returned to Saipan in the late 1800s (Alkire 1984).

All of the Mariana Archipelago, except for Guam, was ruled by Germany from 1899 until 1914. Following World War I, the Northern Mariana Islands became a protectorate of Japan from 1914 to 1945. Saipan was a major sugarcane farming and processing center from the 1920s until World War II (WWII). In the summer of 1944, the U.S. military landed in Saipan with a large invasion force and simultaneously attacked a nearby Japanese fleet. Fierce land battles were fought on Saipan with heavy losses on both sides over a period of a little more than 3 weeks beginning with landings on June 15, 1944. The U.S. Navy and Air Force fired an estimated 180,000 shells on Saipan over a period of 2 days alone (Pratt 1948).

After WWII, Saipan was administered on behalf of the United Nations by the U.S. Navy and then the Department of the Interior as one of the islands included in the Trust Territory of the Pacific Islands. From 1949 to 1962, the Central Intelligence Agency restricted access to the northern half of Saipan and used this area to train foreign agents (Rogers 1995). As described in Chapter 1: "Introduction," the CNMI gained status as a commonwealth of the United States in 1976, and citizens of the CNMI received U.S. citizenship in 1986 (U.S. Department of the Interior 2009b).

In 2010, Saipan had a population of 48,220 persons, a 23% decrease from 62,392 in 2000 but a 231% increase from 14,549 in 1980 (Fig. 8.1.1a; U.S. Bureau of the Census 1983, 2011a).

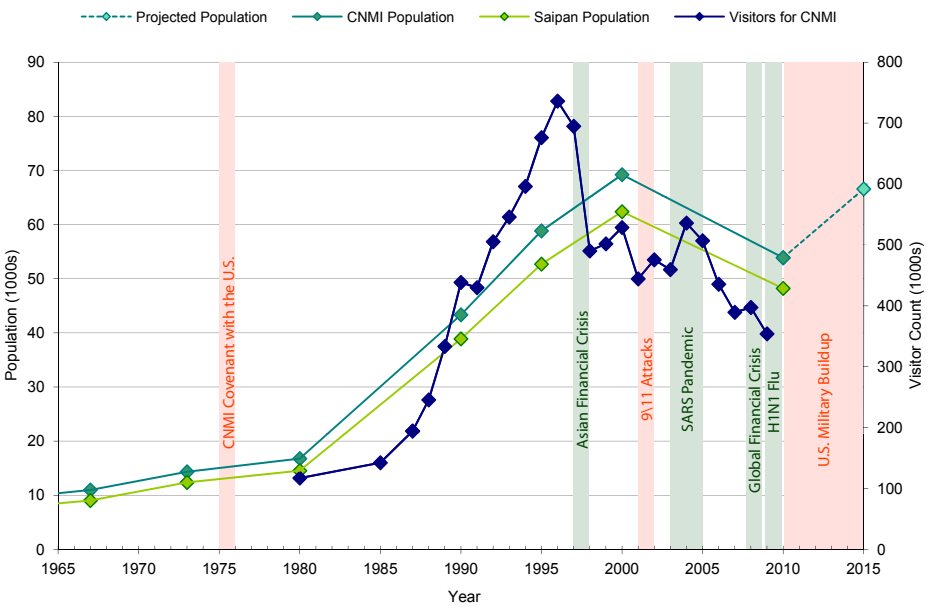


Figure 8.1.1a. Population growth (U.S. Bureau of the Census 1983, 2003, 2011a; CNMI Department of Commerce 2002a; Secretariat of the Pacific Community 2011) and visitor count (Bank of Hawaii 1995; Lucas 1990; U.S. Department of the Interior 1996; CNMI Department of Commerce 2002b; Marianas Visitors Authority) trends on Saipan and in the CNMI during the period of 1965–2015.

8.1.2 Land Use

The major population centers on Saipan are primarily located along the western coastline, in the south near Saipan International Airport, and within the Kagman Peninsula (Fig. 8.1.2a). Approximately 15% of Saipan is designated as public land, and commercial and residential holdings account for 20% and 35% of land use. The remaining 30% consists of unused grassland, secondary forest, or isolated regions of primary forest (Carruth 2003). Small areas of agricultural land are scattered in the southern part of this island. A major project to restore the Bahia Laolao watershed was proposed and funded in 2009 as part of the American Recovery and Reinvestment Act (Rodriquez 2009).

The native vegetation of Saipan has been highly disturbed over the last 300 years. The thickets of native limestone forest believed to have covered this island in the late 1700s and 1800s were mostly cleared in the 1920s by the Japanese to plant sugarcane. During WWII, sugarcane plantations were abandoned, and bombing, fires, and military reconstruction further reduced the native limestone forest. Today, the introduced, low-lying tangantangan tree (*Leucaena glauca*) has replaced both the sugarcane fields and native limestone forest areas on Saipan (Liu and Fischer 2006). Small remnants of native forest remain along steep, low-elevation slopes of the Saipan Upland Mitigation Bank and the Kagman Wildlife Conservation Area (Mueller-Dombois and Fosberg 1998).

Most of the CNMI's wetlands were filled for agricultural use during the Japanese occupation associated with WWII and, more recently, for urban development. Wetlands presently make up < 5% of land in the CNMI, and only an estimated 36% of the original wetlands of the CNMI still exist (Castro et al. 2006). Hagoi Susupi, a small (0.17 km²), brackish lake near the southwest part of Saipan, is surrounded by an extensive marsh area of 2.02 km². This marsh area accounts for 60% of the wetlands in the CNMI (Stinson 1993) and provides 77% of the remaining habitat for the Mariana common moorhen (*Gallinula chloropus guami*), a bird listed both Federally as an endangered species (U.S. Fish and Wildlife Service) and locally as a threatened or endangered species (Berger et al. 2005). The wetland surrounding Hagoi Susupi is also important for both groundwater discharge and flood control. The condition of this marsh area has been affected by wastewater from a sugar mill during the period of Japanese control (1914–1944) and by the introduction of the mosquitofish (*Gambusia affinis*) for mosquito control during WWII and of tilapia (Cichlidae) for aquaculture in the 1950s; both of these fishes are well known for their negative environmental effects (Stinson 1993). Currently, the greatest threats to Hagoi Susupi and its surrounding wetland are development and drawdown for water use.

Five MPAs have been established around Saipan, with 2 of them specifically designated for focal species. The Bahia Laolao Sea Cucumber Reserve was designated in 2000 and the Lighthouse Reef Trochus Reserve, for the conservation of mother-of-pearl shells, in 1982 (Fig. 8.1.3a, top panel). In 2001, 2 no-take marine conservation zones were designated: Bird Island Marine Sanctuary and Forbidden Island Marine Sanctuary. A third no-take zone, Managaha Marine Conservation Area, which is also a popular tourist attraction, was first designated in 2000, but lack of funds meant that enforcement of no-take policies did not begin in earnest until 2002 (Starmer et al. 2008; Wood 2007).

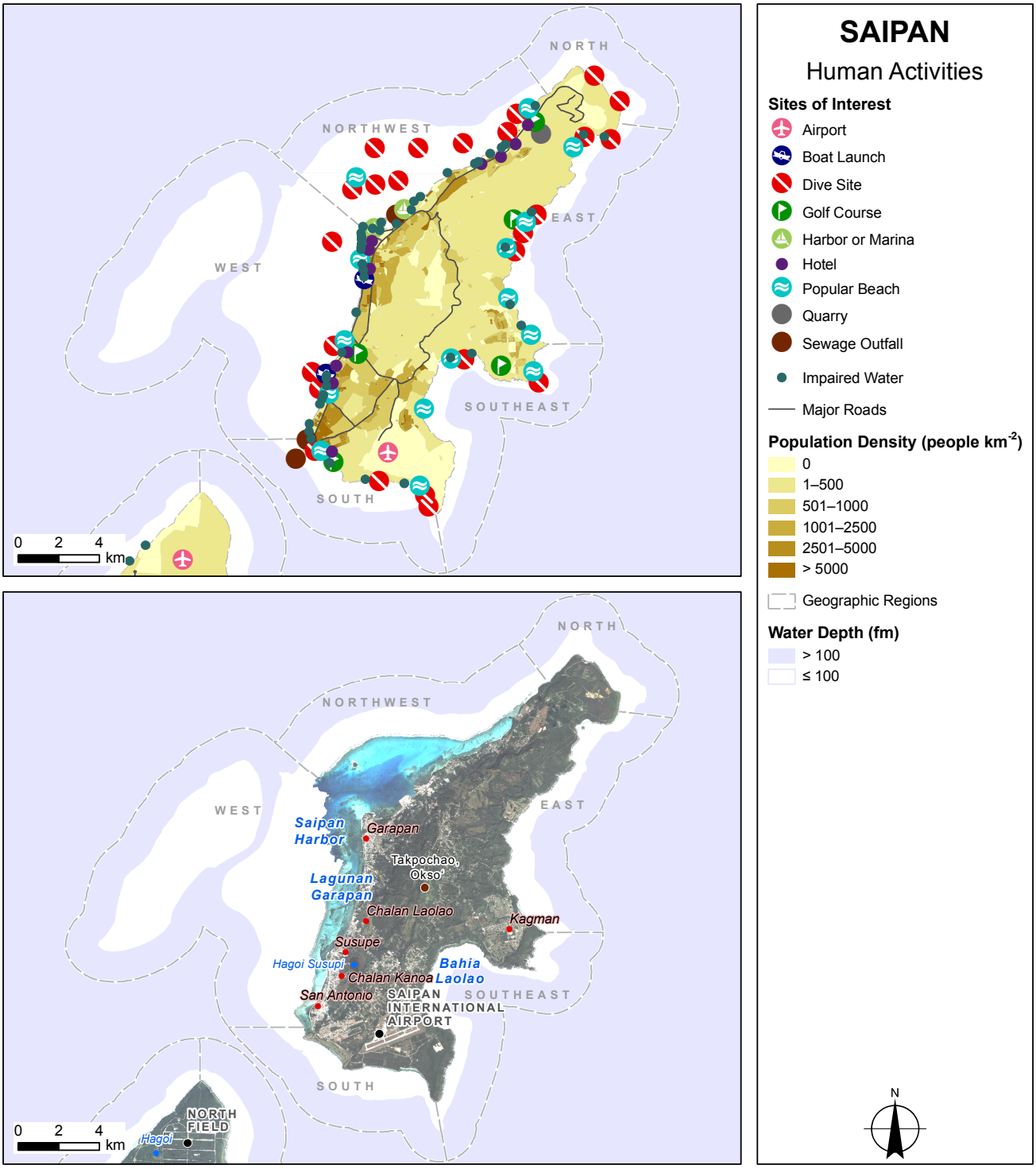


Figure 8.1.2a. Major locations of human activities (*top*) on Saipan that have the potential to affect the marine environment (Placenames.com; Marianas Visitors Authority; Bearden 2008; J Starmer, CNMI Coastal Resources Management Office, pers. comm.; U.S. Geological Survey 2005b) are represented over a population-density map (U.S. Bureau of the Census 2003, 2008). Satellite imagery of Saipan (*bottom*, includes material © 2006 DigitalGlobe Inc. All rights reserved), labeled with places of interest (U.S. Geological Survey).

8.1.3 Geography

Uplifted limestone terraces constitute the primary rock formations on Saipan, as they do on other southern islands in the Mariana Archipelago (Fig. 8.1.3a, bottom panel). Saipan is composed of 3 major limestone units: Tagpochau Limestone, which comprises the oldest limestone from 15–23 million years ago (early Miocene epoch); Mariana Limestone, from the younger Pliocene epoch (2–5 million years ago), and the Tanapag Limestone, the youngest terrace deposits from the

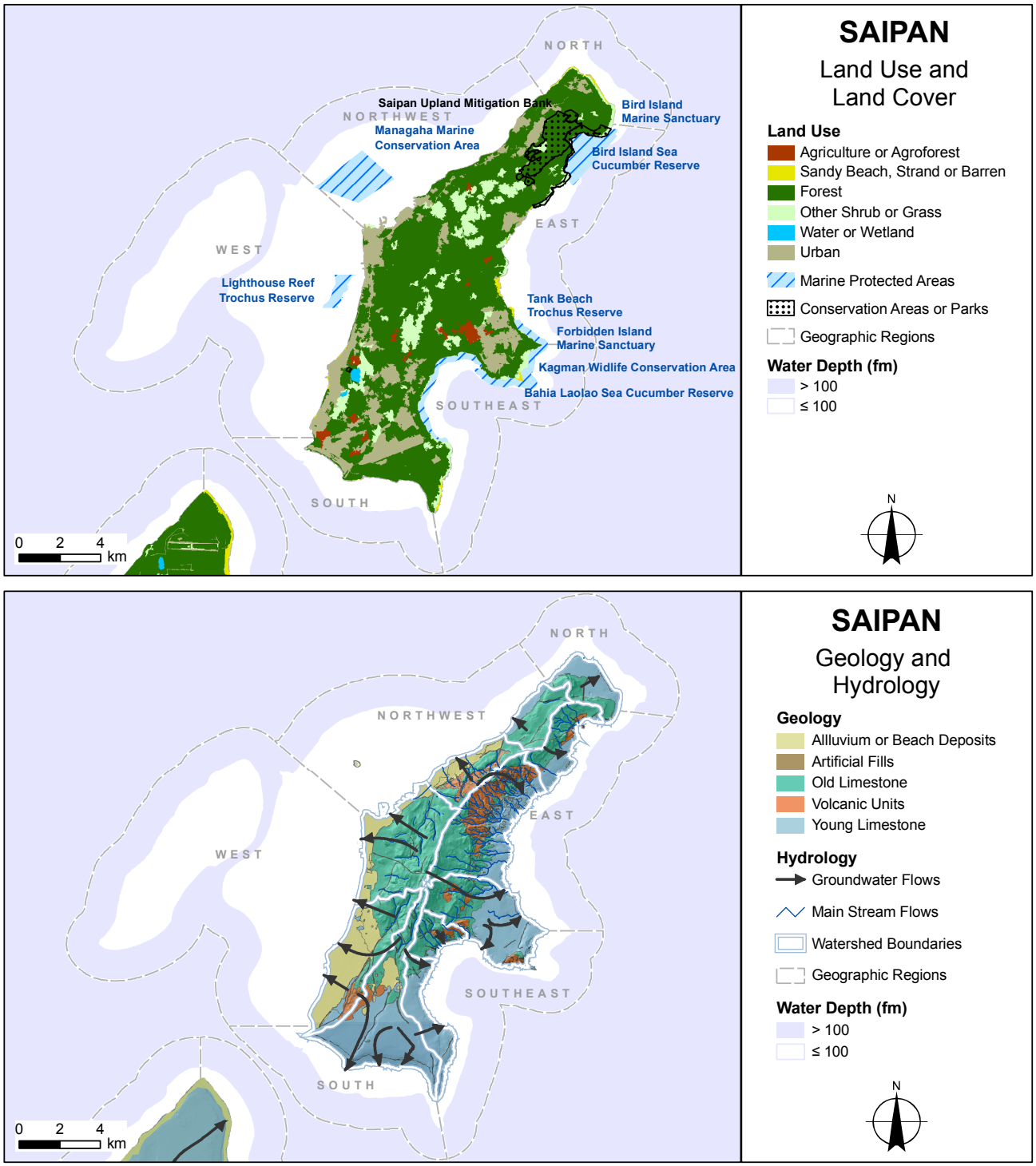


Figure 8.1.3a. Land use (U.S. Department of Agriculture Forest Service 2006b), conservation areas and parks (K Herrmann, CNMI Division of Environmental Quality, pers. comm.), and MPAs (NOAA Marine Protected Areas Center 2008) on Saipan are represented over a vegetation cover map (*top*, Liu and Fischer 2006). Geology, watersheds, main stream flows, and groundwater flows on Saipan (*bottom*, Carruth 2003; M Pangelinan, CNMI Department of Land and Natural Resources, pers. comm.; U.S. Geological Survey 2005a).

Pleistocene-Holocene epoch (0–2 million years ago; Riegl et al. 2008; Fig. 81.3a). A varied layer of thin to moderately thick limestone-derived soils—composed of clays, clay loams, and loams—is also largely present around Saipan. Other limestone areas exhibit karst topographies, which are formed by dissolution of carbonate rocks and characterized by sinkholes, caves, and subterranean passages. A well-known dive site, known as "the Grotto", is found in a large sinkhole that connects to the ocean through several subterranean passages.

In contrast to the features around the islands of Tinian and Rota (see Chapters 7 and 5), the coastal areas of Saipan do not have high, continuous seacliffs, especially on the west (leeward) side, as shown in the combined onshore-offshore slope map (Fig. 8.1.3b). Instead, a coastal plain is inshore of the 2 large, submerged banks to the west of Saipan. A number of volcanic areas are scattered from north to south but mostly occur on the east side of this island, where basement rock with ages estimated at ~ 41 million years (Eocene) and ~ 13 million years (Miocene) is exposed (Fig. 8.1.3a, bottom panel)—covering ~ 10% of Saipan's land area (Carruth 2003). Numerous faults transect Saipan in a north–northeast direction.

Saipan has only 3 perennial streams that together with intermittent streams, mostly on the east side, have a total length of 95.5 km as well as a lake and several isolated wetland areas (Castro et al. 2006). In 2003, Robert Carruth (2003) of the U.S. Geological Survey reported that the resources for 90% of the municipal water consumed on Saipan were 140 shallow wells fed by an average rainfall of ~ 2 m (80 in) and owned by the Commonwealth Utilities Corp. (CUC), the local municipal water utility. Castro et al. (2006) reported a total of 380 wells on Saipan, 191 of which were owned by CUC and 136 of which were owned by CUC and producing drinking water. Groundwater drainage patterns on Saipan are shown as arrows in Figure 8.1.3a, bottom panel. The largest groundwater problem in the CNMI is high chloride concentrations from saltwater intrusion into the basal aquifer, resulting from over pumping of the basal aquifer to keep up with the increasing demand (Castro et al. 2006).

Carruth (2003) reported that the chloride concentrations and rates of groundwater production from CUC's 140 wells were not adequate for providing Saipan residents and visitors with a 24-hour supply of potable water. However, by late 2008, after improvements in storage capacity, CUC said that 75% of Saipan's residents had an uninterrupted water supply (Todeno 2008). CUC wells on Saipan do not produce enough drinking water to meet real demand because of leaks in municipal and homeowner water distribution systems, reported the CNMI Division of Environmental Quality in reports on water quality published in 2006 and 2010 (Castro et al. 2006; Bearden et al. 2010). To avoid problems with the freshwater supply on Saipan, many hotels use reverse osmosis technology to produce freshwater from deep saltwater wells (Todeno 2009), and the resulting discharge of hypersaline water is a controversial environmental issue.

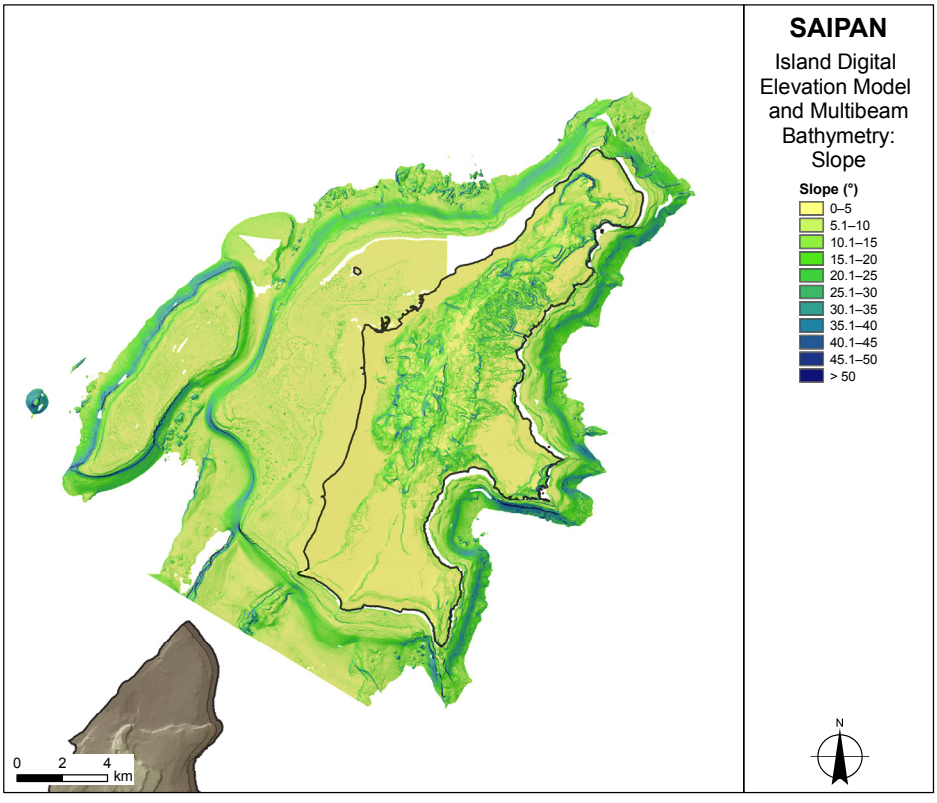


Figure 8.1.3b. Combined slope map using the digital elevation model and multibeam bathymetric data for Saipan.

8.1.4 Economy

Tourism is the major economic driver on Saipan. The CNMI government is one of the main employers on Saipan. Additional sources of revenue come from the Port of Saipan and the offshore Garapan Anchorage (GlobalSecurity.org 2005). Although fishing is not considered a significant industry, local residents depend heavily on reef fishes as a food source, and fishing historically has been considered an important cultural practice.

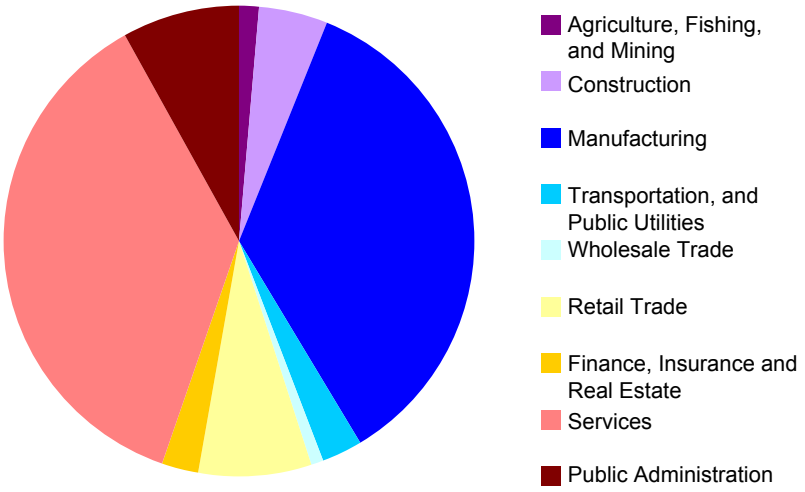
The majority of tourists to the CNMI are from Asia, led by Japan and Korea. Japanese visitors stay an average of 3.5 nights, while Koreans stay an average of 4.5 nights (Van Beukering et al. 2006). In the last few years, China and Russia have become important sources of tourism revenue (U.S. Government Accountability Office [GAO] 2008). Tourism has been negatively affected by global economic conditions; increasing competition from other, less expensive destinations; transportation shortages (flights and ferry); increasing fuel and other costs, including the rising minimum wage; and uncertainties over inclusion of Chinese and Russian visitors in the Guam-CNMI Visa Waiver Program.

The only industry to equal Saipan's tourism industry was the garment industry. Started on Saipan in 1983, the garment industry was once a unique catalyst for Saipan's economy (Fig. 8.1.4a). Gross receipts for this industry peaked in 1998 with more than $1 billion (GAO 2000). The garment industry in 1998 paid $52 million in taxes and fees, accounting for more than 22% of the CNMI government's $234 million in total general fund revenue (GAO 2000). Recent changes in World Trade Organization quotas and U.S. minimum wage and immigration laws significantly reduced the revenue from and number of garment factories in the CNMI until the last garment factory on Saipan closed in February 2009. Garment exports decreased in value from $826 million in 2004 to $3 million in 2009 (CNMI Department of Commerce 2006, 2010).

The garment factories on Saipan had been able to send "Made in the U.S.A" garments into the United States duty free while using foreign workers who were paid below the U.S. minimum wage; thus, their goods were very competitive with foreign products. In 2005, the United States, in accordance with one of the 1994 World Trade Organization Uruguay Round agreements, lifted quota restrictions on garment products from other countries entering the United States, making products from the CNMI less competitive. In 2007, President George W. Bush signed into law a minimum wage bill that raised wages in the CNMI by $0.50 an hour and requires a 9-step yearly increase to bring the CNMI minimum wage in line with the U.S. rate of $7.25 an hour by 2015 (Vallejera 2007). In 2008, the U.S. Congress passed legislation to federalize immigration to the CNMI, which not only may have affected what remained of the garment industry but also could have considerable effect on tourism and foreign investment (GAO 2008). With no manufacturing output, container trade by 2009 had shrunk from 140 to 5 outbound containers per week (Eugenio 2009). The reduction in cargo trade and dramatic rise in fuel costs have caused a rapid increase in the price of all goods in the CNMI. The state of Saipan's economy, combined with the military buildup in Guam, is causing a migration of the workforce out of the CNMI and a shortage of education and health workers (CNMI Department of Commerce 2009).

As the main island of the CNMI, Saipan is the location for almost all major government offices. With the decline in both tourism and the garment industry, the CNMI government general fund revenues fell to $155 million in 2009, a 29% drop from tax and fee revenues in 2004 (CNMI Department of Commerce 2006, 2010). Facing ongoing budget shortfalls, the CNMI government in 2010 cut hours and holidays for its workers and in early 2011 proposed layoffs.

Figure 8.1.4a. Employment by sector on Saipan in 2005 (CNMI Department of Commerce 2008), the year in which the United States lifted quota restrictions on garment products from foreign countries, making "Made in the U.S.A" garments manufactured in Saipan less competitive.



One potentially positive development for the CNMI government and Saipan is the designation in 2009 of the Marianas Trench Marine National Monument, which will be jointly managed by the Department of the Interior, NOAA, and the CNMI. This development could have positive effects on tourism and the economy, including new employment opportunities on Saipan, if and when a Monument office is located there.

The chief domestic commercial fishery in the CNMI is a small-boat, 1-d, troll fishery, and most boats are outboard-powered, runabout-type vessels of 12–24 ft. In addition, a few larger boats are used around the islands north of Saipan, mainly for bottom fishing, and a small charter fleet exists. Trolling is the most common fishing method, but bottom fishing and reef fishing are also popular. Reef fishes not only make up a significant portion of the total commercial catch but also are an important component of the local diet (Hamm et al. 2010).

The Division of Fish and Wildlife (DFW) of the CNMI Department of Lands and Natural Resources, with technical assistance from the Western Pacific Fisheries Information Network (WPacFIN) of the NOAA Pacific Islands Fisheries Science Center, collects nearshore fisheries-dependent creel survey data on primary landing sites of Saipan. According to this survey data (DFW 2009), fishermen around Saipan targeting nearshore species typically use one of the following methods: spearing (scuba or freediving), nets, trolling, or bottom fishing. These fishermen can be based on shore or in a boat.

Spearing and netting data are reported in more detail here because these methods capture the nearshore species typically found on coral reefs. Data collected from the creel surveys for the period of 2006–2008 were extrapolated to include data gaps and estimates of total catch with assistance from WPacFIN. Similar to findings from creel surveys around Guam, boat-based spearfishermen around Saipan mostly captured surgeonfishes (Acanthuridae) and parrotfishes (Scaridae) with 39% and 24% of landed catch by weight (Fig. 8.1.4b), followed by groupers (Serranidae) and emperors (Lethrinidae) with 7% and 6% of landed catch by weight. Gillnet landings were composed of jacks (Carangidae, mostly bigeye scads), emperors, and surgeonfishes with 49%, 21%, and 20% of landed catch by weight.

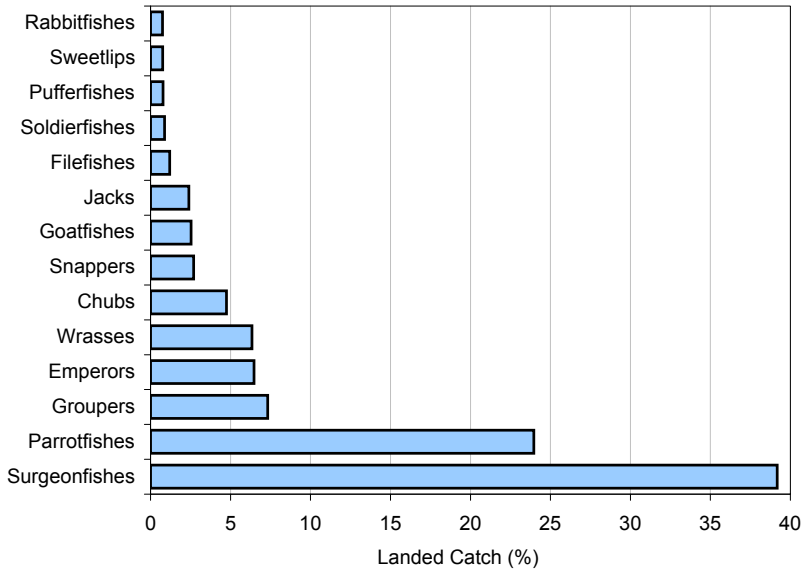


Figure 8.1.4b. Family composition of the landed catch of spearfishermen, by weight as a proportion of total catch weight, around Saipan during the period of 2006–2008 (DFW 2009). Data were collected from boat-based creel surveys conducted by the CNMI DFW and extrapolated to total catch data with assistance from the WPacFIN.

8.1.5 Environmental Issues on Saipan

A number of environmental issues and concerns that could influence the reefs around Saipan have been raised and reported in agency documents (Starmer et al. 2008, 2005; CNMI Department of Commerce 2009):

- Nonpoint source pollution is recognized as the main anthropogenic stressor on Saipan and comes from many diffuse sources:
  - o Eroding badlands
  - o Unpaved road runoff into Bahia Laolao
  - o Beach traffic of off-road vehicles
  - o Runoff during storms

- Point source pollution sources:
  - o Sewage outfalls
  - o Discharge of hypersaline and nutrient-enriched wastewater from reverse osmosis water purification systems, now pumped into deep injection wells with unknown long-term effects
  - o Nutrient discharge from golf courses and agriculture
- Deterioration of power and wastewater infrastructure
- Damage from the Puerto Rico dump, which the Environmental Protection Agency (EPA) mandated to be closed
- Climate change and related effects:
  - o Coral bleaching
  - o Ocean acidification
  - o Shoreline change, especially on Isleta Managaha
  - o Coral disease, resulting from the previously noted effects
- Damage from boating and recreational activities:
  - o Anchoring at dive sites
  - o Jet ski activities
  - o Anchoring of pre-positioned ships in Saipan Harbor and Garapan Anchorage
  - o Wrecked and abandoned vessels
  - o Marine debris from fishing gear
- Pressure on coral reef fisheries from human activities:
  - o Degraded reef habitat
  - o Local declines of commercially important reef fish

The following projects are either proposed or already underway in an effort to improve Saipan's environment (Starmer et al. 2008; CNMI Department of Commerce 2009):

- Active management of coral reefs
- Participation in the Micronesian Challenge and establishment of MPAs
- Rehabilitation of existing power generation facilities
- Development of alternate energy sources
- Rehabilitation of wastewater systems
- Expansion and upgrade of existing water infrastructure to comply with an EPA court order
- Closure of Puerto Rico dump
- Destination enhancements at Hagoi Susupi, the Marianas Trench Marine National Monument, and other areas on and around Saipan
- Resurfacing of secondary roads

8.2 Survey Effort

Extensive biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing coral reef ecosystems around the island of Saipan since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 6 geographic regions around Saipan are delineated in Figure 8.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Saipan. Potential reef habitat around this island is represented by a 100-fm contour shown in white on this map.

Benthic habitat mapping data were collected around Saipan using a combination of acoustic and optical survey methods. MARAMP benthic habitat surveys conducted with multibeam sonar around Saipan, Marpi Bank, Tinian, Tatsumi Reef, and Aguijan covered a total area of 213.4 km^2 in 2003 and 1800 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 8.3: "Benthic Habitat Mapping and Characterization."

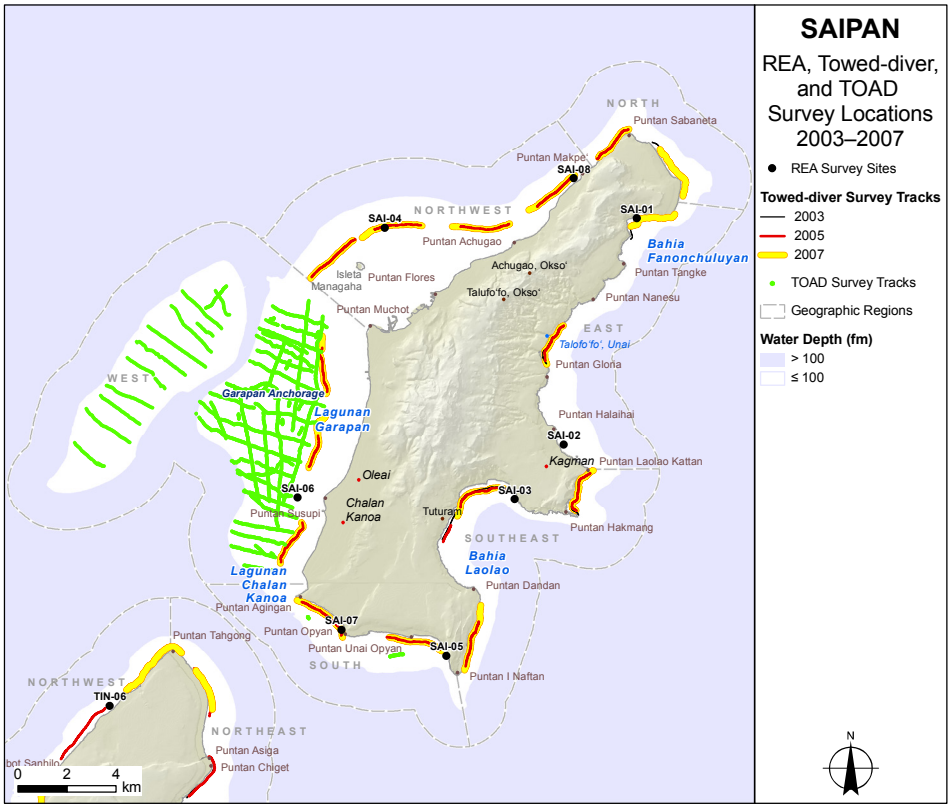


Figure 8.2a. Locations of REA, towed-diver, and TOAD benthic surveys conducted around Saipan during MARAMP 2003, 2005, and 2007 and TOAD surveys conducted in 2004. To aid discussion of spatial patterns, this map delineates 6 geographic regions: north, east, southeast, south, west, and northwest.

Information about the condition, abundance, diversity, and distribution of biological communities around Saipan was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 8.5–8.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 and in 2004 are presented in Table 8.2a, along with their mean depths and total areas or length.

Table 8.2a. Numbers, mean depths (m), total areas (ha), and total lengths (km) of REA, towed-diver, and TOAD surveys conducted around Saipan during MARAMP 2003, 2005, and 2007 and TOAD surveys conducted in 2004. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	5	8	8
	Mean Depth (m)	12.7 (SD 1.4)	12.8 (SD 1.5)	12.8 (SD 1.5)
Benthic	Number of Surveys	6	8	8
	Mean Depth (m)	13.1 (SD 1.6)	12.8 (SD 1.5)	12.8 (SD 1.5)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	6	17	16
	Total Survey Area (ha)	11.8	32.3	37.0
	Mean Depth (m)	11.4 (SD 1)	14.9 (SD 1.7)	14.9 (SD 1.4)
TOAD		**2003**	**2004**	
	Number of Surveys	13	41	
	Total Length (km)	4.39	136.26	

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Saipan were collected using (1) a diverse suite of moored instruments designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007. Results from some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 8.2b, and results are discussed in Section: 8.4: "Oceanography and Water Quality."

Table 8.2b. Numbers of oceanographic instruments deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Saipan during MARAMP 2003, 2005, and 2007. Four types of instruments were moored around Saipan: Coral Reef Early Warning System (CREWS) buoy, sea-surface temperature (SST) buoy, subsurface temperature recorder (STR), and ecological acoustic recorder (EAR). Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Additional deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year								
Instruments	2003	2004		2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
CREWS	1	1	1	1	1	1	–	–	–
SST	–	–	–	–	–	–	1	1	–
STR	–	–	–	–	1	1	4	3	–
EAR	–	–	–	–	–	–	2	1	–
CTD Casts	**2003**			**2005**		**2007**			**Total**
Shallow-water Casts	20			31		38			89
Deepwater Casts	–			4		6			10
Water Samples				**2005**		**2007**			**Total**
				7		4			11

Towed-diver Surveys: Depths

Figures 8.2b–e illustrate the locations and depths of towed-diver-survey tracks around Saipan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

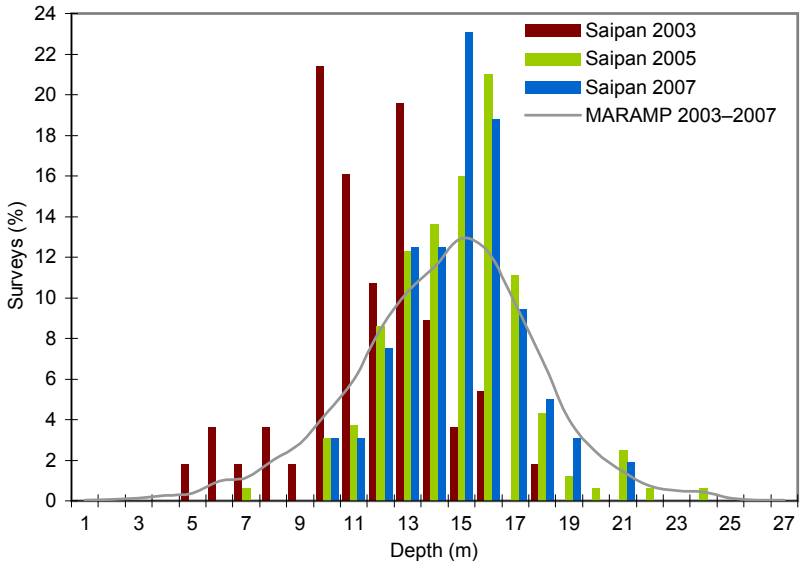


Figure 8.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Saipan during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

During MARAMP 2003, 6 towed-diver surveys were conducted along parts of the forereef slopes in the north, east, and southeast regions of Saipan (Figs. 8.2b and c). The mean depth for all survey segments was 11.4 m (SD 1), and the mean depth of individual surveys ranged from 10.1 m (SD 2.1) to 13 m (SD 3.2).

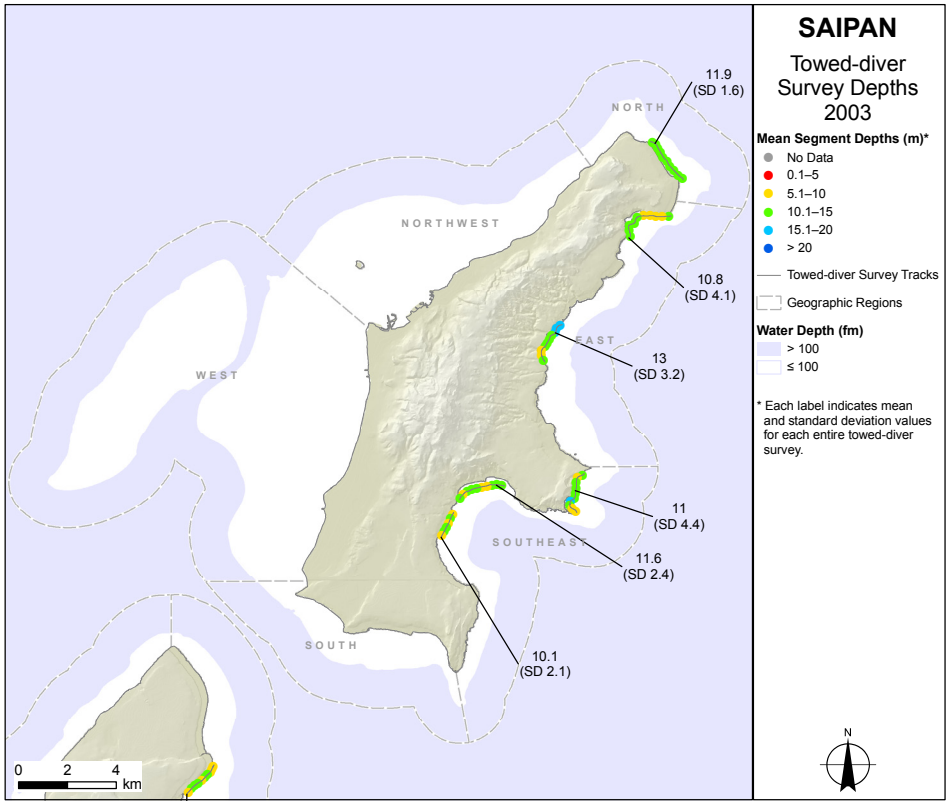


Figure 8.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Saipan during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth in meters (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

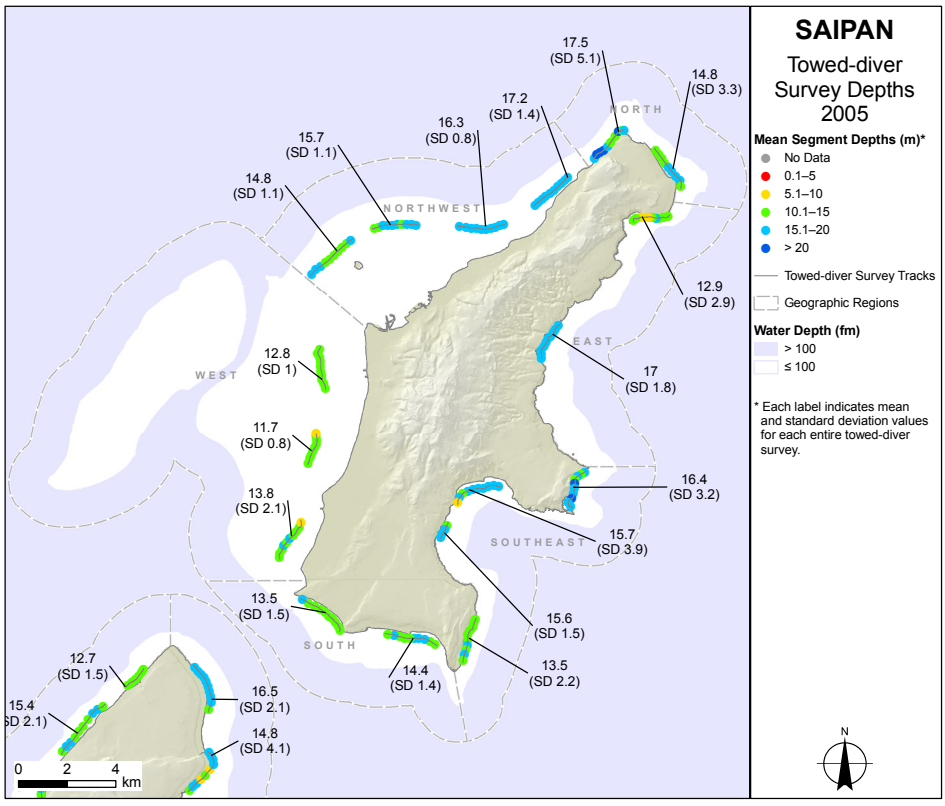


Figure 8.2d. Depths and tracks of towed-diver surveys conducted on forereef habitats around Saipan during MARAMP 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth in meters (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

During MARAMP 2005, 17 towed-diver surveys were conducted along the forereef slopes around most of Saipan (Figs. 8.2b and d). The mean depth for all survey segments was 14.9 m (SD 1.7), and the mean depth of individual surveys ranged from 11.7 m (SD 0.8) to 17.5 m (SD 5.1).

During MARAMP 2007, 16 towed-diver surveys were conducted along the forereef slopes around most of Saipan (Figs. 8.2b and e). The mean depth for all survey segments was 14.9 m (SD 1.4), and the mean depths of individual surveys ranged from 12.6 m (SD 1.9) to 17.7 m (SD 1.7).

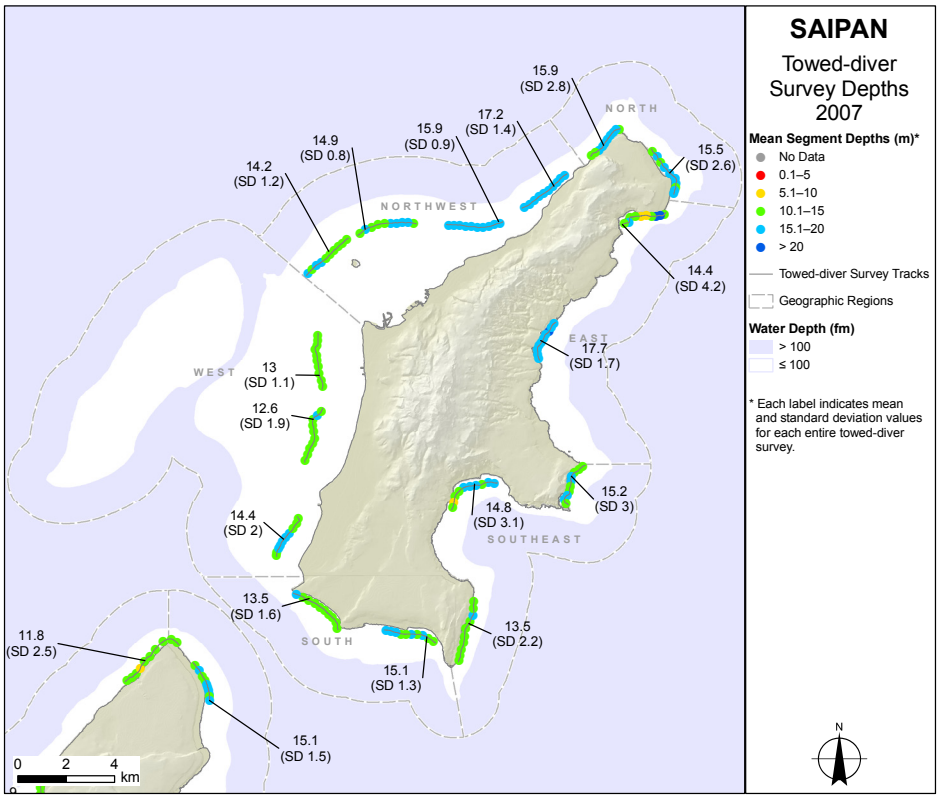


Figure 8.2e. Depths and tracks of towed-diver surveys conducted on forereef habitats around Saipan during MARAMP 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth in meters (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

8.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Saipan were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 15–1000 m around most of Saipan and to ~ 2800 m to the east of Saipan. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed at depths < 5–200 m.

Lidar and multibeam data were also collected by the Naval Oceanographic Office (NAVOCEANO) in 2001. Data were acquired west of Saipan and, most important, included Lagunan Garapan, a large, shallow lagoon that extends between Puntans Muchot and Agingan (for place-names and their locations, see Fig. 8.2a in Section 8.2: Survey Effort).

In addition to data from the MARAMP, the Coral Reef Ecosystem Division (CRED) collected and analyzed optical data in Garapan Anchorage off the west side of Saipan (Rooney et al. 2005) through a contract with the Military Sealift Command (MSC). As part of this contract, the MSC provided funds to facilitate and accelerate the analysis of multibeam bathymetry data already collected as part of CRED's MARAMP. These efforts supported the assessment of the distribution of coral reef resources in Garapan Anchorage with the goal of minimizing impacts on coral-rich habitats from the expanded use of existing anchorage sites and proposed use of additional sites.

As a result of the MSC contract, an additional 41 TOAD surveys were conducted in 2004, covering an estimated 120 linear km of seabed. To estimate the living benthic faunal cover between survey tracks, CRED completed additional analyses of acoustic and optical data. A map showing the predicted locations of sand basins within Garapan Anchorage was

created using textural analysis of multibeam bathymetry data in combination with bathymetry-derived slope (Cutter 2004). A second analysis used the universal kriging geostatistical technique to interpolate percentage of cover of live hard corals between survey tracks and produce a map predicting percentage of coral cover across this anchorage area. The percentage of the seafloor covered by corals was assigned a value of zero in the identified sand basins. Estimates of coral cover from analyses of TOAD video include all types of corals, such as scleractinian (hard) corals, soft corals, sea fans, etc. However, more than 95% of the benthic fauna observations were of live hard corals, so the resulting map predicts distribution primarily for hard coral habitat.

These derived map products are presented and discussed in this section in relation to optical validation data from analyses of towed-diver and TOAD surveys.

8.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 8.3.1a) collected by CRED around Saipan, Marpi Bank, Tinian, Tatsumi Reef, and Aguijan between 2003 and 2007 encompassed an area of 2013.4 km^2. Lidar and multibeam bathymetry data collected by the NAVOCEANO around Garapan Anchorage and Lagunan Garapan in 2001 covered an additional area of 32 km^2 (Fig. 8.3.1b).

Bathymetry acquired around Saipan show that the seafloor on the eastern side of this island descends steeply to a depth of 300 m within 1.5 km of the shore (Fig. 8.3.1a, top panel). Almost the entire west side of this island is fronted by a 21 km long lagoon called Lagunan Garapan. Located seaward of the barrier reef forming Lagunan Garapan is an extensive shallow bank forming the largest shallow shelf in the entire Mariana Archipelago. The shelf extends as much as 6 km offshore and has a surface area of 33 km^2, at depths of ~ 20–50 m. A narrow channel separates this shelf from a second bank of similar depth that covers 25 km^2. North and east of Saipan, the bathymetry also reveals a series of canyons and ridges, running roughly eastward, that punctuate an otherwise gently deepening seabed. These canyons and ridges extend 5–10 km from the shallow shelf, ending at depths > 1000 m. On the seabed southeast of Saipan and in Bahia Laolao, the bathymetry shows debris, which may have been deposited through mass wasting, the movement of soil and surface materials by gravity. A smooth, flat channel separates Saipan from Tinian to the south, within which 2 large ridges are shown.

Backscatter data, despite some artifacts, give an indication of the roughness, hardness, and slope of the seabed around Saipan. On the shallow banks around Saipan, predominantly high backscatter values suggest that these areas may be characterized by hard substrates (Fig. 8.3.1a, bottom panel). In the deeper areas, backscatter values appear to have more variability with higher intensity backscatter values associated with major topographic features, such as the tops of ridges and areas of debris, and lower intensity backscatter values associated with in the flatter areas in between.

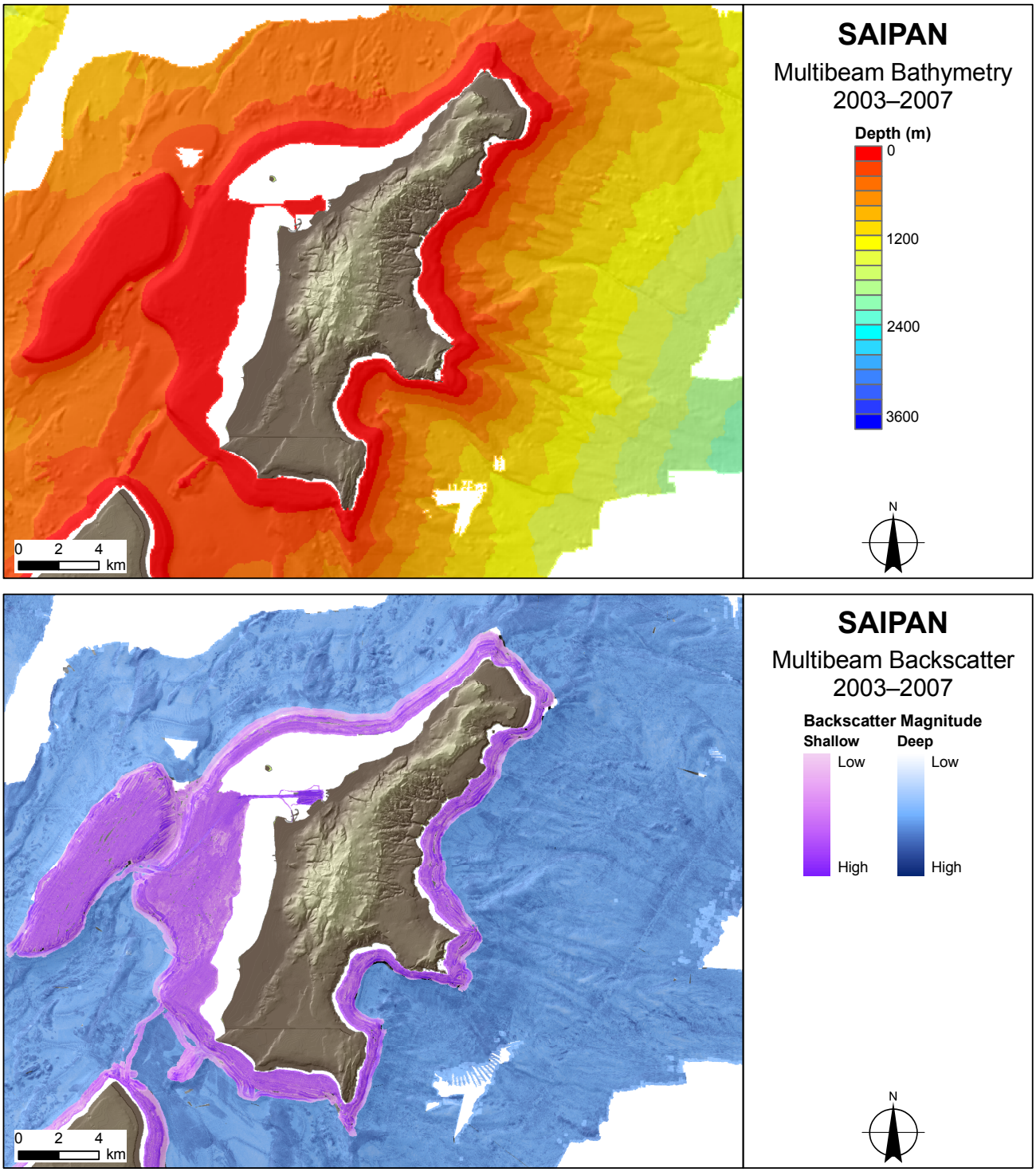


Figure 8.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Saipan during MARAMP 2003 and 2007 at depths of 15–2800 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

High-resolution Bathymetry and Derivatives

Combined lidar and multibeam data collected by the NAVOCEANO in 2001 have recently become available for the Garapan Anchorage and Lagunan Garapan areas. NAVOCEANO lidar data will be incorporated here only in the lagoon areas not covered by CRED-collected multibeam data. A description of the combined lidar multibeam data set is provided in the NAVOCEANO Report of Survey (Naval Oceanographic Office 2001).

The final Saipan depth map is a mosaic of multibeam and lidar data from these 2 sources (Fig. 8.3.1b). Only bathymetric data, and no multibeam backscatter data, are available from these surveys; thus, only bathymetry, slope, rugosity, and bathymetric position index (BPI) zones products for Lagunan Garapan can be derived from the combined data set.

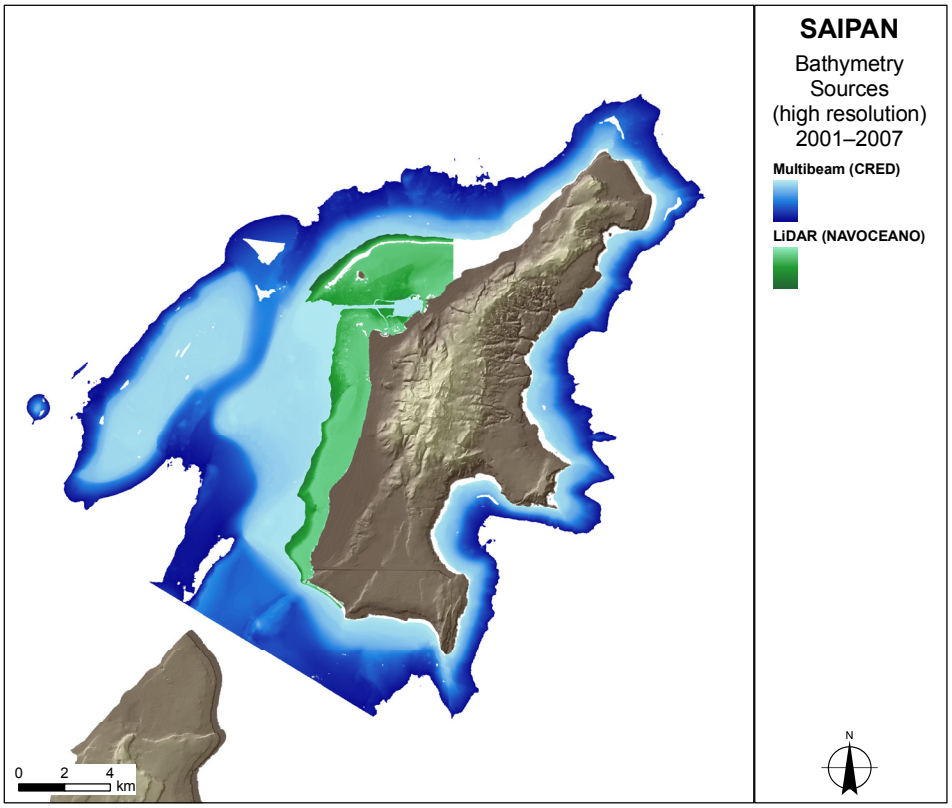


Figure 8.3.1b. Location of multibeam data collected by CRED (shown in blue) and lidar data collected by the NAVOCEANO (shown in green).

High-resolution multibeam data and NAVOCEANO lidar data collected in nearshore (depths of 0–400 m) waters around Saipan were combined into a grid at 5-m resolution to allow for the identification of fine-scaled features (Fig. 8.3.1c). These high-resolution data were used to derive maps showing slope (Fig. 8.3.1d), rugosity (Fig. 8.3.1e), and BPI zones (Fig. 8.3.1f). Together, these maps provide layers of information to characterize the benthic habitats around Saipan.

North of Saipan, the edge of a bank runs close to the coast, and depths of 300 m are reached within a few kilometers of shore. This bank edge is characterized by very steep slopes of > 50°, below which the seabed slopes more gradually. A series of terraces extend away from Saipan's northeast and northwest points and may be related to previous sea level stands.

East of Saipan, a shallow bank ends within 500 m of the shore, below which the seabed forms a descending series of loosely defined terraces. On the terrace edges, high-resolution bathymetry and slope maps reveal a distinctive topographic pattern, which may be related to the presence of coral reef formations. Two major headlands on the east side of Saipan, Puntans Laolao Kattan and Hakmang, both extend into steep sided submarine ridges. These steep slopes are particularly evident at the head of the canyon between the 2 points and south of Putnan Hakmang on the north side of Bahio Laolao. BPI terrain analysis emphasizes the lack of flat seabed and highlights the influence of slope on benthic habitats in this area.

Figure 8.3.1c. High-resolution bathymetry collected around Saipan between 2001 and 2007. This 5-m bathymetry grid, clipped at 400 m, is used as the basis for slope, rugosity, and BPI derivatives.

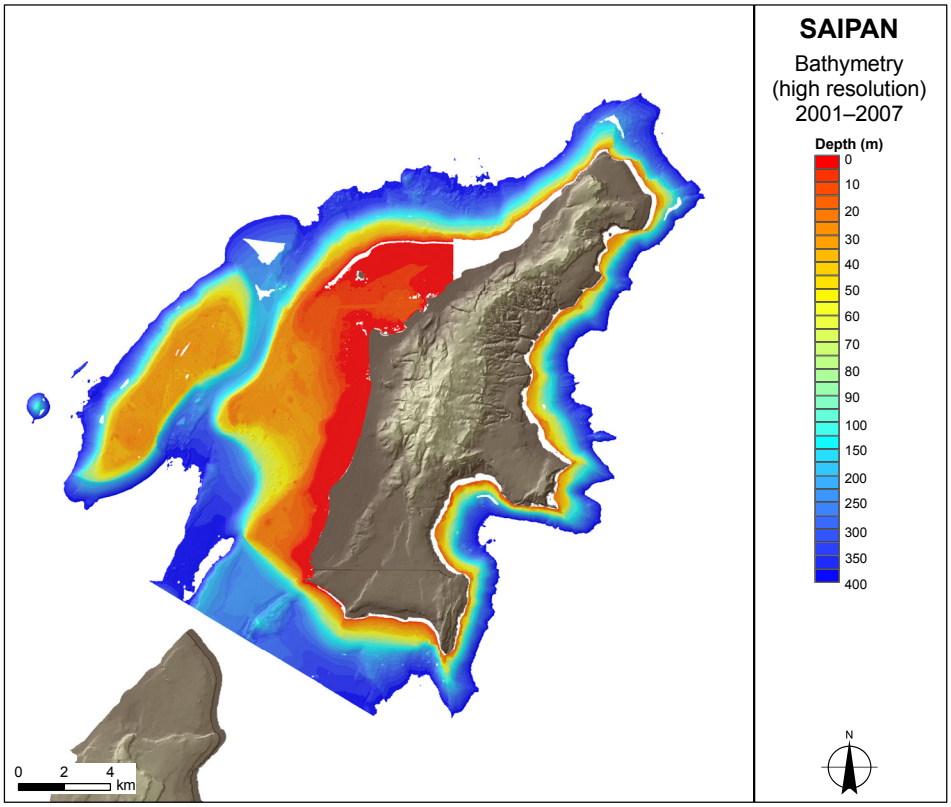
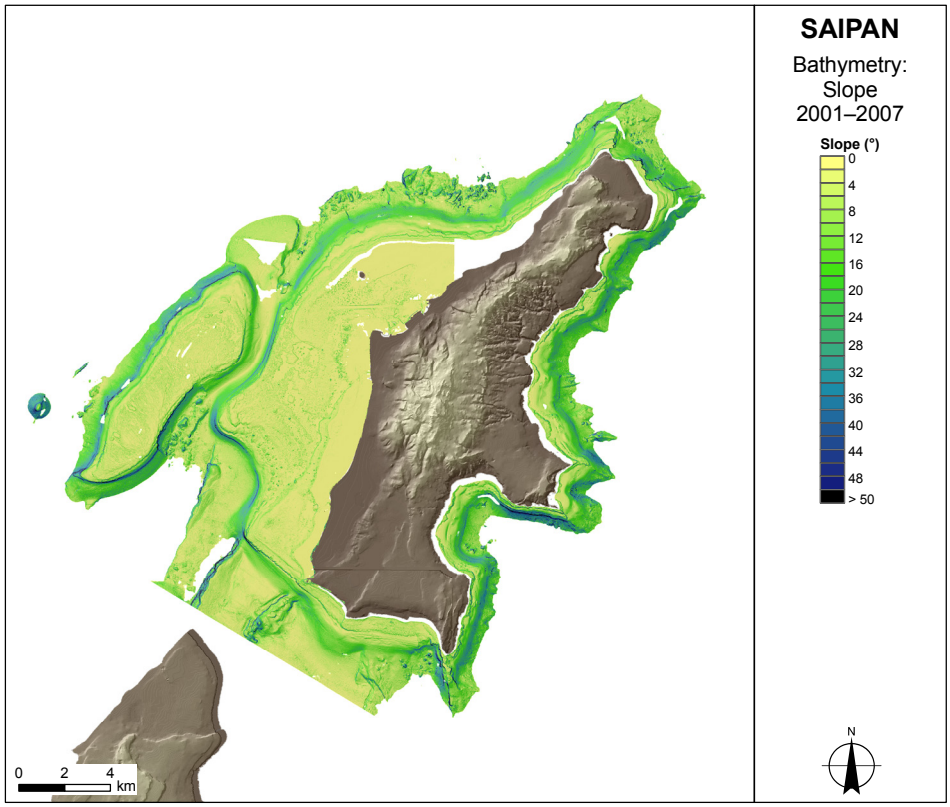


Figure 8.3.1d. Slope (°) of 5-m bathymetric grid around Saipan. Derived from data collected between 2001 and 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades.



South of Saipan, slope and rugosity maps suggest that the channel separating Saipan and Tinian is characterized by very low levels of rugosity, and BPI terrain analysis suggests this channel is classified as an area of flats. The BPI and slope analyses also clearly highlight the steep ridge that crosses this channel. The top of the bank in this area is characterized by a distinctive topographic pattern of mounds and ridges, depicted in the slope, rugosity, and high-resolution bathymetry maps.

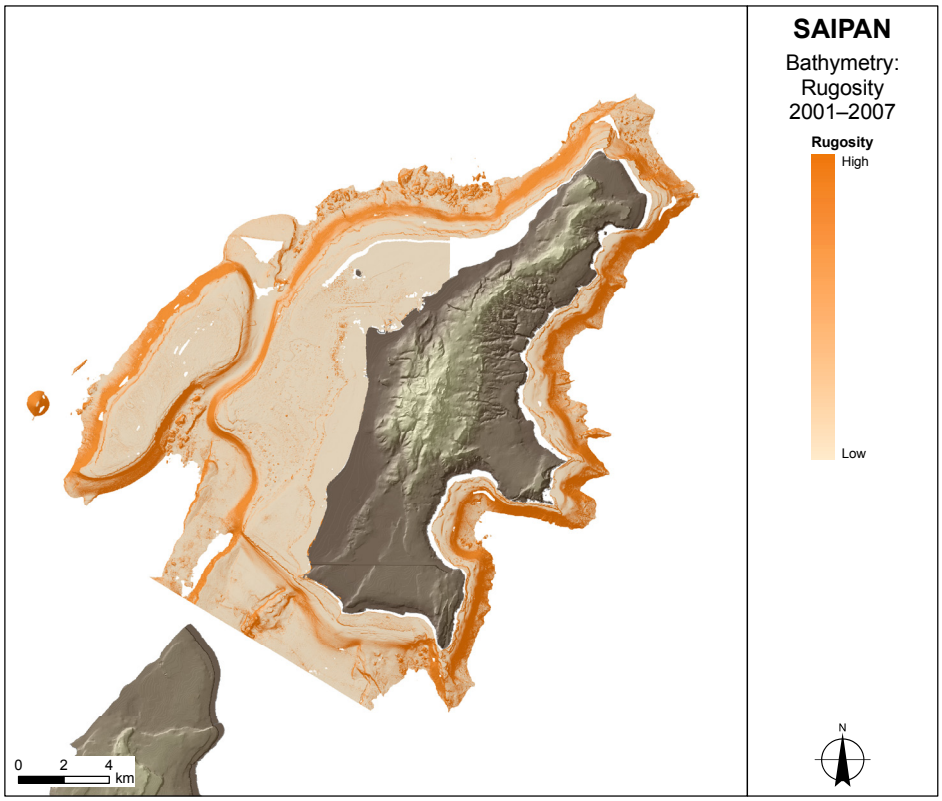


Figure 8.3.1e. Rugosity of 5-m bathymetric grid around Saipan. Derived from data collected between 2001 and 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

Two large, shallow bank areas form significant topographic features west of Saipan. The innermost bank extends offshore for 3–6 km and, with the outer bank, forms Garapan Anchorage. Together, these 2 banks encompass ~ 58 km^2 of seafloor shallower than 50 m. This feature is the largest of its kind in the entire Mariana Archipelago, making it both a unique coral reef habitat and an important anchorage area for large commercial and military vessels. The high-resolution bathymetry, slope, and rugosity data clearly show the topography on these bank tops is characterized by a complex mosaic of mounds and channels, which often supports large areas of coral-rich habitat. Both banks are surrounded by steep slopes that descend into a narrow channel separating them. The base of this channel appears to be very smooth, with low rugosity, although at its southern end, a more rugged topography is shown. West of these banks, a steep pinnacle has a shallow peak at a 100-m depth.

Northwest of Saipan, the most significant topographic features are large blocks of material at the base of the bank slope. Highlighted by the slope, rugosity, and BPI zone maps, this material creates a complex topography that may have been deposited by mass-wasting events.

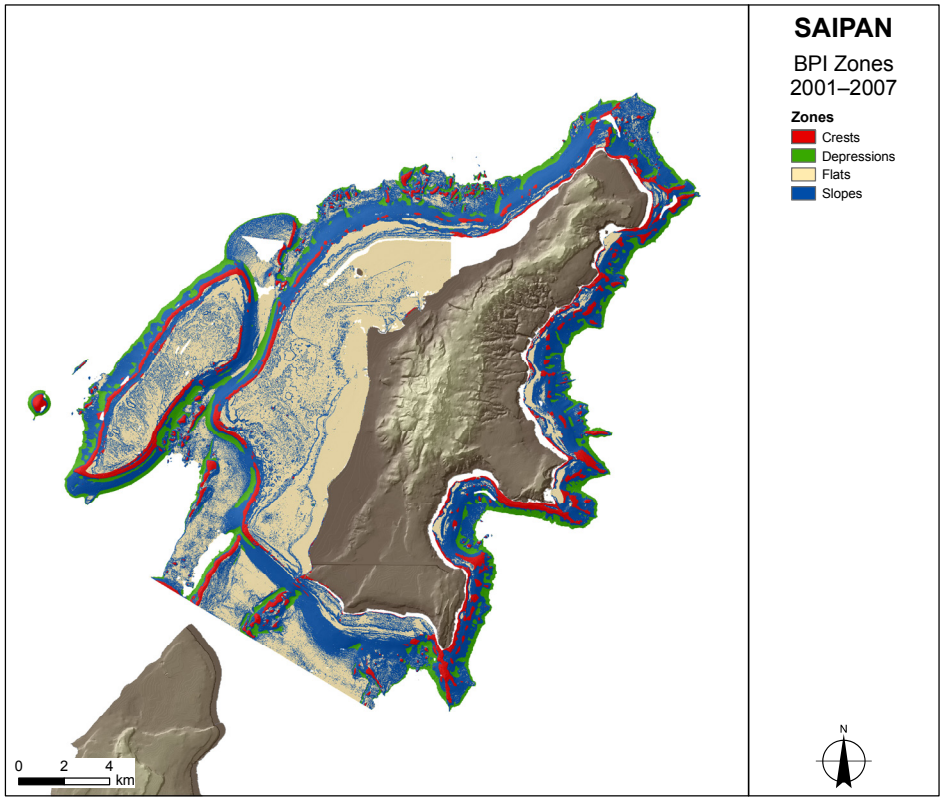


Figure 8.3.1f. BPI zones of 5-m bathymetric grid around Saipan derived from data collected between 2001 and 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

High-resolution Multibeam Backscatter and Derivatives

A number of factors aside from substrate characteristics can affect measured backscatter intensity, including sonar frequency, settings, and slope (see Chapter 2: Methods and Operational Background, Section 2.2.2: "Acoustic Mapping"). In the case of data collected around Saipan, noticeable artifacts are present in the backscatter data that may have resulted from the Reson SeaBat 8101 ER sonar operating at the limit of its capabilities, survey speeds too high for optimum data collection, or steep slopes. Because of these artifacts, unfiltered backscatter data may not accurately reflect the nature of the seabed in these places. To exclude these artifacts from the data, the backscatter data were clipped to a depth of 100 m (Fig. 8.3.1g) prior to deriving the hard–soft substrate map (Fig. 8.3.1h). No backscatter information was available from the lidar data, so only CRED backscatter data are presented in this section.

The backscatter and hard–soft substrate maps show few distinct regional patterns in the distribution of substrate type, but instead show variation at a more local scale. Noticeable areas of hard substrate include a large area in the north part of Garapan Anchorage and a patch of more flat seabed within Bahia Fanonchuluyan, along the shallow shelf south of Saipan. Within Bahia Laolao, southeast of Saipan, the substrate is classified as predominantly soft. This and other areas of soft substrate on the east of Saipan are also characterized with low slopes and rugosity. West of Saipan, the innermost limit of backscatter acquisition was defined by the rim of Lagunan Garapan. Backscatter values in this area show a distinctive pattern with high intensity backscatter recorded along the edge of this lagoon's forereef slope and low intensity backscatter recorded along a narrow strip immediately adjacent (see the inset in Fig. 8.3.1g). A drape of backscatter intensity over 3-D bathymetry clearly shows that soft sediments collect along the outer edge of this lagoon. This pattern of sediment distribution is likely a result of the accumulation of softer sediments within a low-energy lagoon environment that occasionally overtops the lagoon edge and is deposited immediately outside the lagoon. The outer bank of Garapan Anchorage shows a high level of variation, with small-scale patches, between hard and soft substrates, suggesting numerous channels and mounds on this bank. On the north of this bank, a large patch of soft substrate corresponds to a flat area revealed by the bathymetry and derivative maps.

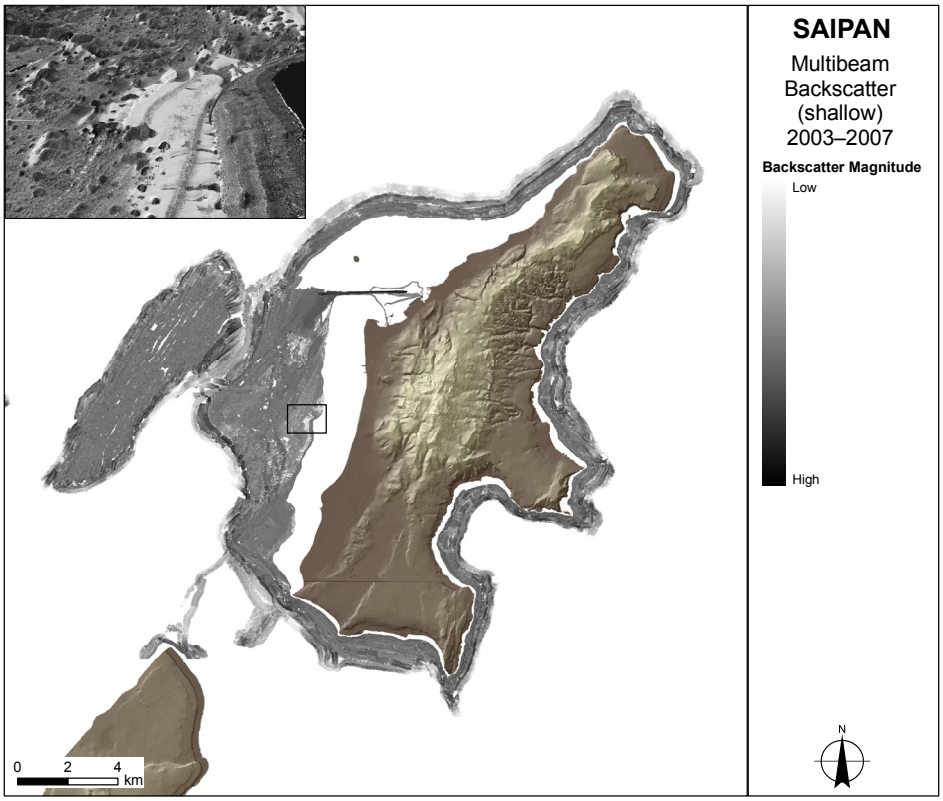


Figure 8.3.1g. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) at depths < 100 m collected around Saipan during MARAMP 2003 and 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates. Inset map shows backscatter draped over 3-D bathymetry in the featured area on the edge of Lagunan Garapan.

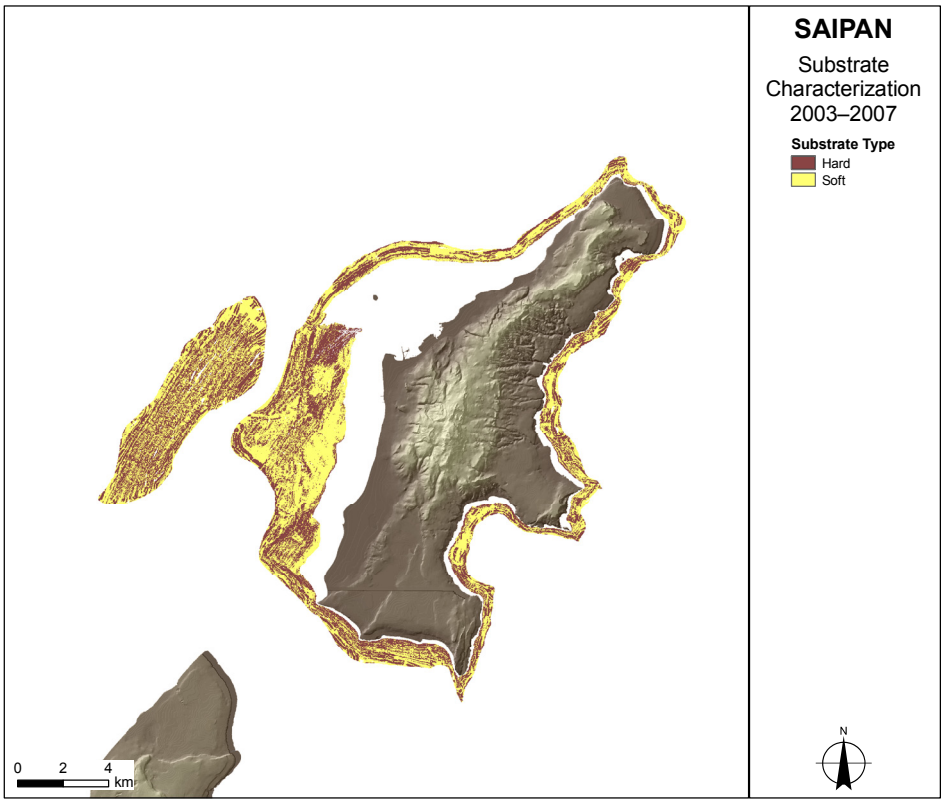


Figure 8.3.1h. Hard and soft substrates (grid cell size: 5 m) at depths < 100 m based upon an unsupervised classification of multibeam bathymetry and backscatter data acquired around Saipan between 2003 and 2007.

8.3.2 Optical Validation

During MARAMP 2003, 13 TOAD optical-validation surveys of forereef habitats were conducted around Saipan at depths < 140 m (Fig. 8.3.2a). In 2004, through the MSC contract described previously, an additional 41 deployments were completed, covering a distance of 140 km. Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live-hard-coral cover.

Covering a distance of 146 km at depths of 5–24 m, 39 towed-diver optical-validation surveys were conducted around Saipan during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

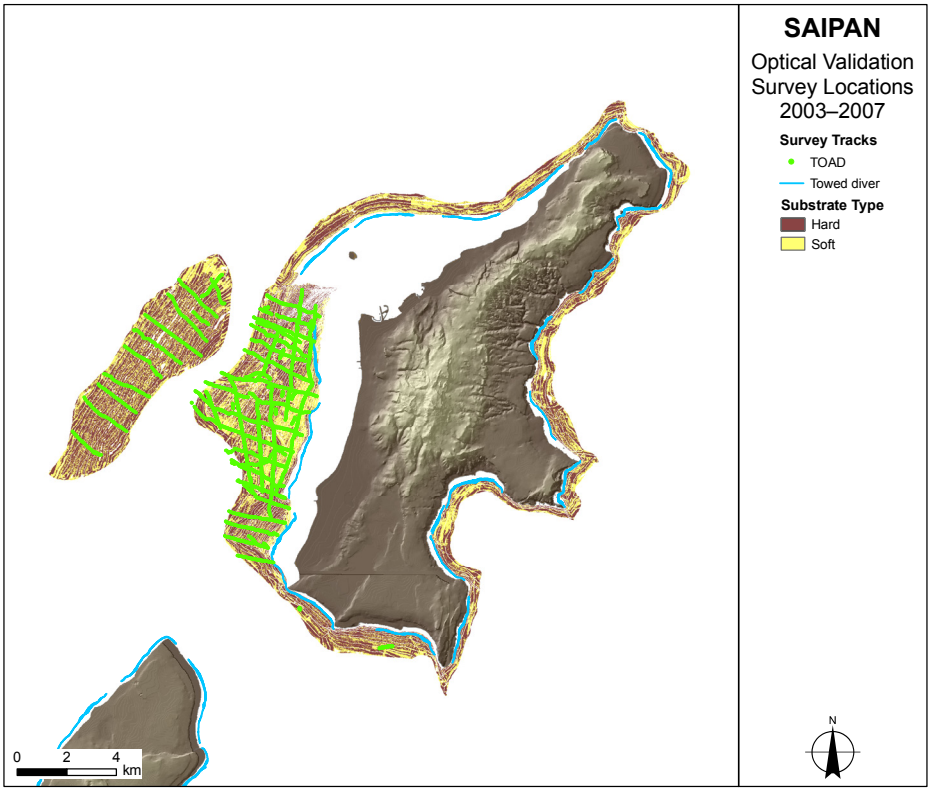


Figure 8.3.2a. Towed-diver tracks from surveys of forereef habitats conducted around Saipan during MARAMP 2003, 2005, and 2007, and TOAD camera sled tracks for surveys conducted during MARAMP 2003 and in 2004 for the MSC contract. Survey tracks are displayed over the multibeam hard–soft substrate map. Data cannot be collected directly under the ship, hence the white lines showing ths ship's path

8.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Saipan are discussed in this section. These descriptions are discussed with reference to the 6 geographic regions around Saipan. Towed-diver observations made around Saipan during MARAMP 2003, 2005, and 2007 revealed a low complexity seabed that was characterized by predominantly hard substrates and low sand cover (Figs. 8.3.3a and b). Live coral cover was generally < 20%, except for a small number of locations described later in this section (Fig 8.3.3c). A large, shallow lagoon, Lagunan Garapan, stretches along the west coast of Saipan, fringed by a barrier reef. Because of its shallow depths it was not possible for towed divers to survey within this lagoon.

Around north Saipan, the nearshore environment was a predominantly hard substrate, as suggested by the low levels of sand cover recorded during towed-diver surveys. Levels of habitat complexity were observed from low to medium, and live coral cover also was observed as low, except for a small patch of higher cover recorded close to Puntan Sabaneta.

In the southeast region, live coral cover from towed-diver surveys generally ranged from 5.1% to 20%, although higher cover was observed in the north part of Bahia Laolao with interpolated live coral cover of up to 75%. The reef habitat present here was described by towed divers as a moderately sloping reef with sand patches.

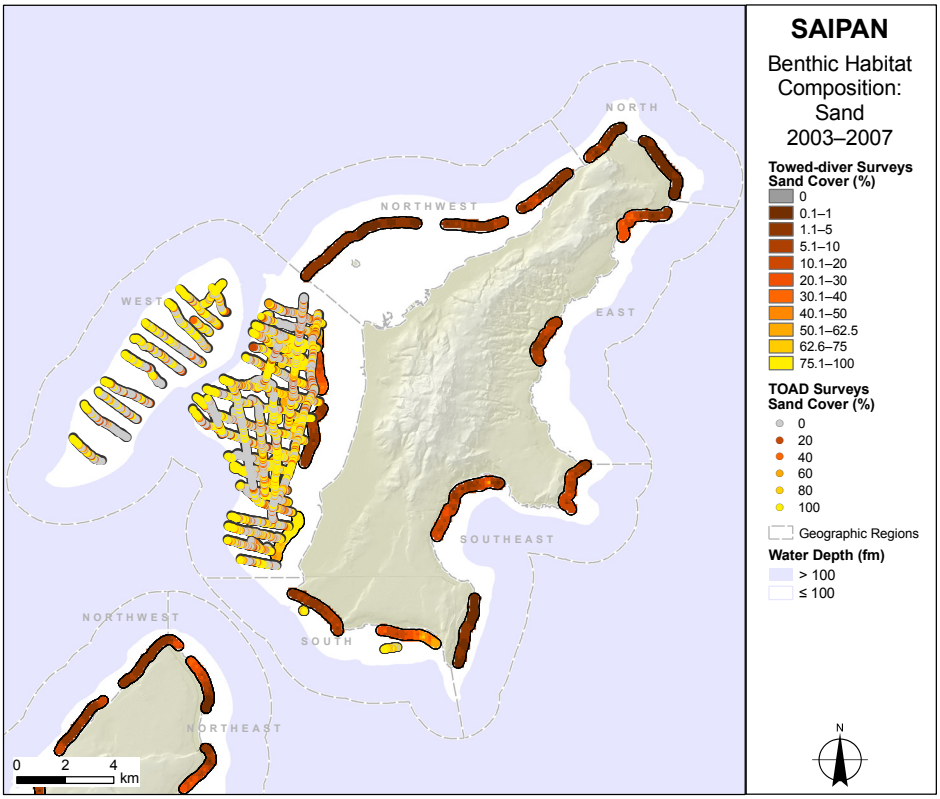


Figure 8.3.3a. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted around Saipan during MARAMP 2003, 2005, and 2007 and analysis of TOAD video collected during MARAMP 2003 and in 2004 for the MSC contract.

Habitat complexity from towed-diver surveys conducted around Saipan ranged from medium to high. Highly complex habitats were observed in the north part of Bahia Fanonchuluyan in the east region; at Puntan Laolao Kattan, located at the border between the east and southeast regions, corresponding to an area described as containing spur-and-groove reefs and vertical walls; and in the southeast region at Puntan Dandan, where divers observed boulders and crags. Sand cover from towed-diver surveys was generally < 20%, with the highest interpolated sand cover of up to 30% recorded in the middle of Bahia Fanonchuluyan.

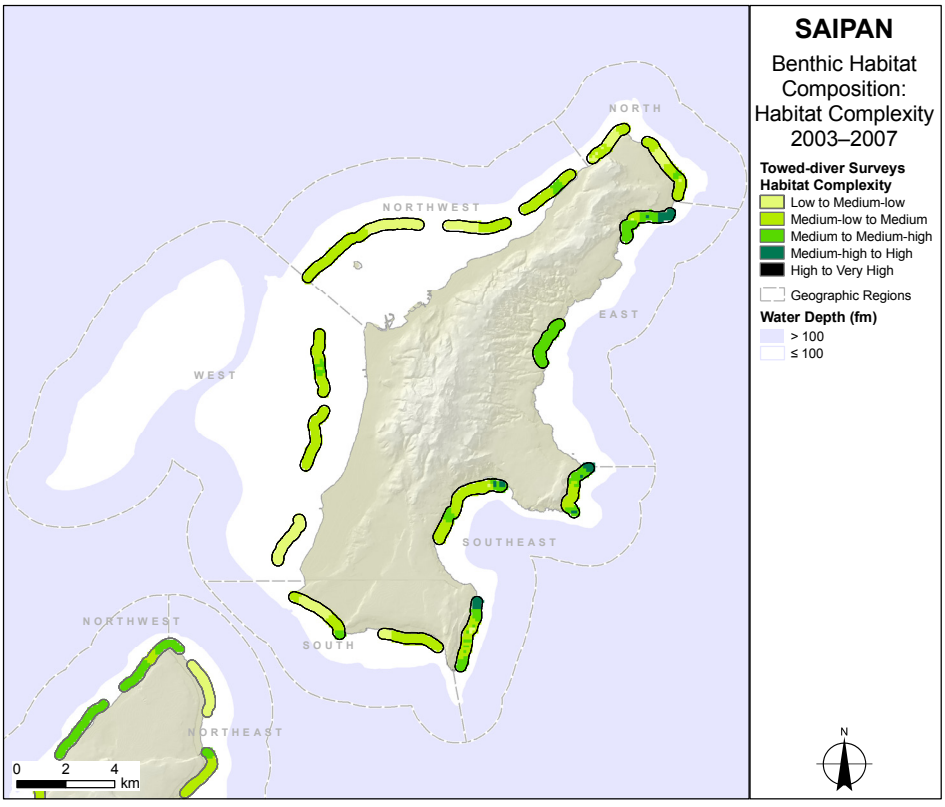
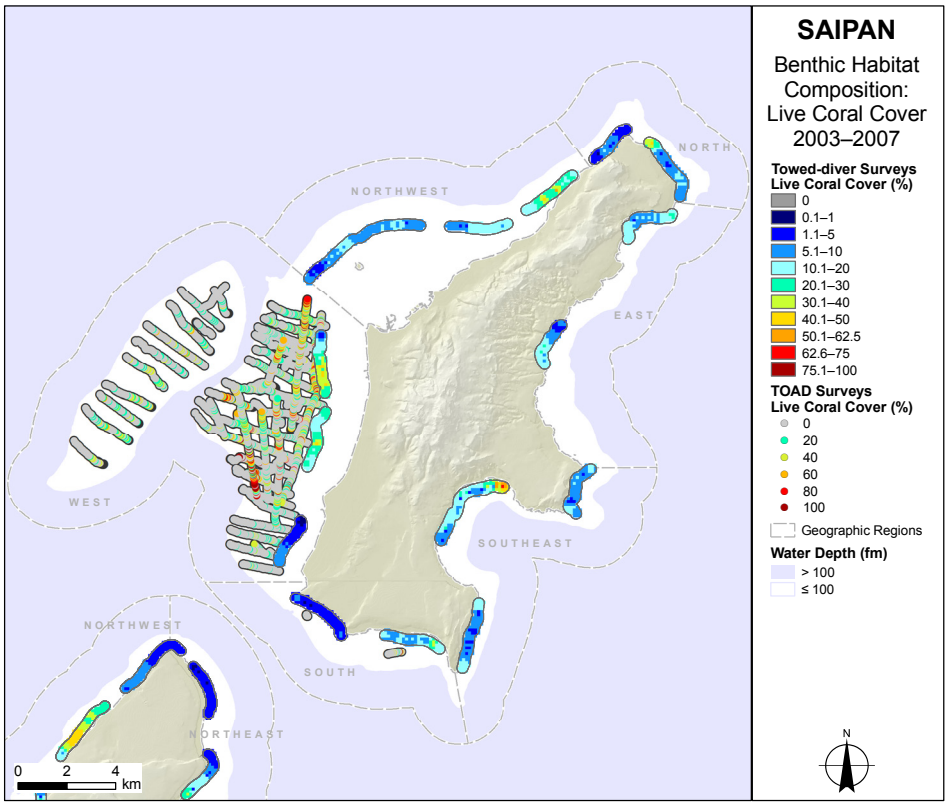


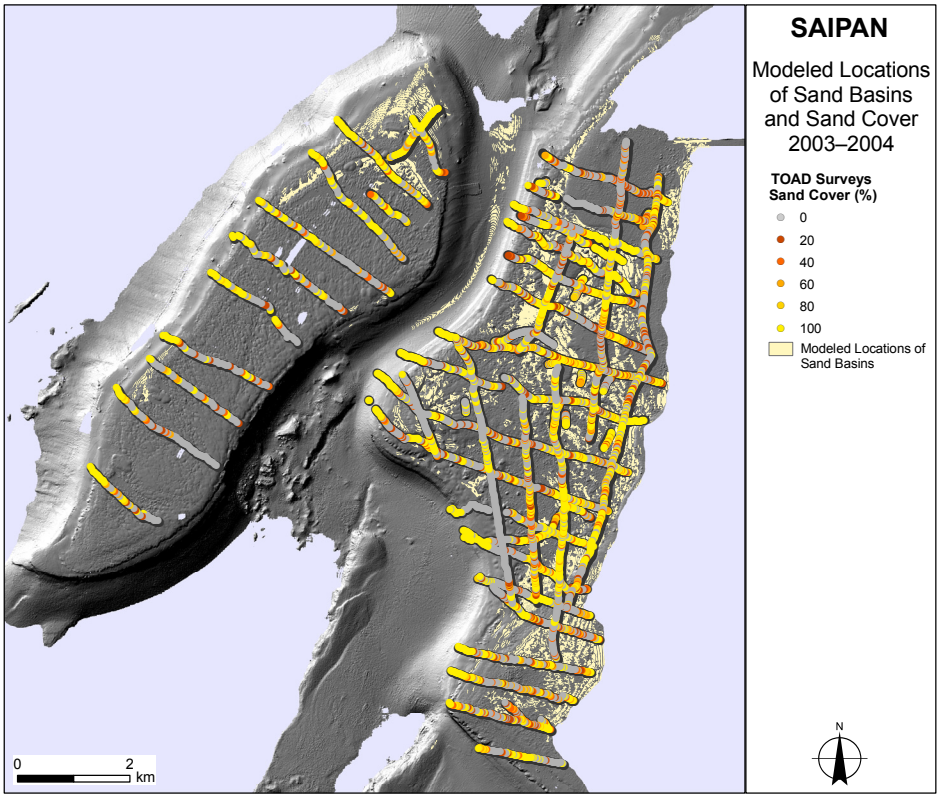
Figure 8.3.3b. Observations of benthic habitat complexity from towed-diver surveys of forereef habitats conducted around Saipan during MARAMP 2003, 2005, and 2007.

Figure 8.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted around Saipan during MARAMP 2003, 2005, and 2007 and analysis of TOAD video collected during MARAMP 2003 and in 2004 for the MSC contract.



Towed-diver surveys recorded low cover of both sand and live corals between Puntans Agingan and Unai Opyan in the south region, suggesting a hard substrate habitat. Habitat complexity was also low. East of Puntan Unai Opyan, however, habitat complexity and sand cover were slightly higher, although still sufficiently low to suggest predominantly hard substrates.

Figure 8.3.3d. Observations of sand cover (%) from analysis of TOAD video overlaying estimated locations of sand basins modeled from the 5-m bathymetry grid (shown in light yellow) in the Garapan Anchorage area (Cutter 2004).



Live coral cover from towed-diver surveys generally ranged from 5.1% to 20%. In deeper waters south of Saipan, analyses of TOAD survey video footage suggest an area of flatter, smoother seabed. Here, analyses of video footage suggest a predominantly sandy seafloor. Live coral cover estimated from TOAD surveys was generally low, although a small number of individual video frames showed high cover, suggesting a patchy distribution of live corals.

In the west region, 2 extensive banks form a large anchorage area, Garapan Anchorage. As described previously at the beginning of this section, additional survey work within this anchorage and further analysis of acoustic data were conducted, allowing for a more complete picture of habitat distribution within this area.

A modeled distribution of sand basins in Garapan Anchorage (Fig. 8.3.3d) shows sand cover is higher on the inner anchorage versus the outer anchorage. The modeled sand basin map, hard–soft map (Fig. 8.3.1h), and analyses of TOAD video footage (Fig. 8.3.3a) together suggest that the outer anchorage is predominantly composed of hard substrate. Sand cover that is higher than in other areas is shown within the flat channels that can be seen on the slope map in between the mound features. Analyses of TOAD video footage also suggest high sand cover along the western edge of the outer anchorage bank top. However, the modeled distribution of sand basins appears to under-represent this long strip of sand, highlighting the importance of ground-truthing modeled products with optical data.

The sand distribution predicted for the inner anchorage area corresponds well to the topographic features revealed by the slope map, with relatively high sand cover in numerous small channels that can be seen on the slope map and low cover on the mounds. Some differences, however, are observed between the map of modeled sand basin distribution and the hard–soft map, which was derived from the unsupervised classification of backscatter data (Fig. 8.3.1g). For example, in the innermost part of the inner anchorage, the hard–soft map shows a large area of soft substrate whereas the modeled sand map predicts a lower sand cover. Analyses of TOAD video footage, meanwhile, suggest high sand cover in this area, although areas of low sand cover were also present, suggesting patchy sand distribution. Similarly, southwest of Puntan Susupi in the west region, the hard–soft map shows an area of predominantly hard substrate and the map of modeled sand basins shows an area of sandy substrate. For this area, TOAD video analyses in this area suggest a mixture of high and low sand cover, although the pattern of sand distribution appears to associate better with the hard–soft map rather than the map of modeled sand basin locations. Some of these differences are likely a result of the thinness of the superficial sediment. Where only a thin layer of sand overlies hard substrates, sand will be seen in video footage but acoustic signals will reflect strongly off the underlying hard substrate and result in high backscatter values.

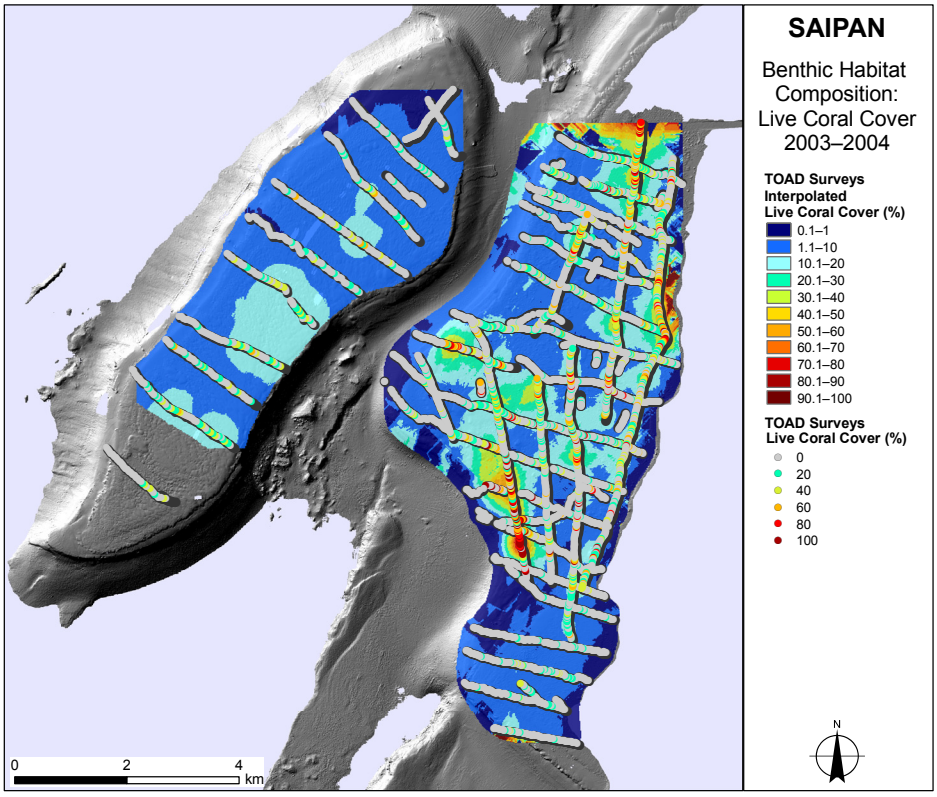


Figure 8.3.3e. Cover (%) observations of live hard corals from analysis of TOAD video overlaying interpolated TOAD values for the percentage of the seafloor covered by corals and other benthic fauna in the Garapan Anchorage area.

Interpolated TOAD video data show a higher concentration of live corals on the inner anchorage area than on the outer anchorage (Fig. 8.3.3e). TOAD video analyses revealed the presence of live corals throughout both anchorage areas, including frequent observations at mesophotic depths (> 30 m). Analyses of TOAD survey video footage suggest that live coral cover was high, with cover of 100% observed in numerous TOAD video images for large areas of mounds, which can be seen on the slope map (Fig. 8.3.1d). Numerous mounds supporting live coral cover on the inner anchorage were found at depths of 30–50 m, suggesting intermediate-depth mesophotic coral ecosystems (MCEs; Locker 2010) Low live coral cover was found on the flat, predominantly sandy channels in between these mounds. Interpolated TOAD data show an area on the southwest edge of the inner anchorage that supports a concentrated area of high coral cover, frequently of 100%. Depths in this area range from ~ 50 to 80 m, and the area extending from the seabed to the top of the bank, appears to have a slightly different character—with smooth areas of moderate slopes rather than the numerous small mounds seen elsewhere on this bank. Analyses of video footage obtained in this area revealed an extensive MCE, formed primarily by the hard coral *Euphyllia paraanacora*.

Within the outer anchorage area, interpolated live coral cover is generally low, although analyses of TOAD videos footage suggest small areas with live coral cover of 40.1%–60% (Fig. 8.3.3e). While the interpolated data provide an indication of areas of relatively high live coral cover, this map oversimplifies the natural spatial heterogeneity in distribution live corals that is revealed by the TOAD video analyses.

Both the TOAD video analyses and interpolated map suggest that, although numerous topographic features can be seen from acoustic data and could indicate the presence of patch reefs, many of these features support few or no live corals. Still, the interpolation of live coral cover in Garapan Anchorage must be treated with some caution. Despite the high number of TOAD deployments conducted, optical data were not available for large areas of Garapan Anchorage. Interpolated products provide a general overview of the patterns of benthic habitat distribution. However, these patterns are less robust in very heterogeneous sites and in areas, such as Garapan Anchorage, where damage from anchor chains has impacted large areas. For these reasons, areas of high coral concentration could have been overlooked if they were not surveyed by TOAD deployments.

8.4 Oceanography and Water Quality

8.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 20 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters at the island of Saipan over the period of August 21–22. Data from these casts show relatively well-mixed surface waters with a narrow range in temperature (< 0.7°C) and salinity (< 0.2 psu). Spatial comparisons of water properties at a depth of 10 m reveal slightly lower temperatures (29.45°C–29.57°C), higher salinities (34.34–34.39 psu), and associated higher densities (21.4–21.44 kg m^{-3}) around the northwest corner of Saipan (casts 7–9) relative to other areas around this island, suggesting greater mixing with deep water or localized upwelling (Fig 8.4.1a). Vertical comparisons of CTD profiles confirm that waters were cooler and well mixed to a depth of 30 m in the north region (Fig. 8.4.1b). This interpretation is consistent with observations of vigorous tidal flows around the northern tip of this island. Waters (casts 17–20) were warmer, slightly less saline, and more stratified in the southeast region than in other areas at Saipan, with the highest temperature of 30.03°C and the lowest salinity of 34.25 psu both recorded in Bahia Laolao (for place-names and their locations, see Fig. 8.2a in Section 8.2: "Survey Effort"). The causal mechanism for these water conditions is unknown but may be simply a diurnal effect (i.e., these casts were collected later in the day than were others). Beam transmission values were > 91% at most cast locations, except in the vicinity of Saipan Harbor (casts 2–3), where transmission values were as low as 82.42%.

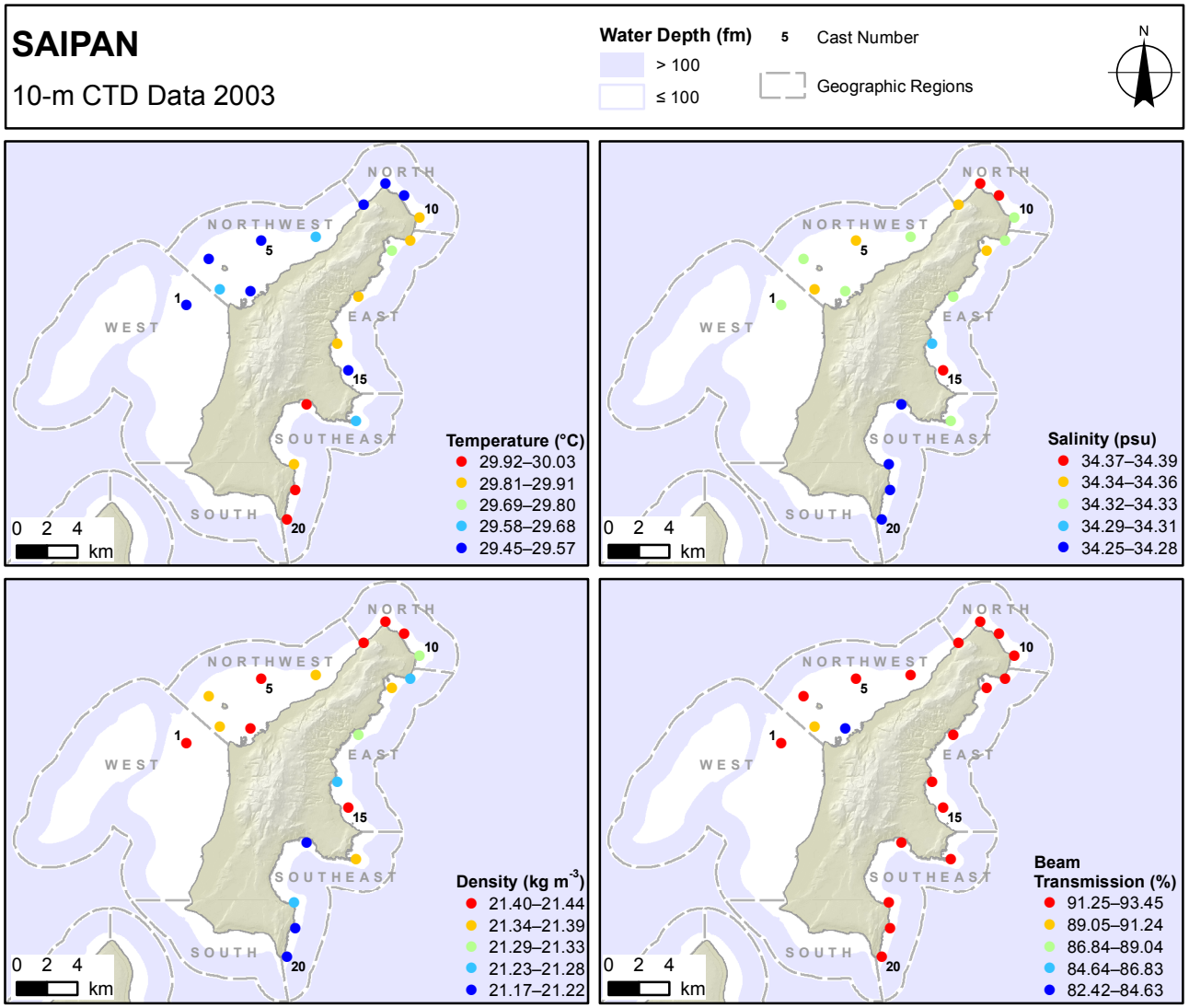


Figure 8.4.1a. Values of (*top left*) water temperature, *(top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts at Saipan on August 21–22 during MARAMP 2003.

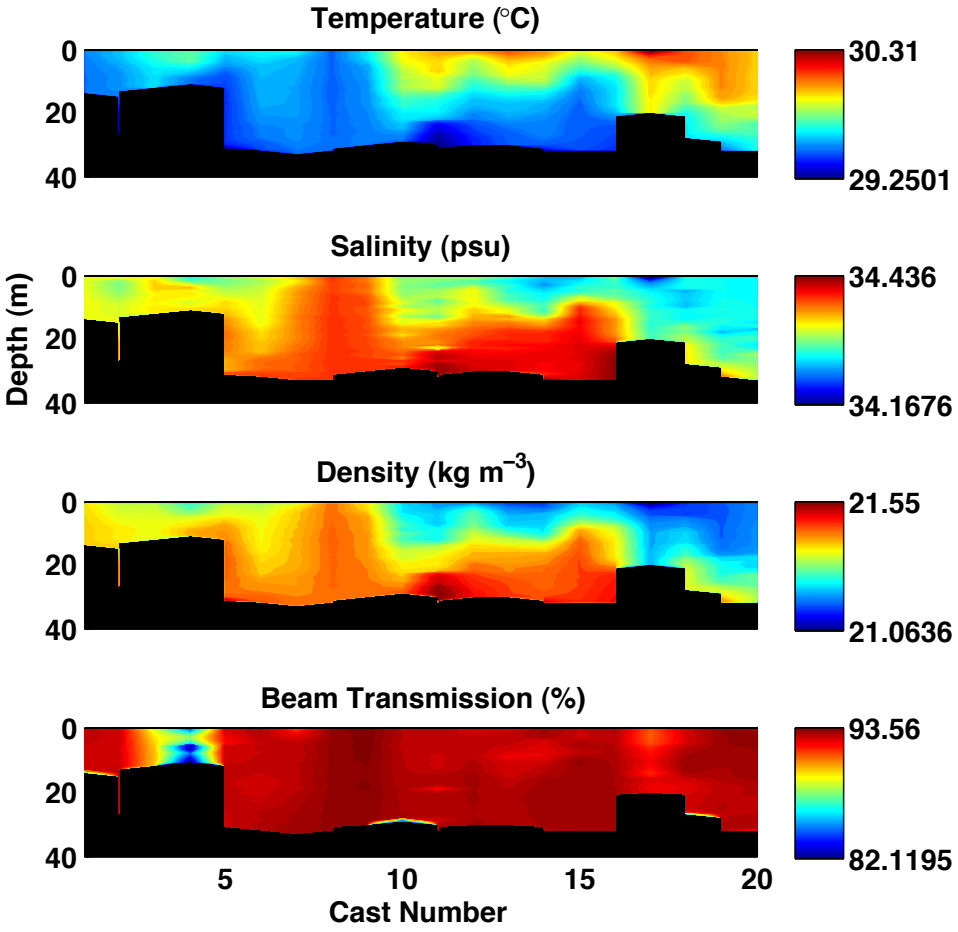


Figure 8.4.1b. Shallow-water CTD cast profiles to a 30-m depth at Saipan on August 21–22 during MARAMP 2003, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–20 in a clockwise direction around Saipan. For cast locations and numbers around this island in 2003, see Figure 8.4.1a.

2005 Spatial Surveys

During MARAMP 2005, shallow-water CTD casts were conducted in nearshore waters at Saipan on September 3–4 and September 22. Data from 27 of these casts show a blend of stratified and well-mixed surface waters, depending on location at Saipan. Spatial comparisons of water properties at a depth of 10 m show lower temperatures (28.59°C), higher salinities (34.56 psu), and associated higher densities (21.88 kg m^{-3}) in the north region than in other areas at Saipan (Fig. 8.4.1c), suggesting greater mixing with deep water or localized upwelling. Beam transmission values were lower (91.96%) in the west region (cast 2) near Saipan Harbor than in other regions. Vertical comparisons (Fig. 8.4.1d) of CTD profiles reveal a well-mixed water column in most cast locations; however, at select locations, the water column exhibited greater stratification (casts 2–3, 6–8, 22–23). Broad ranges in temperature (~ 1°C) and beam transmission (~ 4%) were observed, with the highest temperature (29.34°C) and lowest beam transmission (90.05%) values recorded near Saipan Harbor (cast 2). These large ranges could have resulted from temporal separation in sampling.

Water samples were collected in concert with shallow-water CTD casts at select locations at Saipan in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.12–1.50 µg L^{-1}; total nitrogen (TN), 0.07–0.17 µM; nitrate(NO_3^-), 0.07–0.15 µM; nitrite (NO_2^-), 0.00–0.03 µM; phosphate (PO_4^{3-}), 0.00–0.04 µM; and silicate [$Si(OH)_4$], 0.33–0.77 µM. Minimum nitrite values (0.00) were close to immeasurable levels. Based on data from 6 sample locations, water-quality data show that Saipan Harbor contained the highest Chl-*a* and nutrient values (Fig. 8.4.1e).

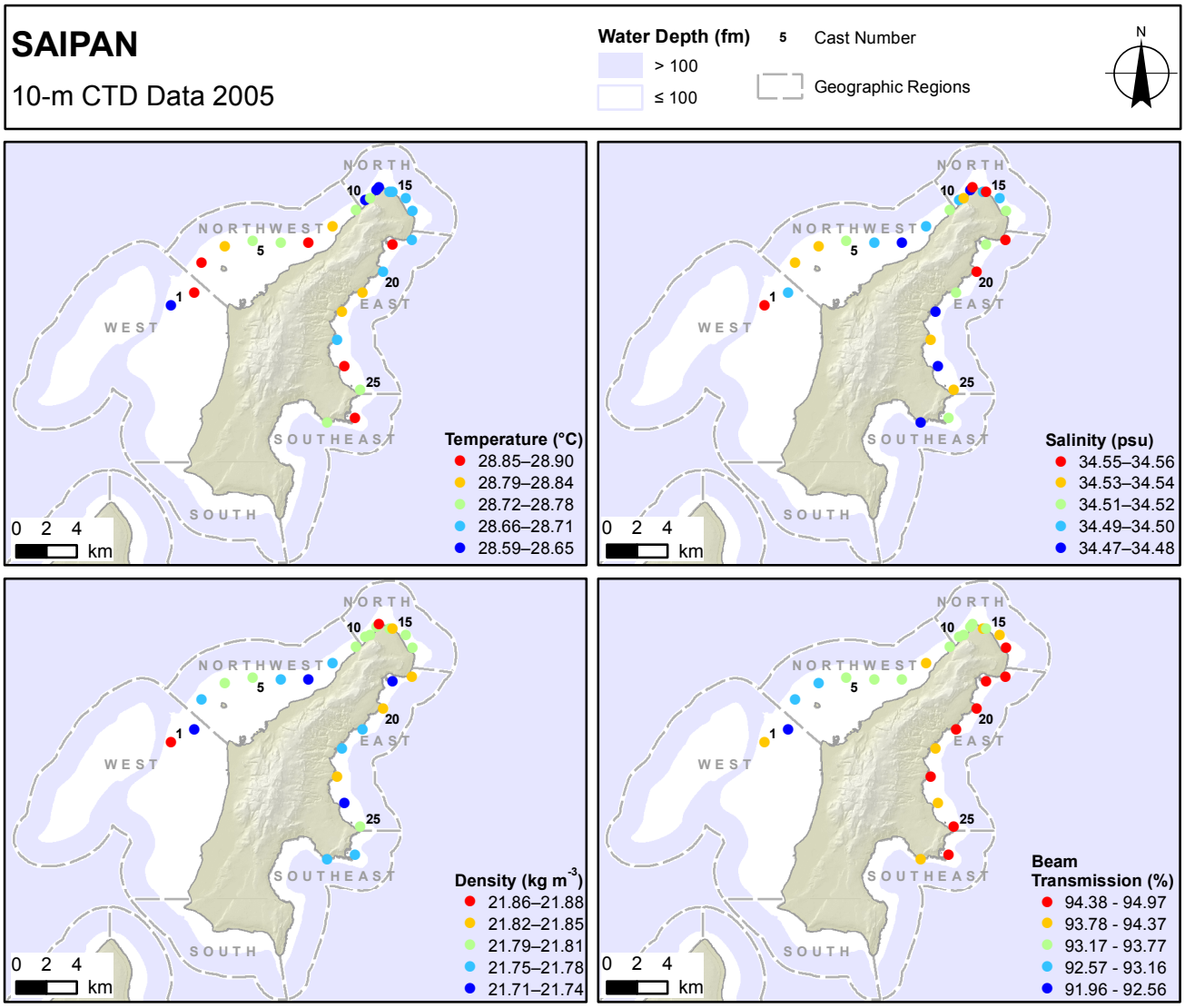


Figure 8.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts at Saipan during MARAMP 2005, with casts 10, 12, 14, 16, and 17 done on September 3, casts 18–27 done on September 4, and casts 1–9, 11, 13, and 15 done on September 22.

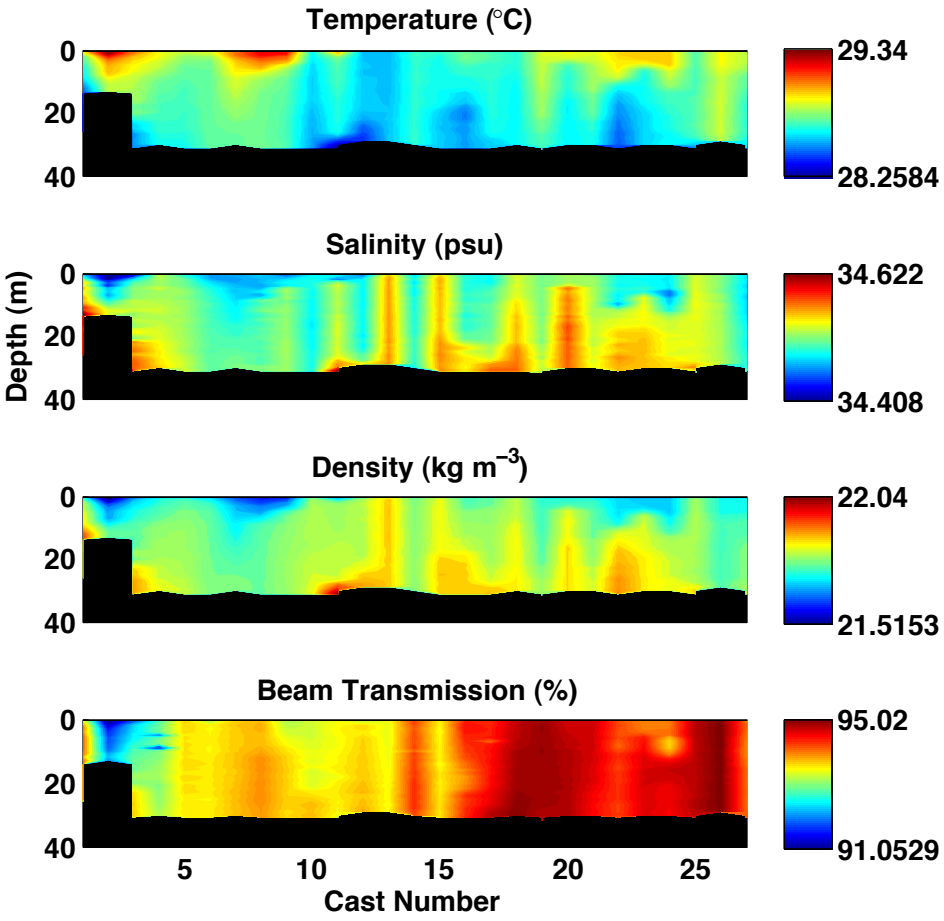


Figure 8.4.1d. Shallow-water CTD cast profiles to a 30-m depth at Saipan during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–27 in a clockwise direction around Saipan. Casts 10, 12, 14, 16, and 17 were completed on September 3, casts 18–27 were done on September 4, and casts 1–9, 11, 13, and 15 were done on September 22. For cast locations and numbers around this island in 2005, see Figure 8.4.1c.

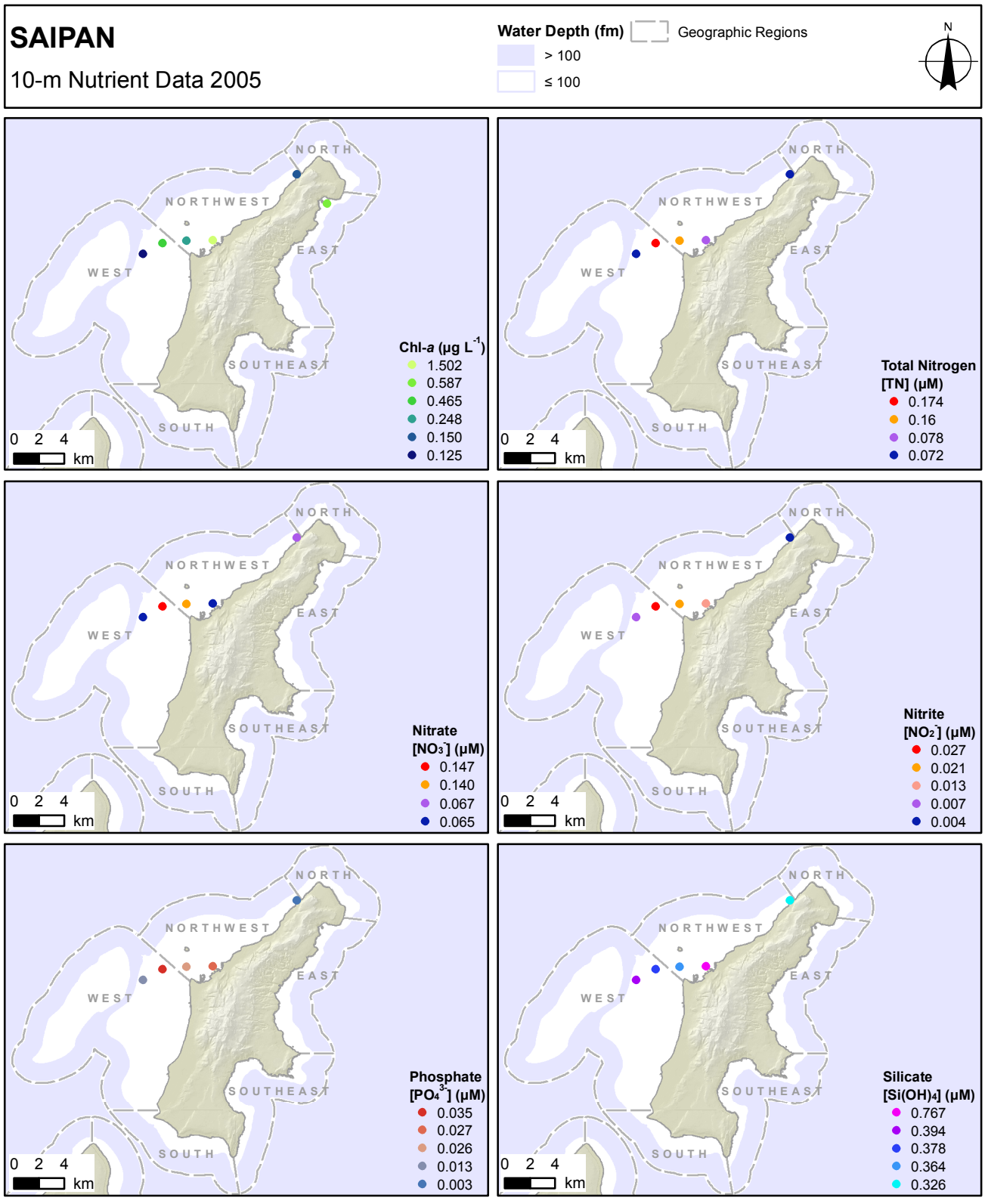


Figure 8.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate concentrations at a 10-m depth, from water samples collected at Saipan on September 22 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, shallow-water CTD casts were conducted in nearshore waters around Saipan over the period of May 19–21. Temperature, salinity, density, and beam transmission values from 37 of these casts varied both spatially and vertically around Saipan. Spatial comparisons of water properties at a depth of 10 m show moderate ranges in temperature (1.09°C), salinity (0.14 psu), density (0.47 kg m^{-3}), and beam transmission (2.04%) values, although these ranges principally result from values from one cast in the east region (cast 20), where colder, more saline, and more dense waters were recorded (Fig. 8.4.1f). Vertical comparisons of CTD profiles reveal substantial ranges in temperature (1.9°C) and salinity (0.3 psu) around Saipan (Fig. 8.4.1g). Areas with the lowest temperatures (27.6°C), highest salinities (34.6 psu), and associated highest densities (22.2 kg m^{-3}) for Saipan were observed in the northwest, north, and southeast regions (casts 15, 20, 26–27). These differences in water properties suggest greater mixing with deep water or localized upwelling in these areas, relative to other areas around this island. Beam transmission values varied around this island, with the lowest values recorded in the vicinity of Saipan Harbor and in the northwest regions (casts 7–12).

Water samples were collected in concert with shallow-water CTD casts at 4 select locations at Saipan in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: Chl-*a*, 0.04–0.12 µg L^{-1}; total nitrogen (TN), 0.03–0.05 µM; nitrate(NO_3^-), 0.02–0.03 µM; nitrite(NO_2^-), 0.01–0.02 µM; phosphate (PO_4^{3-}), 0.05–0.06 µM; and silicate [$Si(OH_4)$], 1.37–2.18 µM. Water-quality data show that Chl-*a* was highest in the northern part of Saipan Harbor in the west region, while most nutrient concentrations were highest in the northwest region near Puntan Makpe` (Fig. 8.4.1h).

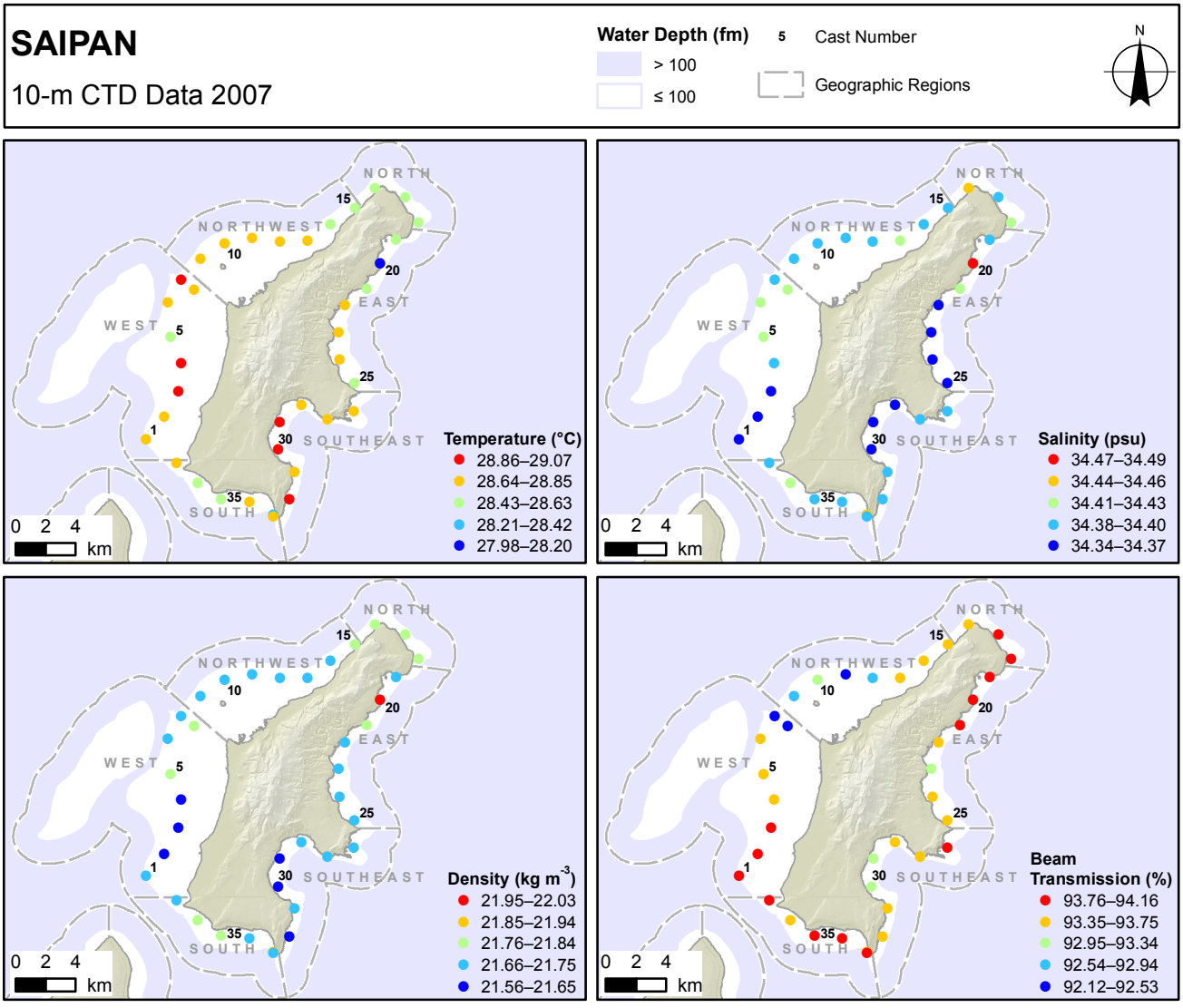


Figure 8.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Saipan on May 19–21 during MARAMP 2007.

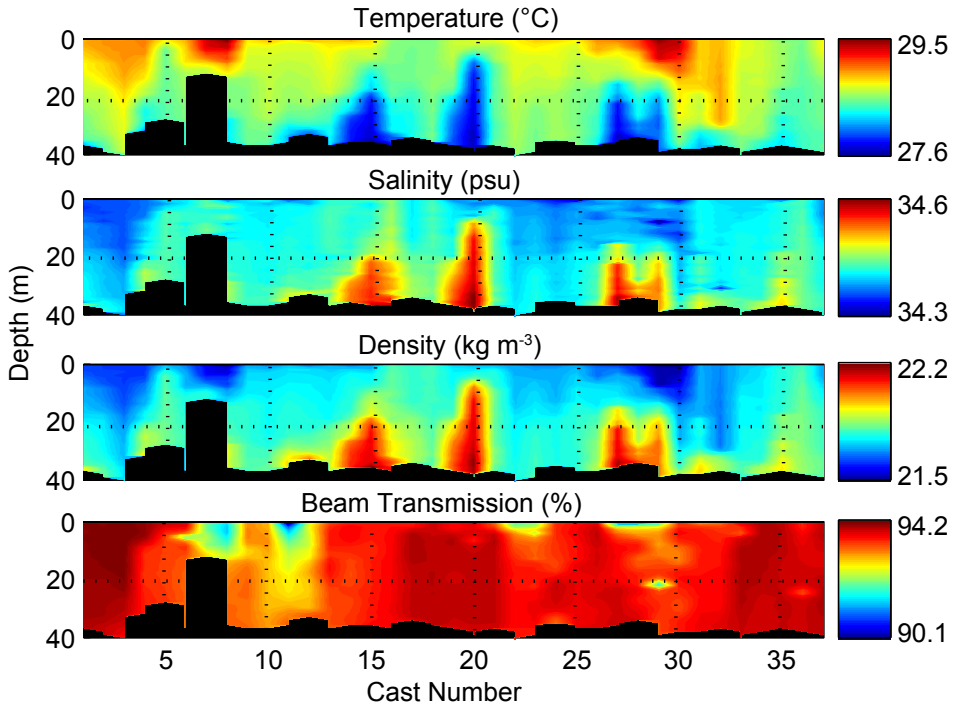


Figure 8.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Saipan on May 19–21 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–37 in a clockwise direction around Saipan. For cast locations and numbers around this island in 2007, see Figure 8.4.1f.

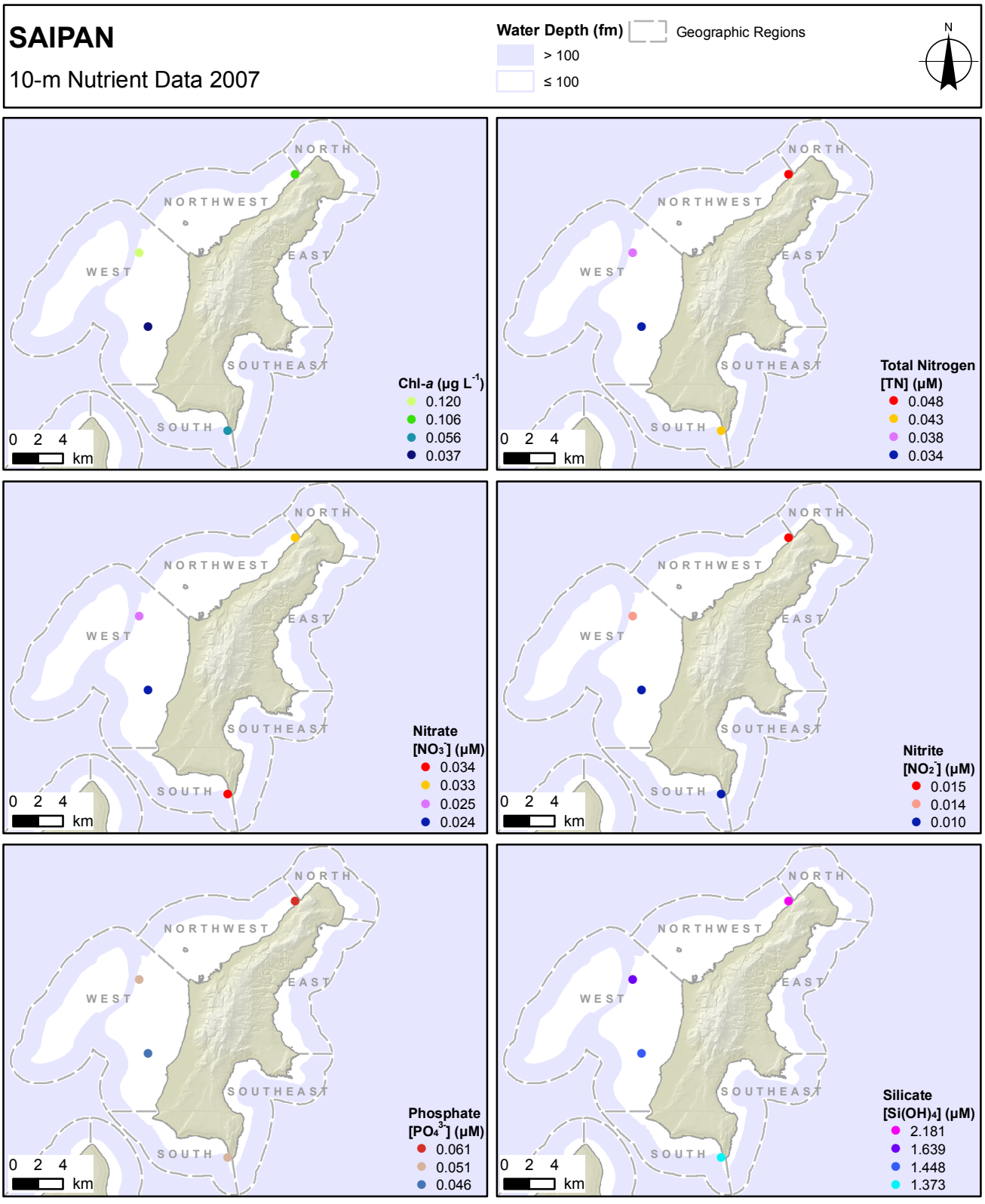


Figure 8.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Saipan on May 19–21 during MARAMP 2007.

Temporal Comparison

Data from shallow-water CTD casts performed around Saipan during MARAMP 2003, 2005, and 2007 show temperature ranges > 1°C within these survey periods, although comparisons between survey years show the maximum temperature was ~ 0.9°C greater in 2003 than in 2005 and 2007. Vertical gradients in all parameters measured were consistently stronger in the regions sheltered from easterly trade winds than in other areas; however, data from MARAMP 2007 show increased stratification with pronounced, localized, deepwater mixing tongues and less spatial homogeneity than in earlier survey years. In each survey year, mixing with deep water or localized upwelling were evident in the north and east regions. Beam transmission values were > 92% at most cast locations; however, beam transmission was generally lowest in the vicinity of Saipan Harbor during each of the survey years. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May, and MARAMP 2003 and 2005 occurred in August and September. This change was made to avoid the typhoon season and reduce the probability of weather disruptions.

Water-quality assessments from water samples collected during MARAMP 2005 and 2007 suggest that Chl-*a*, total nitrogen, nitrate, and nitrite concentrations were much lower in 2007 than in 2005, while phosphate and silicate concentrations were much higher. Whether this variation resulted from a seasonal effect, differences in sample locations between survey years, or some other process is not known at this time. Precipitation data show that MARAMP 2005 occurred during a period of seasonally high precipitation and MARAMP 2007 occurred during a period of seasonally low precipitation (Fig 8.4.2e). The relatively high nutrient and Chl-*a* concentrations observed in 2005 likely are a result of the rise in terrigenous input associated with increases in precipitation. Additionally, strong tidal currents across the Mariana Ridge cause mixing in the southeast and northeast regions around Saipan. This mixing may lead to some nutrient enrichment of surface waters relative to other areas around this island.

8.4.2 Time-series Observations

Between 2003 and 2007, a suite of moored instruments was deployed around Saipan to collect time-series observations of key oceanographic parameters. The locations, depths, time frames, and other details about these deployments are provided in Figures 8.4.2a and b.

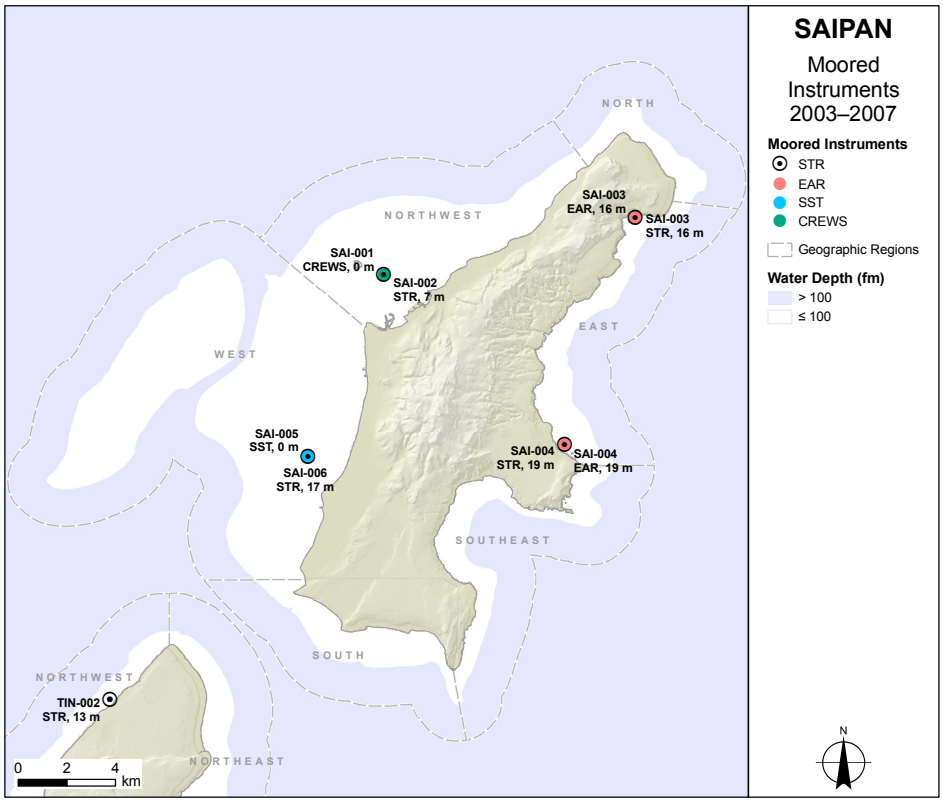


Figure 8.4.2a. Locations, depths, and types of oceanographic instrument moorings deployed at Saipan during MARAMP 2003, 2005, and 2007. Four types of instruments were moored at Saipan: subsurface temperature recorder (STR), ecological acoustic recorder (EAR), sea-surface temperature (SST) buoy, and Coral Reef Early Warning System (CREWS) buoy.

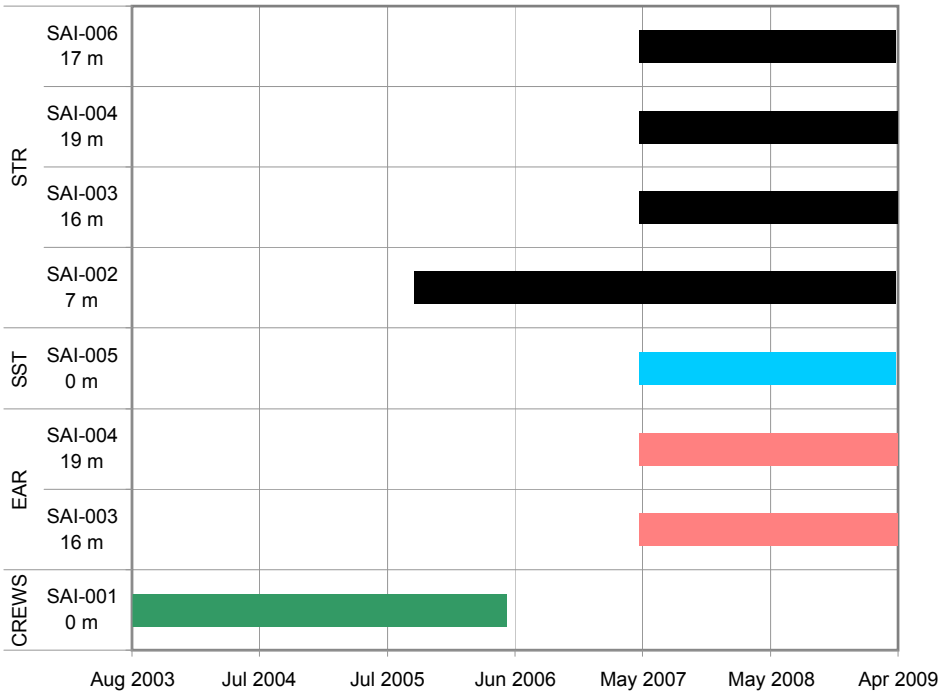


Figure 8.4.2b. Deployment timelines and depths of the oceanographic instruments installed around Saipan during the period from August 2003 to April 2009. A solid bar indicates the period for which data were collected by a single instrument or a series of them deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 8.2b in Section 8.2: "Survey Effort." The time period shown in this figure for data stored on and collected from CREWS buoys may differ from the periods for which telemetered SST data, shown in Figure 8.4.2c, was available.

Satellite-derived (Pathfinder) sea-surface temperature (SST) and in situ temperature observations around Saipan reveal that the seasonal maxima for water temperatures around Saipan usually were reached in late August or September; the monthly maximum climatological mean from Pathfinder-derived SST data was 29.5°C (Fig. 8.4.2c[a]). Winter minima occurred in February with a monthly minimum climatological mean of 27.1°C. SST data and subsurface temperature recorder (STR) data show that water temperatures rose above the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean, around Saipan in August 2003 and September 2006 (Figs. 8.4.2c and d). Still, given the relatively short duration and small magnitude of this period of elevated temperature, widespread mass coral bleaching likely did not occur. It's important to note that satellite-derived SST represents the upper few millimeters of oceanographic temperatures within the region of an island, as opposed to site- or reef-specific temperatures.

Periods of elevated mean wave heights of 2–4 m were usually more frequent during winter (Fig. 8.4.2c[b]). The largest episodic events of wave heights > 4 m, however, tended to happen during periods of warm temperatures. Warm temperatures typically occur August–December, a period when wave heights > 4 m are generally associated with typhoons. This pattern was especially noticeable during the summer of 2004 with the passages of Typhoons Tingting and Chaba.

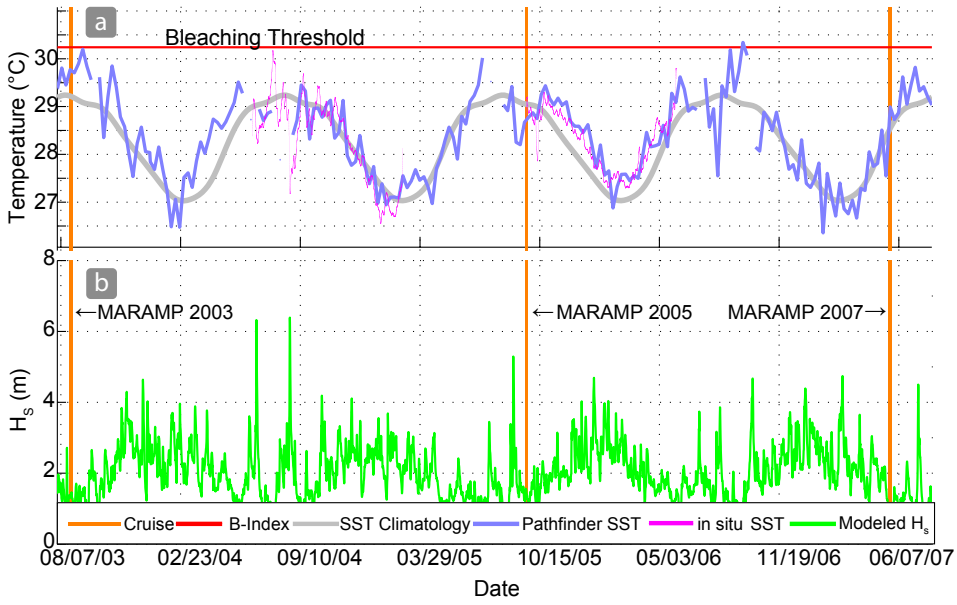


Figure 8.4.2c. Time-series observations of (a) SST and (b) wave height around Saipan for the period between August 2003 and June 2007. Remotely sensed data (SST climatology and weekly Pathfinder-derived SST) and modeled significant wave height (HS) derived from Wave Watch III are shown with CRED in situ temperature data from CREWS buoys (see Figure 8.4.2a for buoy locations). The 2 high points in the modeled wave height in the summer of 2004 show the occurrences of Typhoons Tingting and Chaba. The horizontal red and vertical orange bars represent the satellite-derived bleaching threshold and the MARAMP research cruise dates, respectively.

An STR mooring site was established in 2005 at Saipan. Data from the STR deployed at a depth of 7 m at this site in the northwest region near Isleta Managua show a seasonal temperature variability of 3–4°C (Fig. 8.4.2d). Water temperatures reached ~ 31°C during the months of June–October and fell to a low of ~ 27°C during the months of January–May. Temperature exceeded the coral bleaching threshold of 30.4°C in September 2006. Diurnal temperature fluctuation was ~ 1°C throughout this time series.

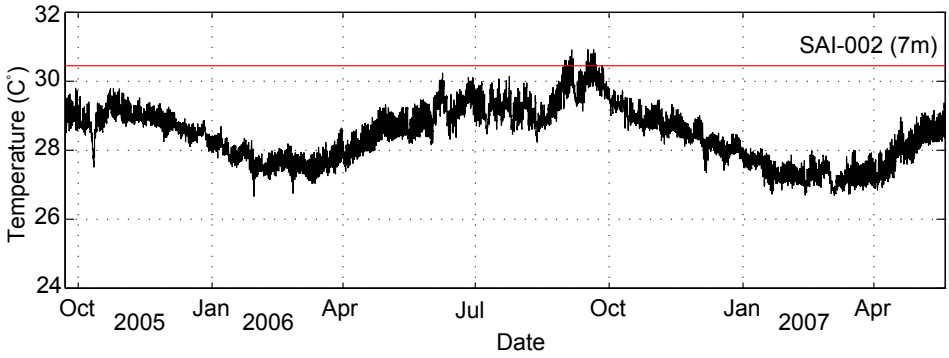


Figure 8.4.2d. Time-series observations of temperature over the period between September 2005 and June 2007 collected from 1 STR mooring site in the northwest region of Saipan at a 7-m depth (see Figure 8.4.2a for the mooring location). The red line indicates the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

Precipitation at Saipan from 2001 to the end of 2008 was highly seasonal with the greatest rainfall occurring in the months of July–September and the lowest occurring in the months of February–April (Fig. 8.4.2e). MARAMP 2003 and 2005 cruises were conducted in August and September, which are months characterized by seasonally high precipitation. In contrast, MARAMP 2007 was conducted in May when rainfall was seasonally low.

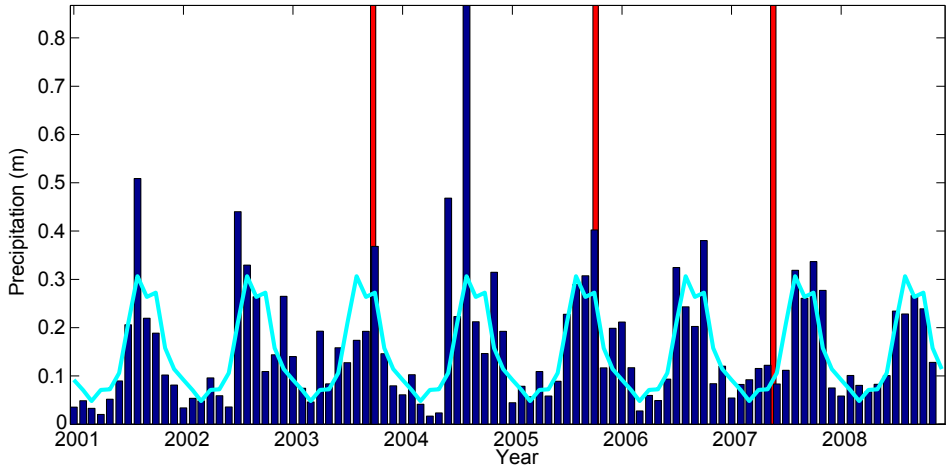


Figure 8.4.2e. Average monthly rainfall (m) from the Saipan Airport from January 2001 to July 2008. The cyan line indicates precipitation climatology (1988–2008) and vertical red bars indicate MARAMP cruise periods. Source: National Weather Service, Honolulu, Hawaii (http://www.prh.noaa.gov/hnl/).

8.4.3 Wave Watch III Climatology

Seasonal wave climatology for Saipan (Fig. 8.4.3a) was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008, and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (~ 75°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the southeast (135°), although they could originate from a broad directional source (90°–200°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from the southwest (~ 240°) and were likely associated with episodic storms. Similar to the regime during typhoon season, the wave regime during the period of February–June (outside the typhoon season) was also characterized by frequent (> 30 d per season), short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season), long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this time and originated from the southwest (~ 240°).

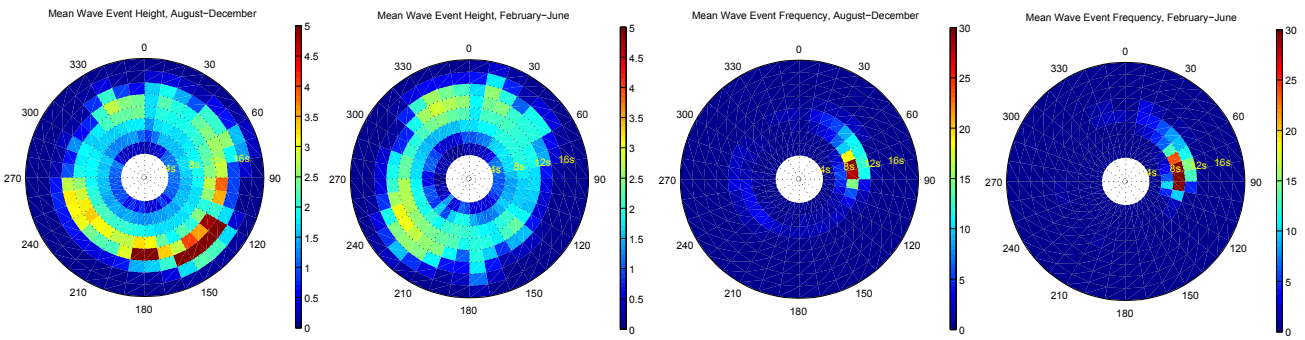
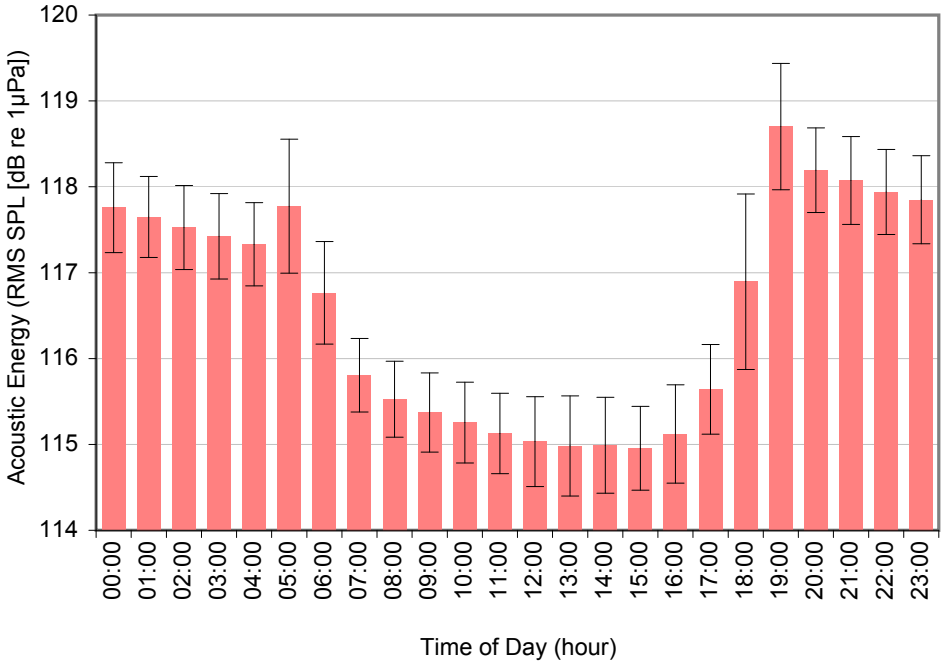


Figure 8.4.3a. NOAA Wave Watch III directional wave climatology for Saipan from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Saipan (15° N, 145°45' E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 out of 150 days of that season.

8.4.4 Bioacoustic Observations

One ecological acoustic recorder (EAR) unit, co-located with REA site SAI-02 in the east region near Puntan Halaihai, provided a dataset from June 1, 2007 to October 4, 2007. A preliminary analysis of this acoustic energy record—as obtained from the periodic, duty-cycle recordings made by this EAR—revealed strong diel variability. Root mean square sound pressure levels were 3–5 dB higher during the night (12–4 a.m.) than during the day (12–4 p.m., Figs. 8.4.4a and b). This variability probably resulted from fluctuations in the acoustic activity of snapping shrimp. In addition, periodic variability is evident on the scale of several weeks. A second EAR unit, co-located with REA site SAI-01 in Bahia Fanonchuluyan in the east region, has not yet been recovered, and, thus, data from this unit has not been retrieved or analyzed and will not be presented in this report.

Figure 8.4.4a. Average hourly acoustic energy, expressed as root mean square (RMS) sound pressure levels (SPL) in decibels (dB) referenced to 1 microPascal (µPa), from an EAR deployed on the east side of Saipan at the passive acoustics monitoring site near Puntan Halaihai from June 2007 to October 2007.



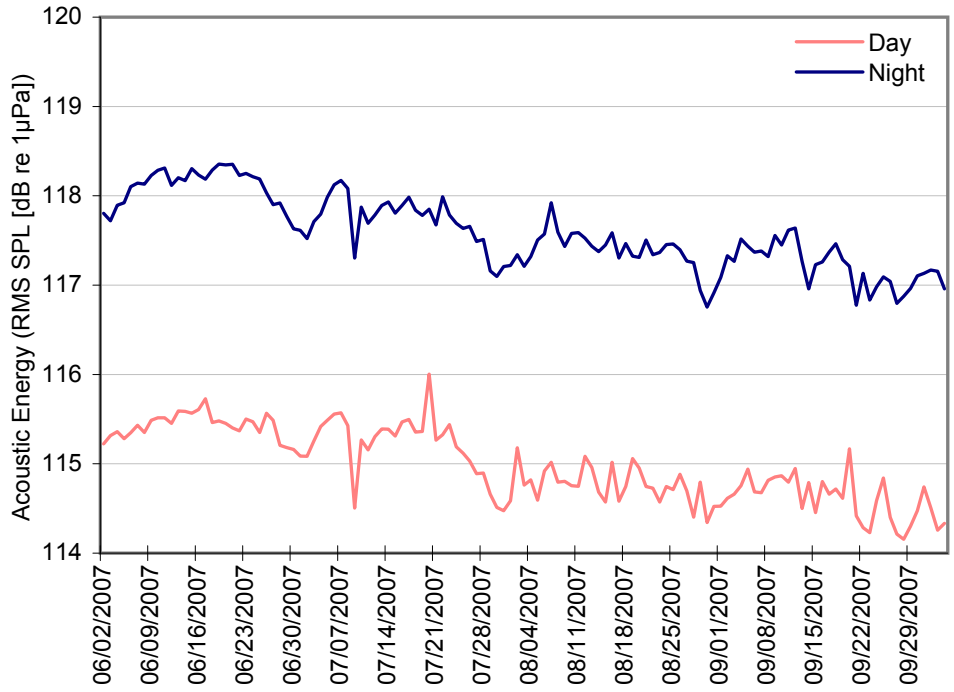


Figure 8.4.4b. Sound pressure levels, averaged over daytime (12–4 p.m.) and nighttime (12–4 a.m.) hours and expressed in root mean square decibels (dB) referenced to 1 microPascal (µPa), at the passive acoustics monitoring site near Puntan Halaihai in the east region of Saipan from June 2007 to October 2007.

During the 4 months in 2007 for which data were recorded by the EAR near Puntan Halaihai, 4 motorized vessel events had an amplitude and duration sufficient enough to trigger the EAR event detector. Vessel activity was recorded in the vicinity of the EAR unit with 2 events on separate days in July and 2 events during the same day in September (Table 8.4.4a). These initial results suggest this location does not typically encounter much vessel activity. Still, continuous monitoring of this site will provide a more comprehensive assessment and may elucidate seasonal patterns of vessel activity that are not evident in this 4-month record.

A variety of acoustic sources produced recordings on the EAR unit: rain, fish sounds, sonar, and motorized vessels, among others. Analysis of all the event-triggered recordings retrieved from the EAR unit near Puntan Halaihai reveals that the dominant sound was rain, which accounted for 68 recorded events in 2007 (Fig. 8.4.4c). Another sound event was a high-pitched metallic whistle that occurred every 2–3 min over a span of 35 min. Initially labeled as an "unknown anthropogenic source," this sound was later associated with its most likely source: military sonar.

Table 8.4.4a. Summary of vessel sounds that were of sufficient amplitude and duration to trigger the event detector of the EAR deployed near Puntan Halaihai in the east region of Saipan from June 2007 to October 2007.

Vessel Events			
Coordinated Univeral Time (UTC)		Chamorro Standard Time (ChST)	
Date	Time	Date	Time
7/19/2007	2:31	7/19/2007	12:31
7/23/2007	20:58	7/24/2007	6:58
9/1/2007	2:29	9/1/2007	12:29
9/1/2007	2:41	9/1/2007	12:41

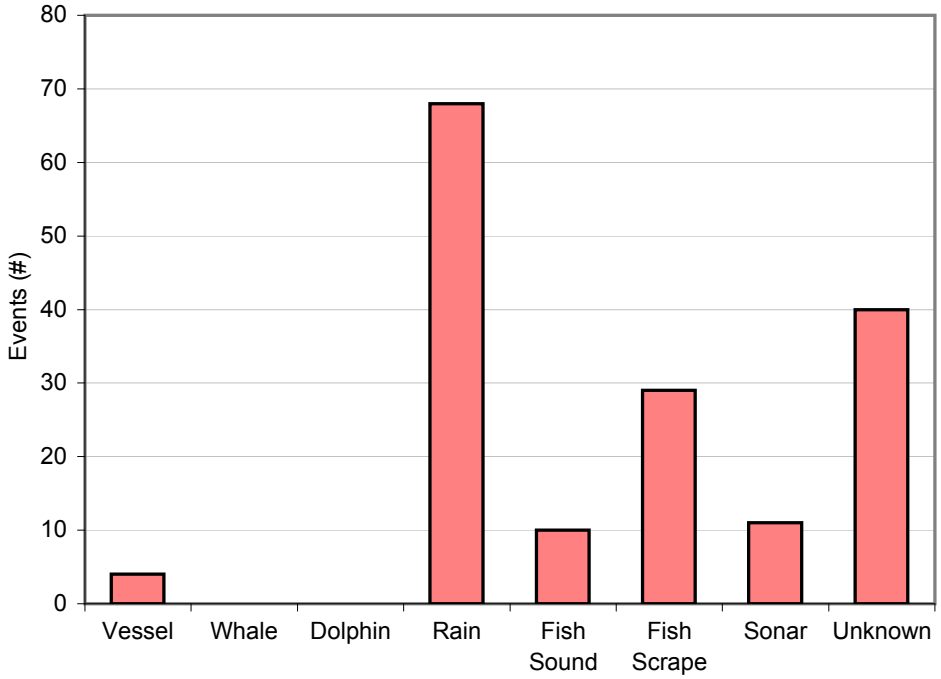


Figure 8.4.4c. Classification of events detected from June 2007 to October 2007 by the EAR deployed at the passive acoustics monitoring site near Puntan Halaihai in the east region of Saipan.

8.5 Corals and Coral Disease

8.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats at the island of Saipan was 21% (SE 2.3). Spatial coverage was limited, but, in the areas surveyed, coral cover was highest north of Tuturam in the southeast region with a mean of 64% over 4 survey segments (Fig. 8.5.1a; for place-names and their locations, see Figure 8.2a in Section 8.2: "Survey Effort"). Coral cover at Saipan was lowest along several segments in the north region.

During MARAMP 2003, the 3 REA benthic surveys using the quadrat method on forereef habitats at Saipan documented 325 coral colonies within a total survey area of 11.25 m^2. Site-specific colony density ranged from 29.6 to 33.1 colonies m^{-2} with an overall sample mean of 28.9 colonies m^{-2} (SE 2.6). The highest colony density was recorded at SAI-03 in the southeast region, and the lowest colony density was observed at SAI-02 in the east region near Puntan Halaihai (Fig. 8.5.1b).

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Saipan was 11% (SE 1). Coral cover was highest in the northwest and west regions with localized high values observed in the northern part of Lagunan Garapan with a mean of 39% for 10 segments and south of Puntan Makpe` with a mean of 34% for 10 segments (Fig. 8.5.1c). Coral cover was low on forereef habitats in all other regions around Saipan, compared with results from surveys conducted around other islands in the Mariana Archipelago.

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 2% (SE 0.4) of coral cover observed on forereef habitats around Saipan appeared stressed in 2005. Stressed-coral cover was highest during a survey in the south region between Puntans Opyan and Agingan (Fig. 8.5.1c) with a mean of 17% over 6 nonconsecutive segments. During this same survey, the greatest mean density of crown-of-thorns seastars (*Acanthaster planci*) observed around Saipan during MARAMP 2005 was recorded. Predation by crown-of-thorns seastars (COTS) is one cause of stress and discoloration in corals, and COTS were found at densities high enough to suggest a potential outbreak in this area (see Section 8.7: "Benthic Macroinvertebrates").

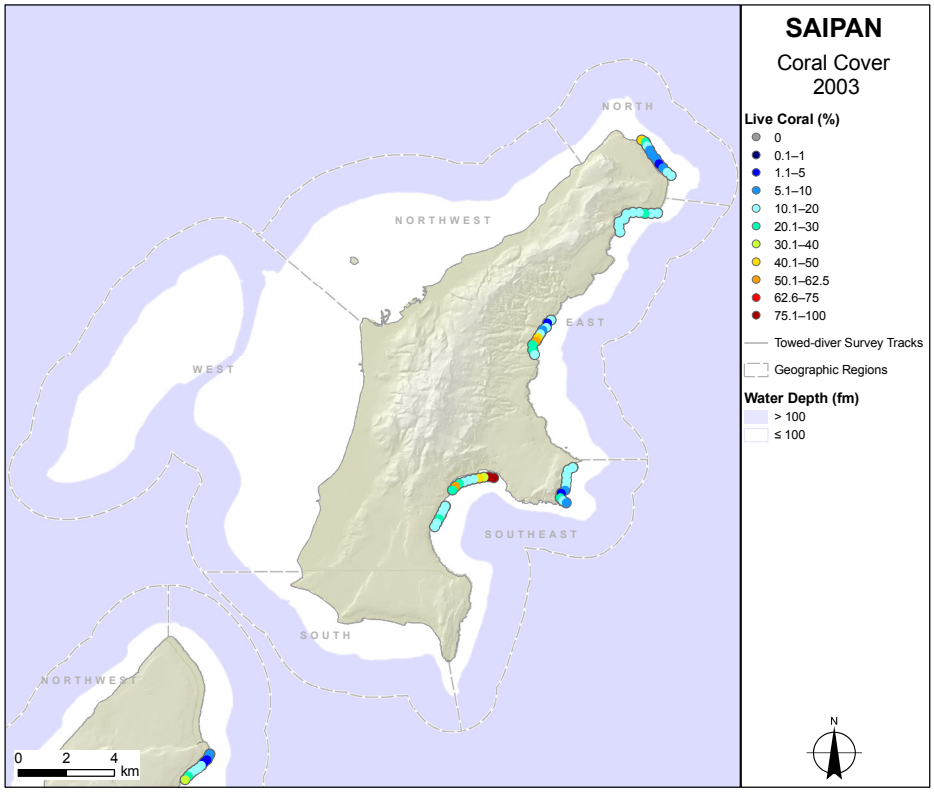


Figure 8.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted at Saipan during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2).

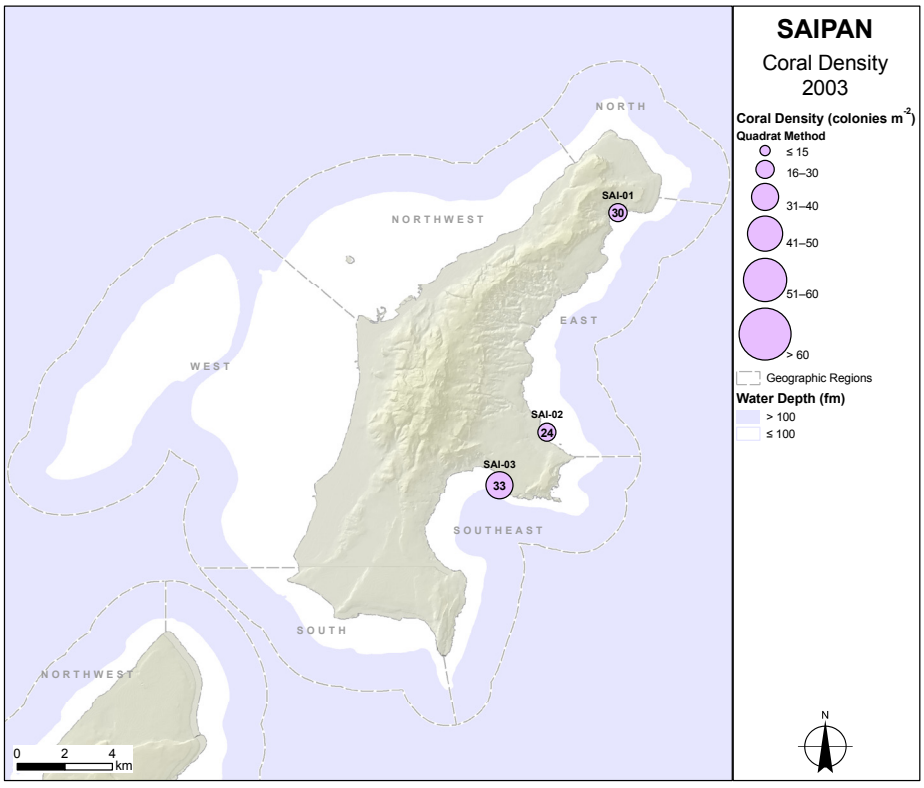


Figure 8.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Saipan during MARAMP 2003. Values are provided within each symbol. The quadrat method was used in 2003 to assess coral-colony density.

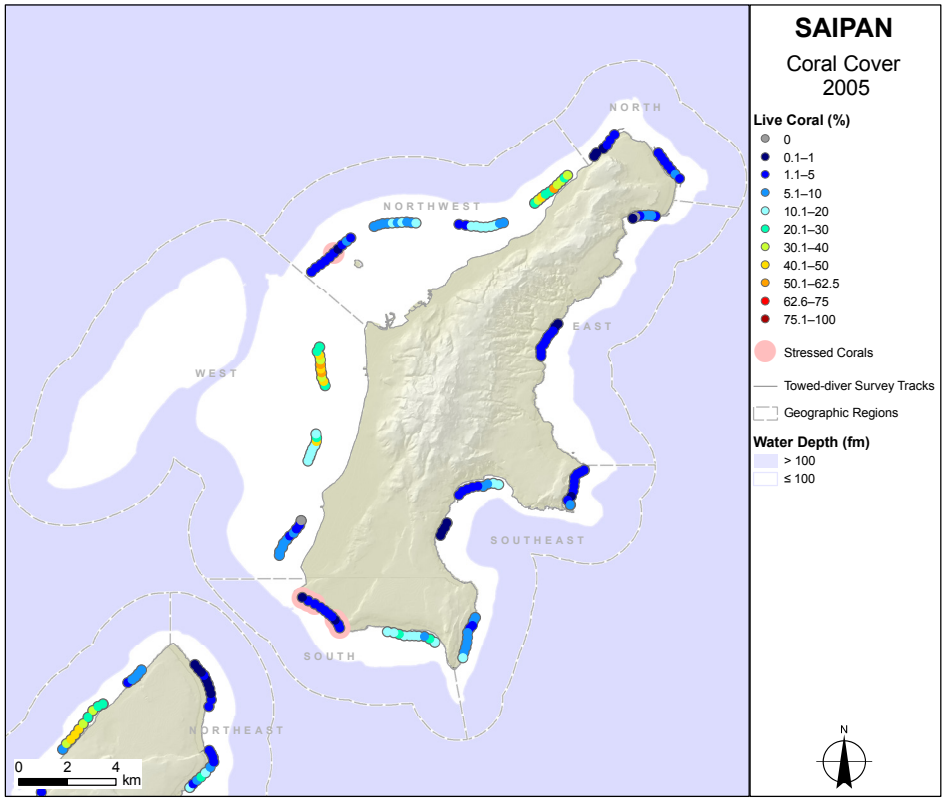


Figure 8.5.1c. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2005. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005.

During MARAMP 2005, 5 REA benthic surveys using the quadrat method on forereef habitats at Saipan documented 963 coral colonies within a total survey area of 20 m^2. Site-specific colony density ranged from 30 to 68.3 colonies m^{-2} with an overall sample mean of 49 colonies m^{-2} (SE 6.4). As in MARAMP 2003 surveys, the highest colony density was recorded at SAI-03 in the southeast region, and the lowest colony density was observed at SAI-02 in the east region near Puntan Halaihai (Fig. 8.5.1d).

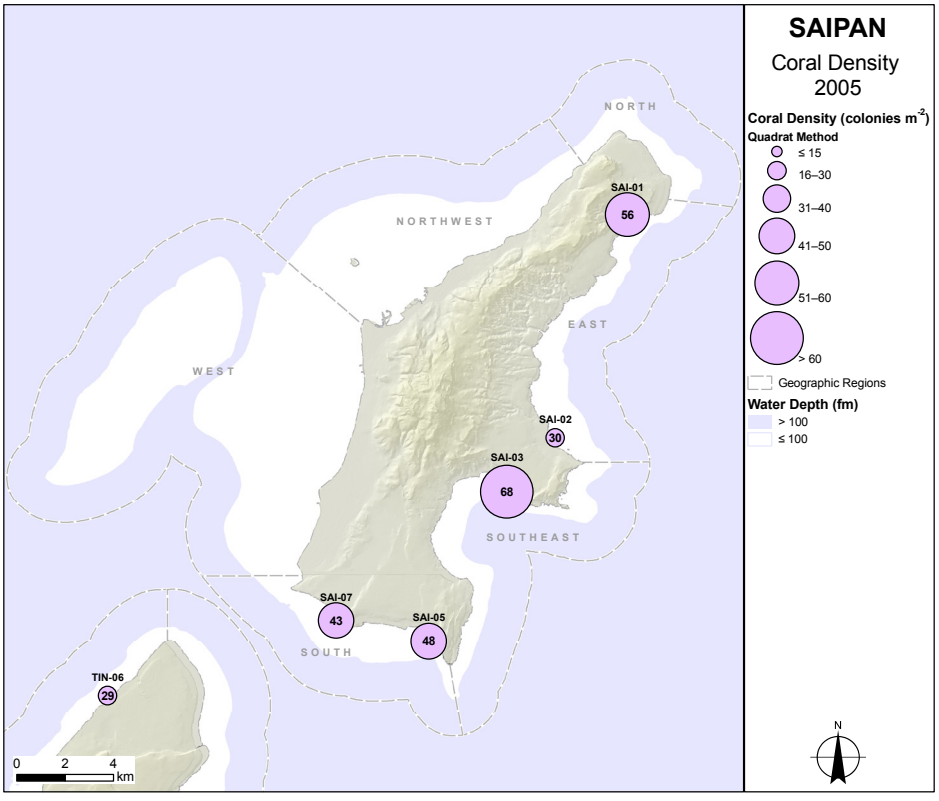


Figure 8.5.1d. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Saipan during MARAMP 2005. Values are provided within each symbol. The quadrat method was used in 2005 to assess coral-colony density.

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Saipan was 10% (SE 0.7). Coral cover was highest in the northwest and west regions with localized areas of high coral cover observed inshore of Lagunan Garupan in the west region with a mean of 25% for 13 segments and south of Puntan Makpè in the northwest region with a mean of 30% for 2 segments (Fig. 8.5.1e). Coral cover was relatively low in all other regions, except for 1 segment with coral cover of 35% in Bahia Laolao in the southeast region and 1 segment with coral cover of 45% west of Puntan I Naftan, the southernmost point of Saipan.

Overall, 6% (SE 0.6) of coral cover observed on forereef habitats around Saipan appeared stressed in 2007 (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease). Stressed-coral cover was high in the north region around the northeast corner of Saipan (Fig. 8.5.1e) with a mean of 17% for 9 nonconsecutive segments. Stressed-coral cover was also noted in the north region near Puntan Sabaneta with a mean of 17% for 6 nonconsecutive segments, in the northwest region near Puntan Achugao with a mean of 21% for 7 nonconsecutive segments, and in the east region along Unai Talofo`fo` with a mean of 19% for 5 nonconsecutive segments. All elevated levels of stressed-coral cover were recorded within a range of 10.1%–40%. Several other isolated areas of stressed-coral cover were noted in the southwest, south, and west regions.

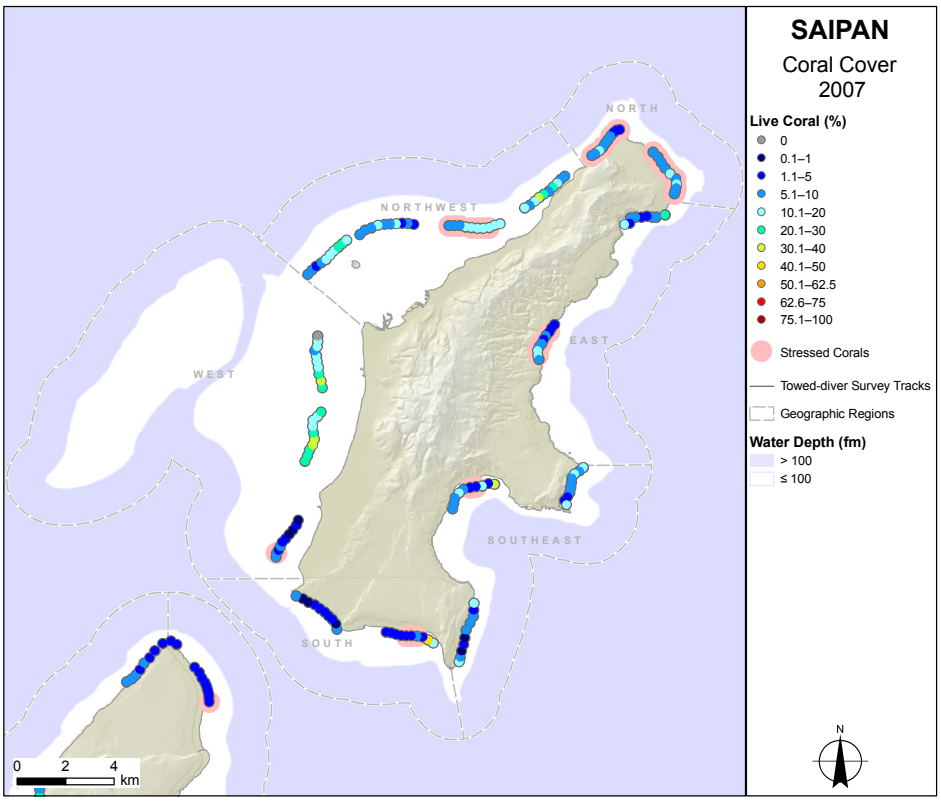


Figure 8.5.1e. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2007.

During MARAMP 2007, 8 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats around Saipan. Site-specific estimates of live-hard-coral cover from these surveys ranged from 2% to 33.3% (Fig. 8.5.1f) with an overall sample mean of 11.2% (SE 3.7). The highest coral cover of 33.3% was observed at SAI-05 in the south region west of Puntan Unai Opyan, and the lowest coral cover of 2% was found at SAI-01 in the northeast region in Bahia Fanonchuluyan.

During MARAMP 2007, 8 REA benthic surveys using the belt-transect method on forereef habitats at Saipan documented 1929 coral colonies within a total survey area of 400 m^2. Site-specific colony densities ranged from 2.6 to 6.4 colonies m^{-2} with an overall sample mean of 4.8 colonies m^{-2} (SE 0.5).

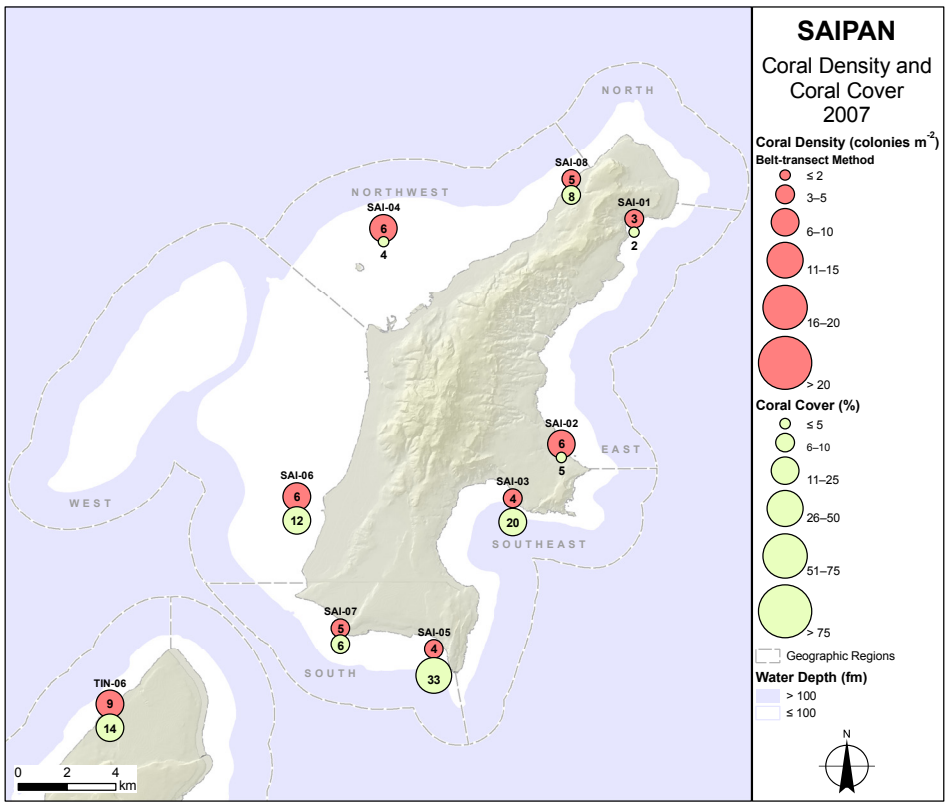


Figure 8.5.1f. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007. Values are provided within or below each symbol. The belt-transect method was used in 2007 to assess coral-colony density.

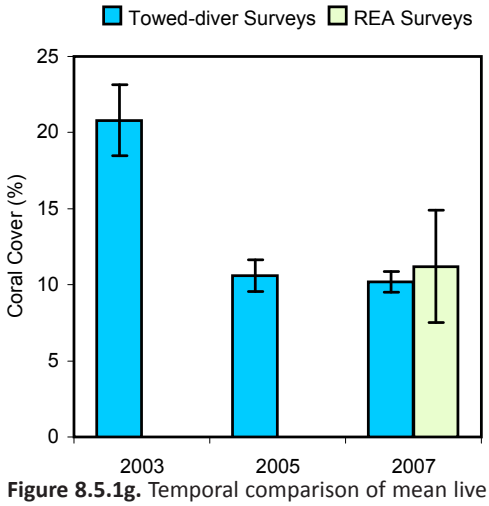


Figure 8.5.1g. Temporal comparison of mean live coral cover (%) from REA and towed-diver benthic surveys conducted on forereef habitats at Saipan during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted around Saipan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Islandwide mean cover of live corals estimated from towed-diver surveys of forereef habitats decreased from 21% (SE 2.3) in 2003 to 11% (SE 1) in 2005 but remained stable with 10% (SE 0.7) in 2007 (Fig. 8.5.1g). In close agreement with the overall mean from towed-diver surveys in 2007, site-specific estimates of coral cover averaged 11.2% (SE 3.7) for the 8 REA sites surveyed at Saipan in 2007 (Saipan was not surveyed for coral cover using the line-point-intercept method in 2003 or 2005). Although towed-diver surveys were more spatially limited in 2003 than in subsequent survey years, the survey tracks examined in 2003 were repeated in 2005 and 2007, and survey results reveal localized decreases in coral cover along those survey tracks (Figs. 8.5.1a, c, and e).

During MARAMP 2003 and 2005, REA benthic surveys of forereef habitats were conducted using the quadrat method around Saipan. Overall mean coral-colony density varied substantially between 2003 and 2005, increasing from 28.9 colonies m^{-2} (SE 2.6) in 2003 to 49 colonies m^{-2} (SE 6.4) in 2005 (Fig. 8.5.1h). At each of the 3 sites surveyed in both years (SAI-01, SAI-02, and SAI-03), colony density increased between 2003 and 2005. This increase likely is a result of recruitment, fragmentation of existing colonies, or both. Site-specific colony densities and the overall mean density of 4.8 colonies m^{-2} (SE 0.5) recorded during MARAMP 2007 were substantially lower than the colony densities observed in 2003 and 2005. However, this decline is likely an artifact of the use of a different method, the belt-transect method, to assess colony density in 2007. The method of placing quadrats used in 2003 and 2005 was highly biased towards surveying hard-bottom substrate where coral was present, whereas the belt-transect method used in 2007 assessed benthos that fell within the transect belts regardless of the nature of the substrate.

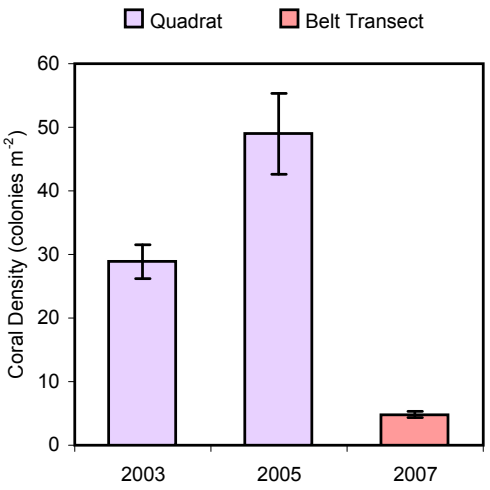


Figure 8.5.1h. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Saipan during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to measure coral-colony density, but the belt-transect method was used in 2007. Error bars indicate standard error (± 1 SE) of the mean.

Coral Generic Richness and Relative Abundance

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Saipan during MARAMP 2003. At least 25 coral genera were observed at Saipan. Generic richness ranged from 14 to 21 with a mean of 17.7 (SE 2) coral genera per site (Fig. 8.5.1i). The highest generic diversity was seen at SAI-01 in the east region in Bahia Fanonchuluyan, and the lowest generic diversity was recorded at SAI-03 in the southeast region.

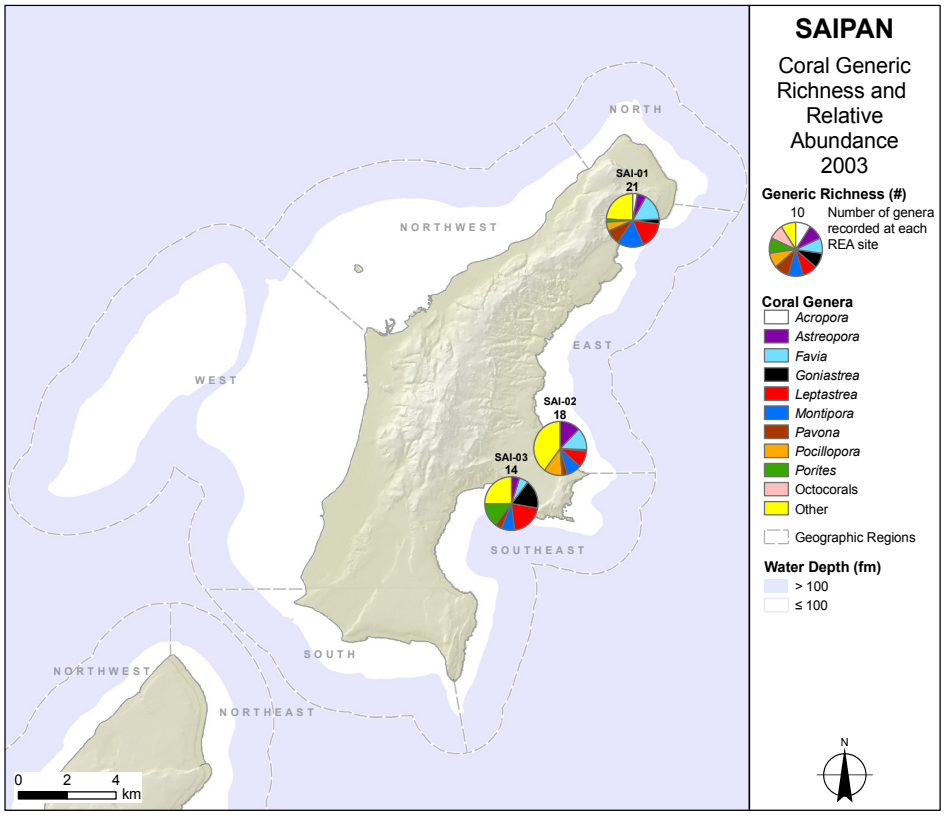


Figure 8.5.1i. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Saipan during MARAMP 2003. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to survey coral genera.

Favia, Leptastrea, and *Montipora* were the most numerically abundant genera, accounting for 11.7%, 15.5%, and 11.1% of the total number of colonies enumerated at Saipan during MARAMP 2003. All other genera individually accounted for < 10% of the total number of colonies. At SAI-01, *Favia*, *Leptastrea*, and *Montipora* all dominated the coral fauna (Fig. 8.5.1i), accounting for 16.2%, 16.2%, and 16.2% of the total number of observed colonies. *Favia* also dominated the coral fauna at SAI-02 in the east region near Puntan Halaihai, accounting for 13.3% of the total number of observed colonies. *Leptastrea* and *Goniastrea* dominated the coral fauna at SAI-03, accounting for 20.2% and 16.9% of the total number of observed colonies.

Five REA benthic surveys of forereef habitats were conducted using the quadrat method at Saipan during MARAMP 2005. At least 25 coral genera were observed at Saipan. Generic richness ranged from 13 to 19 with a mean of 15.6 (SE 1.2) coral genera per site (Fig. 8.5.1j). The highest generic diversity was seen at SAI-07 in the south region near Puntan Opyan, and the lowest generic diversity was recorded at SAI-02 in the east region and SAI-05 in the south region.

Porites, Favia, and *Leptastrea* were the most numerically abundant genera, accounting for 24.1%, 8.9%, and 12.1% of the total number of colonies enumerated at Saipan during MARAMP 2005. All other genera individually accounted for < 10% of the total number of observed colonies. *Porites* dominated the coral fauna at SAI-05 in the south region and SAI-03 in the southeast region (Fig. 8.5.1j), accounting for 71.7% and 34.8% of the total number of observed colonies. *Favia* dominated at SAI-01 and SAI-02, both in the east region, accounting for 20.2% and 15.8% of the total number of observed colonies. *Montipora* dominated at SAI-07 in the south region, accounting for 27.2% of the total number of observed colonies.

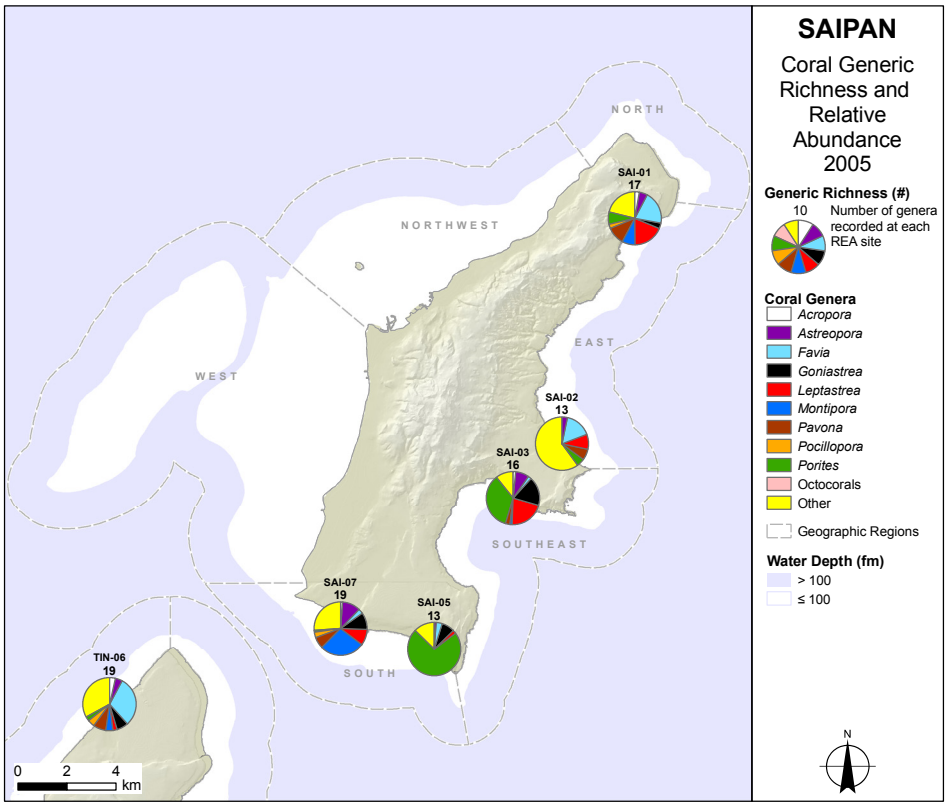


Figure 8.5.1j. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Saipan during MARAMP 2005. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2005 to survey coral genera.

Eight REA benthic surveys of forereef habitats were conducted using the belt-transect method around Saipan during MARAMP 2007. At least 32 coral genera were observed, including the following 11 genera that had not been recorded at Saipan in 2003 or 2005: *Coscinaraea, Cycloseris, Euphyllia, Gardineroseris, Lobophytum, Millepora, Palythoa, Plesiastrea, Sarcophyton, Sinularia*, and an unidentified corallimorph. Generic richness ranged from 11 to 26 with a mean of 18.1 (SE 2) coral genera per site (Fig. 8.5.1k). The highest generic diversities were seen at SAI-02 and SAI-08 in the east and northwest regions, respectively, and the lowest generic diversity was recorded at SAI-05 in the south region.

Porites and *Favia* were the most numerically abundant genera, accounting for 20.1% and 11.6% of the total number of colonies enumerated around Saipan during MARAMP 2007. All other genera individually accounted for < 10% of the total number of observed colonies. Survey results show considerable variability among sites in coral dominance. *Porites* dominated the coral fauna at SAI-03 and SAI-05 in the southeast and south regions (Fig. 8.5.1k), accounting for 37.9% and 68.4% of the total number of colonies enumerated around Saipan. *Favia* dominated the coral fauna at SAI-01 and SAI-02 in the east region, accounting for 28.8% and 17.6% of the total number of observed colonies. *Astreopora* dominated the coral fauna at SAI-06, accounting for 22.3% of the total number of observed colonies. *Goniastrea* dominated the coral fauna at SAI-07 in the south region, accounting for 18.4% of the total number of observed colonies. *Pocillopora* dominated the coral fauna at SAI-04 in northwest region, accounting for 24.2% of the total number of observed colonies.

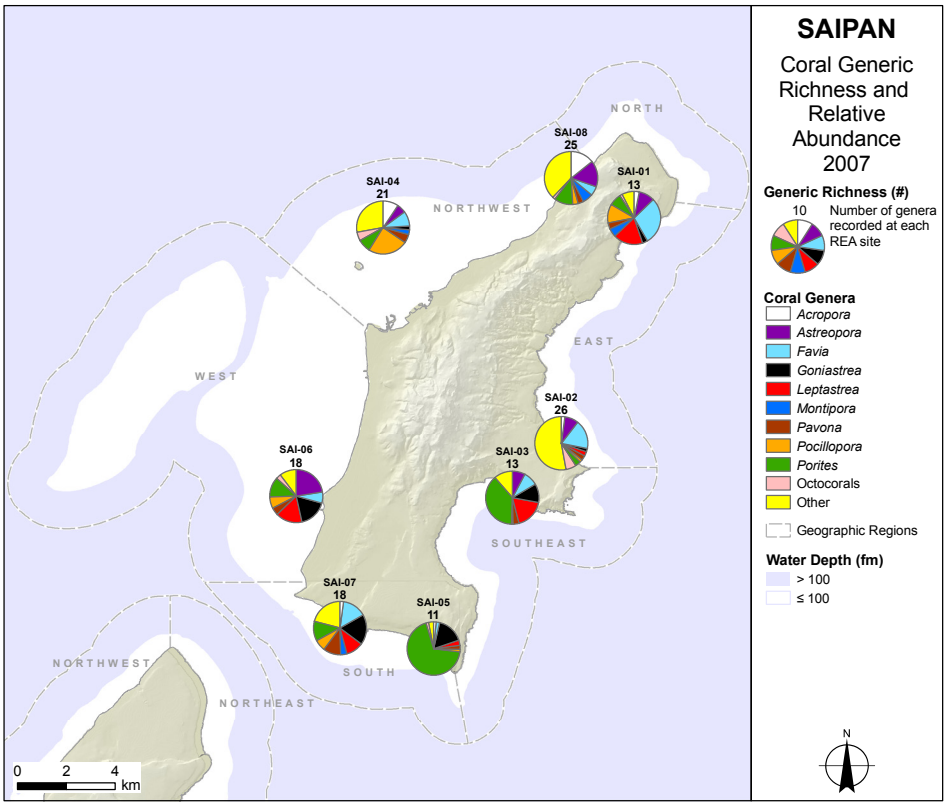


Figure 8.5.1k. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007. The pie charts indicate percentages of relative abundance of key coral genera. The belt-transect method was used in 2007 to survey coral genera.

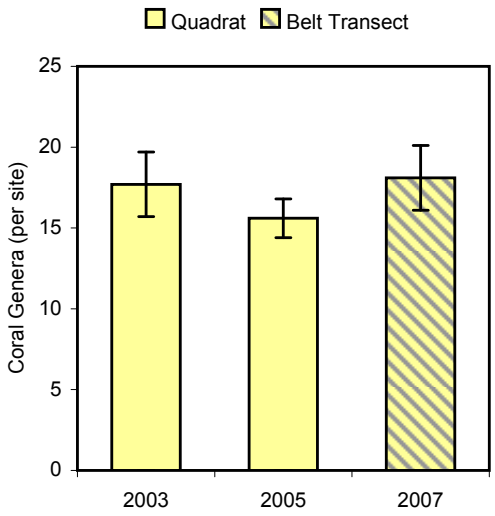


Figure 8.5.1l. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Saipan during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to survey coral genera, but the belt-transect method was used in 2007. Error bars indicate standard error (± 1 SE) of the mean.

Site-specific estimates of generic richness across the 3 MARAMP survey years ranged from 11 to 26 on forereef habitats at Saipan. Site-specific and overall mean generic-richness values (Fig. 8.5.1l) were higher in 2007 with a mean of 18.1 (SE 2) coral genera per site than in 2003 and 2005 with means of 17.7 (SE 2) and 15.6 (SE 1.2) coral genera per site. Note the difference in the size of the area in which corals were censused: the survey area at each site in 2007 was 50 m^2 per site, an area much larger than the 3.75 and 4 m^2 per site surveyed in 2003 and 2005 (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Additionally, the only octocoral genus assessed in 2003 and 2005 was *Heliopora*, whereas all octocoral genera were assessed in 2007.

During the 3 MARAMP survey years, 38 coral genera were observed on forereef habitats at Saipan. *Favia, Porites, Leptastrea*, and *Montipora* were important components of the coral fauna around this island. *Favia* was the most numerically abundant taxon in 2003 and the second-most abundant in 2005 and 2007, accounting for 11.7%, 8.9%, and 11.6% of the total number of colonies enumerated at Saipan. *Porites* was the most numerically abundant taxon in 2005 and 2007, accounting for 24.1% and 20.1% of the total number of colonies. *Leptastrea* was the second-most numerically abundant taxon in 2003 and the third-most abundant in 2005, accounting for 15.5% and 12.1% of the total number of colonies. *Montipora* contributed 11.1% of the total number of observed colonies in 2003. All other taxa contributed < 10% of the total number of observed colonies across the 3 survey years.

Coral Size-class Distribution

During MARAMP 2003, 3 REA benthic surveys of forereef habitats were conducted at Saipan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (52.2%) of corals had maximum diameters ≤ 5 cm (Fig. 8.5.1m). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 32.5%, 8.7%, 5.7%, and 0.9% of colonies recorded at Saipan. At all 3 sites, SAI-01, SAI-02, and SAI-03, a high proportion of colonies were small (≤ 10 cm), accounting for 71.2%, 87.8%, and 95.2% of colonies observed. A correspondingly low proportion (26.1%, 12.2%, and 4.8%) of observed colonies was midsize (11–40 cm) at these 3 sites. Large (> 40 cm) colonies were recorded only at SAI-01 in the east region.

During MARAMP 2005, 5 REA benthic surveys of forereef habitats were conducted at Saipan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (75.2%) of corals had maximum diameters ≤ 5 cm (Fig. 8.5.1n). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 19.4%, 4.5%, and 0.9% of colonies recorded at Saipan. No colonies with maximum diameters > 40 cm were recorded. At each site, the majority (> 65%) of corals were in the smallest (≤ 5 cm) size class.

During MARAMP 2007, 8 REA benthic surveys of forereef habitats were conducted around Saipan using the belt-transect method. The coral size-class distribution from these surveys shows that the majority (76.3%) of corals had maximum diameters ≤ 10 cm (Fig. 8.5.1o). The first 4 size classes (0–5, 6–10, 11–20, and 21–40) accounted for 39%, 37.3%, 14.2%, and 6.9% of colonies recorded around Saipan, and colonies with maximum diameters > 40 cm accounted for 2% of colonies observed. The highest proportions (28.8% and 31.1%) of midsize (11–40 cm) colonies were found at SAI-02 and SAI-05 in the east and south regions, and the highest proportions (96.2% and 91.9%) of small (≤ 10 cm) colonies were observed at SAI-01 and SAI-07 in the east and south regions.

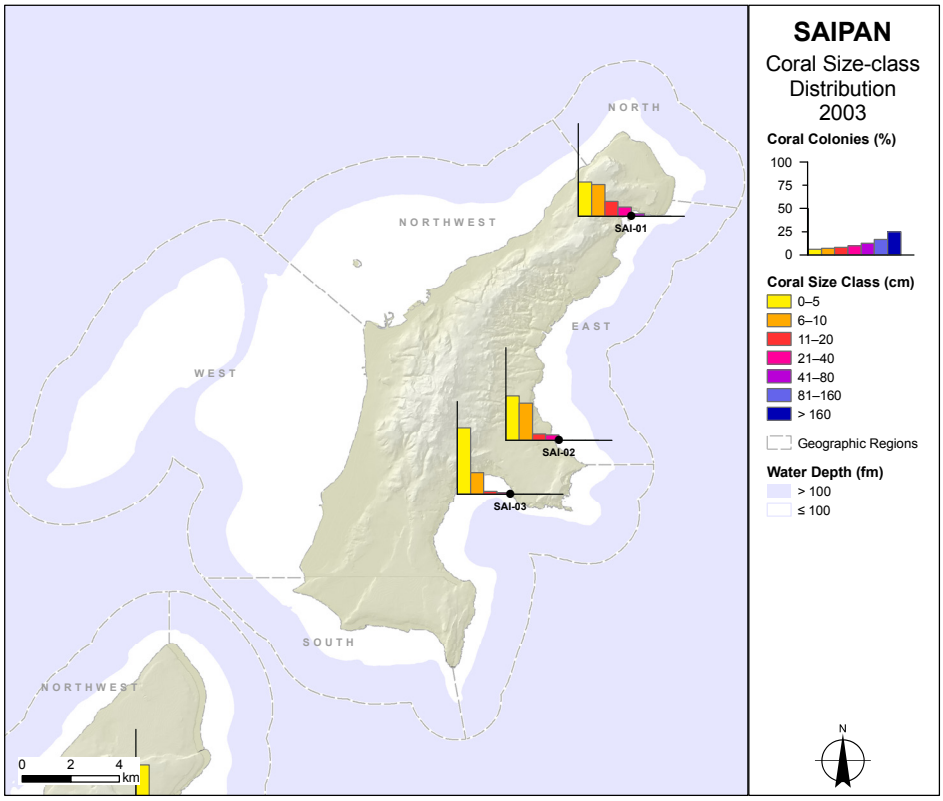


Figure 8.5.1m. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Saipan during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.

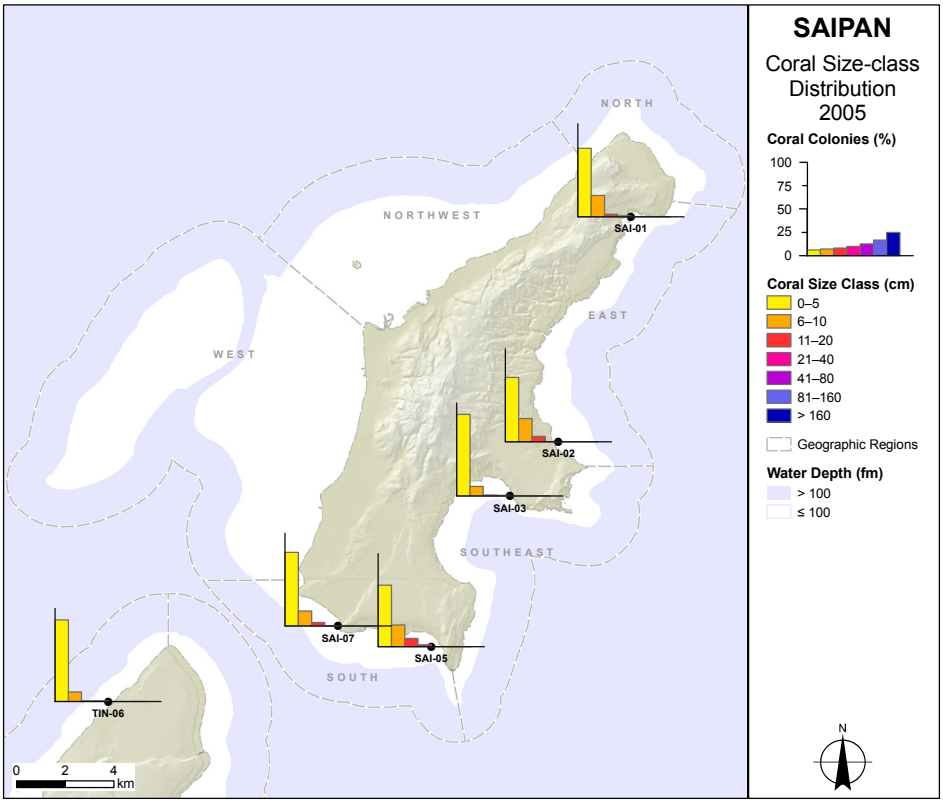


Figure 8.5.1n. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Saipan during MARAMP 2005. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2005 to size corals.

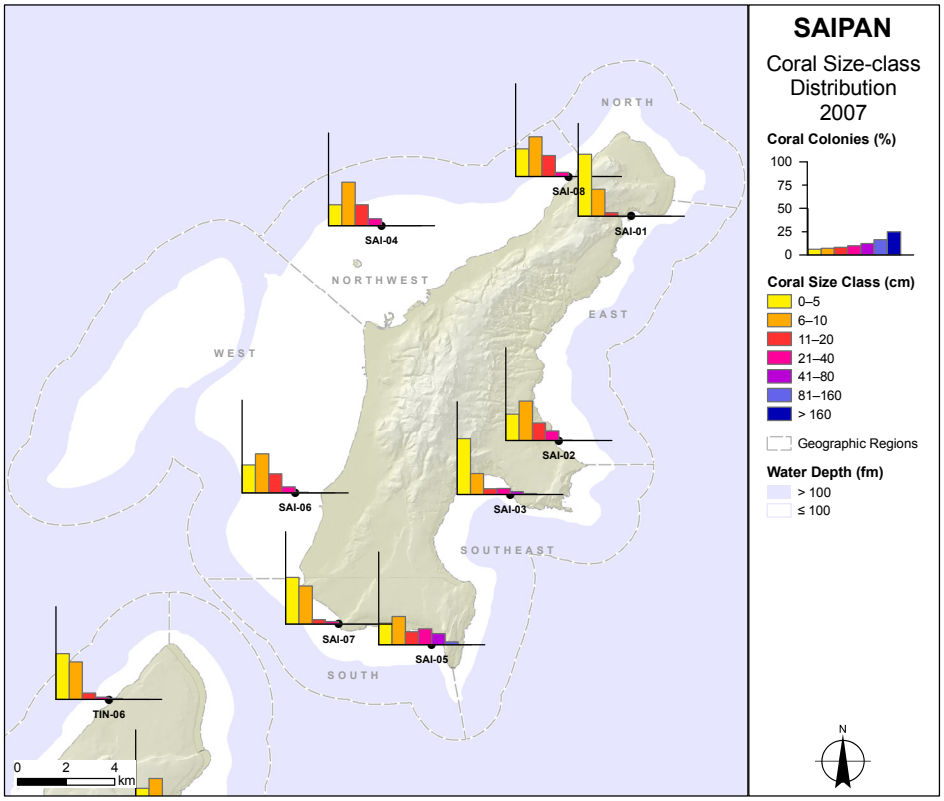


Figure 8.5.1o. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The belt-transect method was used in 2007 to size corals.

Site-specific and overall distribution of estimated coral size classes on forereef habitats at Saipan are affected by inherent biases in the methods used to census and size corals. During MARAMP 2003 and 2005, corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within a quadrat. During MARAMP 2007, corals whose center fell within a belt transect (1 × 25 m) were tallied and binned into 1 of 7 size classes based on visual estimates of maximum colony diameter. This method is better suited to capturing large colonies, but the larger census area likely reduces the number of very small

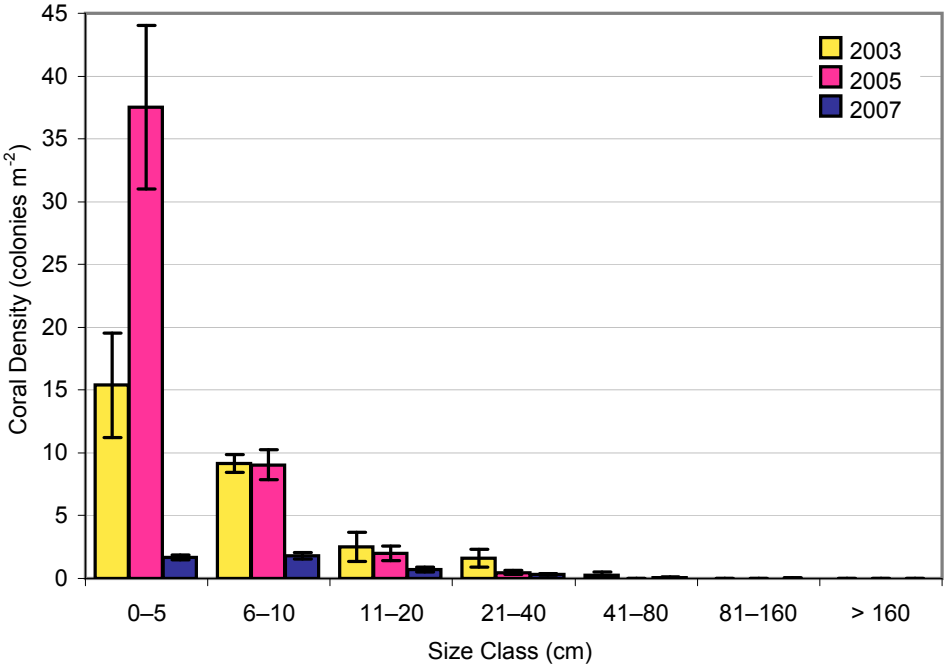


Figure 8.5.1p. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Saipan during MARAMP 2003, 2005, and 2007. The quadrat method was used in 2003 and 2005 to size corals, but the belt-transect method was used in 2007. Error bars indicate standard error (± 1 SE) of the mean.

(≤ 5 cm) colonies that are observed and recorded. For more on these survey methods, see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease."

These methodological biases are reflected in the size-class data by survey year. Data from both 2003 and 2005 show that most coral colonies were in the smallest size class (Fig. 8.5.1p). In 2003 and 2005, more than half (52.2% and 75.2%) of all colonies censused on forereef habitats at Saipan had a maximum diameter ≤ 5 cm, but in 2007 only 39% of colonies were in this smallest size class. Comparing size-class data between survey years when different methods were used is, therefore, inappropriate. Only SAI-01, SAI-02, and SAI-03 in the east and southeast regions were surveyed with the same quadrat method during 2 different survey years, MARAMP 2003 and 2005. At all 3 sites between these survey years, the proportion of colonies in the smallest size class (≤ 5 cm) increased substantially, and the proportion of colonies in other size classes decreased, suggesting that either increased recruitment, colony fragmentation, or both occurred during this period.

8.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted using the belt-transect method at 8 sites on forereef habitats around Saipan, covering a total area of more than 2200 m^2. Coral disease at Saipan was recorded with a mean overall prevalence of 0.4% (SE 0.2), excluding predation. Four major disease conditions were registered at Saipan: bleaching, pigmentation response, fungal infections, and other syndromes of unknown etiology. Of the 6 sites that contained disease, SAI-01 and SAI-05 in the east and south regions exhibited the greatest overall prevalence values of 0.8% and 1.3% (Figs. 8.5.2a and b; the values of overall prevalence shown in this Figure 8.5.2a include predation). Pigmentation response on *Porites* was the most numerous disease condition, accounting for 40% of cases with an overall prevalence of 0.1% at Saipan.

Lesions involving fungal infections were the second-most abundant disease state, accounting for 27% of disease cases. These types of lesions, with an overall prevalence value of 0.8%, were detected mostly at SAI-01 in the east region in Bahia Fanonchuluyan. Additionally, bleaching conditions were quite low with an overall mean prevalence of 0.03% (SE 0.03), and affected colonies were observed primarily at SAI-06 in the west region. Bleaching was mild, focal, and observed on corals of the genus *Platygyra*. Other coral diseases present around Saipan included algal and cyanophyte infections, as well as syndromes of unknown etiology. These were sporadic and occurred at a low mean overall prevalence of 0.09% (SE 0.09) on corals of the genera *Porites* and *Pocillopora*.

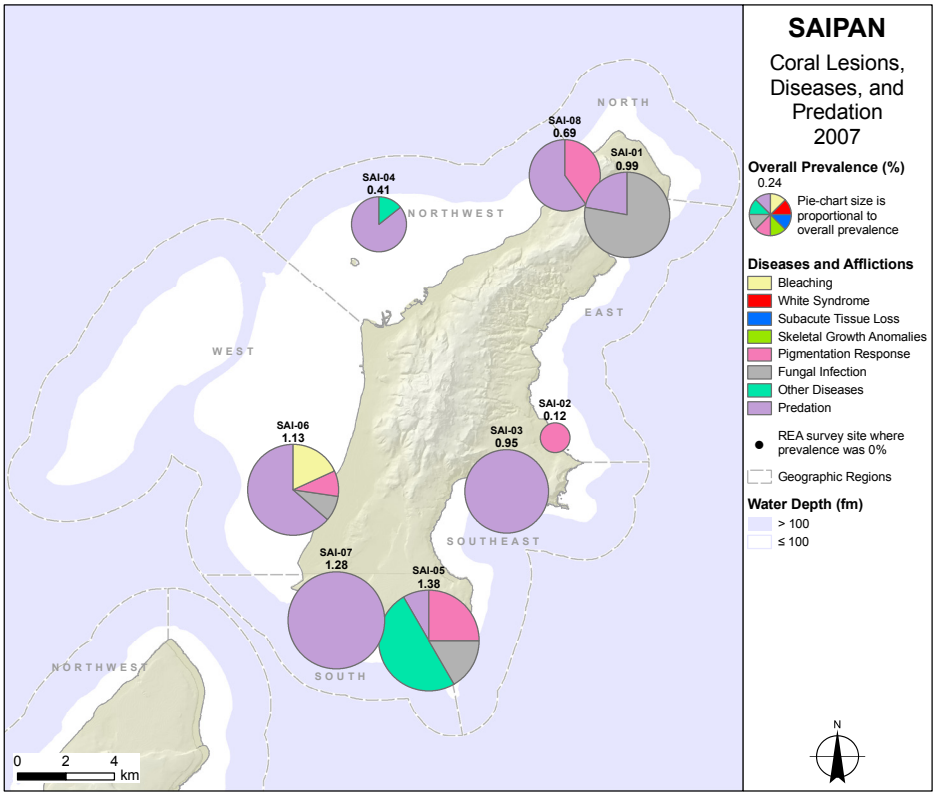


Figure 8.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each site. The color-coded portions of the pie charts indicate disease-specific prevalence.

Cases of coral predation attributable to COTS or corallivorous snails, such as snails from the genus *Drupella*, were observed at all sites except for SAI-02 on the east region near Puntan Halaihai. The greatest levels of predation were registered at SAI-07 and SAI-03 in the south and southeast regions (Fig. 8.5.2b). The coral genera *Porites, Pocillopora*, and *Stylophora* were the main prey of COTS and snails. For more about COTS around Saipan, see Section 8.7: "Benthic Macroinvertebrates."

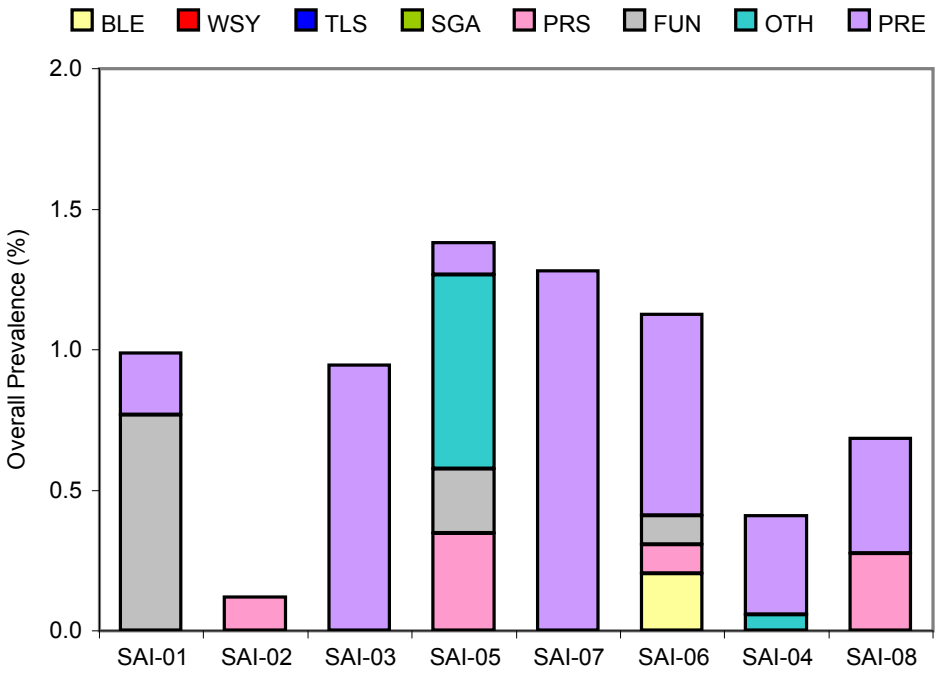


Figure 8.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesions of unknown etiology; PRE: predation by COTS or corallivorous snails.

8.6 Algae and Algal Disease

8.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats at the island of Saipan was 49% (SE 2.9). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 78%, within a range of 40.1%–100%, occurred in the north region (Fig. 8. 6.1a, top left panel). Habitats in this area were primarily composed of continuous spur-and-groove formations of medium-low to medium complexity. The second-greatest mean macroalgal cover of 56% was recorded in the southeast region along the spur-and-groove reefs to the south of Tuturam in Bahia Laolao, where habitat complexity ranged from medium to medium-high (for place-names and their locations, see Figure 8.2a in Section 8.2: "Survey Effort"). Surveys along the pavement reefs of Unai Talofo`fo` in the east region and the area between Puntans Laolao Kattan and Hakmang in the southeast region reported mean macroalgal cover of 54% and 52%. Habitat complexity in these areas was primarily medium, interspersed occasionally with more complex areas of large rock boulders. The survey conducted in Bahia Fanonchuluyan in the east region found a mean macroalgal cover of 35% and habitats of primarily pavement or continuous reef of medium to high complexity.

During MARAMP 2003 and a subsequent deployment in 2004, 54 TOAD surveys were conducted off Saipan Harbor and Garapan Anchorage in depths ≤ 140 m. Analyses of TOAD video footage suggest that macroalgal cover was low in this area, at least as seen in images. Where macroalgae were observed in a given video frame, macroalgal cover was predominantly ≤ 40% (Fig. 8.6.1a, top left panel). A small number of isolated patches of relatively high cover were observed within the anchorage areas at depths of 10–140 m.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Saipan was 31% (SE 2). The survey with the highest mean macroalgal cover of 69%, within a range of 62.6%–75%, occurred south of Tuturam

within Bahia Laolao in the southeast region (Fig. 8.6.1a, middle left panel). Also in the southeast region, the surveys conducted south of Puntan Dandan and between Puntans Laolao Kattan and Hakmang reported higher than average macroalgal cover of 52% and 46%. The habitat in these areas was primarily pavement of medium-low to medium complexity. All 6 surveys conducted in the north and northwest regions also reported relatively high values of macroalgal cover. The surveys conducted immediately south of Puntan Sabaneta, the northernmost point of Saipan, and northwest of Isleta Managaha near SAI-04 reported the greatest cover in the northwest region with 65% and 61%, respectively, and were characterized as low to medium complexity pavement or rock reefs. The lowest macroalgal cover generally were found in the south and west regions.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats around Saipan was 32% (SE 1.6). The survey with the highest mean macroalgal cover of 68%, within a range of 50.1%–75%, occurred northwest of Isleta Managaha in the northwest region (Fig. 8.6.1a, bottom left panel). Habitat in this area predominantly consisted of continuous, gently sloping reef of medium-low complexity. Species of the green algal genus *Halimeda* and brown algal genus *Padina* dominated this substrate, along with species of the red algal genus *Asparagopsis*. Other areas of high macroalgal cover were observed during the 2 surveys conducted in the north region, to the south and east of Puntan Sabaneta, where 52% and 62% of the benthos was dominated by species of the green algae *Microdictyon* and *Halimeda* and the brown alga *Padina*, along with species of the red algal genus *Liagora*. Habitats here were primarily characterized as pavement or rock with complexity ranging from medium-low to medium-high. Reefs in the east region all hosted slightly higher than average values of macroalgal cover. In contrast, in the southeast region, the survey conducted between Puntans Laolao Kattan and Hakmang recorded mean macroalgal cover of 21%, within a range of 5.1%–40%. Pavement reef of medium-low complexity was the predominant habitat type, except in areas where sand prevailed.

During MARAMP 2007, 8 REA benthic surveys of forereef habitats around Saipan were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 0% to 36.3% with an overall mean of 11% (SE 4.4). The survey with the highest macroalgal cover of 36.3% occurred in the northwest region at SAI-08 (Fig. 8.6.1b). Relatively high macroalgal cover was also found at the other REA site in the northwest region, SAI-04, with 21.6%. No macroalgae were recorded in the southeast region at SAI-03.

Turf-algal cover from these REA benthic surveys in 2007 ranged from 20.6% to 79.4% with an overall mean of 60% (SE 7.1). The survey with the highest turf-algal cover of 79.4% occurred in the east region at SAI-02 (Fig. 8.6.1b). Relatively high levels of turf-algal cover were also found in the south region at SAI-07 with 73.5%, in the east region at SAI-01 with 72.5%, and in the west region at SAI-06 with 70.6%. The lowest turf-algal cover of 20.6% was recorded in the southeast region at SAI-03.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats at Saipan was 10% (SE 1.2). The survey with the highest mean crustose-coralline-red-algal cover of 24%, within a range of 10.1%–40%, occurred in Bahia Fanonchuluyan (Fig. 8.6.1a, top right panel), where the habitat consisted of pavement and continuous reef of medium to high complexity. The surveys conducted in the vicinity of Unai Talofo`fo` in the east region and in the southeast region between Puntans Laolao Kattan and Hakmang reported greater than average values for cover of crustose coralline red algae of 12% and 15%, respectively. Habitats in these areas had medium complexity and consisted of pavement with rock boulders. The remaining survey areas, characterized by spur-and-groove formations or continuous reef, reported low cover of < 4%.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Saipan was 9% (SE 0.9). The survey with the highest mean crustose-coralline-red-algal cover of 32%, within a range of 20.1%–40%, occurred on the forereef off Isleta Managaha (Fig. 8.6.1a, middle right panel), where the habitat consisted of continuous reef of medium-low to medium complexity. The surveys conducted in the northwest region near Puntan Achugao and in the west region north of Puntan Susupi reported cover values for crustose coralline red algae of 25%. Both habitats were characterized as gently sloping, continuous reefs of medium-low to medium complexity. All remaining surveys around Saipan reported below average cover values, including 0% cover in the north region.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Saipan was 15% (SE 0.8). The survey with the highest mean crustose-coralline-red-algal cover of 24%, within a range of 5.1%–40%, occurred on the forereef off Isleta Managaha (Fig. 8.6.1a, bottom right panel), where the habitat consisted of con-

tinuous reef of medium-low to medium complexity. Higher than average cover values for crustose coralline red algae with means of 19%–23% were reported for 7 other survey areas: including the northwest region near Puntans Achugao and Makpè, in the east region near Bahia Fanonchuluyan, in the southeast region between Puntans Laolao Kattan and Hakmang and north of Puntan I Naftan, in the south region near Puntan Unai Opyan, and the area to the north of Puntan Susupi.

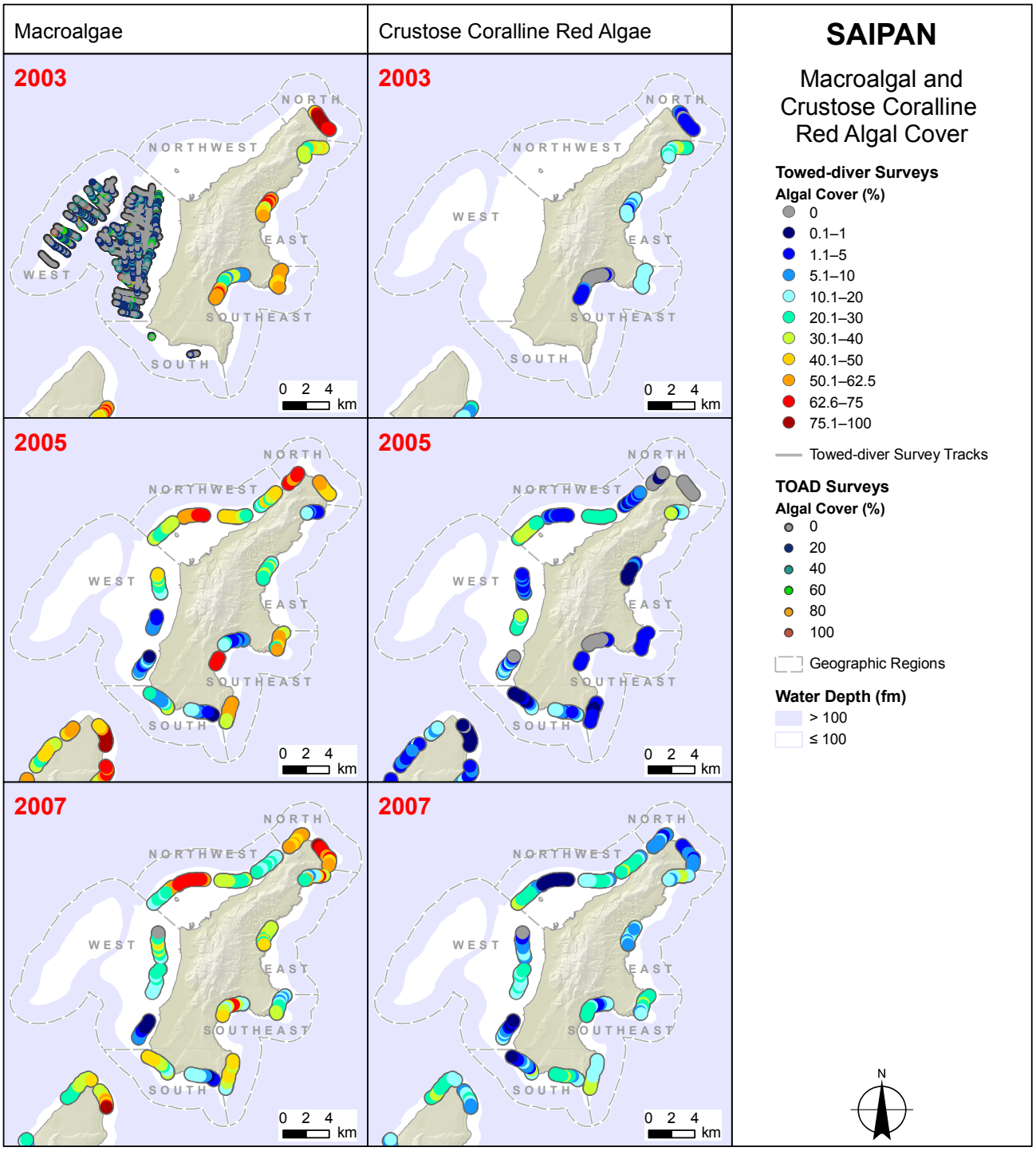


Figure 8.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over 5-min observation segments with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (turf algae were included in towed-diver surveys only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

During MARAMP 2007, 8 REA benthic surveys of forereef habitats around Saipan were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 8.8% with an overall mean of 3% (SE 1). The survey with the highest crustose-coralline-red-algal cover of 8.8% occurred in the south region at SAI-05 (Fig. 8.6.1b). No crustose coralline red algae were recorded at SAI-01 in the east region. Many surveys had crustose-coralline-red-algal cover of ≤ 2%, including SAI-04 with 2%, SAI-08 with 2%, and SAI-07 with 1%.

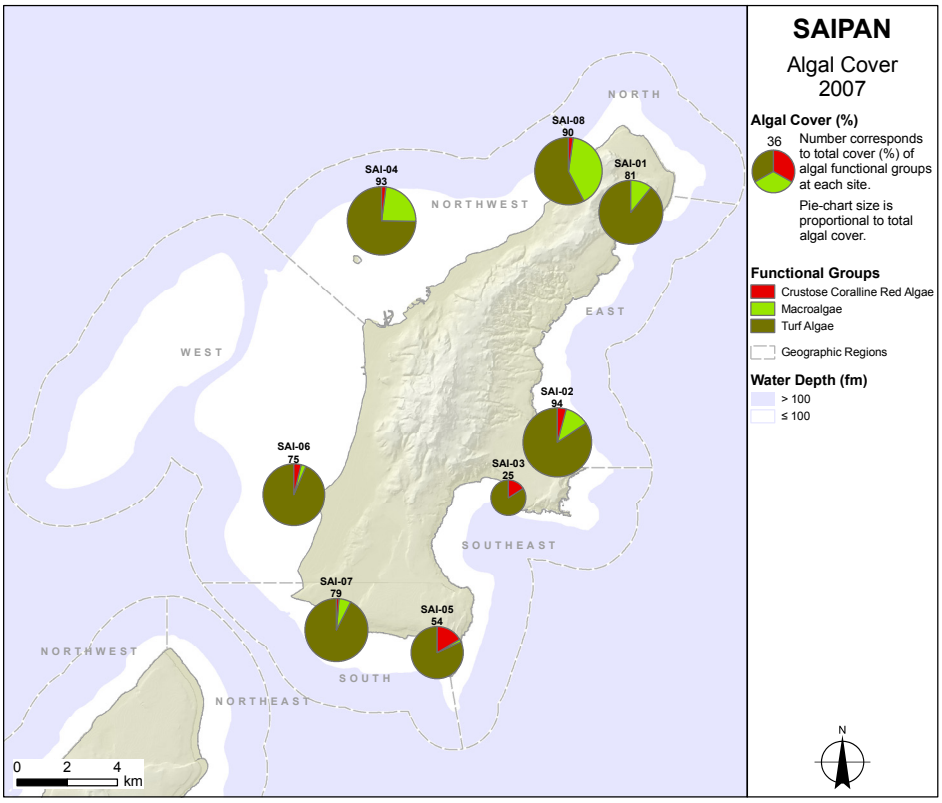


Figure 8.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method around Saipan during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total cover are provided above each symbol.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, islandwide mean cover of macroalgal populations at Saipan, based on towed-diver surveys of forereef habitats, essentially did not change (Fig. 8.6.1c). In general, macroalgae most commonly inhabited pavement of low-to-medium complexity, and the most common macroalgal genera were the green algae *Halimeda* and *Microdictyon*, the brown alga *Padina*, and the red algae *Asparagopsis* and *Liagora*. When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003 (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

From MARAMP 2005 to 2007, 3 substantial differences occurred along reefs in the east region. Macroalgal cover increased by 26% and 29% in the surveys of Bahia Fanonchuluyan and Bahia Laolao, returning to levels similar to those values observed in 2003. Inversely, a 25% decrease occurred between MARAMP 2005 and 2007 in surveys completed between Puntans Laolao Kattan and Hakmang in the southeast region.

Populations of crustose coralline red algae at Saipan, based on towed-diver surveys of forereef habitats, varied as much as 6% in in average cover of the benthos between MARAMP survey years. One factor contributing to differences in cover levels is a change in survey effort: MARAMP 2003 surveys were conducted only in the north, east, and southeast regions, and MARAMP 2005 and 2007 surveys were conducted in all 5 regions. Crustose coralline red algae most commonly inhabited medium to medium-high complexity regions of greater structure than typical macroalgal habitats.

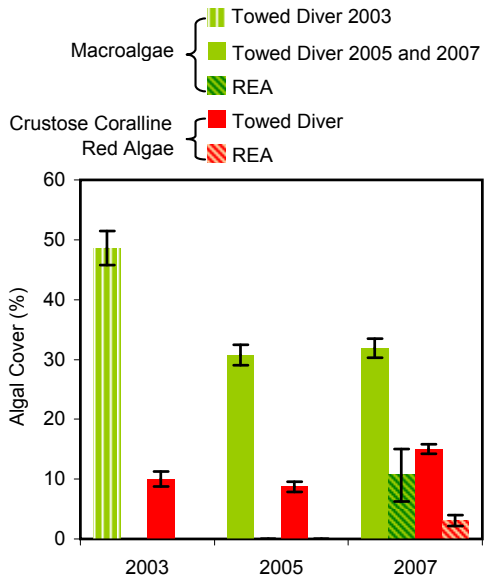


Figure 8.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats at Saipan during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003; surveys were conducted only in the north, east, and southeast regions in 2003 but in all regions in 2005 and 2007. No REA surveys using the line-point-intercept method were conducted at Saipan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

The observed overall mean cover of crustose coralline red algae essentially remained the same between MARAMP 2003 and 2005 (Fig. 8.6.1c). The greatest variability, with decreases of 11%–12%, in mean cover between these survey years was recorded in the 3 surveys conducted in Bahia Fanonchuluyan, along Unai Talofo`fo`, and between Puntans Laolao Kattan and Hakmang. Later, between MARAMP 2005 and 2007, islandwide mean cover of crustose coralline red algae increased 6%, although all surveys conducted south of Puntan Achugao in the west and southwest regions reported decreases in cover of as much as 8%. The highest changes were observed in the southeast region between Puntans Laolao Kattan and Hakmang and northeast of Puntan I Naftan where cover increased by 19% and 20.8%.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites has not been undertaken yet for the southern islands of the Mariana Archipelago. Ultimately, based on microscopic analysis that may be done in the future, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 3 sites on forereef habitats at Saipan. In the field, 13 macroalgal genera (7 red, 4 green, and 2 brown), containing at least 16 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. SAI-02 in the east region had the highest macroalgal generic diversity with 9 genera, containing 10 species, documented in the field. The lowest generic diversity was found at SAI-01 in Bahia Fanonchuluyan in the northeast region with only 3 species representing 2 genera recorded.

Species of the calcified macroalgae *Amphiroa* and *Halimeda* were the most common components of algal communities at Saipan in 2003 (Fig. 8.6.1d), occurring in 44% and 30.1% of sampled photoquadrats . Although neither of these 2 genera was found at SAI-01, they occurred in 67%–92% and 17%–83% of sampled photoquadrats at SAI-02 in the east region and SAI-03 in the southeast region. Of the 16 taxa tentatively identified to species level, only 5 occurred at SAI-01, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Saipan. The greatest diversity was recorded at SAI-02 with 10 distinct species. This site was dominated by species of the green algae *Halimeda* and *Neomeris* and the red alga *Amphiroa*, occurring in 83%, 42%, and 67% of sampled photoquadrats; 5 other taxa occurred in ≤ 16% of sampled photoquadrats. Species of the genus *Neomeris* occurred in 25% and 42% of sampled photoquadrats at SAI-01 and SAI-02 but not at all at SAI-03, which was populated predominantly by species of *Amphiroa*. At the northernmost site in the east region, SAI-01, *Neomeris* was the second-most abundant genus next to *Tricleocarpa* which occurred in 67% of sampled photoquadrats, but only occurred in 8% of photoquadrats at SAI-02 and SAI-03.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2003, occurring in 100%, 47%, and 22% of photoquadrats sampled at Saipan (Fig. 8.6.1d). Although crustose coralline red algae were observed at all sites, the occurrence of this functional group varied broadly with observations recorded in 8%–75% of sampled photoquadrats. Cyanobacteria occurred in 17%–25% of the photoquadrats sampled at Saipan.

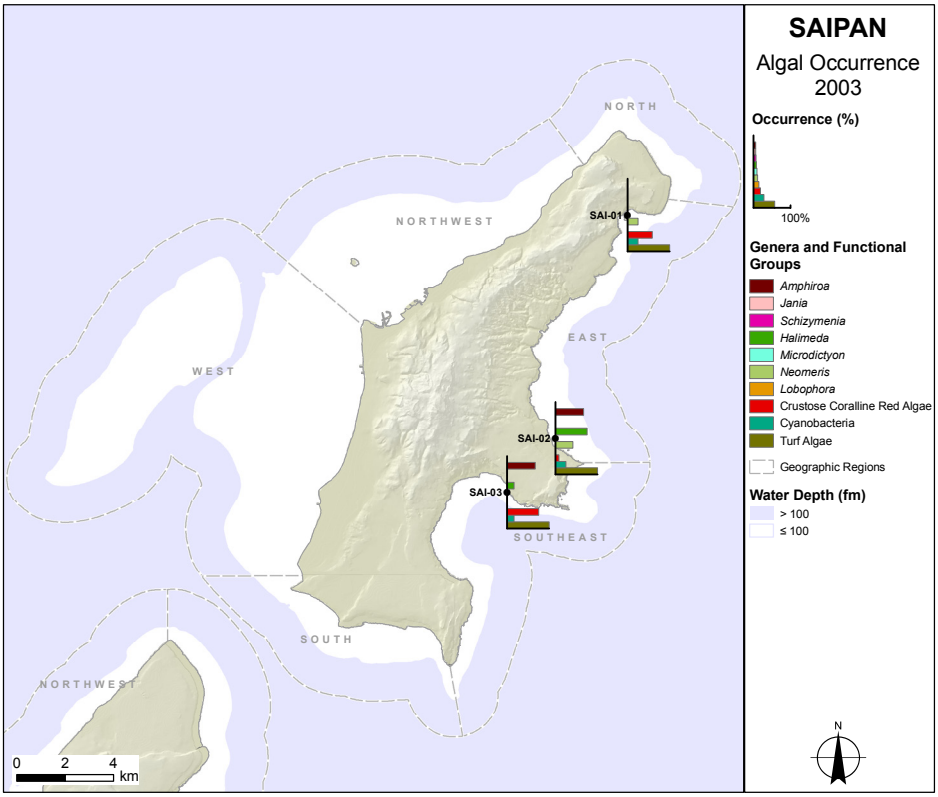


Figure 8.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Saipan during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2005, REA benthic surveys were conducted at 8 sites on forereef habitats around Saipan. In the field, 23 macroalgal genera (9 red, 10 green, and 4 brown), containing at least 23 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, branched, nongeniculate coralline red algae, and cyanophytes—were observed. SAI-02 in the east region had the highest macroalgal generic diversity with 13 genera, containing 13 species, documented in the field. The lowest macroalgal generic diversity was found at SAI-01 in the east region and SAI-03 in the southeast region with 3 species representing 3 genera recorded.

Species of *Halimeda*, the red alga *Jania*, and the brown alga *Dictyota* were all relatively abundant around Saipan in 2005 (Fig. 8.6.1e), occurring in 51%, 27%, and 19% of sampled photoquadrats. Species of the red algae *Amansia, Actinotrichia, Amphiroa*, and *Galaxaura* and the green alga *Caulerpa* were less abundant around this island, occurring in 8%–11% of sampled photoquadrats. However, in many cases, these genera were found in much greater abundance at a single REA site. None of the genera identified during MARAMP 2005 were observed at all 8 sites surveyed around Saipan. Species of *Halimeda* were recorded at 7 of the 8 REA survey sites (they were absent at SAI-01 in Bahia Fanonchuluyan), occurring in 8% of sampled photoquadrats at SAI-03 in the southeast region and in 100% of sampled photoquadrats at both SAI-02 in the east region near Puntan Halaihai and SAI-04 in the west region. The sites with low *Halimeda* abundance—SAI-01, SAI-03, SAI-05—were all protected from a northeast exposure, and this protection may help explain patterns in the distribution of this genus around Saipan. Species of the calcified alga *Jania* were recorded at 4 of the 8 REA sites, occurring in 25%–58% of sampled photoquadrats, at SAI-04, SAI-06, SAI-07, SAI-08 but were absent in the east and southeast regions.

Turf algae, crustose coralline red algae, and cyanobacteria were all exceptionally common in 2005, occurring in 97%, 60%, and 45% of sampled photoquadrats around Saipan. Communities of both turf algae and crustose coralline red algae were prevalent at all sites. Turf algae occurred in 83%–100% of sampled photoquadrats, and crustose coralline red algae, with more varied abundance, was found in 16%–83% of sampled photoquadrats (Fig. 8.6.1e). Although cyanobacteria were not documented at SAI-01 or SAI-02, they occurred in 50%–83% of photoquadrats sampled at all other sites.

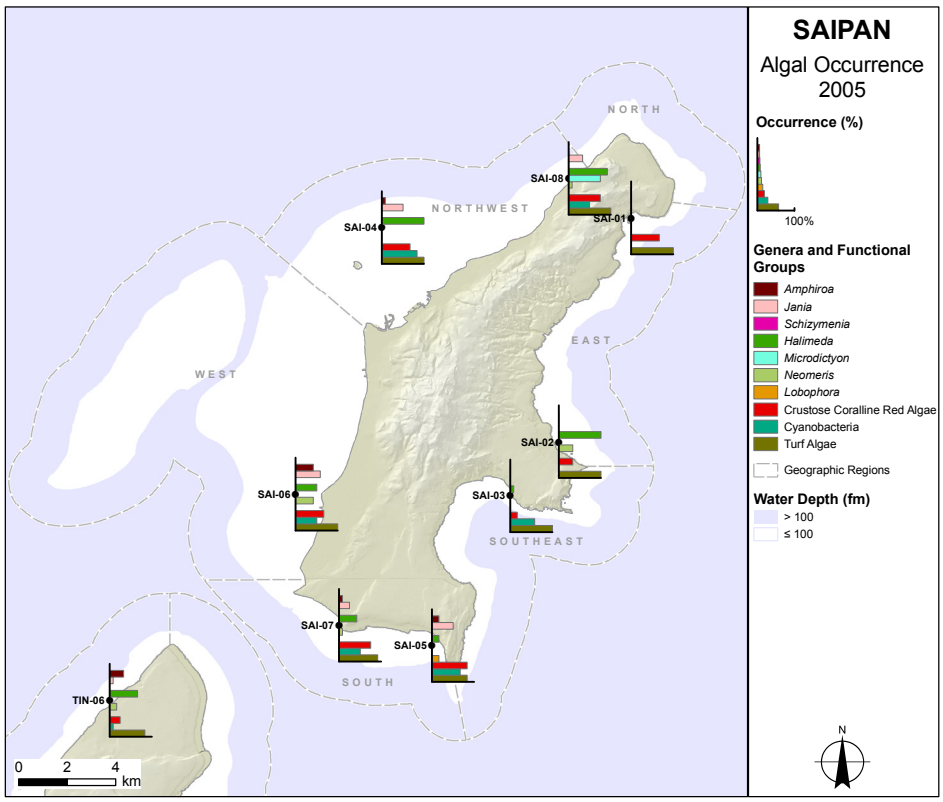


Figure 8.6.1e. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted around Saipan during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2007, REA benthic surveys were conducted at 8 sites on forereef habitats around Saipan. In the field, 26 macroalgal genera (14 red, 10 green, and 2 brown), containing at least 46 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. SAI-02 near Halaihai in the east region had the highest macroalgal generic diversity with 13 genera, containing 17 species, documented in the field. SAI-03 in the southeast region and SAI-05 in the south region had the lowest macroalgal generic diversity with 4 species representing 4 genera recorded.

Species of *Halimeda* were the most common components of the algal communities around Saipan in 2007 (Fig. 8.6.1f), occurring in 45% of photoquadrats sampled. Species of the red algae *Tolypiocladia* and *Amphiroa* were also moderately abundant, both occurring in 26% of the photoquadrats sampled at Saipan; however, these 2 genera were mutually exclusive at every site. Species of *Tolypiocladia* occurred only at sites on the northern half of Saipan (SAI-01: 33%; SAI-02: 75%; SAI-04: 92%; SAI-08: 8%), while species of *Amphiroa* occurred only in habitats surrounding the southern half of the island (SAI-02: 33%; SAI-03: 42%; SAI-05: 50%; SAI-06: 33%; SAI-07: 42%). Species of *Neomeris*, *Microdictyon*, and *Padina* occurred in 18%, 12.5%, and 17% of sampled photoquadrats. Although some genera occurred in relatively high abundance, none were recorded at all sites.

Cyanobacteria and turf algae were ubiquitous at every site in 2007, occurring in 82% and 52% of photoquadrats sampled around Saipan. Turf algae were observed in 7%–100% of sampled photoquadrats, whereas cyanobacteria were found in 67%–100% of sampled photoquadrats (Fig. 8.6.1f). Crustose coralline red algae were recorded in 19% of sampled photoquadrats around the island but were absent from both sites in the east region, SAI-01 Bahia Fanonchuluyan and SAI-02 near Puntan Halaihai, and from SAI-04 in the northwest region.

The number of macroalgal genera recorded on forereef habitats at Saipan increased from 13 to 23 genera between MARAMP 2003 and 2005—and rose by 3 genera to 26 in 2007. Species diversity also increased between MARAMP 2003 and 2007 with 16, 23, and 46 species recorded in 2003, 2005, and 2007. Five additional sites were surveyed in 2005 and 2007 beyond the 3 sites surveyed in 2003. This greater survey effort likely accounts for some of the increase in the number of observed genera from 2003 to 2007 (for information on data limitations, see Chapter 2: "Methods and Operational Background, Section 2.4: "Reef Surveys"). Species of *Halimeda* consistently exhibited high values of occurrence during the 3 survey years with an average occurrence range of 30.1%–51%; however, no patterns in occurrence were detected (Fig. 8.6.1g). Species of *Amphiroa* also were observed in relatively high abundance in 2003 and 2007, occurring in 44%

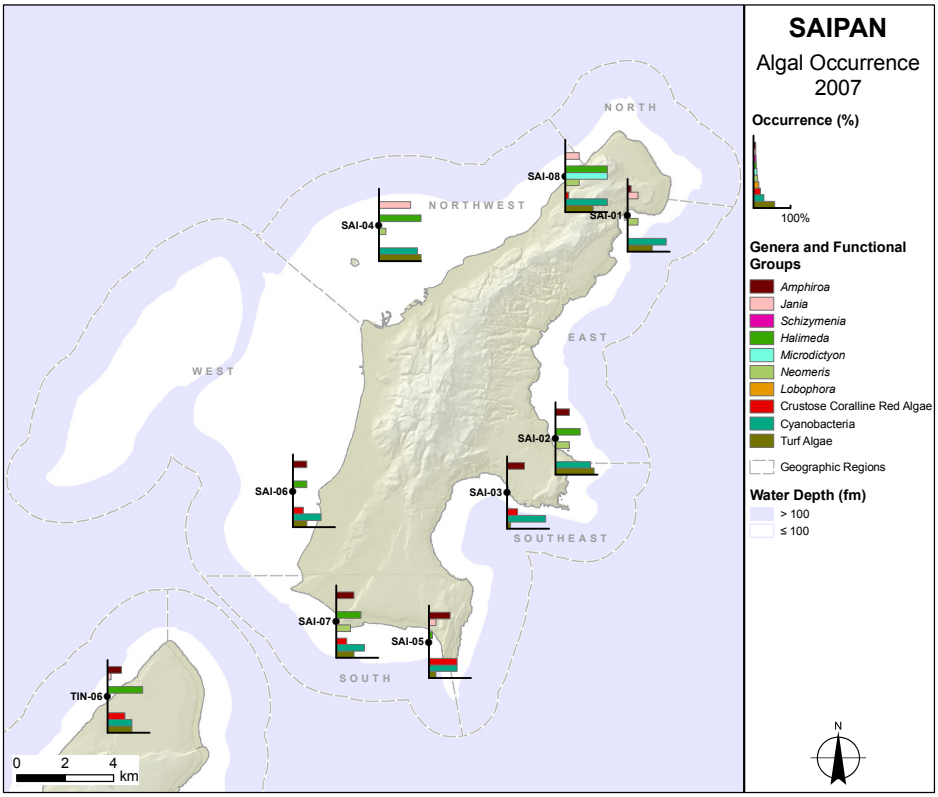


Figure 8.6.1f. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of x-axis denotes 100% occurrence.

and 26% of sampled photoquadrats; however, no individuals were recorded in 2005. Other common genera were *Jania*, *Dictyota*, *Tricleocarpa*, *Neomeris*, and *Tolypiocladia*.

The occurrence of crustose coralline red algae on forereef habitats at Saipan differed greatly between MARAMP survey years but with no clear pattern, increasing from 47% in 2003 to 60% in 2005 and decreasing to 18% in 2007. Turf-algal occurrence at Saipan declined slightly from 100% in 2003 to 97% in 2005 and continued to decrease in 2007 to 52%. Occurrence values of cyanobacteria climbed from 22% in 2003 to 45% in 2005 then jumped to 82% in 2007.

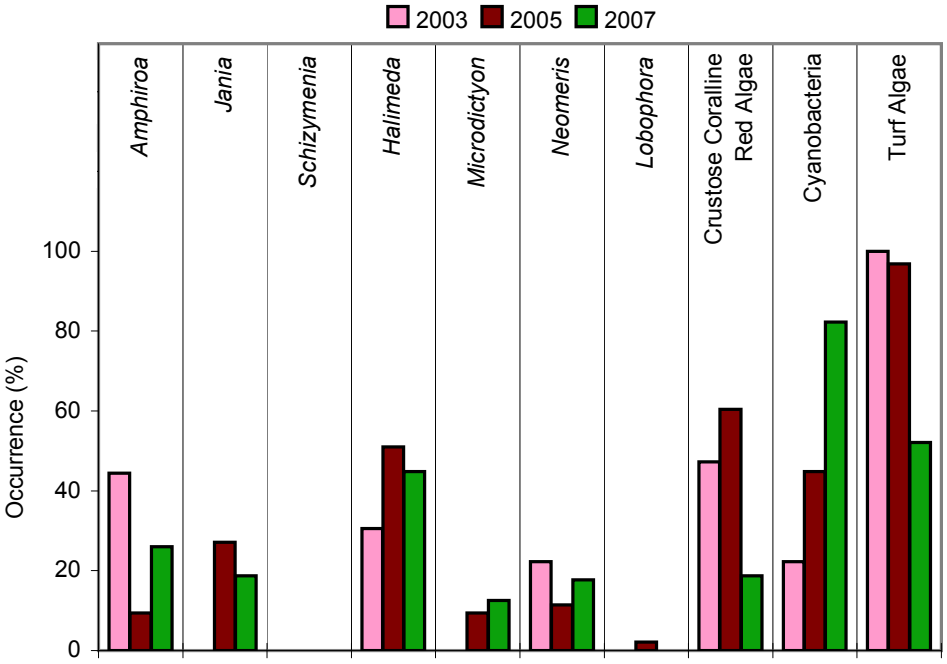


Figure 8.6.1g. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Saipan during MARAMP 2003, 2005, and 2007.

8.6.2 Surveys for Coralline Algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 8 sites on forereef habitats around Saipan, covering a total reef area of more than 2200 m^2. Disease of coralline algae was found at 5 sites with a mean overall density of 0.67 cases 100 m^{-2} (SE 0.28). The highest density value of 2 cases 100 m^{-2} was recorded at SAI-02 near Puntan Halaihai in the east region (Figs. 8.6.2a and b). Three major types of diseases were registered around Saipan: coralline lethal orange disease, coralline white band syndrome, and a coralline cyanobacterial disease. Coralline lethal orange disease was the most numerous disease around Saipan, representing 86% of all cases islandwide. Only 1 case each of cyanobacerial disease, at SAI-02 in the east region, and white band syndrome, at SAI-06 in the west region, were detected.

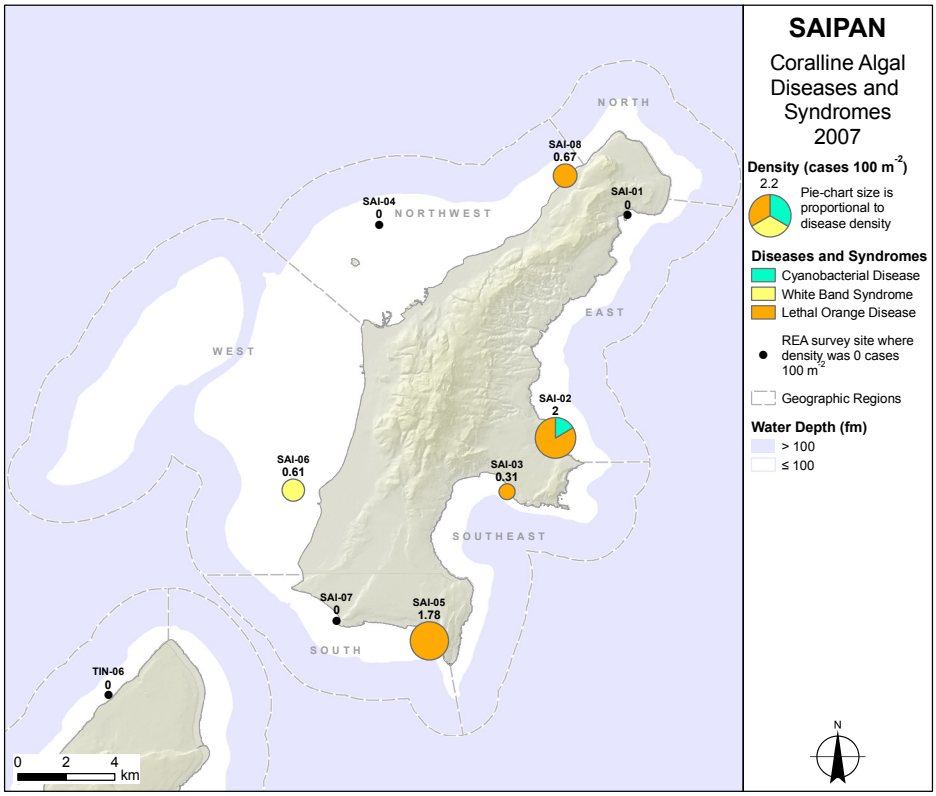


Figure 8.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats around Saipan during MARAMP 2007. The color-coded portions of the pie charts indicate disease-specific density.

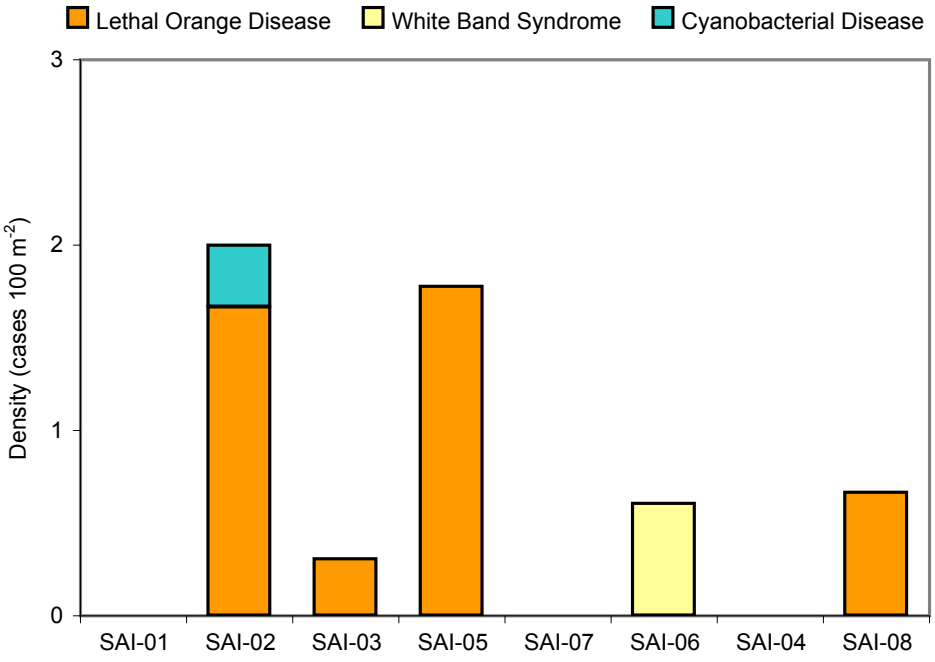


Figure 8.6.2b. Densities (cases 100 m^{-2}) of the coralline-algal diseases from REA benthic surveys conducted on forereef habitats around Saipan during MARAMP 2007.

8.7 Benthic Macroinvertebrates

8.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Saipan through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys are provided in Chapter 3: "Archipelagic Comparisons".

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 3 REA surveys and 6 towed-diver benthic surveys were conducted, and in 2005, 8 REA surveys and 17 towed-diver benthic surveys were performed around Saipan. In 2007, because of the lack of a scientific diver with expertise in invertebrates, no REA surveys were conducted; however, 16 towed-diver benthic surveys were completed. Also, when considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, towed-diver surveys suggested low daytime macroinvertebrate abundance on forereef habitats around Saipan compared to the rest of the Mariana Archipelago. Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density around Saipan—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 8.7.1d, h, l, and p). Because of the variable REA survey effort, with 3 surveys in 2003, 6 in 2005, and no surveys in 2007, temporal comparisons of REA data are not presented (see Chapter 2: "Methods and Operational Background, Section 2.4.7: "Benthic Macroinvertebrates").

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at all 3 REA sites and in 5 of the 6 towed-diver surveys conducted at Saipan (Fig. 8.7.1a). Surveys in 2003 were conducted only in the east, southeast, and north regions. The sample mean density of giant clams from REA surveys was 2.86 organisms 100 m^{-2} (SE 0.46), and the overall mean density from towed-diver surveys was 0.009 organisms 100 m^{-2} (SE 0.004). Survey results suggest giant clams were most abundant at REA site SAI-01 in Bahia Fanonchuluyan in the east region with 3.57 organisms 100 m^{-2} (for place-names and their locations, see Fig. 8.2a in Section 8.2: "Survey Effort"). Among the towed-diver surveys at Saipan, all of which were conducted in the north, east, or southeast regions, the survey completed between Puntans Laolao Kattan and Hakmang in the southeast region had the highest mean density of giant clams with 0.022 organisms 100 m^{-2}; segment densities from on this survey ranged from 0 to 0.173 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.015 organisms 100 m^{-2}, recorded along the shoreline north of Tuturam; segment densities ranged from 0 to 0.056 organisms 100 m^{-2}.

During MARAMP 2005, giant clams were observed at 5 of the 8 REA sites and in 12 of the 17 towed-diver surveys conducted around Saipan (Fig. 8.7.1b). The overall mean density of giant clams from REA surveys was 1 organism 100 m^{-2} (SE 0.33), and the islandwide mean density from towed-diver surveys was 0.018 organisms 100 m^{-2} (SE 0.003). Survey results suggest giant clams were most abundant at SAI-02 in Bahia Fanonchuluyan in the east region, SAI-04 north of Isleta Managaha in the northwest region, and SAI-07 near Puntan Opyan in the south region, each with 2 organisms 100 m^{-2}. Among all towed-diver surveys around this island, the survey completed in Bahia Fanonchuluyan had the highest mean density of giant clams with 0.05 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.294 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.048 organisms 100 m^{-2}, recorded in the northwest region near Puntan Achugao; segment densities ranged from 0 to 0.16 organisms 100 m^{-2}.

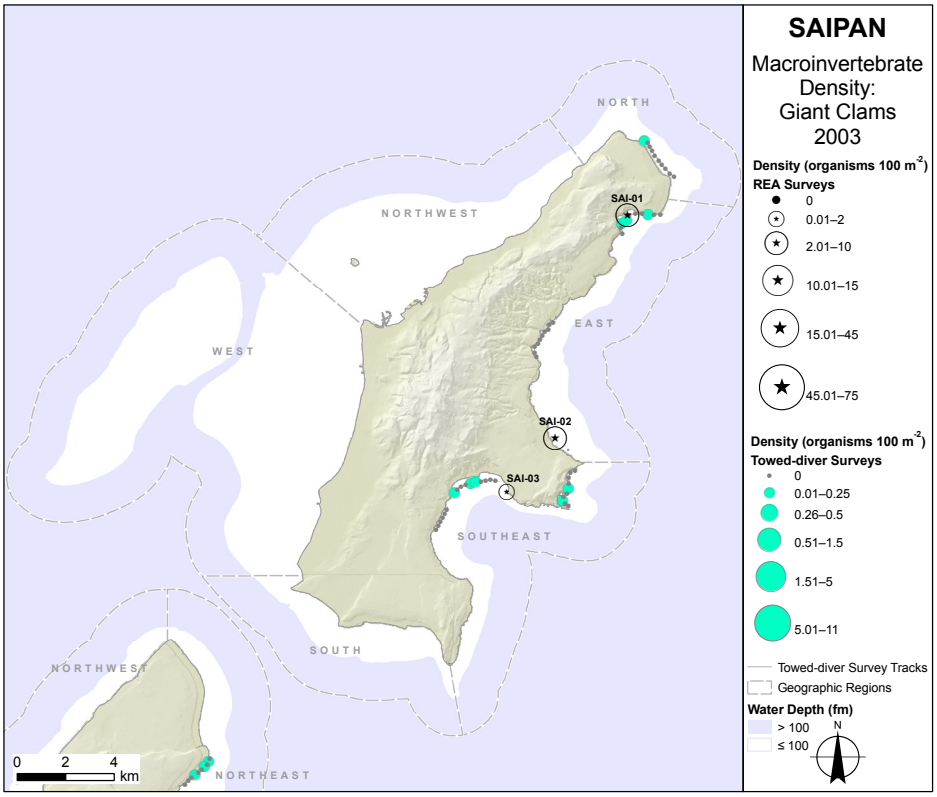


Figure 8.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted at Saipan during MARAMP 2003.

During MARAMP 2007, giant clams were observed in 8 of the 16 towed-diver surveys conducted around Saipan (Fig. 8.7.1c) with an islandwide mean density of 0.012 organisms 100 m^{-2} (SE 0.003). Among all towed-diver surveys around this island, the survey completed along Talofo`fo`, Unai in the east region had the highest mean density of giant clams with 0.063 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.16 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.046 organisms 100 m^{-2}, recorded north of Tuturam in Bahia Laolao in the southeast region; segment densities ranged from 0 and 0.253 organisms 100 m^{-2}.

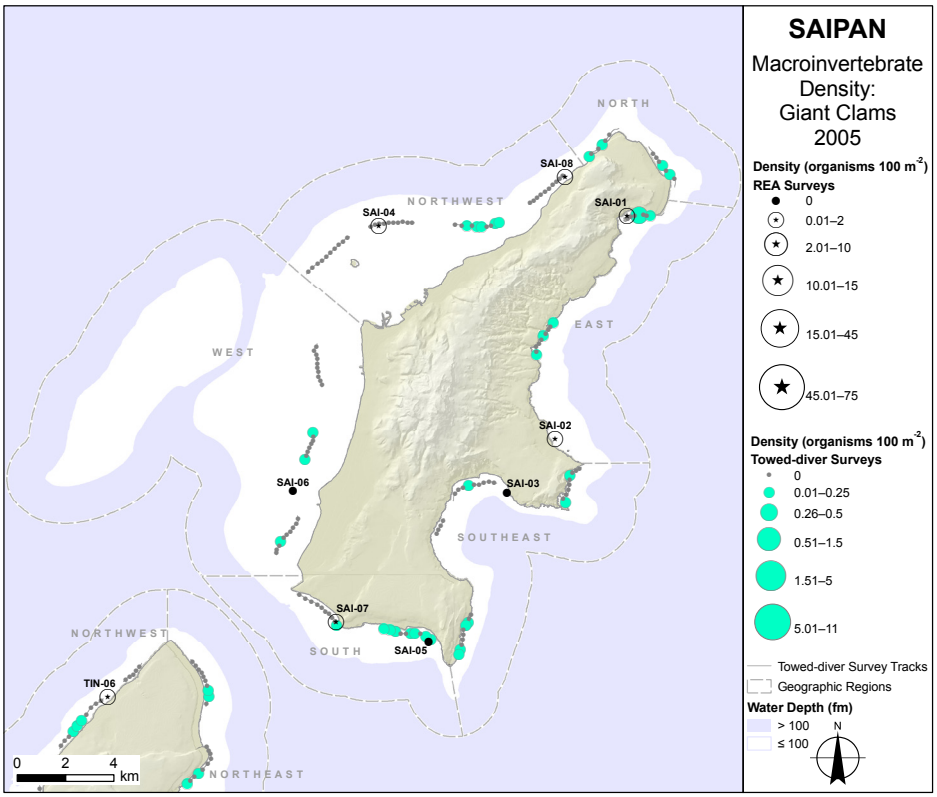


Figure 8.7.1b. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2005.

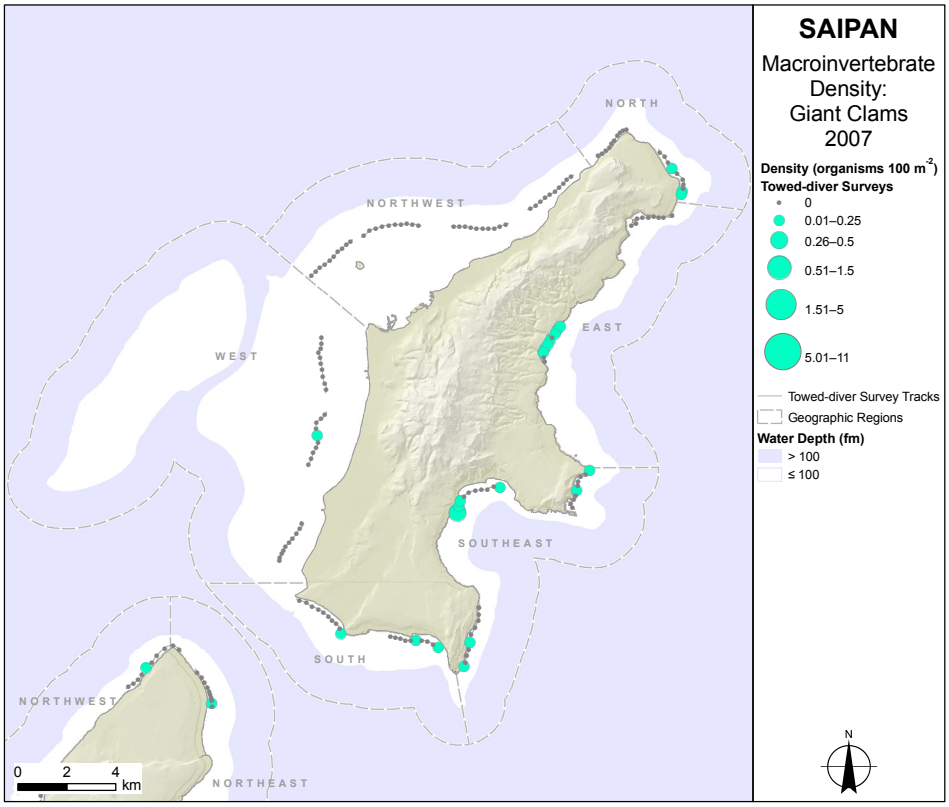


Figure 8.7.1c. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007.

Towed-diver surveys suggested low abundance of giant clams around Saipan during MARAMP survey periods, relative to the rest of the Mariana Archipelago (Fig. 8.7.1d). Minor fluctuations in density were observed, but this variation is not necessarily indicative of changes in the population structure of giant clams (For information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

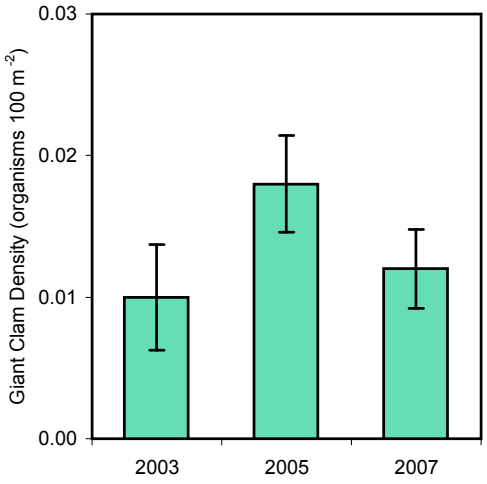


Figure 8.7.1d. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Saipan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Crown-of-thorns Seastars

During MARAMP 2003, crown-of-thorns seastars (*Acanthaster planci*) were observed at 1 of the 3 REA sites surveyed and in 4 of the 6 towed-diver surveys conducted at Saipan (Fig. 8.7.1e). SAI-01 in Bahia Fanonchuluyan in the east region had a COTS density of 7.14 organisms 100 m^{-2}. The overall mean density of COTS from towed-diver surveys was 0.045 organisms 100 m^{-2} (SE 0.035). Among the towed-diver surveys at Saipan, all of which were conducted in the north, east, or southeast regions, the survey completed between Puntans Laolao Kattan and Hakmang in the southeast region had the highest mean density of COTS with 0.199 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.95 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.04 organisms 100 m^{-2}, recorded north of Taturam in Bahia Laolao in the southeast region; segment densities ranged from 0 to 0.143 organisms 100 m^{-2}.

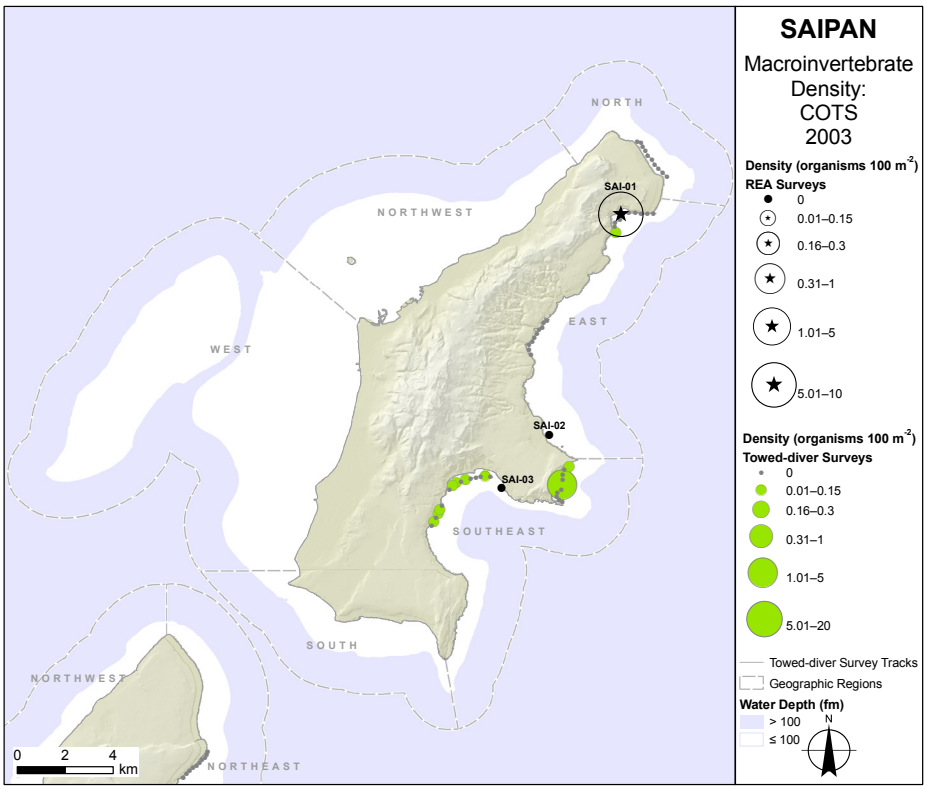


Figure 8.7.1e. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted at Saipan during MARAMP 2003.

During MARAMP 2005, COTS were observed at 1 of the 8 REA sites surveyed and in 13 of the 17 towed-diver surveys conducted around Saipan (Fig. 8.7.1f). SAI-01 in the east region had a COTS density of 1 organism 100 m^{-2}. The islandwide mean density of COTS from towed-diver surveys was 0.062 organisms 100 m^{-2} (SE 0.017). The majority of COTS recorded during towed-diver surveys were observed in the south region. Among all towed-diver surveys around this island, the survey completed between Puntans Opyan and Agingan in the south region had the highest mean density of COTS with 0.35 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.25 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.24 organisms 100 m^{-2}, recorded between Puntans Unai Opayan and Opyan; segment densities ranged from 0 to 0.7 organisms 100 m^{-2}. The third-greatest mean density was 0.112 organisms 100 m^{-2}, recorded in the east region in Bahia Fanonchuluyan; segment densities ranged from 0 to 0.324 organisms 100 m^{-2}.

During MARAMP 2007, COTS were observed in 10 of the 16 towed-diver surveys conducted around Saipan (Fig. 8.7.1g) with an islandwide mean density of 0.012 organisms 100 m^{-2} (SE 0.003). Among all towed-diver surveys around this island, the survey completed in the northwest region near Puntan Achugao had the highest mean density of COTS with 0.09 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.42 organisms 100 m^{-2}.

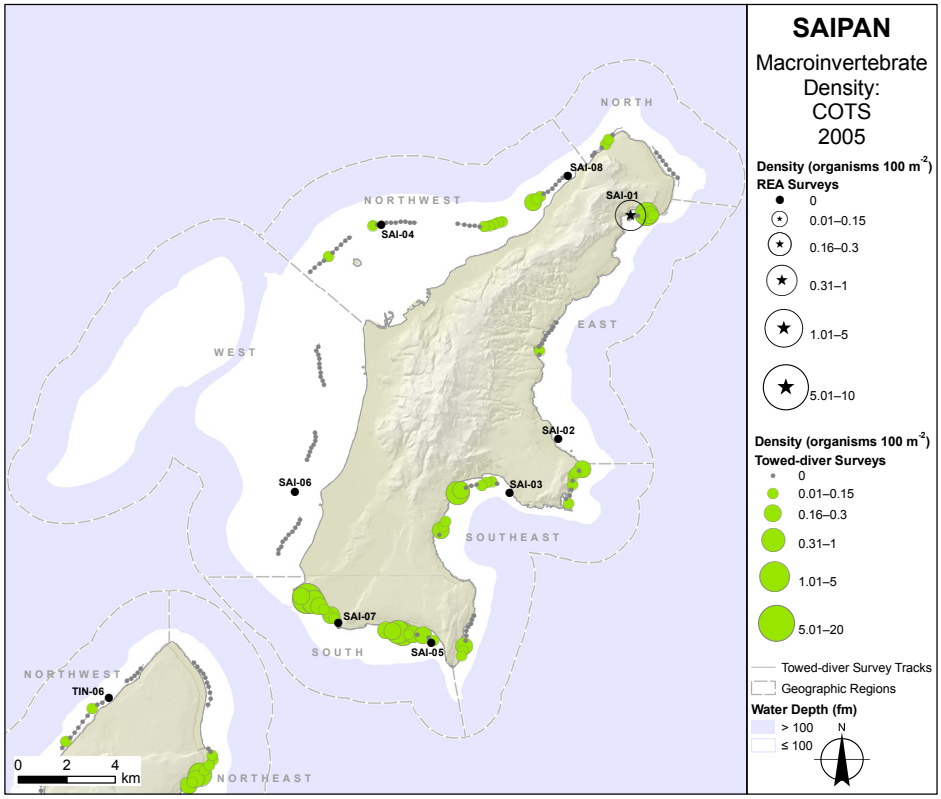


Figure 8.7.1f. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2005.

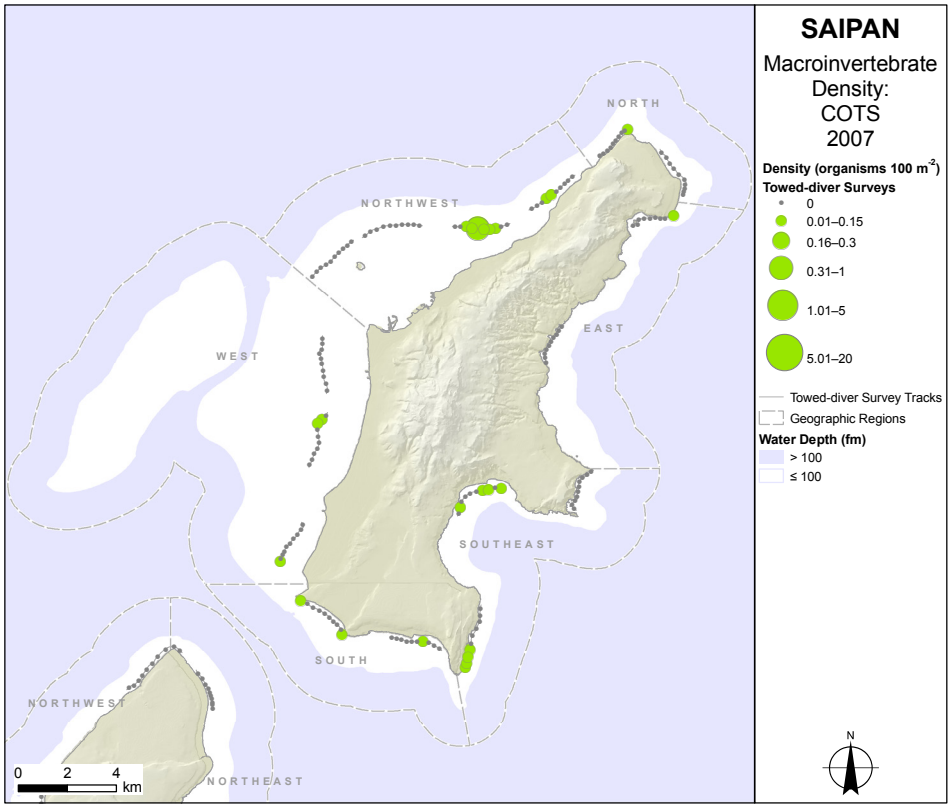


Figure 8.7.1g. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007.

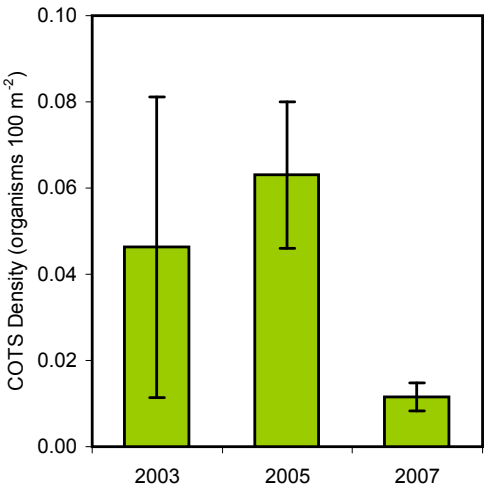


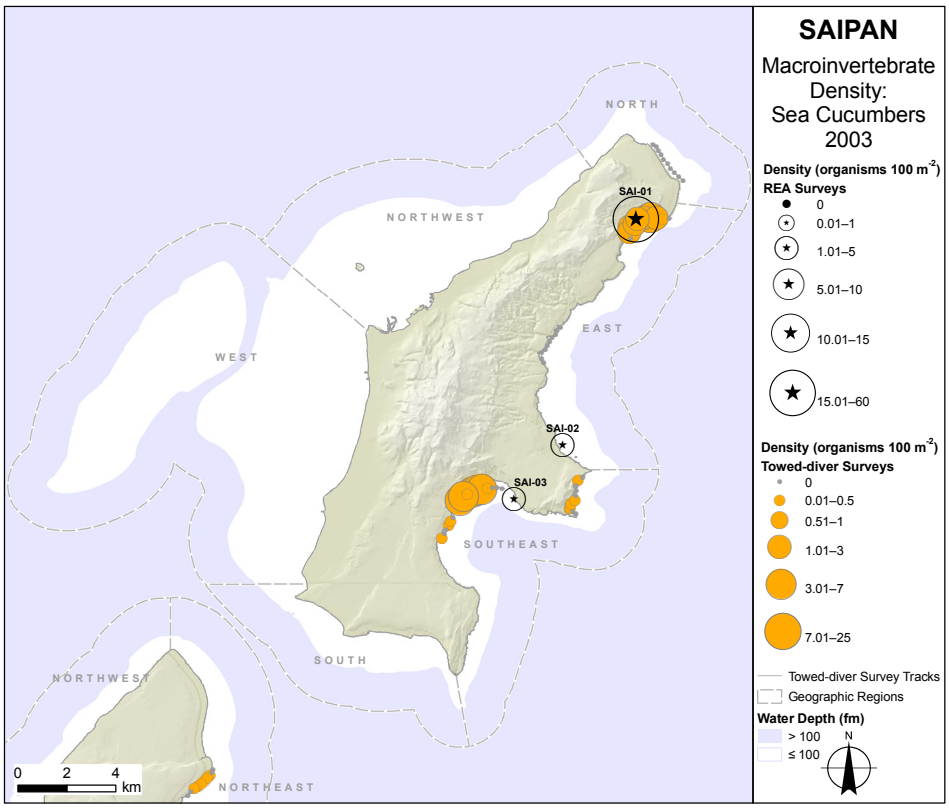
Figure 8.7.1h. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Saipan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

During MARAMP 2003 and 2005, individual towed-diver surveys suggested high daytime densities of COTS in localized areas around Saipan, compared to other areas surveyed around Saipan. However, densities from surveys conducted in 2007 were down from values recorded in previous survey years (Fig. 8.7.1h), suggesting a sharp decline in COTS population. Given that these corallivorous seastars can decimate a reef, understanding whether their observed densities signify an outbreak is important. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure established for using scuba divers to conduct MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms km^{-2} (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of density and considering each towed-diver survey as an individual reef area, localized areas with relatively high densities that suggest that they were undergoing an outbreak were found during MARAMP 2003 and 2005. In 2003, such areas were observed during a towed-diver survey between Puntans Laolao Kattan and Hakmang in the southeast region with 0.199 organisms 100 m^{-2}. In 2005, the aforementioned density criterion was met in 2 towed-diver surveys in the south region between Puntans Unai Opyan and Agingan with 0.35 and 0.24 organisms 100 m^{-2}. COTS density naturally fluctuates with food availability and variation in recruitment success (Birkeland and Lucas 1990; Fabricius et al. 2010; and Yamaguchi 1987).

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at all 3 REA sites surveyed and in 4 of the 6 towed-diver surveys conducted at Saipan (Fig. 8.7.1i). The sample mean density from REA surveys was 15.43 organisms 100 m^{-2} (SE 11.96),

Figure 8.7.1i. Density (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys conducted of forereef habitats at Saipan during MARAMP 2003.



and the overall mean density from towed-diver surveys was 0.568 organisms 100 m^{-2} (SE 0.161). Survey results suggest sea cucumbers were most abundant at SAI-01 with 11 organisms 100 m^{-2} and with 91% of these observations containing species within the genus *Stichopus*. The other recorded genus was *Holothuria*. Among the towed-diver surveys at Saipan, all of which were conducted in the north, east, or southeast regions, the survey completed north of Tuturam in Bahia Laolao in the southeast region had the highest mean density of sea cucumbers with 1.9 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 4.183 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers was 1.39 organisms 100 m^{-2}, recorded in Bahia Fanonchuluyan in the east region; segment densities ranged from 0 to 3.059 organisms 100 m^{-2}.

During MARAMP 2005, sea cucumbers were observed at 5 of the 8 REA sites surveyed and in 15 of the 17 towed-diver surveys conducted around Saipan (Fig. 8.7.1j). The overall mean density of sea cucumbers from REA surveys was 5.37 organisms 100 m^{-2} (SE 3.57), and the islandwide mean density from towed-diver surveys was 0.34 organisms 100 m^{-2} (SE 0.08). Survey results suggest sea cucumbers were most abundant at SAI-01 with 30 organisms 100 m^{-2}; all of them came from the genus *Stichopus*. In 2005, 91% of all sea cucumbers recorded were from the genus *Stichopus*; the only other representative genus was *Holothuria*. Among all towed-diver surveys around this island, the survey completed in Bahia Fanonchuluyan in the east region had the highest mean density of sea cucumbers with 3.21 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 10.3 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.63 organisms 100 m^{-2}, recorded in the northwest region near Puntan Achugao; segment densities ranged from 0 to 1.91 organisms 100 m^{-2}.

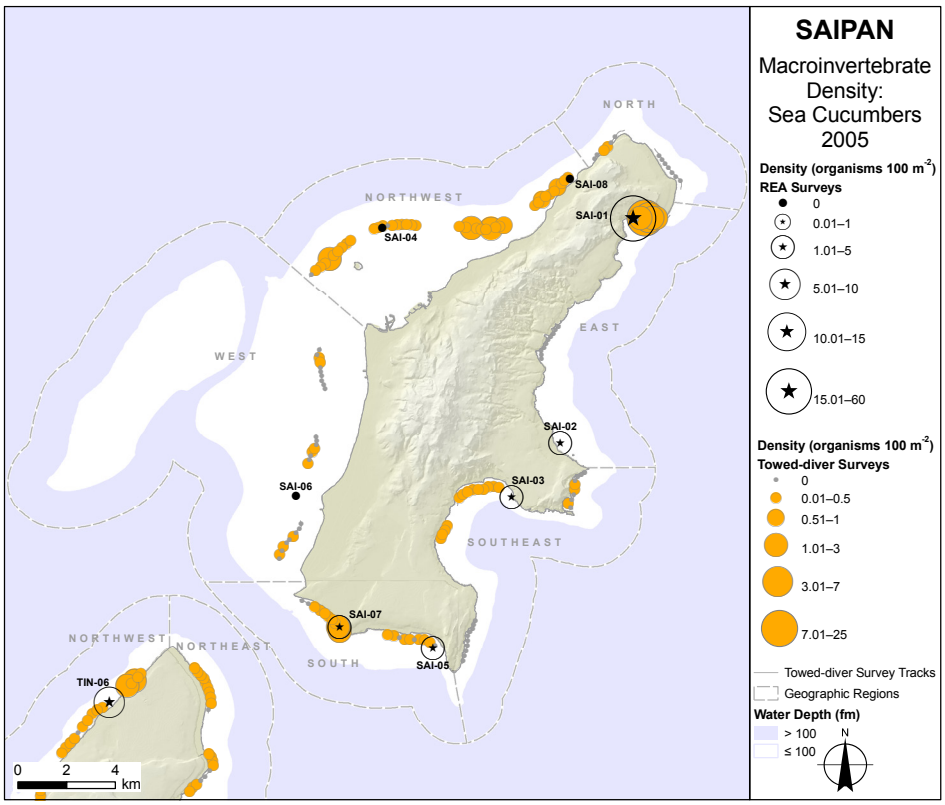


Figure 8.7.1j. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2005.

During MARAMP 2007, sea cucumbers were observed in 15 of the 16 towed-diver benthic surveys conducted around Saipan (Fig. 8.7.1k) with an islandwide mean density of 3.45 organisms 100 m^{-2} (SE 0.09). Among all towed-diver surveys around Saipan, the survey completed in Bahia Fanonchuluyan in the east region had the highest mean density of sea cucumbers with 3.07 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 7.77 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 1.11 organisms 100 m^{-2}, recorded just west of Isleta Managaha in the northwest region; segment densities ranged from 0.02 to 3.3 organisms 100 m^{-2}.

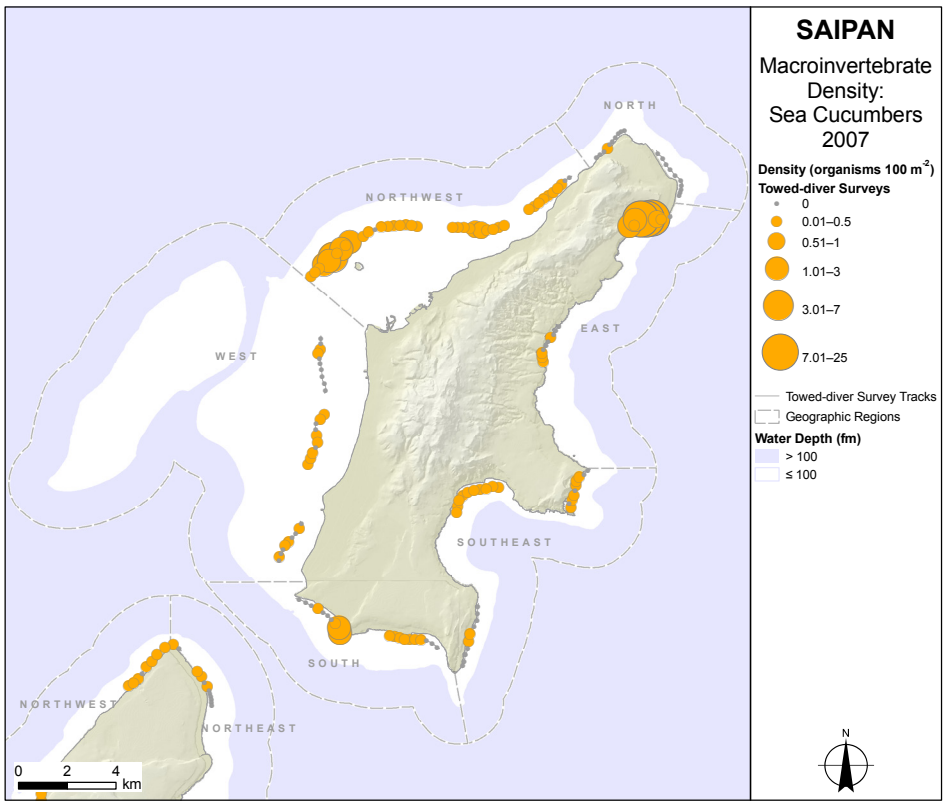


Figure 8.7.1k. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007.

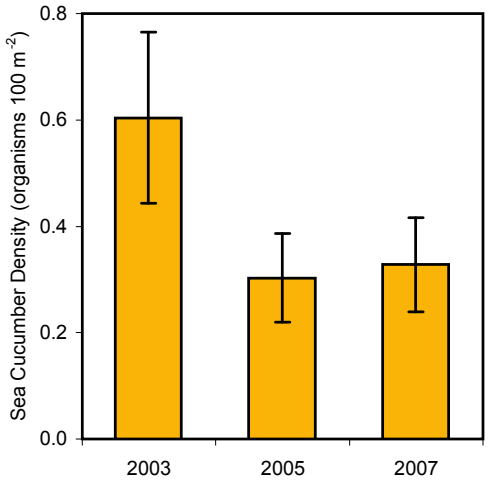


Figure 8.7.1l. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Saipan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver and REA surveys across the 3 MARAMP survey years suggested low daytime abundance of sea cucumbers around Saipan, relative to the rest of the Mariana Archipelago, with the exception of surveys conducted in the east region in Bahia Fanonchuluyan, where densities of sea cucumbers were higher than anywhere else around this island. The overall observed mean density of sea cucumbers from towed-diver surveys was lower in 2005 and 2007 than in 2003 (Fig. 8.7.1l). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (For information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Sea Urchins

During MARAMP 2003, sea urchins were observed at both REA sites surveyed and in 5 of the 6 towed-diver surveys conducted at Saipan (Fig. 8.7.1m). The sample mean density of sea urchins from REA surveys was 49.33 organisms 100 m^{-2} (SE 28.9), and the overall mean density from towed-diver surveys was 1.37 organisms 100 m^{-2} (SE 0.33). Survey results suggest sea urchins were most abundant at SAI-03, located between Puntans Hakmang and Tuturam in the southeast region, with 107 organisms 100 m^{-2}. At this site, 61% of sea urchins were of the genus *Diadema*, 28% were rock-boring urchins in the genus *Echinostrephus*, and 11% were of the genus *Echinothrix*. SAI-02 had the second-greatest density of sea urchins with 16 organisms 100 m^{-2}. Three genera were recorded at this site: *Echinostrephus*, *Echinometra*, and *Echinothrix*. The rock-boring urchin *Echinostrephus* accounted for 87.5% of sea urchins recorded.

Among the towed-diver surveys conducted at Saipan in 2003, all of which were conducted in the north, east, or southeast regions, the survey completed south of Tuturam in the southeast region had the highest mean density of sea urchins with 2.81 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 7.19 organisms 100 m^{-2}. The second-greatest mean density of sea urchins was 2.54 organisms 100 m^{-2}, recorded in the north region east of Puntan Sabaneta; segment densities ranged from 0 to 11.3 organisms 100 m^{-2}.

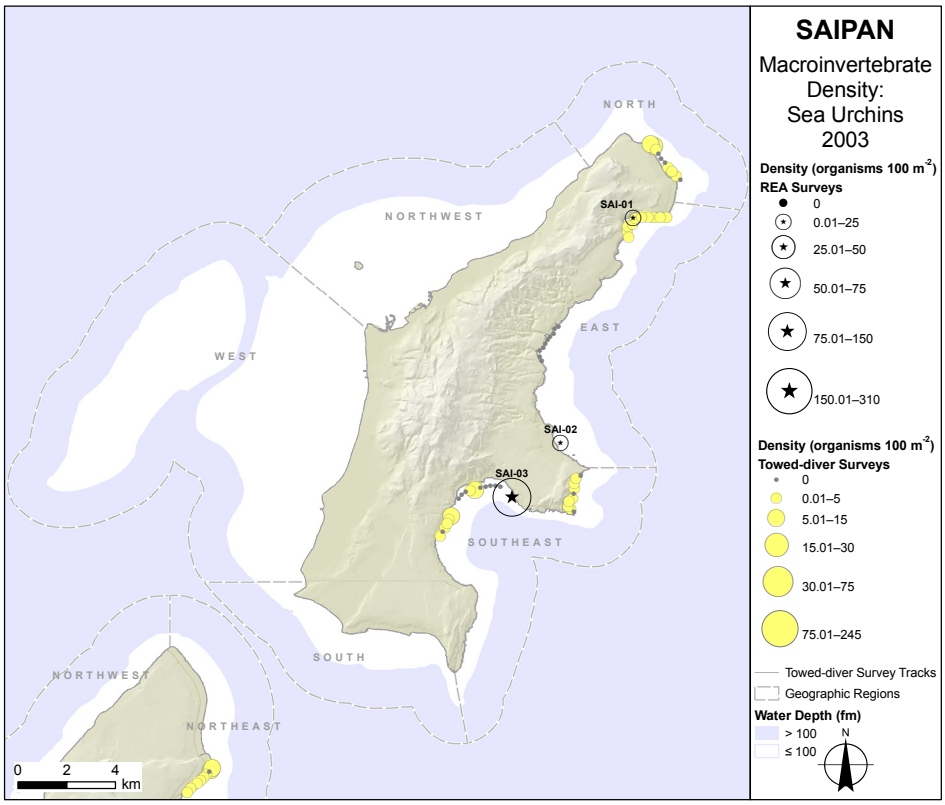


Figure 8.7.1m. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted at Saipan during MARAMP 2003.

During MARAMP 2005, sea urchins were observed at 4 of the 8 REA sites surveyed and in 14 of the 17 towed-diver surveys conducted around Saipan (Fig. 8.7.1n). The overall mean density of sea urchins from REA surveys was 3.38 organisms 100 m^{-2} (SE 1.66), and the islandwide mean density from towed-diver surveys was 2.36 organisms 100 m^{-2} (SE 0.56). Survey results suggest sea urchins were most abundant at SAI-04, located in the northwest region north of Isleta Managaha, with a mean density of 12 organisms 100 m^{-2}. Among all towed-diver surveys around this island, the survey completed around Puntan Sabaneta in the north region had the highest mean density of sea urchins with 19.84 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 34.88 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 13.28 organisms 100 m^{-2}, recorded between Puntans Dandan and I Naftan in the southeast region; segment densities ranged from 3.38 to 38.92 organisms 100 m^{-2}. The third-greatest mean density was 3.84 organisms 100 m^{-2}, recorded south of Puntan Makpe` in the northwest region; segment densities ranged from 0 to 21.02 organisms 100 m^{-2}.

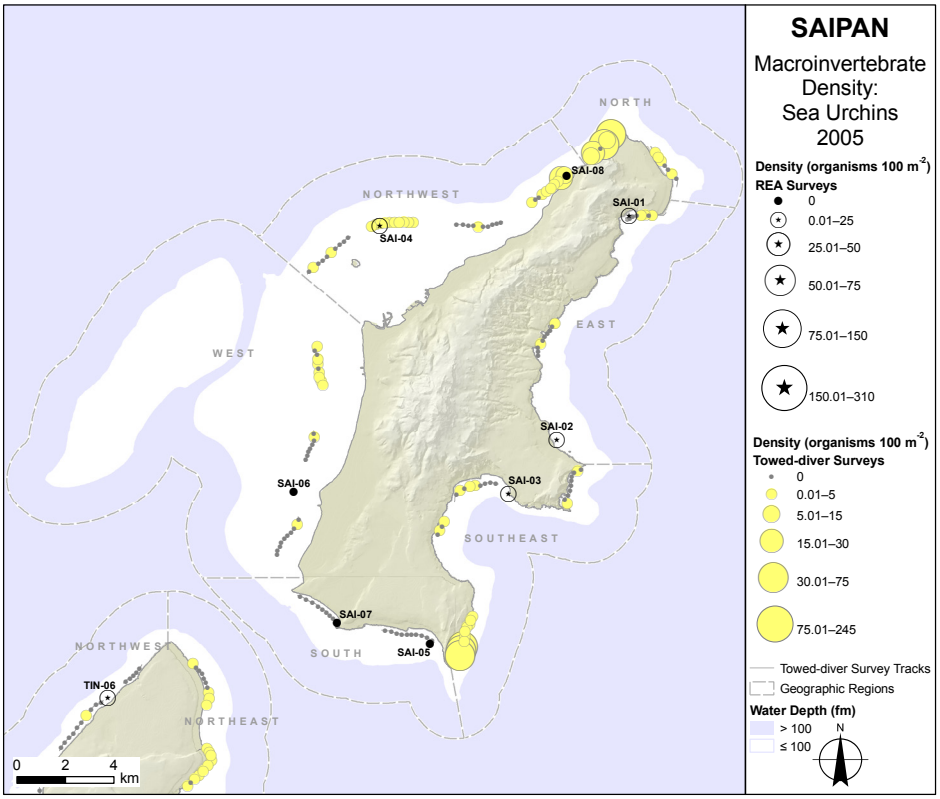


Figure 8.7.1n. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2005.

During MARAMP 2007, sea urchins were observed in all 16 of the towed-diver surveys conducted around Saipan (Fig. 8.7.1o) with an islandwide mean density of 2.3 organisms 100 m^{-2} (SE 0.47). Among all towed-diver surveys around this island, the survey completed near Puntan Sabaneta in the north region had the highest mean density of sea urchins with 15.37 organisms 100 m^{-2}; segment densities from this survey ranged from 2.66 to 38.66 organisms 100 m^{-2}. The

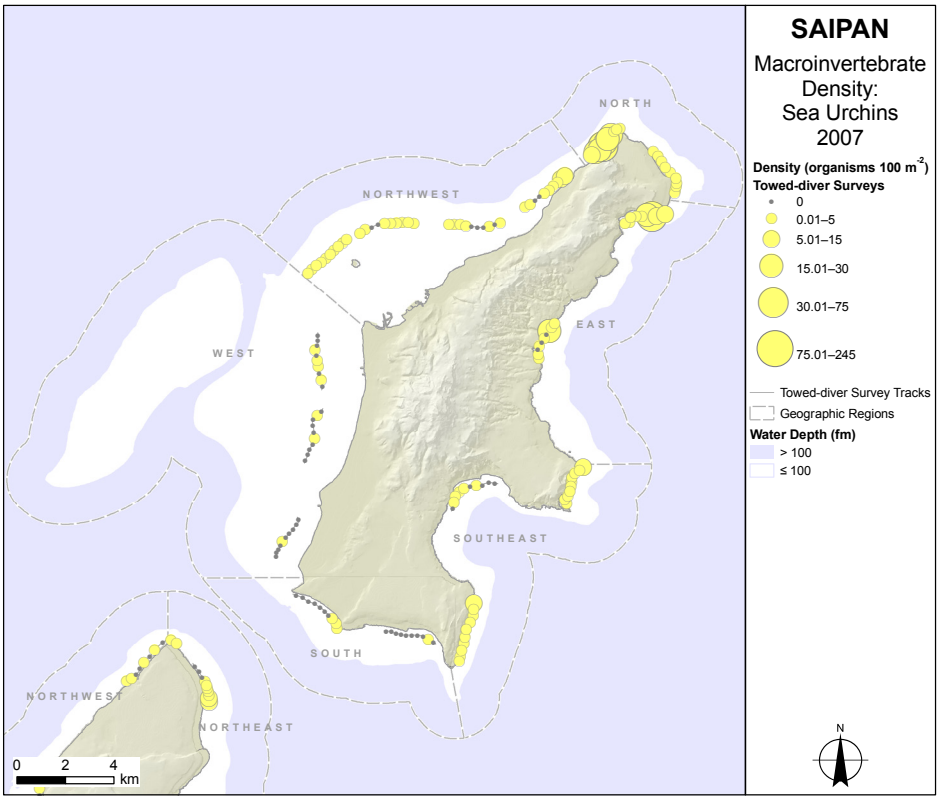


Figure 8.7.1o. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007.

second-greatest mean density of sea urchins from a towed-diver survey was 9.12 organisms 100 m^{-2}, recorded in Bahia Fanonchuluyan in the east region; segment densities ranged from 0.33 to 39.95 organisms 100 m^{-2}. The third-greatest mean density of sea urchins was 2.12 organisms 100 m^{-2}, recorded along Talofo`fo`, Unai in the east region; segment densities ranged from 0 to 20.43 organisms 100 m^{-2}.

Towed-diver surveys suggested low daytime abundance of sea urchins around Saipan, compared to the rest of the Mariana Archipelago, with the exception of the north coast stretching from Puntan Makpe` in the northwest region to Puntan Tangke in the east region. The overall observed mean density of sea urchins from towed-diver surveys was lower in 2003 than in 2007 (Fig. 8.7.1p). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea urchins (For information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

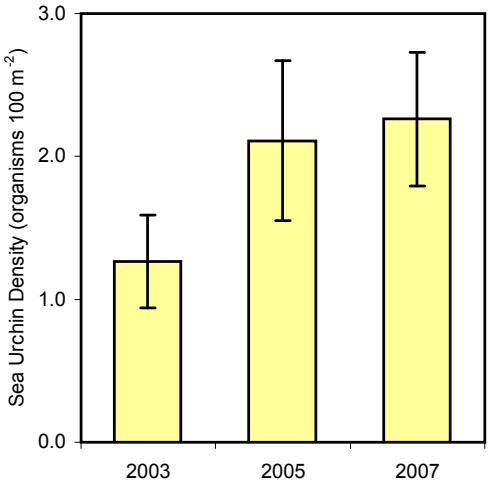


Figure 8.7.1p. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Saipan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

8.8 Reef Fishes

8.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 6 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats at the island of Saipan. The overall estimated mean biomass of large fishes at this island, calculated as weight per unit area, was 0.13 kg 100 m^{-2} (SE 0.06), a low value compared to other survey areas in the Mariana Archipelago. Since surveys were conducted only in the north, east, and southeast regions, it is not possible to discern any clear spatial patterns in the distribution of large-fish biomass (Fig. 8.8.1a). Stingrays accounted for the greatest proportion (51%) of overall mean large-fish biomass with a single porcupine ray (*Urogymnus africanus*) contributing 0.07 kg 100 m^{-2} to overall mean large-fish biomass. Barracudas (Sphyraenidae) composed the second-greatest proportion (23%) or 0.03 kg 100 m^{-2} of overall mean large-fish biomass. Surgeonfishes (Acanthuridae) and parrotfishes (Scaridae) were also common, accounting for 6% and 7% of overall large-fish biomass. The sleek unicornfish (*Naso hexacanthus*) was the major surgeonfish species by biomass, while the ember parrotfish (*Scarus rubroviolaceus*) was the major parrotfish species. Reef sharks (Carcharhinidae) were rarely encountered at Saipan, with a single grey reef shark (*Carcharhinus amblyrhynchos*) observed near Puntan Hakmang in the southeast region.

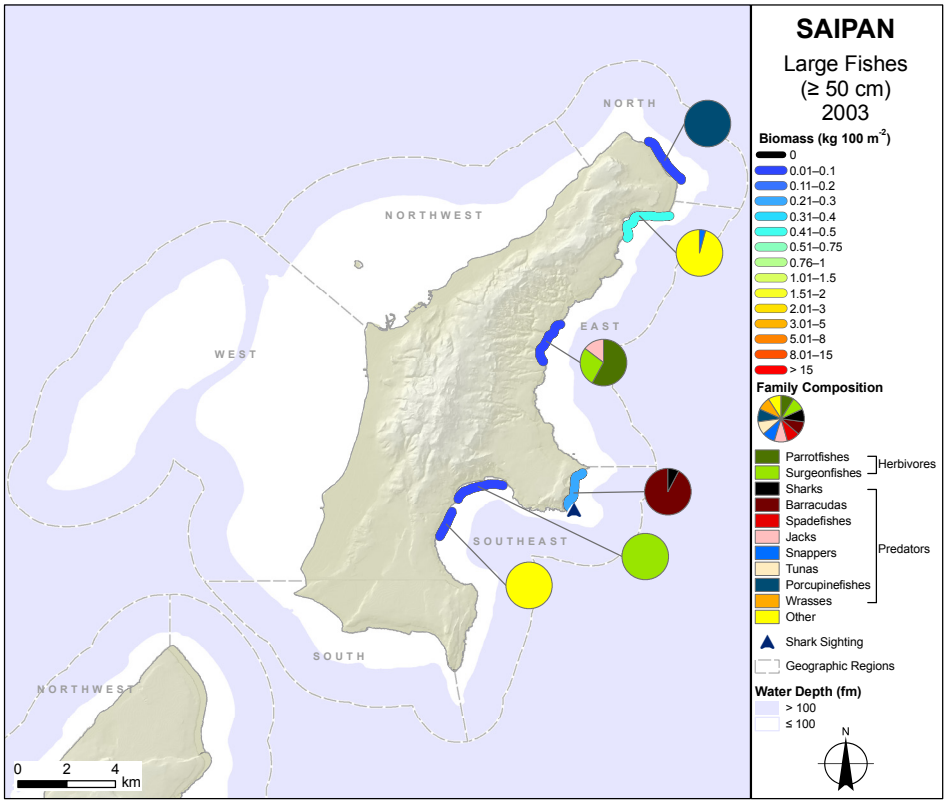


Figure 8.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted at Saipan during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

During MARAMP 2005, 17 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Saipan. The islandwide estimated mean biomass of large fishes was 0.27 kg 100 m^{-2} (SE 0.07), a moderate value compared to other survey areas in the Mariana Archipelago but higher than the biomass observed at Saipan in 2003. Biomass values for large fishes were highest in the west region (Fig. 8.8.1b). Barracudas accounted for the greatest proportion (43%) or

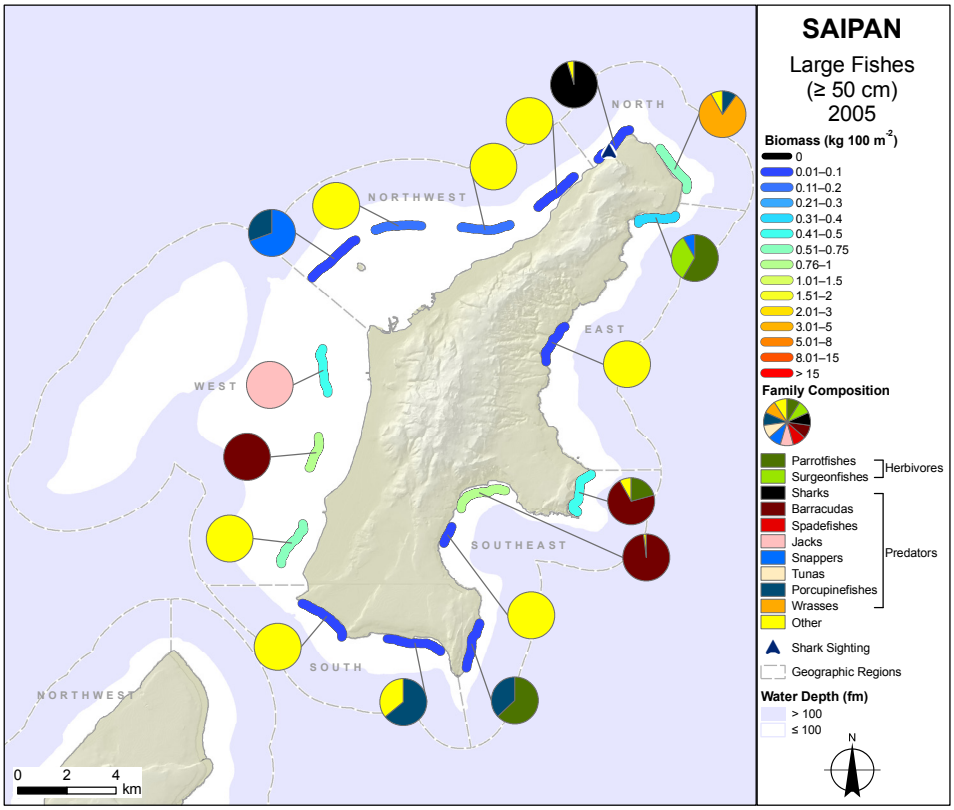


Figure 8.8.1b. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Saipan during MARAMP 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

0.11 kg 100 m^{-2} of islandwide large-fish biomass, with a school of Heller's barracuda (*Sphyraena helleri*) contributing 84% of barracuda biomass. Jacks (Carangidae) composed the second-greatest proportion (10%) of overall large-fish biomass, which was entirely made up by a single school of snubnose pompano (*Trachinotus blochii*) observed during one survey. A single blacktip reef shark (*Carcharhinus melanopterus*) was the only shark observed during towed-diver surveys in 2005.

During MARAMP 2007, 16 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Saipan. The islandwide estimated mean biomass of large fishes was 0.27 kg 100 m^{-2} (SE 0.12), a moderate value compared to other survey areas in the Mariana Archipelago but similar to the biomass observed around Saipan in 2005. Biomass values for large fishes were highest in the east and north regions (Fig. 8.8.1c). Jacks accounted for the greatest proportion (43%) or 0.12 kg 100 m^{-2} of islandwide mean large-fish biomass. The bigeye trevally (*Caranx sexfaciatus*) was the most abundant jack species with a large school observed in the west region. Parrotfishes, wrasses (Labridae), and barracudas were also common, contributing 11%, 8%, and 6% of overall large-fish biomass. The ember parrotfish and the steephead parrotfish (*Chlorurus microrhinos*) were the 2 most abundant parrotfishes in terms of biomass. Near Puntan Laolao Kattan in the southeast region, 1 blacktip reef shark was observed.

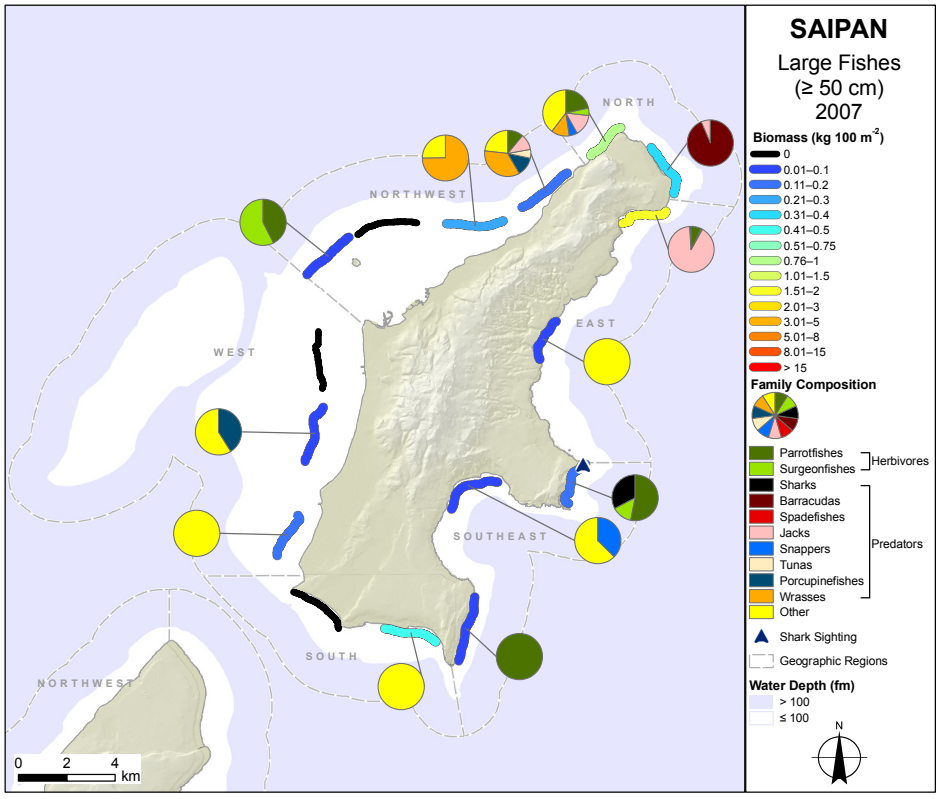


Figure 8.8.1c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Saipan during MARAMP 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

Large-fish biomass from towed-diver surveys of forereef habitats at Saipan was lower during MARAMP 2003 than in subsequent survey periods (Fig. 8.8.1d). This temporal pattern could be a consequence of differences in survey effort and location: only 6 surveys were completed in 2003 and only in the north, east, and southeast regions. During MARAMP 2005 and 2007, islandwide mean large-fish biomass was similar at 0.27 kg 100 m^{-2}; a value close to the average for the 4 southern, populated islands of the Mariana Archipelago. Barracudas, jacks, and parrotfishes contributed large proportions of large-fish biomass around Saipan; however, no single species consistently accounted for a majority of this biomass. Reef shark sightings were infrequent, with only 1 sighting recorded per survey period.

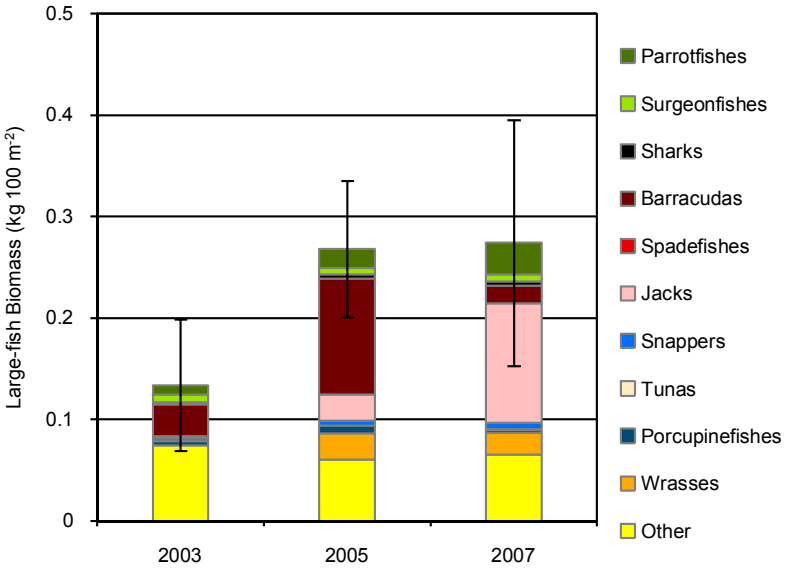


Figure 8.8.1d. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Saipan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Total fish biomass for the 5 REA sites surveyed in forereef habitats at Saipan during MARAMP 2003 was low, compared to other sites in the Mariana Archipelago, with an overall sample mean of 2.51 kg 100 m^{-2} (SE 0.53). The highest biomass of 4.18 kg 100 m^{-2} was observed at SAI-03 in the southeast region (Fig. 8.8.1e). Surgeonfishes accounted for the largest proportion (33%) or 0.84 kg 100 m^{-2} of total fish biomass at Saipan. The 3 major species in terms of biomass in 2003 were the brown surgeonfish (*Acanthurus nigrofuscus*), striated surgeonfish (*Ctenochaetus striatus*) and orangespine unicornfish (*Naso lituratus*). Wrasses and parrotfishes were also common, accounting for 13% and 12% of total fish biomass. No reef sharks were observed during these site-specific fish surveys in 2003.

Based on REA surveys conducted during MARAMP 2003, species richness at Saipan was relatively moderate with a range of 26–38 species 100 m^{-2}. The lowest diversity was seen at SAI-06 in the west region, and the highest diversity was found at

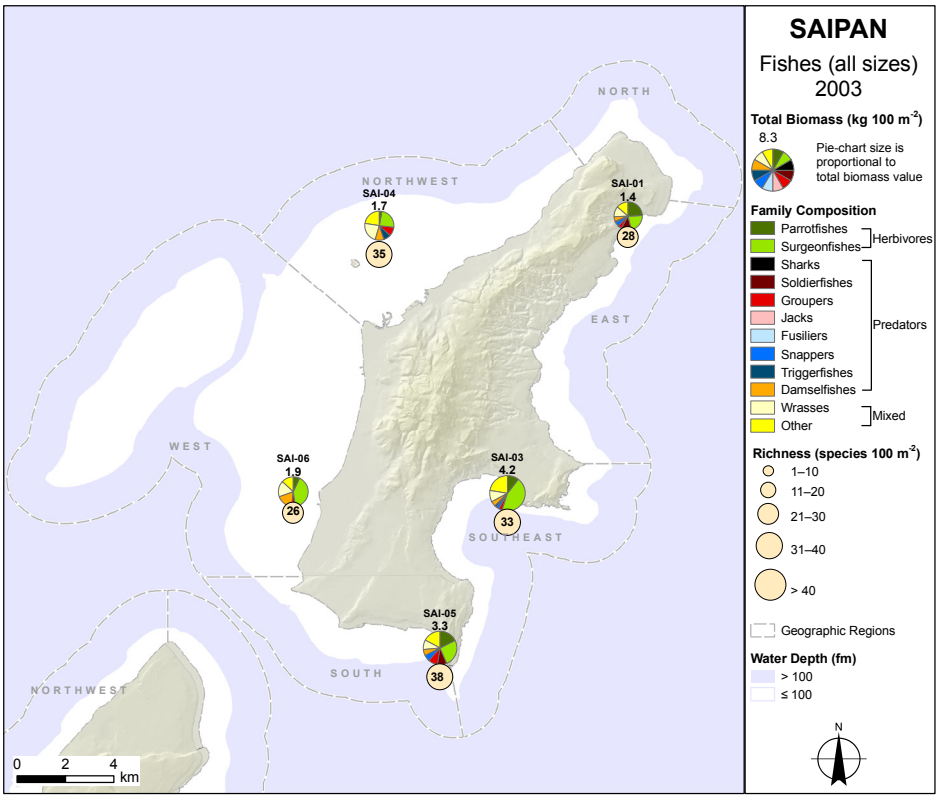


Figure 8.8.1e. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Saipan during MARAMP 2003.

SAI-05 in the south region (Fig. 8.8.1e). Wrasses were observed in the greatest diversity with 23 species recorded in 2003. Katherine's wrasse (*Cirrhilabrus katherinae*) was the most abundant wrasse species. Damselfishes (Pomacentridae) were the most abundant fish taxa overall with the reticulate dascyllus (*Dascyllus reticulatus*) dominating counts with an overall mean density of 34 individuals 100 m^{-2}.

Total fish biomass for the 8 REA sites surveyed in forereef habitats around Saipan during MARAMP 2005 was low, compared to other sites in the Mariana Archipelago, with an overall sample mean of 3.86 kg 100 m^{-2} (SE 1.20). The highest biomass of 11.76 kg 100 m^{-2} was observed at SAI-02 in the east region (Fig. 8.8.1f). Surgeonfishes accounted for the largest proportion (42%) or 1.64 kg 100 m^{-2} of total fish biomass around Saipan with the orangespot surgeonfish contributing 45% of surgeonfish biomass. No large, predatory species, such as jacks and reef sharks, were observed during these site-specific fish surveys in 2005.

Based on REA surveys conducted during MARAMP 2005, species richness around Saipan was moderate and slightly lower than levels observed in 2003 with a range of 20–31 species 100 m^{-2}. The lowest diversity was seen at SAI-08 in the northwest region, and the highest diversity was found at SAI-01 and SAI-07 in the east and south regions (Fig. 8.8.1f). Consistent with observations made in 2003, wrasses were the most diverse family with 26 species recorded around Saipan in 2005. The ornamented wrasse (*Halichoeres ornatissimus*) was the most abundant wrasse species. Damselfishes were the most abundant taxa of fishes overall with the ocellate damselfish (*Pomacentrus vaiuli*) dominating counts with an overall mean density of 47 individuals 100 m^{-2}.

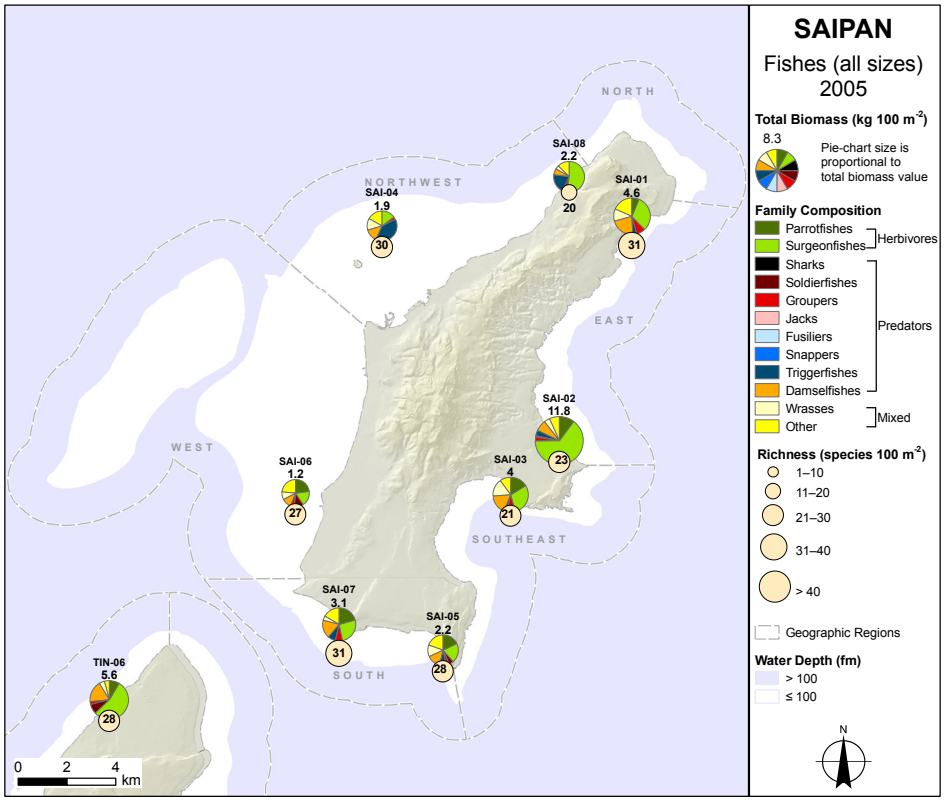


Figure 8.8.1f. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats around Saipan during MARAMP 2005.

Total fish biomass for the 8 REA sites surveyed in forereef habitats around Saipan during MARAMP 2007 was low, compared to other sites in the Mariana Archipelago, with an overall sample mean of 2.07 kg 100 m^{-2} (SE 0.33). The highest biomass of 3.66 kg 100 m^{-2} was found at SAI-01 in the east region (Fig. 8.8.1g). Parrotfishes and surgeonfishes contributed most to biomass: 24% and 18%, respectively. The ember parrotfish accounted for the greatest proportion (37%) of parrotfish biomass, while the striated surgeonfish (*Ctenochaetus striatus*) contributed the greatest proportion (36%) of surgeonfish biomass. Similar to observations made in 2003 and 2005, no large, predatory species such as jacks and reef sharks were observed during these site-specific fish surveys in 2007.

Based on REA surveys conducted during MARAMP 2007, species richness around Saipan varied among REA sites with a range of 14–32 species 100 m^{-2}. The lowest diversity was seen at SAI-08 in the northwest region, while the highest diversity was found at SAI-03 in the southeast region (Fig. 8.8.1g). Wrasses were again the most diverse family with 27 species recorded around Saipan in 2007. The red-lined wrasse (*Halichoeres biocellatus*) was the most abundant wrasse species. Damselfishes dominated counts, and the ocellate damselfish was the most abundant damselfish species with an overall mean density of 24 individuals 100 m^{-2}.

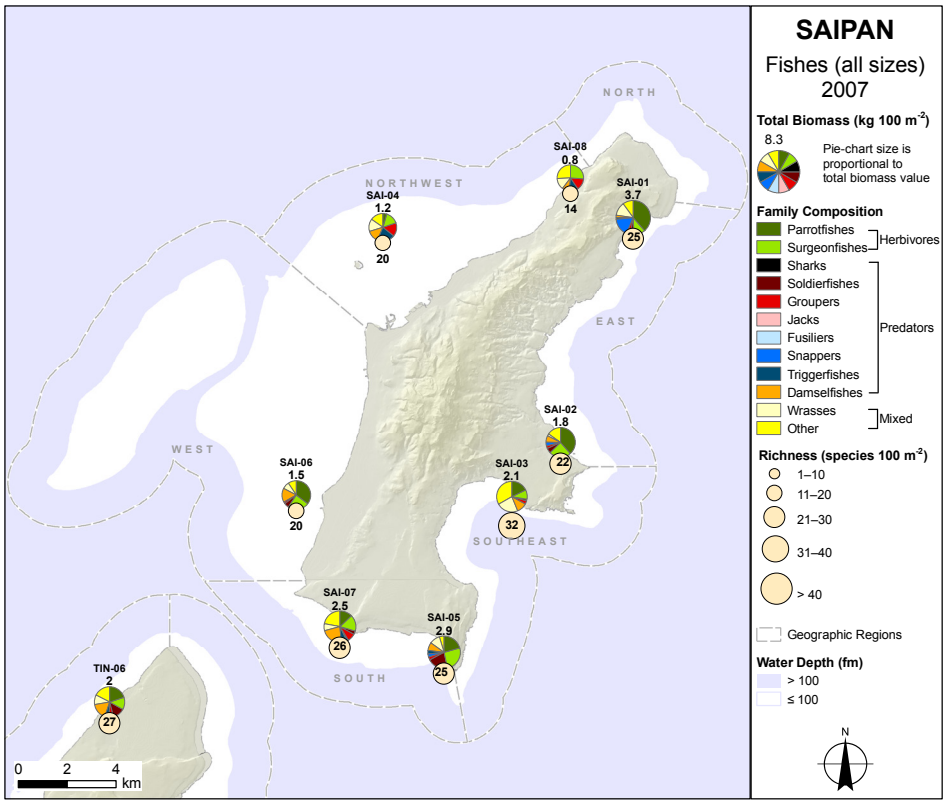


Figure 8.8.1g. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats around Saipan during MARAMP 2007.

During MARAMP 2005 and 2007, total fish biomass in forereef habitats around Saipan was marginally higher in the east region, and in 2003 the highest biomass was observed in the southeast region. As with the other southern islands in the Mariana Archipelago, the dominant families for the 3 MARAMP survey years were surgeonfishes, wrasses, and parrotfishes. Total fish biomass remained fairly consistent from MARAMP 2003 to 2007 (Fig. 8.8.1h) with a mean across the 3

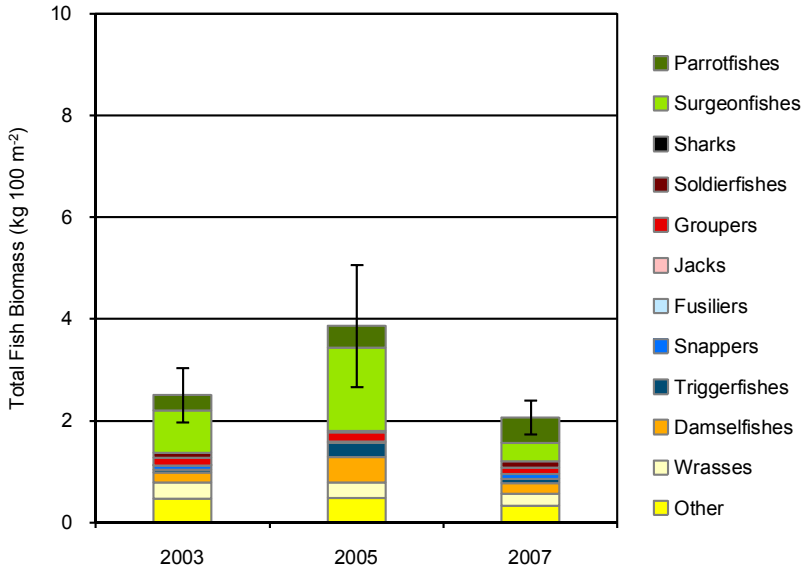


Figure 8.8.1h. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted around Saipan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

years of 2.81 kg 100 m^{-2} (SE 0.54), a value only slightly higher than the lowest average for the Mariana Archipelago, which was recorded around Guam.

Species richness at Saipan was highest during MARAMP 2003 with 32 species 100 m^{-2} and declined to 26 and 23 species 100 m^{-2} during MARAMP 2005 and 2007. A similar pattern was seen around Tinian but not at other islands. The reasons for this apparent decrease in species richness around Saipan are not clear. Overall, species richness around Saipan during all MARAMP surveys was 27 species per 100 m^{-2}, a level comparable to values observed around Tinian and much higher than the diversity seen around Guam. Wrasses were consistently the most diverse family with an average of 25 species observed over the 3 MARAMP survey years. Damselfishes were the most abundant taxa of fishes overall and dominated counts in each of the 3 survey periods.

8.9 Marine Debris

8.9.1 Marine Debris Surveys

During MARAMP 2003, no sightings of marine debris were recorded in the 6 towed-diver surveys conducted on forereef habitats at the island of Saipan.

During MARAMP 2005, 1 piece of unexploded munition and 2 sightings of other man-made objects were recorded in the 17 towed-diver surveys conducted on forereef habitats around Saipan (Fig. 8.9.1a). In the west region, 1 pipe that hosted a large amount of coral growth was noted south of Puntan Susupi (for place-names and their locations, see Fig. 8.2a in Section 8.2: "Survey Effort"). A mooring anchor consisting of a toppled block with ground tackle was observed in the northern pat of Garapan Anchorage. Finally, a munition was observed northeast of Isleta Managaha in the northwest region. This munition site appears to be well known, as it is marked on readily available NOAA charts. No derelict fishing gear or wrecks were identified.

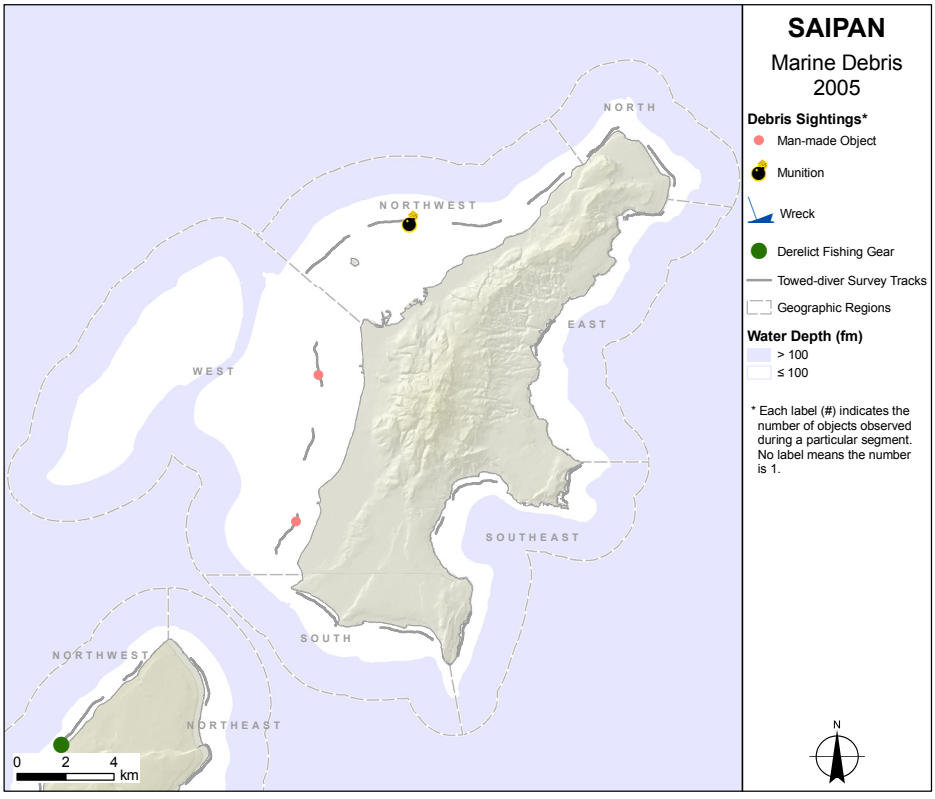


Figure 8.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2005. Symbols indicate the presence of specific debris types.

During MARAMP 2007, 1 sighting of derelict fishing gear, 1 munition sighting, and 2 sightings of other man-made objects were recorded in the 16 towed-diver surveys conducted on forereef habitats around Saipan (Fig. 8.9.1b). A fishing net was seen near Puntan Laolao Kattan in the southeast region. The 2 sightings of man-made objects were an anchor in the

west region adjacent to Lagunan Garapan and a mooring, including a ball and line, in the northwest region. As in previous MARAMP survey years, a munition sighting was recorded in the northwest region northeast of Isleta Managaha. No wrecks were identified.

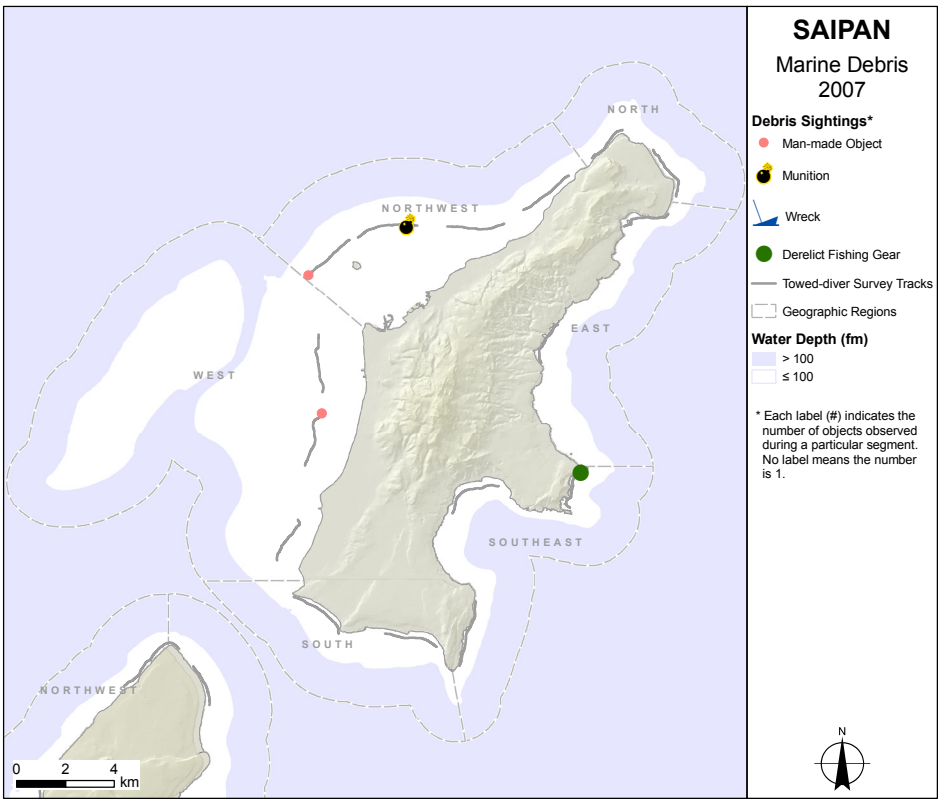


Figure 8.9.1b. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Saipan during MARAMP 2007. Symbols indicate the presence of specific debris types.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments. Still, the location of the munition sighting in the northwest region, northeast of Isleta Managaha, was the same in 2005 and 2007.

8.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Saipan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. Biological information from towed-diver surveys was integrated to derive 3 composite indices that provide assessments of the relative ecological conditions of forereef habitats in the 4 populated, southern islands of Saipan, Tinian, Rota, and Guam.

The *Benthic Condition Index for Guam, Rota, Tinian, and Saipan* was derived by equally weighting observations of the following 5 parameters from towed-diver benthic surveys around these 4 islands: cover of live hard corals, stressed corals, macroalgae, and crustose coralline red algae and density of (COTS). The *Fish Condition Index for Guam, Rota, Tinian, and Saipan* was derived from 2 equally weighted parameters from towed-diver fish surveys: density and biomass of large fishes (≥ 50 cm in TL). The overall *Coral Reef Condition Index for Guam, Rota, Tinian, and Saipan* was derived from an equal weighting of these benthic and fish indices. These condition indices were calculated using ranks assigned to the biological variables from towed-diver surveys conducted around Saipan, relative to all surveys performed around the 4 populated, southern islands of Saipan, Tinian, Rota, and Guam for each survey year. To indicate changes in these ranks between survey years, these indices were visualized on a map within survey areas, which are represented by color-coded

and irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007 (towed-diver-survey tracks were often similar but not exactly the same in each survey year). For more details about the methodology behind these indices, see Chapter 2: "Methods and Operational Background," Section 2.5: "Ecosystem Integration." Each of these 3 condition indices is presented for Saipan on a map in Figure 8.10b. Reef condition indices for the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," providing ranks for Saipan as well as the other 13 islands covered in this report.

Comparison of Western and Eastern Habitats

The distribution of anthropogenic pressures around Saipan shows an east–west gradient, with the highest levels of human activities with the potential to affect coral ecosystems occurring along the west coast of Saipan. The majority of the resident population of Saipan is located on the west coast, and this shoreline also has the most intensive tourist development with associated recreational activities, such as scuba diving and water sports (Fig. 8.1.2a in Section 8.1.2: "Land Use"). In addition, locations along the west coast have suffered from water-quality issues because of point source pollution, from sources such as sewage outfalls and discharge of hypersaline and nutrient-enriched wastewater from reverse osmosis units used by some facilities that cater to tourists, and because of nonpoint source pollution like runoff during storms (Starmer et al. 2005). The CNMI beach water-quality monitoring program revealed that many beach locations within the Lagunan Garapan (from Puntan Achugao south to Puntan Susupi), and to a lesser extent locations on the southwest coast, failed to meet required water-quality standards. In most cases, elevated bacterial levels were thought to be associated with sewage system failures, which could also result in the delivery of high levels of nutrients to lagoon waters (Bearden et al. 2008).

Despite the apparent anthropogenic impacts occurring on the west side of Saipan, the distribution of live hard corals around this island suggests that, in general, average coral cover was higher on western forereef habitats than on eastern habitats (Fig. 8.10a). Mean cover of live corals for the northwest and west regions was 18% and 14% in 2005 and 2007, compared with a mean of 5% and 7% for all other regions. Results from 3 towed-diver surveys stand out as having the highest levels of coral cover at Saipan. One survey, located in the northwest region just south of Puntan Makpe`, characterized the benthos as moderately sloped, continuous reef of medium complexity. The other 2 surveys, conducted in the northern part of the west region parallel to the Lagunan Garapan, recorded medium complexity continuous reef, which shifted to medium-low complexity patch reefs as surveys progressed from south to north.

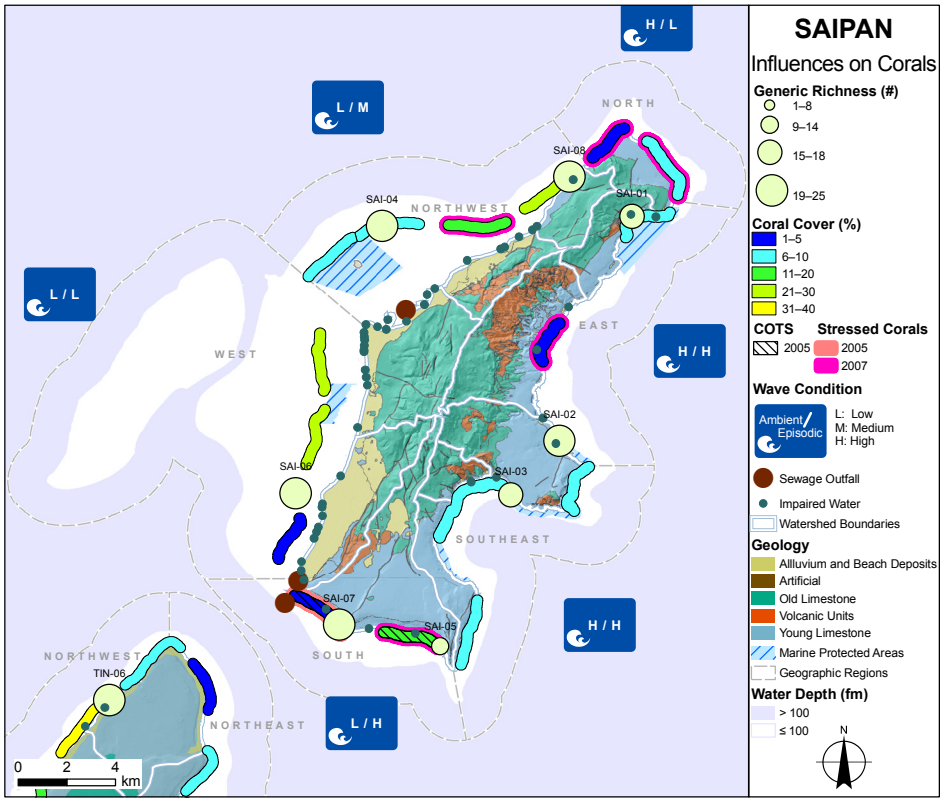


Figure 8.10a. Cover (%) observations of live and stressed corals from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Saipan during MARAMP 2005 and 2007, presented with geology, watersheds, impaired water sites, and other factors (Carruth 2003; M Pangelinan, CNMI Department of Land and Natural Resources, pers. comm.; Bearden et al. 2008). Values of coral cover and generic richness represent averages of data from both survey years, where available; otherwise values represent data from the single year surveyed. Towed-diver-survey areas combine overlapping survey tracks for both MARAMP survey years. Colored outlines represent areas where estimates of stressed-coral cover were > 10%, and diagonal lines indicate areas where COTS density was > 0.15 organisms 100 m^{-2}. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.

Variation in the benthic communities at Saipan may be related to the different geological, topographic, and oceanographic characteristics of the 2 sides of Saipan. West of Saipan, the distribution of marine habitats is influenced by the presence of 2 extensive, shallow shelves. The most westerly of the these shelves provides a shallow platform, located at depths of 30–40 m and covering an area of ~ 20 km^2. This bank is surrounded by steep slopes that descend to > 200 m. The easterly shelf is located at depths of 20–40 m, covers an area of ~ 30 km^2, and abuts the shallow Lagunan Garapan that runs along much of the southwestern coastline. This inner shelf continues around the rest of Saipan, albeit in much narrower form. In combination, these 2 shelf areas provide an extensive area of shallow, hard substrate suitable for coral reef development. In contrast, no such extensive shallow areas are present to the north, east, or south of Saipan. Where a shallow shelf is present, it is very narrow, increasing in width only within embayments. This pattern is highlighted in the map of benthic zones, which shows the lack of flat zones (Fig 8.3.1f in Section 8.3: "Benthic Mapping and Characterization"). South of Saipan, the seafloor slopes gradually to a depth of 50 m less than 1 km from the coast. Southeast of Saipan, the shelf is even narrower, with the edge lying at a depth of 20 m less than 300 m from the shore. East of Saipan, terraces at depths of 20 m and 30 m are within 300 m of the shore. North of Saipan, the shelf is slightly more extensive, with a series of terraces at depths of 20 m, 50 m, and 60 m. At the northern points of Saipan, these features extend a little farther from the coast (e.g., the terrace at a depth of 40 m is ~ 500 m offshore), forming submarine peninsulas with the terraced platforms reflecting previous sea levels. This lack of large shallow areas in these regions around Saipan limits the habitat suitable for reef development.

In addition to the reduced availability of suitable substrate for coral reef development, habitats east of Saipan are subject to greater exposure to wind and wave energy than are habitats in the west, both in terms of ambient wave energy and episodic high-energy events like typhoons (Fig. 8.10a). Some studies have suggested that high-energy environments can favor development of reefs with low coral cover dominated by small, robust colonies (Storlazzi et al. 2001).

Although levels of live coral cover were lower on forereef habitats east of Saipan than on habitats west of this island, the benthic communities in most survey areas appeared to be in good condition in 2007, with medium or high ranks for surveys in the east and southeast regions in the calculated *Benthic Condition Index* for Guam, Rota, Tinian, and Saipan (Fig. 8.10b). These ranks suggest that the relatively low coral cover in these areas may reflect the natural character of the reefs there, because of the geological, topographic, and oceanographic factors described previously, and may not result from human activities.

Similarly, the east–west pattern described previously did not appear to influence fish communities at Saipan, where survey results were mixed between survey locations, years, and techniques (Fig. 8.10c).

Garapan Anchorage

The 2 extensive shelf areas are unique features to Saipan and form the Garapan Anchorage, which is an area of particular management interest because of the anticipated expansion of anchorage areas to support the proposed increase of military activity in the CNMI. Acoustic mapping of this area revealed an interesting topography on the bank tops, which are characterized by a complex mosaic of channels and mounds, interpreted to be coral mounds. At the request of the Department of Defense, CRED conducted additional surveys to provide a comprehensive map of areas of high coral cover or other biological significance. Extensive optical surveys using the TOAD were done, and their results were used to provide an interpolated map of live coral cover (Fig. 8.3.3c in Section 8.3: "Benthic Mapping and Characterization") and locations of sand basins (Fig. 8.3.3a), covering the entire anchorage area. Results from both towed-diver surveys and analyses of TOAD video footage show an area of high coral cover along the eastern edge of the inner anchorage, adjacent to the Lagunan Garapan. These results also are illustrated in the *Coral Reef Condition Index* (Fig. 8.10b), analysis that highlights 2 towed-diver surveys completed along the edge of this lagoon. These 2 survey areas had high ranks in the *Benthic Condition Index* in both 2005 and 2007, a reflection of the high cover values for live corals and crustose coralline red algae, relative to cover levels for macroalgae.

In addition to the numerous patches of high coral cover observed during towed-diver surveys in the inner anchorage area, analyses of video footage from TOAD surveys identified significant coral resources in deeper waters. The highest levels of live coral cover were recorded in the depth range of 61–70 m, at least as seen in a majority of images, with average cover of live corals > 60%. These data suggest the presence of important coral communities in both shallow and deep waters, and the value associated with the planning of future anchorage sites to minimize affects on coral reef ecosystems. These results highlight the importance of monitoring at the full range of depths in which coral communities may be present to ensure that managers of coral reef resources are informed of important mesophotic coral communities.

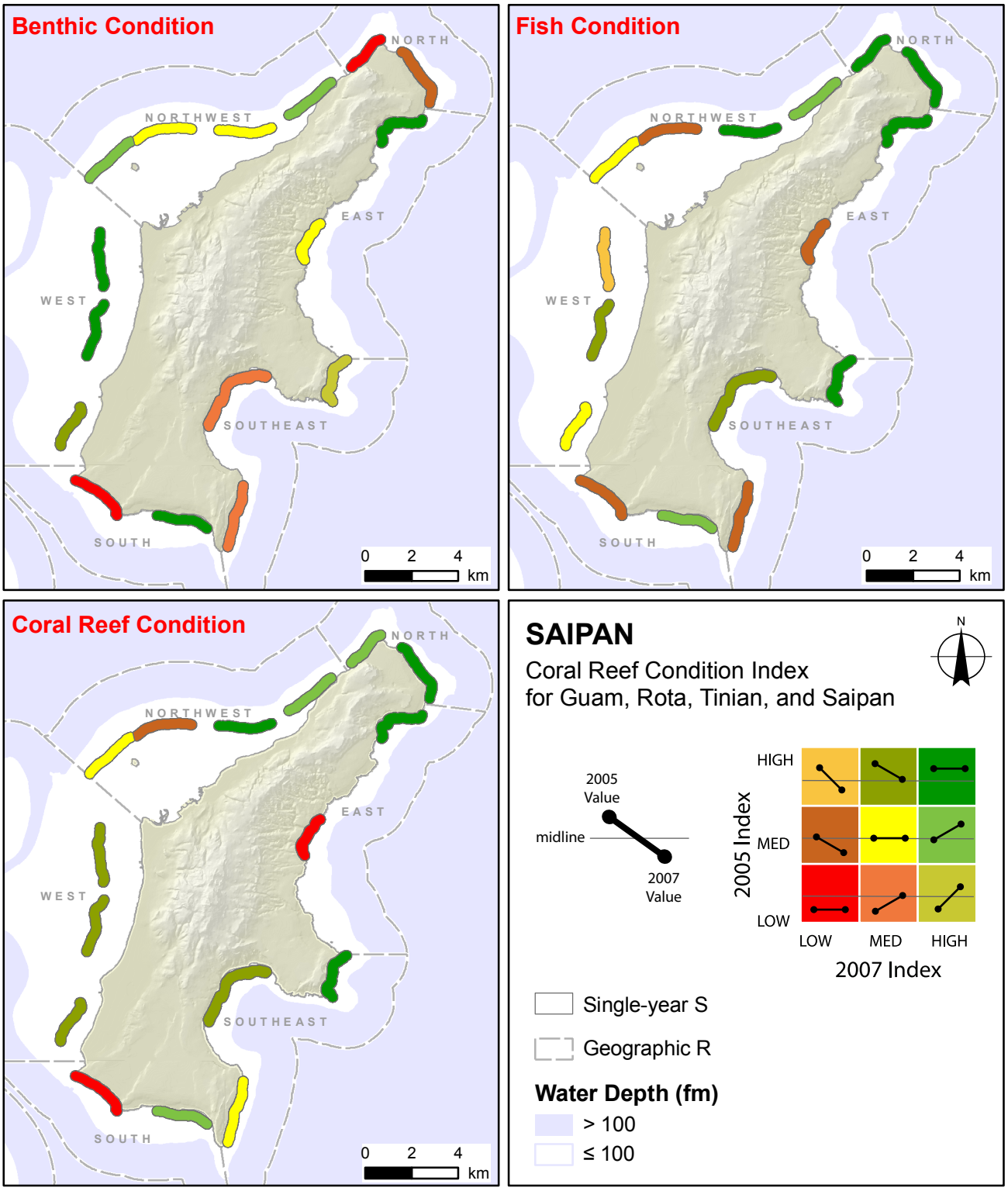


Figure 8.10b. The *Coral Reef Condition Index* for Guam, Rota, Tinian, and Saipan, as well as the associated *Benthic Condition Index* and *Fish Condition Index*, reflect the condition of the benthic and fish communities and their integrated ecosystem for each towed-diver-survey area, *relative to other survey areas around the 4 populated, southern islands*. These maps indicate changes in index ranks between MARAMP 2005 and 2007 for towed-diver-survey areas around Saipan. Survey areas are represented by irregular polygonal buffers derived from towed-diver-survey tracks that overlapped in 2005 and 2007. No index value is calculated for areas with only one year of survey data. A high rank means superior condition relative to other survey areas around the 4 populated, southern islands. The survey area along the northern coast of Saipan, for example, has a high rank for both 2005 (y-axis) and 2007 (x-axis) and, thus, is assigned the bright-green color that corresponds to the top-right square in the legend. The position of the horizontal bar above the midline in this square also reflects that this survey area maintained a high rank in both years.

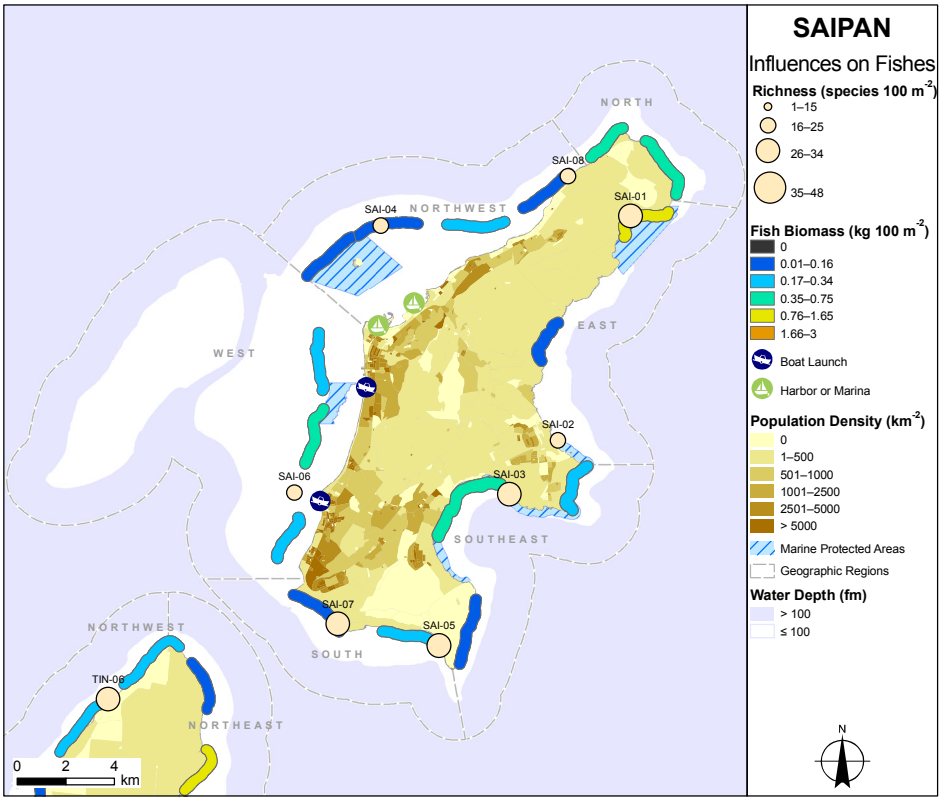


Figure 8.10c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver surveys and species richness from REA fish surveys conducted on forereef habitats around Saipan during MARAMP 2005 and 2007, presented over a map of human population density (U.S. Bureau of the Census 2003, 2008). Biomass and richness values represent averages of data from both survey years, but, if surveys were conducted during one year only, then values represent data from that single year. Towed-diver-survey areas combine overlapping survey tracks for both MARAMP survey years; survey tracks are often similar but not necessarily the same between survey years.

Bahia LaoLao and Bird Island Sea Cucumber Reserve

An area of particular interest in the southeast region is Bahia Laolao, also known as Laulau Bay. This area supported some of the highest levels of live coral cover recorded by towed divers in 2003. However, coral cover was generally recorded at the same low level observed elsewhere around Saipan in 2005 and 2007. Coral cover was 6%–10% from towed-divers surveys on either side of the Bay, a range similar to the islandwide means of 11% in 2005 and 10% in 2007.

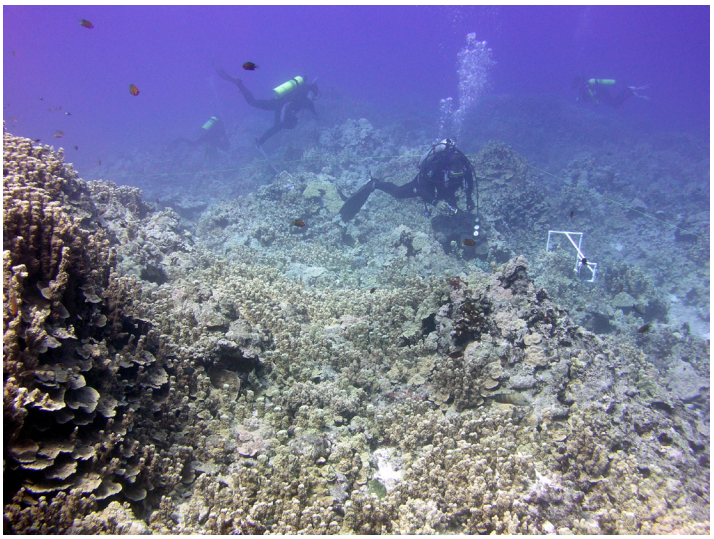


Figure 8.10d. REA divers surveying *Porites rus*-dominant SAI-03 site. *NOAA photo by Robert Schroeder*

One segment of a towed-diver survey conducted in Bahia Laolao in 2007 recorded mean coral cover of 35% in an area notable for having the highest habitat complexity observed within this bay. Located ~ 600 m from this survey segment, REA site SAI-03 in 2007 had coral cover of 20%, one of the highest levels of coral cover recorded at Saipan REA sites (Fig. 8.10d). These results suggest a degree of local patchiness in the coral cover within this bay that is characterized by complex and varied habitats.

Overall, benthic conditions in Bahia Laolao were low in 2005, with low values of coral cover and high levels of macroalgal cover observed during towed-diver surveys in some areas in this bay (Fig. 8.10a). Low densities of COTS were observed throughout the bay during the 3 MARAMP survey years, while cover of stressed corals was recorded at > 10% in several segments of towed-diver surveys. High macroalgal cover was observed by towed divers during the 3 MARAMP survey years. In 2005, the highest macroalgal cover observed around Saipan was recorded south of Tuturam, with a mean macoralgal cover of 69%, com-

pared to the islandwide mean of 31%. Finally, it is important to note that persistent, high macroalgal cover in Bahia Laolao was recorded during seasonal precipitation peaks (MARAMP 2003 and 2005) and lows (MARAMP 2007). Although it is hypothesized that high macroalgal cover indicates a degraded reef system in this area, if no historical records of high coral cover exist, it is not possible to determine with certainty that this area ever exhibited a high percentage of cover of hard coral species. High macroalgal cover may represent the natural state.

If high macroalgal cover is a recent development, it may be a result of water-quality issues that are known to affect this area. Poor water quality usually coincides with increased nutrients, which can favor the faster-growing algae over coral colonies in the competition for space. Independent surveys by the CNMI Department of Enviornmental Quality also have noted poor reef conditions in this area (Bearden et al. 2008). When examining oceanographic data collected by CRED through shallow-water (≤ 30 m) CTD casts during MARAMP 2003, elevated temperatures were coupled against lower densities and salinities at sampling locations to the north and south of Bahia Laolao, verus results from other sampling locations at Saipan, possibly a result of terrigenous inputs associated with increased seasonal precipitation. Two shallow-water casts completed in 2007 along the interior of this bay yielded comparable results despite seasonally low precipitation. Additionally, strong tidal currents across the Mariana Ridge may cause mixing in the southeast and northeast regions around Saipan. This mixing may lead to some additional nutrient enrichment of surface waters in Bahia Laolao, relative to other areas around Saipan.

Bahia Laolao is a marine protected area, which was originally designated for the protection of sea cucumbers in 2000, following several years of over-harvesting (CNMI Public Law 11-63; Trianni 2000). Some of the highest densities of sea cucumbers observed during towed-diver surveys were recorded here in 2003. In contrast, towed-diver surveys in 2005 and 2007 recorded sea cucumber densities that were fairly low in comparison to results in other survey areas around Saipan. This decline could be a result of natural variation in the populations present, but because sea cucumbers are the focal species of this reserve, the apparent decline could be a potential cause for concern.

A second marine reserve designated in 2000 for the protection of sea cucumbers, the Bird Island Sea Cucumber Reserve is located in Bahia Fanonchuluyan in the northeast region. This sea cucumber reserve is nested within the larger Bird Island Marine Sanctuary, which was designated in 2001. The highest densities of sea cucumbers recorded at Saipan in 2005 and 2007 and the second-highest densities in 2003 were observed during towed-diver surveys in this bay. In both 2003 and 2007, the greatest densities recorded during REA benthic surveys were observed at SAI-01, also within Bahia Fanonchuluyan. Sea cucumbers were most commonly encountered in habitats of hard-substrate reef, with rubble and boulders, that also supported high numbers of sea urchins. Cracks and crevices within the reef matrix, coupled with areas of vertical walls increased localized habitat complexity. The high densities of sea cucumbers observed here relative to other parts of Saipan may be evidence of successful management actions to protect and recover this previously depleted resource.

Crown-of-thorns Seastars

During MARAMP 2005, towed-diver surveys recorded COTS in high abundance in the south region of Saipan with densities of up to 20 organisms 100 m^{-2} (Fig. 8.10e). This region is an area of a potential outbreak, according to the definitions presented in Section 8.7: "Benthic Macroinvertebrates." Towed-diver surveys in 2005 in the south region also recorded very low live coral cover, within a range of 0.1%–5% from the survey completed between Puntans Agingan and Opyan, where stressed-coral cover also was recorded, and within a range of 5.1%–30% from the survey completed between Puntans Opyan and I Naftan. Similar levels of coral cover were recorded during MARAMP 2007, except that values for stressed-coral cover were elevated between Puntans Opyan and I Naftan. However, few COTS were observed in 2007, in comparison with results from 2005, reflecting the extreme variability and potentially



Figure 8.10e. A COTS seen on a reef off southern Saipan. *NOAA photo by Kevin Lino*

cryptic nature of these organisms. Diver observations in this region also noted that COTS were seen in areas where the benthos was composed of large, flat pavement, an atypical environment for COTS, which are usually seen in areas with live or distressed corals. In areas where corals were observed, divers noted that corals were subject to a large amount of predation from COTS.

8.11 Summary

This section presents an overview of the status of coral reef ecosystems around the island of Saipan and some of the key natural processes and anthropogenic activities influencing them. MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along forereef habitats around Saipan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Saipan chapter are included in the appropriate discipline sections. One noteworthy limitation, for example, is the focus of MARAMP observations on forereef habitats to the exclusion of the many shallow backreef flats around Saipan. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter.

To simplify interpretation of ecosystem conditions around Saipan, a *Benthic Condition Index*, a *Fish Condition Index*, and an integrated *Coral Reef Condition Index* were developed to reflect ecosystem conditions at specific locations around Saipan, relative to locations around the 4 populated, southern islands of Guam, Rota, Tinian, and Saipan and based on MARAMP 2005 and 2007 surveys only (see Section 8.10: "Ecosystem Integration"). By synthesizing large amounts of complex, interdisciplinary information, these reef condition indices assist resource managers in identifying potential relationships between various ecosystem components. The conditions of the fish and benthic communities and the overall ecosystem around Saipan, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

The following summary highlights key attributes of the coral reef ecosystems around Saipan (for place-names and their locations, see Fig. 8.2a in Section 8.2: "Survey Effort"):

- Saipan has 90% of the total CNMI population. As a result of the development and tourism on the west coast of Saipan, this area has suffered from water-quality problems.

- Two large, submerged, flat banks extend (1) ~ 10 km to the west of Saipan and (2) from the Saipan Harbor area in the north to the southern shore of this island. These 2 banks are used as the primary anchorage for commercial and military vessels in the CNMI.

- Only a few streams exist on Saipan, and they are located to the west of Okso` Talufo`fo and Okso` Achugao along the northeast coast of this island.

- Benthic habitats on the east coast of Saipan have a reduced availability of suitable substrate for coral reef development because of the absence of the broad shelves found along the west coast. Habitats east of Saipan also are exposed to considerable wind and wave energy.

- Wave model output shows typical trade wind swells from the north and east and high wave energy from storm tracks from the southeast.

- STR and satellite-derived (Pathfinder) SST data show that temperatures surpassed the bleaching threshold for a brief period in September 2006.

- Interestingly, results from towed-diver surveys show that mean cover of live hard corals was higher on the west coast of Saipan than in other areas around this island, despite anthropogenic impacts from resident populations and tourist visits. This pattern is likely a result of greater habitat availability for reef development and shelter from wave energy on the west coast.

- Overall mean coral-colony density for Saipan, based on REA surveys, was substantially higher in 2003 with

28.9 colonies m^{-2} than in 2005 with 49 colonies m^{-2}. This increase was observed at all 3 sites surveyed in these years and could be a result of recruitment, fragmentation of existing colonies, or both.

- The level of coral disease, recorded during REA surveys in 2007, was low around Saipan, compared to other surveyed areas in the Mariana Archipelago, with a mean overall prevalence of 0.4%. Coral bleaching was mild and localized with an overall mean prevalence around Saipan of only 0.03%; affected colonies were mainly observed in the west region. Stressed-coral cover, recorded during towed-diver surveys, was absent in 2003, low in 2005, and more widespread in 2007. High numbers of crown-of-thorns seastars (COTS), relative to other areas surveyed in the Mariana Archipelago, were observed during towed-diver surveys in 2003 and 2005. Localized areas that may have been undergoing an outbreak included areas near Puntans Laolao Kattan and Hakmang in the southeast region in 2003 and Puntans Unai Opyan and Agingan in the south region in 2005. However, by 2007, observed COTS densities were low in these areas.

- Three major coralline-algal diseases were recorded around Saipan in 2007: coralline lethal orange disease, coralline white band syndrome, and coralline cyanobacterial disease. Coralline lethal orange disease was the most numerous overall around Saipan.

- An area of high coral cover, compared to other areas survyed at Saipan, was recorded by towed divers on the east side of the inner bank of Garapan Anchorage. In the *Benthic Condition Index* for Guam, Rota, Tinian, and Saipan, the edge of this lagoon had a high rank in both 2005 and 2007. Results from analyses of TOAD video footage suggest that live coral cover was > 60% at depths of 61–70 m around this anchorage area. This area is of particular interest because of the anticipated expansion of anchorage areas with the proposed increase in military activity in the CNMI.

- Densities of giant clams were generally low at Saipan during all survey years, compared to results for the rest of the Mariana Archipelago. Abundance was greatest along the eastern half of Saipan. Sea cucumbers and sea urchins were fairly ubiquitous around this island during all years.

- Areas with high macroalgal cover, relative to other survey areas in the Mariana Archipelago, were recorded during towed-diver surveys in all 3 MARAMP survey years. In 2003, in the north region east of Puntan Sabaneta, macroalgal cover was 76%. In 2005, macroalgal cover was highest (69%) in the southern part of Bahia Laolao in the southeast region, and, in 2007, northwest of Isleta Managaha in the northwest region, macroalgal cover was 68%. The highest cover of crustose coralline red algae (> 20%) from towed-diver surveys at Saipan was in Bahia Fanonchuluyan in the east region in 2003 and 2007 and off Isleta Managaha in 2005 and 2007.

- Bahia Laolao had relatively low coral cover, compared to the rest of the Mariana Archipelago, over the 3 MARAMP survey periods, as well as high macroalgal cover, giving it a low rank in the *Benthic Condition Index*. This bay has been known to have poor water quality. An area of mass wasting (landslides and erosion) is located in the center of this bay. Bahia Laolao is a marine protected area for sea cucumbers; however, densities there were low, compared to densities recorded in other regions, in 2005 and 2007, a condition that may be a cause for concern for local managers.

- Bird Island Sea Cucumber Reserve, located in Bahia Fanonchuluyan on the northeast coast of Saipan, is also a marine protected area for sea cucumbers. This area had the highest densities of sea cucumbers around this entire island in 2005 and 2007 and the second-highest densities in 2003, suggesting successful management of this previously depleated fishery.

- Large-fish biomass at Saipan, based on towed-diver surveys, was low in 2003 and moderate in 2005 and 2007, relative to other areas surveyed in the Mariana Archipelago. Biomass of large fishes in 2005 was greater in the west region than in other regions, although moderate large-fish biomass was observed in Bahia Laolao and along the northern tip of Saipan. Surveys in the west region in 2007 recorded very low biomass, compared to other regions, with either no or only a few individual fishes observed per survey. In 2007, the greatest large-fish biomass was observed during a survey in the north region southwest of Puntan Sabaneta. Similarly, compared to REA survey results at other islands of the Mariana Archipelago, total fish biomass was low and species richness was moderate for Saipan in all MARAMP survey years.

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9 ANATAHAN

9.1 Introduction

The island of Anatahan, located at ~ 16°21′ N and 145°40′ E, is the southernmost island of the Northern Islands Municipality of the Commonwealth of the Northern Mariana Islands (CNMI). This island is situated 120 km north of Saipan and 40 km south of Sarigan. Elongated east–west, Anatahan is ~ 3 km wide and 9 km long with a land area of 33.91 km^2 (Fig. 9.1a). A compound summit caldera, formed by at least 3 craters, dominates Anatahan. The highest point, at an elevation of 788 m, is on the western rim of the west caldera. The calderas of Anatahan are surrounded by steeply sloping flanks (Fig. 9.1b), which continue for some distance underwater. Northeast of this island, a submarine volcano known as NE Anatahan rises to a depth of 460 m below the sea surface. Although previously inhabited, Anatahan currently has no permanent residents. This island was declared off limits because of volcanic activity that has been ongoing since the first known eruption in May 2003.

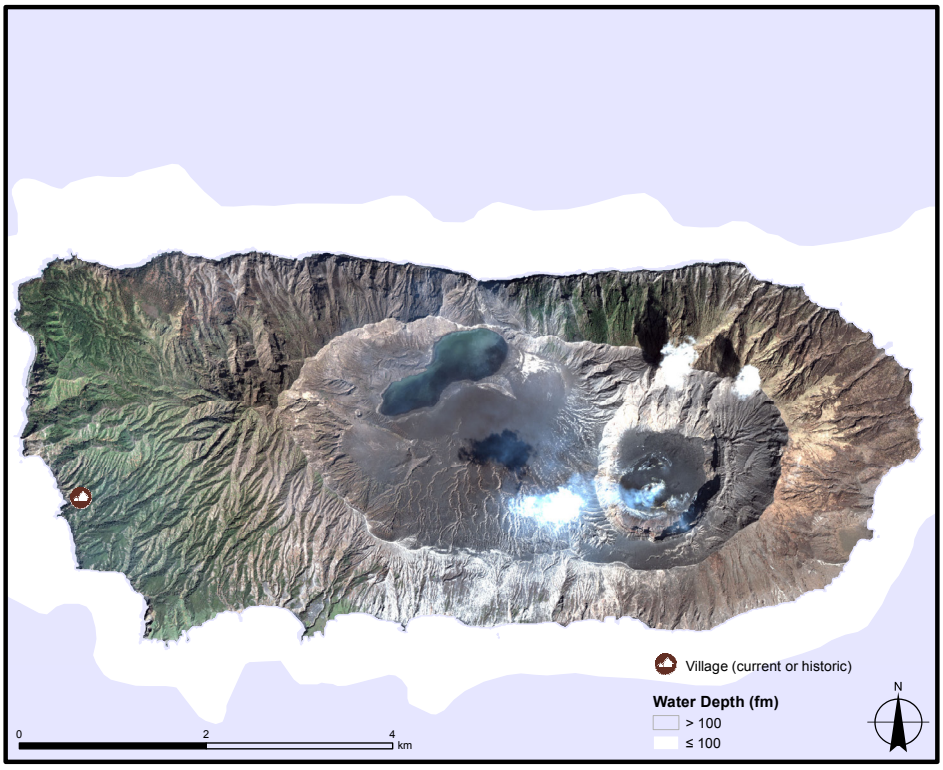


Figure 9.1a. Satellite image of Anatahan, labeled to show the historic village near the west coast (© 2005 DigitalGlobe Inc. All rights reserved).



Figure 9.1b. Anatahan, viewed from the southeast; the highest point of this island is on the western rim of the west caldera, and steeply sloping flanks surround most of this island. *NOAA photo*

9.1.1 History and Demographics

Anatahan has a general political history that follows the history of the CNMI as a whole, which is described in more detail in Chapter 1: "Introduction" and Chapter 8: "Saipan," Section 8.1.1: "History and Demographics."

Beginning in the early 1900s, small populations of < 50 persons have lived sporadically on this island, cultivating coconuts, corn, and sugarcane. When German administrator Georg Fritz visited Anatahan in 1901, he found no archaeological evidence of early Chamorro settlements (Spennemann 2006). A review of the population by German administrators in 1901 recorded 8 Chamorro and 3 Carolinian inhabitants on Anatahan; they probably were living there for copra production (Fitzner 1901; Cruz et al. 2000). During the period of rule by Japan, which began after World War I (WWI), limited copra production continued on Anatahan, supporting several Japanese and 45 Chamorro inhabitants. By the end of World War II (WWII), copra production had ceased, American authorities had moved Chamorro inhabitants to Saipan, and the only recorded residents on this island were a Japanese administrator and his wife. In 1945, this couple was joined by ~ 30 survivors of 3 Japanese ships that had been bombed and shipwrecked. In 1950, the administrator's wife left Anatahan after she was widowed, and, in 1951, following repeated efforts by the U.S. Navy to convince them that WWII was indeed over, the 19 remaining survivors surrendered and were picked up by an American detachment from Saipan (Trefalt 2003).

Anatahan has been mostly uninhabited in recent decades, because of the seismic and thermal activity of Anatahan Volcano. In 1993, following an earthquake swarm, the islands of Anatahan, Sarigan, and Farallon de Medinilla were declared off limits, and the island was subsequently evacuated again in 2003. Anatahan village, located in the southwestern section of this island, was covered with ash by the major eruption in 2003 (Siebert and Simkin 2002–).

9.1.2 Geography

Anatahan's compound caldera, as it appears in a digital elevation model (Fig. 9.1.2a), takes up nearly half of this island's surface and has a shape similar to the outline of this island. This caldera can be divided into east and west craters, each with different characteristics. The west caldera is ~ 2.3 × 5 km and has a floor of ponded lava with pyroclastic deposits (rock and dust ejected by volcanic activity). Before the 2003 eruption, the east caldera was 2 km wide and included 2 craters, an outer crater with a rim that joined the west caldera and a steep-sided, inner crater. The 2003 eruption formed a new, third crater within this east caldera; it is not yet known what other modifications may have occurred to this island's topography. The highest point on the rim of the east caldera is 540 m. Steep slopes surround this crater's rim and descend to the coast, cut with deep ravines (Siebert and Simkin 2002–).

The volcanic eruption that began on May 10, 2003, was the first eruptive activity recorded at Anatahan. Focused on the east caldera, this explosive vent eruption in 2003 was accompanied by pyroclastic flows (of volcanic ash, dust, and rocks down volcanic slopes), phreatic explosions (of steam, mud, rock, and other volcanic material caused by interactions of water and volcanic rock or lava), lava flows, and extrusion of lava domes. Ash plumes, continuing through the rest of May, were carried west by prevailing winds, and another explosion in June destroyed the lava domes in the east caldera's inner crater. From 2004 to 2006, volcanic activity continued with less intensity and various episodes of explosive eruptions, lava dome creation and destruction, and ash plumes. More recent recorded activity included a series of eruptions that began in December 2007 with ash and gas plumes continuing through August 2008 (Siebert and Simkin 2002–).

Anatahan was heavily forested historically but has been extensively damaged by feral animals, mainly pigs and goats; rats also have been observed on this island (Cruz et al. 2000; Atkinson and Atkinson 2000). The steep slopes around this island exacerbate effects of deforestation, and recruitment is prevented by feral ungulates feeding on seedlings. Even since 1994, when visiting scientists described a heavily forested island, significant habitat destruction has occurred (Cruz et al. 2000). Anatahan's vegetation, as surveyed in 2000, was primarily swordgrass with small pockets of trees and bare areas where disturbance had been greatest (Cruz et al. 2000). The May 2003 volcanic eruption destroyed much of the vegetation on Anatahan (Cruz et al. 2003).

9.1.3 Economy

Historically, the economy of Anatahan was centered on copra production, the level of which has varied over time. During the period of administration by Germany from 1899 through WWI, Anatahan was leased to the trading organization Pagan Gesellschaft for copra production (Spennemann 1999b). This product was the mainstay of the German economy in the

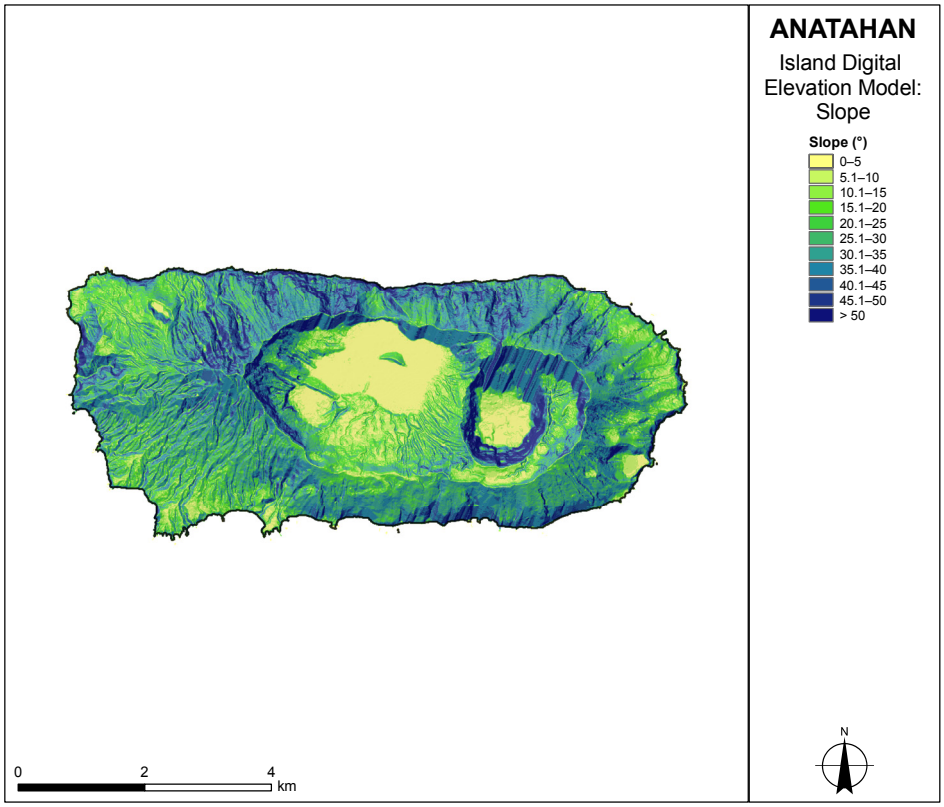


Figure 9.1.2a. Slope map using the digital elevation model (grid cell size: 10 m) for Anatahan. Values reflect the maximum rate of change in elevation between neighboring cells. This model was derived from data obtained prior to the 2003 volcanic eruption.

Marshalls Islands and in much of Micronesia; however, a series of typhoons between 1904 and 1907 resulted in a 50% reduction in production (Spennemann 1999b). More recent occupants of Anatahan, until their evacuation in 1993, probably relied on homesteading.

9.1.4 Environmental Issues on Anatahan

How badly marine habitats have been affected by volcanic activity is not yet fully clear. The only Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) surveys around Anatahan described in this report were conducted ~ 4 months after the beginning of the major eruption in 2003. Divers observed large volumes of ash covering coral reefs, mainly on the west side of this island. Ash plumes continued from 2003 to 2008 and, because of variable wind conditions, likely have affected other parts of Anatahan and the coral reef ecosystems around this island. Additional surveys are required to determine the extent to which reefs have been affected and whether signs of recovery on the worst affected areas are apparent. Low visibility in the waters around Anatahan in 2005 and 2007 prevented additional survey work; however, the Coral Reef Ecosystem Division (CRED) conducted limited surveys in 2009, the results and analysis of which will be presented in future reports.

The most significant land-based environmental issue on Anatahan is the high number of feral animals, such as goats and pigs (goats are thought to number ~ 6000; Cruz et al. 2000). These animals cause substantial damage to this island's native flora. The CNMI Division of Fish and Wildlife began a management program that focused on controlling this feral animal problem beginning in May 2002, but work subsequently ceased in 2003 because of volcanic activity (Cruz et al. 2003).

Anatahan supports only 4 species of forest birds: Micronesian honeyeater (*Myzomela rubrata*), Micronesian starling (*Aplonis opaca*), Micronesian megapode (*Megapodius laperouse*), which is listed federally as endangered (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), and very low numbers of the near-threatened (BirdLife International 2008) white-throated ground-dove (*Gallicolumba xanthonura*). This small number of species found on Anatahan is a consequence of this island's lack of suitable habitat, which results from destruction by feral animals (Cruz et al. 2003). A population of ~ 1000 Mariana fruit bats (*Pteropus mariannus mariannus*), an endemic subspecies listed federally as threatened (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), also has been observed on this island (Cruz et al. 2000; Cruz et al. 2003).

9.2 Survey Effort

Biological, physical, and chemical observations collected under MARAMP documented the conditions and processes influencing the coral reef ecosystems around the island of Anatahan since 2003. Because of poor conditions and safety concerns caused by volcanic activity, biological surveys around this island were limited in 2003 and not attempted in 2005 or 2007. More details about the extent and time frame of the survey effort around Anatahan are discussed in this section. The disparate areas around this island are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around Anatahan are delineated in Figure 9.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Anatahan. Potential reef habitat is represented by a 100-fm contour shown in white on this map.

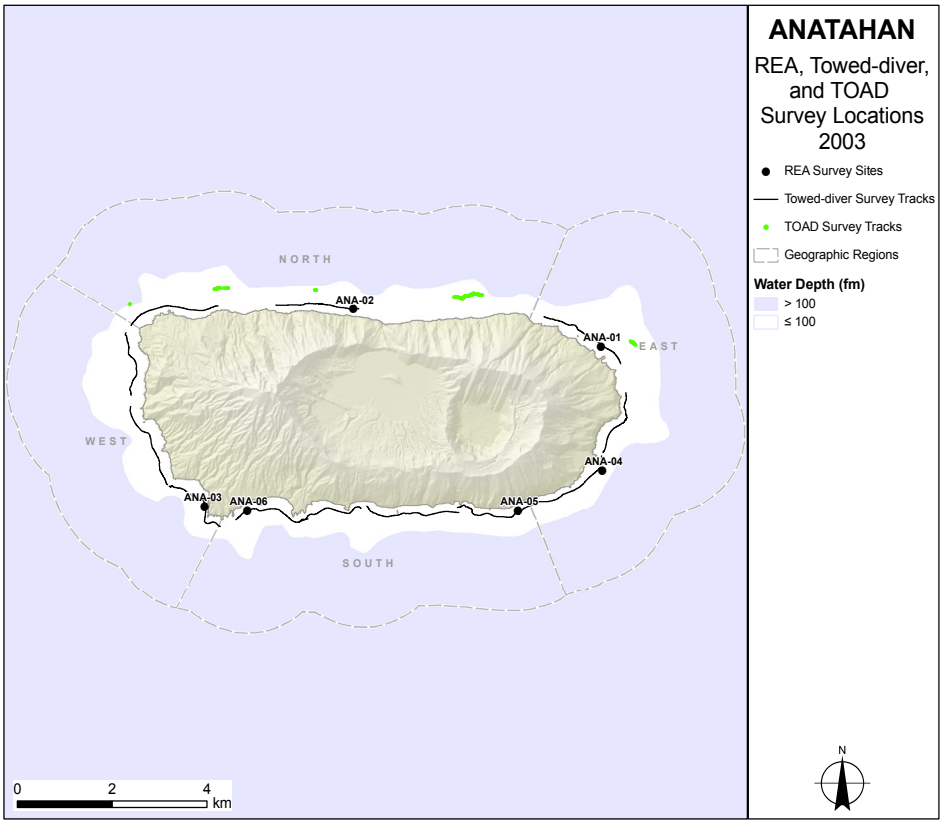


Figure 9.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Anatahan during MARAMP 2003. To aid discussion of spatial patterns, this map delineates 4 geographic regions: north, east, south, and west.

Benthic habitat mapping data were collected around Anatahan using a combination of acoustic and optical-survey methods. MARAMP benthic habitat mapping surveys conducted around this island with multibeam sonar covered a total area of 2228 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 9.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Anatahan was collected using REA, towed-diver, and TOAD surveys during MARAMP 2003. The results of these surveys are reported in Sections 9.5–9.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003 are presented in Table 9.2a, along with their mean depths and total area and length.

Table 9.2a. Numbers, mean depths (m), total area (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Anatahan during MARAMP 2003. REA survey information is provided for both fish and benthic surveys, the latter of which includes assessments of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year
REA		**2003**
Fish	Number of Surveys	3
	Mean Depth (m)	11.7 (SD 3.2)
Benthic	Number of Surveys	6
	Mean Depth (m)	11.7 (SD 3.2)
Towed Diver		**2003**
	Number of Surveys	12
	Total Survey Area (ha)	21.2
	Mean Depth (m)	12.9 (SD 1.4)
TOAD		**2003**
	Number of Surveys	5
	Total Length (km)	1.07

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Anatahan were collected using (1) subsurface temperature recorders (STRs) designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005 and 2007, and water sampling was performed during MARAMP 2005 and 2007 (see Chapter 2: "Methods and Operational Background," Section 9.4: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 9.2b. Results are discussed in Section: 9.4: "Oceanography and Water Quality."

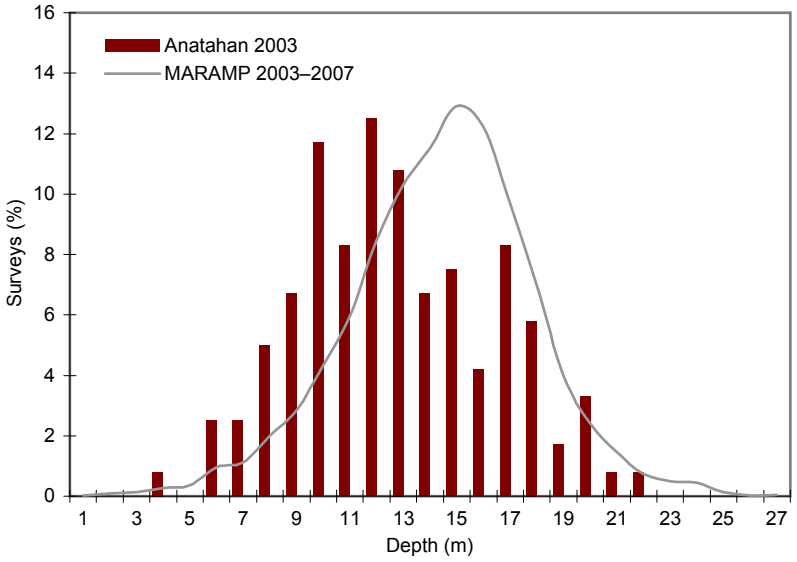
Table 9.2b. Numbers of STRs deployed, shallow-water and deepwater CTD casts performed, and water samples collected at Anatahan during MARAMP 2003. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	**2003**	**2005**		**2007**		**2009**	**Lost**
	Deployed	**Retrieved**	**Deployed**	**Retrieved**	**Deployed**	**Retrieved**	
STR	2	1	1	1	1	1	1
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	25	3		3			31
Deepwater Casts	–	2		–			2
Water Samples		**2005**		**2007**			**Total**
		3		2			5

Towed-diver Surveys: Depths

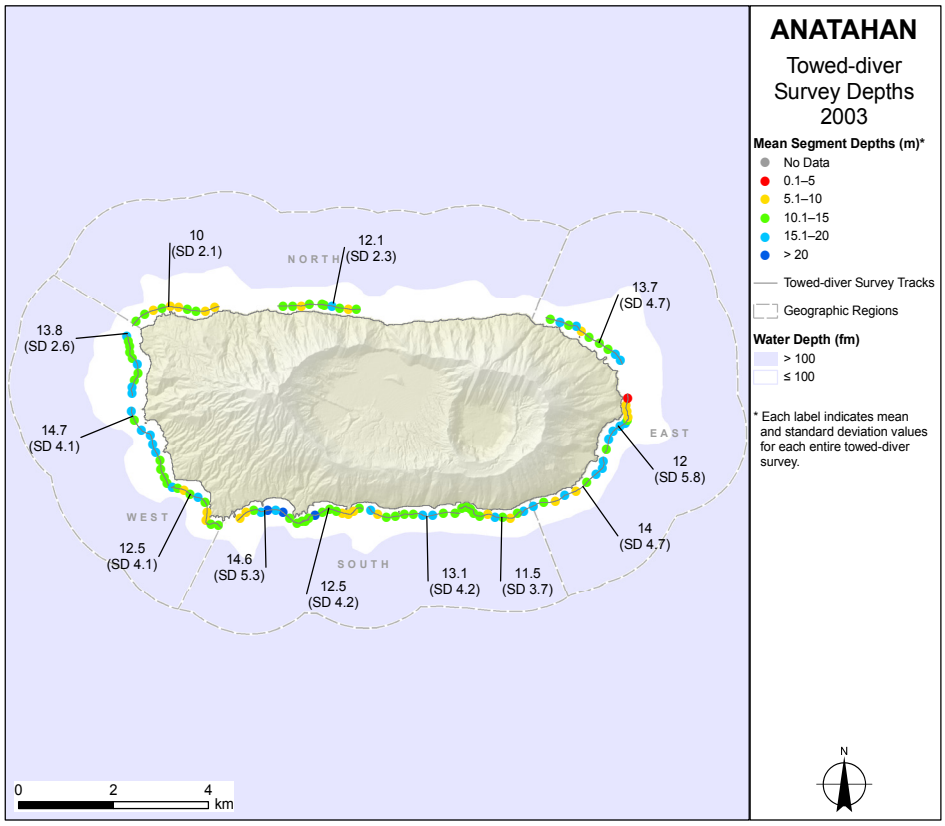
Figures 9.2b and c illustrate the locations and depths of towed-diver-survey tracks around Anatahan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003.

Figure 9.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Anatahan during MARAMP 2003. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during 2003, 2005, and 2007.



During MARAMP 2003, 12 towed-diver surveys were conducted along the forereef slopes around most of Anatahan (Figs. 9.2b and c). The mean depth of all benthic survey segments was 12.9 m (SD 1.4), and the mean depths of individual surveys ranged from 10 m (SD 2.1) to 14.7 m (SD 4.1). Because of suspended ash particulates in the water column, visibility during most of these towed-diver surveys was highly restricted.

Figure 9.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Anatahan during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.



9.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Anatahan were conducted during MARAMP 2003 and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 400–1800 m. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of < 207 m.

9.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 9.3.1a) collected by CRED around the islands of Anatahan, Alamagan, Sarigan, and Guguan and Zealandia Bank during MARAMP 2007 encompassed an area of 2228 km^2. No specific acoustic survey was undertaken at Anatahan, but low-resolution multibeam data were obtained in 2007, using the NOAA Ship *Hi`ialakai* during recovery of a moored oceanographic instrument. Limited coverage was achieved north and south of Anatahan, and additional data were obtained along 2 transit lines north and northeast of this island. No shallow-water multibeam data were acquired using the R/V *Acoustic Habitat Investigator*.

No multibeam data were collected in nearshore waters; therefore, no high-resolution bathymetry data were available for analysis of slope, rugosity, or bathymetric position index zones. Because the area of interest for coral reef monitoring is limited to shallow waters, conducting these analyses using deepwater bathymetry data was not merited. Thus, in this section, deepwater multibeam bathymetry and backscatter data are presented, but no further derivatives, from either multibeam bathymetry or backscatter, are shown.

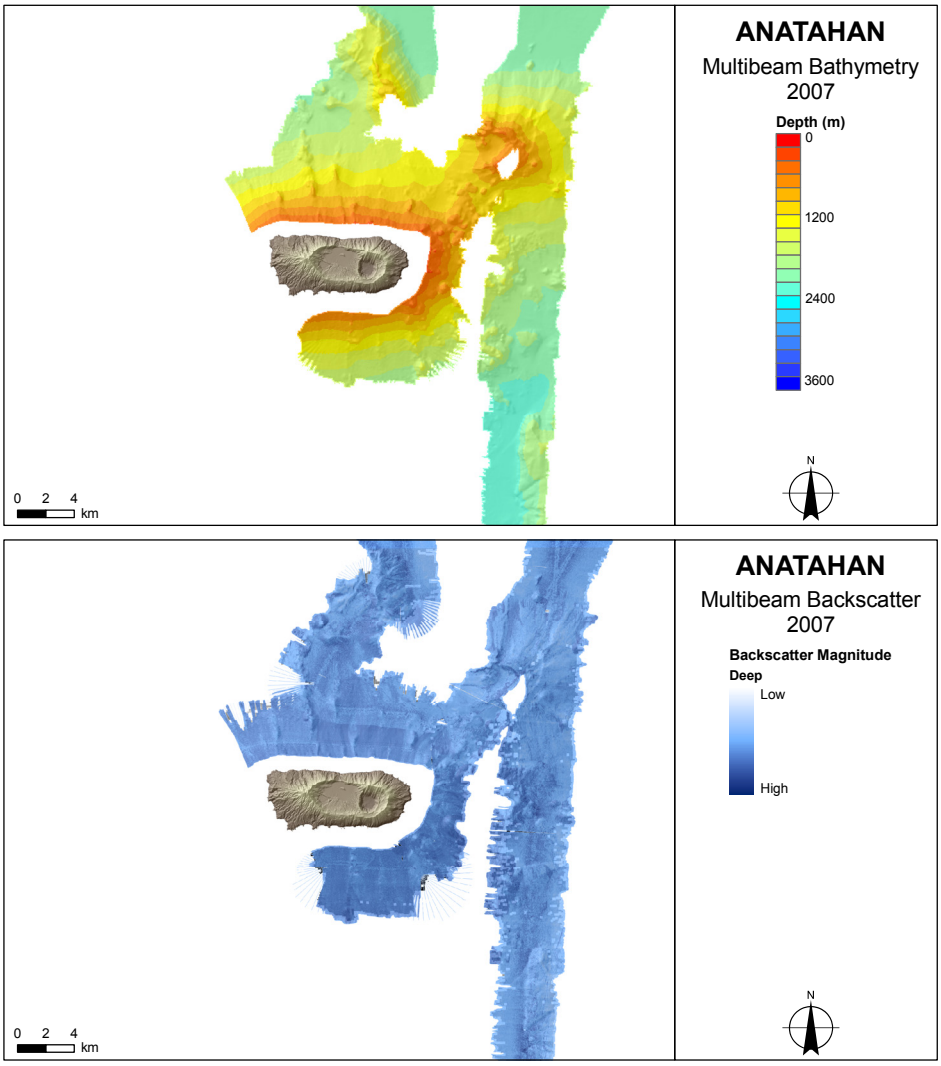
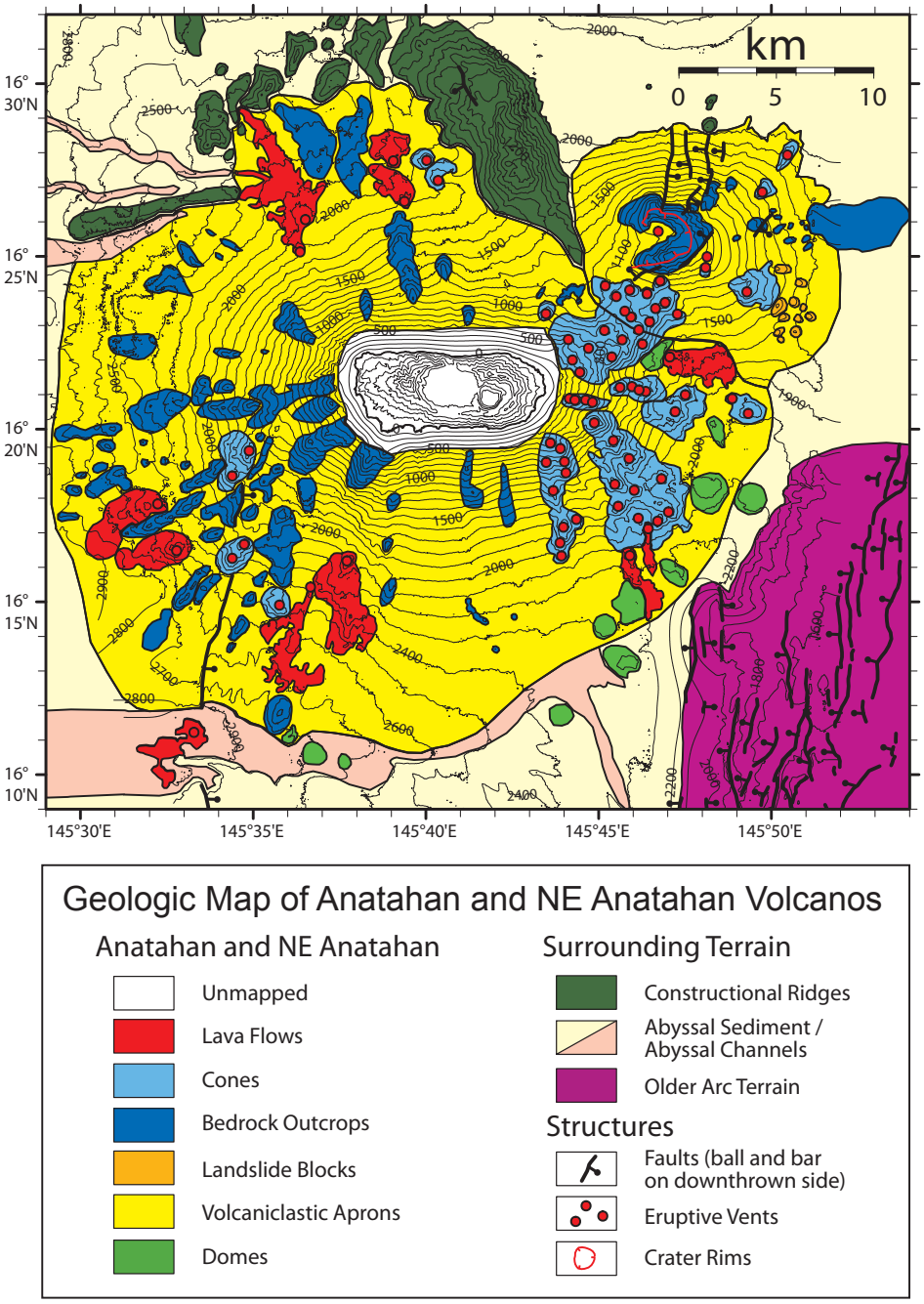


Figure 9.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Anatahan during MARAMP 2007 at depths of 400–1800 m. Deep-backscatter data (blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

The submarine flanks of Anatahan were also surveyed in 2003 and 2004 as part of the "Submarine Ring of Fire" project, which was funded by the NOAA Office of Ocean Exploration and the NOAA VENTS Program. As part of this project, volcanoes of the Mariana Arc were surveyed and multibeam bathymetry and sidescan data were acquired. Data from these surveys were collated and interpreted by Chadwick et al. (2005) and used to produce a geologic map for the submarine flanks of Anatahan Volcano. This geologic map is presented here (Fig. 9.3.1b) to provide context for the more limited data obtained by CRED.

A major volcanic eruption was recorded in May 2003 at Anatahan and volcanic activity continued through August 2008, as described in more detail in Section 9.1.2: "Geography." Because of this ongoing activity, keep in mind that data presented here only provide a snapshot of the nature of the seabed around Anatahan, which has been altered as a result of volcanic activity, such as lava flows and deposits of ash and coarser volcanic material.

Figure 9.3.1b. Geologic units and structures of the submarine flanks of Anatahan Volcano, including NE Anatahan, the satellite submarine volcano northeast of the island of Anatahan, from Chadwick et al. (2005).



The extremely limited coverage of the low-resolution multibeam data for Anatahan makes it difficult to draw many conclusions about the nature of the seabed around this island. North and south of this island, the limited CRED multibeam bathymetry data show flanks descending to a depth of ~ 1800 m at the limit of the data. Data presented by Chadwick et al. (2005; Fig. 9.3.1b) and the additional bathymetry obtained by CRED with the 2 transit swaths north of Anatahan suggest that these flanks continue to depths > 2000 m.

These same data also reveal 2 topographic highs north of Anatahan. The first, located directly north of Anatahan, rises to a depth < 1050 m from the ~ 2000-m depth of the surrounding seabed. This topographic high is the southern edge of a large topographic feature identified by Chadwick et al. (2005) as a "constructional ridge," which is estimated to be older than the main volcanic feature of Anatahan. The second topographic high, northeast of Anatahan, is part of a satellite submarine volcano, named "NE Anatahan" by Chadwick et al. (2005). CRED multibeam data reveal that this volcano rises to a depth of 575 m on its crater rim. An area of bumpy topography between Anatahan and NE Anatahan, which is visible on the CRED multibeam (Fig. 9.3.1a, top panel), has been classified by Chadwick et al. (2005) as "volcanic cones overlying eruptive vents." These cones and vent features continue around to the area southeast of Anatahan. Additional volcanic cones are visible in the multibeam bathymetry in deep (1700–2000 m) waters north of Anatahan and west of the large constructional ridge. The low-resolution multibeam bathymetry data obtained by CRED also reveal ridges north and south of Anatahan.

The low-resolution backscatter data collected around Anatahan by CRED also highlight some of the same topographic features. The crater rim of NE Anatahan, for example, is characterized by high backscatter values, supporting the classification by Chadwick et al. (2005) of the rim as "bedrock outcrops." Semicircles of high-intensity backscatter are recorded between Anatahan and NE Anatahan, marking the edges of the volcanic cones mapped by Chadwick et al. (2005). The ridges that shown in the multibeam bathymetry north and south of Anatahan, despite not having distinctly different backscatter intensity from the surrounding seabed, are identified by Chadwick et al. (2005) as "bedrock ridges." In general, backscatter intensity appears fairly uniform, supporting the conclusion by Chadwick et al. (2005) that the majority of the flanks of Anatahan are covered with smooth, volcaniclastic aprons composed primarily of fragments of volcanic debris.

9.3.2 Optical Validation

During MARAMP 2003, 5 TOAD optical-validation surveys, covering a distance of 1.07 km, were conducted around Anatahan (Fig. 9.3.3a). Surveys were conducted in depths of ~ 25 m to > 100 m, although lack of underlying bathymetry data and unreliable depth readings from the TOAD system mean it is not possible to obtain exact depths for these surveys. Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live coral cover.

Covering a distance of 21 km in depths of 4–22 m, 12 towed-diver optical-validation surveys of forereef habitats, were conducted around Anatahan during MARAMP 2003. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

9.3.3 Habitat Characterization

Sand cover, habitat complexity, and live-hard-coral cover around Anatahan are discussed in this section. MARAMP 2003 surveys were conducted around Anatahan in September, ~ 4 months after a period of major volcanic activity that began in May 2003. Towed-diver surveys and analyses of TOAD video footage suggested predominantly sandy substrates supporting very low levels of live coral cover. Towed divers observed ash covering benthic habitat in most surveys.

North and northeast of Anatahan, towed-diver surveys recorded sand cover of 50.1%–100% (Fig. 9.3.3a) over habitats of low to medium complexity (Fig. 9.3.3b). Analyses of video obtained from the 3 TOAD surveys conducted in this same area suggest a seabed with no sand (Fig. 9.3.3a); however, understand that substrate cover was recorded as "unconsolidated" and not differentiated further because of the difficulty of distinguishing between sand and other soft sediments from video imagery alone. Live coral cover from towed-diver surveys was < 20%, and no hard corals were observed in any of the analyzed TOAD video frames (Fig. 9.3.3c); however, 6 video frames recorded north of Anatahan suggested the presence of non-hard corals. North of Anatahan, habitats including sand-flats and reefs were observed during towed-diver surveys.

Apart from one bay in the western part of the south region, south and southeast of Anatahan, sand cover from towed-diver surveys was generally lower than it was north and northeast of this island, with cover primarily < 50%. Towed-diver surveys suggested locally variable live coral cover, within a range of 1.1%–30%. The highest level of habitat complexity was

Figure 9.3.3a. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted and analyses of TOAD video collected around Anatahan during MARAMP 2003.

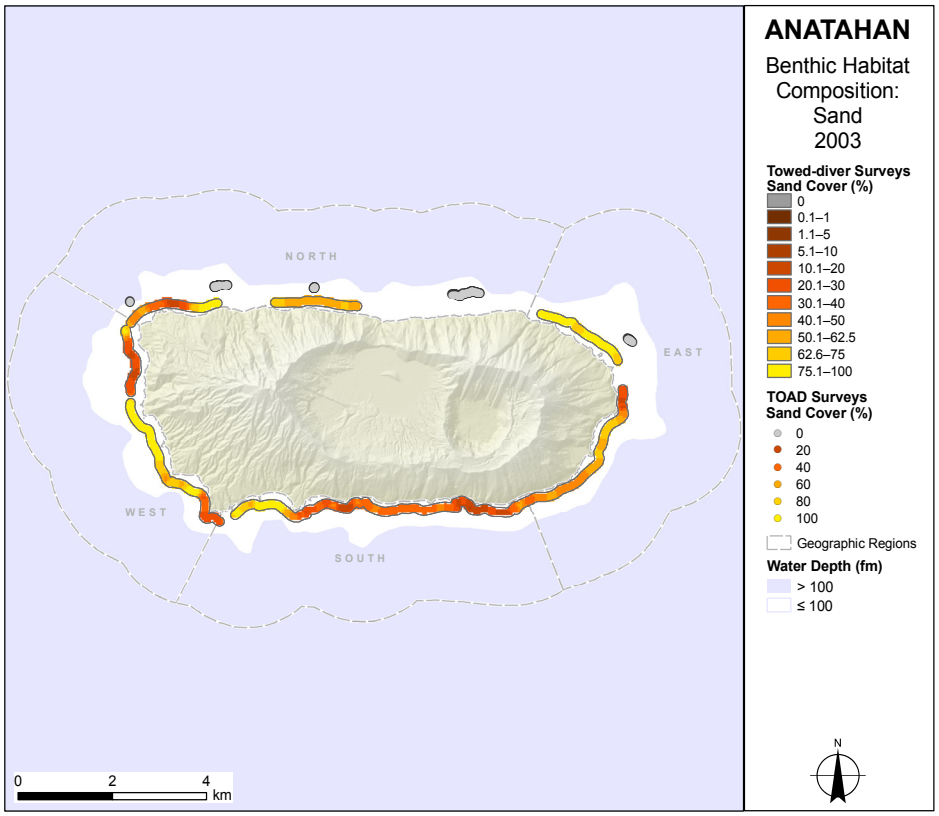
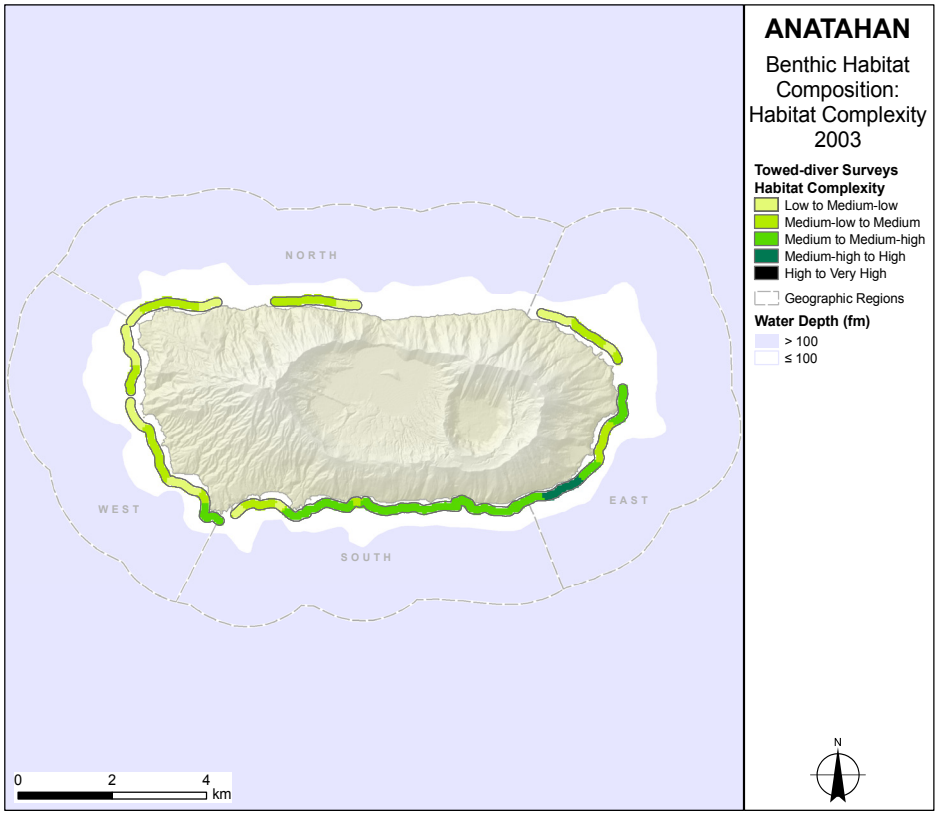


Figure 9.3.3b. Observations of benthic habitat complexity from towed-diver surveys of forereef habitats conducted around Anatahan during MARAMP 2003.



observed in the southern part of the east region, where medium to medium-high complexity was recorded within a small section of 1 survey. The habitat encountered was classified as sand-flats with boulders during towed-diver surveys.

The west region of Anatahan was characterized as soft-sediment habitats with sand cover of 20.1%–100%, based on towed-diver surveys. The habitat here had sand-flats with boulders but with relatively high sand components compared to other parts of this island, suggesting that sand was the dominant substrate. The lowest values of live coral cover at Anatahan, based on towed-diver surveys, consistently were recorded in this region with live coral cover < 5%.

At the northwestern point of this island, some of the highest levels of live coral cover for Anatahan, within a range of 5.1%–30%, were documented during towed-diver surveys. As in other areas around Anatahan, soft sediments dominated habitat observations, and sand cover of 10.1%–100% was recorded during towed-diver surveys. A very short TOAD survey was completed in this area, but only 2 video frames were analyzed. Analyses of both of these frames suggested that the substrate was rock, but it was not possible to classify any benthic fauna from this video footage.

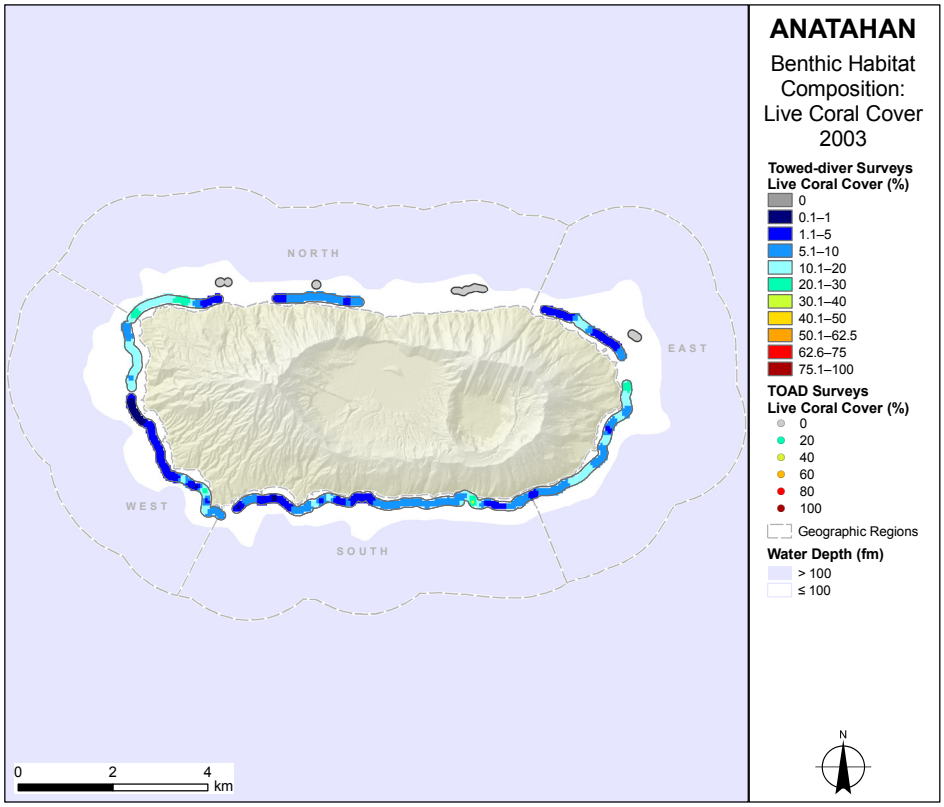


Figure 9.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Anatahan during MARAMP 2003.

9.4 Oceanography and Water Quality

9.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 25 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around Anatahan on September 10. Temperature, salinity, and density values varied both spatially and vertically. Spatial comparisons of water properties at a depth of 10 m suggest a moderate range in temperature (0.66°C), salinity (0.18 psu), and density (0.37 kg m^{-3}) values around Anatahan. The warmest temperature and lowest salinity values were found in the south region, while cooler and more saline waters were recorded in the east region (Fig. 9.4.1a). Vertical comparisons of CTD profiles reveal strong variability in stratification around this island: well-mixed, warm waters were observed around most of this island with the exception of the east region (casts 12–17), where substantial differences of 3.9°C and 0.7 psu were recorded in temperature and salinity values (Fig. 9.4.1b). This large variation in temperature values likely resulted from upwelling of cold, subsurface waters; however, it is difficult to discern from available data the physical mechanism behind this change.

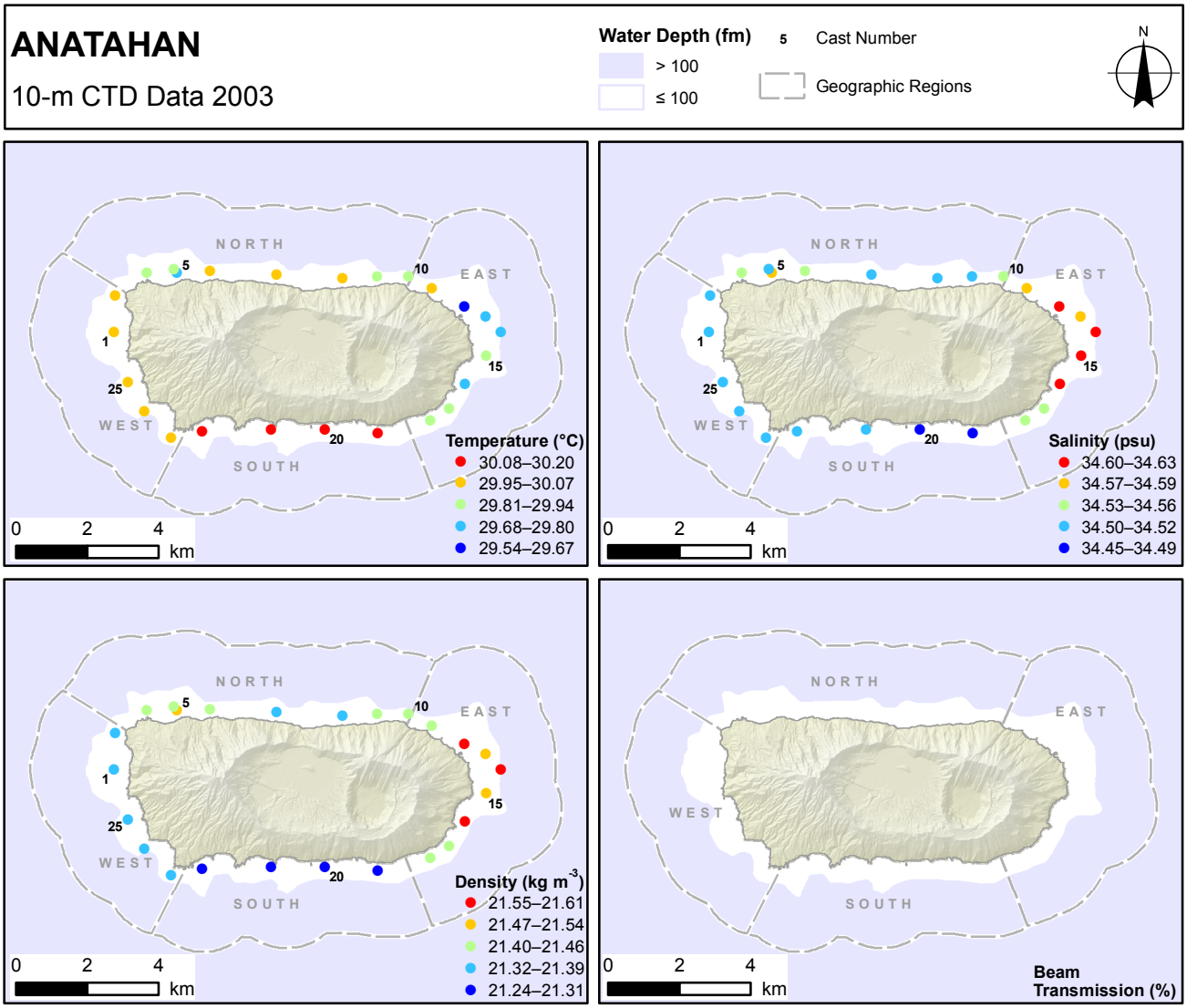


Figure 9.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts around Anatahan on September 10 during MARAMP 2003.

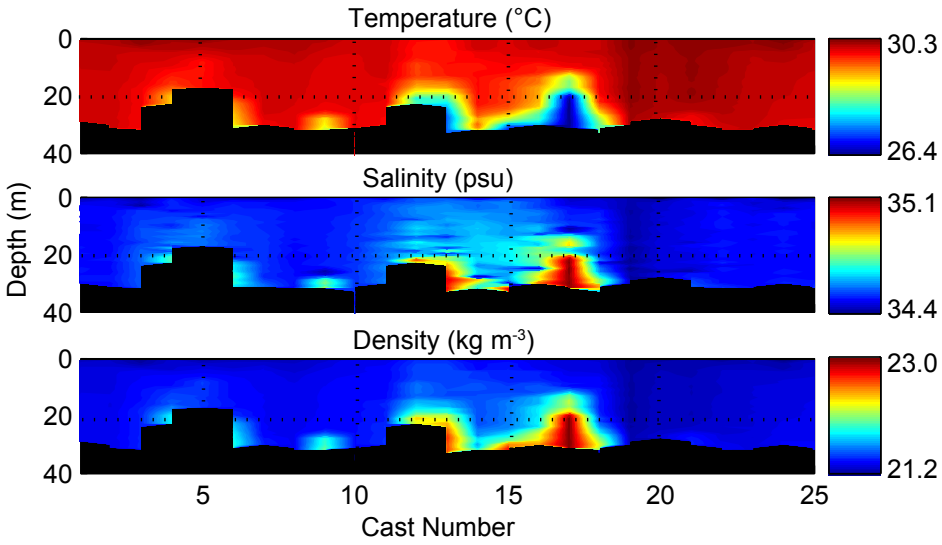


Figure 9.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Anatahan on September 10 during MARAMP 2003, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–25 in a clockwise direction around Anatahan. For cast locations and numbers around this island in 2003, see Figure 9.4.1a.

2005 Spatial Surveys

Eruptions and other volcanic activity prior to MARAMP 2005 sent ash and debris into the nearshore waters, affecting the surrounding environment and limiting the extent of hydrographic data collected during this survey period. On September 23, 2005, 3 shallow-water CTD casts were conducted at Anatahan. Temperature, salinity, and density values varied both spatially and vertically. Spatial comparisons of water properties at a depth of 10 m suggest moderate ranges in temperature (0.96°C), salinity (0.17 psu), and density (0.49 kg m^{-3}) values (Fig. 9.4.1c). Vertical comparisons of CTD profiles reveal water properties with large differences in temperature (1.6°C), salinity (0.4 psu), and density (0.8 kg m^{-3}) values (Fig. 9.4.1d).

Water samples were collected in concert with the 3 shallow-water CTD casts conducted at Anatahan in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.163–0.187 µg L^{-1}; total nitrogen (TN), 0.063–0.075 µM; nitrate (NO_3^-), 0.032–0.057 µM; nitrite (NO_2^-), 0.008–0.031 µM; phosphate (PO_4^{3-}), 0.027–0.092 µM; and silicate [$Si(OH_4)$], 0.567–1.206 µM. Based on data from the 3 sample locations, Chl-*a*, phosphate, silicate, and nitrite values were highest in the west region (Fig. 9.4.1e), where temperature values were also greatest.

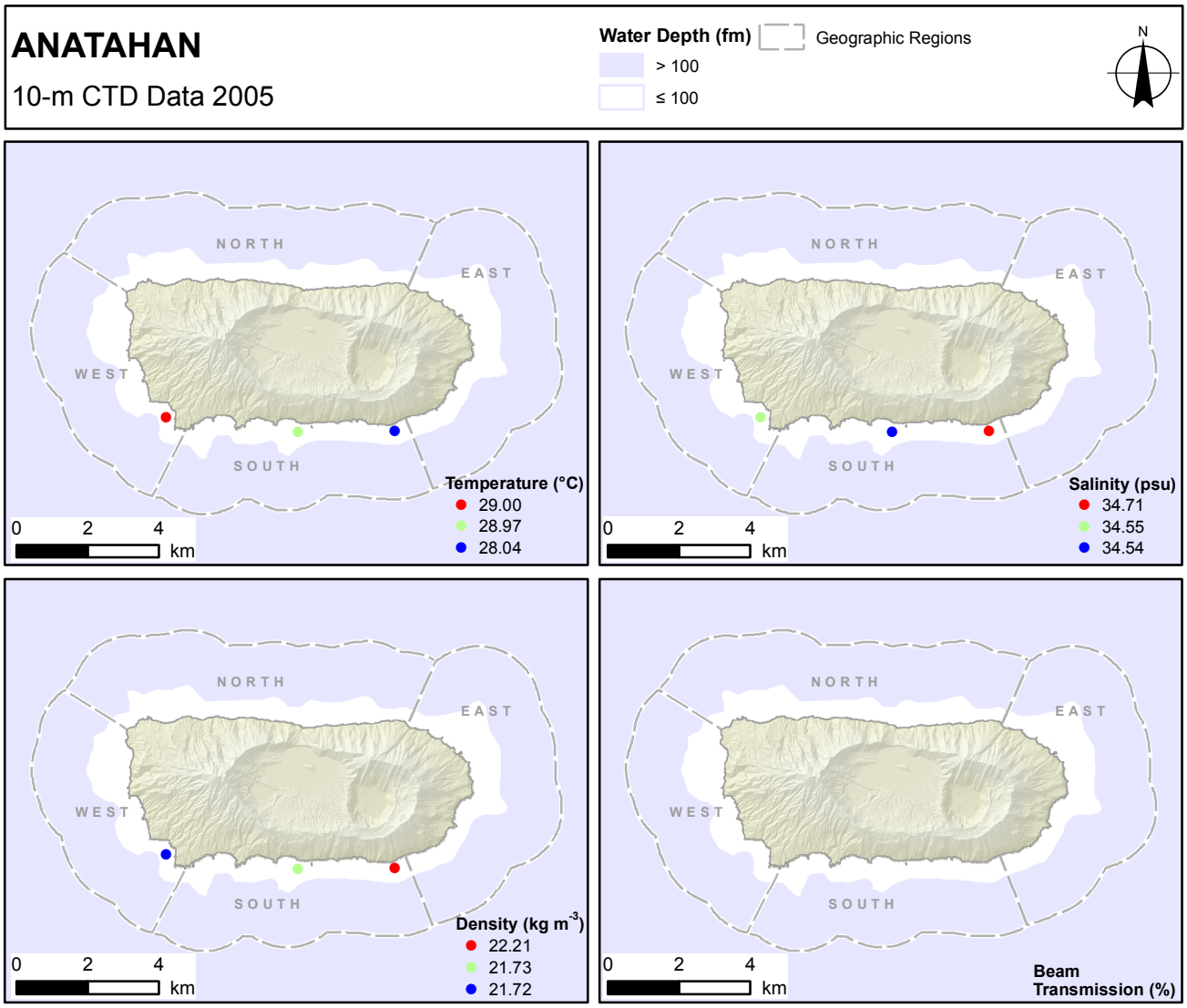
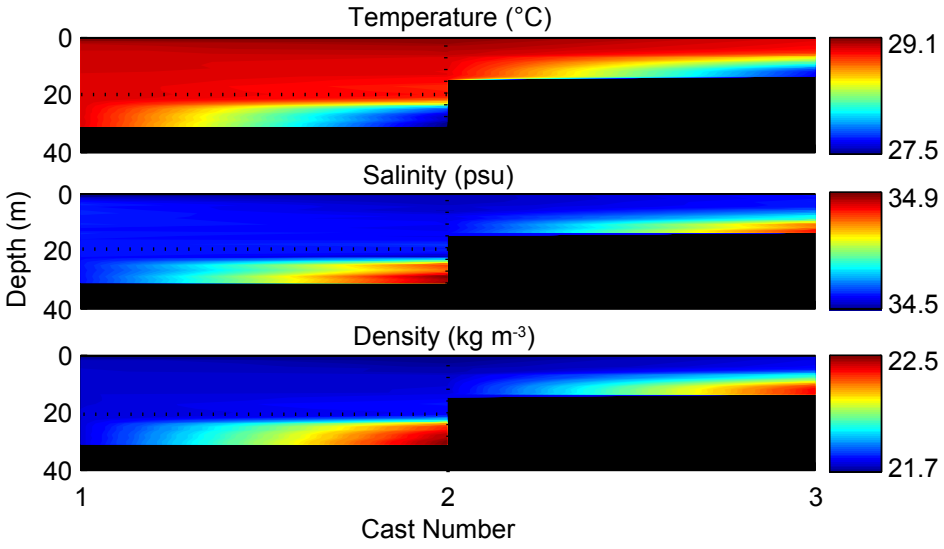


Figure 9.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts conducted at Anatahan on September 23 during MARAMP 2005.

Figure 9.4.1d. Shallow-water CTD cast profiles to a 30-m depth at Anatahan on September 23 during MARAMP 2005, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations shown in Figure 9.4.1c.



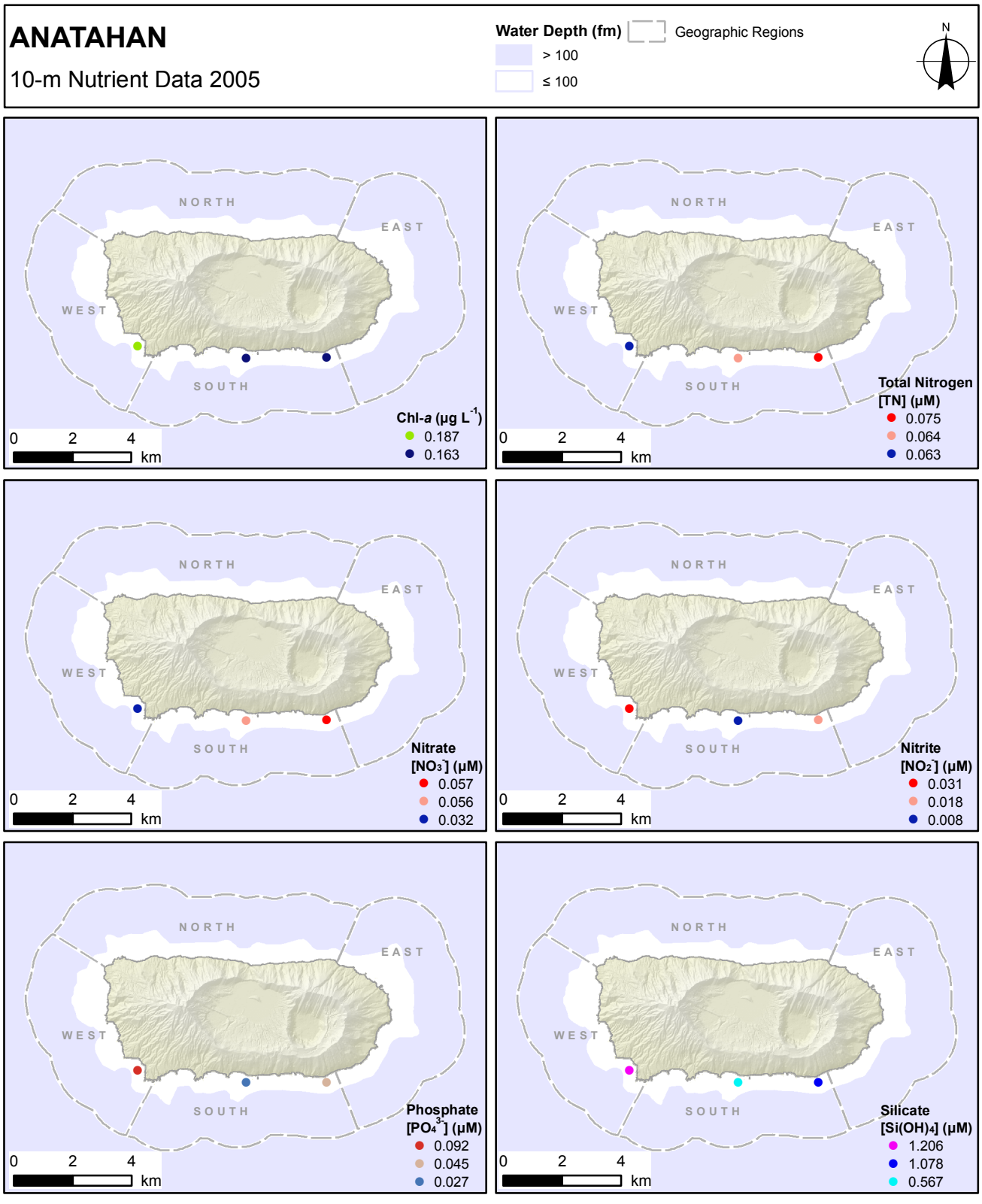


Figure 9.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Anatahan on September 23 during MARAMP 2005.

2007 Spatial Surveys

Eruptions and other volcanic activity prior to MARAMP 2007 sent ash and debris into the nearshore waters, affecting the surrounding environment and limiting the extent of hydrographic data collectedduring this survey period. On May 27, 2007, 3 shallow-water CTD casts were conducted in the south region. Spaital comparisons of water properties at a depth of 10 m suggest small ranges in temperature (0.18°C), salinity (0.04 psu), and density (0.08kg m^{-3}), and beam transmission (0.04%) values (Fig. 9.4.1f). Beam transmission was low (~ 91%) for this geographic region, compared to results from other locations surveyed in the Mariana Archipelago. Vertical comparisons of CTD profiles (Fig. 9.4.1g) revealed a stratified water column with highly turbid waters recorded at depths of 5–10 m, likely a result of ash and other debris from the recent volcanic eruption. A moderate range in temperature (0.7°C) values and small ranges in salinity (0.1 psu), density (0.3 kg m^{-3}), and beam transmission (1.5%) values were recorded.

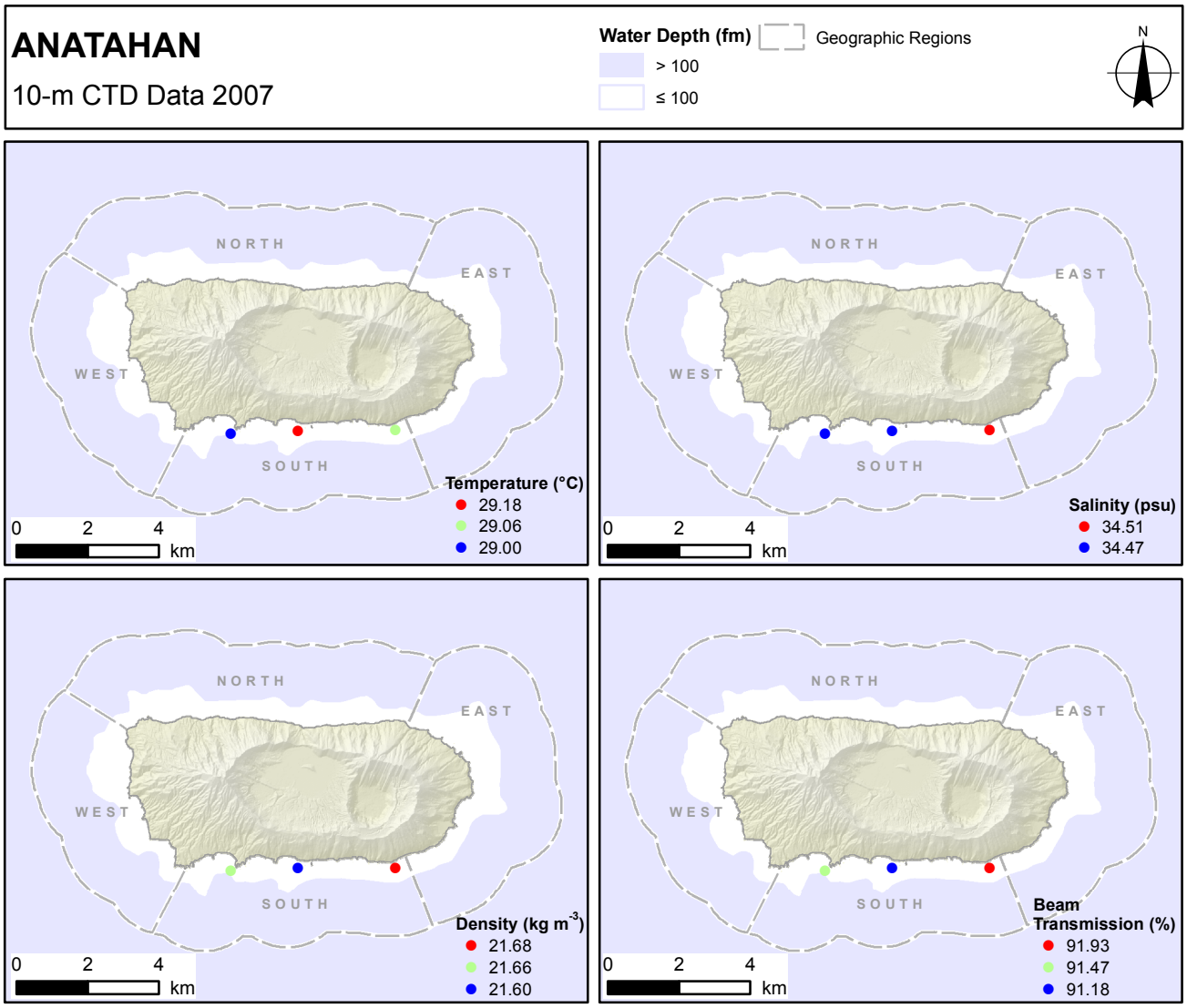


Figure 9.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts conducted at Anatahan on May 27 during MARAMP 2007.

Water samples were collected in concert with a shallow-water cast at 1 select location at Anatahan in 2007 to assess water-quality conditions. The following values of measured parameters were recorded: Chl-*a*, 0.08 µg L^{-1}; total nitrogen (TN), 0.027 µM; nitrate (NO^{3-}), 0.024 µM; nitrite (NO^{2-}), 0.003 µM; phosphate ($PO4^{3-}$), 0.040 µM; and silicate [$Si(OH)_4$], 1.321 µM (Fig. 9.4.1h).

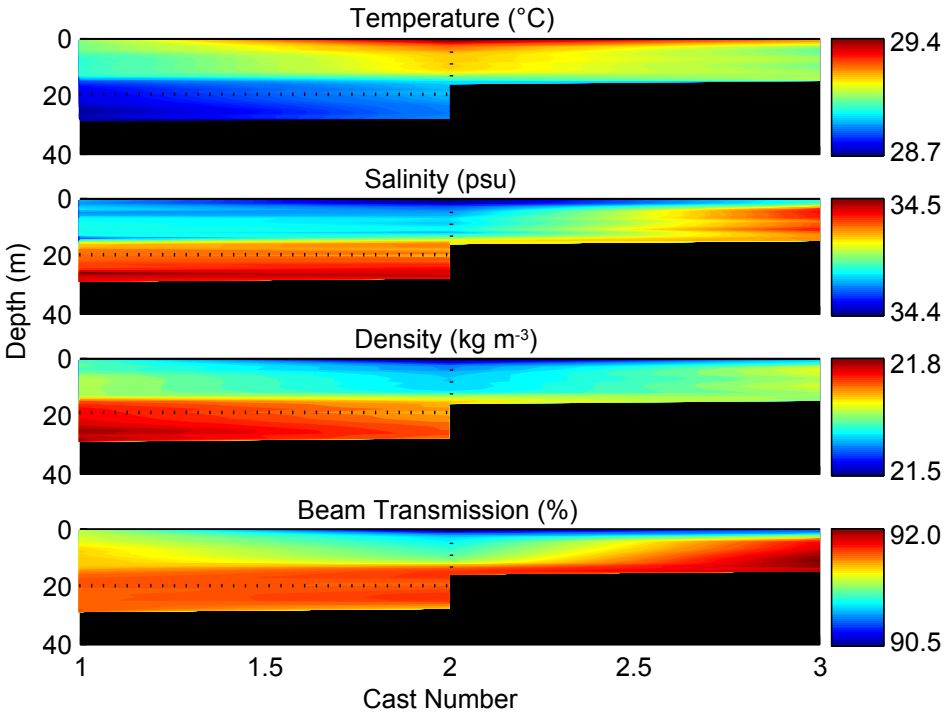


Figure 9.4.1g. Shallow-water CTD cast profiles to a 30-m depth at Anatahan on May 27 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations in the south region shown in Figure 9.4.1f.

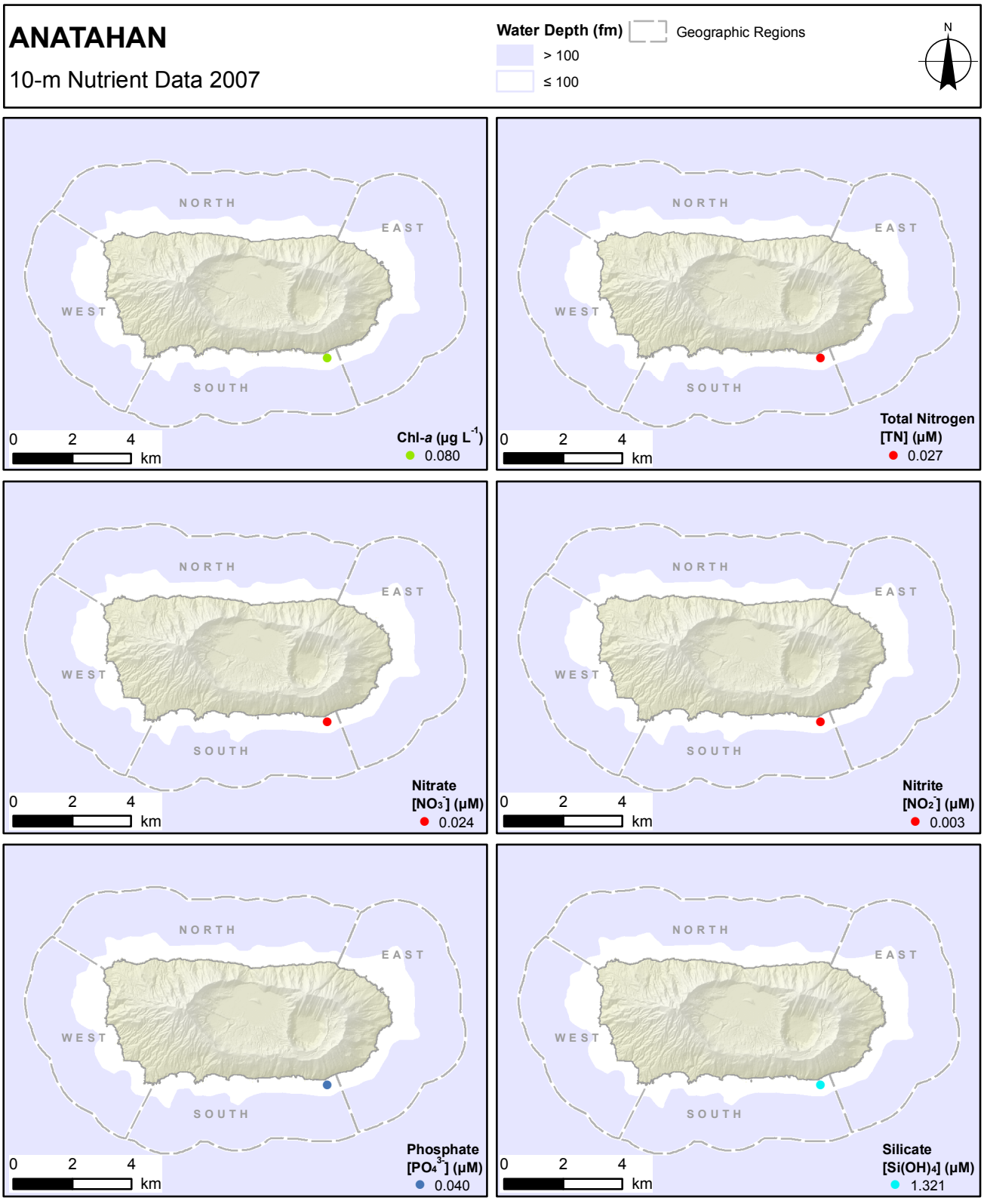


Figure 9.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate, at a 10-m depth from water samples collected at a single cast location at Anatahan on May 27 during MARAMP 2007.

Temporal Comparison

Given the lack of hydrographic data collected during MARAMP 2005 and 2007 and with the seasonal difference in sampling (MARAMP 2007 occurred in May, while MARAMP 2003 and 2005 occurred in September), it is not possible to make meaningful interannual comparisons of oceanographic conditions at Anatahan.

9.4.2 Time-series Observations

Between 2003 and 2007, subsurface temperature recorders (STRs) were deployed at Anatahan to collect time-series observations of temperature, a key oceanographic parameter influencing reef conditions (Fig. 9.4.2a). The location, depth, and time frame of the deployments at Anatahan are provided in Figures 9.4.2a and b.

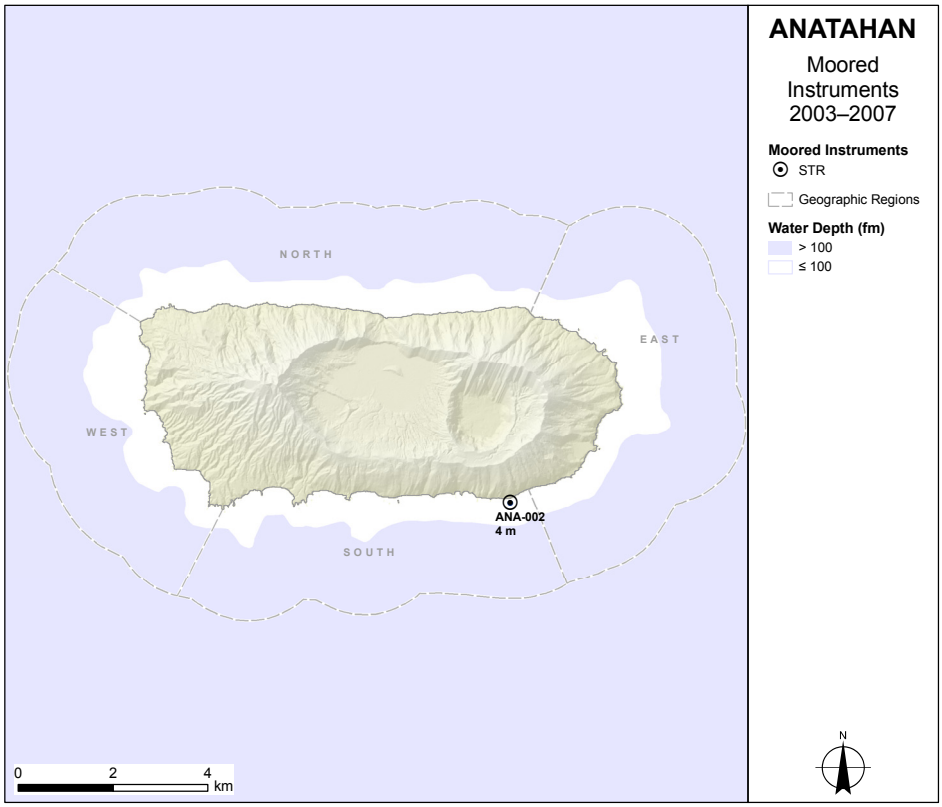


Figure 9.4.2a. Location and depth of STRs deployed at Anatahan during MARAMP 2003, 2005, and 2007.

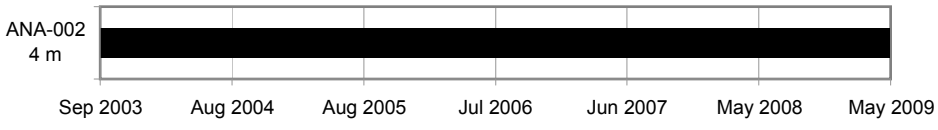


Figure 9.4.2b. Deployment timeline and depth of the STRs moored at Anatahan during the period from September 2003 to May 2009. A solid bar indicates the period for which temperature data were collected by a series of STRs deployed and retrieved at mooring site ANA-002. For more information about deployments and retrievals, see Table 9.2b in Section 9.2: "Survey Effort."

Temperature data collected by STRs deployed at a depth of 4 m in the south region show seasonal temperature variability of ~ 3°C between summer and winter months (Fig. 9.4.2c) Water temperatures reached ~ 30.5°C during the months of June–October and fell to a low of ~ 27°C from January–May. Superimposed on this seasonal temperature variability were frequent intraseasonal fluctuations. Temperature values, for example, dropped nearly 3°C in July 2004 for ~ 2 weeks before sharply increasing to typical summertime temperatures. Sharp decreases in temperature also were observed in September 2004 and summer 2005. Temperatures in September 2006 reached the coral bleaching threshold, defined as 1°C above the monthly maximum climatological mean.

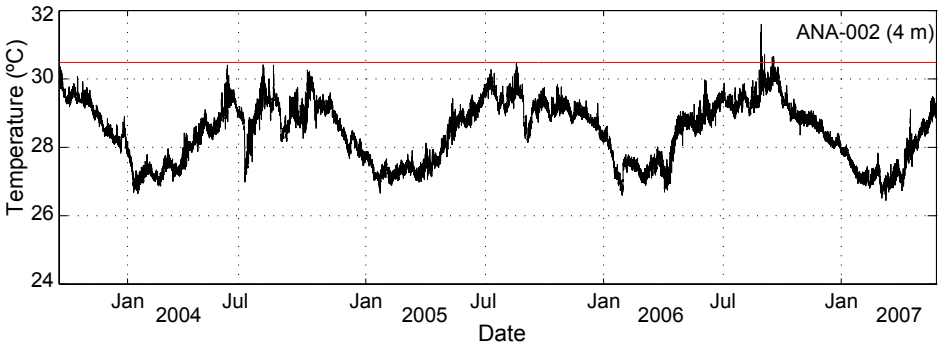


Figure 9.4.2c. Time-series observations of temperature over the period between September 2003 and July 2007 collected from 1 STR mooring site (ANA-002) in the south region at a 4-m depth at Anatahan (see Figure 9.4.2a for mooring location). The red line indicates the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

9.4.3 Wave Watch III Climatology

Seasonal wave climatology for Anatahan was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008 (Fig 9.4.3a), and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells, characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–2.5 m) wave events originating from the east (~ 80°–90°). Superimposed on these short-period swells were large (> 5 m), long-period (12–16 s) wave events from the southeast–southwest (130°–210°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–4.0 m) could occur from any direction, although weighted slightly larger from the south (130°–260°), and likely were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) also was characterized by frequent (> 30 d per season), short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season), long-period (12–14 s) swells with slightly larger wave heights (~ 2–3 m) also occurred during this period and could originate from any direction.

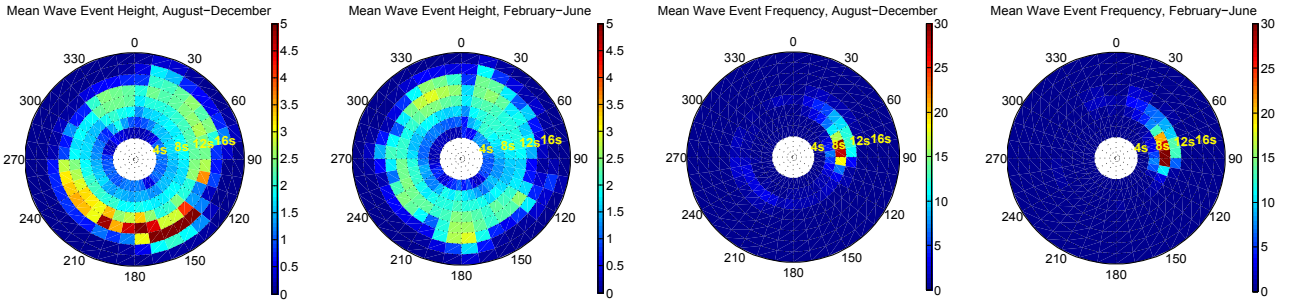


Figure 9.4.3a. NOAA Wave Watch III directional wave climatology for Anatahan from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Anatahan (16° N, 145° E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

9.5 Corals and Coral Disease

9.5.1 Coral Surveys

Anatahan volcano erupted on May 10, 2003, sending a massive column of volcanic ash and gas > 10 km above sea level. Falling ash buried parts of this island in a layer more than 45 cm thick, and traveled west from Anatahan in prevailing winds. Heavy ash settled on the coasts of this island, particularly in the north and west regions, covered coral reefs, and greatly altered light penetration and reef conditions. Because low-level volcanic activity continued during the MARAMP survey periods, REA and towed-diver surveys of corals were not completed at Anatahan in 2005 or 2007. In those years, getting near this island was dangerous, and the large amount of volcanic ash in the water column reduced visibility to close to zero.

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats for the island of Anatahan was 8% (SE 0.6). Coral cover was relatively low along all forereef areas surveyed around Anatahan, compared to other survey areas in the Mariana Archipelago. Localized areas of high coral cover, within a range of 20.1%–30%, were observed around this island's easternmost point over 1 segment, in the western part of the north region over 3 segments, and the southwestern part of the west region over 1 segment (Fig. 9.5.1a). An additional area of high coral cover, within a range of 20.l%–40%, was recorded in the south region over 2 segments. Observations of recently dead corals and diversity of dead coral skeletons, made during towed-diver surveys, suggested that reefs north of Anatahan may have been extensive prior to the eruption in 2003.

During MARAMP 2003, 5 REA benthic surveys using the quadrat method on forereef habitats at Anatahan documented 408 coral colonies within a total survey area of 18.75 m^2. Site-specific colony density ranged from 10.7 to 34.4 colonies m^{-2} with an overall sample mean of 21.8 colonies m^{-2} (SE 4.4). The highest colony density was recorded at REA site ANA-05 in the south region, and the lowest colony density was observed in the west region at ANA-03 (Fig. 9.5.1b).

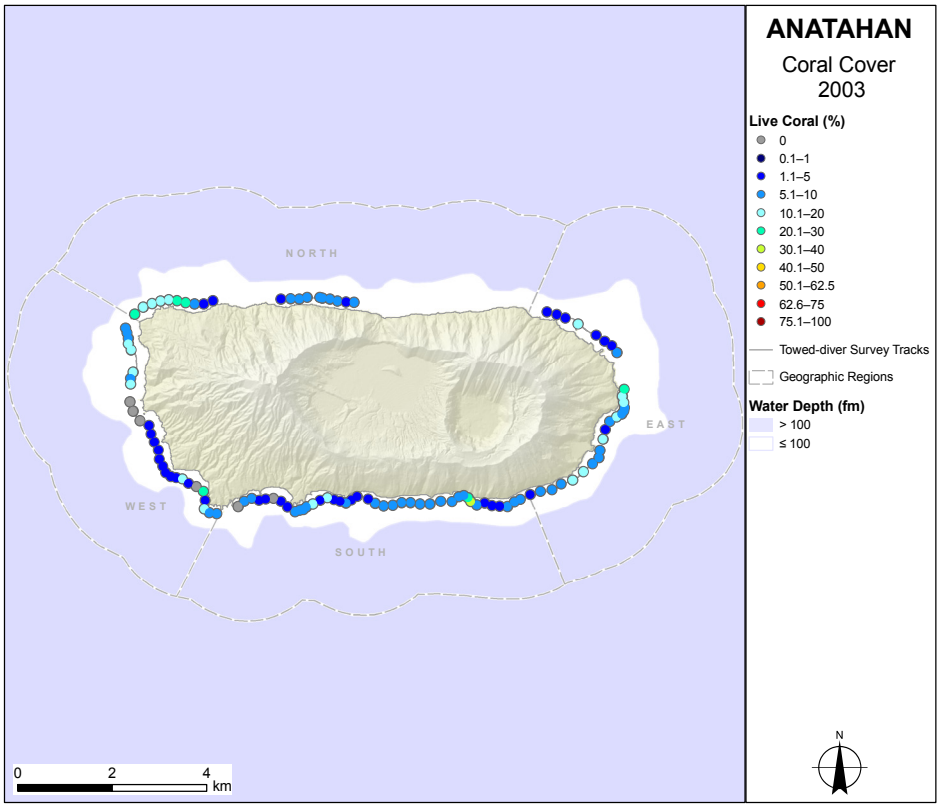


Figure 9.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 m x 10 m (~ 2000 m^2).

Figure 9.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. Values are provided within or above each symbol. The quadrat method was used in 2003 to assess coral-colony density.

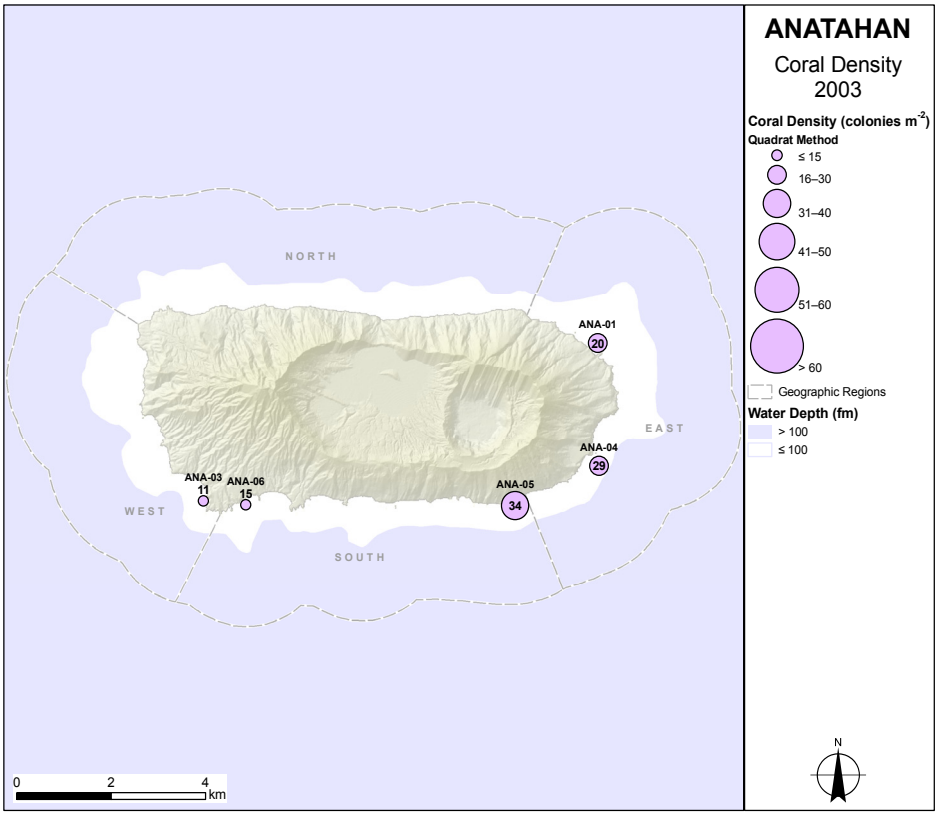
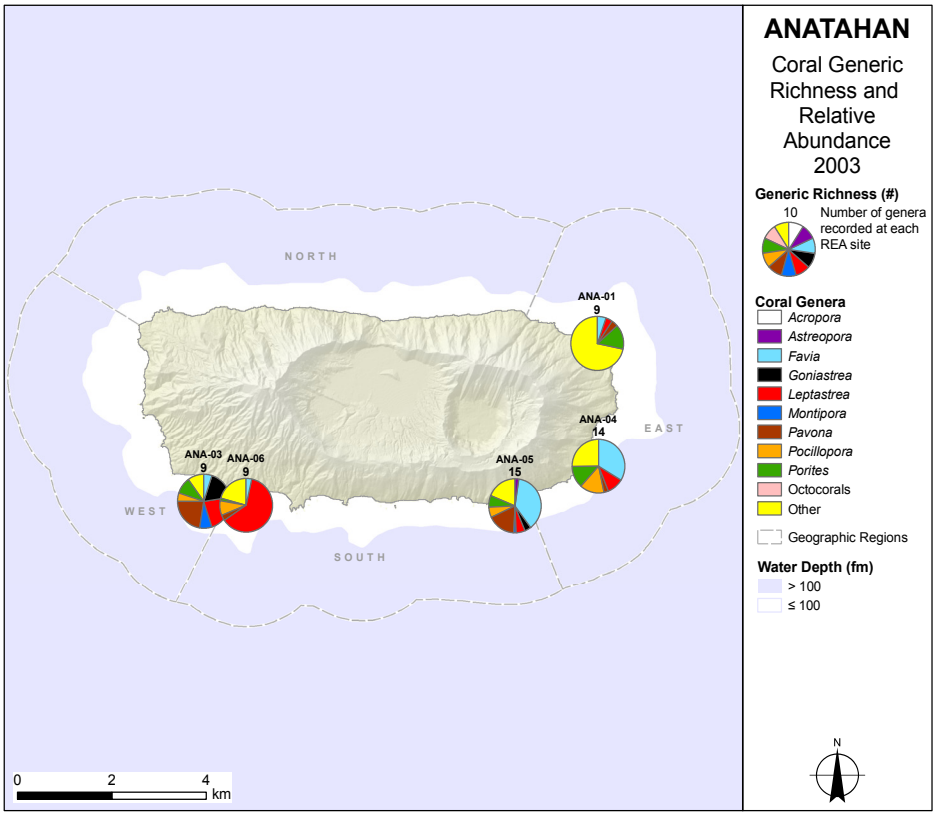


Figure 9.5.1c. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. The pie charts indicate the percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to survey coral genera.



Coral Generic Richness and Relative Abundance

Five REA benthic surveys of forereef habitats were conducted using the quadrat method at Anatahan during MARAMP 2003. During this survey period, 20 coral genera were observed at Anatahan. Generic richness ranged from 9 to 15 with a mean of 11.2 (SE 1.4) coral genera per site and 20 genera observed overall at Anatahan. The highest generic diversity was seen at ANA-05 in the south region, and the lowest generic diversity was recorded at 3 sites: ANA-01, ANA-03, and ANA-06 in the east, west, and south regions (Fig. 9.5.1c).

Leptastrea, *Favia* and *Pavona* were the most numerically abundant genera, contributing 20.8%, 16.9%, and 10% of the total number of colonies enumerated at Anatahan in 2003. All other genera individually contributed < 10% of the total number of colonies. *Leptastrea* and *Pavona* dominated the coral fauna at ANA-03 in the west region, each contributing 22.5% of the total number of colonies at this site. *Leptastrea* was the most abundant genus at ANA-06 in the south region, contributing 62.1% of the total number of colonies at this site. *Favia* dominated the coral fauna at ANA-04 and ANA-05 in the east and south regions, accounting for 33.3% and 37.2% of the total number of colonies at these sites. *Montastrea* dominated the coral fauna at ANA-01 in the east region, contributing 50% of the total number of colonies at this site.

Coral Size-class Distribution

During MARAMP 2003, 5 REA benthic surveys of forereef habitats were conducted at Anatahan using the quadrat method. The coral size-class distributions from these surveys show that the majority (75.4%) of corals had maximum diameters ≤ 5 cm (Figs. 9.5.1d and e). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 17.6%, 5.3%, and 1.8% of colonies recorded. No colonies with maximum diameter > 40 cm were observed. At each REA site, a majority (> 60%) of corals were in the smallest size class (0–5 cm).

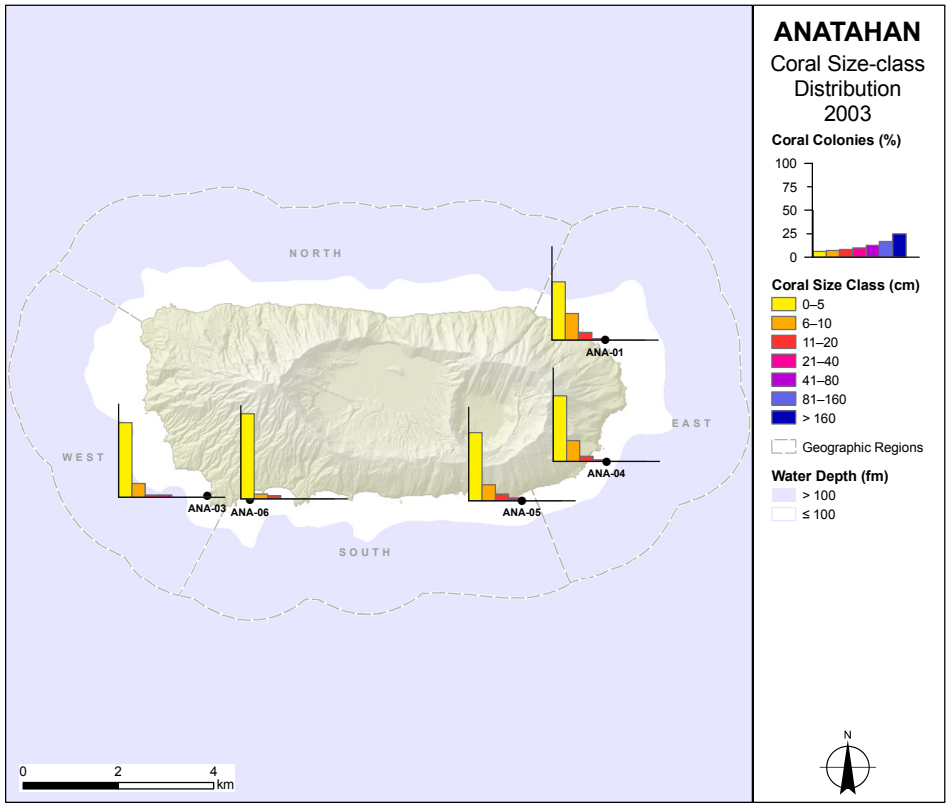


Figure 9.5.1d. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.

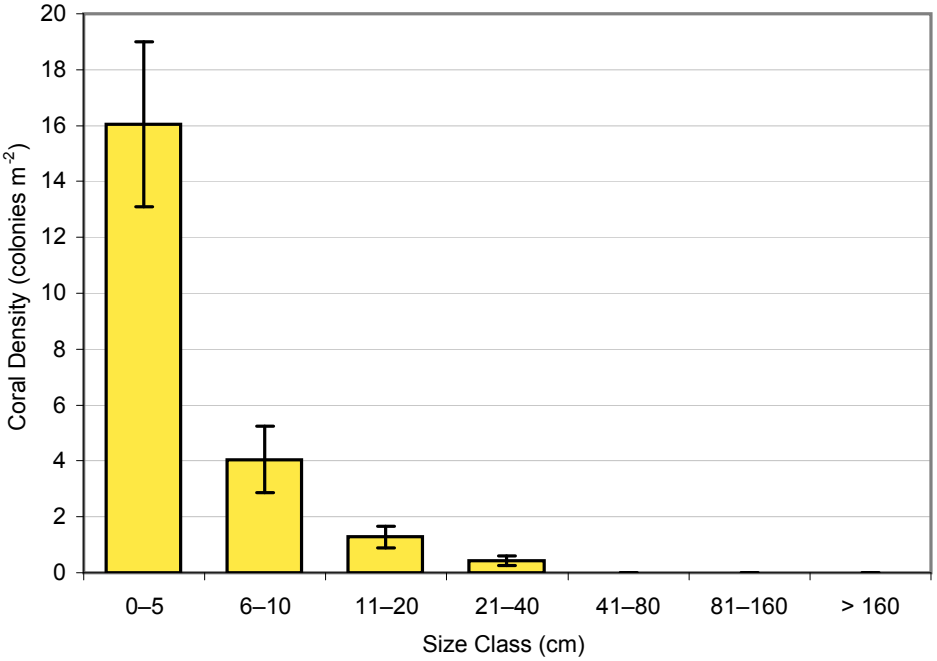


Figure 9.5.1e. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. The quadrat method was used in 2003 to size corals. Error bars indicate standard error (± 1 SE) of the mean.

9.5.2 Coral-disease Surveys

Anatahan was not surveyed for coral disease and predation during MARAMP 2003, 2005, and 2007.

9.6 Algae and Algal Diseases

9.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

Towed-diver surveys at Anatahan were completed in September 2003, when large amounts of ash were frequently seen on reefs or in the water column. For example, during a survey in the southern part of the west region, divers reported that everything on the seafloor appeared "dead" for the entire length of this survey. Such observations make it apparent that the coral reef ecosystem at Anatahan had already suffered significant effects from the volcanic eruptions that began in May 2003.

From MARAMP 2003 towed-diver surveys, mean macroalgal cover around the island of Anatahan was 14% (SE 1.6) (Fig. 9.6.1a). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 48%, within a range of 0%–75%, occurred in the northern part of the west region (Fig. 9.6.1b, left panel). Habitat in this area primarily was composed of low-relief pavement of low complexity. The second-and third-greatest levels of macroalgal cover, with means of 34% and 30%, were observed during the 2 surveys completed in the southern part of the east region. Habitats observed during these surveys mostly had rock boulders and were characterized as medium and medium-high complexity. All other surveys conducted in 2003 recorded macroalgal cover ≤ 6%.

TOAD surveys completed in the north and east regions of Anahatan during MARAMP 2003 were conducted at depths of 1–100 m. Based on analyses of TOAD video footage obtained from the 5 completed surveys, the observed seabed had no macroalgae and was primarily composed of unconsolidated sediment, such as volcanic ash (Fig. 9.6.1b, left panel).

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Anatahan was 8% (SE 0.7; Fig. 9.6.1a). The survey with the highest mean crustose-coralline-red-algal cover of 22%, within a range of 5.1%–30%, occurred along the coast in the center of the south region (Fig. 9.6.1b, right panel). Habitat observed during this survey primarily was of medium-high complexity and composed of rock boulders interspersed with pavement. In the west and north regions, 4 surveys recorded the lowest levels of crustose-coralline-red-algal cover with means of 2%–3%. Habitats seen during these surveys primarily were pavement of low to medium-low complexity.

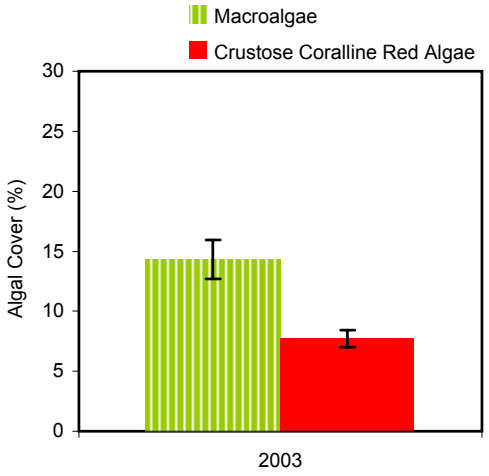


Figure 9.6.1a. Algal cover (%) values for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003. Macroalgal cover includes turf algae in addition to macroalgae. Error bars indicate standard error (± 1 SE) of the mean.

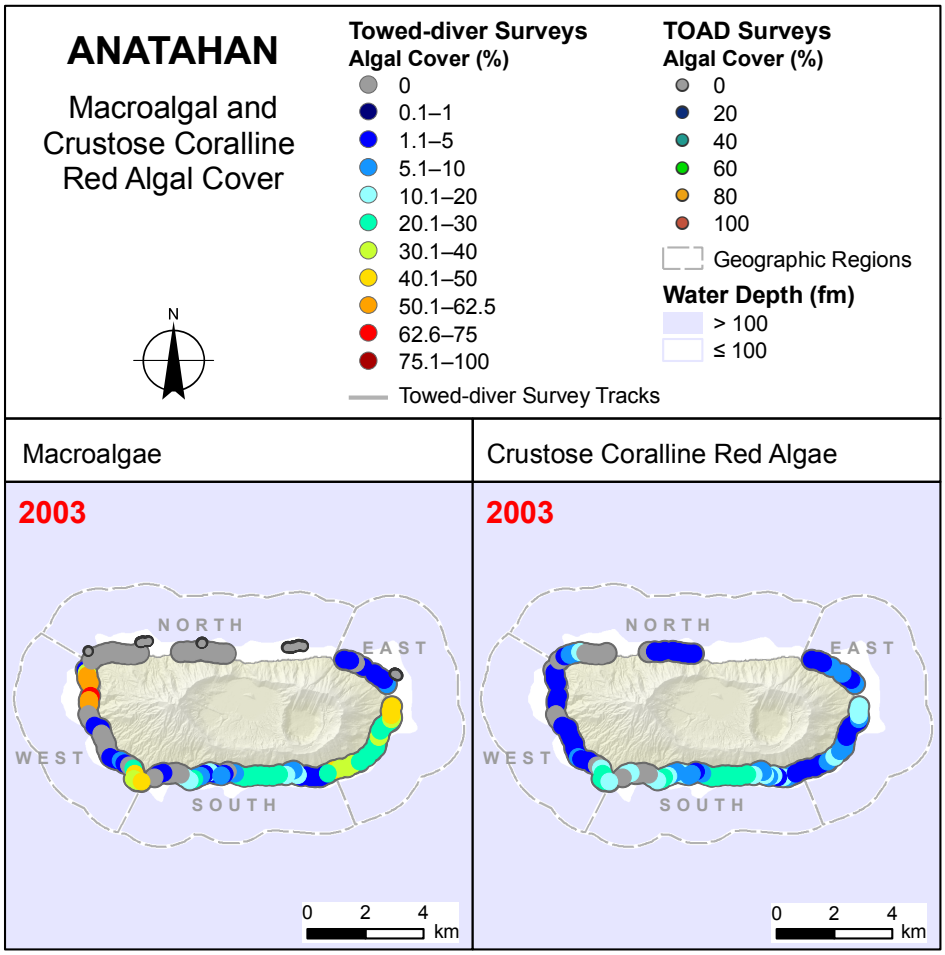


Figure 9.6.1b. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003. Each large, colored point represents an estimate over a 5-min observation segment with a towed-diver survey swath of ~ 200 × 10 m (~ 2000 m^2). The left panel shows observations of both macroalgae and turf algae. In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 4 sites on forereef habitats at Anatahan. In the field, 7 macroalgal genera (4 red, 1 brown, and 2 green), containing at least 7 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanobacteria—were observed. REA site ANA-04 in the east region had the highest macroalgal generic diversity recorded in the field with 6 genera, containing 6 species, documented. The lowest macroalgal generic diversity was found at ANA-06 in the western part of the south region.

Macroalgal cover at Anatahan overall was low compared to results for other islands surveyed in the Mariana Archipelago, likely because of the recent eruption. The most frequently observed genus was the red alga *Jania*, recorded in only 10.4% of the photoquadrats sampled at Anatahan (Figs. 9.6.1c and d). A single species of the calcified, green algal genus *Halimeda* and a single species of the calcified, red algal genus *Peyssonnelia* were each recorded in 8.3% of sampled photoquadrats. Species of the red algal genus *Hypoglossum*, brown algal genus *Lobophora*, and green algal genus *Neomeris*, as well as an unidentified member of the red algal order Gelidiales, were each recorded in < 5% of sampled photoquadrats. Algal biodiversity was much higher along the southeastern coast than along the southwestern coast. Of the 7 genera recorded at Anatahan, all except *Jania* were recorded at ANA-04 in the east region. At this site, *Peyssonnelia* was the most abundant macroalgal genus, although this genus only occurred in 25% of photoquadrats sampled at this site. All other genera found at ANA-04 occurred in < 16.7% of the photoquadrats sampled at this site. At ANA-05, located only 2 km to the west of ANA-04 in the south region, only 3 genera were observed, and species of *Jania* were found in 41.7% of sampled photoquadrats, the highest abundance recorded for this genus at Anatahan. The only algal genus recorded at ANA-03 in the west region was *Lobophora*, found in 8.3% of sampled photoquadrats. No macroalgal genera were observed at ANA-06 in the south region; however, the algal functional groups of turf algae and crustose coralline red algae were seen at this site.

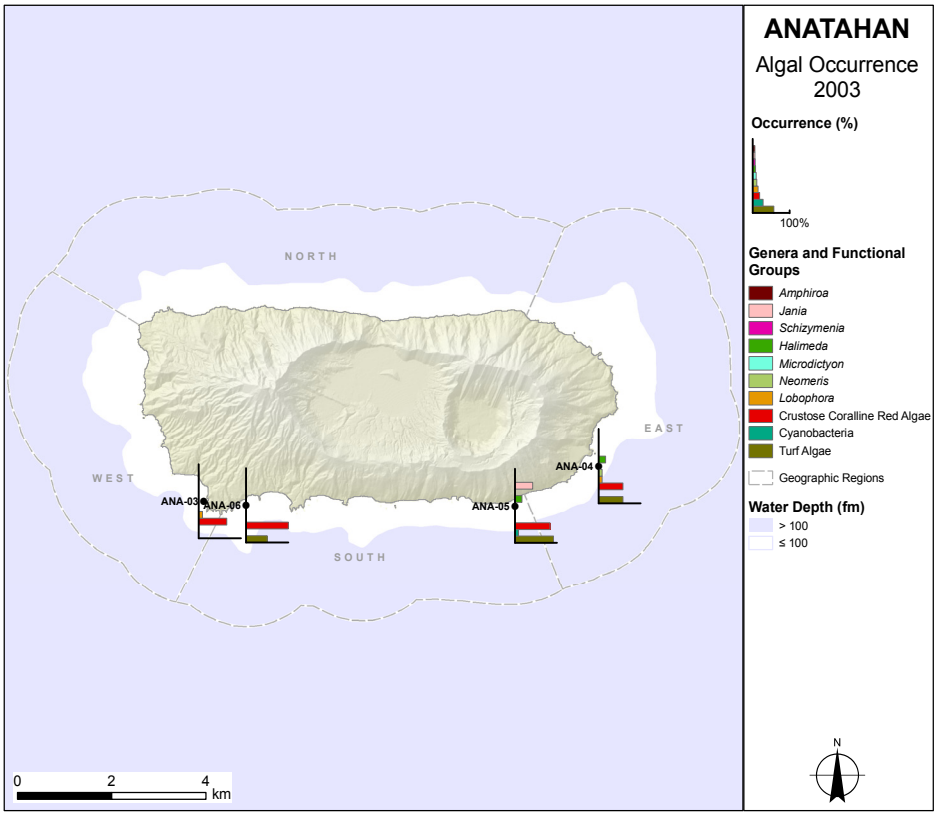


Figure 9.6.1c. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

Turf algae and crustose coralline red algae were both common in 2003, occurring in 50% and 77.1% of photoquadrats sampled at Anatahan (Figs. 9.6.1c and d). Unusually, turf algae, the main benthic substrate cover in most coral reef ecosystems,were not recorded at all sites surveyed at Anatahan; this functional group was absent from ANA-03, the westernmost site. Turf-algal occurrence at Anatahan appeared proportional to macroalgal occurrence, as this functional group was most abundant when macroalgal occurrence was also highest, with the exception of results from ANA-06, where turf algae were found in 50% of sampled photoquadrats and no macroalgae were recorded. Common at every site surveyed at Anatahan, crustose coralline red algae were the most abundant functional group recorded in the field. Along the southwestern coast, where macroalgal diversity and occurrence were low, crustose coralline red algae were recorded in 100% and 66.7% of photoquadrats sampled at ANA-06 and ANA-03. On reefs along the southeastern coast, where macroalgal diversity was highest, crustose coralline red algae were found in 58.3% and 83.3% of photoquadrats sampled at ANA-04 and ANA-05. Cyanobacteria only occurred in 2.1% of sampled photoquadrats.

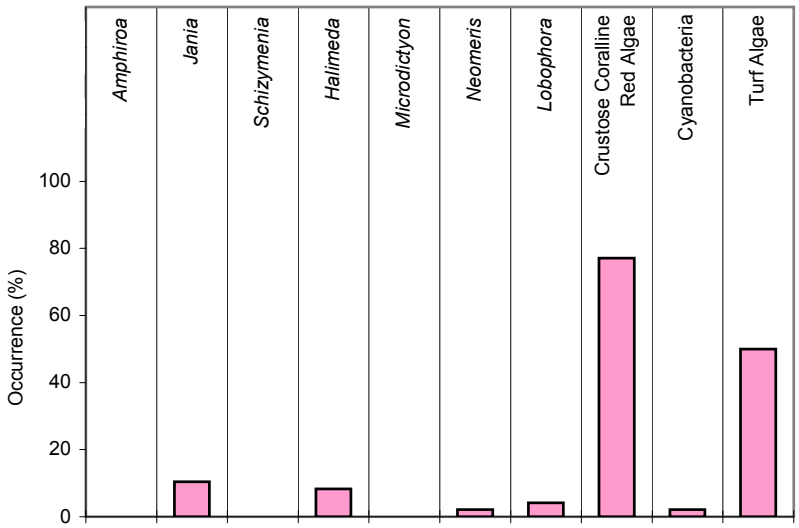


Figure 9.6.1d. Occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Anatahan during MARAMP 2003.

9.6.2 Coralline-algal-disease Surveys

No surveys for coralline-algal disease were conducted at Anatahan during MARAMP 2003, 2005, or 2007.

9.7 Benthic Macroinvertebrates

9.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were surveyed on forereef habitats around the island of Anatahan through benthic REA and towed-diver benthic surveys during MARAMP 2003. This section describes by group the results of these surveys. A list of additional taxa observed during the REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 4 REA benthic surveys and 12 towed-diver surveys were conducted. Because low-level volcanic activity continued through 2008, benthic macroinvertebrate surveys were not completed at Anatahan in 2005 or 2007. In those years, getting near this island was dangerous, and the large amount of volcanic ash in the water column made visibility close to zero. The restricted visibility during the MARAMP 2003 towed-diver surveys likely negatively biased estimated densities of macroinvertebrates. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea

urchins, may under-represent the number of individuals present. Overall, both the REA and towed-diver surveys revealed low daytime abundance of macroinvertebrates on forereef habitats around Anatahan.

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at 2 of the 4 REA sites surveyed and in 4 of the 12 towed-diver surveys conducted around Anatahan. The sample mean density of giant clams from REA surveys was 1.75 organisms 100 m^{-2} (SE 1.03), and the overall mean density from towed-diver surveys was 0.004 organisms 100 m^{-2} (SE 0.002). Survey results suggest that giant clams were most abundant at REA site ANA-05 in the eastern part of the south region with 4 organisms 100 m^{-2} (Fig. 9.7.1a). Among all towed-diver surveys around this island, 2 surveys completed in the south region had the highest mean densities of giant clams with 0.025 and 0.01 organisms 100 m^{-2}; segment densities from these surveys ranged from 0 to 0.102 organisms 100 m^{-2}.

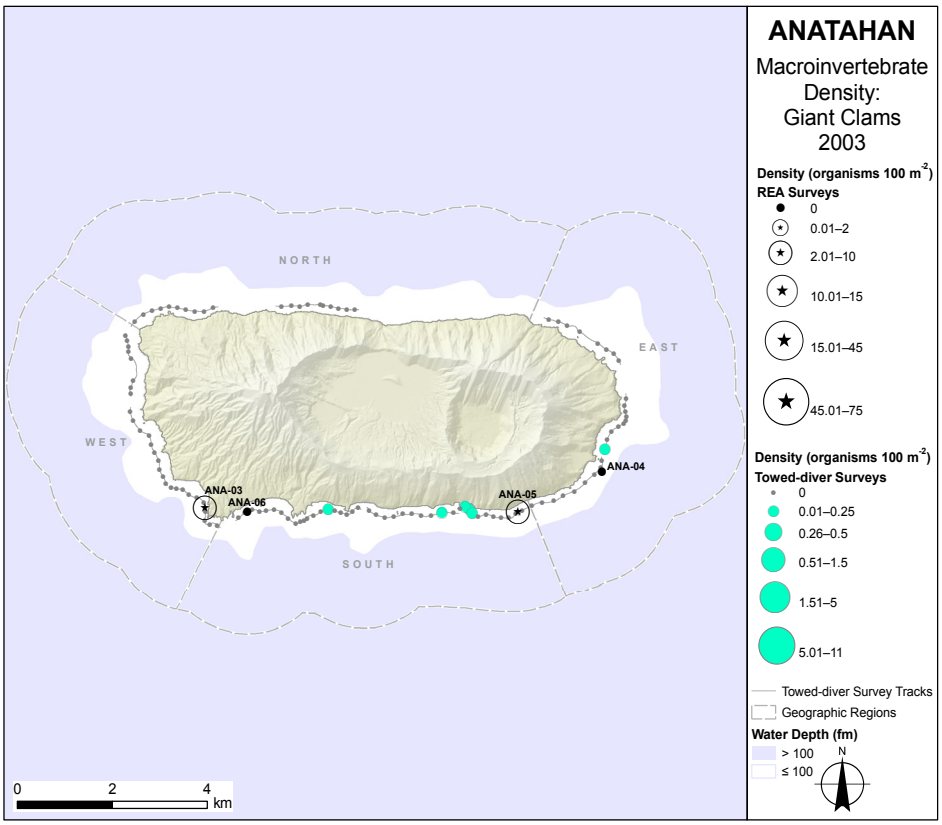


Figure 9.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003.

Crown-of-thorns Seastars

During MARAMP 2003, no crown-of-thorns seastars (*Acanthaster planci*) were observed at the 4 REA sites surveyed at Anatahan, but 1 of the 12 towed-diver surveys had recordings of COTS (Fig. 9.7.1b). The COTS density from this towed-diver survey in the south region was 0.001 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.046 organisms 100 m^{-2}.

Sea Cucumbers

During MARAMP in 2003, sea cucumbers were observed at 2 of the 4 REA sites surveyed and in 10 of the 12 towed-diver surveys conducted around Anatahan. The sample mean density of sea cucumbers from REA surveys was 1.5 organisms 100 m^{-2} (SE 1.19), and the overall mean density from towed-diver surveys was 0.1 organisms 100 m^{-2} (SE 0.03). Species from 2 genera were observed at REA sites: *Stichopus* and *Actinopyga*. *Stichopus* was the only genus recorded in the west region at ANA-03, the site with the highest sea cucumber density of 5 organisms 100 m^{-2}, and *Actinopyga* was observed only at ANA-06 in the western part of the south region. Among all towed-diver surveys around this island, the survey completed in the northern part of the west region had the highest mean density of sea cucumbers with 0.85 organisms 100 m^{-2};

segment densities from this survey ranged from 0 to 2.88 organisms 100 m^{-2} (Fig. 9.7.1c). The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.14 organisms 100 m^{-2}, recorded in the western part of the south region; segment densities ranged from 0 to 0.86 organisms 100 m^{-2}.

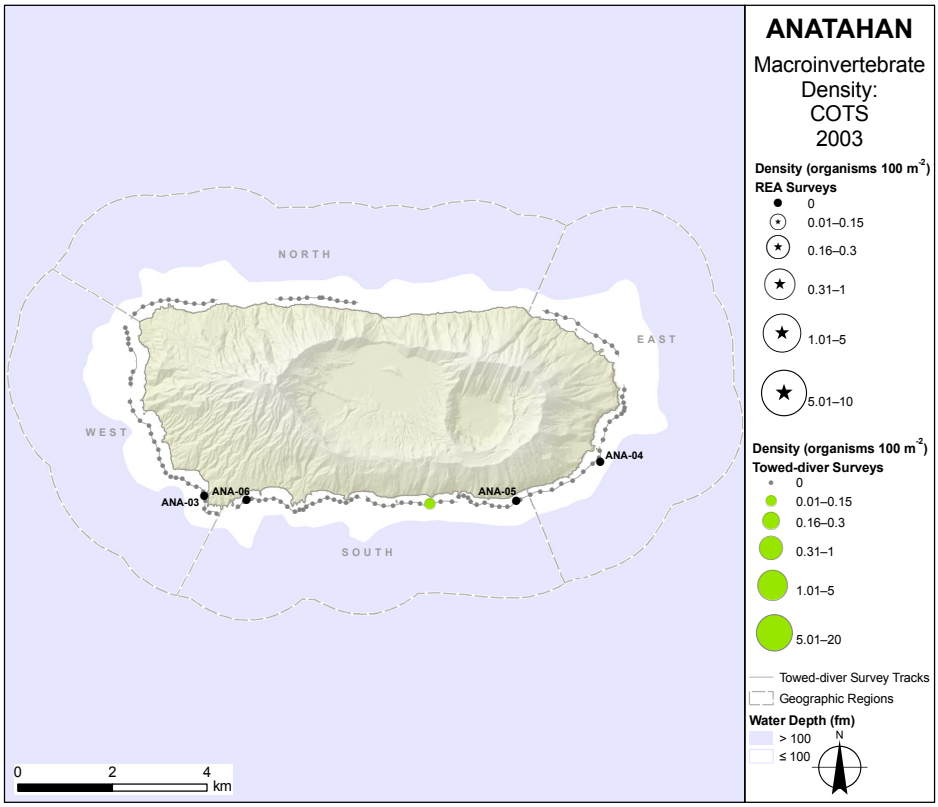


Figure 9.7.1b. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003.

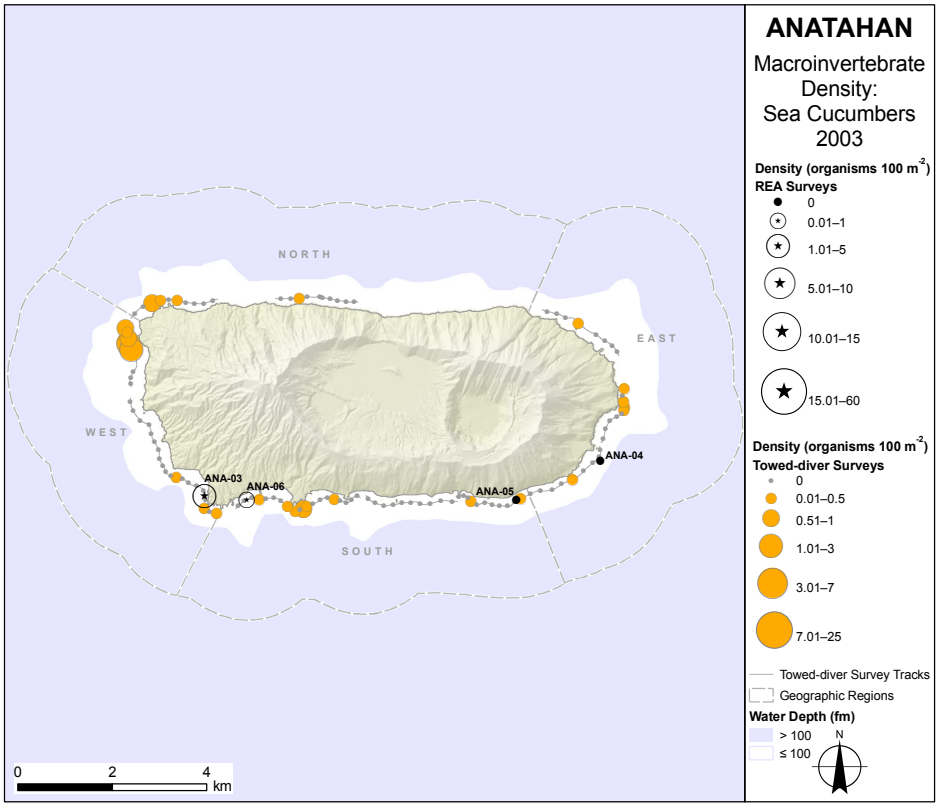


Figure 9.7.1c. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003.

Sea Urchins

During MARAMP 2003, sea urchins were observed at 3 of the 4 REA sites surveyed and in 6 of the 12 towed-diver surveys conducted around Anahatan. The overall sample mean of sea urchin density from REA surveys was 26.5 organisms 100 m^{-2} (SE 16.99), and the islandwide mean density from towed-diver surveys was 0.07 organisms 100 m^{-2} (SE 0.04). Survey results suggest that sea urchins were most abundant at ANA-05 in the eastern part of the south region with 72 organisms 100 m^{-2} (Fig. 9.7.1d). Rock-boring urchin species from the genus *Echinostrephus* accounted for 97% of sea urchins recorded at ANA-05 in the south region. Overall, species from the genus *Echinostrephus* accounted for 97% of sea urchins observed at all REA sites surveyed at Anatahan. Other genera found at Anatahan included *Echinothrix* and *Diadema.*

Among all towed-diver surveys conducted around Anatahan in 2003, the survey completed in the eastern part of the south region had the highest mean density of sea urchins with 0.69 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 4.68 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 0.04 organisms 100 m^{-2}, recorded in the western part of the south region; segment densities ranged from 0 to 0.21 organisms 100 m^{-2}.

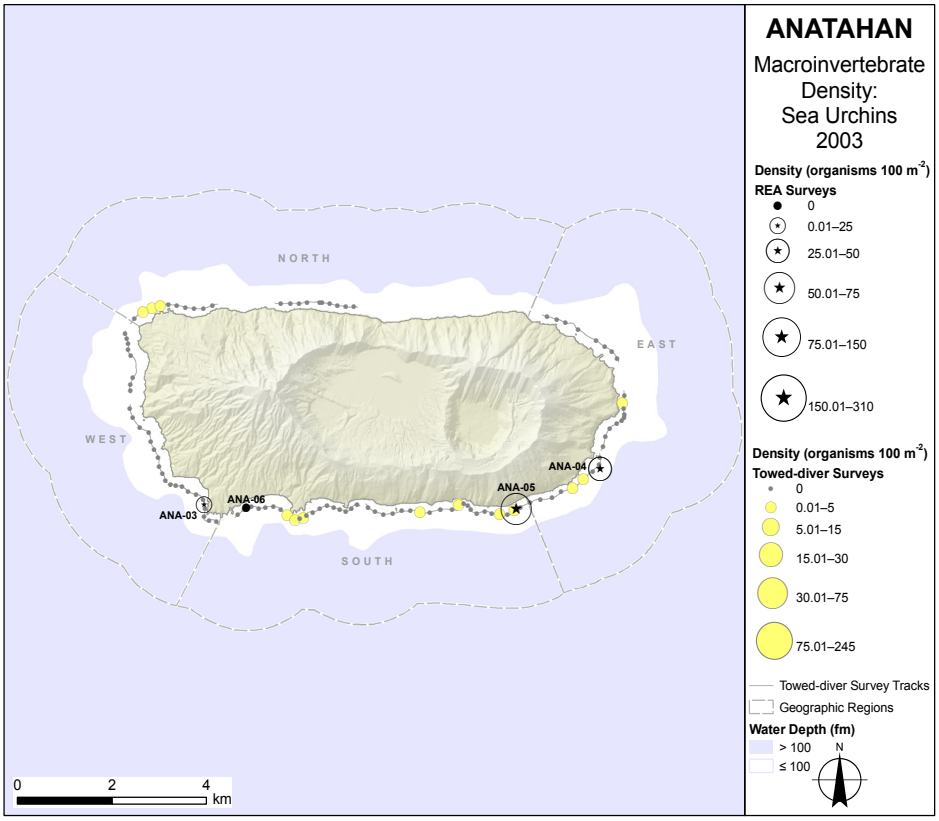


Figure 9.7.1d. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003.

9.8 Reef Fishes

9.8.1 Reef Fish Surveys

Anatahan Volcano erupted on May 10, 2003, and by the time that MARAMP 2003 occurred in September 2003, underwater visibility was low and towed-diver fish surveys were restricted to areas where visibility was > 5 m. Because low-level volcanic activity continued through 2008, fish surveys were not completed at Anatahan in 2005 or 2007.

Large-fish Biomass

During MARAMP 2003, 12 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around Anatahan. The overall estimated mean biomass of large fishes around this island, calculated as weight per unit area, was 0.22 kg 100 m^{-2} (SE 0.07). Biomass values for large fishes were highest along the southeastern coast, where jacks (Carangidae) and snappers (Lutjanidae) were observed (Fig. 9.8.1a). Jacks accounted for the greatest proportion (38%) or 0.08 kg 100 m^{-2} of overall mean large-fish biomass. The bluefin trevally (*Caranx melampygus*) was the major jack species, contributing 30% of overall mean biomass of large fishes. Reef sharks (Carcharhinidae) and snappers were the next-most important families in terms of biomass, accounting for 0.05 kg 100 m^{-2} and 0.04 kg 100 m^{-2} of overall mean large-fish biomass. During this survey period, 7 reef sharks were observed: 5 grey reef sharks (*Carcharhinus amblyrhynchos*) and 2 whitetip reef sharks (*Triaenodon obesus*). Grey reef sharks contributed 81% of shark biomass at Anatahan. The twinspot snapper (*Lutjanus bohar*) was the dominant snapper species by biomass, accounting for 84% of snapper biomass.

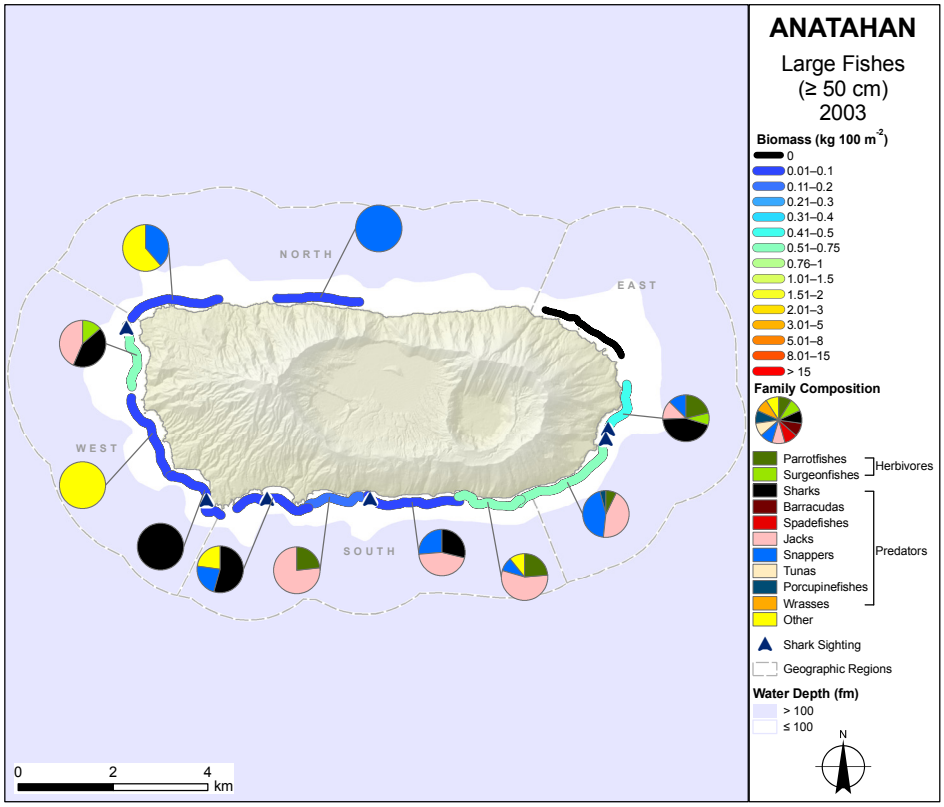


Figure 9.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted around Anatahan during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside the survey area over which it is shown.

Total Fish Biomass and Species Richness

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Anatahan during MARAMP 2003 was low compared to other sites in the Mariana Archipelago, with an overall sample mean of 2.81 kg 100 m^{-2} (SE 2.55). The highest biomass of 7.90 kg 100 m^{-2} was observed at REA site ANA-03 in the west region (Fig. 9.8.1b). Overall, snappers accounted for the largest proportion (34%) or 0.94 kg 100 m^{-2} of total fish biomass, and the twinspot snapper (*Lutjanus bohar*) contributed 51% of snapper biomass and 17% of total fish biomass. Surgeonfishes (Acanthuridae) were the second-most important family in terms of biomass, accounting for 0.47 kg 100 m^{-2} of total fish biomass. The striated surgeonfish (*Ctenochaetus striatus*) contributed 67% of surgeonfish biomass. No sharks were observed during this survey period.

Based on REA surveys conducted during MARAMP 2003, species richness was relatively low at Anatahan with a range of 1–34 species 100 m^{-2}. The highest diversity was found at ANA-03. Wrasses (Labridae) and damselfishes (Pomacentridae) were observed with the greatest diversity, each with 9 species recorded. The cleaner wrasse (*Labroides dimidiatus*) was the most numerically abundant wrasse species. Jacks (Carangidae) dominated counts, and the island trevally (*Carangoides orthogrammus*) was the most abundant jack species with > 20 individuals 100 m^{-2} recorded, nearly all of them < 10 cm in size. The brown surgeonfish (*Acanthurus nigrofuscus*) was the second-most numerically abundant species with 6.2 individuals 100 m^{-2} recorded.

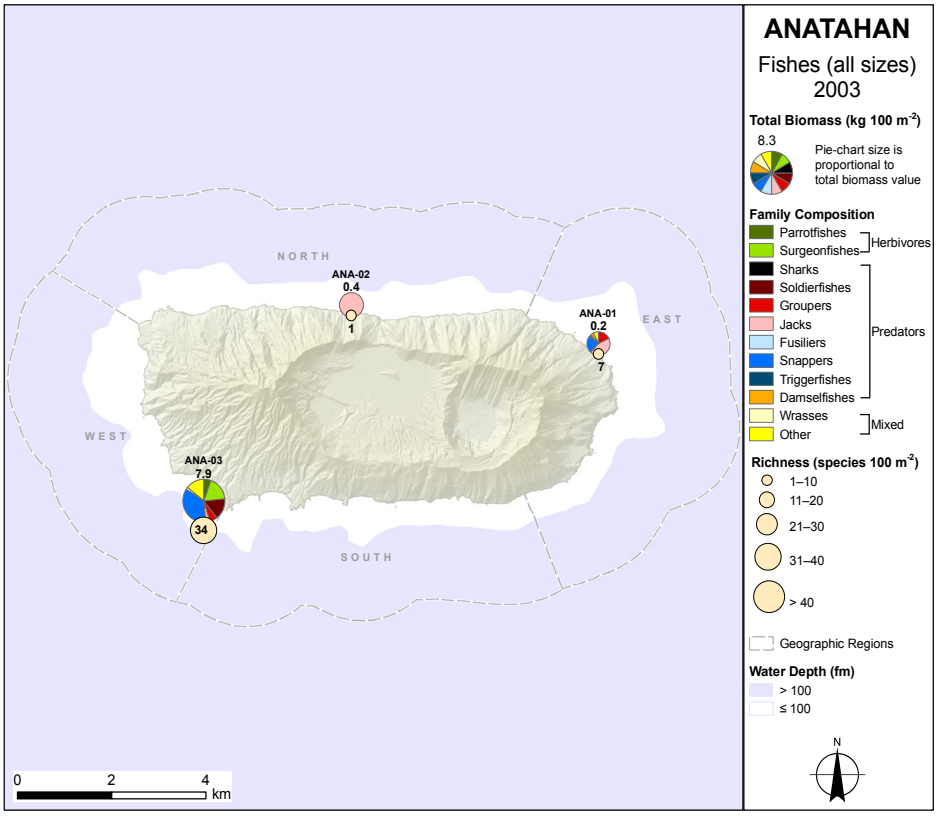


Figure 9.8.1b. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Anatahan during MARAMP 2003.

9.9 Marine Debris

9.9.1 Marine Debris Surveys

During MARAMP 2003, only 1 sighting of a man-made object in the south region was recorded during the 12 towed-diver surveys conducted around the island of Anatahan (Fig. 9.9.1a). No additional descriptive information about this observation was documented. No munitions, wrecks, or other man-made objects were observed. Observations of debris are positive identifications, but absence of reports does not imply lack of debris.

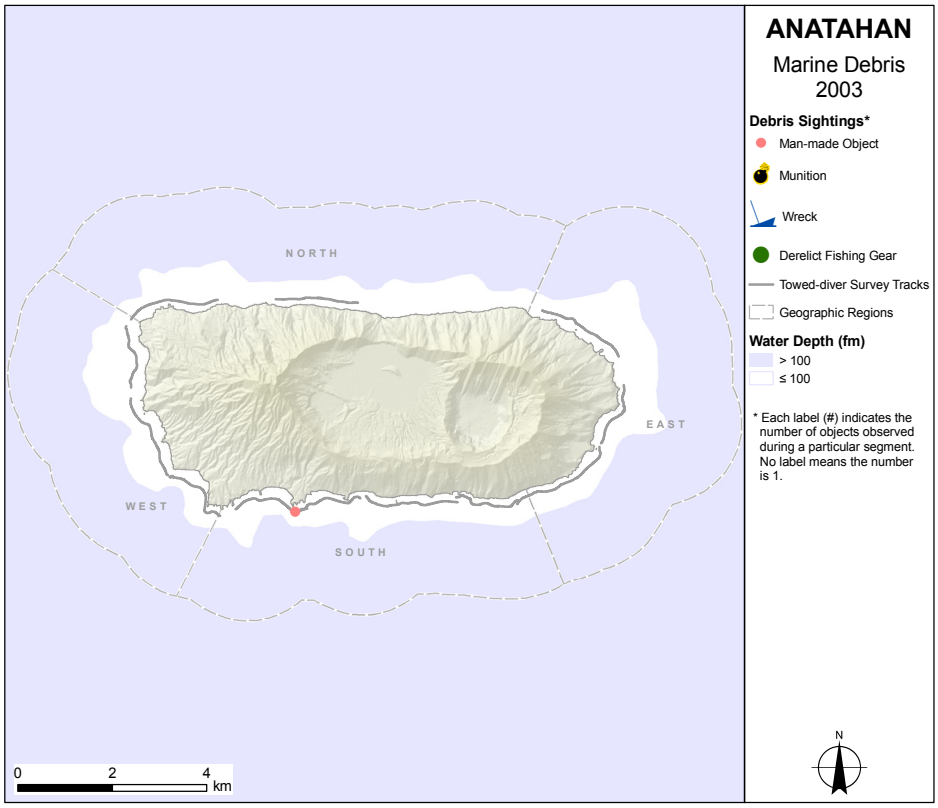


Figure 9.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003. The single, pink symbol indicates the presence of a man-made object.

9.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Anatahan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations on an archipelagic scale of various ecosystem elements and their potential relationships across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Anatahan as well as the other 13 islands covered in this report.

In May 2003, Anatahan experienced a large volcanic eruption from its eastern crater, the first eruptive activity recorded on this island. This eruption was accompanied by flows of volcanic ash, dust, and rocks as well as explosions of steam, mud, and other volcanic material. Much of the vegetation on Anatahan was damaged by this volcanic activity (Fig. 9.10a). Extensive ash plumes from this eruption were carried west by prevailing winds. The effects of this volcanic activity overwhelmed any discernable patterns in the distribution and condition of the coral reef ecosystem components that may have been present around Anatahan before 2003.

MARAMP surveys at Anatahan, conducted only 4 months after this major eruption in September 2003, were hampered by the reduced visibility caused by extensive ash deposits. Because of these poor conditions and safety concerns, no biological surveys were attempted at this island in 2005 or 2007, although oceanographic instruments were deployed and recovered.

Figure 9.10a. Anatahan, devoid of vegetation after the May 2003 volcanic eruption, as seen from the NOAA Ship *Hi`ialakai* in 2005. *NOAA photo by Robert Schroeder*



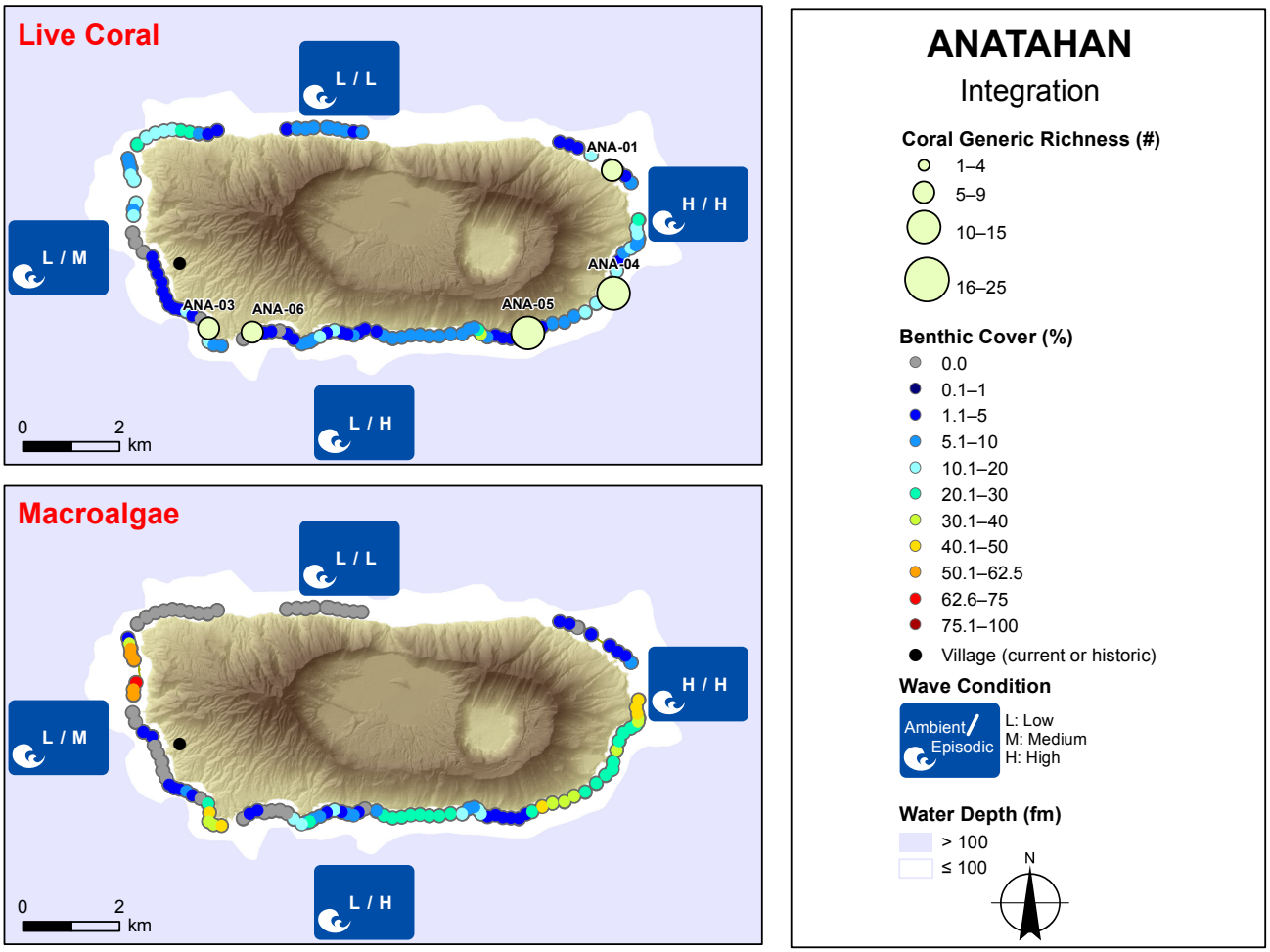


Figure 9.10b. Cover (%) observations of live hard corals and macroalgae from towed-diver surveys and coral generic richness from REA surveys conducted on forereef habitats around Anatahan during MARAMP 2003. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region. The black dot on the west side of Anatahan shows the approximate location of uninhabited Anatahan village.

The north and west regions appeared most affected by the volcanic eruption in 2003. In both regions, divers observed a seabed covered with a thick layer of ash above which only high coral pinnacles protruded. Live-hard-coral cover from towed-diver surveys in the north and west regions ranged from 0% to 30% (Fig. 9.10b). Cover estimates for both macroalgae and crustose coralline red algae were similarly low in both regions, compared to levels observed for other regions at Anatahan, with the exception of a section of the survey conducted in the west region, with macroalgal cover of 30%–75% (Fig. 9.10b). TOAD surveys conducted north of Anatahan, at greater depths (up to 100 m) than depths for towed-diver surveys, suggested a substrate of volcanic ash with no live corals or macroalgae, at least as observed in the analyzed video frames. Because of low visibility, no REA benthic surveys for corals or algae were conducted in these areas of high ash cover. The dominant habitats, described during towed-diver surveys, were sand-flats and reefs north of Anatahan and carbonate pavement, sand-flats, and boulders to the west. The abundance of recently dead corals and diversity of dead coral skeletons, observed during towed-diver surveys, suggested that reefs north of Anatahan may have been extensive prior to the eruption in 2003.

Both east and south of Anatahan, the habitat was described as sand-flats with boulders during towed-diver surveys. The observed ashfall was much thinner in the east and south regions than in the other regions, with a veneer of fine ash covering the reef rather than a thick blanket of ash. Prevailing wind at the time of the eruption in 2003 likely carried the ash plume to the west. As in the west and north regions, live coral cover was low, with means of 0%–30% from the 7 towed-diver surveys conducted in the east and south regions. The only exception was the coral cover of 30.1%–40% observed for 1 segment of a survey conducted in the south region (Fig. 9.10b). Macroalgal cover, with means of 0%–50%, was higher in the south and east regions than in the north region (Fig. 9.10b). Southeast of Anatahan, reefs appeared slightly less affected by volcanic ash than reefs observed elsewhere at this island. The highest levels of coral density and generic richness at Anatahan were found at REA sites ANA-04 and ANA-05 in the east and south regions (Fig. 9.10b), although live coral cover from nearby towed-diver surveys was low with means < 30%. Macroalgal cover from towed-diver surveys in the southern part of the east region was moderately high, within a range of 20.1%–50%, compared with results from other surveys conducted at Anatahan, and the highest algal diversity was recorded at ANA-04.

Biomass of large fishes (≥ 50 cm in TL) around Anatahan likely was underestimated during towed-diver surveys, as a result of the poor visibility caused by the suspended ash in the water column. Notably, estimated total fish biomass was low from REA surveys of fishes of all sizes and species conducted in the north region, where visibility was especially low. Visibility, at ~ 12 m, was greater in the southern part of the west region at ANA-03, where the highest values of total fish biomass (7.9 kg 100 m^{-2}) and species richness (34 species 100 m^{-2}) at Anatahan were observed.

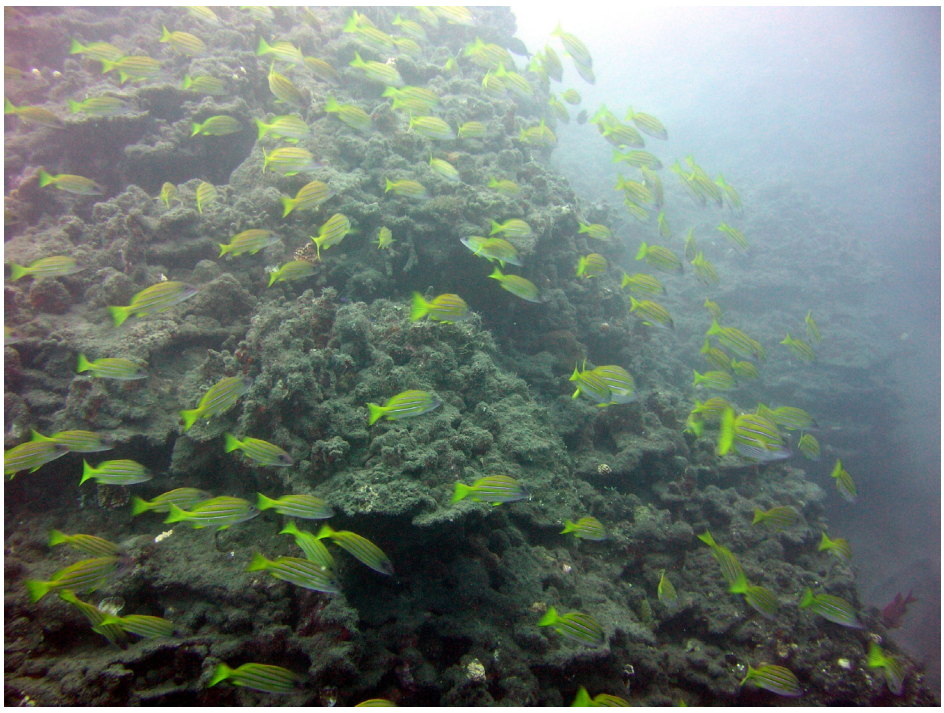


Figure 9.10c. Snappers (Lutjanidae) above ash-silted corals at Anatahan. *NOAA photo by Robert Schroeder*

Although the volcanic activity of Anatahan has not reached the level of a major eruption since 2003, ash likely continues to impact the coral reef ecosystems around this island. During MARAMP 2003, divers noted that rainfall washed ash from this island onto adjacent reefs. CTD casts conducted in 2007 in the south region at a depth of 10 m recorded low beam transmission (~ 91 %), and examination of vertical CTD profiles showed highly turbid waters at depths of 5–10 m, a result of ash and other volcanic debris in the water column (Figs. 9.4.1f and g in Section 9.4.1: "Hydrographic Data"). During surveys conducted at Anatahan in May 2009, divers reported that ash continued to cover much of the substrate around this island (Fig. 9.10c).

9.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Anatahan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Anatahan chapter also are included in the relevant discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Anatahan, relative to the ecosystems around all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Anatahan as well as some of the key natural processes influencing these ecosystems:

- The southernmost island of the CNMI's Northern Islands Municipality, Anatahan has a land area of 33.91 km^2 and is located 120 km north of Saipan and 40 km south of Sarigan.

- Because of increased seismic and thermal activity of Anatahan Volcano, this island has been mostly uninhabited in recent decades. Anatahan village, located on the southwestern part of this island, was covered with ash from the major volcanic eruption in 2003.

- The full extent to which the marine habitats have been affected by recent volcanic activity is not known. During the limited MARAMP surveys conducted in 2003, ~ 4 months after eruptions began in May 2003, divers observed large volumes of ash covering many of the coral reefs around Anatahan, mainly on the northern and western sides. Ash plumes continued intermittently through 2008 and likely have affected other areas at this island as a result of variable wind conditions.

- Wave model output shows ambient trade wind swells impact the east region. Episodic wave energy from storm tracks impact the south and east regions and to a lesser extent the west region.

- In 2005, and to a lesser extent 2007, the waters surrounding Anatahan were a deep brown color because of the copious amounts of ash and volcanic input. Visibility was < 0.6 m, and no benthic or fish surveys were conducted in either year. This entire island was void of vegetation, so any precipitation likely resulted in strong terrigenous input to surrounding waters.

- The overall mean for live coral cover around Anatahan was 8%, estimated from towed-diver surveys conducted during MARAMP 2003.

- Generic diversity for marcroalgae at Antahan, based on REA surveys conducted in 2003, was much higher in the east region than in the west region. The highest macroalgal cover from a towed-diver survey conducted at Anatahan was recorded in the west region. The north region was largely devoid of macroalgae. Crustose-coralline-red-algal cover was very low in the north and west regions, compared to results from other islands in the Mariana Archipelago.

- Because of reduced visibility due to ash in the water column from recent volcanic activity, fish surveys in 2003 were restricted to areas where visibility was estimated at > 5 m. As a result, surveys were conducted haphazardly around this island, and the overall mean biomass of large fishes (≥ 50 cm in TL) was very low compared to the levels observed at other islands in this archipelago. Biomass of large fishes from towed-diver surveys was highest along the southeastern coast, where jacks (Carangidae) and snappers (Lutjanidae) were observed. This area appeared to be least affected by ashfall.

- Total fish biomass from REA surveys of fishes of all sizes and species conducted off north Anatahan during MARAMP 2003 was very low compared to values found at other islands in the Mariana Archipelago, with surveys hampered by reduced visibility. The highest total fish biomass was seen in the west region at ANA-03, where snappers accounted for the largest proportion of total fish biomass at that site. No sharks were recorded during REA surveys in 2003.

- Very few giant clams, crown-of-thorns seastars (*Acanthaster planci*), or sea cucumbers were observed in 2003 during both towed-diver and REA surveys conducted around Anatahan.

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10 SARIGAN

10.1 Introduction

The island of Sarigan is located at 16°42′ N, 145°78′ E, in the middle of the Mariana Arc between Anatahan and Guguan. This island is ~ 2.5 km wide and 2.7 km long with a land area of 4.47 km^2, making it the fourth-smallest island of the Mariana Archipelago (Fig. 10.1a). The highest elevation on Sarigan, at 538 m, is on its summit crater. Located south of the center of Sarigan, this summit crater is 750 m wide and surrounded by steep slopes to the south and more gently sloping hills to the north (Fig. 10.1b).

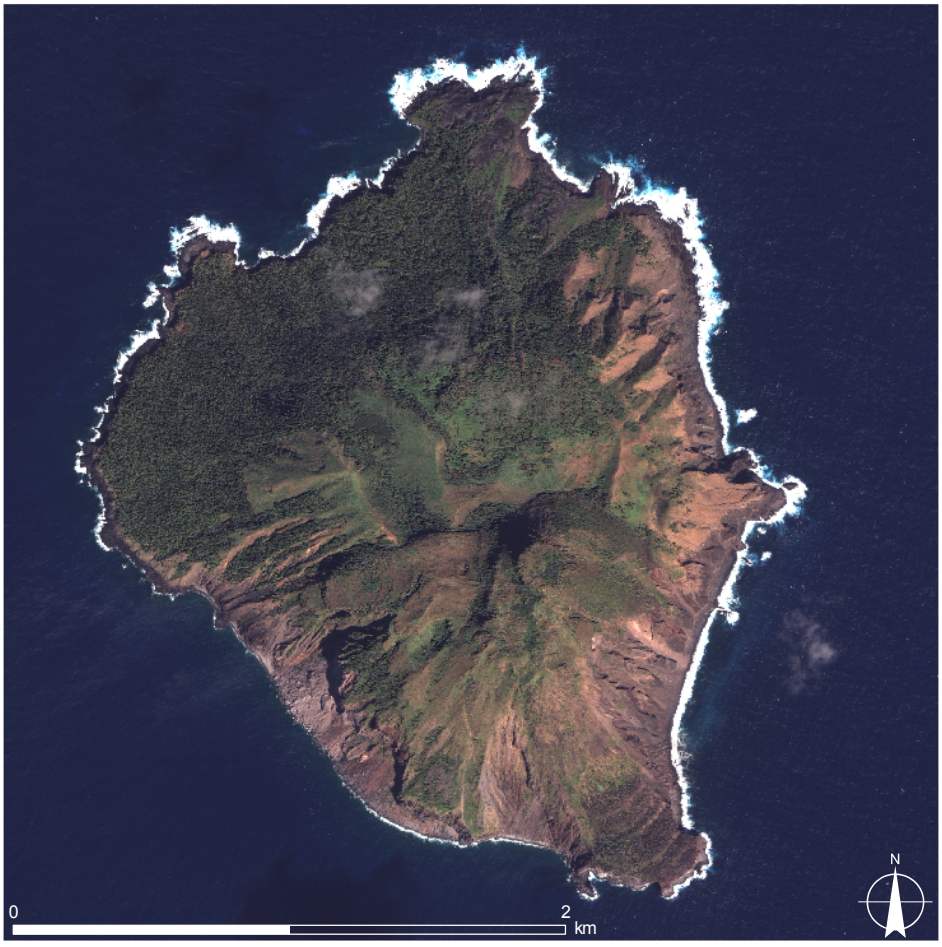


Figure 10.1a. Satellite image of Sarigan (© 2004 DigitalGlobe Inc. All rights reserved).



Figure 10.1b. Sarigan viewed from the south. *NOAA photo*

10.1.1 History and Demographics

Historically, Sarigan was inhabited by the Chamorro people, as suggested by the archaeological artifacts, such as pottery and latte sets, found by the German administrator Georg Fritz in the early 1900s (Spennemann 2006). This island was later used as a penal colony, which was established in 1900 by German administrators. Prisoners of this colony both established and maintained a copra plantation. In 1906, the prisoners were removed when Japanese interests leased the land for commercial copra production (Marianas Avifauna Conservation Working Group 2008). Later, in 1909, the German administration leased Sarigan to the trading association Pagan Gesselschaft for a period of 3 years for the exploitation of bird plumage. During this time, up to 8 Caroline islanders and 6 Japanese bird catchers were resident on this island, and this population was later reduced to 2 persons as a result of low bird counts. The lease to this trading association was terminated early in 1911 because, in violation of the conditions of the lease, no planting of coconut palms had occurred (Spennemann 1999b).

In the 1930s, 10–20 families lived on Sarigan, but all residents were removed after World War II (Marianas Avifauna Conservation Working Group 2008). Sarigan currently is thought to be uninhabited. However, the *Northern Islands Homestead Act of 2008*, which was signed into law by the Governor of the Commonwealth of the Northern Mariana Islands (CNMI) in January 2010, may increase the population in the coming years. This legislation, CNMI Public Law 16-50, recognizes that residents of the "islands north of Saipan" have no formal homesteads, allows residents to have agricultural lots and facilities, encourages resettlement by former residents, and initiates and promotes economic development.

10.1.2 Geography

Sarigan is formed by the exposed portion of a largely submarine volcano with a summit crater containing a small ash cone. Lava flowed from 2 lava domes near the south crater rim, reached the coast, and extended out to sea creating the steep cliffs and irregular shorelines of this island (Siebert and Simkin 2002–). The summit crater is surrounded by very steep slopes to the south, while the slopes around the north of Sarigan are much gentler (Fig. 10.1.2a and b). The slopes of this island are dissected with ravines and end in coastal cliffs. In the center of this island, below the crater, a small plateau is present.

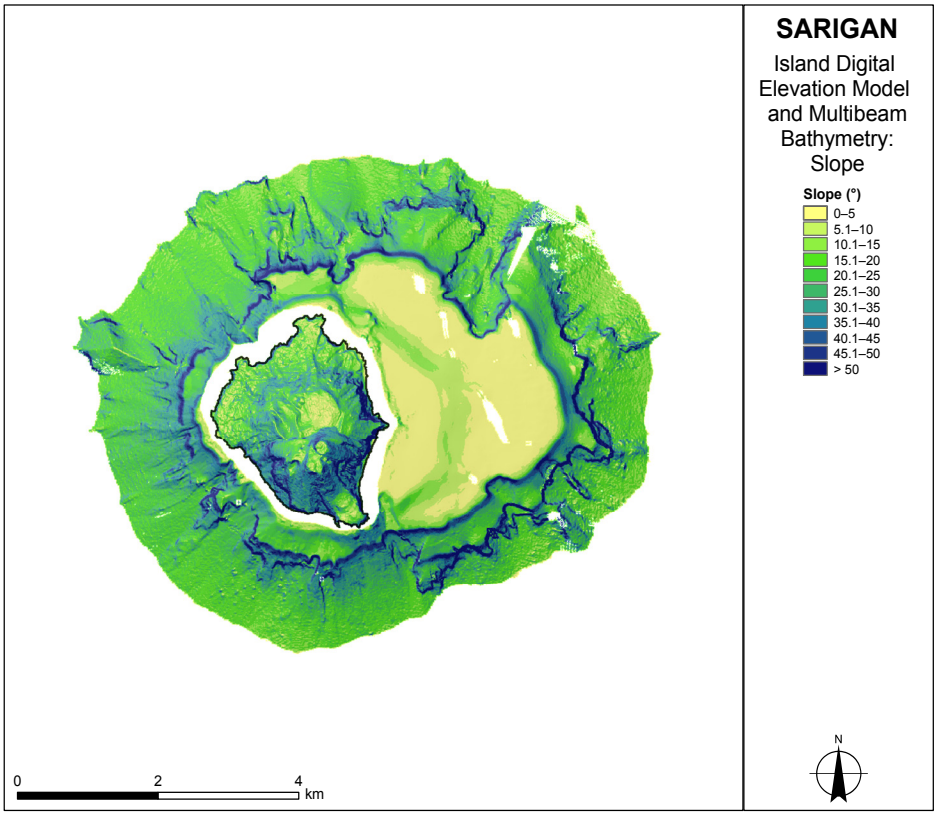


Figure 10.1.2a. Combined slope map using the digital elevation model (grid cell size: 10 m) and multibeam bathymetric data (grid cell size: 10 m) for Sarigan. Values reflect the maximum rate of change in elevation between neighboring cells.

The date of the last eruption of the Sarigan volcano is not known, but the sparse vegetation on the lava flows of this island suggests that the most recent eruption and lava flows occurred during the Holocene Epoch (11,700 years to present; Siebert and Simkin 2002–).



Figure 10.1.2b. Sarigan viewed from the east, showing the summit crater left (or south) of center, steep southern slopes, flat plateau in center, and gentler northern slopes. *NOAA photo by Robert Schroeder*

The steepest slopes of this island, on the east and south sides, are sparsely vegetated with grasses and ferns, while the more gradual slopes on the north and west sides support native and coconut forests (Fig. 10.1.2c). Native forests also are common within the ravines, and patchy stands of trees are present on the plateau. Although native forests have been damaged severely by feral animals, most notably goats, an eradication program managed by the CNMI Division of Fish and Wildlife (DFW) has enabled some recovery to take place in recent years (Martin et al. 2008).

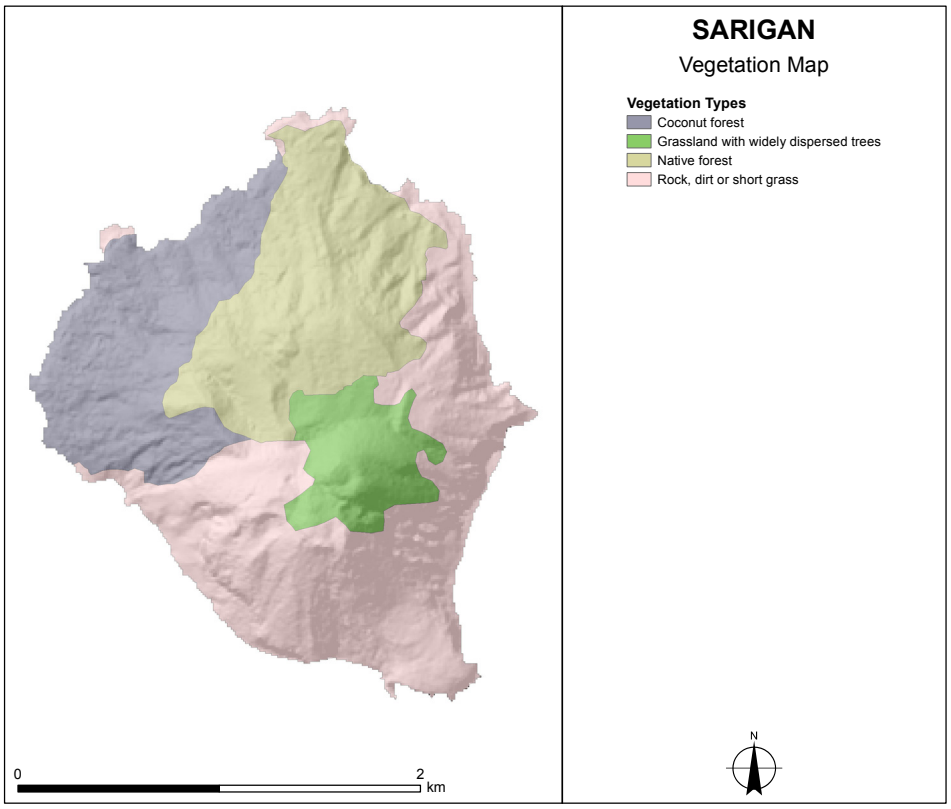


Figure 10.1.2c. Map showing approximate locations of the 4 major vegetation types found on Sarigan, based on surveys conducted in 2006 by the CNMI DFW (Martin et al. 2008).

10.1.3 Environmental Issues on Sarigan

Sarigan supports a number of important species of flora and fauna. Five bird species have been observed during surveys on Sarigan: the endangered Micronesian megapode (*Megapodius laperouse*), a bird listed both as an endangered species federally (U.S. Fish and Wildlife Service) and as a threatened or endangered species locally (Berger et al. 2005) as well as the Micronesian honeyeater (*Myzomela rubrata*), Micronesian starling (*Aplonis opaca*), collared kingfisher (*Halcyon chloris*), and white-throated ground dove (*Gallicolumba xanthonura*), which is locally protected from hunting by regulation (Berger et al. 2005). During surveys conducted in 2006 by the CNMI DFW, the Mariana fruit-dove (*Ptilinopus roseicapilla*), a species federally protected by the *Migratory Bird Treaty Act* (List… 2010) and listed locally as threatened or endangered (Berger et al. 2005), was recorded for the first time on Sarigan (Martin et al. 2008). This island has been selected to receive relocated endemic birds from Saipan, Rota, and Tinian, where they are threatened by the introduced brown treesnake (*Boiga irregularis*), which already has resulted in the extinction of 9 forest birds and 2 native lizards on Guam (Marianas Avifauna Conservation Working Group 2008). Sarigan also supports a small population (~ 150–200) of the Mariana fruit bat (*Pteropus mariannus mariannus*), an endemic subspecies listed federally as threatened and locally as threatened or endangered (Martin et al. 2008; U.S. Fish and Wildlife Service; Berger et al. 2005).

Anthropogenic pressures around Sarigan are relatively few, given its isolated location and lack of inhabitants. Feral animals have caused severe destruction to the natural ecosystems, although some recovery has occurred. The possible establishment of homesteads on Sarigan and the infrastructure development that would come with them could affect the native flora and fauna of this island if these resources go unmanaged. Fishing activity within the CNMI tends to focus around the southern islands of the Mariana Archipelago, with multiday fishing trips on the islands and banks south of Guguan (Western Pacific Fishery Management Council 2009).

10.2 Survey Effort

Biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing the coral reef ecosystems around the island of Sarigan since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 3 geographic regions around

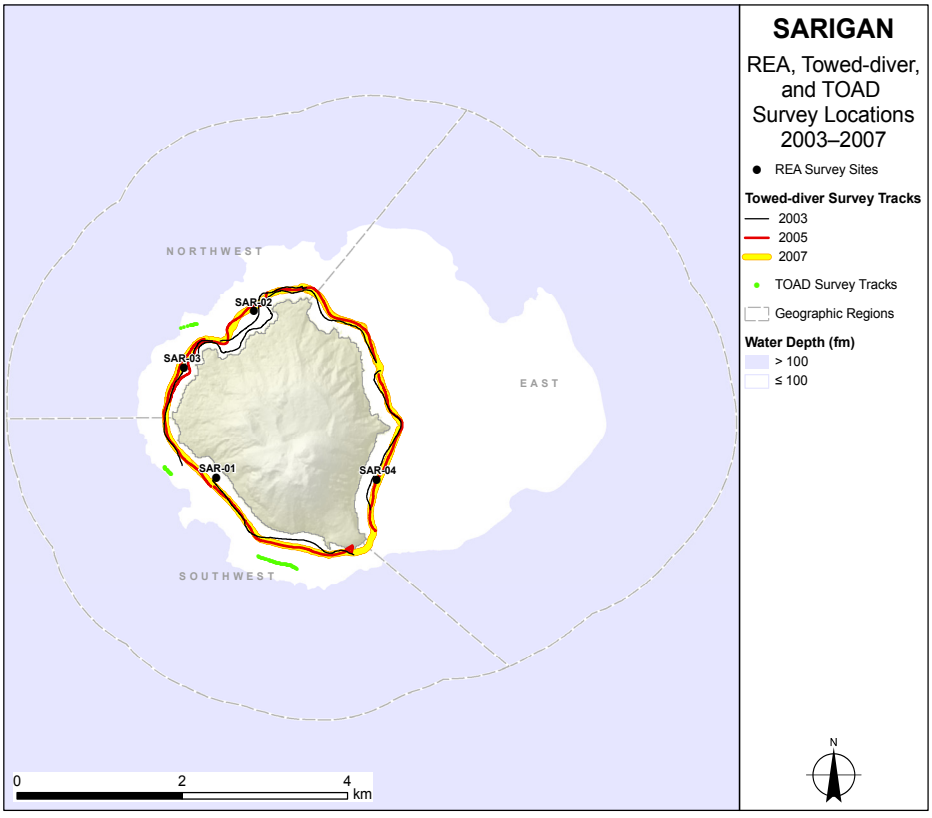


Figure 10.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Sarigan during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 3 geographic regions: northwest, east, and southwest.

Sarigan are delineated in Figure 10.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Sarigan. Potential reef habitat is represented by a 100-fm contour shown in white on this map.

Benthic habitat mapping data were collected around Sarigan using a combination of acoustic and optical-survey methods. MARAMP benthic habitat mapping surveys conducted around this island with multibeam sonar covered a total area of 2228 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 10.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Sarigan was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 10.5–10.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 10.2a, along with their mean depths and total areas or length.

Table 10.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Sarigan during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	3	3	3
	Mean Depth (m)	12.5 (SD 0.5)	12.8 (SD 0.3)	12.8 (SD 0.3)
Benthic	Number of Surveys	3	3	3
	Mean Depth (m)	12.5 (SD 0.5)	12.8 (SD 0.3)	12.8 (SD 0.3)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	6	5	6
	Total Survey Area (ha)	10.6	10.1	12.3
	Mean Depth (m)	12.1 (SD 4.3)	16.3 (SD 1.5)	16.6 (SD 1.8)
TOAD		**2003**		
	Number of Surveys	3		
	Total Length (km)	0.78		

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Sarigan were collected using (1) subsurface temperature recorders (STR) designed for long-term observations of high-frequency variability, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-a analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007 (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 10.2b. Results are discussed in Section: 10.4: "Oceanography and Water Quality."

Table 10.2b. Numbers of STRs deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Sarigan during MARAMP 2003, 2005, and 2007. One type of instrument, a subsurface temperature recorder (STR) was installed on the seafloor. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Additional deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
STR	1	1	1	1	2	2	–
CTD Casts	2003	2005		2007			Total
Shallow-water Casts	7	9		10			26
Deepwater Casts	–	4		2			6
Water Samples		2005		2007			Total
		1		4			5

Towed-diver Surveys: Depths

Figures 10.2b and c illustrate the locations and depths of towed-diver-survey tracks around Sarigan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

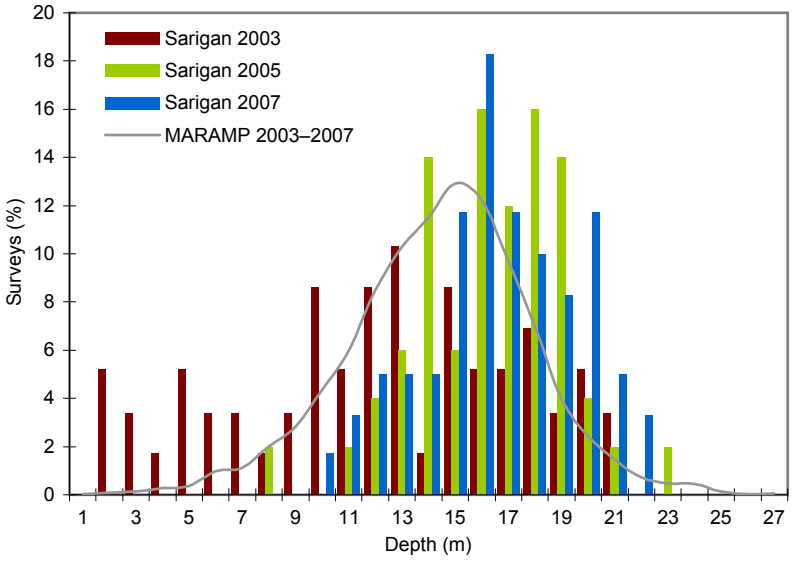


Figure 10.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Sarigan during MARAMP 2003. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during 2003, 2005, and 2007.

During MARAMP 2003, 6 towed-diver surveys were conducted along the forereef slopes around Sarigan (Figs. 10.2b and c, top panel). The mean depth of all survey segments was 12.1 m (SD 4.3), and the mean depths of individual surveys ranged from 3.8 m (SD 2.5) to 14.9 m (SD 3.5).

During MARAMP 2005, 5 towed-diver surveys were conducted along the forereef slopes of Sarigan (Figs. 10.2b and c, middle panel). The mean depth of all survey segments was 16.3 m (SD 1.5), and the mean depths of individual surveys ranged from 14.3 m (SD 4) to 18.5 m (SD 3.2).

During MARAMP 2007, 6 towed-diver surveys were conducted along the forereef slopes of Sarigan (Figs. 10.2b and c, bottom panel). The mean depth of all survey segments was 16.6 m (SD 1.8), and the mean depths of individual surveys ranged from 14.9 m (SD 2.7) to 19.2 m (SD 3).

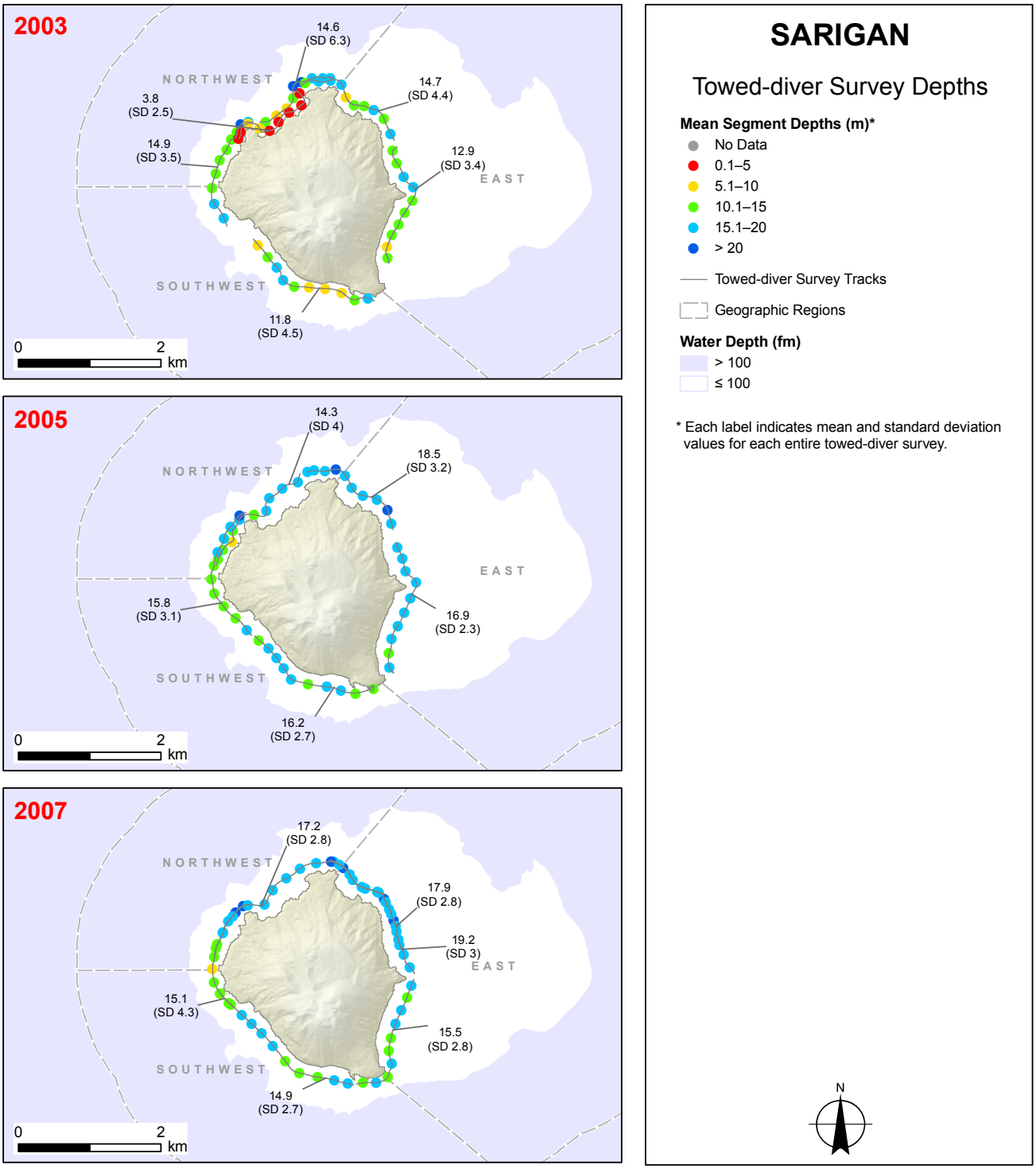


Figure 10.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Sarigan during MARAMP 2003, 2005, 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

10.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Sarigan were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 15–1900 m. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of < 207 m.

10.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 10.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around the islands of Sarigan, Alamagan, Anatahan, and Guguan, as well as Zealandia Bank, during MARAMP 2007 encompassed an area of 2228 km^2. Near-complete coverage was achieved around Sarigan, with multibeam data obtained in waters down to 1500 m west of Sarigan and to 1900 m east of this island.

Multibeam bathymetry acquired around Sarigan reveals an extensive shallow shelf surrounding this island (Fig. 10.3.1a, top panel). This shelf, at depths of 30–150 m, extends for 2.7 km east of Sarigan. Ridges and canyons radiate from this shelf. West of this island, two large ridges also are shown in the multibeam bathymetry. On the flanks, the multibeam bathymetry reveals blocks of material that may be the result of mass wasting (the movement of soil and surface materials by gravity). North of this island at a depth of 1250 m, a small cone on the flanks rises to a depth of 930 m. A larger cone, south of Sarigan, rises to a depth of 720 m and connects to the main flanks by a ridge at a depth of 880–890 m.

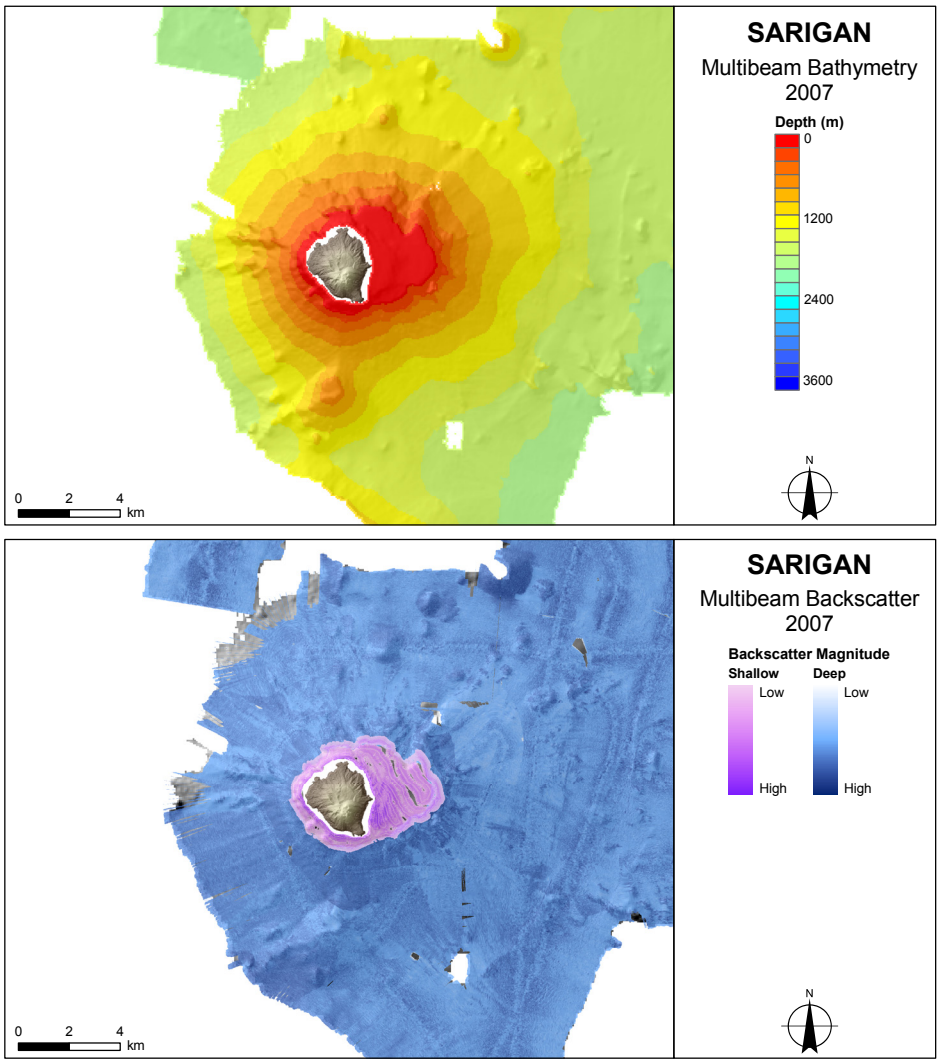


Figure 10.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Sarigan during MARAMP 2007 in depths of 15–1900 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30-kHz Konsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

As described in Chapter 2: "Methods and Operational Background," Section 2.2: "Benthic Habitat Mapping and Characterization," multibeam backscatter intensity can provide information about the roughness and hardness of the seafloor. Backscatter data aquired around Sarigan have artifacts in some areas, for example, southwest of this island, but patterns in backscatter intensity mainly appear to be related to topographic features. Backscatter intensity on the flanks surrounding the shallow shelf is high, suggestsing that these areas may be characterized by hard substrates (Fig. 10.3.1a, bottom panel). Similarly, high backscatter values were recorded on the cone north of Sarigan and where blocky material is shown along the flanks. In contrast, the larger cone south of Sarigan had low backscatter values, suggesting that this area may be covered with soft sediments.

High-resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in nearshore (depths of 0–800 m) waters around Sarigan were combined into a grid at 10-m resolution to allow for the identification of fine-scaled features (Fig. 10.3.1b). These high-resolution data were used to derive maps of slope (Fig. 10.3.1c), rugosity (Fig. 10.3.1d), and bathymetric position index (BPI) zones (Fig. 10.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Sarigan.

The high-resolution bathymetry data (Fig. 10.3.1b) reveal the presence of several terraces rather than just one shelf. The slope map shows that the shallowest mapped seabed has a complex, irregular topography (Fig. 10.3.1c). Below this area, a flat, low-rugosity shelf is located at a depth of 40–60 m and extends for 700 m (Fig. 10.3.1d). This shelf is surrounded by low to moderately steep slopes of 10º–20º with low rugosity levels. A more extensive, low-rugosity shelf, at depths of 100–160 m, is 1.3 km at its widest point. These 2 shelves are delineated clearly through the BPI analysis. The very steep slopes of > 50º that border this deeper shelf continue around this island, although, west of Sarigan, channels and ridges intersect this shelf break. Moderately steep flanks then descend to depths of 250–400 m, whereupon a second steep edge is reached. Below it, the flanks are characterized by higher rugosity levels.

In the shallowest waters surveyed, the BPI analysis identifies reef crests. However, this classification is likely an artifact of the methodology, since no data are available for immediately inshore areas and no comparison can be made to the innermost cells of the grid. Instead, these areas probably should be characterized as slopes.

Overall, the seabed around Sarigan has a fairly complex topography, as revealed by the BPI analysis, which shows that the sloping flanks below the flat zones are interrupted by crests and depressions (Fig. 10.3.1e).

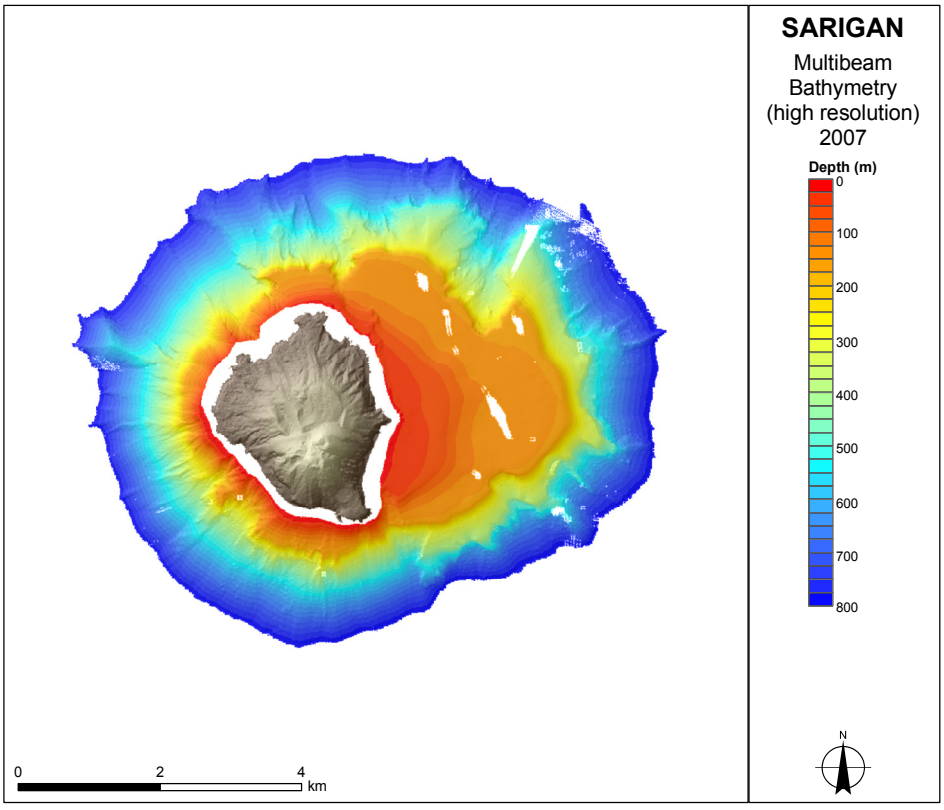


Figure 10.3.1b. High-resolution multibeam bathymetry collected around Sarigan during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives.

Figure 10.3.1c. Slope (°) of 10-m bathymetric grid around Sarigan. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades.

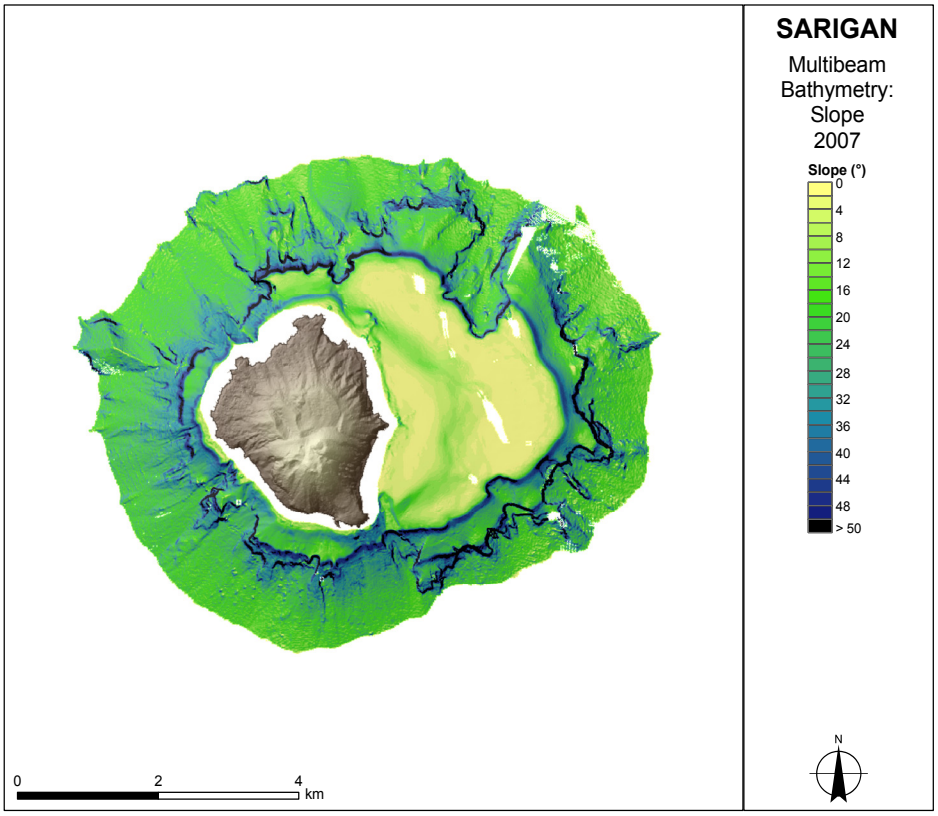
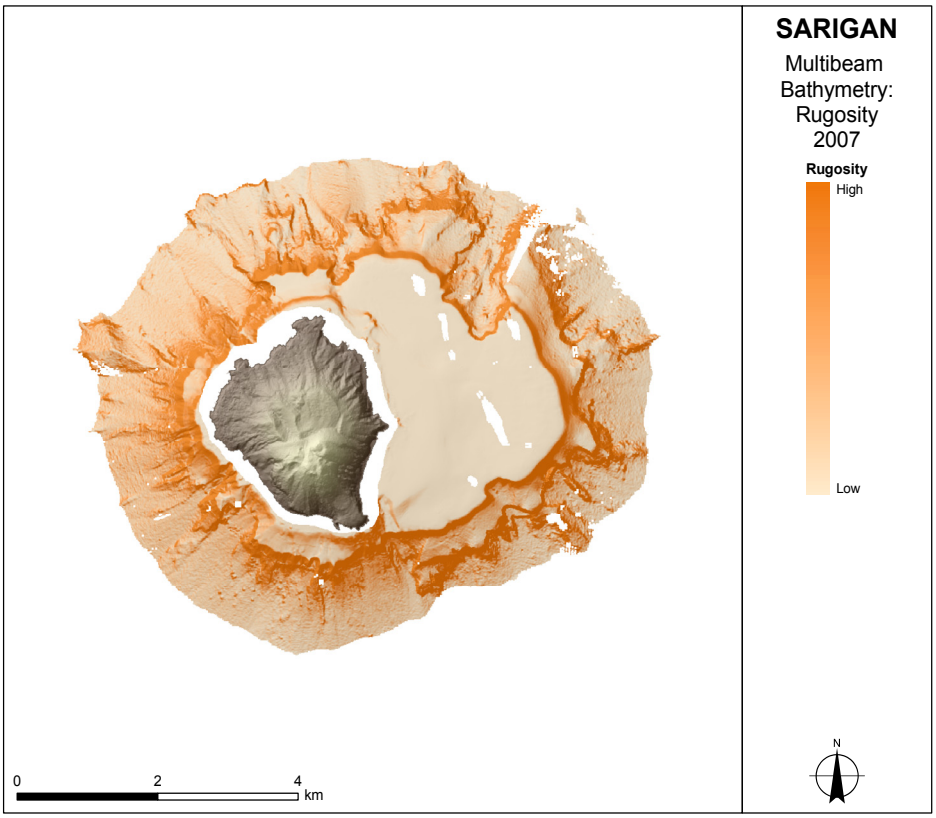


Figure 10.3.1d. Rugosity of 10-m bathymetric grid around Sarigan. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.



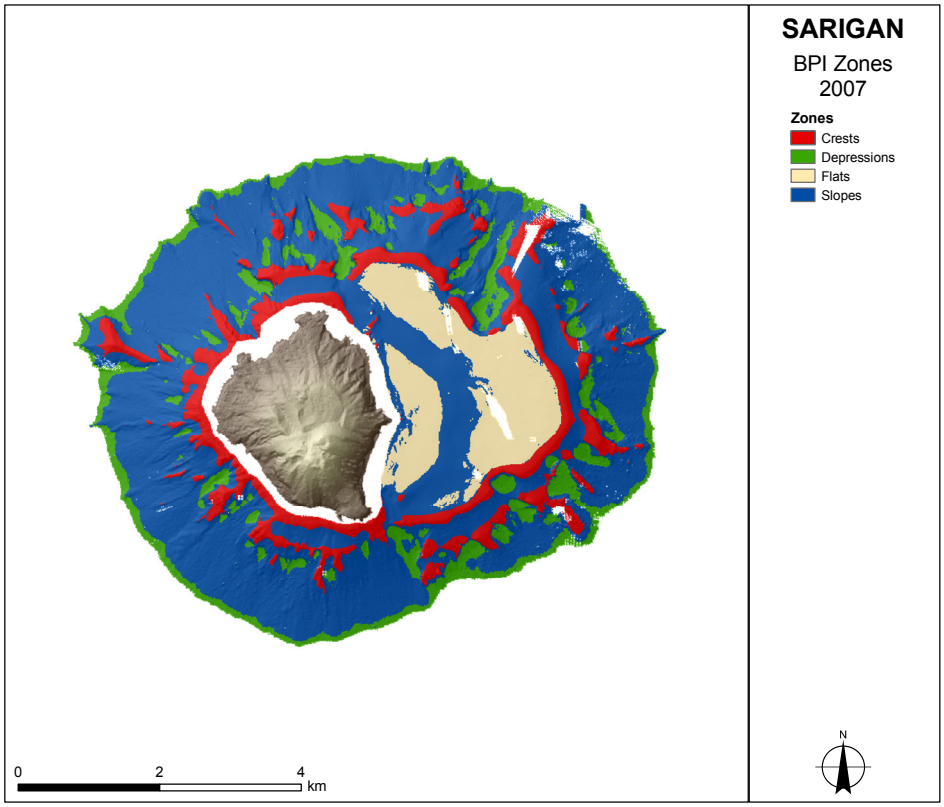


Figure 10.3.1e. BPI zones of 10-m bathymetric grid around Sarigan derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

High-resolution Multibeam Backscatter and Derivatives

High-resolution backscatter data acquired around Sarigan have some artifacts, such as gaps in the data, and some sharp contrasts between swaths west of this island that did not appear to relate to any topographic features (Fig. 10 3.1f). To reduce the effect of these artifacts on the hard–soft classification, the backscatter data were clipped to a depth of 100 m prior to carrying out the classification. Although the hard–soft analysis is a useful tool to help interpret the seabed character around Sarigan, it should be noted that the ground-truth data underlying the classification was based on other islands with different geological characteristics, and no specific ground-truth data were available from Sarigan to inform the classification. Nevertheless, the classification does provide some indication of the distribution of different substrate types around this island.

East of Sarigan, the more extensive coverage shows some distinct patterns in the recorded backscatter intensity. Most noticeably, linear streaks in the backscatter suggest variation in the acoustic nature of the substrate upon the shelf (Fig. 10.3.1f). These same streaks are highlighted in the hard–soft analysis, which classifies alternating streaks of hard and soft substrate (Fig. 10.3.1g). No topographic features can be seen on the high-resolution bathymetry that associate with this pattern; however, the continuation of this pattern across several adjacent swaths suggest that these streaks are not likely to be artifacts of the data. Rather, the linear streaks may reflect the distribution of soft sediments across the shelf top, with higher backscatter values corresponding to areas where soft sediments are thinner or absent. No optical validation data are available in this area to confirm the nature of the substrate. Elsewhere on the shelf, the distribution of hard and soft substrates appears to be more uniform.

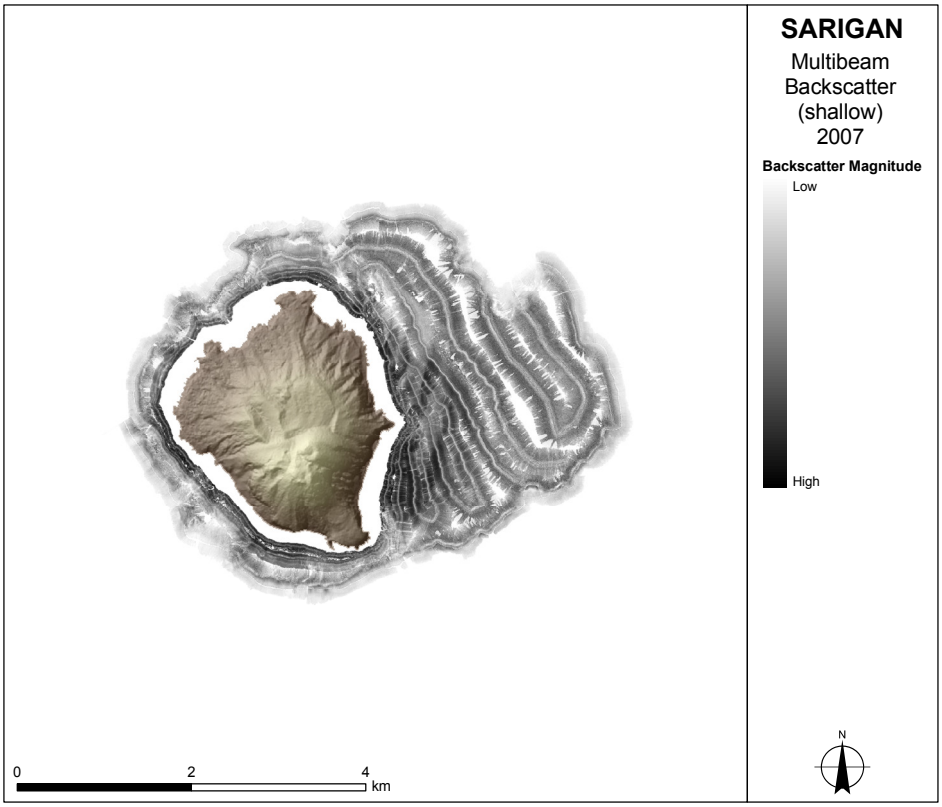


Figure 10.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) collected around Sarigan during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

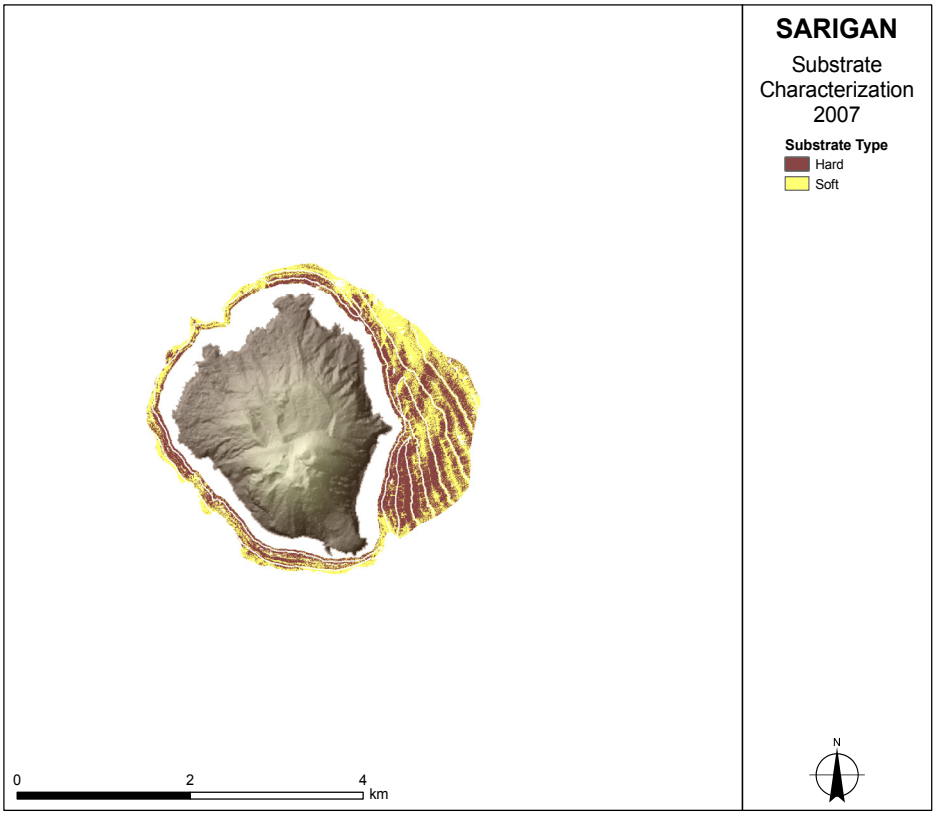


Figure 10.3.1g. Hard and soft substrates (grid cell size: 5 m) at depths < 100 m, based upon an unsupervised classification of multibeam bathymetry and backscatter data acquired around Sarigan in 2007. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

10.3.2 Optical Validation

During MARAMP 2003, a total of 3 TOAD optical-validation surveys, covering a distance of 0.78 km in depths of 76–207 m, were conducted around Sarigan (Fig. 10.3.2a). Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live coral cover.

Covering a distance of 33 km in depths of 2–23 m, 17 towed-diver optical-validation surveys of forereef habitats, were conducted around Sarigan during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover, and habitat complexity using a 6-level categorical scale from low to very high.

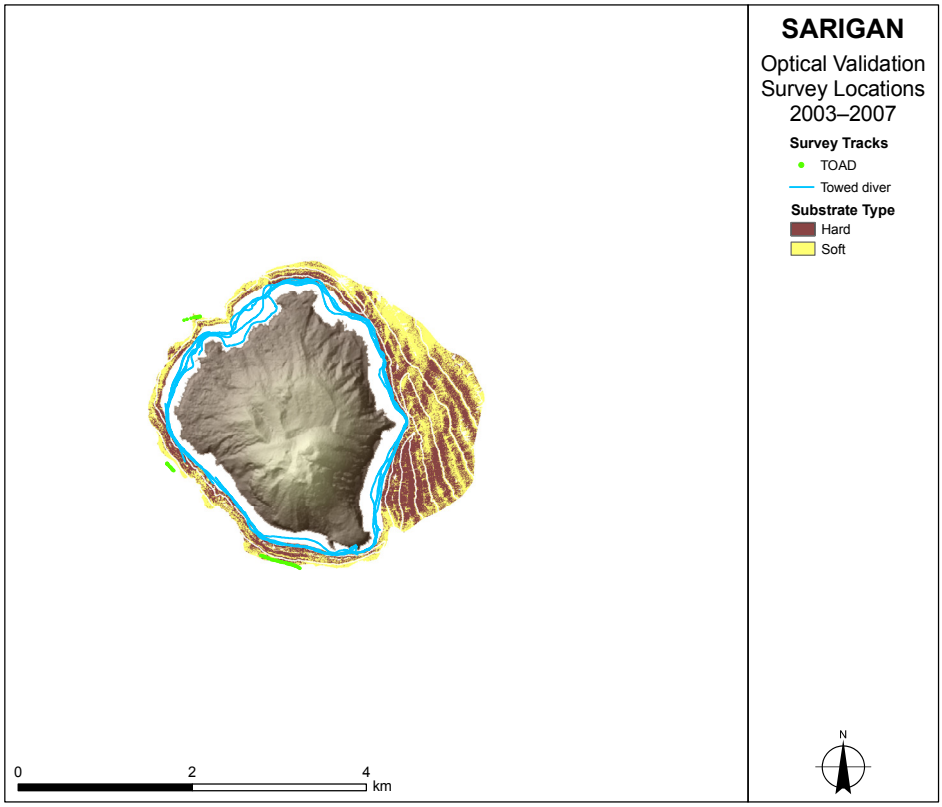


Figure 10.3.2a. Towed-diver tracks from surveys of forereef habitats conducted around Sarigan during MARAMP 2003, 2005, and 2007 and TOAD camera-sled tracks for MARAMP 2003. Survey tracks are displayed over multibeam hard–soft substrate map. Because data cannot be collected right under the ship, white lines are visible.

10.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Sarigan are discussed in this section. These descriptions are organized by the 3 geographic regions around Sarigan. Optical-validation surveys conducted around Sarigan during MARAMP 2003, 2005, and 2007 reveal local variability in the distribution of habitats around this island.

Around east Sarigan, sand cover was patchy, with interpolated sand cover ranging from 5.1% to 50% (Fig. 10.3.3a, top panel). Habitat complexity was most frequently recorded as medium to medium-high during towed-diver surveys, although a small number of patches with lower and higher habitat complexity were also observed (Fig. 10.3.3a, middle panel). Within the east region, moderate levels of live coral cover were observed with interpolated cover generally < 20%, although 2 small patches were observed where live coral cover of 20.1%–62.5% was recorded (Fig. 10.3.3a, bottom panel). Habitats observed by towed divers within this region included rocky crags, boulders and pinnacles, and sand with boulder patch reefs.

Habitat complexity, ranging from low to high, was more variable in the northwest region than in the east region. As in the east region, sand cover was locally patchy, ranging from 5.1% to 62.5% and reflecting the variable nature of the seabed. Habitat was characterized as boulder patches, steep walls, and continuous rock reef. Live coral cover appeared to be more consistent, predominantly ranging from 5.1% to 30%. Analyses of TOAD video footage obtained on the flanks at depths of 91–190 m suggested hard substrates with no sand recorded. No live corals were observed in any of the analyzed footage.

In the southwest region, towed-diver surveys recorded habitats of medium to high complexity over boulder reefs and continuous reef with sand patches and live coral cover of 1.1%–40%. Estimates of sand cover from towed-diver surveys were generally < 20%, although a small patch of higher sand cover was observed and appears to associate with a channel between 2 ridges shown in the bathymetry. Two TOAD surveys conducted in this region suggest predominantly hard substrate with only one analyzed video frame showing any sand. No live corals were observed within either of these surveys, although soft corals were noted.

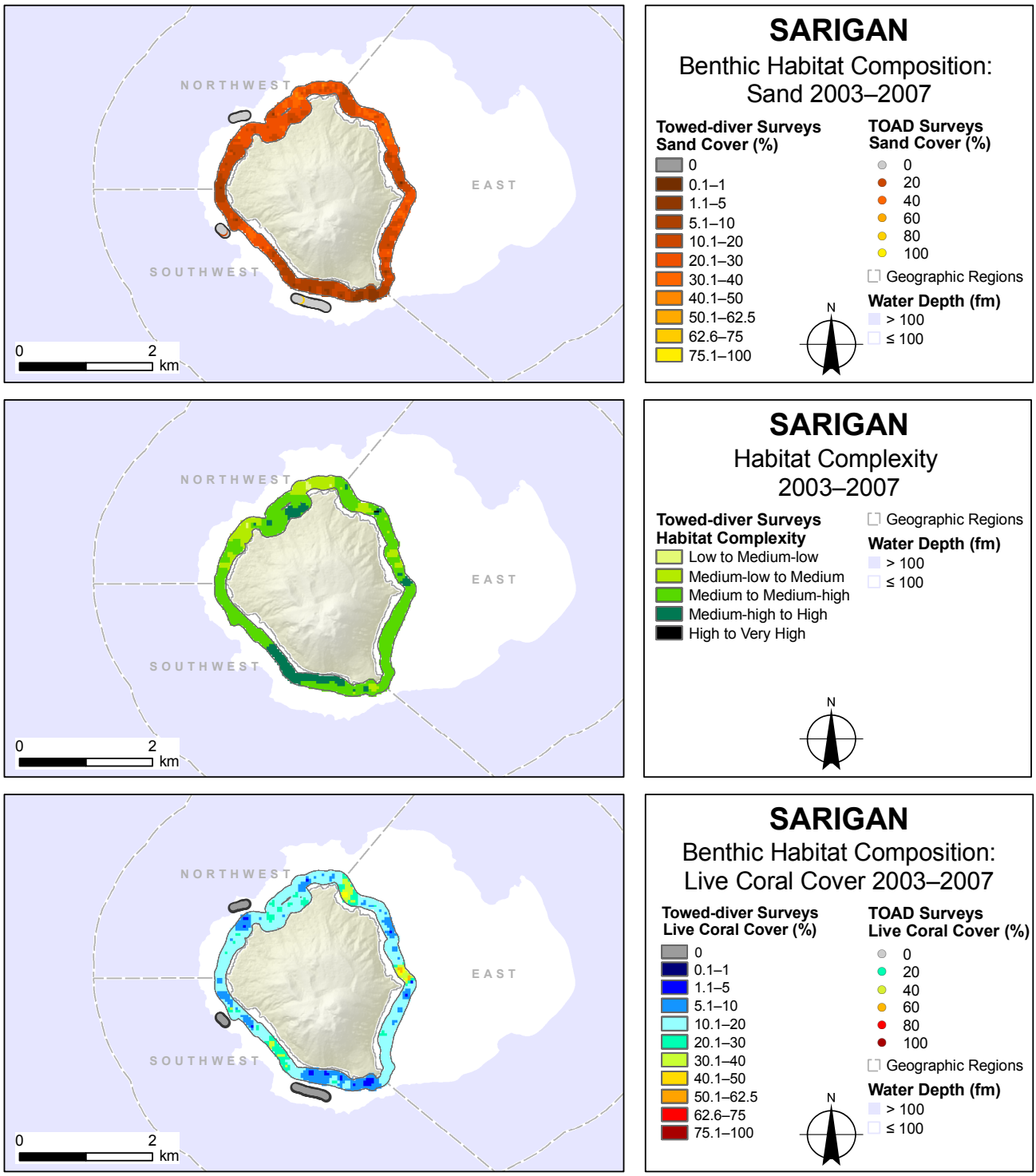


Figure 10.3.3a. Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) live-hard-coral cover (%) from towed-diver surveys of forereef habitats conducted and analyses of TOAD video collected around Sarigan during MARAMP 2003, 2005, and 2007.

10.4 Oceanography and Water Quality

10.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 7 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters at the island of Sarigan on August 24. Temperature, salinity, and density values from these casts varied both spatially and vertically (Figs. 10.4.1a and b). Spatial comparisons of water properties at a depth of 10 m suggest a minimal range in temperature (0.15°C) values and moderate ranges in salinity (0.02 psu) and density (0.05 kg m^{-3}) values. Temperature values were slightly higher in the east region (casts 4–5, 6) than in the northwest and southwest regions (casts 1–3, 7; Fig. 10.4.1a). Vertical comparisons of CTD profiles reveal differences in water properties that were larger than the variation seen in spatial comparisons, with broad ranges in temperature (1.5°C) and density (0.7 kg m^{-3}) values and a moderate range in salinity (0.3 psu) values. Well-mixed waters were prominent at Sarigan, except in the northwest region at cast 3, where colder, less saline water was recorded below a depth of 25 m (Fig. 10.4.1b).

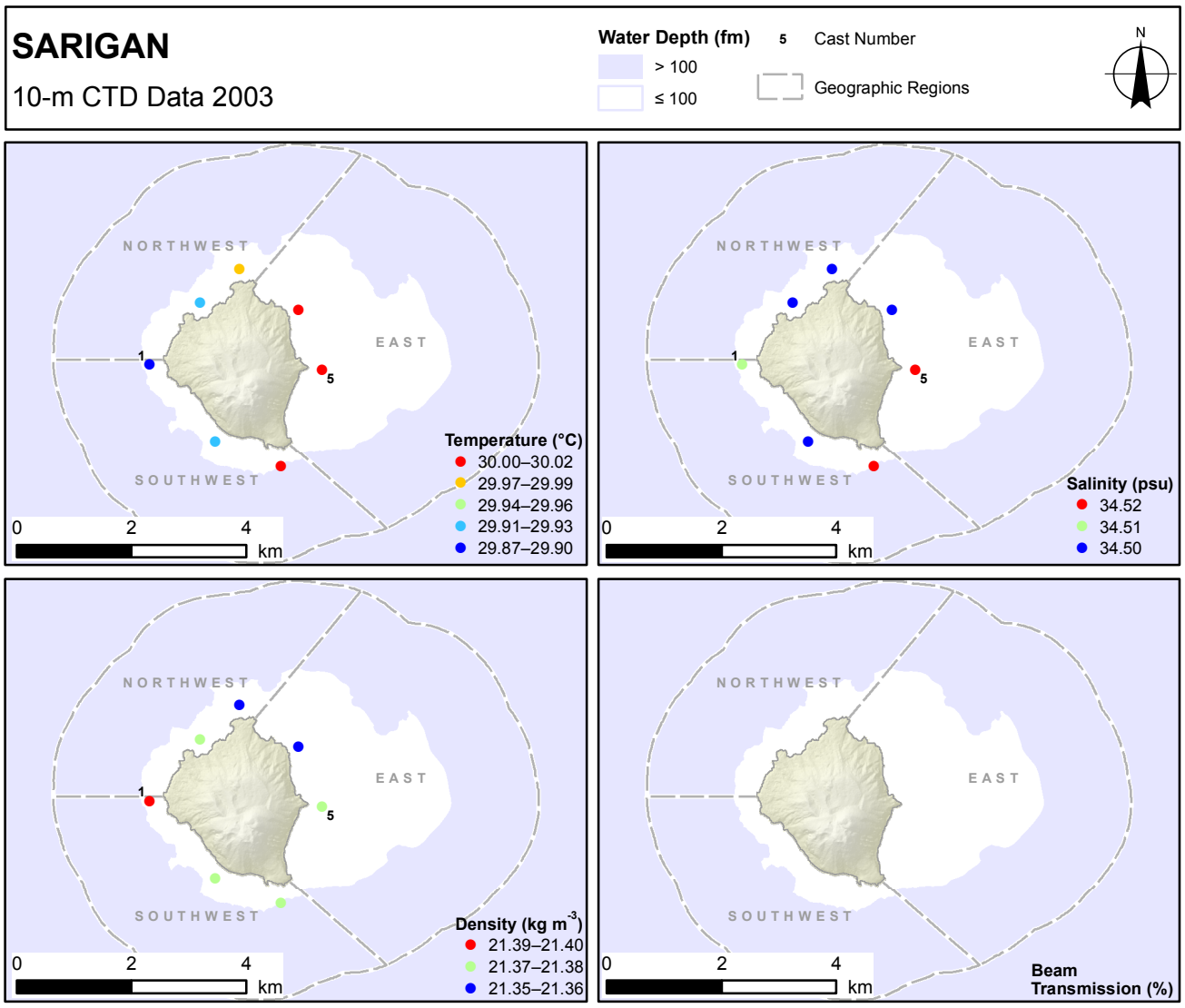


Figure 10.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts at Sarigan on August 24 during MARAMP 2003.

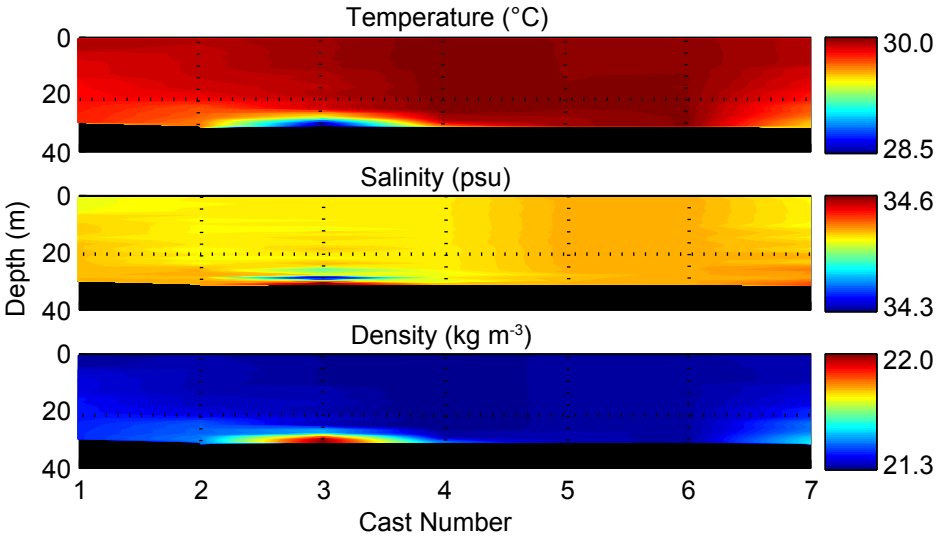


Figure 10.4.1b. Shallow-water CTD cast profiles to a 30-m depth at Sarigan on August 24 during MARAMP 2003, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–7 in a clockwise direction around Sarigan. For cast locations and numbers around this island in 2003, see Figure 10.4.1a.

2005 Spatial Surveys

During MARAMP 2005, 9 shallow-water CTD casts were conducted in nearshore waters at Sarigan on September 18. Temperature, salinity, density, and beam transmission values from these casts varied both spatially and vertically (Figs. 10.4.1c and d). Spatial comparisons of water properties at a depth of 10 m suggest small ranges in temperature (0.2°C), salinity (0.02 psu), and beam transmission (< 1%) values and a broad range in density (0.08 kg m^{-3}) values (Fig. 10.4.1c). Vertical comparisons of CTD profiles also reveal small ranges in temperature (0.4°C), salinity (0.1 psu), density (0.2 kg m^{-3}), and beam transmission (< 1%) values (Fig. 10.4.1d). Well-mixed waters were prominent at this island, except for at cast 1, located on the border between the northwest and southwest regions, where colder, less saline water was recorded below a depth of 10 m (Fig. 10.4.1d).

Water samples were collected in concert with shallow-water CTD casts at a single select location in the northwest region in 2005 to assess water-quality conditions (Fig. 10.4.1e). The following values of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.201 µg L^{-1}; total nitrogen (TN), 0.066 µM; nitrate (NO_3^-), 0.044 µM; nitrite (NO_2^-), 0.023 µM; phosphate (PO_4^{3-}), 0.034 µM; and silicate [$Si(OH)_4$], 0.756 µM.

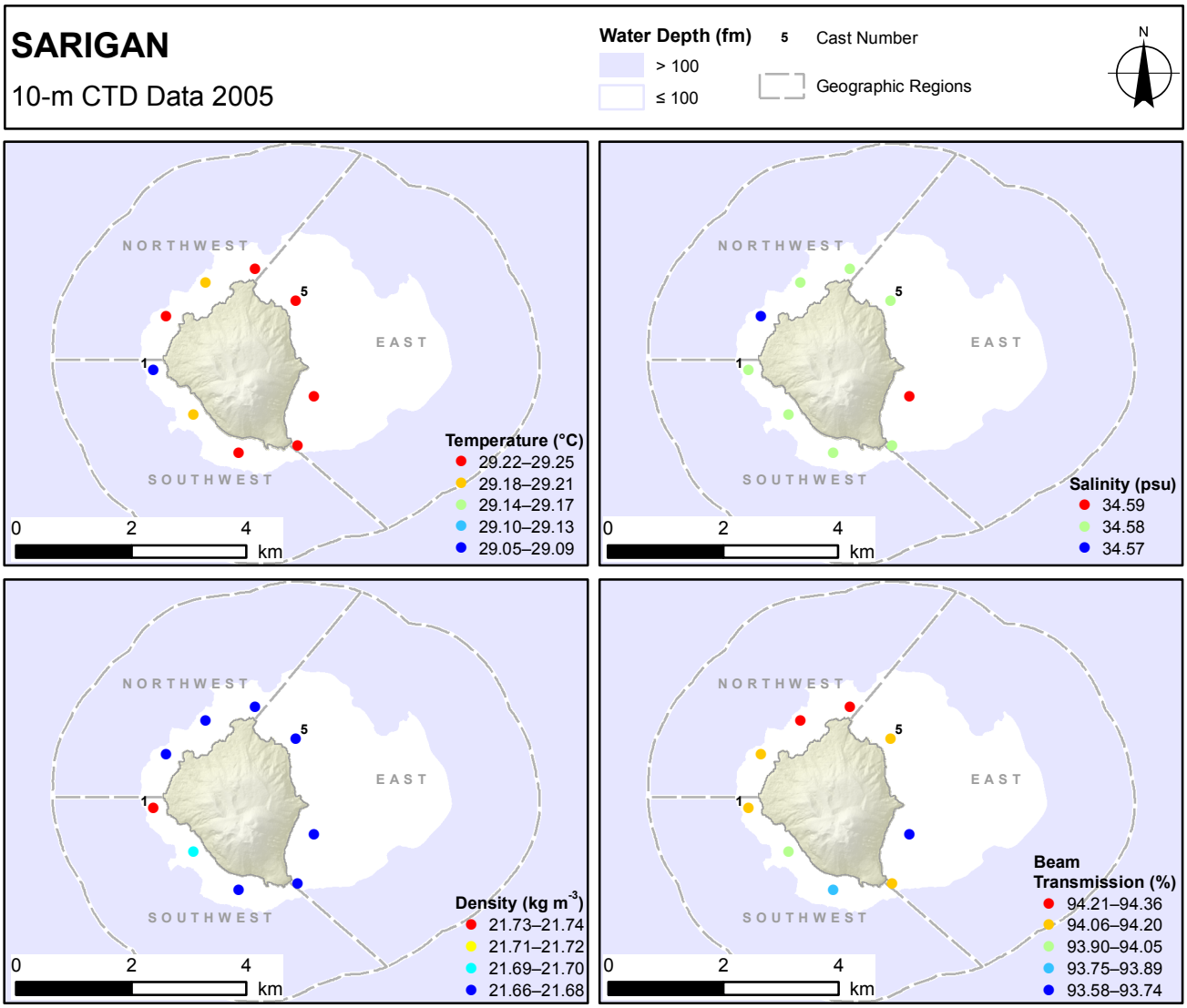


Figure 10.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts at Sarigan on September 18 during MARAMP 2005.

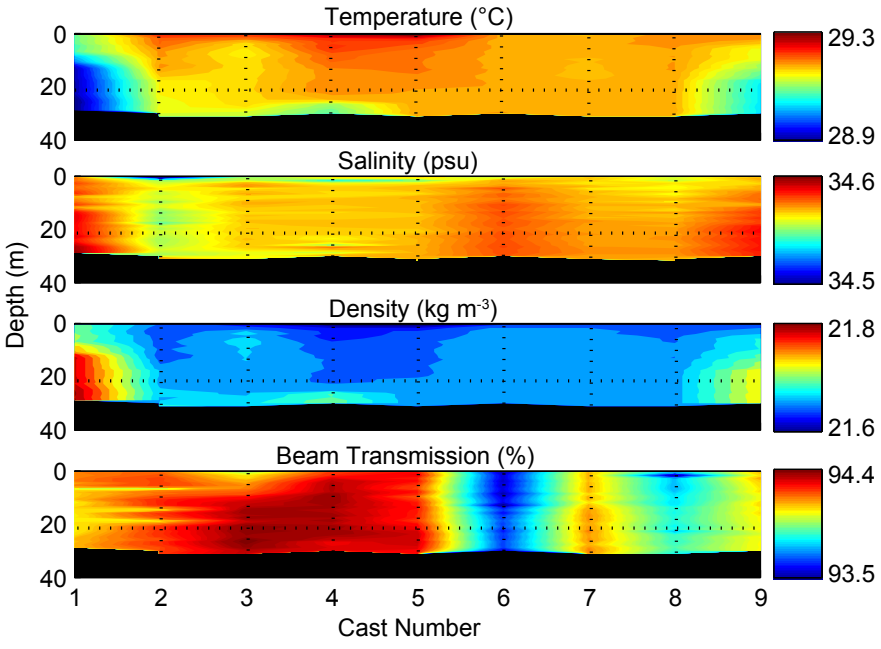


Figure 10.4.1d. Shallow-water CTD cast profiles to a 30-m depth at Sarigan on September 18 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–9 in a clockwise direction around Sarigan. For cast locations and numbers around this island in 2005, see Figure 10.4.1c.

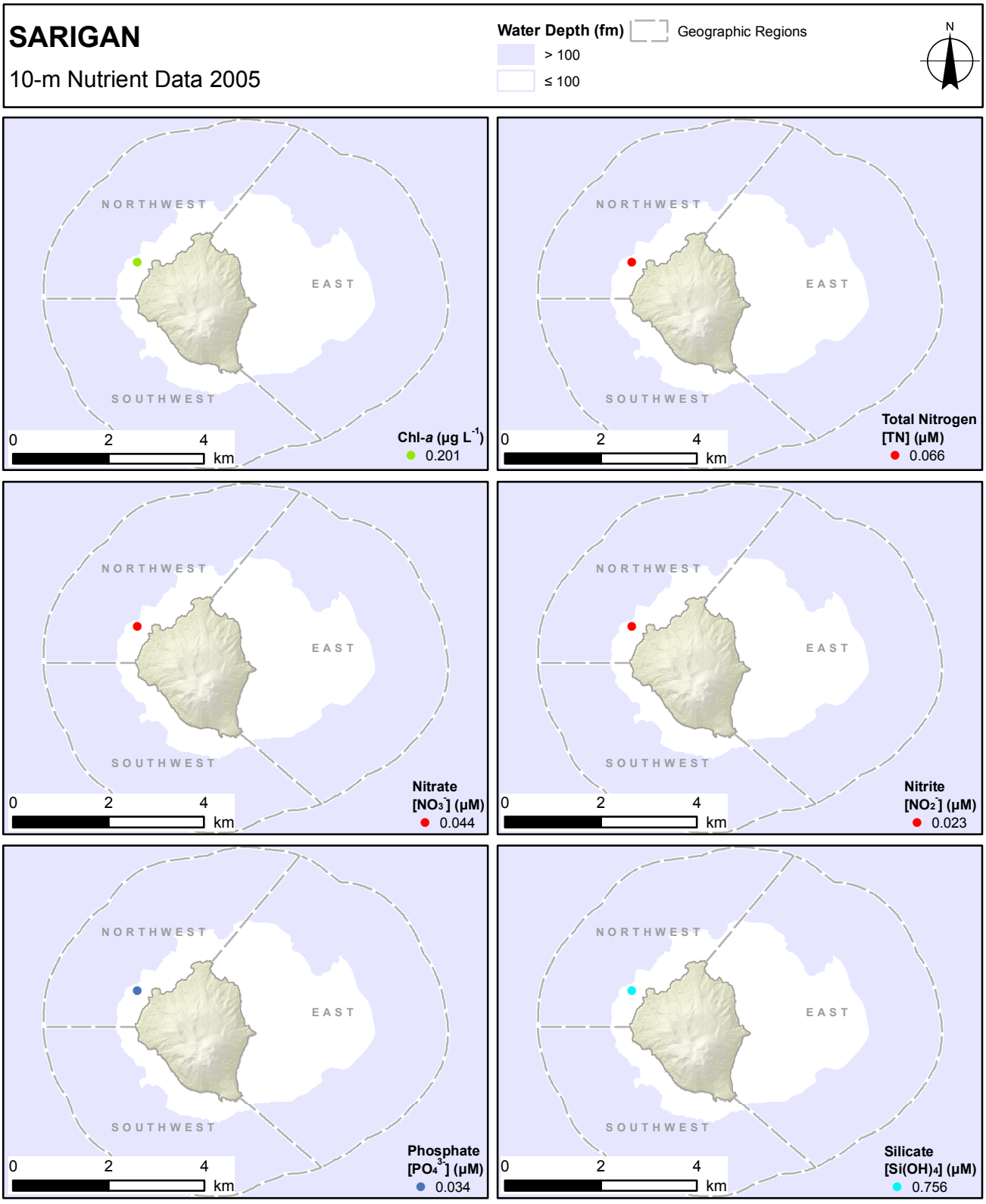


Figure 10.4.1e. Concentrations of (*top left*) chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth from water samples collected at Sarigan on September 18 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, 10 shallow-water CTD casts were conducted in nearshore waters around Sarigan on May 26. Temperature, salinity, density, and beam transmission values from these casts varied both spatially and vertically (Figs. 10.4.1f and g). Spatial comparisons of water properties at a depth of 10 m suggest a moderate range in temperature (0.45°C) values and small ranges in salinity (0.13 psu), density (0.25 kg m^{-3}), and beam transmission (< 1%) values (Fig. 10.4.1f). Temperatures recorded at cast 10 in the southwest region were anomalously cooler compared to values found at all other cast locations at Sarigan, and data from this cast are the main reason behind the difference recorded in temperatures. Vertical comparisons of CTD profiles reveal water properties with moderate ranges in temperature (0.5°C), salinity (0.2 psu), and density (0.4 kg m^{-3}) values and a small range in beam transmission (1%) values (Fig. 10.4.1g). Differences in mixing and stratification around this island were present. Warm, well-mixed waters were recorded in the east region (casts 4–8), while cooler, more saline subsurface waters were recorded below a depth of 5 m in the southwest region (casts 9–10).

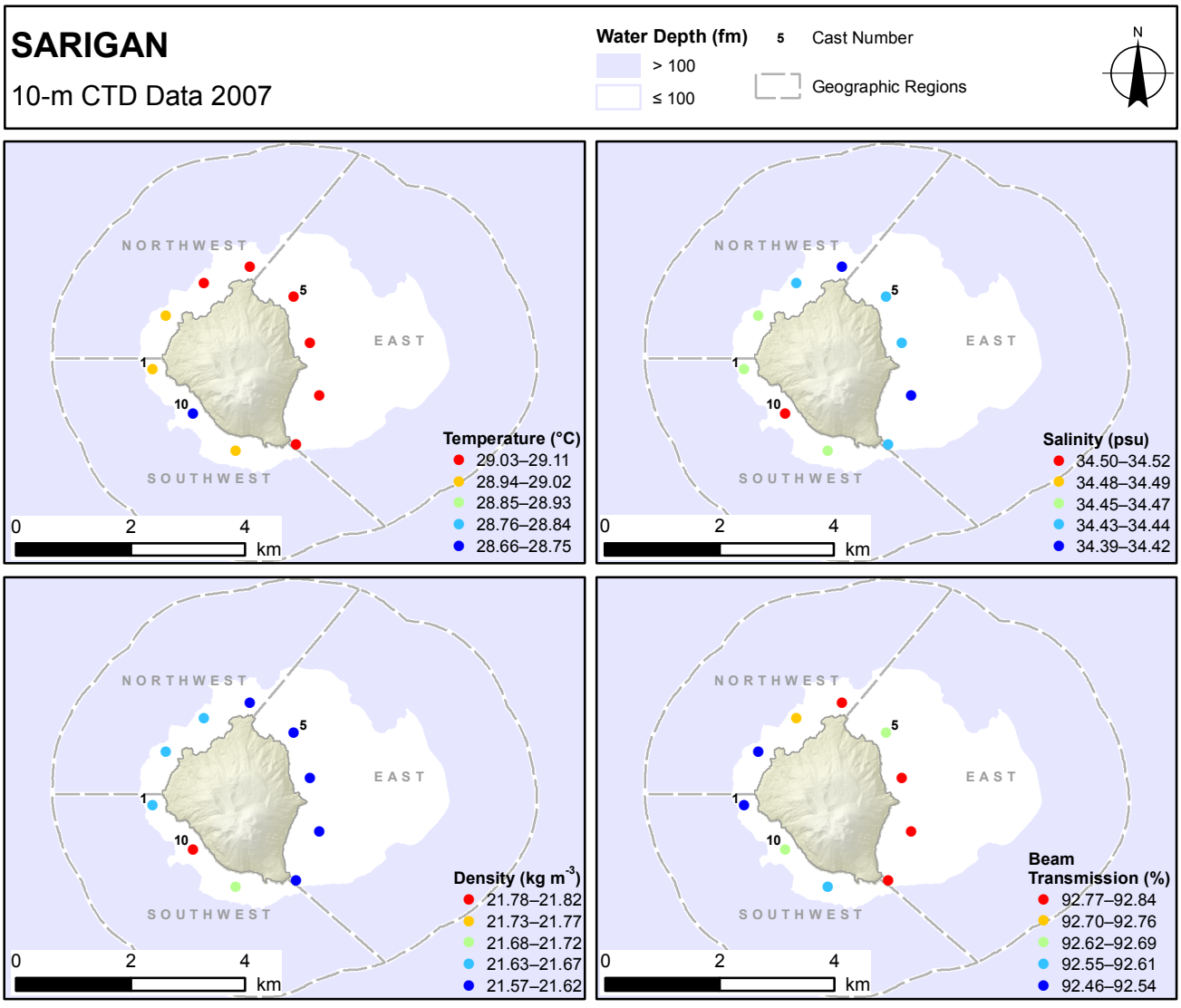


Figure 10.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) bean transmission at a 10-m depth from shallow-water CTD casts around Sarigan on May 26 during MARAMP 2007.

Water samples were collected in concert with shallow-water CTD casts at 4 select locations at Sarigan in 2007 (Fig. 10.4.1h). The following ranges of measured parameters were recorded at Sarigan: Chl-*a*, 0.037–0.086 µg L^{-1}; total nitrogen (TN), 0.047–0.101 µM; nitrate (NO_3^-), 0.043–0.083 µM; nitrite (NO_2^-), 0.004–0.018 µM; phosphate (PO_4^{3-}), 0.04–0.065 µM; silicate [$Si(OH_4)$], 1.115–2.561 µM. The highest values of Chl-*a* were recorded in the southwest region, while the highest values of total nitrogen, nitrate, nitrite, phosphate, and silicate were all recorded in the northwest region.

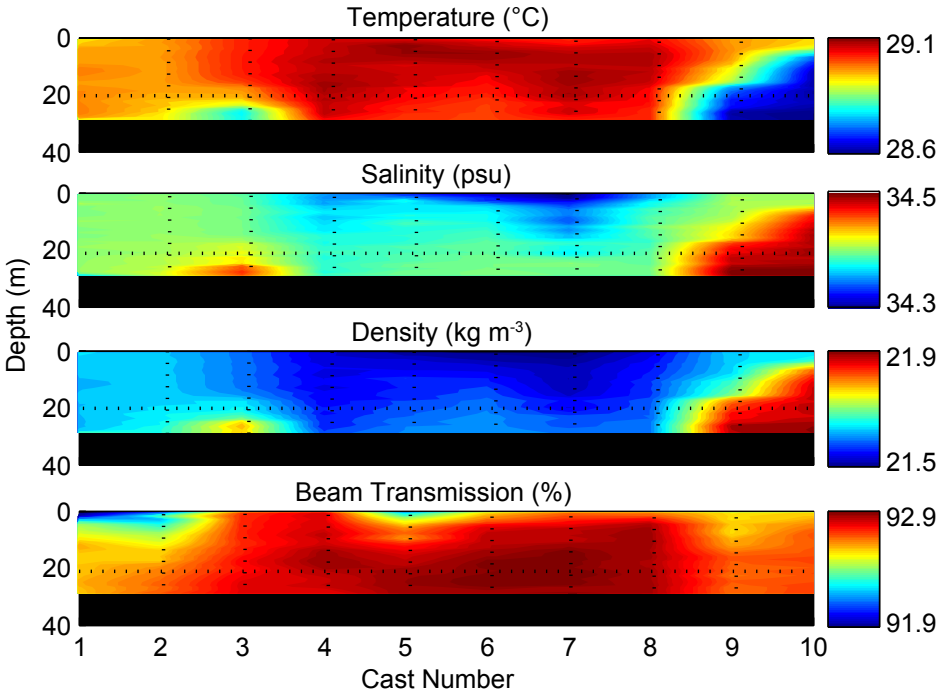


Figure 10.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Sarigan on May 26 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–10 in a clockwise direction around Sarigan. For cast locations and numbers around this island, see Figure 10.4.1f.

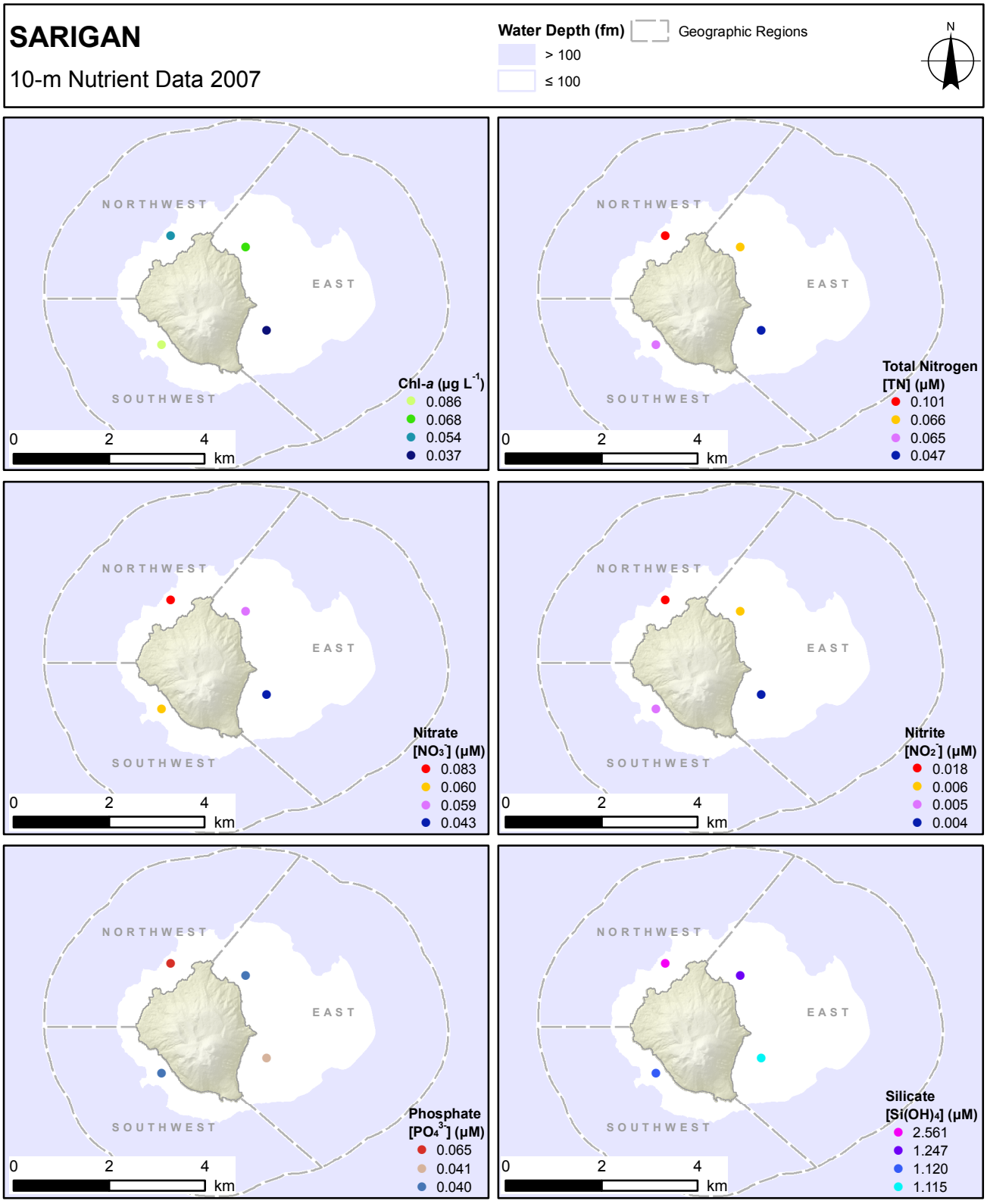


Figure 10.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate, at a 10-m depth from water samples collected at Sarigan on May 26 during MARAMP 2007.

Temporal Comparison

Temporal comparisons of shallow-water CTD data collected during MARAMP 2003, 2005, and 2007 suggest a dynamic oceanographic environment. Data from CTD casts completed in 2005 and 2007 reveal generally minimal to moderate spatial and vertical variability; however, data from 2003 show a greater spatial variance in water properties, as relatively cool water (28.5°C; 1.5°C colder than surface waters) originating from below a depth of 30 m was recorded in the southwest region and may have resulted from upwelling or internal tide activity. When comparing water-quality data between survey years, Chl-*a* concentrations were greater in 2007 than in 2005, and all other parameters measured were much greater in 2007 than in 2005. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May, and MARAMP 2003 and 2005 occurred in September and October. This change was made to avoid the typhoon season and reduce the probability of weather disruptions. Wind and wave conditions are generally higher during the wet season (July–December) with stronger trade winds prominent on the east side of Sarigan. Higher winds and waves likely caused more mixing during MARAMP 2003 and 2005, and calmer weather potentially allowed for increased stratification in 2007. Further investigation will help make these particular results and trends more apparent.

10.4.2 Time-series Observations

Between 2003 and 2007, subsurface temperature recorders (STR) were deployed at Sarigan to collect time-series observations of temperature, a key oceanographic parameter influencing reef conditions (Fig. 10.4.2a). The locations, depths, time frames, and other details about these deployments are provided in Figures 10.4.2a and b.

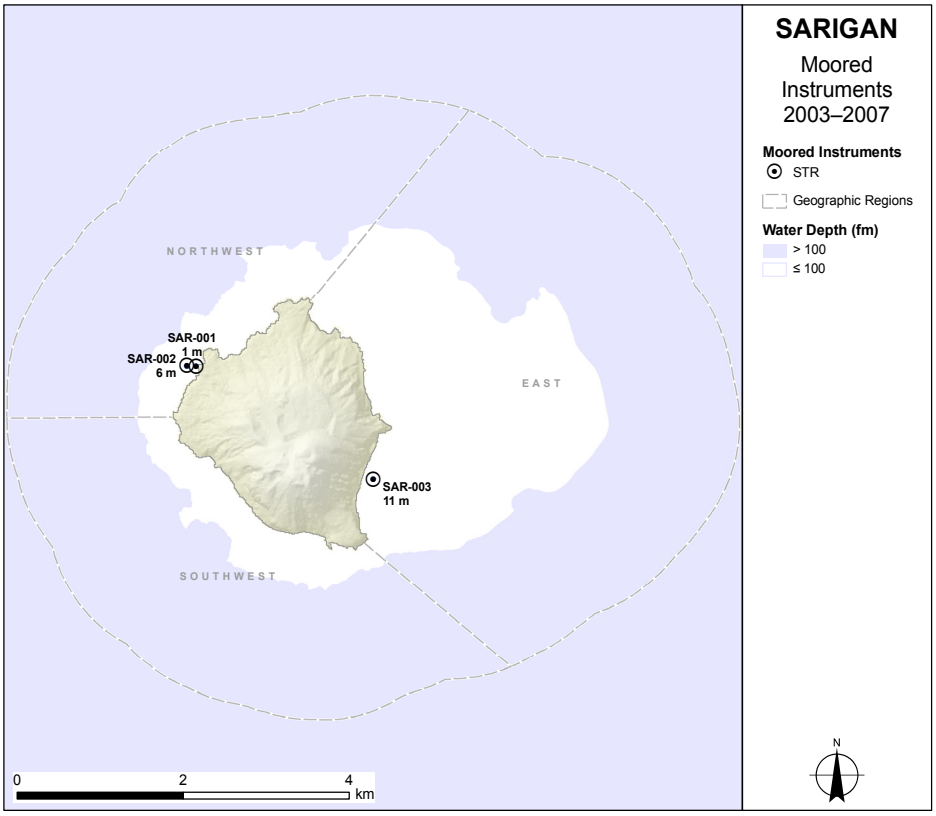


Figure 10.4.2a. Locations and depth of STRs deployed at Sarigan during MARAMP 2003, 2005, and 2007.

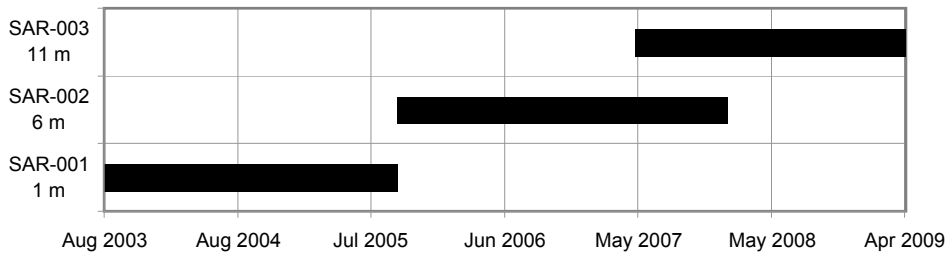


Figure 10.4.2b. Deployment timelines and depths of the STRs moored at Sarigan during the period from August 2003 to April 2009. A solid bar indicates the period for which data were collected by an instrument that was deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 10.2b in Section 10.2: "Survey Effort."

Data from 2 STRs deployed at depths of 1 and 6 m at Sarigan show seasonal temperature variability of ~ 4°C (Fig. 10.4.2c). Water temperatures reached 30°C during the months of June–October and fell to a low of ~ 26.5°C during the months of January–May. Intraseasonal temperature variability was prominent throughout this time series, with oscillations of 0.5°C–1.5°C occurring multiple times within a season. The sharpest decline in temperature was recorded in June 2004 at SAR-001 in the northwest region, when temperature dropped ~ 2.5°C for a week before increasing 3.5°C to typical summer temperatures. The cause of this dramatic temperature change is unknown, but transient oceanographic features (e.g., eddies) can lead to abrupt and transitory temperature fluctuations.

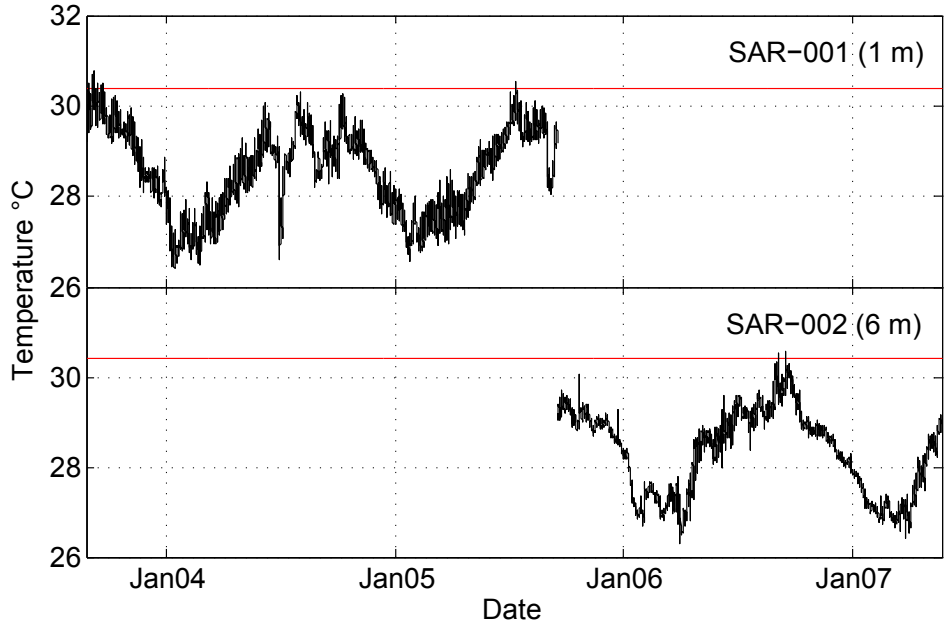


Figure 10.4.2c. Time-series observations of temperature over the period between September 2003 and December 2007 collected from 2 STRs deployed in the northwest region of Sarigan (see Figure 10.4.2a for mooring locations). The red lines represent the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

10.4.3 Wave Watch III Climatology

Seasonal wave climatology for Sarigan was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008, and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (Fig. 10.4.3a). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–2.5 m) wave events originating from the east (~ 80º–90º). Superimposed with these short-period swells were large (> 5 m), long-period (12–16 s) wave events principally from the south (160º–190º). These large, episodic waves were generated primarily by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–4 m) occurred from any direction, although weighted slightly larger from the south (110º–260º) and likely associated with episodic, moderate-sized, or distant storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside typhoon season) also was characterized by frequent (> 30 d per season), short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season), long-period (12–14 s) swells with moderate wave heights (~ 2–3 m) also occurred during this period and originated from any direction.

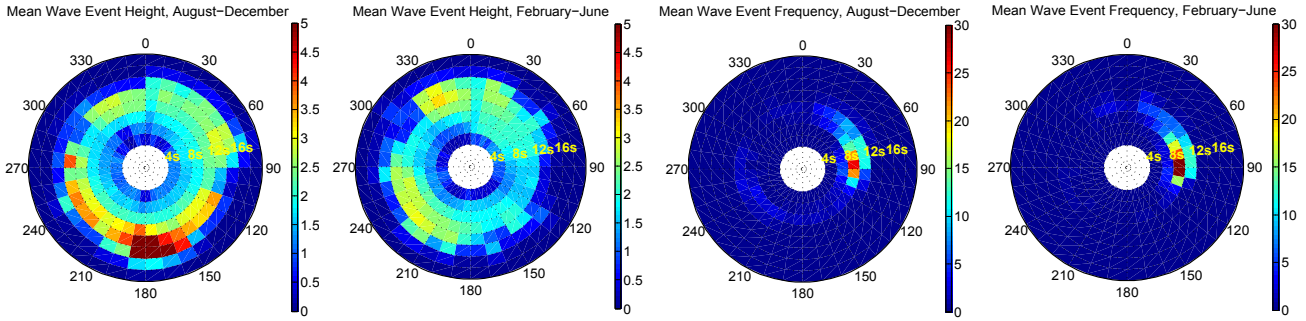


Figure 10.4.3a. NOAA Wave Watch III directional wave climatology for Sarigan from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Sarigan (16° N, 145° E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

10.5 Corals and Coral Disease

10.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Sarigan was 18% (SE 2). Localized areas of high coral cover were recorded in the east region over 2 consecutive survey segments with a mean of 63% and in the southwest region over 2 consecutive segments with a mean of 42% (Fig. 10.5.1a, top panel). Generally, coral cover was lowest in the southern part of the southwest region.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Sarigan was 13% (SE 1.5). Coral cover was highest in the east region, on the border between the east and northwest regions, and within one segment located in the northwest region, with a mean of 33% for 4 segments (Fig. 10.5.1a, middle panel). Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 0.8% (SE 0.2) of coral cover observed on forereef habitats around Sarigan appeared stressed. Stressed-coral cover was low for the majority of reefs surveyed in 2005 at Sarigan, compared to other areas surveyed in the Mariana Archipelago.

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Sarigan was 14% (SE 1). Coral cover was highest in the northern part of the east region with a mean of 32% for 3 segments (Fig. 10.5.1a, bottom panel). Overall, 0.9% (SE 0.3) of coral cover observed on forereef habitats appeared stressed. Stressed-coral cover was low for the majority of reefs surveyed in 2007 at Sarigan, compared to other areas surveyed in the Mariana Archipelago.

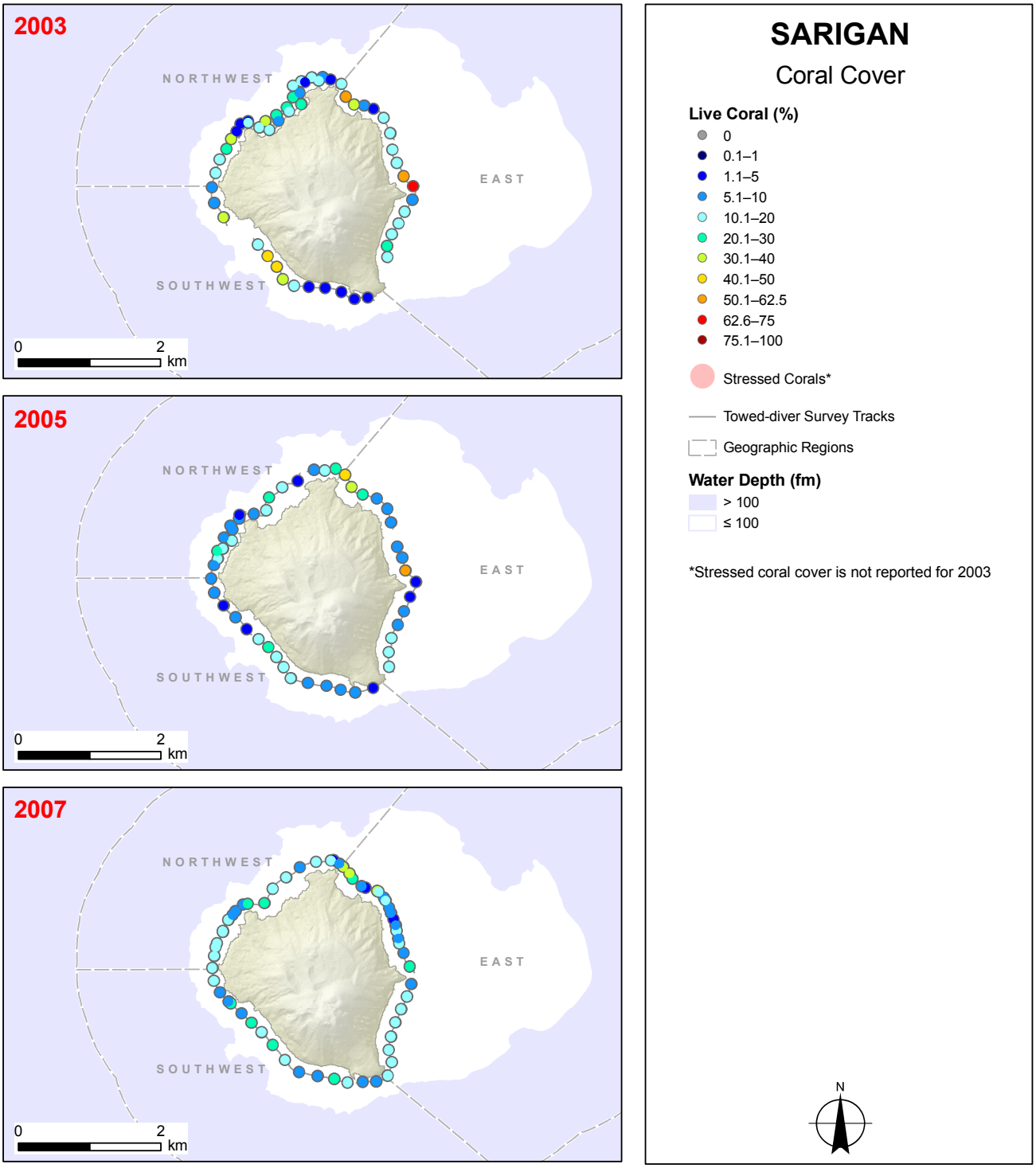


Figure 10.5.1a. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Sarigan during MARAMP 2003, 2005, and 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005 and 2007.

During MARAMP 2003, 3 REA benthic surveys using the quadrat method on forereef habitats at Sarigan documented 512 coral colonies within a total survey area of 11.25 m^2. Site-specific colony density ranged from 32.8 to 60.5 colonies m^{-2} with an overall sample mean of 45.5 colonies m^{-2} (SE 8.1). The highest colony density was recorded at REA site SAR-01 in the southwest region, and the lowest colony density was observed at SAR-02 in the northwest region (Fig. 10.5.1b, top panel).

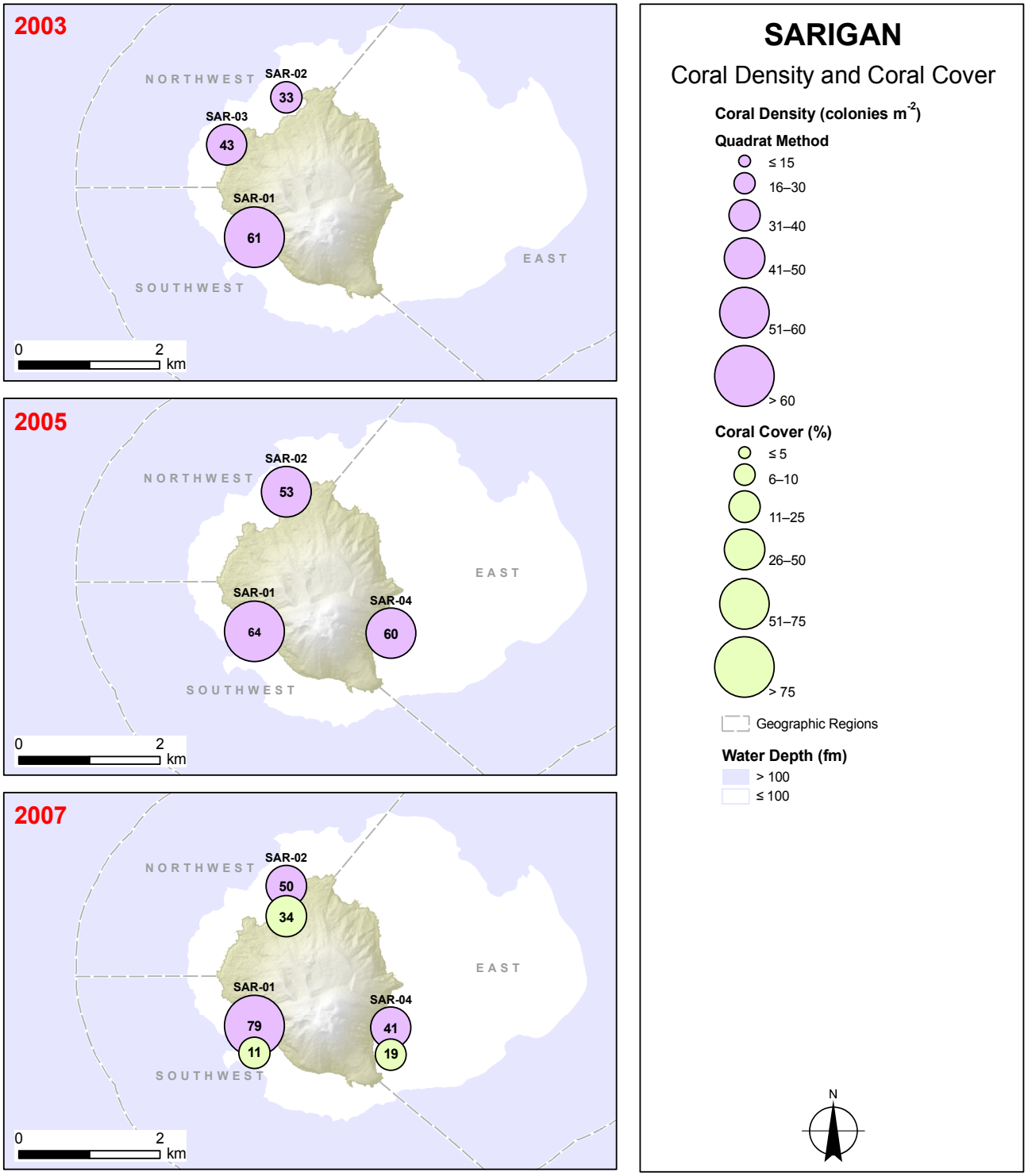


Figure 10.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Sarigan during MARAMP 2003, 2005, and 2007, as well as cover (%) observations of live corals from REA benthic surveys during MARAMP 2007. Values are provided within each symbol. The quadrat method was used in the 3 survey years to assess coral-colony density.

During MARAMP 2005, 3 REA benthic surveys using the quadrat method on forereef habitats at Sarigan documented 705 coral colonies within a total survey area of 12 m^2. Site-specific colony density ranged from 53 to 63.5 colonies m^{-2} with an overall sample mean of 58.3 colonies m^{-2} (SE 3.1). The highest colony density was recorded at SAR-01 in the southwest region, and the lowest colony density was observed at SAR-02 in the northwest region (Fig. 10.5.1b, middle panel).

During MARAMP 2007, 3 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Sarigan. Site-specific estimates of live-hard-coral cover from these surveys ranged from 10.8% to 34.3% with an overall sample mean of 21.2% (SE 6.9). Coral cover was highest at SAR-02 in the northwest region and lowest at SAR-01 in the southwest region (Fig. 10.5.1b, bottom panel).

During MARAMP 2007, 3 REA benthic surveys using the quadrat method on forereef habitats at Sarigan documented 520 coral colonies within a total survey area of 10 m^2. Site-specific colony density ranged from 41 to 79 colonies m^{-2} with an overall sample mean of 56.5 colonies m^{-2} (SE 11.5). The highest colony density was recorded at SAR-01 in the southwest region, and the lowest colony density was observed at SAR-04 in the east region (Fig. 10.5.1b, bottom panel).

Islandwide mean cover of live corals estimated from towed-diver surveys of forereef habitats was slightly higher in 2003 than in 2005 and 2007 with overall sample means of 18% (SE 2) in 2003, 12.9% (SE 1.5) in 2005, and 14.2% (SE 1.0) in 2007 (Fig. 10.5.1c). In the 3 MARAMP survey years, observed coral cover was slightly higher in the east region than in other regions at Sarigan. For the 3 sites surveyed using the line-point-intercept method in 2007, coral cover ranged from 10.8% to 34.3%, with an overall sample mean of 21.2% (SE 9.6). Estimates of live coral cover from REA benthic surveys generally exceeded observations from towed-diver surveys because REA surveys target hard-bottom communities whereas towed-diver surveys include more variable substrate.

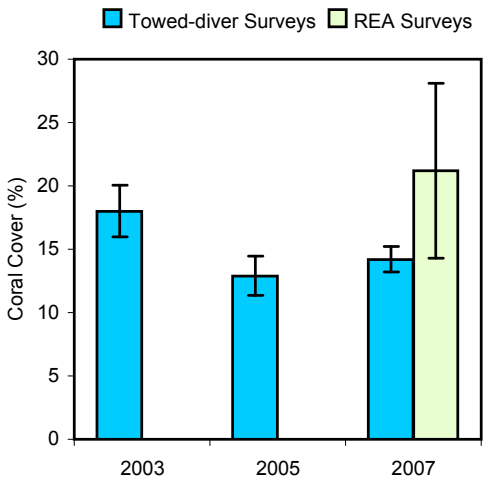


Figure 10.5.1c. Temporal comparison of mean live-coral-cover (%) values from REA and towed-diver benthic surveys conducted on forereef habitats around Sarigan during MARAMP 2003, 2005, and 2007. No REA coral-cover surveys using the line-point-intercept method were conducted at Sarigan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Overall mean coral-colony density from REA benthic surveys of forereef habitats at Sarigan did not vary substantially between the 3 MARAMP survey years witih overall sample means of 45.5 colonies m^{-2} (SE 8.1) in 2003, 58.3 colonies m^{-2} (SE 4.3) in 2005, and 56.5 colonies m^{-2} (SE 11.5) in 2007 (Fig. 10.5.1d). Increased colony density could be a result of increased recruitment, fragmentation of existing colonies, or both.

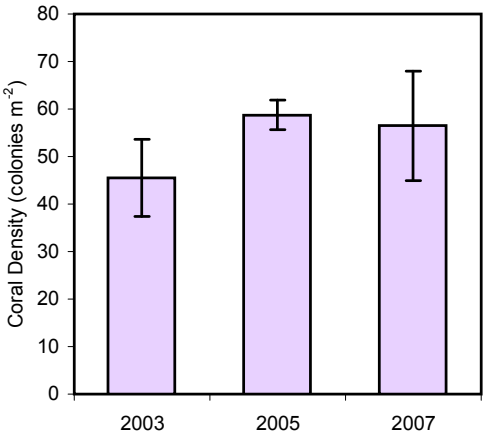


Figure 10.5.1d. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Sarigan during MARAMP 2003, 2005, and 2007. The quadrat method was used in all survey years to measure coral-colony density. Error bars indicate standard error (± 1 SE) of the mean.

Coral Generic Richness and Relative Abundance

Three REA benthic surveys were conducted using the quadrat method at Sarigan during MARAMP 2003. At least 16 coral genera were observed at Sarigan. Generic richness ranged from 14 to 16 with a mean of 15.3 (SE 0.7) coral genera per site. Generic diversities were similar at all sites with 2 more genera recorded at SAR-01 and SAR-02, in the southwest and northwest regions, than at SAR-03 in the northwest region (Fig. 10.5.1e, top panel).

Pavona, Leptastrea, *Astreopora, Favia,* and *Porites* were the most numerically abundant genera, contributing 16.7%, 14.5%, 11%, 10.9%, and 10.5% of the total number of colonies enumerated at Sarigan in 2003. All other genera individually accounted for < 10% of the total number of colonies. *Leptastrea* dominated the coral fauna at SAR-01, contributing 27.8% of the total number of colonies recorded at that site. *Favia* dominated at SAR-02, accounting for 20.3% of the total number of colonies. *Pavona* dominated at SAR-03, contributing 15.4% of the total number of colonies.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Sarigan during MARAMP 2005. At least 20 coral genera were observed at Sarigan. Generic richness was similar at all sites, ranging from 15 to 16 with a mean of 15.3 (SE 0.3) coral genera per site. One extra genus was recorded at SAR-02 in the northwest region than at SAR-01 and SAR-04 in the southwest and east regions (Fig. 10.5.1e, middle panel). *Porites, Pavona, Astreopora,* and *Favia* were the most numerically abundant genera, contributing 22%, 21.2%, 12.7%, and 9.9% of the total number of

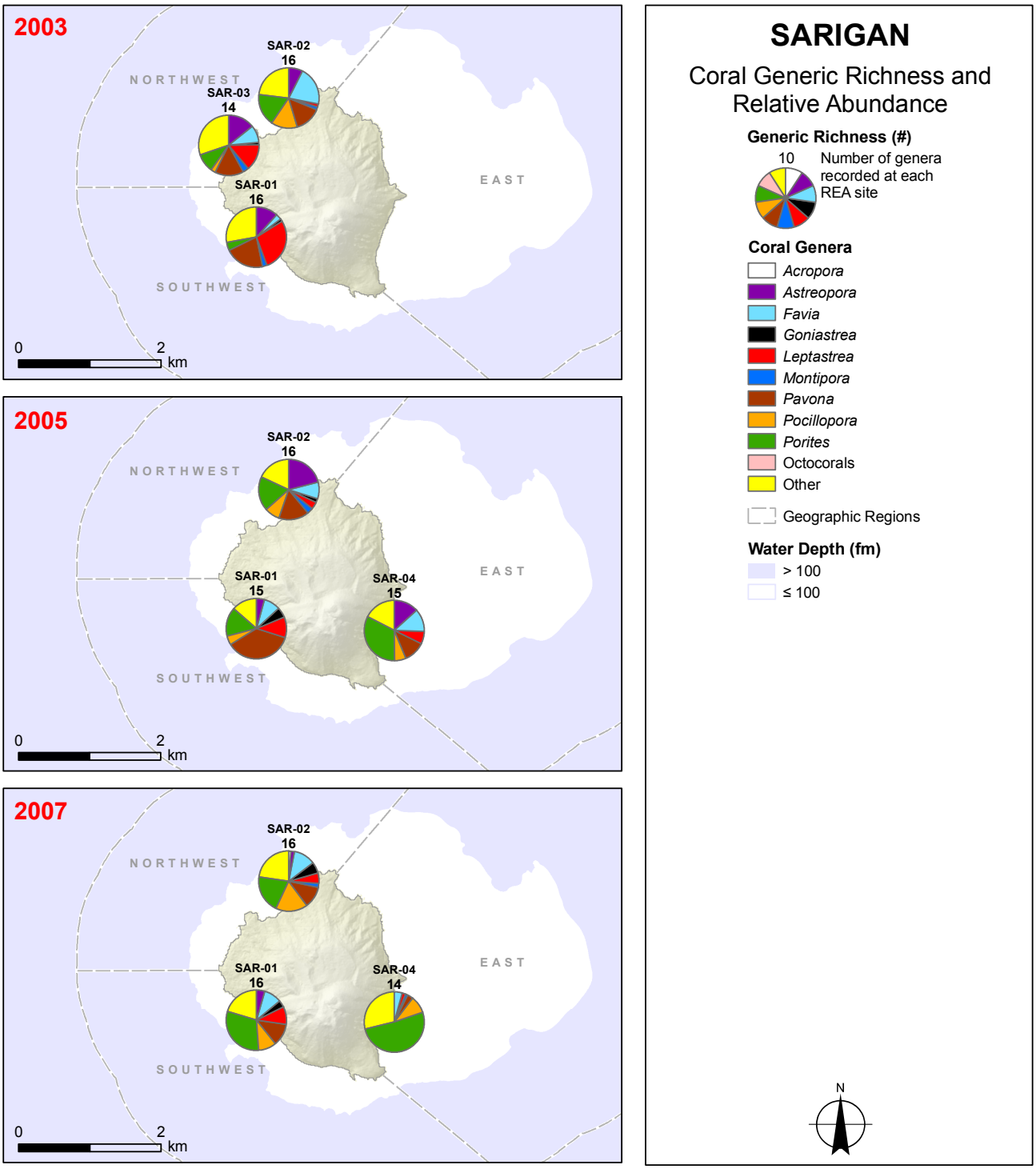


Figure 10.5.1e. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Sarigan during MARAMP 2003, 2005, and 2007. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in all survey years to survey coral genera.

colonies enumerated at Sarigan in 2005. All other genera individually accounted for < 10% of the total number of colonies. *Pavona* dominated at SAR-01, contributing 36.2% to the total number of colonies at that site. *Astreopora* dominated the coral fauna at SAR-02, accounting for 20.8% of the total number of colonies. *Porites* dominated at SAR-04, contributing 32.2% of the total number of colonies.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Sarigan during MARAMP 2007. At least 19 coral genera were observed at Sarigan. Similar to the results from 2003 and 2005, little variation was observed between sites in generic richness, which ranged from 14 to 16 with a mean of 15.3 (SE 0.7) genera per site. The highest generic diversities were recorded at SAR-01 and SAR-02 in the southwest and northwest regions, and the lowest generic diversity was recorded at SAR-04 in the east region (Fig. 10.5.1e, middle panel). *Porites* and *Pocillopora* were the most numerically abundant genera, contributing 34.1% and 11.9% to the total number of colonies enumerated at Sarigan in 2007. All other genera individually accounted for < 10% of the total number of colonies. *Porites* dominated the coral fauna at all 3 REA sites (SAR-01, SAR-02 and SAR-04), contributing 31%, 20.2%, and 51.2% of the total number of colonies recorded at those sites.

Site-specific estimates of generic richness across the 3 MARAMP survey years ranged from 14 to 16 on forereef habitats at Sarigan. Site-specific and overall mean generic richness values were similar in the 3 years with means in a range of 15.3–15.5 genera per site (Fig, 10.5.1f). At each individual site, generic richness varied at most by one genus between successive survey periods. The quadrat method was used in the 3 survey years to assess generic richness.

Across the 3 MARAMP survey years, 25 coral genera were observed on forereef habitats at Sarigan. *Pavona* was the most abundant component of the coral fauna in 2003 surveys, contributing 16.7% of colonies enumerated at Sarigan and the second-most abundant taxon in 2005, accounting 21.2% of the total number of colonies. *Porites* contributed 22% in 2005 and 34.1% in 2007 to the total number of colonies enumerated. *Astreopora* was the third-most abundant taxon in 2003 and 2005, accounting for 11% and 12.7% of the total number of colonies. *Leptastrea* contributed 14.5% of the total number of colonies enumerated in 2003. *Favia* was the fourth-most numerically abundant taxon in 2003 and 2005, accounting for 11% and 10% of the total number of colonies enumerated. All other taxa contributed < 10% of the total number of colonies across the 3 survey years.

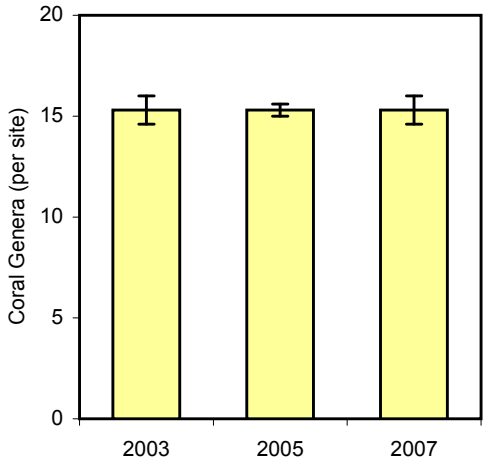


Figure 10.5.1f. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Sarigan during MARAMP 2003, 2005, and 2007. The quadrat method was used in the 3 survey years to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

Coral Size-class Distribution

During MARAMP 2003, 3 REA benthic surveys of forereef habitats were conducted at Sarigan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (78.4%) of corals had maximum diameters ≤ 5 cm (Fig. 10.5.1g, top panel). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 15.7%, 4.6%, and 1.4% of colonies recorded. No colonies measuring > 40 cm maximum diameter were recorded. At all REA sites a majority (> 60%) of corals were in the smallest size class (0–5 cm).

During MARAMP 2005, 3 REA benthic surveys of forereef habitats were conducted at Sarigan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (76.9%) of corals had maximum diameters ≤ 5 cm (Fig. 10.5.1g, middle panel). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 16.4%, 5.1%, and 1.7% of colonies recorded. No colonies measuring > 40 cm maximum diameter were recorded. At all REA sites a majority (> 70%) of corals were in the smallest size class (0–5 cm).

During MARAMP 2007, 3 REA benthic surveys of forereef habitats were conducted at Sarigan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (69.4%) of corals had maximum diameters ≤ 5 cm (Fig. 10.5.1g, bottom panel). The next 4 size classes (6–10, 11–20, 21–40, and > 40 cm) accounted for 22.3%, 6.0%, 1.9%, and 0.4% of colonies recorded. At all REA sites a majority (> 60%) of corals were in the smallest size class (0–5 cm).

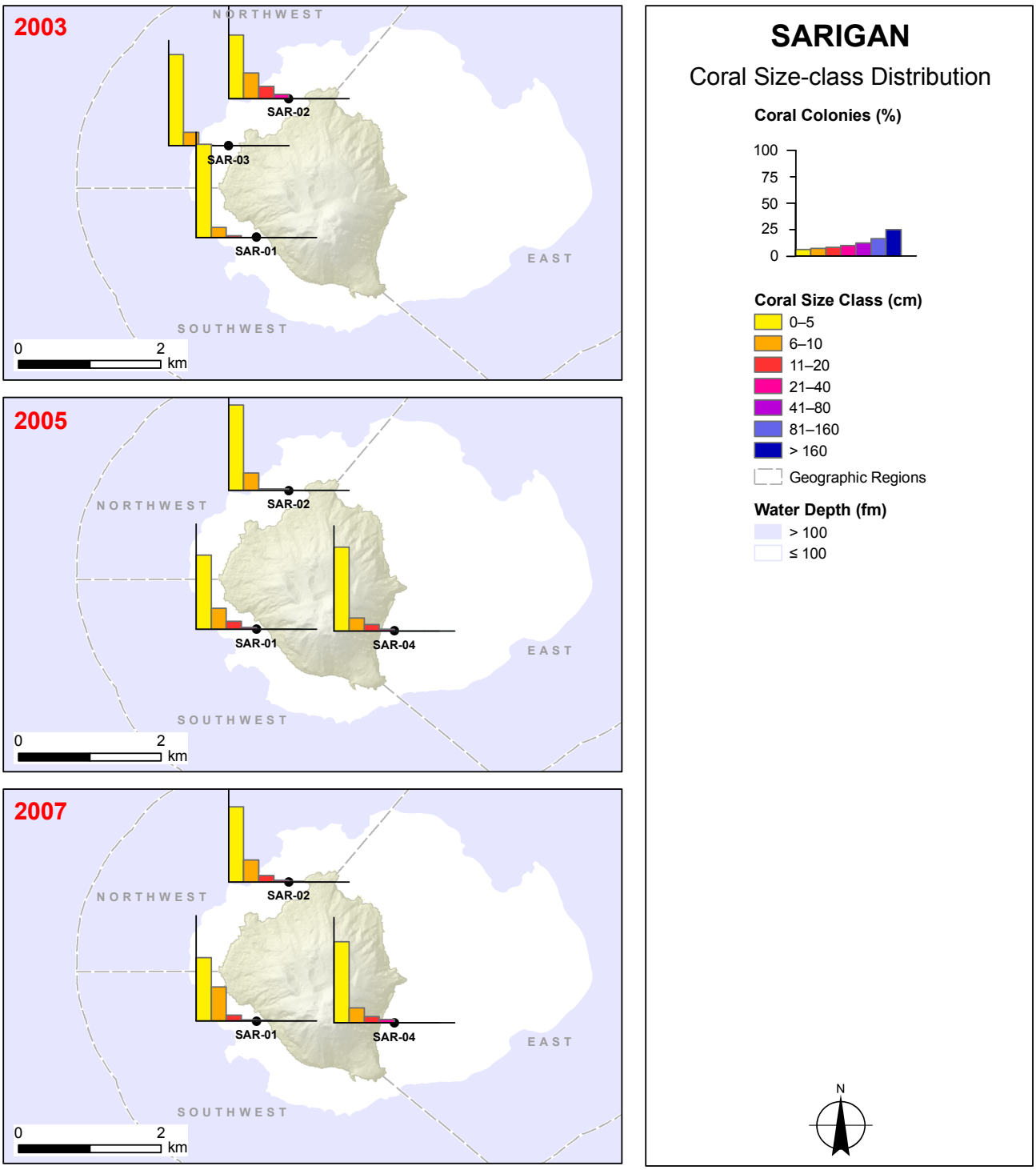


Figure 10.5.1g. Size-class distribution of hard corals from REA benthic surveys of forereef habitats conducted at Sarigan during MARAMP 2003, 2005, and 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in all survey years to size corals.

Site-specific and overall distributions of estimated coral size classes on forereef habitats at Sarigan are affected by inherent biases in the method used to census and size corals. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within

the quadrat. For more on this survey method, see Chapter 2, "Methods and Operational Background," Section 2.4.5: "Corals and Coral Disease."

In the 3 survey years, the majority of coral colonies were in the smallest size class (≤ 5 cm; Fig. 10.5.1h). The overall sample mean proportion of colonies in the smallest size class decreased slightly from 2003 to 2005 (78.4% and 76.9%, respectively), with a further small decrease by 2007 (69.4%). Variable patterns of change in the proportion of colonies in the smallest size class existed among sites surveyed in successive years. At SAR-01 in the southwest region, the observed proportion decreased between 2003 and 2005 and again in 2007. At SAR-02 in the northwest region, the proportion increased from 2003 to 2005 and then decreased in 2007. At SAR-04 in the east region, the proportions were nearly the same in 2005 and 2007. An increase in the proportion in the smallest size class may be a result of recruitment, fragmentation of existing colonies, or both, while a shift toward higher proportions in the larger size classes may reflect growth coupled with the absence of compensatory recruitment or fragmentation. Minor variations between years in size-class distribution likely derive from chance differences in the placement of individual quadrats. Thus, it appears from these data that variable dynamics of recruitment, fragmentation, and growth occurred among the 3 sites that were surveyed in more than one year.

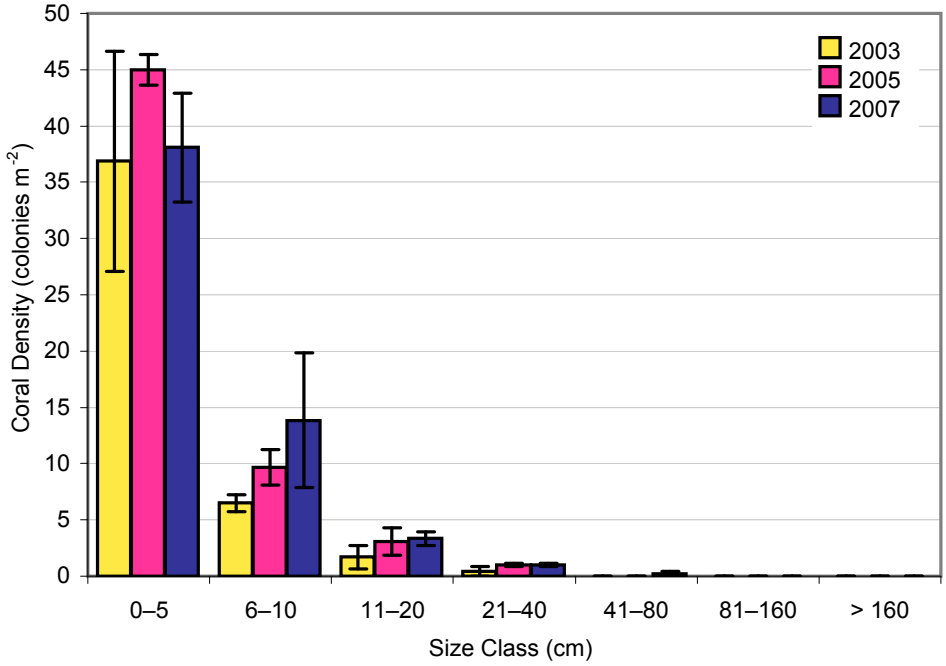


Figure 10.5.1h. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Sarigan during MARAMP 2003, 2005, and 2007. The quadrat method was used in each of the 3 survey years to size corals. Error bars indicate standard error (± 1 SE) of the mean.

10.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted at 3 sites on forereef habitats at Sarigan, covering a total area of 900 m^2. Surveys detected 14 cases of disease, translating to an overall mean prevalence of 0.04% (SE 0.02). Coral-colony counts at all REA sites at Sarigan were conducted using the quadrat method, resulting in high coral-colony densities and, therefore, low disease prevalence values, relative to the levels found at sites at other islands surveyed using the belt-transect method.

Three disease conditions were observed at Sarigan: fungal infection, an infestation by the encrusting sponge *Terpios,* and bleaching. All 3 sites contained disease, however in low prevalences (Fig. 10.5.2a and b). Eight cases of fungal infection were recorded at Sarigan, with over 50% occurring at SAR-04, particularly on corals of the genus *Cyphastrea*. Cases of fungal infection were also present at SAR-01 and SAR-02. *Terpios* infestations were noticeable at SAR-04 and SAR-01 on a variety of coral genera including *Turbinaria*, *Porites*, *Montipora*, *Astreopora*, and *Pavona*. Finally, one case of bleaching was observed at SAR-02 in the northwest region. No signs of the crown-of-thorns seastar (*Acanthaster planci)* or coral-livorous snail predation scars were noticed at the sites surveyed.

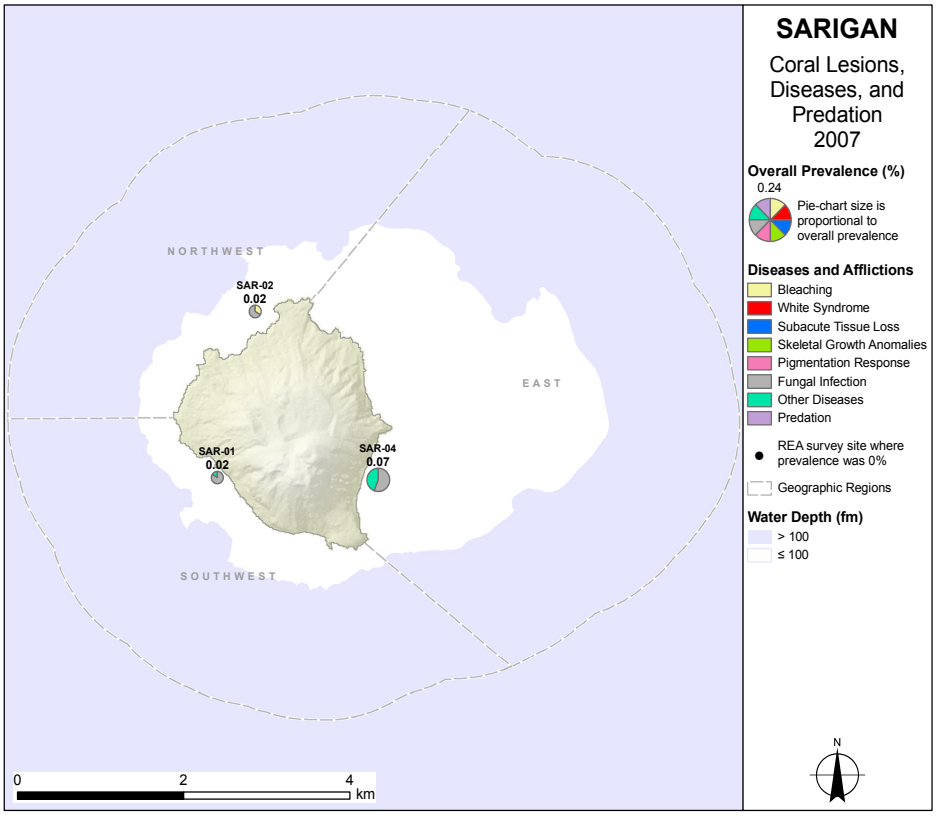


Figure 10.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys conducted at Sarigan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie chart indicate disease-specific prevalence.

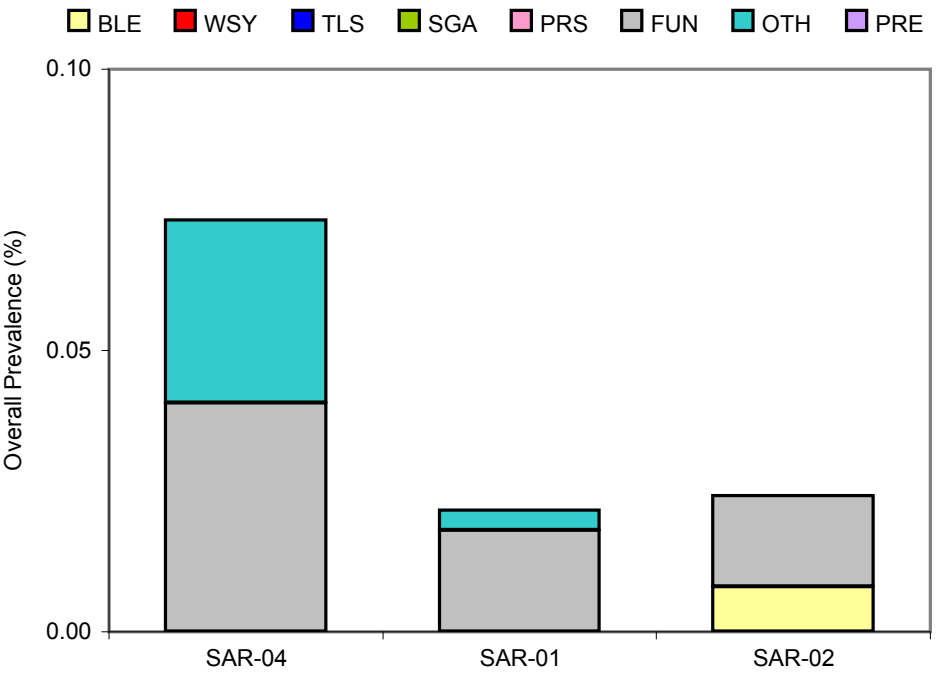


Figure 10.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA surveys conducted at Sarigan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesions of unknown etiology; PRE: COTS or corallivorous snails.

10.6 Algae and Algal Disease

10.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Sarigan was 42% (SE 2.1). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. Two surveys had the highest mean macroalgal cover of 49%, within a range of 30.1%–75%. The first of these surveys was completed on a track that straddled the southwest and northwest regions, over predominantly pavement and rock boulder habitat of medium-high complexity for 7 survey segments and low to medium-low complexity for 3 segments (Fig. 10.6.1a, top left panel). The second survey traversed the border of the northwest and east regions, beginning near the northern tip of this island. The lowest mean macroalgal cover from a towed-diver survey with was 33.7%, within a range of 20.1%–50%, recorded in the northwest region, also near the northern tip of Sarigan.

TOAD surveys completed at Sarigan during MARAMP 2003 were conducted at depths of 78–207 m. Analyses of TOAD video footage obtained from a survey conducted south of Sarigan, in the southwest region at depths of 78–100 m, suggested that macroalgal cover was high with 60%–100%, at least as observable from a majority of images (Fig. 10.6.1a, top left panel). Two short surveys, 1 in the northwest region and 1 in the southwest region, were less successful with only 9 video frames successfully classified; no macroalgae were observed within these images.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Sarigan was 24% (SE 2.3). The survey with the highest mean macroalgal cover of 40.1%, within a range of 30.1%–62.5%, occurred along the west side and crossed the border between the southwest and northwest regions (Fig. 10.6.1a, middle left panel). Habitat of medium complexity was found throughout this survey. The lowest mean macroalgal cover from a towed-diver survey was 3.1%, within a range of 1.1%–10%, recorded along the northern shoreline and across the border between the east and northwest regions.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats around Sarigan was 16% (SE 1.1). The survey with the highest mean macroalgal cover of 24.2%, within a range of 5.1%–40%, occurred in the northwest region (Fig. 10.6.1a, bottom left panel). Habitat in the middle of this survey was characterized by a steep wall; however, the remaining survey area had habitat of medium complexity over continuous reef strewn with boulders. The lowest mean macroalgal cover from a towed-diver survey was 11.5%, within a range of 10.1%–30%, recorded on the west coast, crossing the border between the southwest and northwest regions. This survey recorded medium-complexity habitat of large boulders on one half and continuous reef on the other half, with cyanobacteria found in the middle of this survey.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats at Sarigan were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 0% to 15.7% with an overall sample mean of 5.9% (SE 4.9). The survey with the highest macroalgal cover occurred at REA site SAR-02 in the northwest region (Fig. 10.6.1b). No macroalgae were recorded in the east region at SAR-04. Macroalgal cover was low at 2% at SAR-01 in the southwest region.

Turf-algal cover from these REA benthic surveys ranged from 31.4% to 45.1% with an overall sample mean of 39.5% (SE 4.2). The highest turf-algal cover was observed at SAR-01 in the southwest region (Fig. 10.6.1b). The survey with the lowest turf-algal cover occurred in the northwest region at SAR-02.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Sarigan was 11% (SE 1.1). The survey with the highest mean crustose-coralline-red-algal cover of 19%, within a range of 10.1%–30%, occurred in the southwest region (Fig. 10.6.1a, top right panel) over rock boulder and pavement habitat of medium-high complexity. The lowest mean cover of crustose coralline red algae from a towed-diver survey was 3.5%, within a range of 1.1%–10%, recorded along the northern coast across the border between the east and northwest regions.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Sarigan was 3% (SE 0.7). The survey with the highest mean crustose-coralline-red-algal cover of 6.8%, within a range of 0.1%–

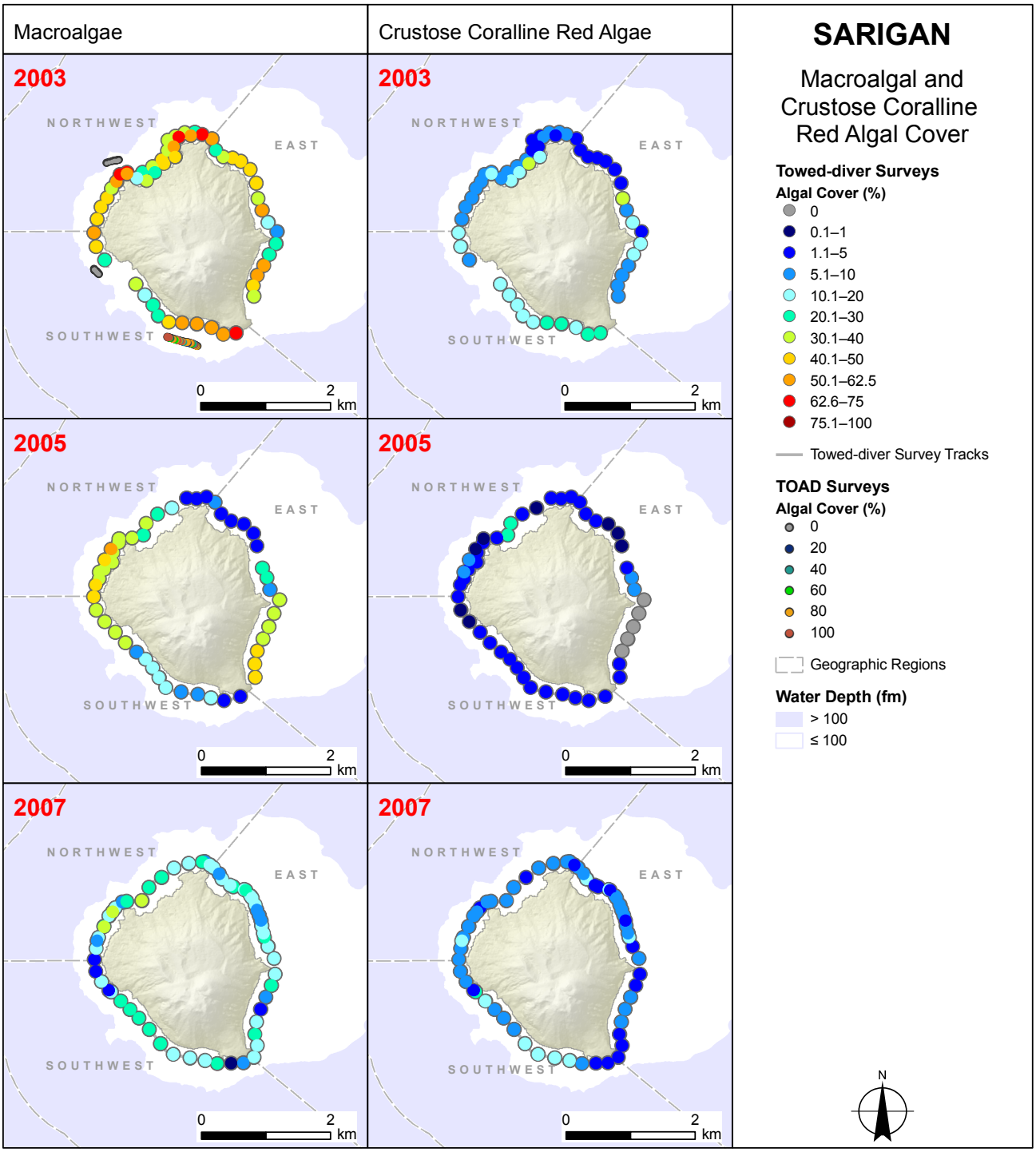


Figure 10.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Sarigan during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m²). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

30%, occurred in the northwest region (Fig. 10.6.1a, middle right panel). The lowest mean cover of crustose coralline red algae from a towed-diver survey was 1.8%, within a range of 0.1%–5%, recorded in the east region.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Sarigan was 8% (SE 0.6). The survey with the highest mean crustose-coralline-red-algal cover of 13%, within a range of 5.1%–30%, occurred in the southwest region (Fig. 10.6.1a, bottom right panel). Habitat consisted primarily of medium to medi-

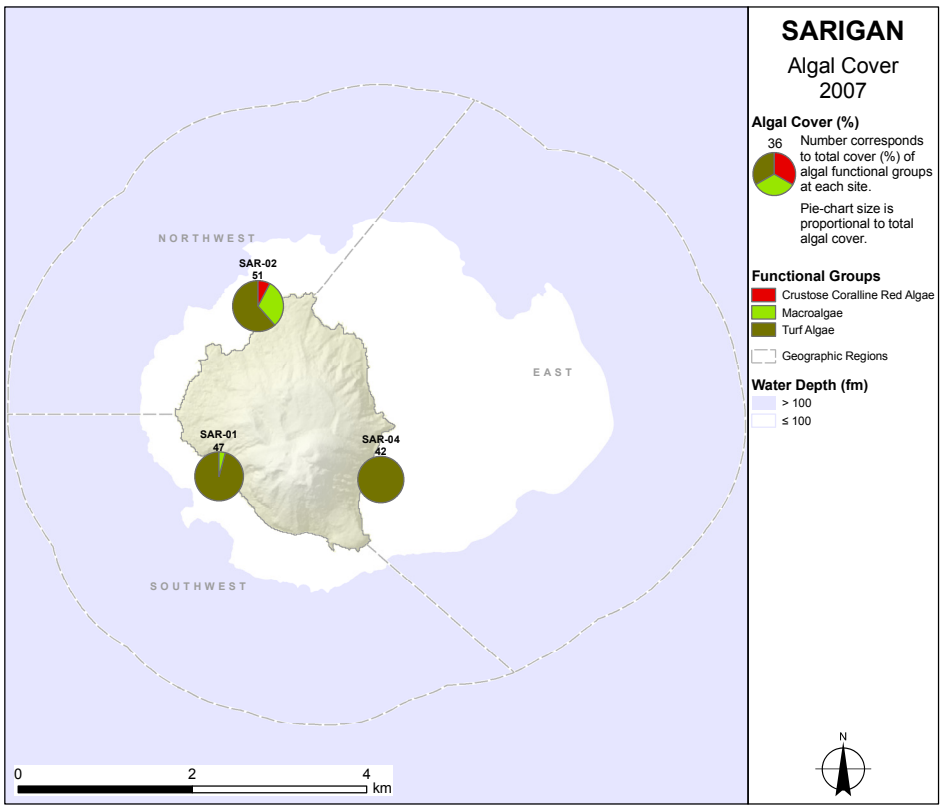


Figure 10.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method at Sarigan during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

um-high complexity boulder reef on moderately sloped habitat, shifting to continuous reef and boulders in sand (boulder patch reef). The lowest mean cover of crustose coralline red algae from a towed-diver survey was 2.7%, within a range of 0.1%–10%, recorded in the northwest region.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats at Sarigan were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 3.9% with an overall sample mean of 1.3% (SE 0.9). The survey with the highest crustose-coralline-red-algal cover occurred at SAR-02 (Fig. 10.6.1b). No crustose coralline red algae were recorded at SAR-01 in the southwest region or SAR-04 in the east region.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, islandwide mean cover of macroalgal populations around Sarigan, based on towed-diver surveys of forereef habitats, was lower in 2007 than in 2005 with means of 24% (SE 2.3) in 2005 and 16% (SE 1.1) in 2007 (Fig. 10.6.1c). When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Between MARAMP survey years, no area at Sarigan consistently had the highest or lowest macroalgal cover recorded during towed-diver survey. A survey area that crossed the border between the southwest and northwest regions had the highest levels of macroalgal cover recorded in both 2003 and 2005 with means of 49% and 40.1%, but the survey

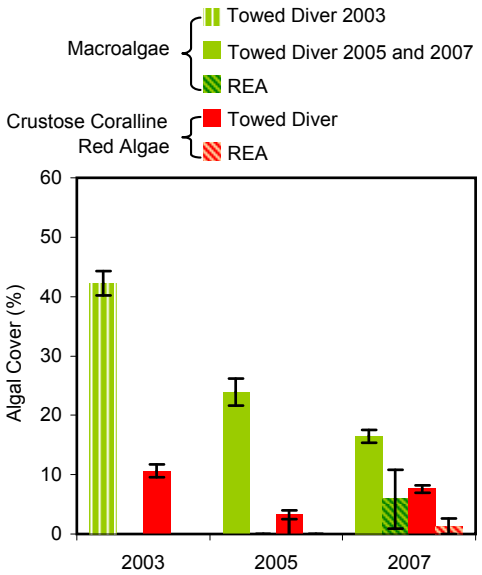


Figure 10.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Sarigan during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

completed in that same area in 2007 had the lowest macroalgal cover for that survey year with a mean of 11.5%.

Crustose-coralline-red-algal populations around Sarigan, based on towed-diver surveys of forereef habitats, varied by as much as 8% in average cover of the benthos between MARAMP survey years, with islandwide means of 11% (SE 1.1) in 2003, 3% (SE 0.7) in 2005, and 8% (SE 0.6) in 2007. During MARAMP 2003 and 2007 survey years, the highest mean crustose-coralline-red-algal cover occurred in the southwest region. In each of the 3 survey periods, the lowest cover of crustose coralline red algae was found near the northern tip of Sarigan in either the northwest or east regions.

REA surveys using the line-point-intercept method were conducted only in 2007. Values for both macroalgal and crustose-coralline-red-algal cover from these surveys were lower than results from towed-diver surveys.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 3 sites on forereef habitats at Sarigan. In the field, 5 macroalgal genera (1 red and 4 green), containing at least 7 species, as well as 2 additional algal functional groups—turf algae and cyanobacteria—were observed. SAR-02 in the northwest region had the highest macroalgal generic diversity with 4 genera, containing 6 species, documented in the field. The lowest macroalgal diversity was found at SAR-03, also located in the northwest region, with 1 species representing 1 genus recorded.

Species of the green algal genus *Boodlea* were common at every site surveyed at Sarigan in 2003, occurring in 22.2% of sampled photoquadrats, and this genus was the only one to occur at all sites. Species of the calcified, red algal genus *Amphiroa* and 3 species of the calcified, green algal genus *Halimeda* were equally abundant, each occurring in 16.7% of sampled photoquadrats (Fig. 10.6.1d, top panel). However, species of *Amphiroa* and *Halimeda* did not occur at SAR-03 in the northwest region, where species of *Boodlea* were the only macroalgae observed. Two other green algal genera were recorded in 2003, *Chlorodesmis* and *Valonia* (previously recognized as *Ventricaria*); they were found in low abundance compared to *Boodlea*, occurring in only 8.3% of the photoquadrats sampled at the sites where they were observed.

Turf algae were exceptionally common in 2003, occurring in 94.4% of photoquadrats sampled at Sarigan (Fig. 10.6.1d, top panel). Crustose coralline red algae were absent at all sites. Cyanobacteria were less common compared to turf algae, occurring in 19.4% of sampled photoquadrats. Turf-algal communities were ubiquitous and extremely common at all sites, and although cyanobacteria also were observed at all sites, this functional group was much more abundant in the northwest region at SAR-03, where it occurred in 41.7% of sampled photoquadrats, than in the southwest and northwest regions, where cyanobacteria occurred in only 8.3% of photoquadrats sampled at SAR-01 and SAR-02.

During MARAMP 2005, REA benthic surveys were conducted at 3 sites on forereef habitats at Sarigan. In the field, 11 macroalgal genera (4 red, 5 green, and 2 brown), containing at least 12 species, as well as 2 additional algal functional groups—turf algae and crustose coralline red algae—were observed. SAR-01 in the southwest region had the highest macroalgal generic diversity with 8 genera, containing 8 species, documented in the field. The lowest macroalgal generic diversity was found at SAR-02 in the northwest region and SAR-04 in the east region, each with 6 genera representing 6 species recorded.

Of the 11 different genera identified in the field at Sarigan in 2005, 7 occurred in > 10% of sampled photoquadrats. Species of the red algal genus *Jania* were common at all 3 sites surveyed, occurring in 52.8% of sampled photoquadrats (Fig. 10.6.1d, middle panel). This genus was observed in particularly high abundance at SAR-04 in the east region and SAR-01 in the southwest region, occurring in 75% and 58.3% of sampled photoquadrats, but was found in only 25% of photoquadrats sampled at SAR-02 in the northwest region. At SAR-02, 4 genera—*Jania*, *Amphiroa, Chlorodesmis*, and *Halimeda*—were seen in 25% of sampled photoquadrats. The only other genus observed at all sites was the brown algal genus *Dictyota*, recorded in 19.4% of photoquadrats sampled at Sarigan. Another brown algal genus, *Lobophora*, occurred in a greater percentage of sampled photoquadrats than did *Dictyota*, even though it was only found at 2 sites and only in

high abundance (75%) at SAR-01. The green algal genus *Bryopsis* occurred in 22.2% of sampled photoquadrats; however, this genus was only observed at SAR-04, where it occurred in 66.7% of sampled photoquadrats, second to *Jania* at that site. The genera *Chlorodesmis, Amphiroa,* and *Halimeda* occurred in 16.7%, 11.1% and 11.1% of sampled photodquarats and were the only genera to occur at SAR-01 and SAR-02 in 2005.

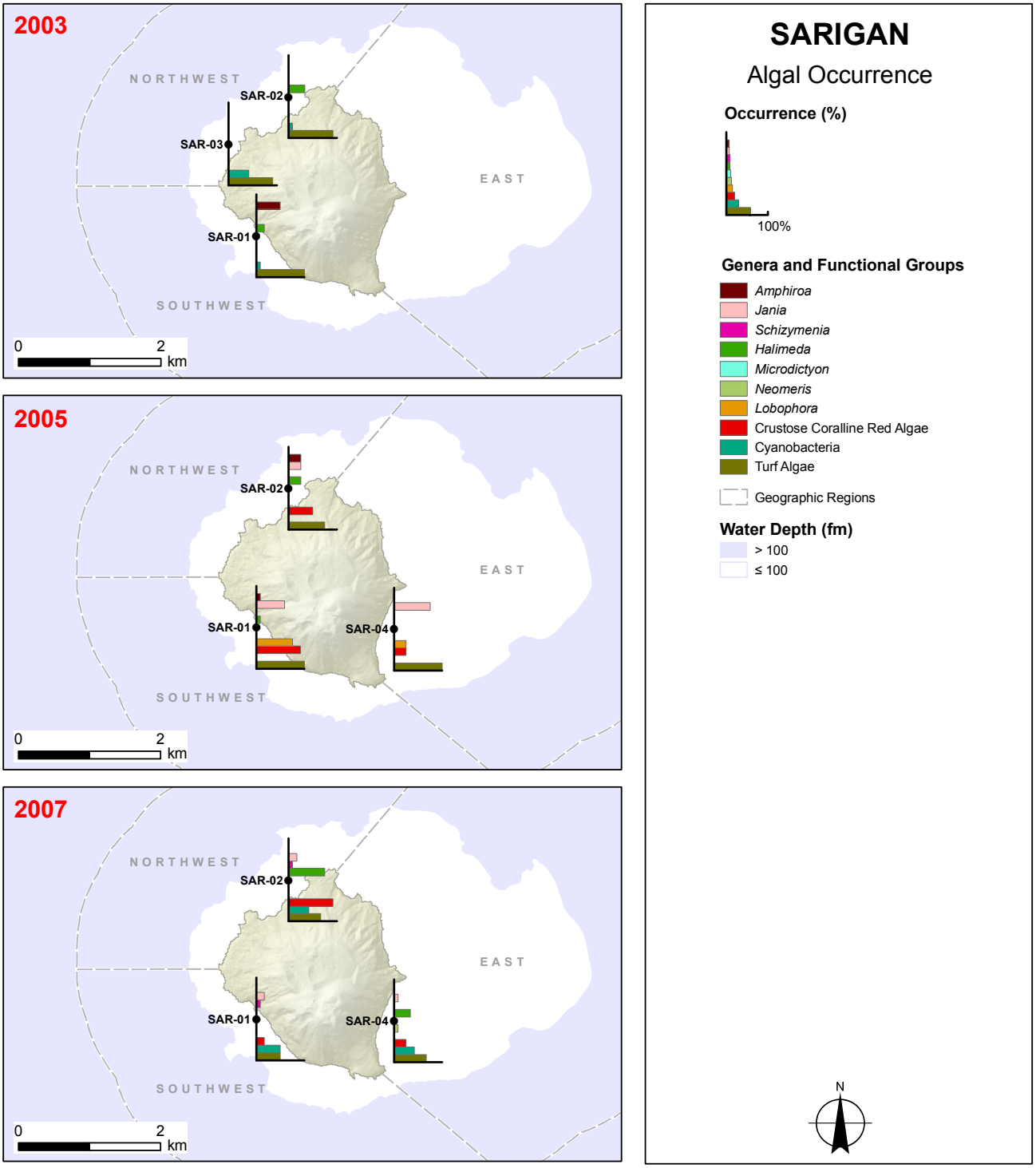


Figure 10.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA algal surveys of forer-eef habitats conducted at Sarigan during MARAMP 2003, 2005, and 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

Turf algae and crustose coralline red algae were both common in 2005, occurring in 91.7% and 55.6% of photoquadrats sampled at Sarigan (Fig. 10.6.1d, middle panel). Turf-algal communities, ubiquitous at all sites, were found in 75%–100% of sampled photoquadrats. Also observed at all sites, crustose coralline red algae were present in 25%–91.7% of sampled photoquadrats. The absence of cyanobacteria in MARAMP 2005 surveys conducted at Sarigan is peculiar; however, an alga unidentifiable to the scientist completing REA benthic surveys at Sarigan was recorded at roughly the same abundance levels observed for cyanobacteria in 2003 (occurrence values of 8.3%–16.7%), and it is possible that this "mystery alga" was cyanobacteria.

During MARAMP 2007, REA algal surveys were conducted at 3 sites on forereef habitats around Sarigan. In the field, 9 macroalgal genera (3 red, 4 green, and 2 brown), containing at least 9 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanobacteria—were observed. SAR-02 in the northwest region and SAR-04 in the east region each contained 5 distinct macroalgal genera, representing 5 species. A slightly lower algal diversity was found at SAR-01 with 4 species representing 4 genera.

The genus *Halimeda* was the most common macroalgal genus at Sarigan in 2007, occurring in 36.1% of sampled photoquadrats (Fig. 10.6.1d, bottom panel). This genus was recorded in high abundance at SAR-02 and SAR-04 in the northwest and east regions, seen in 75% and 33.3% of sampled photoquadrats, but was not found at SAR-01 in the southwest region. A similar pattern was observed for the genus *Boodlea,* which also was recorded only at SAR-02 and SAR-04; this genus occurred in 50% of photoquadrats sampled at each of these sites. The genus *Jania* was the only algal genus observed in the field at all 3 sites, occurring in 13.9% of sampled photoquadrats islandwide with site-specific occurrence values of 8.3%–16.7%.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2007, occurring in 61.1%, 44.5%, and 44.4% of photoquadrats sampled at Sarigan (Fig. 10.6.1d, bottom panel). Crustose-coralline-red-algal communities were ubiquitous at all sites, although occurrence values varied substantially within a range of 16.7%–91.7%. Turf algae and cyanobacteria, also prominent components of the algal community at all sites, were observed in 50%–66.7% and 41.7%–50% of sampled photoquadrats.

The number of macroalgal genera recorded on forereef habitats around Sarigan increased from 5 in 2003 to 11 in 2005 but decreased to 9 in 2007. The substitution of SAR-04 in the east region for SAR-03 in the northwest region after MARAMP 2003 may account for some of this change in algal diversity. In both 2005 and 2007, 5 macroalgal genera were found at SAR-04, compared to observations of just a single genus and species at SAR-03 in 2003. Macroalgal diversity at SAR-01 and SAR-02 was lower in 2003 and 2007 than in 2005. The genus *Halimeda* was the only taxon that was observed in each of the 3 MARAMP survey years, suggesting that the diversity of the marine flora at Sarigan may be influenced by seasonal variability. Subsequent surveys may provide additional insight into this hypothesis.

Turf algae was recorded in 61.1%–94.4% of photoquadrats sampled at Sarigan during MARAMP 2003, 2005, and 2007, with the greatest occurrence recorded in 2003 and the lowest in 2007 (Fig. 10.6.1e). Because identical site locations were

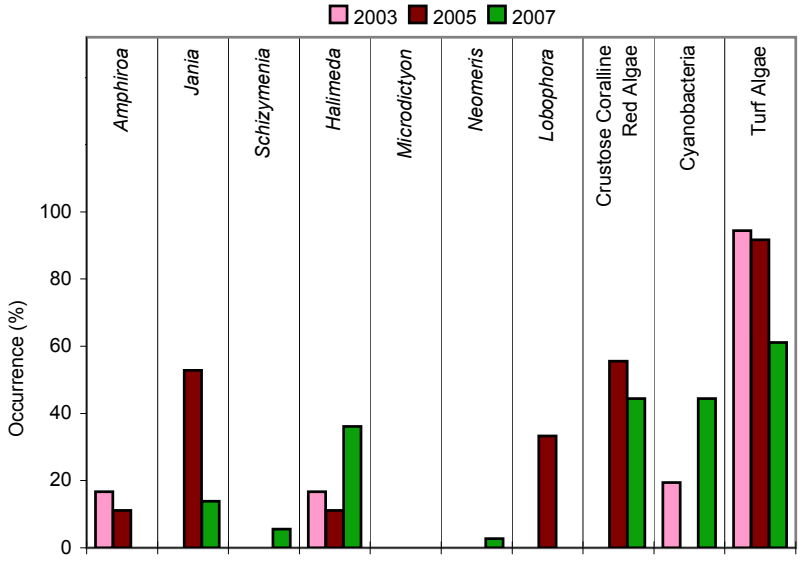


Figure 10.6.1e. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Sarigan during MARAMP 2003, 2005, and 2007.

surveyed in both 2005 and 2007, the reduction in occurrence from 91.7% to 61.1% could indicate loss of benthic turf-algal cover; however, it is important to consider seasonal variability as a potential explanation since MARAMP 2005 surveys were conducted in September and MARAMP 2007 surveys were conducted in May. No trends showing increasing or decreasing abundance of the functional groups crustose coralline red algae or cyanobacteria were obvious.

10.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 3 sites on forereef habitats at Sarigan. These surveys covered a total reef area of ~ 900 m^{-2} and detected no cases of coralline-algal disease.

10.7 Benthic Macroinvertebrates

10.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Sarigan through benthic REA and towed-diver survey methods during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 3 REA benthic surveys and 6 towed-diver surveys were conducted around Sarigan, and, in 2005, 3 REA surveys and 5 towed-diver benthic surveys were performed. In 2007, 3 REA surveys and 6 towed-diver benthic surveys were completed around Sarigan. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, both REA and towed-diver surveys revealed low daytime macroinvertebrate abundance on forereef habitats around Sarigan. Minor fluctuations in densities between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density on forereef habitats around Sarigan—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 10.7.1b, d, f, and h).

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at all 3 REA sites surveyed and in 4 of the 6 towed-diver surveys conducted around Sarigan (Fig. 10.7.1a, top panel). The overall sample mean density of giant clams from REA surveys was 5.67 organisms 100 m^{-2} (SE 1.4), and the islandwide mean density from towed-diver surveys was 0.03 organisms 100 m^{-2} (SE 0.01). Survey results suggest giant clams were most abundant along the western half of this island. The highest density among REA sites at Sarigan, at 8 organisms 100 m^{-2}, was recorded at REA site SAR-01 in the southwest region. Among all towed-diver surveys around this island, the survey completed in the northwest region had the highest mean density of giant clams with 0.09 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.3 organisms 100 m^{-2}.

During MARAMP 2005, giant clams were observed at 2 of the 3 REA sites surveyed and in 4 of the 5 towed-diver surveys conducted around Sarigan (Fig. 10.7.1a, middle panel). The overall sample mean density of giant clams from REA surveys was 1.67 organisms 100 m^{-2} (SE 1.20), and the islandwide mean density from towed-diver surveys was 0.097 organisms 100 m^{-2} (SE 0.01). The highest density among REA sites, at 4 organisms 100 m^{-2}, was recorded at SAR-01. Among all towed-diver surveys around this island, the surveys completed in the northwest region had the highest mean density of giant clams with 0.17 and 0.13 organisms 100 m^{-2}; segment densities from these surveys ranged from 0 to 0.56 organisms 100 m^{-2}.

During MARAMP 2007, giant clams were observed at all 3 REA sites surveyed and in all 6 towed-diver surveys conducted around Sarigan (Fig. 10.7.1a, bottom panel). The overall sample mean density of giant clams from REA surveys was 1.47 organisms 100 m^{-2} (SE 0.59), and the islandwide mean density from towed-diver surveys was 0.05 organisms 100 m^{-2} (SE 0.01). The highest density among REA sites, at 2.33 organisms 100 m^{-2}, was recorded at SAR-04 in the southeast. Among all towed-diver surveys around this island, the survey completed across the border between the southwest and northwest regions had the highest mean density of giant clams with 0.13 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.29 organisms 100 m^{-2}.

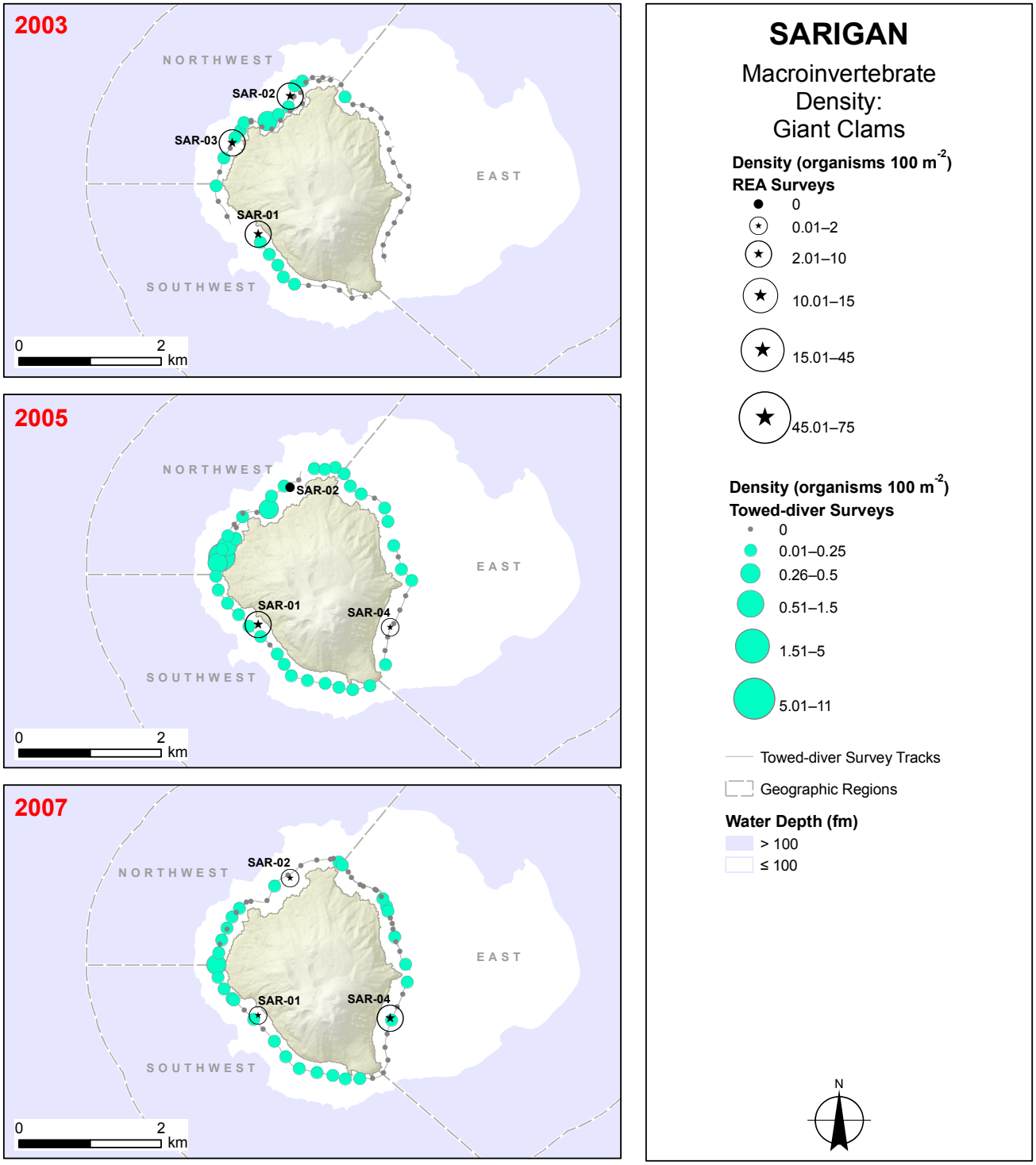


Figure 10.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Sarigan during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggested low abundance of giant clams around Sarigan during the 3 MARAMP survey periods. In each survey year, densities of giant clams were greater along the western half of this island than on the east side. The overall observed mean density of giant clams was higher in 2005 than in 2003 and 2007 (Fig. 10.7.1b). Minor fluctuations in density are not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

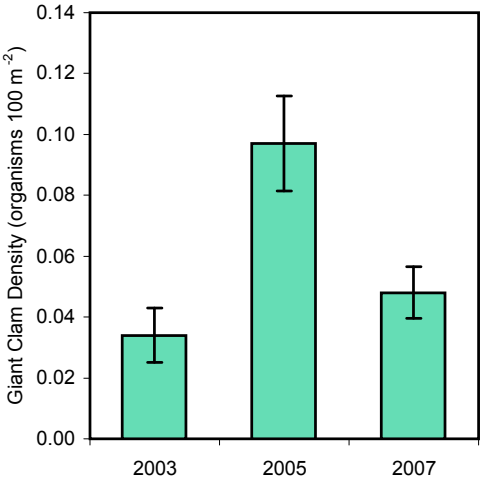


Figure 10.7.1b. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Sarigan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Crown-of-thorns Seastars

During MARAMP 2003, no crown-of-thorns seastars (*Acanthaster planci*) were observed at the 3 REA sites surveyed at Sarigan, and only 1 of the 6 towed-diver surveys had recordings of COTS (Fig. 10.7.1c, top panel). This towed-diver survey in the southwest region had a mean density of 0.002 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.05 organisms 100 m^{-2}.

During MARAMP 2005, no COTS were observed at the 3 REA sites surveyed at Sarigan, and only 1 of the 5 towed-diver surveys had recordings of COTS (Fig. 10.7.1c, middle panel). This towed-diver survey in the southwest region had a mean density of 0.001 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.06 organisms 100 m^{-2}.

During MARAMP 2007, no COTS were observed at the 3 REA sites surveyed or in any of the towed-diver surveys conducted around Sarigan (Fig. 10.7.1c, bottom panel).

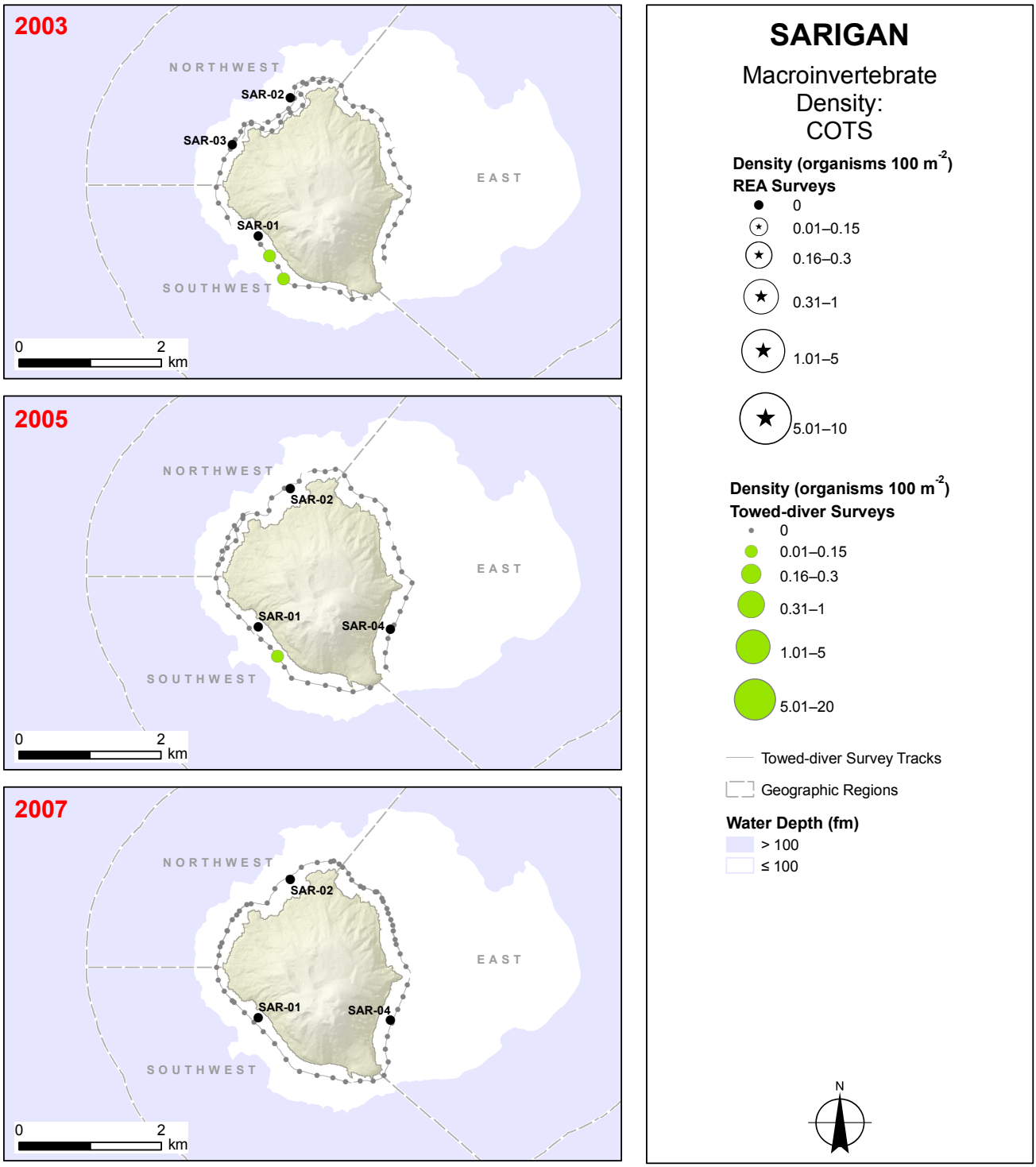


Figure 10.7.1c. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Sarigan during MARAMP 2003, 2005, and 2007.

Towed-diver benthic surveys revealed virtually no COTS at Sarigan during the 3 MARAMP survey years (Fig. 10.7.1d). In 2003 and 2005, COTS were observed only in the southwest region at very low densities.

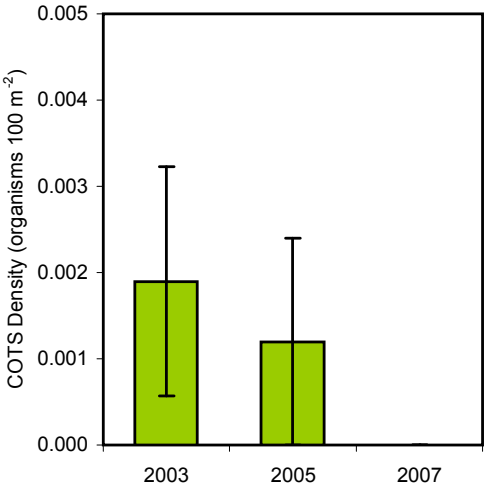


Figure 10.7.1d. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Sarigan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at 2 of the 3 REA sites surveyed and in 5 of the 6 towed-diver surveys conducted around Sarigan (Fig. 10.7.1e, top panel). The overall sample mean density from REA surveys was 0.67 organism 100 m^{-2} (SE 0.33), and the islandwide mean density of sea cucumbers from towed-diver surveys was 0.55 organisms 100 m^{-2} (SE 0.22). Species from 2 genera were observed during REA surveys: *Stichopus* and *Actinopyga.* Among all towed-diver surveys around Sarigan, the survey completed in the northwest region had the highest mean density of sea cucumbers with 2.02 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 10.94 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 1.09 organisms 100 m^{-2}, recorded along the north shore; segment densities from this survey ranged from 0.23 to 4.16 organisms 100 m^{-2}.

During MARAMP 2005, sea cucumbers were observed at 2 of the 3 REA sites surveyed and in 4 of the 5 towed-diver surveys conducted around Sarigan (Fig. 10.7.1e, middle panel). The overall sample mean density from REA surveys was 2 organisms 100 m^{-2} (SE 1.53), and the islandwide mean density of sea cucumbers from towed-diver surveys was 0.22 organisms 100 m^{-2} (SE 0.07). The highest density of sea cucumbers was observed at SAR-01 in the southwest region with 5 organisms 100 m^{-2}—all of which were from the genus *Stichopus*. During REA surveys at Sarigan, *Stichopus* and *Holothuria* were the only observed genera. Among all towed-diver surveys around Sarigan, the survey conducted across the border between the southwest and northwest regions had the highest mean density with 0.85 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.91 organisms 100 m^{-2}.

During MARAMP 2007, sea cucumbers were observed at 2 of the 3 REA sites surveyed and in all 6 towed-diver surveys conducted around Sarigan (Fig. 10.7.1e, bottom panel). The overall sample mean density from REA surveys was 1.33 organisms 100 m^{-2} (SE 0.88), and the islandwide mean density of sea cucumbers from towed-diver surveys was 0.4 organisms 100 m^{-2} (SE 0.09). Similar to results from 2005, the highest density of sea cucumbers was recorded at SAR-01 in the southwest region with 3 organisms 100 m^{-2}—89% of which were from the genus *Stichopus* and 11% from the genus *Pearsonothuria.* During REA surveys around Sarigan, *Stichopus, Pearsonothuria,* and *Holothuria* were the 3 observed genera. Among all towed-diver surveys around Sarigan, the survey conducted across the border between the southwest and northwest regions had the highest mean density with 1.22 organisms 100 m^{-2}; segment densities from this survey ranged from 0.37 to 4.24 organisms 100 m^{-2}.

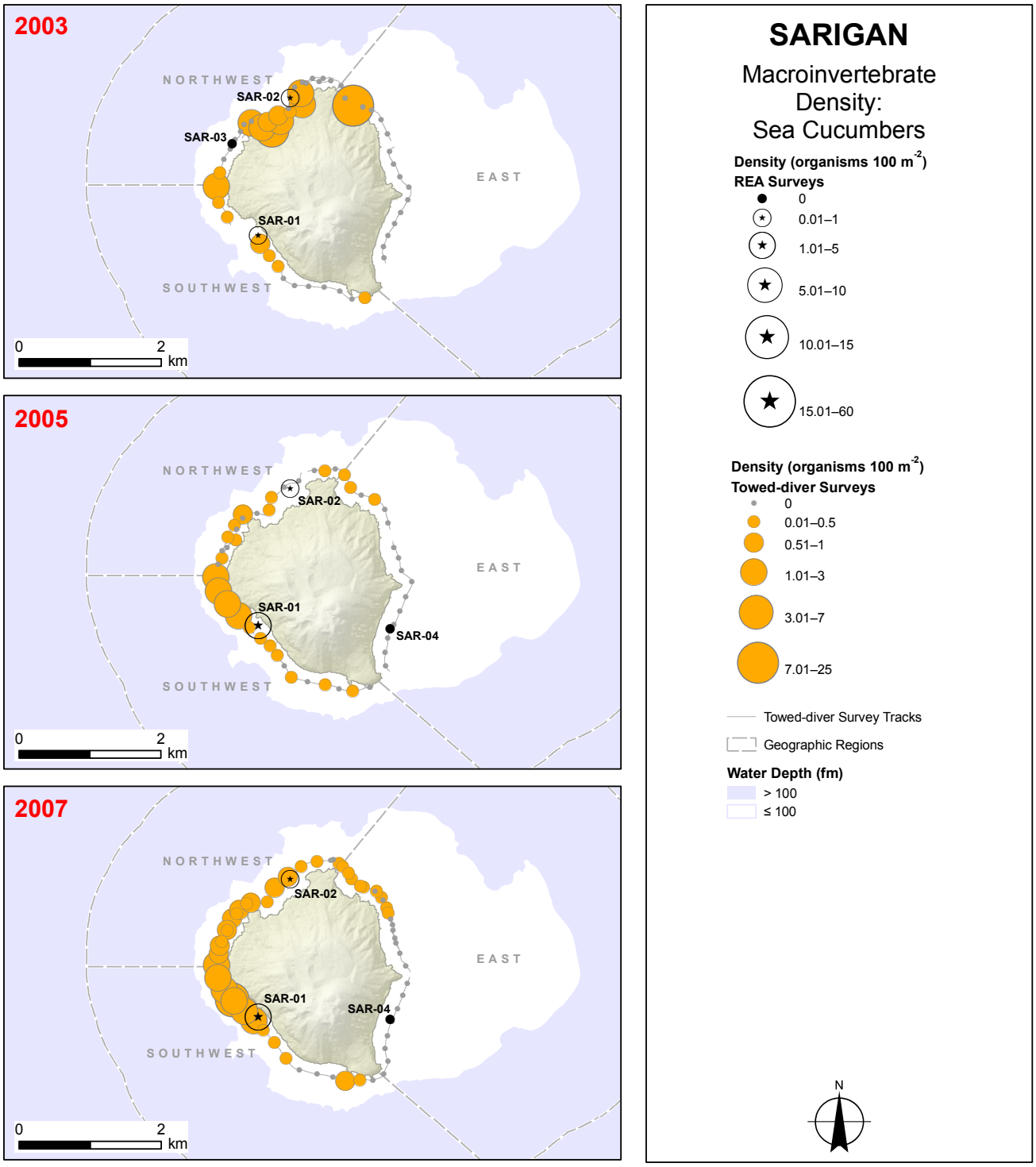


Figure 10.7.1e. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Sarigan during MARAMP 2003, 2005, and 2007.

Both towed-diver surveys and REA surveys suggested low daytime abundance of sea cucumbers around Sarigan during the 3 MARAMP survey years (Fig. 10.7.1f). In each survey year, observed densities of sea cucumbers were greater along the western part of this island. Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

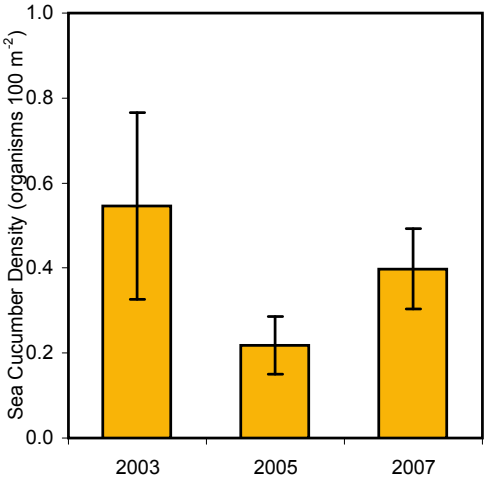


Figure 10.7.1f. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Sarigan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Urchins

During MARAMP 2003, sea urchins were observed at all 3 REA sites surveyed and in 5 of the 6 towed-diver surveys conducted around Sarigan (Fig. 10.7.1g, top panel). The overall sample mean density from REA surveys was 91.33 organisms 100 m^{-2} (SE 57.37), and the islandwide mean density of sea urchins from towed-diver surveys was 0.35 organisms 100 m^{-2} (SE 0.1). The highest density of sea urchins was recorded at SAR-03 in the northwest region with 206 organisms 100 m^{-2}. Four genera were observed at this REA site: *Echinostephus*, *Echinometra*, *Echinothrix*, and *Diadema.* The rock-boring urchin, *Echinostrephus*, was the dominant urchin genus at all sites, accounting for 95% of recorded urchins. Among all towed-diver surveys around Sarigan, the survey completed in the northwest region had the highest mean density at 0.84 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.5 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed at 1 of the 3 REA sites surveyed and in 4 of the 5 towed-diver surveys conducted around Sarigan (Fig. 10.7.1g, middle panel). The density for this REA survey was 3 organisms 100 m^{-2}, and the islandwide mean density of sea urchins from towed-divers surveys was 0.09 organisms 100 m^{-2} (SE 0.05). All observed sea urchins at SAR-02 in the northwest region were from the genus *Echinostrephus.* Among all towed-diver surveys around Sarigan, the survey completed in the east region had the highest mean density of 0.26 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.28 organisms 100 m^{-2}. The towed-diver survey conducted had the second-greatest density of sea urchins from a towed-diver survey was 0.12 organisms 100 m^{-2}, recorded in the southwest region; segment densities ranged from 0 to 0.9 organisms 100 m^{-2}.

During MARAMP 2007, sea urchins were observed at 2 of the 3 REA sites surveyed and in 4 of the 6 towed-diver surveys conducted around Sarigan (Fig. 10.7.1g, bottom panel). The overall sample mean density from REA surveys was 1.22 (SE 1.06), and the islandwide mean density of sea urchins from towed-diver surveys was 0.15 organisms 100 m^{-2} (SE 0.06). The highest density of sea urchins, at 3.33 organisms 100 m^{-2}, was recorded at SAR-02. All observed urchins from REA surveys were from the genus *Echinostrephus.* Among all towed-diver surveys around Sarigan, the survey completed across the border between the southwest and east regions had the highest mean density at 0.41 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.18 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 0.2 organisms 100 m^{-2}, recorded in the east region; segment densities ranged from 0 to 1.91 organisms 100 m^{-2}.

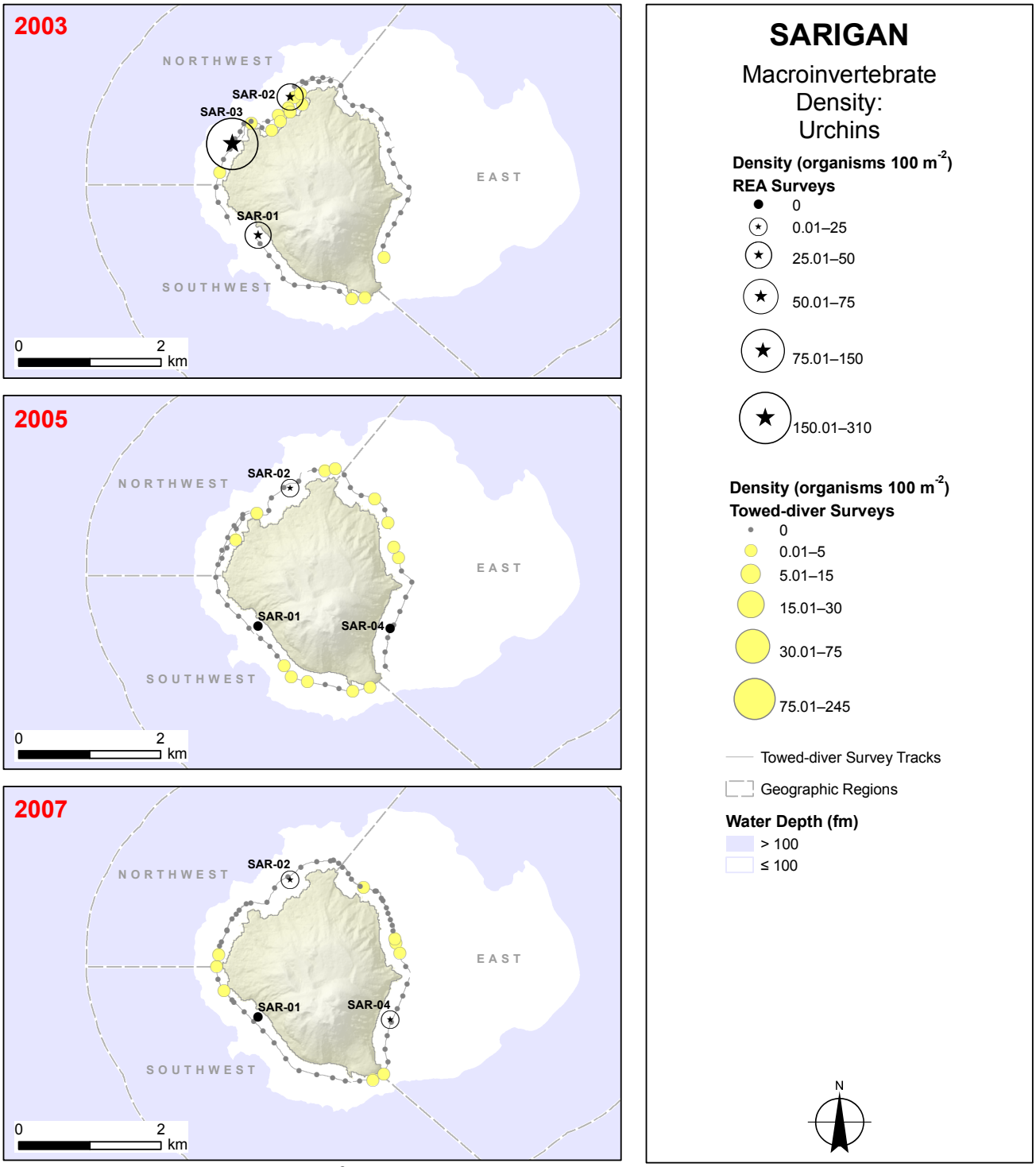


Figure 10.7.1g. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Sarigan during MARAMP 2003, 2005, and 2007.

The overall observed mean density of sea urchins around Sarigan was higher in 2003 than in 2005 and 2007 (Fig. 10.7.1h). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Although sea urchins were not recorded to the genus level during towed-diver surveys, REA surveys suggested that the majority of the sea urchin species observed at Sarigan were rock-boring urchins from the genus *Echinostrephus*.

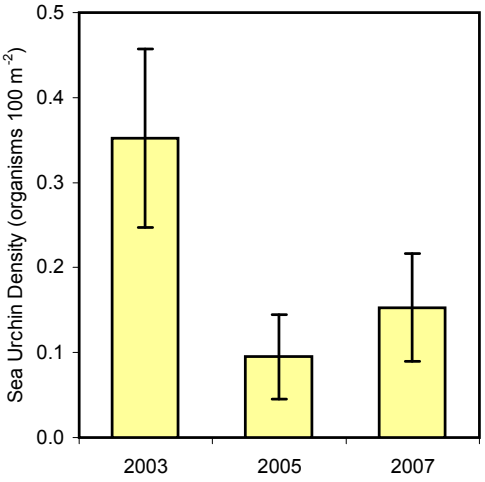


Figure 10.7.1h. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Sarigan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

10.8 Reef Fishes

10.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 6 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Sarigan. The overall estimated mean biomass of large fishes around this island calculated as weight per unit area, was 0.72 kg 100 m^{-2} (SE 0.25). Observed large-fish biomass was highest in the east region where sharks were common (Fig. 10.8.1a, top panel). Reef sharks (Carcharhinidae) and nurse sharks (Ginglymostomatidae) accounted for 53% (0.38 kg 100 m^{-2}) of overall large-fish biomass. During this survey period, 5 sharks were observed: 2 whitetip reef sharks (*Triaenodon obesus*) and 3 tawny nurse sharks (*Nebrius ferrugineus*). Snappers (Lutjanidae) and jacks (Carangidae) were also common, contributing 12% and 9% of overall mean biomass of large fishes. The twinspot snapper (*Lutjanus bohar*) contributed 0.05 kg 100 m^{-2}, while the giant trevally (*Caranx ignobilis*) contributed the next greatest proportion to overall large-fish biomass with 0.04 kg 100 m^{-2}.

During MARAMP 2005, 5 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Sarigan. The overall estimated mean biomass of large fishes was 0.64 kg 100 m^{-2} (SE 0.19). Observed large-fish biomass was highest in the southwest region, where a large school of bigeye trevally (*Caranx sexfaciatus*) was observed during a single survey (Fig. 10.8.1a, middle panel). Jacks, reef sharks, and nurse sharks accounted for 69% of overall large-fish biomass. The bigeye trevally contributed the greatest proportion of overall mean biomass of large fishes with 0.19 kg 100 m^{-2}. During this survey period, 6 sharks were observed: 2 whitetip reef sharks, 2 tawny nurse sharks, and 2 blacktip reef sharks (*Carcharhinus melanopterus*).

During MARAMP 2007, 6 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Sarigan. The overall estimated mean biomass for large fishes was 0.69 kg 100 m^{-2} (SE 0.26). The observed large-fish biomass was highest in the east and southwest regions, where sharks and jacks were common (Fig. 10.8.1a, bottom panel). Consistent with observations made in 2005, jacks, reef sharks, and nurse sharks contributed the greatest proportion (75%) of overall large-fish biomass. A large (~ 100) school of bigeye trevally was observed in the southwest region, making the bigeye trevally the major jack species by biomass, accounting for 94% (0.26 kg 100 m^{-2}) of jack biomass. Reef sharks and nurse sharks accounted for 35% of overall mean biomass of large fishes with the tawny nurse shark contributing the greatest proportion of shark biomass. During this survey period, 7 sharks were observed: 4 grey reef sharks (*Carcharhinus amblyrhynchos*), 2 tawny nurse sharks, and 1 whitetip reef shark.

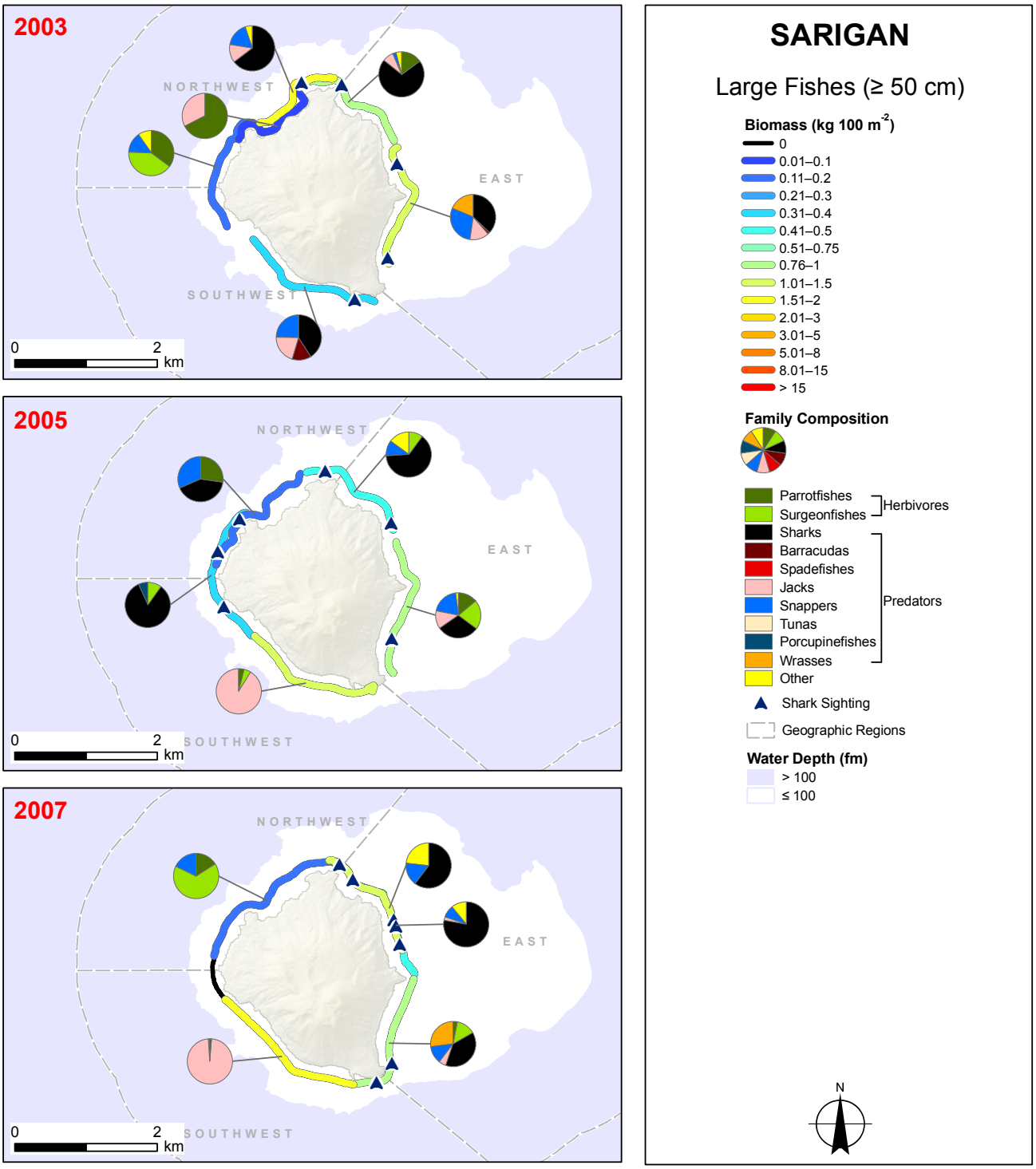


Figure 10.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted around Sarigan during MARAMP 2003, 2005, and 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside the survey area over which it is shown.

Large-fish biomass from towed-diver surveys of forereef habitats was moderate compared to the archipelago-wide mean biomass and was observed at fairly consistent levels in the 3 MARAMP survey periods (Fig. 10.8.2b). Large-bodied predatory fishes, such as jacks, reef sharks, and nurse sharks accounted for 65% or more of overall estimated large-fish biomass across the 3 survey periods. Of note was the observation of a large school of bigeye trevally in the southwest region in both 2005 and 2007. No consistent spatial patter in large-fish biomass was observed during the 3 survey periods; however, the

highest large-fish biomass in 2005 and 2007 was recorded in the southwest region, where, in each year, a school of bigeye trevally was observed. Other notable observations included 3 sightings of the humphead wrasse (*Cheilinus undulatus*), with 2 sightings in 2007 and 1 sighting in 2003.

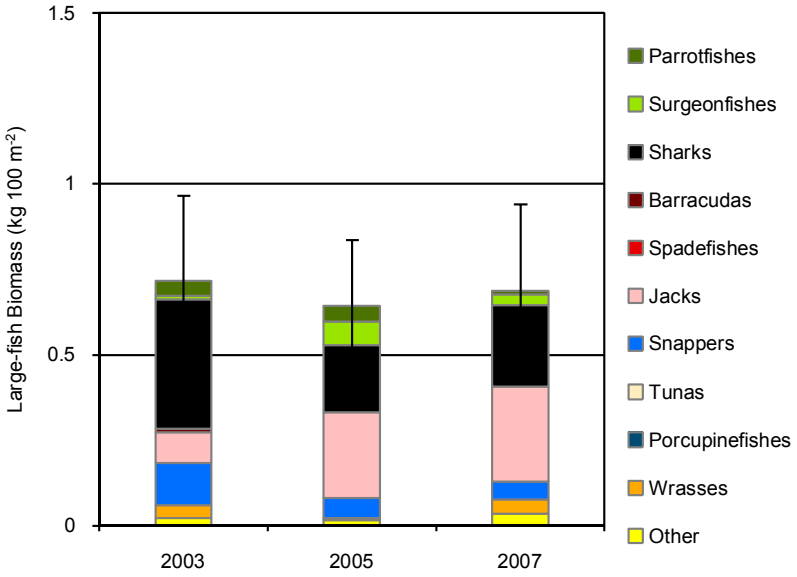


Figure 10.8.1b. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Sarigan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Sarigan during MARAMP 2003 was high compared to other sites in the Mariana Archipelago, with an overall sample mean of 11.54 kg 100 m^{-2} (SE 6.42). The highest biomass of 24.23 kg 100 m^{-2} was observed at REA site SAR-02 in the northwest region, and the lowest biomass of 3.5 kg 100 m^{-2} was found at SAR-01 in the southwest region (Fig. 10.8.1c, top panel). A large (200 cm in TL) tawny nurse shark was observed at SAR-02, contributing 47% (5.44 kg 100 m^{-2}) of total fish biomass at . No other species of sharks were observed during this survey period. Surgeonfishes (Acanthuridae) accounted for the second greatest proportion (15%) or 1.78 kg 100 m^{-2} of total fish biomass. The orangespot surgeonfish (*Acanthurus olivaceus*) dominated surgeonfish biomass, accounting for 34% (0.61 kg 100 m^{-2}) of surgeonfish biomass. Parrotfishes (Scaridae) were also fairly common, contributing 0.97 kg 100 m^{-2} to total fish biomass.

Based on REA surveys conducted during MARAMP 2003, species richness at Sarigan was high with a range of 36–44 species 100 m^{-2}, compared to the archipelago-wide mean for this survey period (31.1 species observed 100 m^{-2}). The highest diversity was observed at SAR-03 in the northwest region (Fig. 10.8.1c, top panel). Wrasses (Labridae) and surgeonfishes were the 2 most represented families with 18 and 14 species observed. The fivestripe wrasse (*Thalassoma quinquevittatum*) was the most abundant wrasse species, and the orangespine unicornfish (*Naso lituratus*) was the most abundant surgeonfish species. Damselfishes (Pomacentridae) were the most numerically abundant family overall, and the midget chromis (*Chromis acares*) dominated counts with 41 individuals 100 m^{-2} observed.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Sarigan during MARAMP 2005 was moderate compared to other sites in the Mariana Archipelago, with an overall sample mean of 6.98 kg 100 m^{-2} (SE 0.62). The highest biomass of 7.82 kg 100 m^{-2} was observed at SAR-01 in the southwest region (Fig. 10.8.1c, middle panel). Surgeonfishes accounted for the greatest proportion (31%) or 2.2 kg 100 m^{-2} of total fish biomass. Surgeonfish biomass was spread across several species with no single species dominating biomass (8 species contributed between 8% and 16% each of surgeonfish biomass). Eagle rays (*Aetobatus narinari*), observed at SAR-01, accounted for the second-greatest proportion (16%) of total fish biomass. No sharks were observed during this survey period.

Based on REA surveys conducted during MARAMP 2005, species richness was moderate, compared to other sites surveyed in the Mariana Archipelago, with a range of 27–32 species 100 m^{-2}. The highest diversity was observed at SAR-01 in the southwest region (Fig. 8.1c, middle panel). Consistent with observations made in 2003, wrasses and surgeonfishes were the 2 most represented families with 16 and 14 species recorded. The ornate wrasse (*Halichoeres ornatissimus*) was the most numerically abundant wrasse species observed, while the brown surgeonfish (*Acanthurus nigrofuscus*) was the most numerically abundant surgeonfish species. Damselfishes dominated counts, and the midget chromis was the most

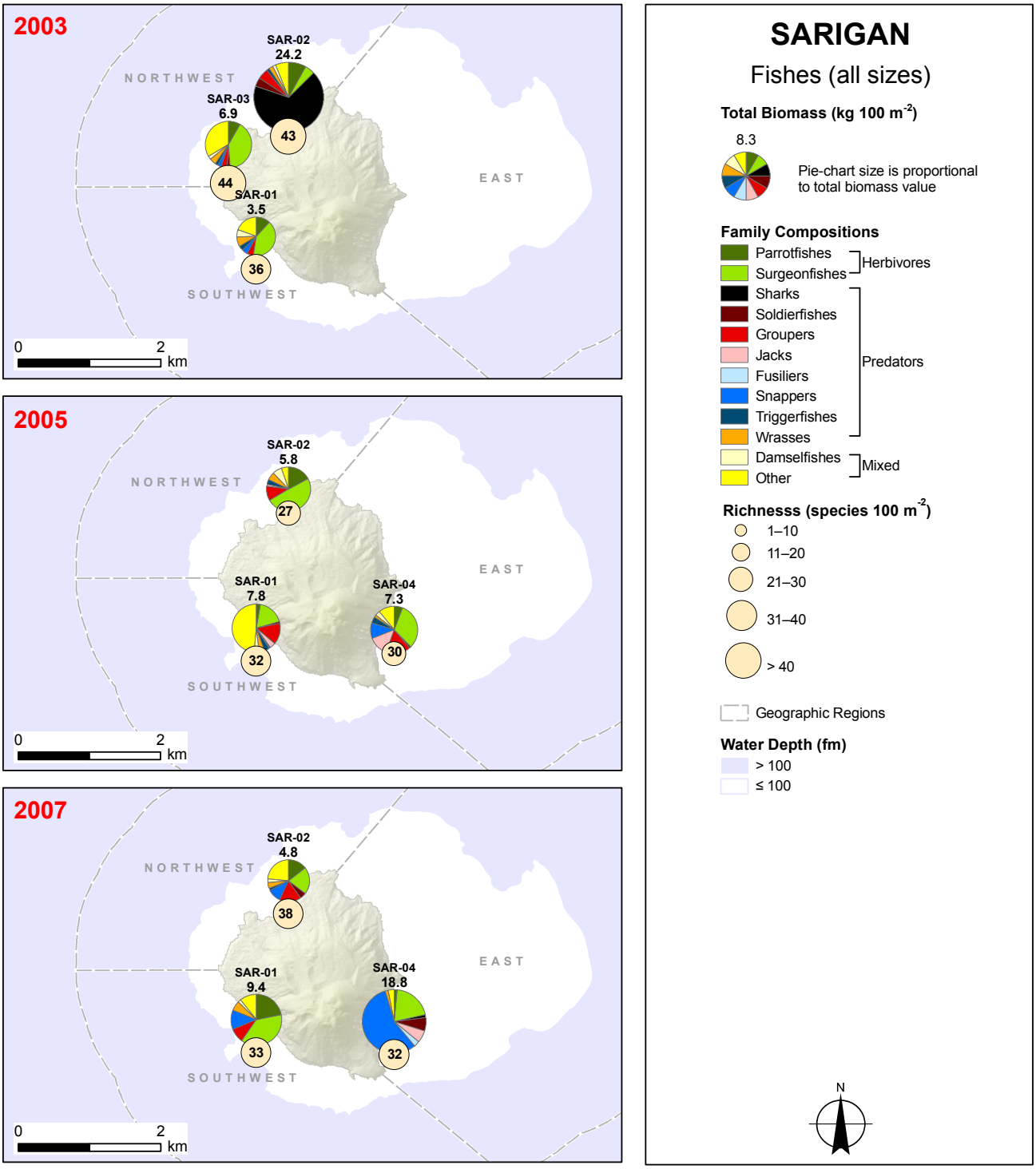


Figure 10.8.1c. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Sarigan during MARAMP 2003, 2005, and 2007.

abundant species with more than 29 individuals 100 m^{-2}. The amethyst anthias (*Pseudanthias pascalus*) was the second most numerically abundant species with 20 individuals 100 m^{-2} observed.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Sarigan during MARAMP 2007 was high compared to other sites surveyed in the Mariana Archipelago, with an overall sample mean of 10.97 kg 100 m^{-2} (SE 4.13). The highest biomass of 18.79 kg 100 m^{-2} was observed at SAR-04 in the east region (Fig. 10.8.1c, bottom panel). Snappers and surgeonfishes accounted for the greatest proportions of total fish biomass with 4.03 kg 100 m^{-2} (37%) and 2.75 kg

100 m^{-2} (25%). The midnight snapper (*Macolor macularis*), black and white snapper (*Macolor niger*), and twinspot snapper dominated snapper biomass, contributing 2 kg 100 m^{-2}, 1.05 kg 100 m^{-2}, and 0.55 kg 100 m^{-2} of total fish biomass. The orangespine unicornfish dominated surgeonfish biomass, accounting for 39% or 1.07 kg 100 m^{-2} of surgeonfish biomass.

Based on REA surveys conducted during MARAMP 2007, species richness at Sarigan was moderate compared to other sites surveyed in the Mariana Archipelago with a range of 32–38 species 100 m^{-2}. The highest diversity was observed at SAR-02 in the northwest region. Wrasses and surgeonfishes were the 2 most represented families with 21 and 14 species recorded. Damselfishes were the most numerically abundant family overall, and the midget chromis dominated counts with 86 individuals 100 m^{-2} observed.

No persistent spatial patterns were observed for the total fish biomass in forereef habitats at Sarigan between the 3 MARAMP survey periods. When compared with the rest of the Mariana Archipelago, the overall total fish biomass for Sarigan was high, but it was close to the average biomass for the northern islands. The overall sample mean of total fish biomass was highest in 2003, at 11.54 kg 100 m^{-2} (SE 6.42), when a large (200 cm in TL) tawny nurse shark contributed half of total fish biomass. Estimated total fish biomass was lower in 2005 than in 2003 and 2007 (Fig. 10.8.1d). Surgeonfishes generally accounted for a large proportion of total fish biomass with 15%–31%. The orangespot surgeonfish and orangespine unicornfish tended to dominate surgeonfish biomass.

Mean species richness ranged from 30 to 41 species 100 m^{-2} for the 3 MARAMP survey periods, with no clear spatial pattern in species richness observed at the island level. Wrasses and surgeonfishes were consistently the 2 most represented families with an average of 18 and 14 species recorded. Damselfishes were the most numerically abundant fish species with the midget chromis dominating counts in each of the 3 survey periods.

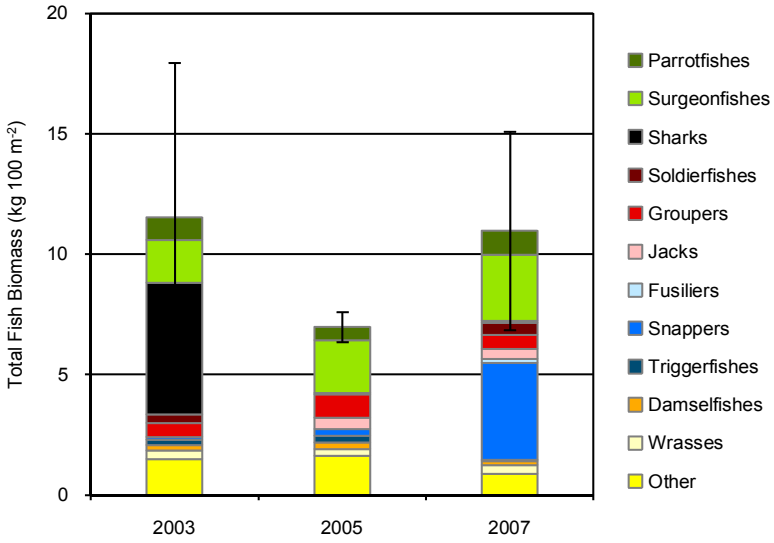


Figure 10.8.3d. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Sarigan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

10.9 Marine Debris

10.9.1 Marine Debris Surveys

During MARAMP 2003, no marine debris was found in the 6 towed-diver surveys conducted on forereef habitats around the island of Sarigan. During MARAMP 2005, only 1 sighting of derelict fishing gear, in the northwest region, was recorded in the 5 towed-diver surveys conducted. No additional descriptive information regarding this sighting was documented. During MARAMP 2007, in the southwest region, only 1 sighting of derelict fishing gear, consisting of fishing line, was recorded in the 6 towed-diver surveys conducted around Sarigan. No munitions, wrecks, or other man-made objects were identified in the 3 MARAMP survey years.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments.

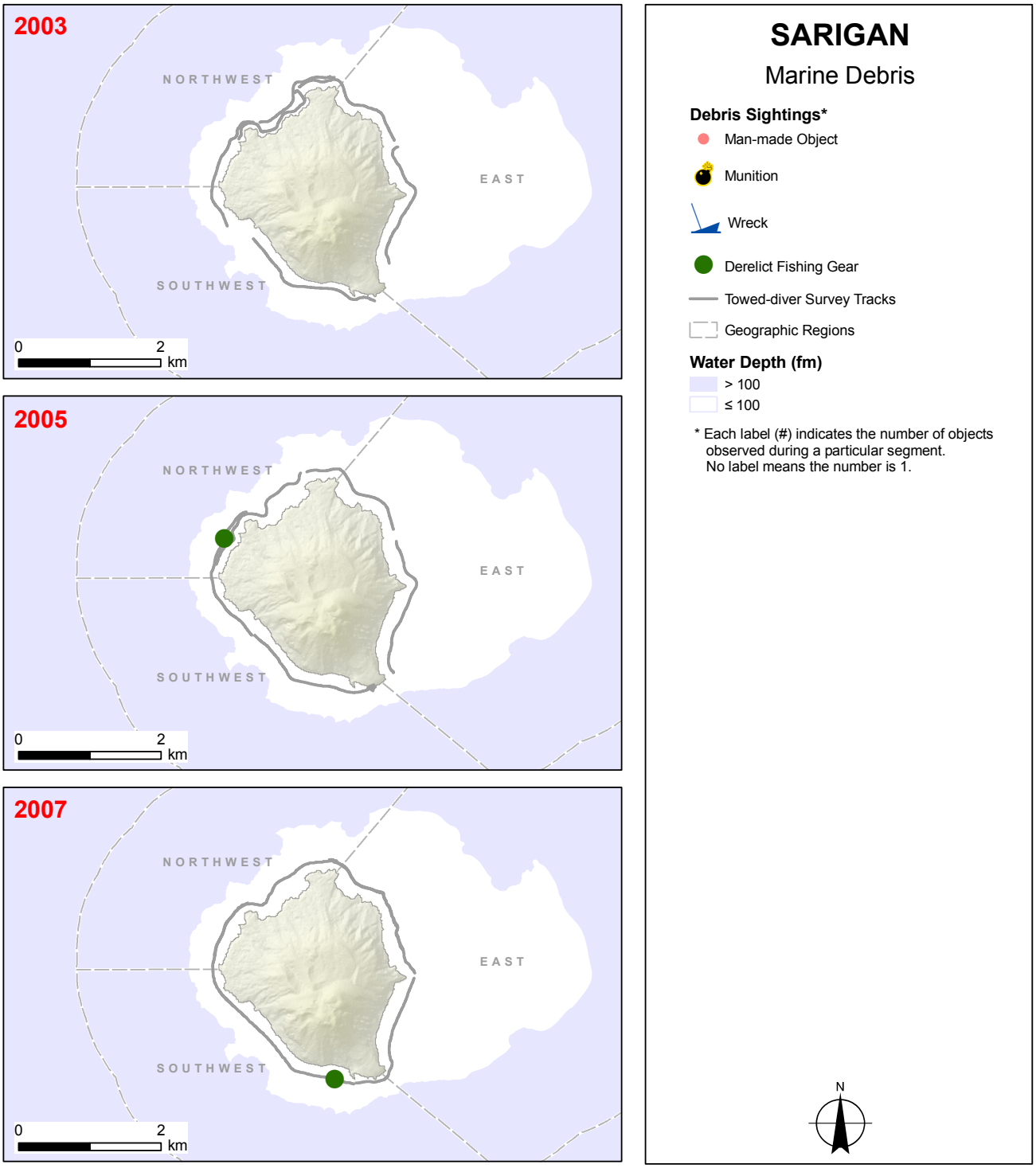


Figure 10.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Sarigan during MARAMP 2005 and 2007. No debris sightings were recorded in 2003. Symbols indicate the presence of a specific debris type.

10.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Sarigan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations on an archipelagic scale of different ecosystem elements and their potential relationships across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Sarigan as well as the other 13 islands covered in this report.

Sarigan, located between Anatahan and Guguan in the middle of the Mariana Arc, is the fourth-smallest island of the Mariana Archipelago. Like other northern, volcanic islands, Sarigan has an onshore topography characterized by steep slopes, particularly on the south and east sides of this island.

The main feature of Sarigan's seascape is the extensive shelf area that extends east for 2.7 km. This shelf, at depths of 30–150 m, is composed of at least 2 terraces (Fig. 10.10a). A very shallow shelf may extend farther around this island, although the absence of bathymetry data at depths < 15 m means it is not possible to confirm this possibility (Fig. 10.3.1b in Section 10.3.1: "Acoustic Mapping").

In the northwest and southwest regions, multibeam bathymetry suggested a seafloor shaped by numerous ridges and canyons that radiate away from Sarigan. The substrate encountered was predominantly hard with < 30% sand cover (Fig. 10.3.3a in Section 10.3.3: "Habitat Characterization"). This hard substrate formed steep walls and boulders, and continuous reef was observed in some places.

Cover of live hard corals, based on towed-diver surveys, in the northwest and southwest regions of Sarigan was generally low in 2005 and 2007, compared to the levels observed in the east region, with most recorded values < 20% and some areas with cover of 20.1%–30% (Fig. 10.10a; see also Fig. 10.5.1a in Section 10.5.1: "Coral Surveys"). In 2003, the observed distribution of live corals was more variable with cover of 40.1%–50% recorded for 2 survey segments in the southwest region. Corals in survey areas appeared healthy: no stressed-coral cover was observed during towed-diver surveys, and very low prevalence of coral disease was found during REA surveys (Fig. 10.5.2a in Section 10.5.2: "Surveys for Coral Disease and Predation").

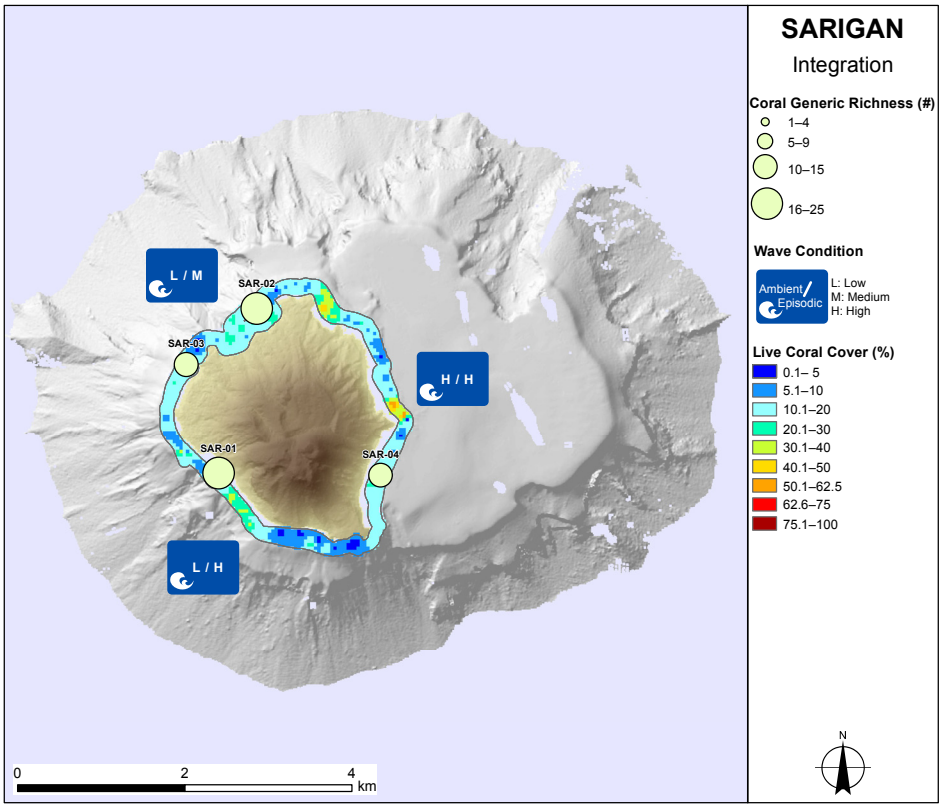


Figure 10.10a. Cover (%) observations of live hard corals from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Sarigan during MARAMP 2003, 2005, and 2007. Values of coral cover represent interpolated estimates from the 3 MARAMP survey years, and values of generic richness represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region. Underlying these data in grey scale is the hillshade bathymetry.

Densities of sea cucumbers, particularly of *Stichopus chloronotus*, were much higher on non-shelf areas around Sarigan than on the shelf area (Fig. 10.7.1e in Section 10.7.1: Benthic Macroinvertebrate Surveys"), and overall abundance of sea cucumbers around Sarigan was high compared to densities seen at other northern islands of the Mariana Archipelago (Fig 3.6.1c in Chapter 3: Archipelagic Comparison," Section 3.6.1: "Density Distribution: Giant Clams, Sea Urchins, and Sea Cucumbers"). Giant clams also were more abundant on the west side of Sarigan than in the east region (Figs. 10.10b and 10.7.1a).

Despite the markedly different topography revealed by multibeam bathymetry east of Sarigan, the benthic communities around this island appeared fairly alike in character, based on observations from towed-diver surveys. The proportion of sand to hard substrate, the levels of habitat complexity, and descriptions of habitats observed in the east region were similar to the conditions recorded in the southwest and northwest regions. The distribution of benthic macroinvertebrates, particularly of sea cucumbers and giant clams, differed greatly on different sides of this island. Cover of live hard corals, based on towed-diver surveys, was slightly higher in the east region than in the northwest and southwest regions, with coral cover of 10.1–30% recorded for most survey segments. Two distinct survey areas in the east region had coral cover of 30.1%–75%: one in a bay east of the northern tip of Sarigan and another just north of the easternmost point of this island.



Figure 10.10b. A giant clam (*Tridacna* sp.) on a western reef at Sarigan. *NOAA photo by Danny Merritt*



Figure 10.10c. Diver observing sharks at Sarigan. *NOAA photo*

The fish communities observed around Sarigan had moderately high diversity, compared to the fish communities seen at other islands of the Mariana Archipelago (Fig. 10.8.1f in Section 10.8.1: "Reef Surveys"). Values of total fish biomass and species richness from REA surveys varied fairly widely between the 3 MARAMP survey years, but they were among the highest recorded at any island in the Mariana Archipelago in 2003. Sharks were observed frequently during towed-diver surveys (Figs. 10.10c and 10.8.1f), and other notable observations included 3 sightings of the humphead wrasse (*Cheilinus undulatus*): 2 sightings in 2007 and 1 sighting in 2003.

10.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Sarigan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Sarigan chapter are included in the relevant discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Sarigan, relative to the ecosystems around all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Sarigan as well as some of the key natural processes influencing these ecosystems:

- Sarigan is positioned in the center of the Mariana Arc, between Anatahan and Guguan, and is the fourth-smallest island of the Mariana Archipelago with a land area of 4.9 km^2.

- Like other islands of the CNMI, Sarigan is formed by the exposed portion of a largely submarine volcano. A summit crater is located on southern part of this island. Steep cliffs and irregular shorelines were created by lava flows that reached the coast and extended out to sea from 2 lava domes near the southern crater rim. Sparse vegetation on these lava flows indicates that the last eruption may have occurred in the Holocene age, although the exact date is not known.

- Sarigan is thought to have been uninhabited since the last residents were removed after WWII. However, legislation encouraging repatriation was signed into law in 2010 and may result in repopulation of this island in the future. Because of its lack of inhabitants and isolated location, Sarigan has relatively few anthropogenic pressures on its marine environment, although multiday fishing trips around the islands and banks south of Guguan potentially may affect fish stocks and associated habitats around Sarigan.

- An extensive, shallow shelf that extends east for 2.7 km at depths of 30–150 m surrounds Sarigan. The very steep slopes that border the deepest part of this shelf continue around this island, and, west of this island, this shelf break is intersected by channels and ridges.

- Overall, the seabed around Sarigan, based on the high-resolution bathymetry data, has a fairly complex topography, and BPI analysis reveals that sloping flanks below flat zones are interrupted by crests and depressions.

- In the east region, habitat complexity was predominantly medium to medium-high. Towed-diver surveys documented patchy sand cover and habitats that included rocky crags, boulders and pinnacles, and sand with boulder patch reefs.

- In the northwest region, habitat complexity ranged from low to high. The seabed was variable, with patchy sand cover and habitats ranging from boulder patches to steep walls and continuous rock reef. Analyses of TOAD video footage obtained on flanks at depths of 91–190 m suggested hard substrates with no sand cover or live-hard-coral cover observed.

- In the southwest region, boulder reef and continuous reef with sand patches were recorded during the 2 towed-diver surveys conducted in this region, suggesting predominantly hard substrate with no live coral cover and sparse, localized sand cover.

- Wave model output shows ambient trade wind swells impacting the east region. Episodic wave energy from storm tracks impacts the east and southwest regions and to a lesser extent the northwest region.

- CTD casts revealed mostly well-mixed waters, except in 2003, when results from a single cast location in the northwest region showed a 1.5˚C reduction in temperature between waters at depths > 25 m and surface waters. Time-series data from 2 STRs deployed in the northwest region at depths of 1 and 6 m show large variation (~ 4°C) in temperature values on intraseasonal time scales, indicating a dynamic thermal environment.

- The overall sample mean for live coral cover at Sarigan was 22.6%, based on REA surveys conducted using the line-point-intercept method during MARAMP 2007. Islandwide estimates of coral cover from towed-diver surveys ranged from 13%–18% across the 3 MARAMP survey years, a moderate level compared to values seen at other islands in the Mariana Archipelago.

- At the 3 REA sites surveyed using the belt-transect method in 2007, 14 cases of coral disease were found, resulting in an overall mean prevalence of 0.04%. Three disease states were recorded at Sarigan, including, in order of numerical abundance, fungal infection, infestation by the encrusting sponge genus *Terpios*, and bleaching. No signs of predation scars from the crown-of-thorns seastar (*Acanthaster planci*) or corallivorous snails were reported at these 3 sites. Densities of COTS from towed-diver surveys were extremely low in 2003 and 2005, and no COTS were observed in 2007.

- Results from towed-diver surveys conducted in the 3 MARAMP survey years reveal that both *Tridacna* giant clams and sea cucumbers were more common along the west side of Sarigan than along the east side. Also, both towed-diver and REA surveys in 2003 showed that sea urchins were more common on the west side than on the east side. Abundance of sea cucumbers was high, compared to values found at other northern islands in the Mariana Archipelago.

- Islandwide mean cover of macroalgae from towed-diver surveys conducted around Sarigan was lower in 2007 than in in 2005. In each of the 3 survey years, the lowest cover of crustose coralline red algae was found near the northern tip of this island during towed-diver surveys in either the northwest region or east region. No signs of coralline-algal disease were observed.

- Across the 3 MARAMP survey periods, overall estimated mean biomass of large fishes was stable and moderate, relative to levels seen at other northern islands in the Mariana Archipelago. Observed large-fish biomass was highest in 2003 with an islandwide mean of 0.72 kg 100 m^{-2}. Large-bodied, predatory species such as jacks (Carangidae), reef sharks (Carcharhinidae), and nurse sharks (Ginglymostomatidae) accounted for 65% or more of large-fish biomass in each of the 3 survey periods. A large school of bigeye trevally (*Caranx sexfaciatus*) was seen in the southwest region in 2005 and 2007. Also of note were 3 sightings of the humphead wrasse (*Cheilinus undulates*), with 1 sighting in 2003 and 2 sightings in 2007.

- Total fish biomass around Sarigan, based from REA surveys for fishes of all sizes and species, was similar to the average for the northern islands. Estimated total fish biomass was highest in 2003, with an overall sample mean of 11.54 kg 100 m^{-2}. A large (200 cm in TL) tawny nurse shark (*Nebrius ferrugineus*) contributed almost half of this overall biomass in 2003.

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11 GUGUAN

11.1 Introduction

The island of Guguan is located at 17°19′ N, 145°50′ E in the middle of the Mariana Arc, 32 km south of Alamagan and 67 km north of Sarigan. The third-smallest island in the Mariana Archipelago, Guguan is ~ 3 km long by 2 km wide with a land area of 4.24 km^2 (Fig. 11.1a). This island is formed from 2 volcanoes: a younger volcano in the north and an older, eroded volcano in the south that forms a high plain. The highest point on this island, with an elevation of 287 m, is on the rim of the eroded southern volcano (Fig. 11.1b).

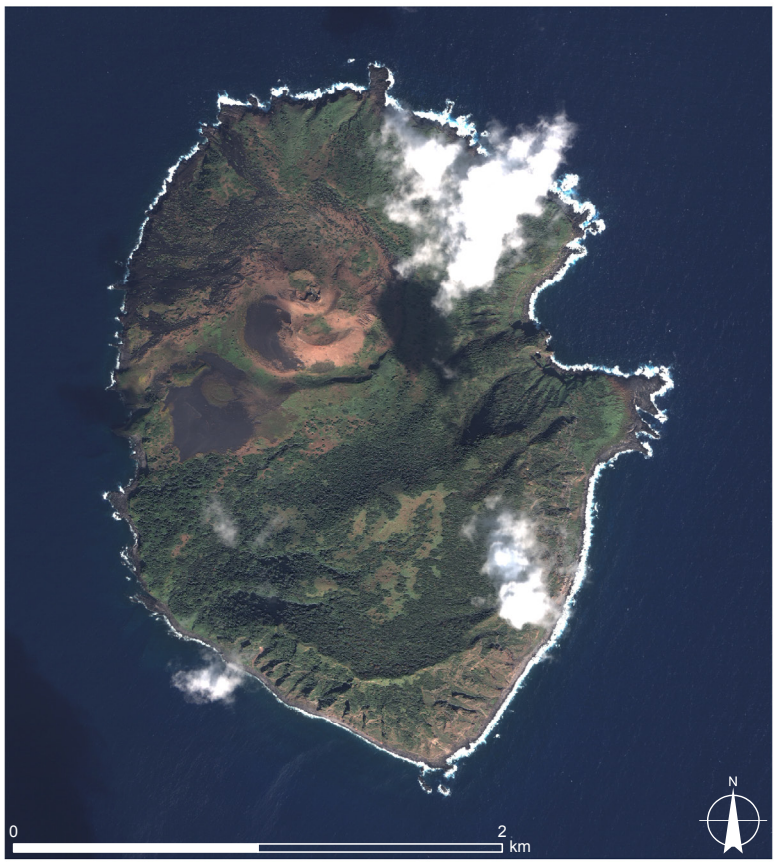


Figure 11.1a. Satellite image of Guguan (© 2004 DigitalGlobe Inc. All rights reserved).



Figure 11.1b. Guguan's eroded south volcano with the only steep slopes on the island, as seen from the NOAA Ship *Hi'ialakai* in 2007. *NOAA photo*

11.1.1 History and Demographics

Guguan is not currently and may have never been inhabited. No archaeological evidence of Chamorro occupation has been found (Spennemann 2006), and any inhabitants present on this island in 1695 would have been removed when the Spanish forced inhabitants of the Northern Mariana Islands to relocate to Guam (Rogers 1995). In 1909, while under German administration, Guguan was leased to the Pagan Gesellschaft (a trading association) for exploitation of bird plumage for a period of 3 years, along with Farallon de Pajaros, Maug, Asuncion, Agrihan, Sarigan, and Farallon de Medinilla. During this time, Japanese bird catchers employed on these islands may have been temporary residents (Spennemann 1999b), and other fishing or hunting parties may have resided periodically on this island. Since 1978, the CNMI Constitution has prohibited inhabitation of Guguan (CNMI Constitution).

Guguan falls within the Northern Islands Municipality of the Commonwealth of the Northern Mariana Islands (CNMI), and the political history of Guguan follows that of the CNMI as a whole, which is described in more detail in Chapter 1: "Introduction" and Chapter 8: "Saipan," Section 8.1.1: "History and Demographics."

11.1.2 Geography

In comparison to its neighbor islands, Alamagan and Sarigan, Guguan has a relatively low elevation and less steep slopes. The eroded volcano on the southern part of this island forms a plateau, bounded along the southern coast by the steepest slopes observed on this island (Fig. 11.1.2a). The northern volcano has 3 coalescing cones and a breached summit crater that fed lava flows to the west that resulted from a volcanic eruption in ~ 1883 (Siebert and Simkin 2002). Large cinder fields and cinder cones are also present (Cruz et al. 2000). No eruptions have been recorded since 1883; however, this island is still geologically active, as features of the landscape, such as lagoons formed by craters, seen by visitors to this island in the late 19th and early 20th century are no longer evident possibly as a result of movement of these topographic features (Cruz et al. 2000; Siebert and Simkin 2002).

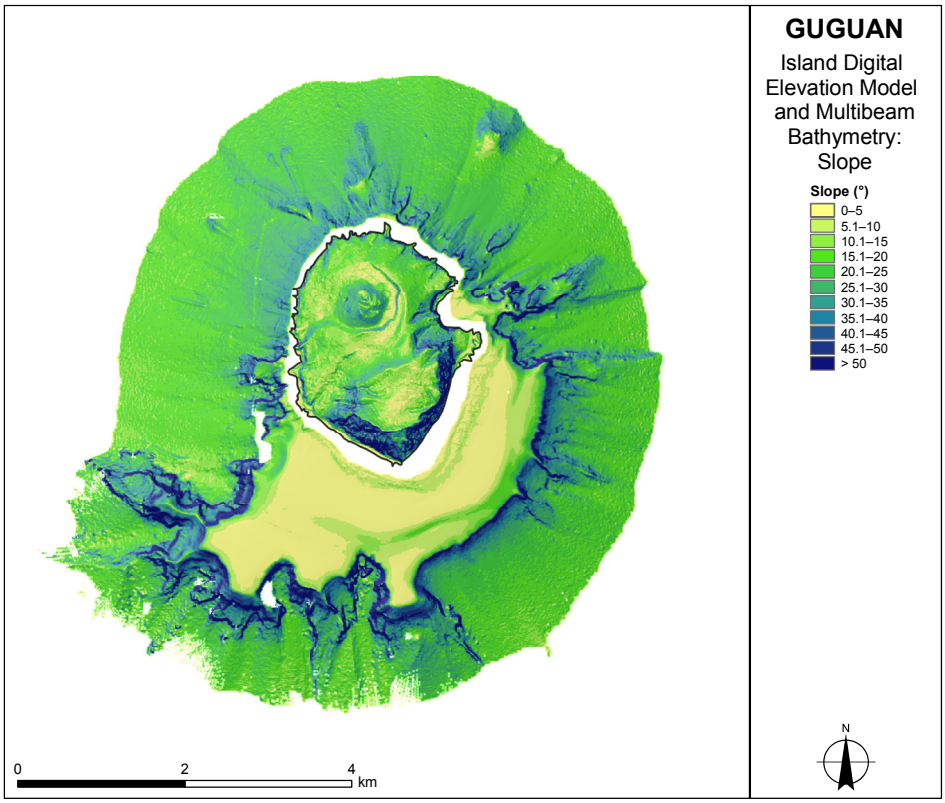


Figure 11.1.2a. Combined slope map using the digital elevation model and bathymetric data for Guguan (grid cell size: 10 m).

While the lava flows on the northwestern side of this island are not vegetated, the rest of this island supports various types of plant communities (Fig. 11.1.2b). In particular, the southern part of Guguan is heavily vegetated. The southern plateau is dominated by sword grass (*Miscanthus floridulus*), while the rugged hills and valleys support dense forests. Small numbers of coconut palms also are present, likely remaining from previous efforts to establish plantations (Cruz et al. 2000).

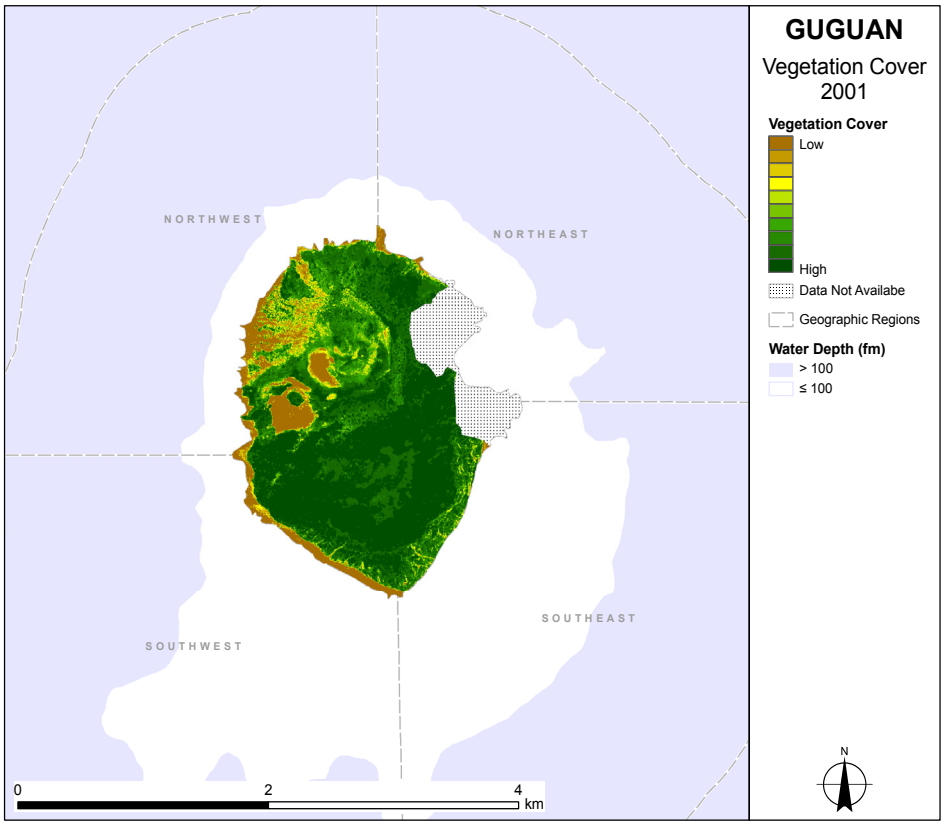


Figure 11.1.2b. Vegetation cover on Guguan, derived using the Normalized Difference Vegetation Index from a satellite image (grid cell size: 4 m; IKONOS Carterra Geo Data, 2001). Hatched lines indicate areas where data are not available because cloud cover obscures the satellite image.

11.1.3 Environmental Issues on Guguan

Guguan is unique, in that it is relatively undisturbed and supports a diverse range of habitats with large numbers of a variety of wildlife species including seabirds, land birds, fruit bats, and coconut crabs. The forests of Guguan support a high abundance and density of native tree species, relative to the forests on other islands of the Mariana Archipelago (Cruz et al. 2000).

Guguan is part of a protected reserve established under Article XIV of the CNMI Constitution and managed by the CNMI Division of Fish and Wildlife. This legislation states that Guguan is to remain uninhabited, and no permanent structures can be built on this island, except for those built to enhance the preservation and protection of natural resources (CNMI Constitution). Guguan is preserved as a habitat for plants and wildlife, including a number of birds species such as the Micronesian starling (*Aplonis opaca*) and Micronesian honeyeater (*Myzomela rubrata*). Guguan, among the northern islands of the Mariana Archipelago, has the highest abundance of the Micronesian megapode (*Megapodius laperouse*), which is listed Federally as endangered and locally as threatened or endangered (U.S. Fish and Wildlife Service; Berger et al. 2005), and has some of the most important seabird rookeries in the northern islands (Cruz et al. 2000). The large bird populations present on Guguan, compared to other islands in the Mariana Archipelago, flourish in the absence of monitor lizards, feral animals, or other large predators, although rats are fairly abundant on some parts of this island (Cruz et al. 2000). Guguan also supports a stable population of the Mariana fruit bat (*Pteropus mariannus mariannus*), an endemic subspecies Federally listed as threatened and locally as threatened or endangered (Cruz et al. 2000; U.S. Fish and Wildlife Service; Berger et al. 2005).

Because of Guguan's isolated location, lack of inhabitants and most feral animals, and its protected status, anthropogenic effects are likely few around this island.

11.2 Survey Effort

Biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing the coral reef ecosystems around the island of Guguan since 2003. The spatial extent and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around Guguan are delineated in Figure 11.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Guguan. Potential reef habitat is represented by a 100-fm contour shown in white on this map.

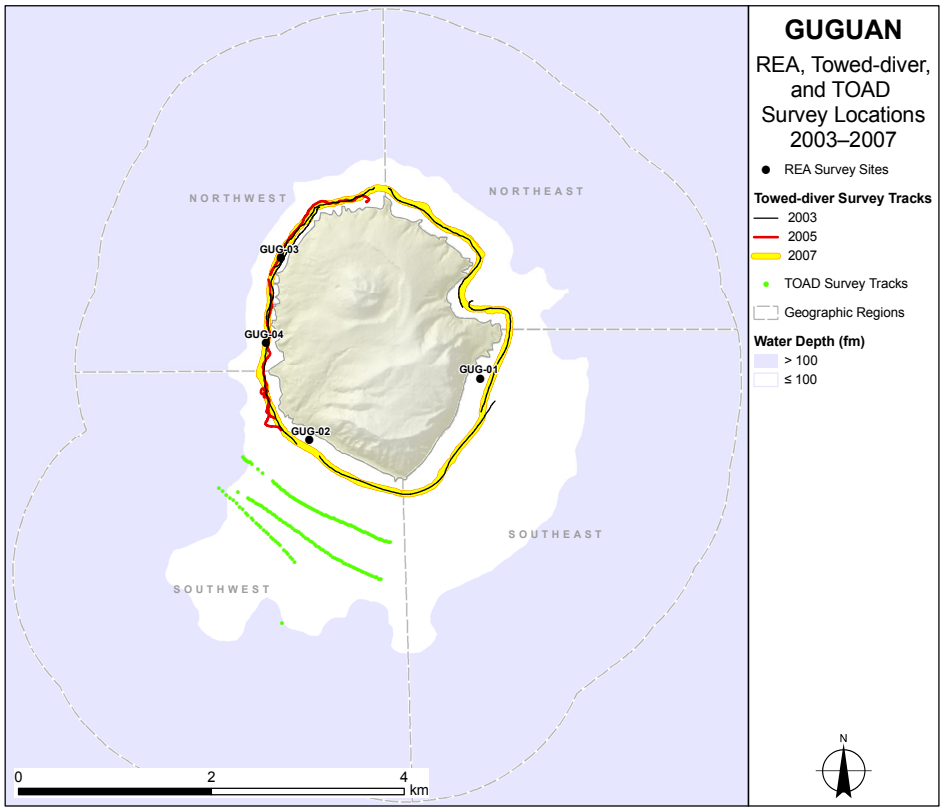


Figure 11.2a. Locations of REA, towed-diver, and TOAD benthic surveys conducted around Guguan during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 4 geographic regions: northeast, southeast, southwest, and northwest.

Benthic habitat mapping data were collected around Guguan using a combination of acoustic and optical-survey methods. MARAMP benthic habitat mapping surveys conducted around this island with multibeam sonar covered a total area of 2228 km^2 in 2007. Optical validation and habitat characterization were conducted using towed-diver and TOAD surveys that documented live-hard-coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 11.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Guguan was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 11.5–11.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 11.2a, along with their mean depths and total areas and length.

Table 11.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Guguan during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	3	2	3
	Mean Depth (m)	12 (SD 1)	10 (SD 1.4)	12 (SD 1)
Benthic	Number of Surveys	3	2	3
	Mean Depth (m)	12 (SD 1)	10 (SD 1.4)	12 (SD 1)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	6	3	5
	Total Survey Area (ha)	10.3	3.9	10.5
	Mean Depth (m)	13.7 (SD 1.9)	17.3 (SD 2.9)	16.1 (SD 2.2)
TOAD		**2003**		
	Number of Surveys	3		
	Total Length (km)	6.94		

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Guguan were collected using: (1) subsurface temperature recorders (STR) designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water samples were collected in 2007 (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 11.2b. Results are discussed in Section: 11.4: "Oceanography and Water Quality."

Table 11.2b. Numbers of STRs deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Guguan during MARAMP 2003, 2005, and 2007. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons".

Observation Type	Year						
Instruments	**2003**	**2005**		**2007**		**2009**	**Lost**
	Deployed	**Retrieved**	**Deployed**	**Retrieved**	**Deployed**	**Retrieved**	
STR	1	1	1	1	1	1	–
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	10	6		9			25
Deepwater Casts	–	3		1			4
Water Samples		**2005**		**2007**			**Total**
		–		3			3

Towed-diver Surveys: Depths

Figures 11.2b and c illustrate the locations and depths of towed-diver-survey tracks around Guguan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

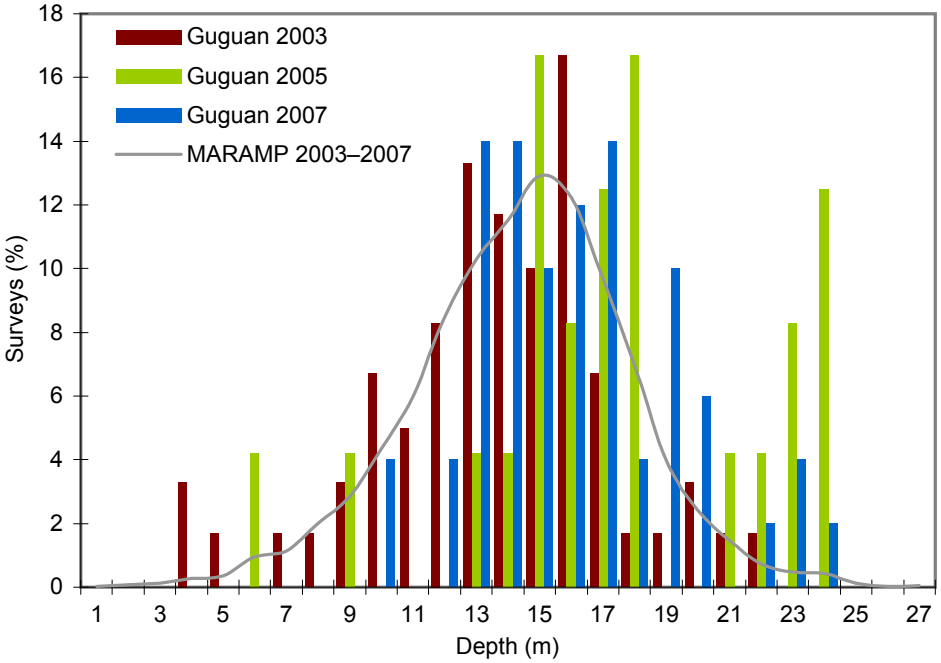


Figure 11.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted around Guguan during MARAMP 2003. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depths from all towed-diver surveys conducted around the Mariana Archipelago during 2003, 2005, and 2007.

During MARAMP 2003, 6 towed-diver surveys were conducted along the forereef slopes around Guguan (Figs. 11.2b and c, top panel). The mean depth of all survey segments was 13.7 m (SD 1.9), and the mean depths of individual surveys ranged from 10.1 m (SD 5.9) to 15.3 m (SD 3).

During MARAMP 2005, 3 towed-diver surveys were conducted along the forereef slopes around part of Guguan (Figs. 11.2b and c, middle panel). The mean depth of all survey segments was 17.3 m (SD 2.9), and the mean depths of individual surveys ranged from 15.3 m (SD 5.5) to 20.6 m (SD 4.4).

During MARAMP 2007, 5 towed-diver surveys were conducted along the forereef slopes around Guguan (Figs. 11.2b and c, bottom panel). The mean depth of all survey segments was 16.1 m (SD 2.2), and the mean depths of individual surveys ranged from 13.7 m (SD 2.9) to 19.2 m (SD 4.2).

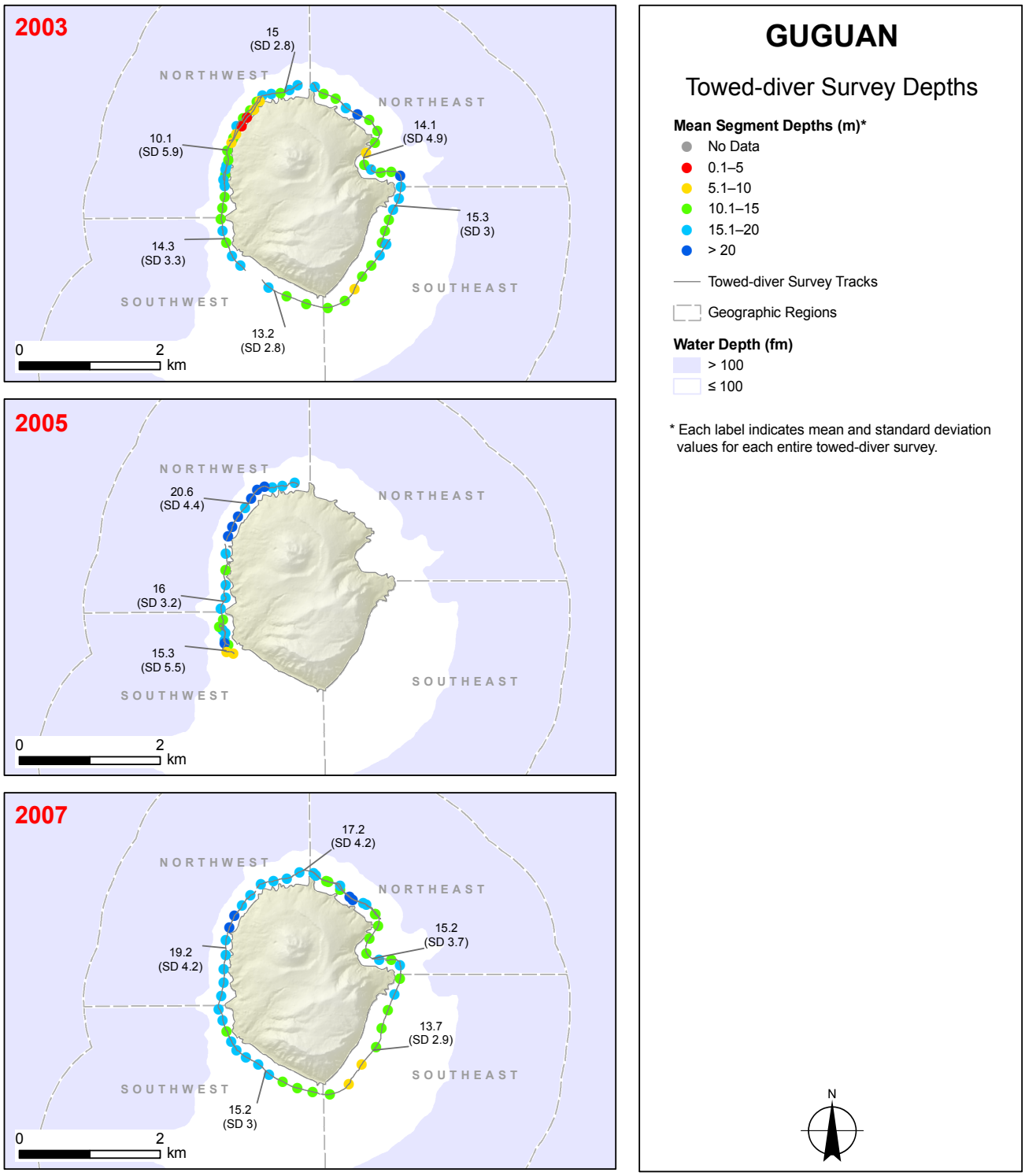


Figure 11.2c. Depths and tracks of towed-diver surveys conducted around Guguan during MARAMP 2003, 2005, 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

11.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Guguan were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 15–2300 m. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of < 270 m.

11.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 11.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around the islands of Guguan, Alamagan, Zealandia Bank, Sarigan, and Anatahan during MARAMP 2007 encompassed an area of 2228 km^2. Good coverage was achieved east of Guguan, with multibeam data obtained at depths down to 1990–2340 m, but coverage west of Guguan was limited to a maximum depth of 900–1600 m.

The low-resolution multibeam bathymetry data collected around Guguan reveal fairly uniform slopes around much of this island (Fig. 11.3.1a, top panel). The data show the flanks to be smooth, with very little blocky material usually indicative of mass wasting (the movement of soil and surface materials by gravity). South of Guguan, the seabed character is very different, with irregularly shaped shelves. A shallow shelf is located at depths of 25–50 m, and another shelf is present at depths of 80–130 m. Ridges and channels radiate from the edge of this deep shelf.

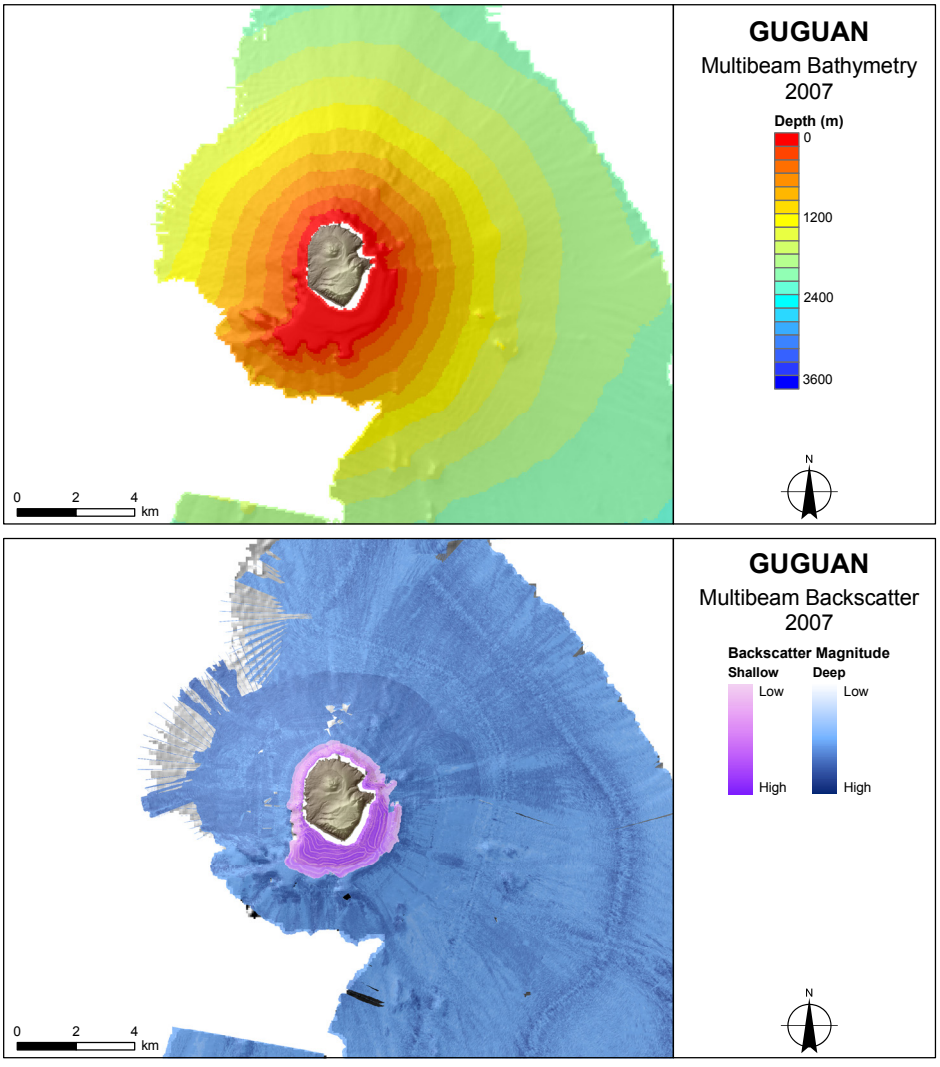


Figure 11.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Guguan during MARAMP 2007 in depths of 15–2300 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

As described in Chapter 2: "Methods and Operational Background," Section 2.2: "Benthic Habitat Mapping and Characterization," multibeam backscatter intensity can provide information about the roughness and hardness of the seafloor. Low-resolution backscatter data collected around Guguan appear to have some artifacts, which make it difficult to determine patterns in the acoustic characteristics of the seabed. These artifacts are most noticeable north of Guguan, where there is a sharp contrast between shallow and deep swaths, and east of the island, where some linear patterns are shown on the backscatter map (Fig. 11.3.1a, bottom panel) but do not appear to relate to any bathymetric feature. Despite these issues, the backscatter data generally appear to correlate to topographic features. The most obvious patterns are on the shelves south of this island. High-intensity backscatter is recorded on the shallow shelf, suggesting that this shelf likely is composed of hard substrates. In contrast, the deep shelf is characterized by low-intensity backscatter, indicative of soft substrates. Below the deep shelf, the radiating ridges are characterized by high-intensity backscatter, whereas the channels in between have lower backscatter intensity suggesting the accumulation of soft sediments.

High-resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in nearshore (0–800 m) waters around Guguan were combined into a grid at 10-m resolution to allow for the identification of fine-scaled features (Fig. 11.3.1b). These high-resolution data also were used to derive benthic maps of slope (Fig. 11.3.1c), rugosity (Fig. 11.3.1d), and bathymetric position index (BPI) zones (Fig. 11.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Guguan.

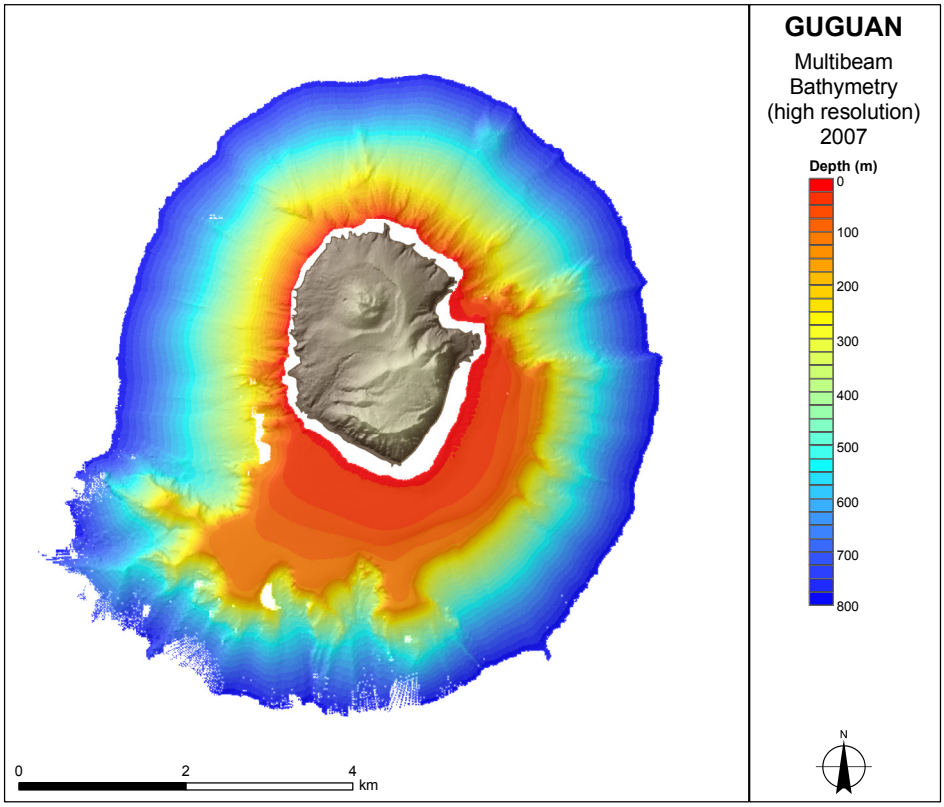


Figure 11.3.1b. High-resolution multibeam bathymetry collected around Guguan during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives.

Northeast and northwest of Guguan, narrow ridges begin in the shallowest areas surveyed and continue to depths of 100–300 m. Apart from these ridges, the flanks are characterized by relatively smooth, moderately steep (15°–25°) slopes, highlighted by the homogeneity of the BPI zones mapped in these areas (Fig. 11.3.1e). In the northeast region, the seabed within a small bay is characterized by low-rugosity values and no slopes, and the BPI analysis delineates a small flat zone.

The high-resolution multibeam bathymetry data display the detail of the shelves that surround the southern and southeastern coasts of this island. The BPI analysis suggests that these shelves provide a large area of flat seabed in an otherwise steeply sloping terrain. The shallow shelf is shown in the slope map to be flat and smooth. The inner edge of the shallow shelf is bordered by a narrow zone of complex topography that may represent spur-and-groove habitat. A low to moderately steep slope (5°–20°) separates the shallow shelf from the deeper one, which itself gently slopes to the shelf break at 130–140 m. Along the shelf edge, very steep slopes of > 50° are shown in the slope map, from which narrow ridges extend.

Some of these ridges are very short, but others extend for more than 1 km horizontally. Between the ridges, narrow channels are shown. In some locations, the irregular shelf edge forms submarine peninsulas with wide channels between them. The steep sides of these channels are highlighted by the slope and rugosity maps.

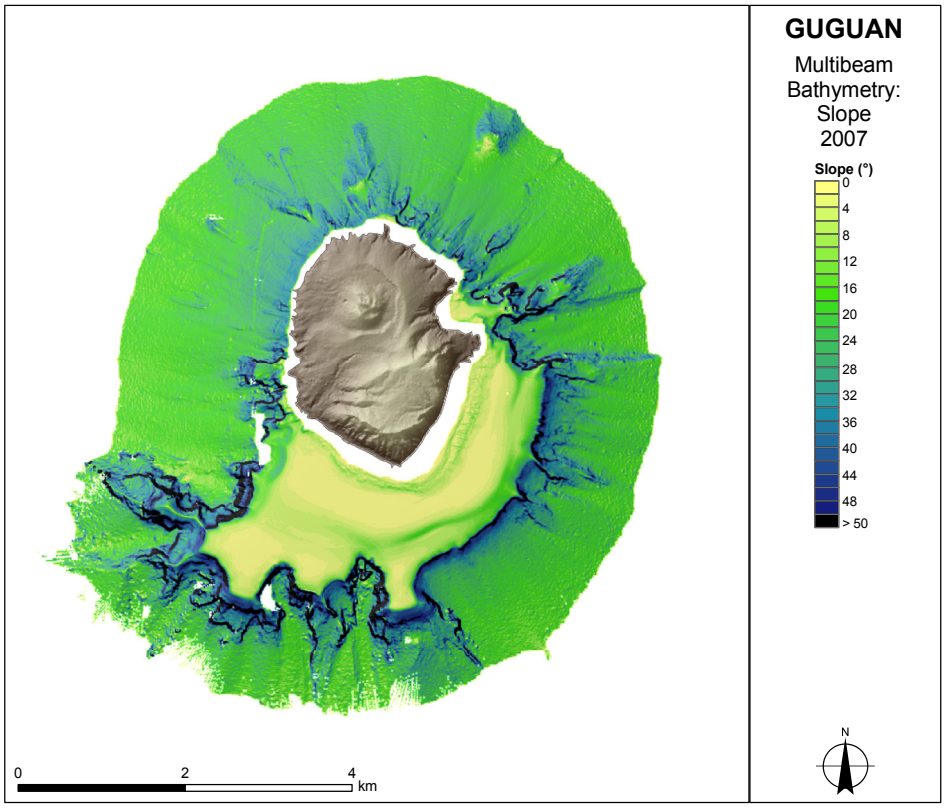


Figure 11.3.1c. Slope (°) of 10-m bathymetric grid around Guguan. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades.

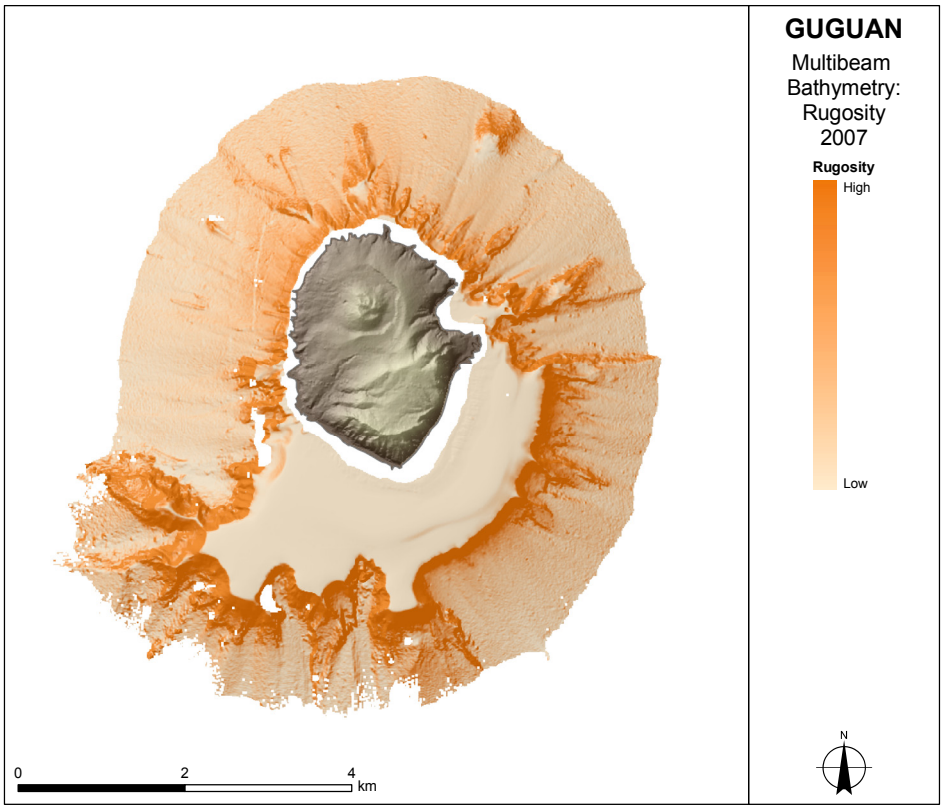


Figure 11.3.1d. Rugosity of 10-m bathymetric grid around Guguan. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

Reef crests are identified by the BPI analysis in the shallowest waters surveyed around northern Guguan; however, this classification is likely an artifact of the methodology, since no data are available for immediately inshore areas and no comparison can be made to the innermost cells of the grid. Instead, these areas probably should be characterized as slopes.

Overall, the topographic character of Guguan, which is characterized by steep slopes to the north and west and an extensive shelf to the south, appears to be very similar to the topography of neighboring island Sarigan.

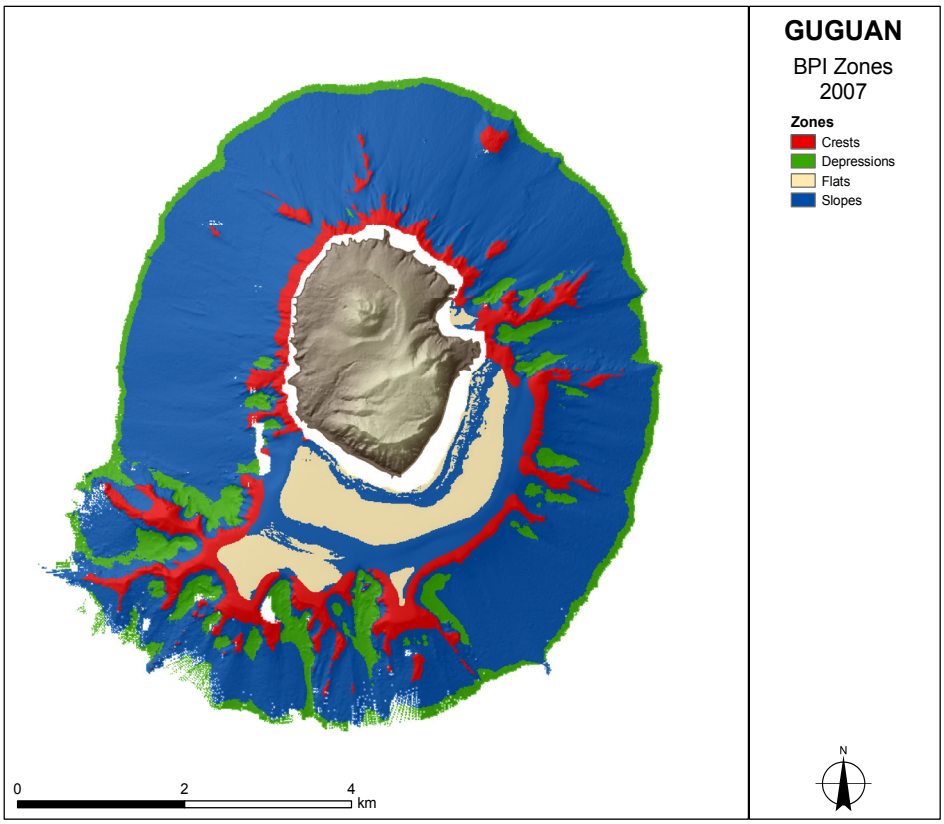


Figure 11.3.1e. BPI zones of 10-m bathymetric grid around Guguan derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

High-Resolution Multibeam Backscatter and Derivatives

High-resolution backscatter data acquired around Guguan, in particular data collected north of this island, have some noticeable artifacts, such as data gaps and other patterns that may result from steep slopes rather than acoustic properties of the seafloor (Fig. 11 3.1f). Nevertheless, some patterns are evident that appear to relate to seafloor characteristics, and these are most clearly seen in the areas where greatest coverage was achieved. To reduce the effect of these artifacts on the hard–soft classification, the backscatter data were clipped to a depth of 100 m prior to carrying out this classification. Although the hard–soft analysis is a useful tool to help interpret the seabed character around Guguan, it should be noted that the ground-truthing data underlying the classification were based on other islands with different geological characteristics, and no specific ground-truthing data were available from Guguan to inform this classification. Nevertheless, this classification does provide some indication of the distribution of different substrate types around this island.

Data collected on the shelf area south and east of Guguan are characterized by high backscatter values, and the hard–soft analysis classifies these same areas as having hard substrates (Figs. 11 3.1f and g). As the shelf deepens south of Guguan, the backscatter intensities lessen, and the outer shelf area is classified as having soft substrates, although the depth and slope may also influence these data. East of this island, the submerged peninsula extending from the shelf is classified as having hard substrates, with soft substrates recorded in the channels on either side.

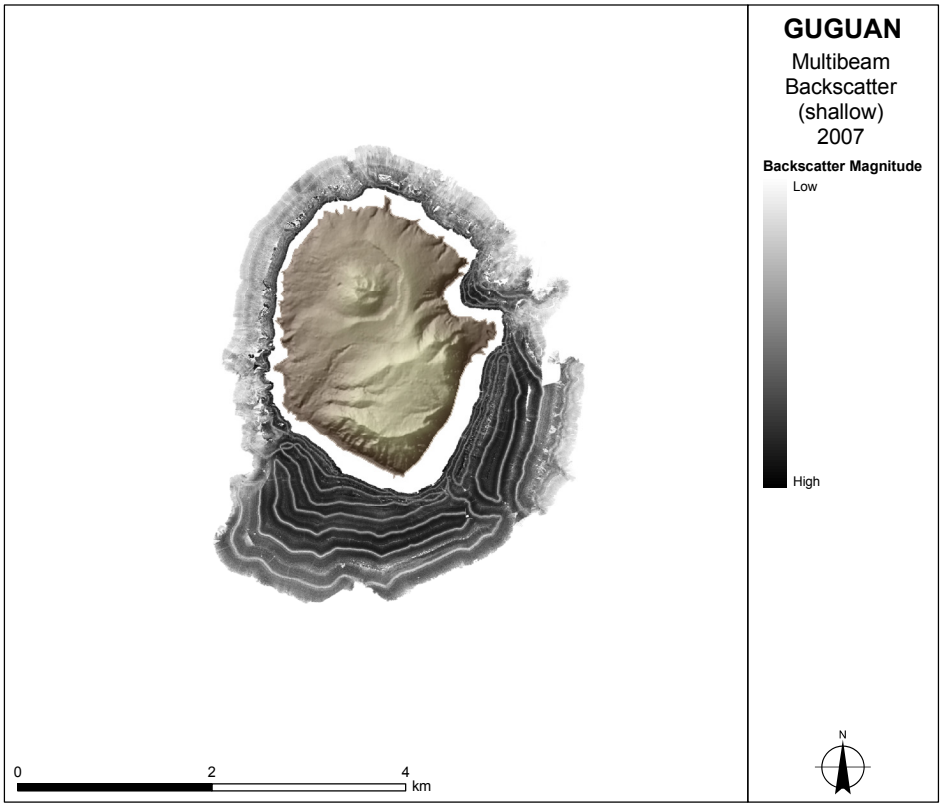


Figure 11.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) collected around Guguan during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

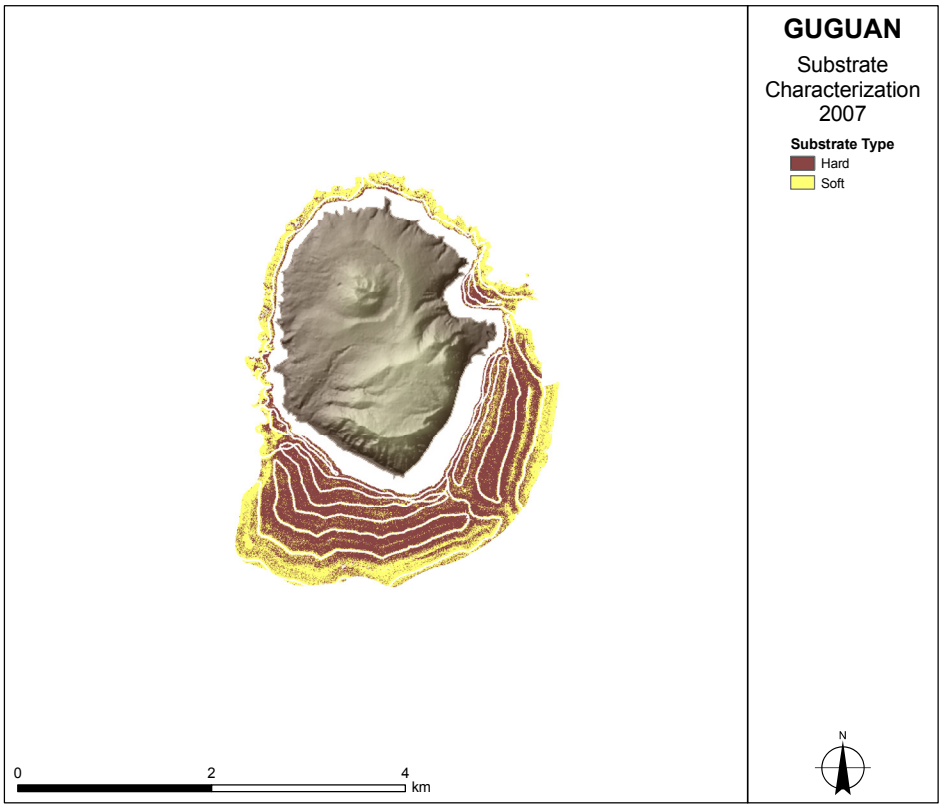


Figure 11.3.1g. Hard and soft substrates (grid cell size: 5 m) at depths < 100 m based upon an unsupervised classification of multibeam bathymetry and backscatter data acquired around Guguan in 2007. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

11.3.2 Optical Validation

During MARAMP 2003, 3 TOAD optical-validation surveys, covering a distance of ~ 7 km at depths of 41–270 m, were conducted around Guguan (Fig. 11.3.2a). Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live-hard-coral cover.

Covering a distance of 25 km at depths of 4–24 m, 14 towed-diver optical-validation surveys were conducted around Guguan during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

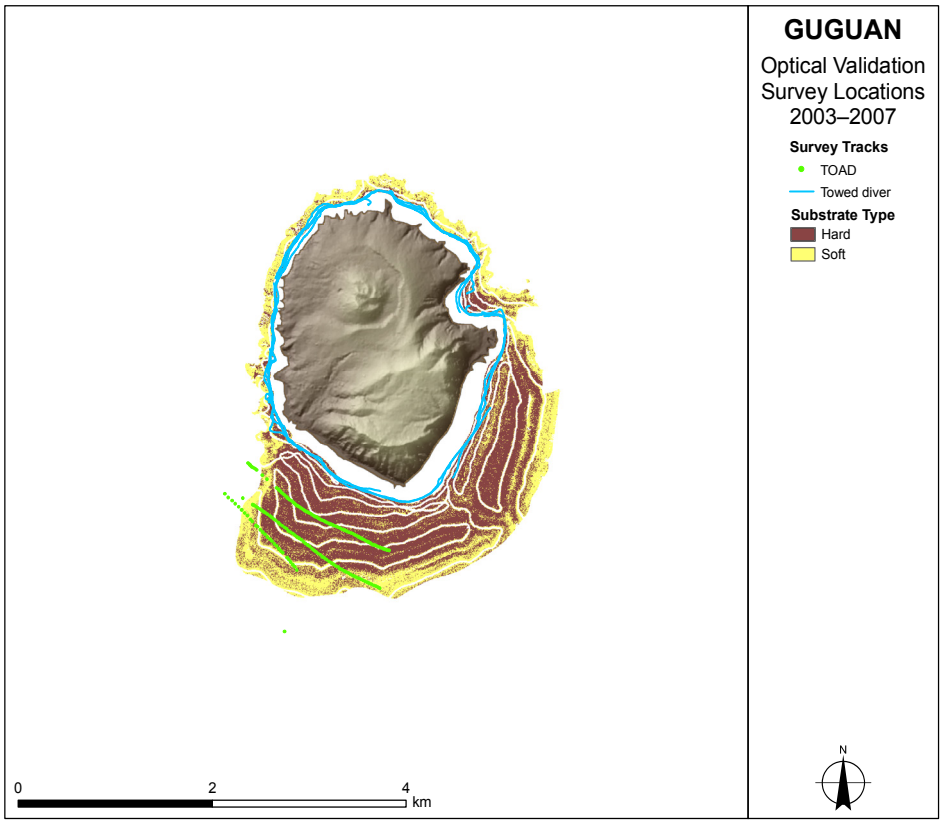


Figure 11.3.2a. Towed-diver tracks from surveys conducted around Guguan during MARAMP 2003, 2005, and 2007 and TOAD camera-sled tracks for MARAMP 2003. Survey tracks are displayed over multibeam hard–soft substrate map. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

11.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Guguan are discussed in this section. These descriptions are organized by the 4 geographic regions around Guguan.

In the northeast and northwest regions, where the seabed is characterized by steep slopes and narrow ridges, the substrate was predominantly hard, as suggested by the low sand cover (< 10%) recorded during towed-diver surveys, relative to other areas surveyed in the Mariana Archipelago (Fig. 11.3.3a, top panel). Habitats of medium to high complexity were characterized as high-relief, spur-and-groove formations with some walls (Fig. 11.3.3a, middle panel). Live coral cover was consistently observed at moderately high levels compared to other islands in the Mariana Archipelago, and interpolated live coral cover in these regions primarily was 10.1%–40% but reached 75% for 2 segments in the northeast region (Fig. 11.3.3a, bottom panel). Around the eastern point of Guguan, in an area of medium to high complexity habitats, interpolated live coral cover of 20.1%–62.5% was recorded.

In the southwest and southeast regions, towed divers surveyed the shallow shelf. There, habitat complexity was lower than the habitats observed north of this island. Habitats along the southern coast of Guguan were classified as medium-low to medium-high complexity in most locations. Sand cover was higher there than on the non-shelf areas with interpolated sand cover of 1.1%–50% recorded. The highest sand cover was observed around the southern point of this island. Live coral cover varied around Guguan, with the lowest levels of coral cover (< 20%) observed around the southern point and in the southwest region, corresponding to the areas of highest sand cover. Analyses of the video footage acquired from TOAD

surveys made on the deeper shelf in the southwest region at depths of 41–270 m suggested that the substrate there was also sandy, with 100% sand cover observed in nearly all video frames. This high sand cover contrasts the hard–soft analysis that classified this area as one of hard substrates. This disparity likely is a result of this shelf area's support of a thin veneer of sand, visible on the video footage but not of sufficient depth to influence acoustic characteristics. Low live coral cover was observed in this TOAD video footage, with only 2 video frames from a single survey at depths of 33–34 m suggesting coral cover of 20%. The remainder of analyzed video footage was devoid of visible benthic fauna.

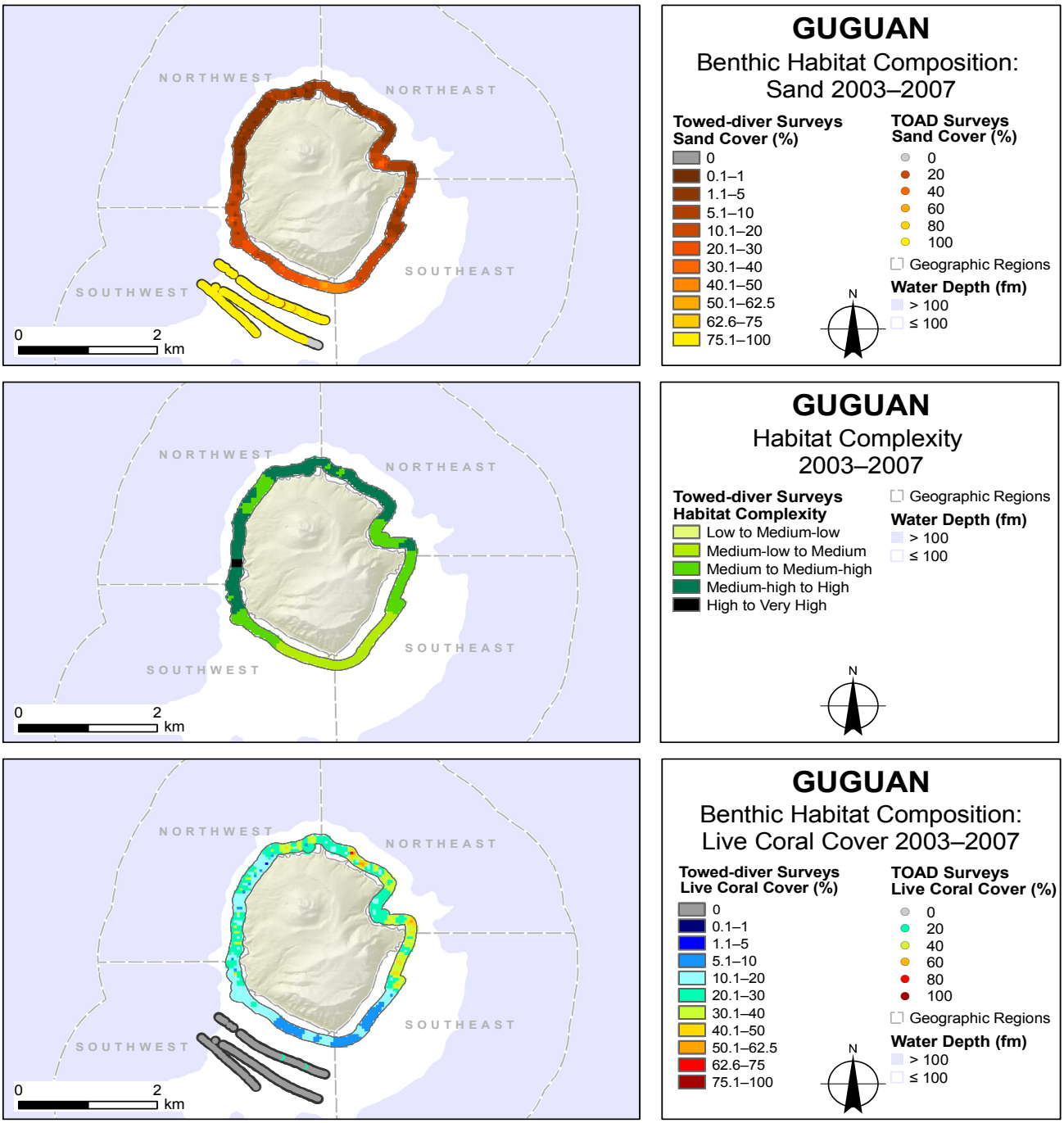


Figure 11.3.3a. Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) live-hard-coral cover (%) from towed-diver surveys conducted and analyses of TOAD video collected around Guguan during MARAMP 2003, 2005, and 2007.

11.4 Oceanography and Water Quality

11.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 10 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the island of Guguan on September 11. Temperature, salinity, and density values varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest small differences in temperature (0.1°C), salinity (0.1 psu), and density (0.1 kg m^{-3}) values; however, recorded temperature values were slightly lower and salinity values were higher in the northwest and northeast regions (casts 1-6) than in the southwest and southeast regions (casts 7–10; Fig. 11.4.1a). Vertical comparisons of CTD profiles reveal water properties with a moderate range in temperature (0.8°C), salinity (0.2 psu), and density (0.5 kg m^{-3}) values (Fig. 11.4.1b). Well-mixed waters were recorded around most of Guguan (casts 4–10), except in the northwest region (casts 1–3), where increased stratification was observed because of the presence of cool, subsurface water at depths > 15 m.

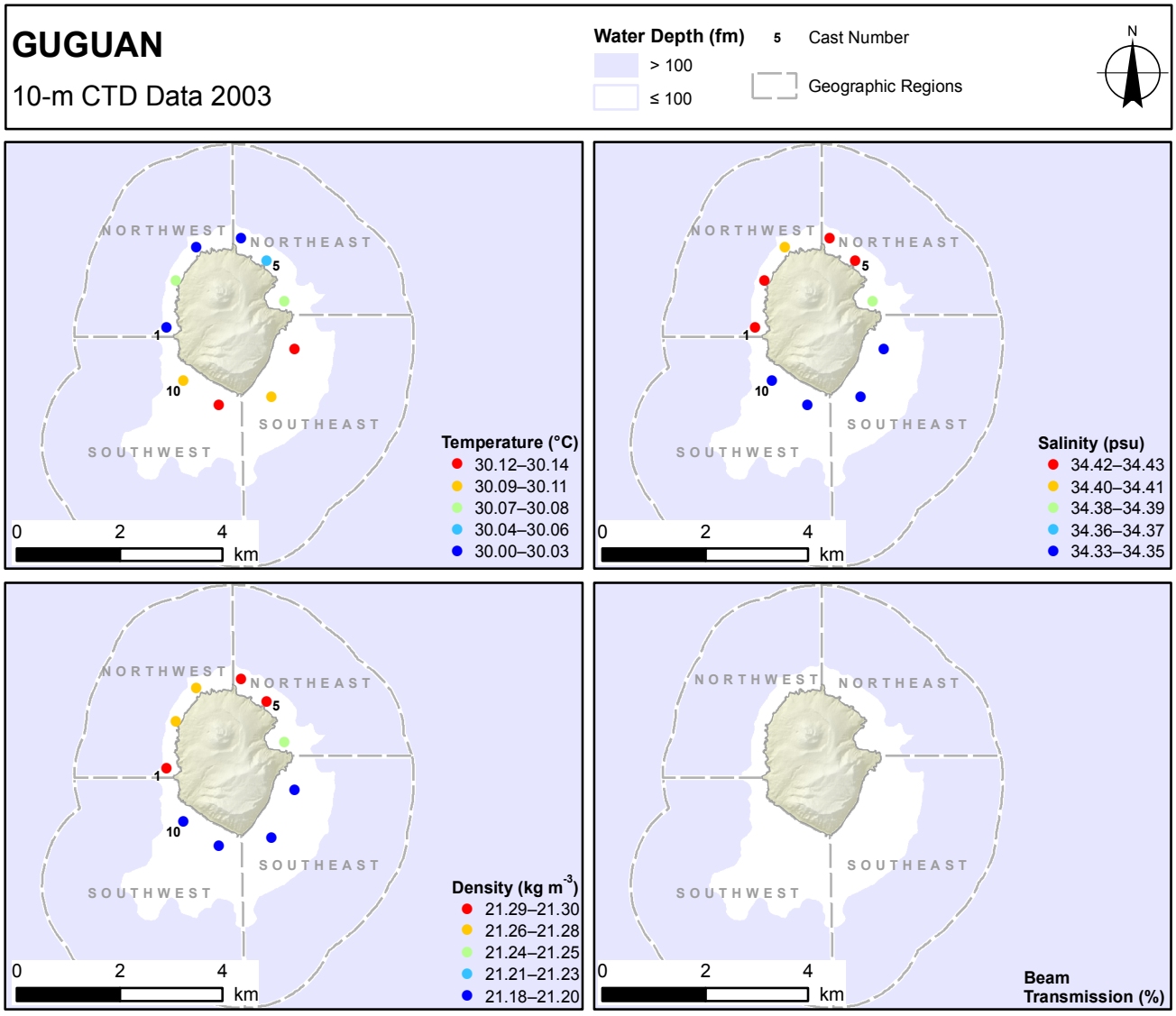


Figure 11.4.1a. Values of *(top left)* water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts around Guguan on September 11 during MARAMP 2003.

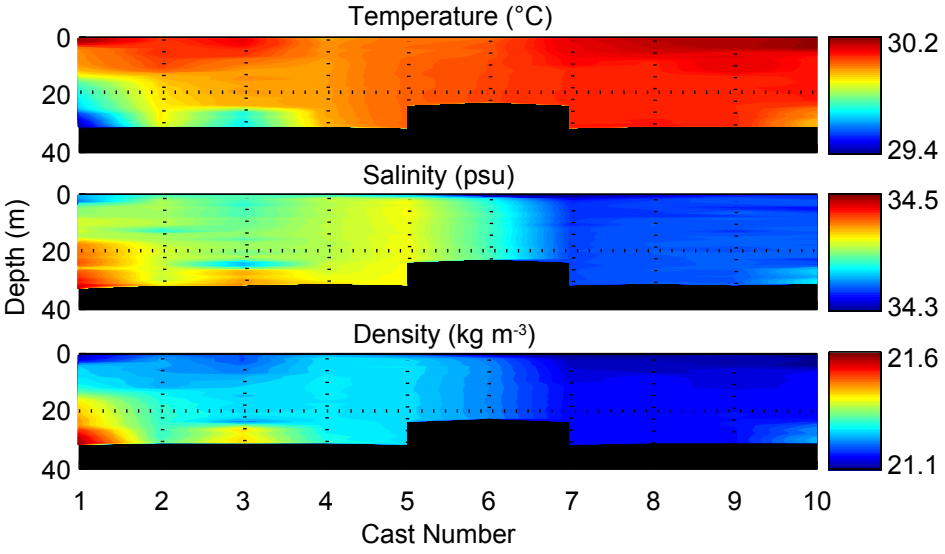


Figure 11.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Guguan on September 11 during MARAMP 2003, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–10 in a clockwise direction around Guguan. For cast locations and numbers around this island in 2003, see Figure 11.4.1a.

2005 Spatial Surveys

During MARAMP 2005, 6 shallow-water CTD casts were conducted in nearshore waters at Guguan on September 5. Temperature, salinity, density, and beam transmission values varied both spatially and vertically at this island. Spatial comparisons of water properties at a depth of 10 m suggest small differences in temperature (0.2°C), salinity (0.04 psu), and density (0.1 kg m^{-3}) values (Fig. 11.4.1c); however, a moderate range in beam transmission (2.7%) values was observed at Guguan. Vertical comparisons of CTD profiles reveal a well-mixed water column, with waters in the northwest region (casts 1–3) slightly cooler and more saline than waters in the southwest (Fig. 11.4.1d). As a result of low water clarity at cast 1 in the northwest region, the difference in beam transmission values at this island was broader than the ranges in values for all other parameters measured.

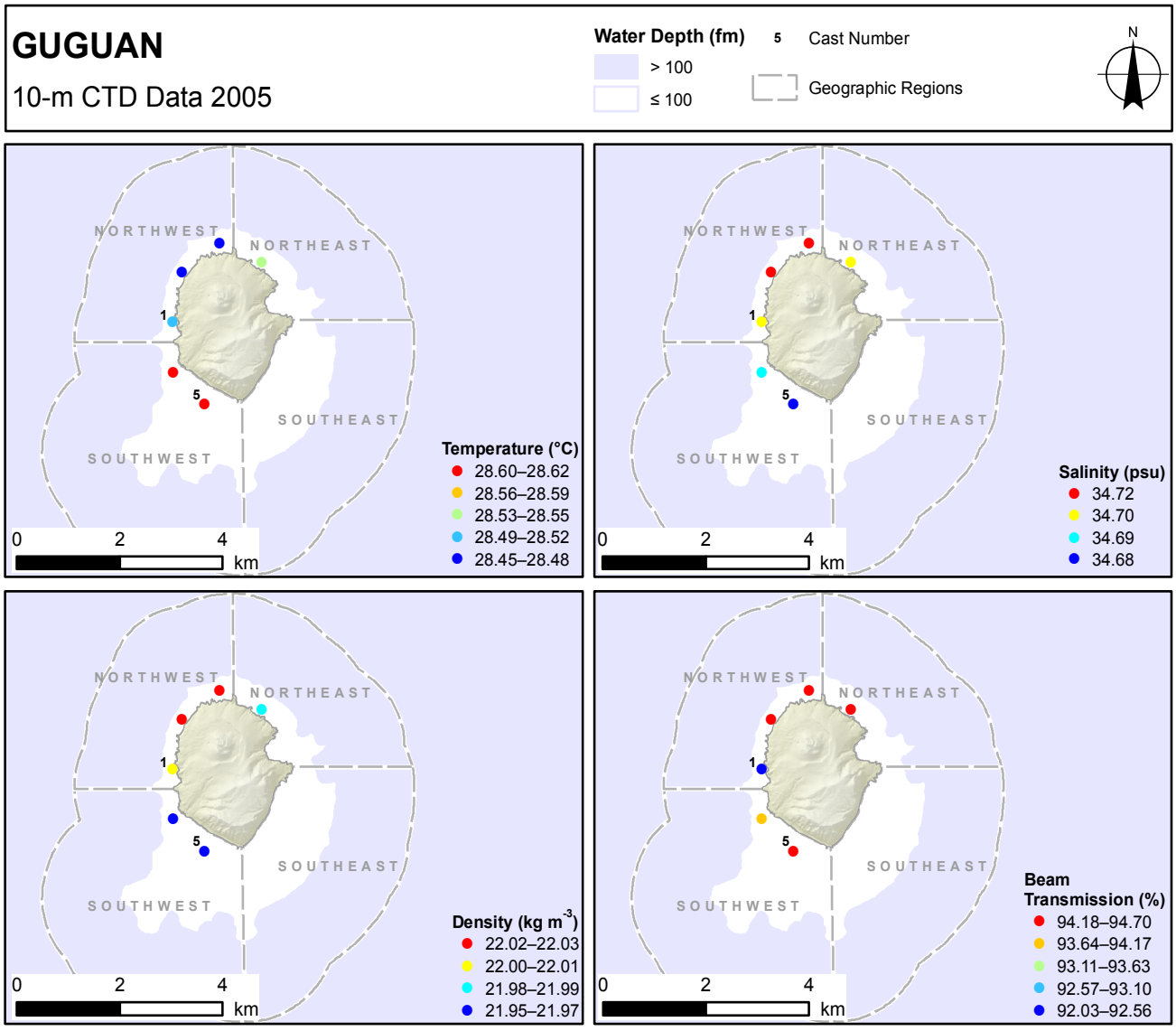


Figure 11.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts at Guguan on September 5 during MARAMP 2005.

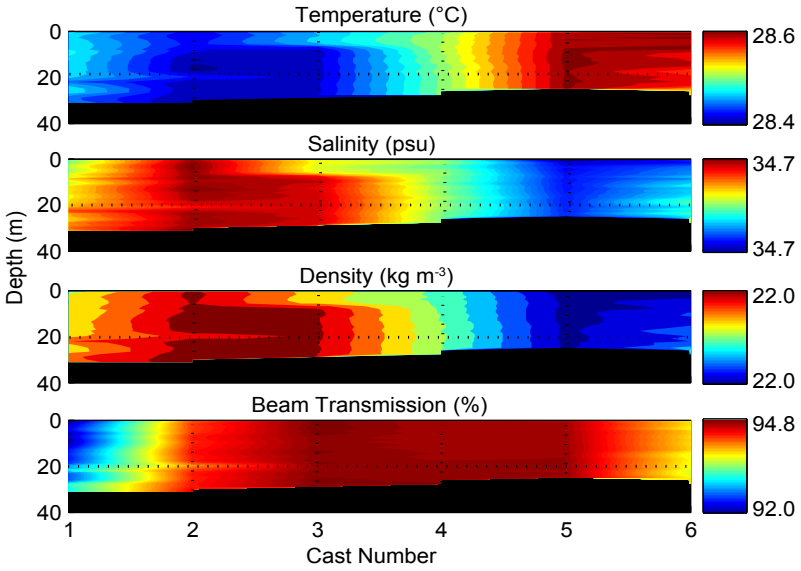


Figure 11.4.1d. Shallow-water CTD cast profiles to a 30-m depth at Guguan on September 5 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–6 in a clockwise direction around Guguan. For cast locations and numbers around this island in 2005, see Figure 11.4.1c.

2007 Spatial Surveys

During MARAMP 2007, 9 shallow-water CTD casts were conducted in nearshore waters around Guguan on June 8. Temperature, salinity, density, and beam transmission values varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest moderate differences in temperature (0.5°C) and salinity (0.3 psu) values and small differences in density (0.1 kg m^{-3}) and beam transmission (< 1%) values. However, temperature, salinity, and beam transmission values were slightly lower in the northwest and southwest regions (casts 1–3, 9) than in the northeast and southeast regions (casts 4–8; Fig. 11.4.1e). Vertical comparisons of CTD profiles reveal water properties with broad differences in temperature (1.5°C), salinity (0.5 psu), density (0.7 kg m^{-3}), and beam transmission (1.8%) values (Fig. 11.4.1f). Well-mixed waters were recorded in the northeast and southeast regions, but stratification with large vertical temperature gradients were recorded in the northwest and southwest regions, particularly in the northwest region where cool, subsurface water was found at depths > 15 m (casts 1–3).

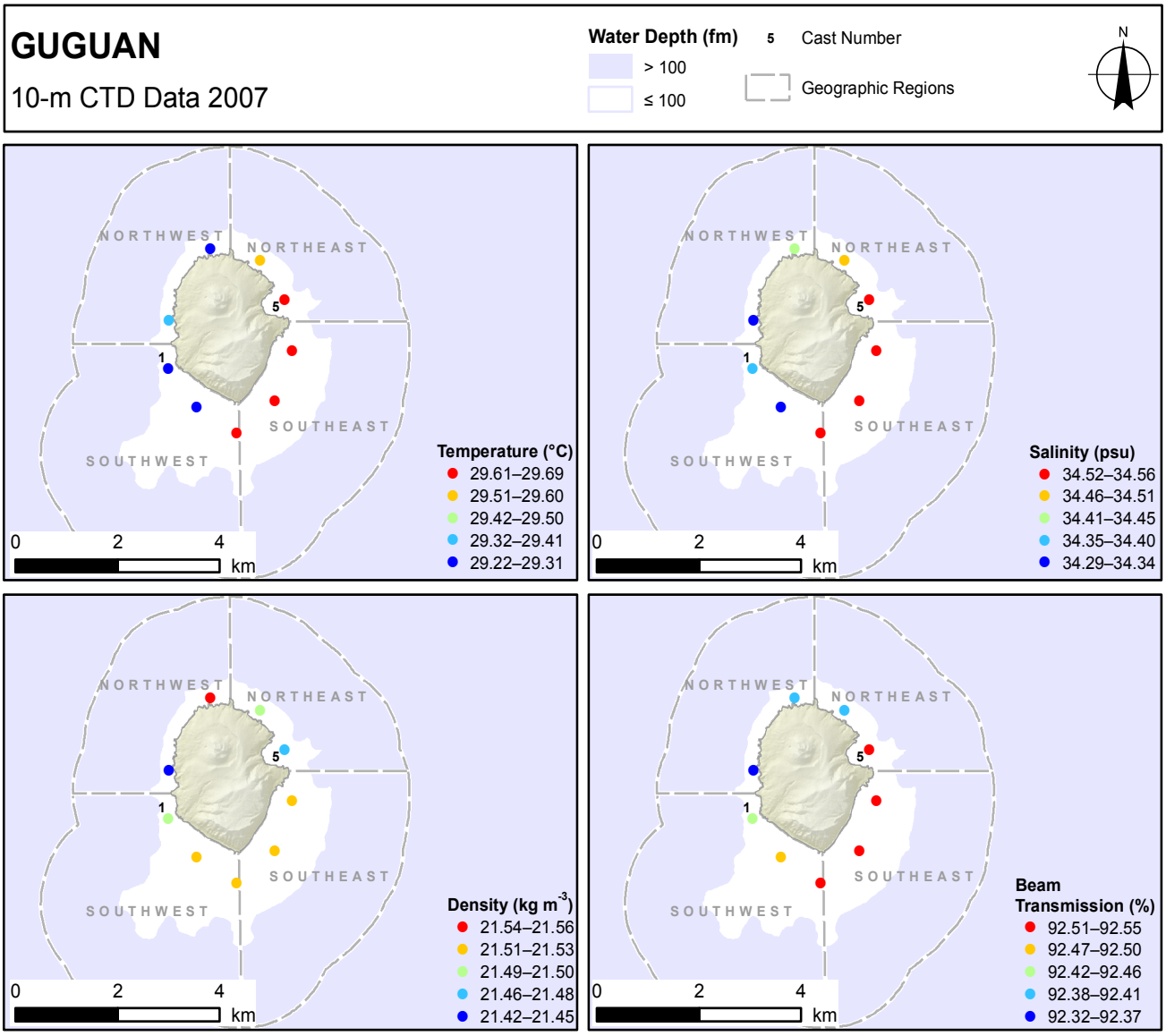


Figure 11.4.1e. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Guguan on June 8 during MARAMP 2007.

Water samples were collected in concert with swallow-water CTD casts at 3 select locations at Guguan in 2007 to assess water-quality conditions (Fig. 11.4.1g). The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.026 –0.071 µg/L; total nitrogen (TN), 0.006–0.083 µM; nitrate (NO_3^-), 00.068 µM; nitrite (NO_2^-), 0.003–0.017 µM; phosphate (PO_4^{3-}), 0.034–0.041 µM; silicate [$Si(OH)_4$], 1.89–1.98 µM. Water-quality parameters generally were observed at the relatively low levels typical of the Western Pacific Warm Pool's oligotrophic, oceanic surface layers, except for silicate, which had high values with the highest concentrations in the southwest region.

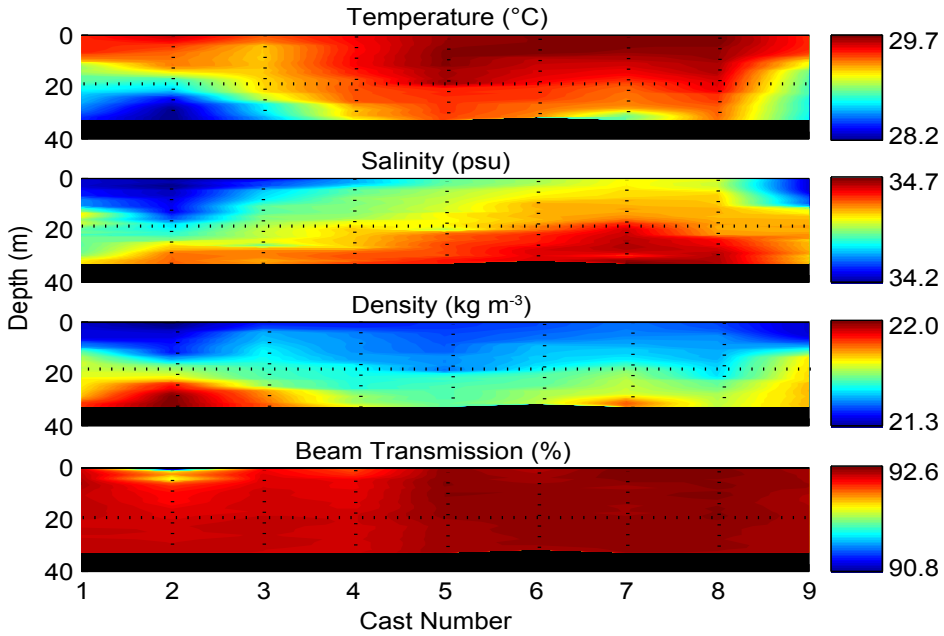


Figure 11.4.1f. Shallow-water CTD cast profiles to a 30-m depth around Guguan on June 8 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–9 in a clockwise direction around Guguan. For cast locations and numbers around this island in 2007, see Figure 11.4.1e.

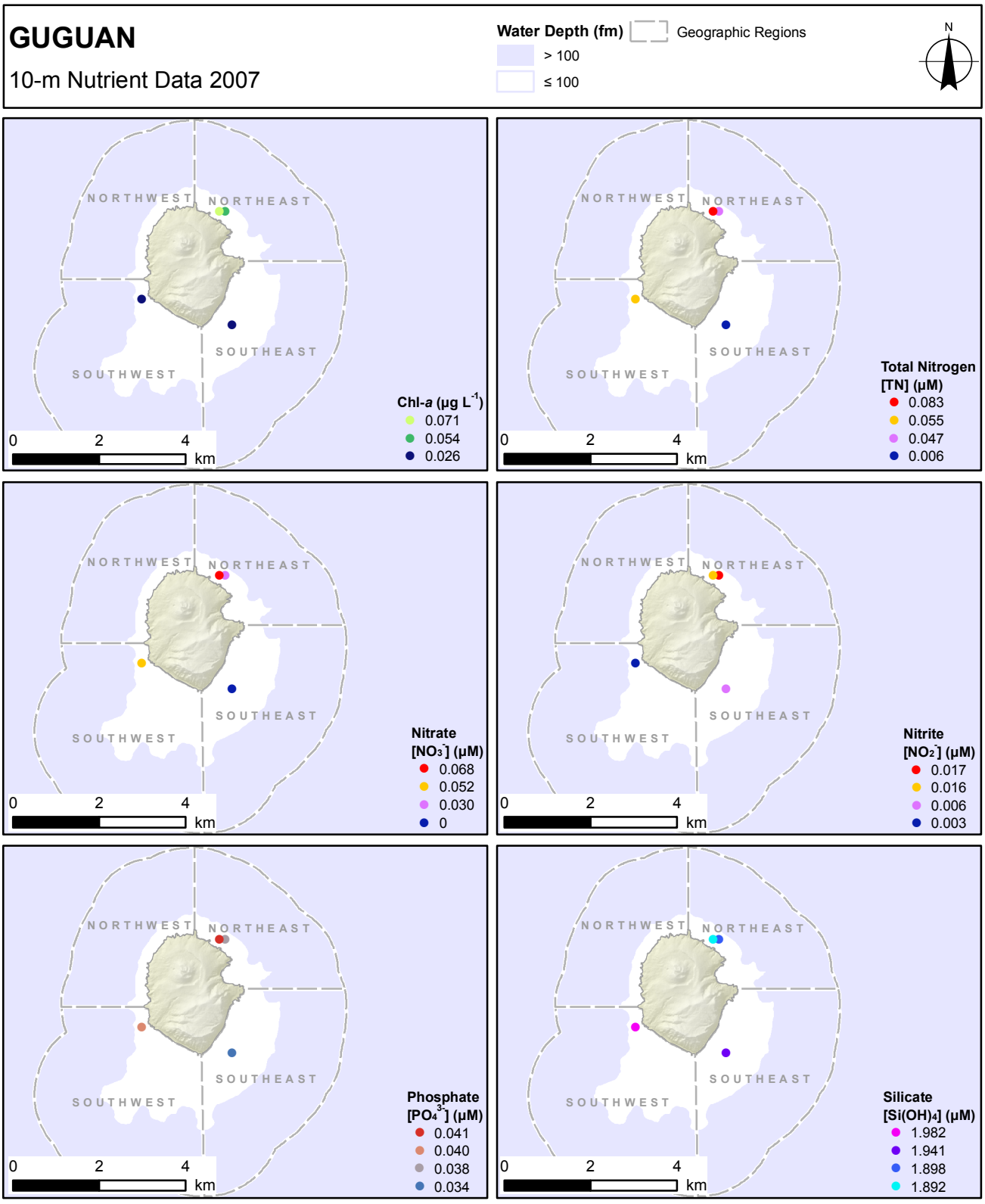


Figure 11.4.1g. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Guguan on June 8 during MARAMP 2007.

Temporal Comparison

Temporal comparisons between MARAMP survey periods of shallow-water CTD data collected around Guguan during MARAMP 2003, 2005, and 2007 suggest a dynamic physical oceanographic environment. Low spatial variability and moderate vertical variability were observed in 2003 and 2005, and, in 2007, strong spatial variability in water properties was recorded with coldwater (28.2°C; 1.5°C colder than surface waters) intrusions originating from depths > 30 m recorded in the northwest and southwest regions. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in June, and MARAMP 2003 and 2005 occurred in September. This change was made to avoid the typhoon season and reduce the probability of weather disruptions.

11.4.2 Time-series Observations

Between 2003 and 2007, subsurface temperature recorders (STRs) were moored at a single location at Guguan to collect time-series observations of temperature, a key oceanographic parameter influencing reef conditions (Fig. 11.4.2a). The location, depth, time frames, and other details about these deployments are provided in Figures 11.4.2a and b

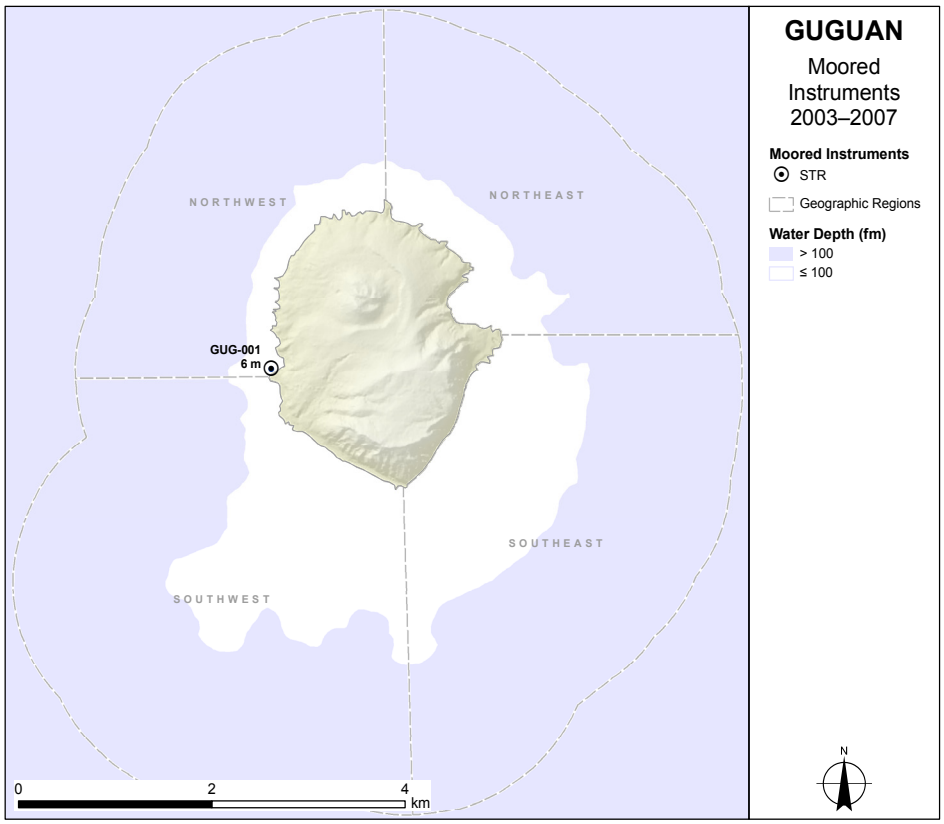


Figure 11.4.2a. Location and depth of the STR deployed at Guguan during MARAMP 2003, 2005, and 2007.

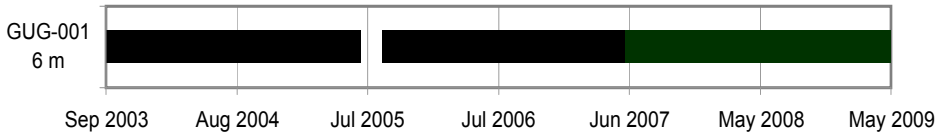


Figure 11.4.2b. Deployment and retrieval timeline and depth of the STR installed at Guguan at a depth of 6 m during the period from September 2003 to May 2009. A solid bar indicates the period for which temperature data were collected by a series of STRs deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 11.2b in Section 11.2: "Survey Effort."

Temperature data from STRs deployed a depth of 6 m at a single location in the northwest region show seasonal temperature variability of ~ 4°C (Fig. 11.4.2c). Water temperatures reached 29°C–30°C during the months of June–October and fell to a low of ~ 27°C during the months of January–May. Superimposed with this seasonal temperature variability are frequent intraseasonal fluctuations. For example, recorded temperatures dropped nearly 3°C in July 2004 for ~ 1 week before sharply increasing to typical summertime levels. Similar changes in temperature were observed in September 2004 and in the summer of 2005. Additionally, temperature values exceeded the coral bleaching threshold for the region in July 2005 and September 2006; however, the duration of these events was < 1 d. Diurnal temperature fluctuations were ~ 0.25°C throughout this time series.

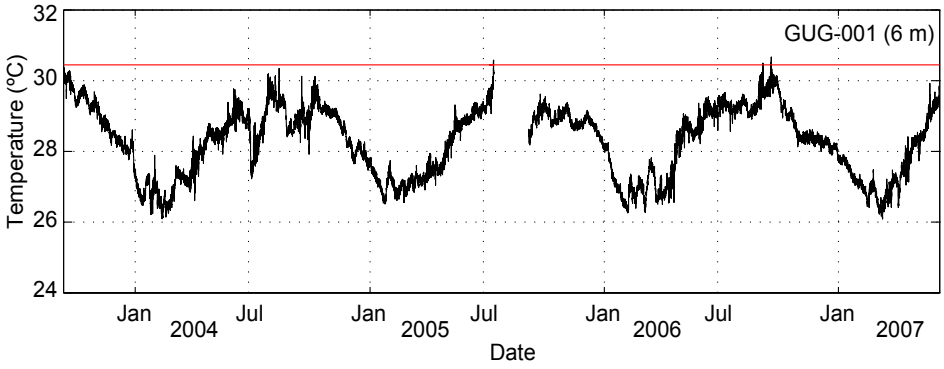


Figure 11.4.2c. Time-series observations of temperature over the period between September 2003 and June 2007 collected from 1 STR morning site at a depth of 6 m (see Figure 11.4.2a for mooring location). The red line indicates the coral bleaching threshold, which is defined as 1°C above the maximum climatological mean.

11.4.3 Wave Watch III Climatology

Seasonal wave climatology for Guguan (Fig 11.4.3a) was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008, and seasons were selected to elucidate waves generated by typhoons, which most frequently occur between the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (~ 80°–90°). Superimposed with these short-period swells were large (> 5 m), long-period (12–16 s) wave events from the south (160°–190°) and south-southeast (200°–210°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from any direction, although weighted slightly larger from the south (100°–250°), and likely were associated with episodic, moderate-sized, or distant storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) also was characterized by frequent (> 30 d per season) and short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season) and long-period (12–14 s) swells with small wave heights (~ 2–3 m) also occurred during this period and originated from any direction.

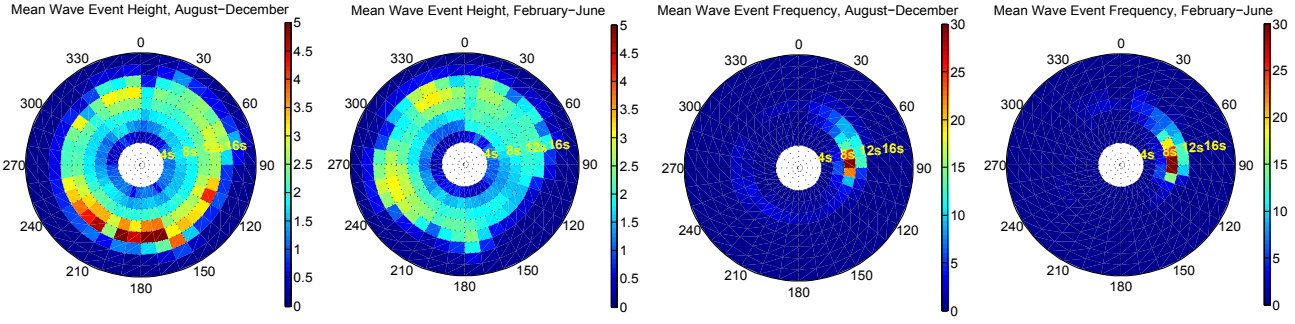


Figure 11.4.3a. NOAA Wave Watch III directional wave climatology for Guguan from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Guguan (17° N, 145° E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

11.5 Corals and Coral Disease

11.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Guguan was 23% (SE 1.9). Coral cover was highest along the western and eastern coasts with a range of 20.1%–50% over numerous segments (Fig. 11.5.1a, top panel).

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats at Guguan was 10% (SE 1). Because of weather constraints, 2 towed-diver surveys were conducted at Guguan in 2005, with less complete spatial coverage compared to the survey efforts in 2003 and 2007. Coral cover generally was low on the reef areas surveyed around Guguan in 2005, relative to results from other islands in the Mariana Archipelago (Fig. 11.5.1a, middle panel).

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 0.4% (SE 0.1) of coral cover observed on forereef habitats at Guguan appeared stressed. Stressed-coral cover was low for the majority of reef areas surveyed at Guguan in 2005.

From MARAMP 2007 towed-diver surveys, mean cover of live corals on forereef habitats around Guguan was 27% (SE 2). Coral cover generally was higher in the northern regions than in the southern regions, with the highest coral cover of 34% over 29 segments found during the survey that crossed the border of the northwest and northeast regions (Fig. 11.5.1a, bottom panel). Overall, 0.3% (SE 0.17) of coral cover observed on forereef habitats around Guguan appeared stressed in 2007. Stressed-coral cover was low, compared to other areas surveyed in the Mariana Archipelago, for the majority of reef areas surveyed around Guguan.

During MARAMP 2007, 3 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Guguan. Site-specific estimates of live-hard-coral cover from these surveys ranged from 8.8% to 20.6% with an overall sample mean of 15.4% (SE 3.5). Live coral cover was highest at REA site GUG-01 in the southeast region and lowest at GUG-02 in the southwest region (Fig. 11.5.1b, bottom panel).

During MARAMP 2003, 3 REA benthic surveys using the quadrat method on forereef habitats at Guguan documented 356 coral colonies within a total survey area of 11.25 m^2. Site-specific colony density ranged from 19.7 to 41.3 colonies m^{-2} with an overall sample mean of 31.6 colonies m^{-2} (SE 6.3). The highest colony density was recorded at GUG-02 in the southwest region, and the lowest colony density was observed at GUG-03 in the northwest region (Fig. 11.5.1b, top panel).

During MARAMP 2007, 3 REA benthic surveys using the quadrat method on forereef habitats at Guguan documented 557 coral colonies within a total survey area of 12 m^2. Site-specific colony density ranged from 43 to 48.8 colonies m^{-2} with an overall sample mean of 46.4 colonies m^{-2} (SE 1.8). The highest colony density was recorded at GUG-01 in the southeast region. Colony density was similarly high at GUG-03 in the northwest region and slightly lower at GUG-02 in the southwest region (Fig. 11.5.1b, bottom panel).

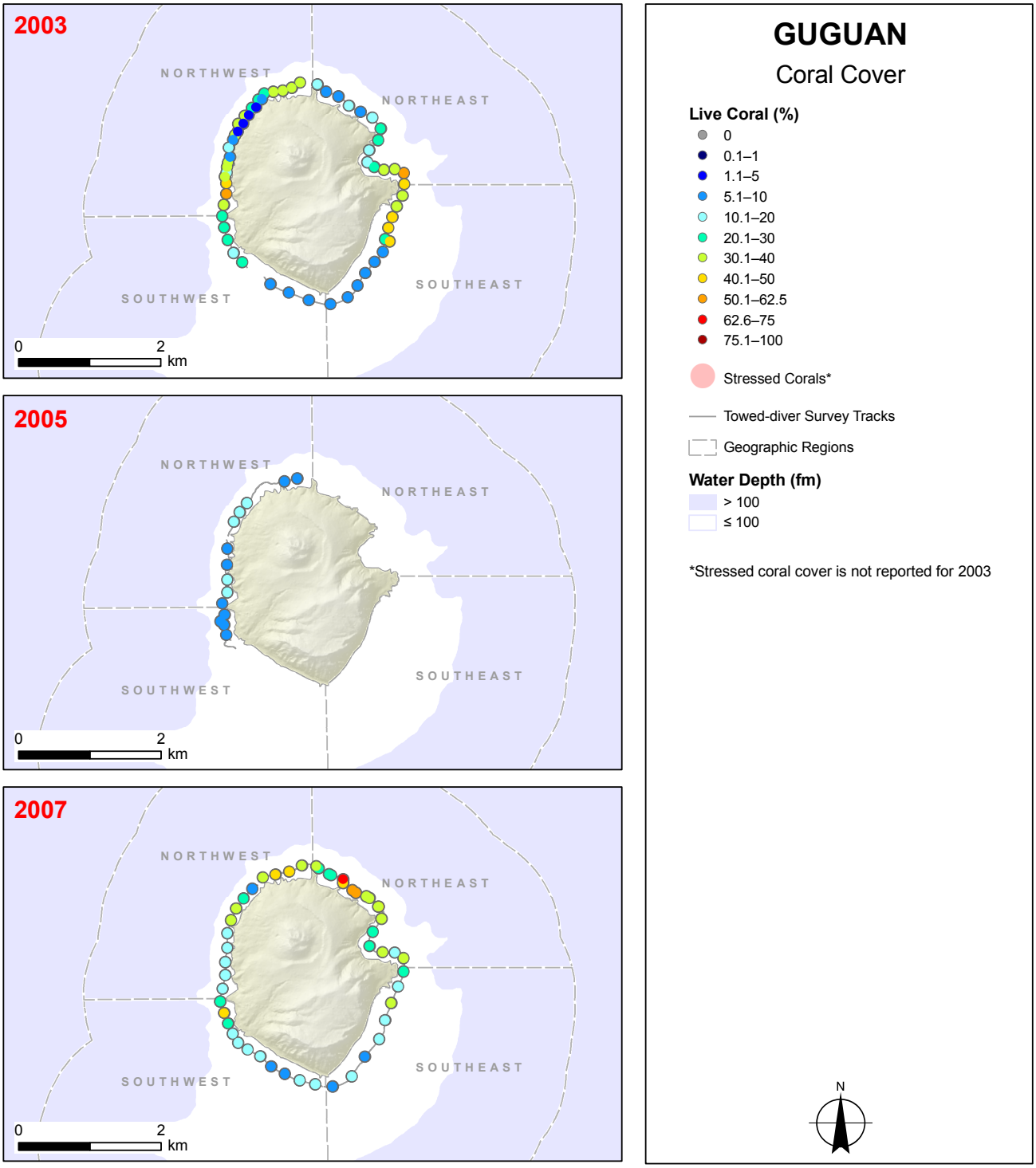


Figure 11.5.1a. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Guguan during MARAMP 2003, 2005, and 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols are shown only for segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005 and 2007.

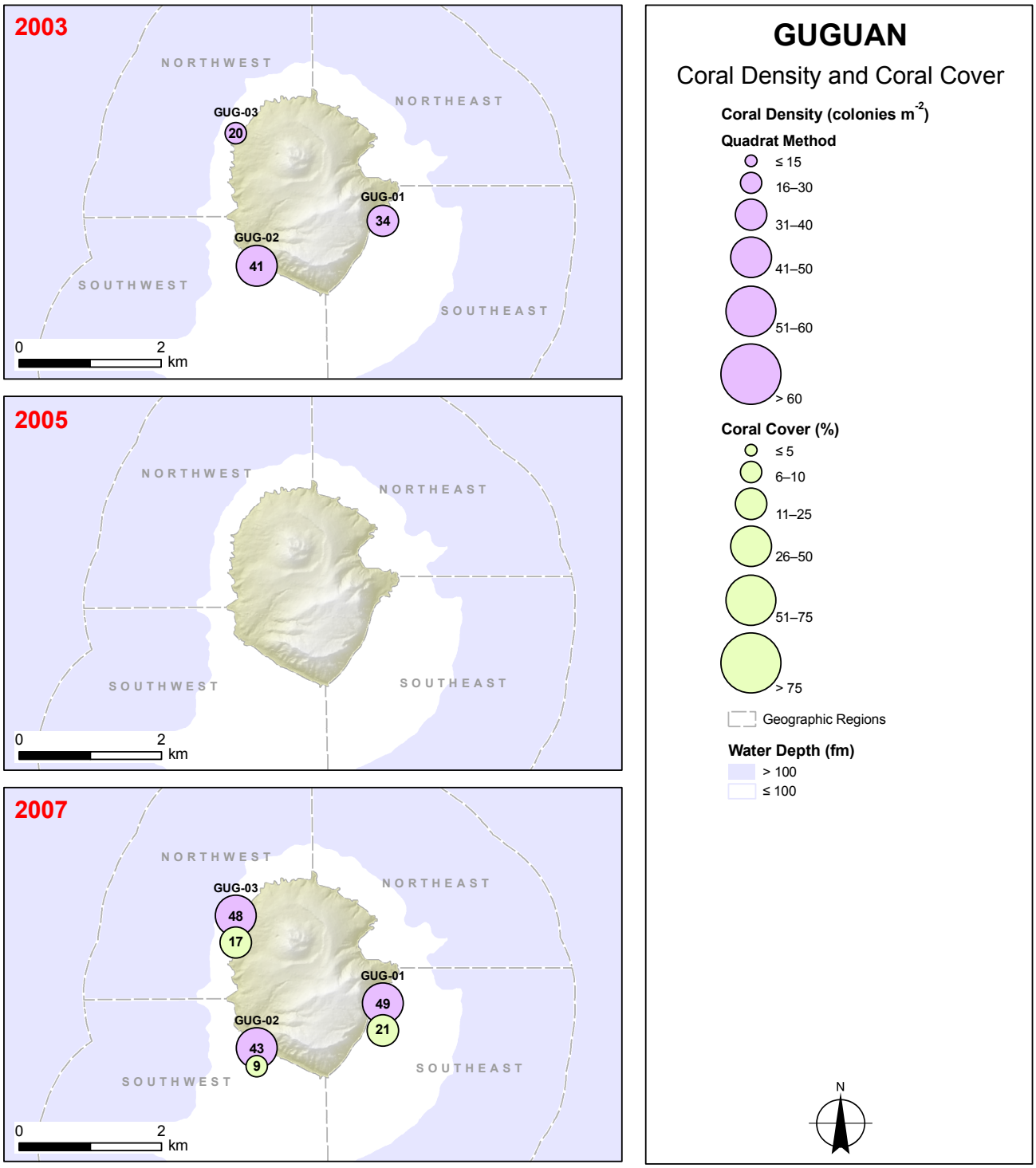


Figure 11.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Guguan during MARAMP 2003 and 2007, and cover (%) observations of live corals from REA benthic surveys during MARAMP 2007. Values are provided within each symbol. The quadrat method was used in 2003 and 2007 to assess coral-colony density.

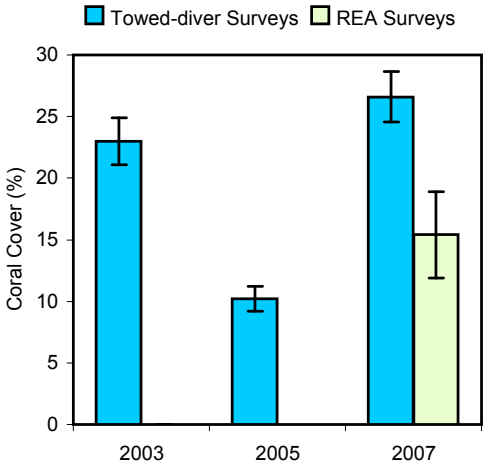


Figure 11.5.1c. Temporal comparison of mean live-coral-cover (%) values from REA and towed-diver benthic surveys conducted on forereef habitats around Guguan during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted around Guguan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

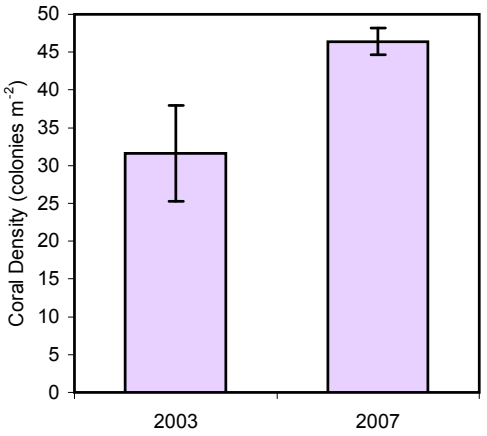


Figure 11.5.1d. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Guguan during MARAMP 2003 and 2007. Guguan was not surveyed for colony density in 2005. The quadrat method was used in 2003 and 2007 to measure coral-colony density. Error bars indicate standard error (± 1 SE) of the mean.

Islandwide mean cover of live corals estimated from towed-diver surveys of forereef habitats was 22.6% (SE 1.9) in 2003, 10.2% (SE 1.0) in 2005, and 26.6% (SE 2.0) in 2007 (Fig. 11.5.1c). Survey effort in 2005 primarily was limited to the northwest region, where coral cover was low; thus, average cover was lower in 2005 than in 2003 and 2007. Guguan was not surveyed for coral cover using the line-point-intercept method in 2003 or 2005. For the 3 REA sites surveyed using the line-point-intercept method in 2007, overall mean coral cover was 15.4% (SE 3.5).

Overall mean coral-colony density from REA benthic surveys of forereef habitats at Guguan increased from 31.6 colonies m^{-2} (SE 6.3) in 2003 to 46.4 colonies m^{-2} (SE 1.8) in 2007 (Fig. 11.5.1d). This rise in colony density could have resulted from increased recruitment or fragmentation of existing colonies. The quadrat method was used in both 2003 and 2007 to assess coral colony density at Guguan.

Coral Generic Richness and Relative Abundance

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Guguan during MARAMP 2003. At least 18 coral genera were observed. Generic richness ranged from 14 to 15 with a mean of 14.7 (SE 0.3) coral genera per site (Fig. 11.5.1e, top panel). No strong spatial pattern in generic diversity was seen.

Pavona, Favia, and *Leptastrea* were the most numerically abundant genera, contributing 23.1%, 12.6%, and 12% to the total number of colonies enumerated at Guguan in 2003. All other genera individually contributed < 10% of the total number of colonies. The genus *Pavona* dominated the coral fauna at all 3 sites surveyed, accounting for 22%, 29.7%, and 17.6% to the total number of colonies enumerated at GUG-01, GUG-02, and GUG-03.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Guguan during MARAMP 2007. At least 22 coral genera were observed. Generic richness ranged from 16 to 20 with a mean of 17.7 (SE 1.2) coral genera per site (Fig. 11.5.1e, bottom panel). The highest generic diversity was seen at GUG-01 in the southeast region, and the lowest generic diversity was recorded at GUG-02 in the southwest region.

Favia, Pavona, Pocillopora, and *Leptastrea* were the most numerically abundant genera, contributing 23.3%, 22.1%, 11.7%, and 11.5% of the total number of colonies enumerated at Guguan in 2007. All other genera individually accounted for < 10% of the total number of colonies. The genera *Favia* and *Pavona* co-dominated at GUG-01, each contributing 26.2% of the total number of colonies observed at that site. As in 2003, the genus *Pavona* dominated at GUG-02, accounting for 23.8% of the total number of colonies recorded at that site, but the genus *Favia* dominated at GUG-03, contributing 26.8% of the total number of colonies observed at that site.

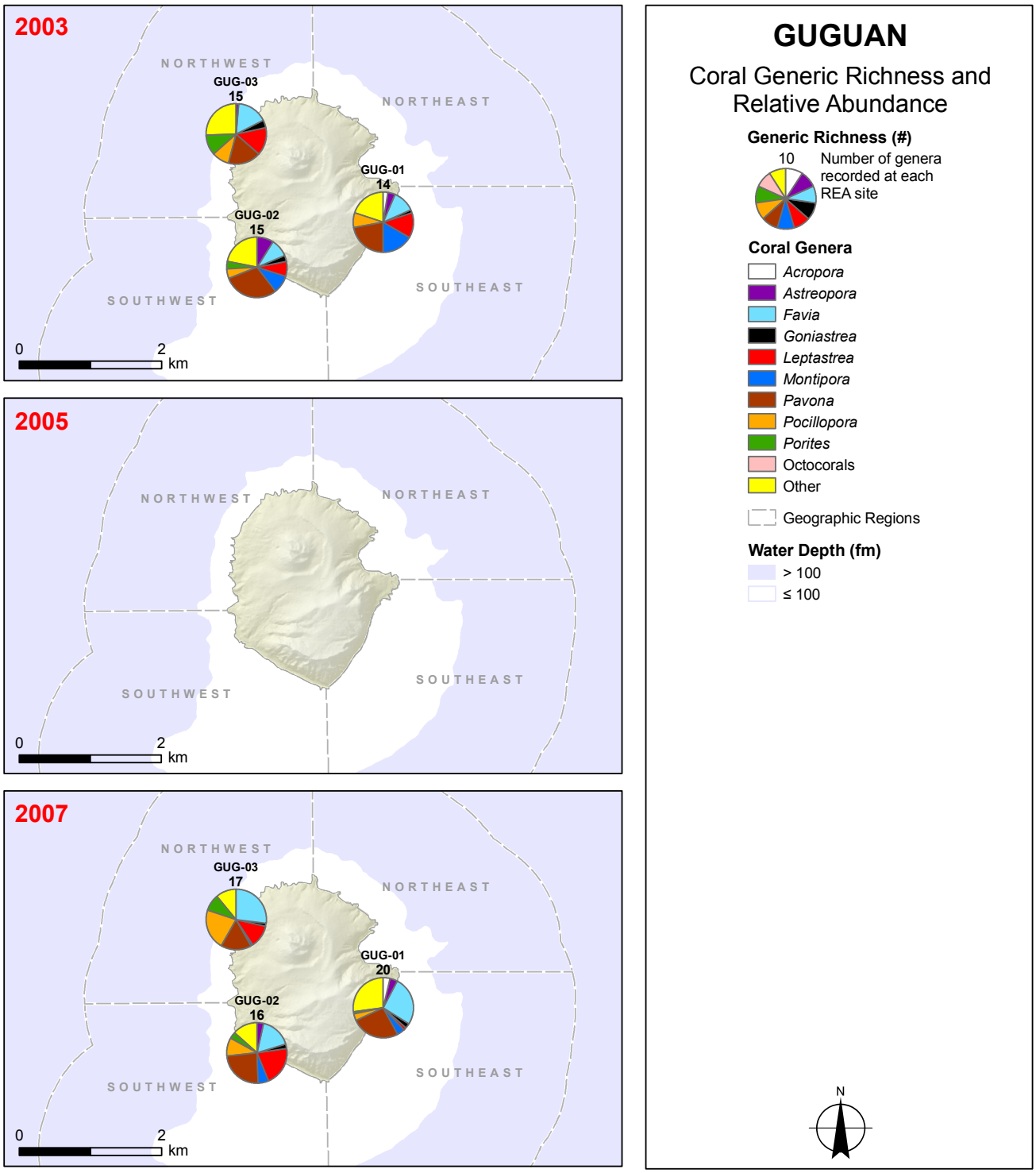


Figure 11.5.1e. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Guguan during MARAMP 2003 and 2007. Guguan was not surveyed for generic richness in 2005. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in both years to survey coral genera.

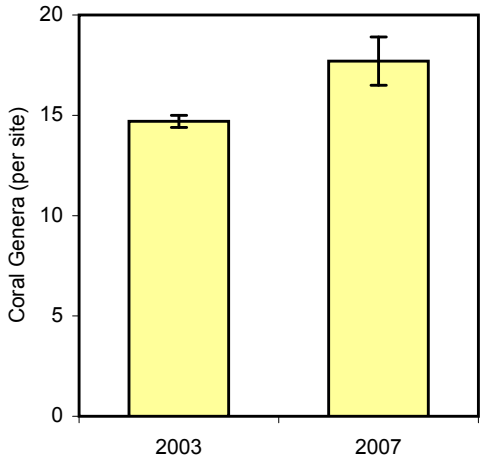


Figure 11.5.1f. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Guguan during MARAMP 2003 and 2007. Guguan was not surveyed for generic richness in 2005. The quadrat method was used in both years to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

Site-specific estimates of generic richness from MARAMP 2003 and 2007 ranged from 14 to 20 on forereef habitats. Overall sample means of generic richness were lower in 2003 than in 2007 with 14.7 (SE 0.3) in 2003 to 17.7 (SE 1.2) in 2007 (Fig. 11.5.1f). This change in estimates resulted from the observation of a few colonies of 4 genera in 2007 (*Echinopora, Leptoria, Hydnophora*, and *Stylocoeniella*) that were not recorded in 2003.

During the 2 survey years, 23 coral genera were observed on forereef habitats at Guguan. The genera *Pavona*, *Favia*, and *Leptastrea* were important components of the coral fauna, accounting for > 10% of the total number of colonies enumerated at Guguan in both survey years. The genus *Pavona* was the most abundant taxon in 2003 and the second-most abundant taxon in 2007, contributing 23.1% and 22.1% of the total number of colonies recorded. The genus *Favia* was the most abundant taxon in 2007 and the second-most abundant in 2003, contributing 23.3% and 12.6% of the total number of colonies enumerated. *Leptastrea* was the third-most abundant taxon in 2003 and the fourth-most abundant taxon in 2007, contributing 12% and 11.5% of the total number of colonies. The contribution of the genus *Pocillopora* slightly exceeded that of the genus *Leptastrea* in 2007, contributing 11.7% of the total number of colonies. All other taxa contributed < 10% of the total number of colonies enumerated at Guguan in both survey years.

Coral Size-class Distribution

During MARAMP 2003, 3 REA benthic surveys of forereef habitats were conducted at Guguan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (55.8%) of corals had maximum diameters ≤ 5 cm (Fig. 11.5.1g, top panel). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 29.9%, 9.1%, and 5.2% of colonies recorded. No colonies with maximum diameters > 40 cm were recorded. At GUG-01 and GUG-02 in the southeast and southwest regions, a majority (> 63%) of corals was in the smallest size class (≤ 5 cm), and at GUG-03 in the northwest region only 40.5% of corals had maximum diameters ≤ 5 cm.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats were conducted at Guguan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (83%) of corals had maximum diameters ≤ 5 cm, and only 0.3% had maximum diameters > 40 cm (Fig. 11.5.1g, bottom panel). Corals in the size classes 6–10, 11–20, and 21–40 cm, accounted for 13.7%, 1.5%, and 1.4% of colonies recorded. At each REA site, a majority (> 69%) of corals were in the smallest size class (≤ 5 cm).

Site-specific and overall distributions of estimated coral size classes on forereef habitats at Guguan are affected by inherent biases in the method used to census and size corals. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. For more on this survey method, see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease."

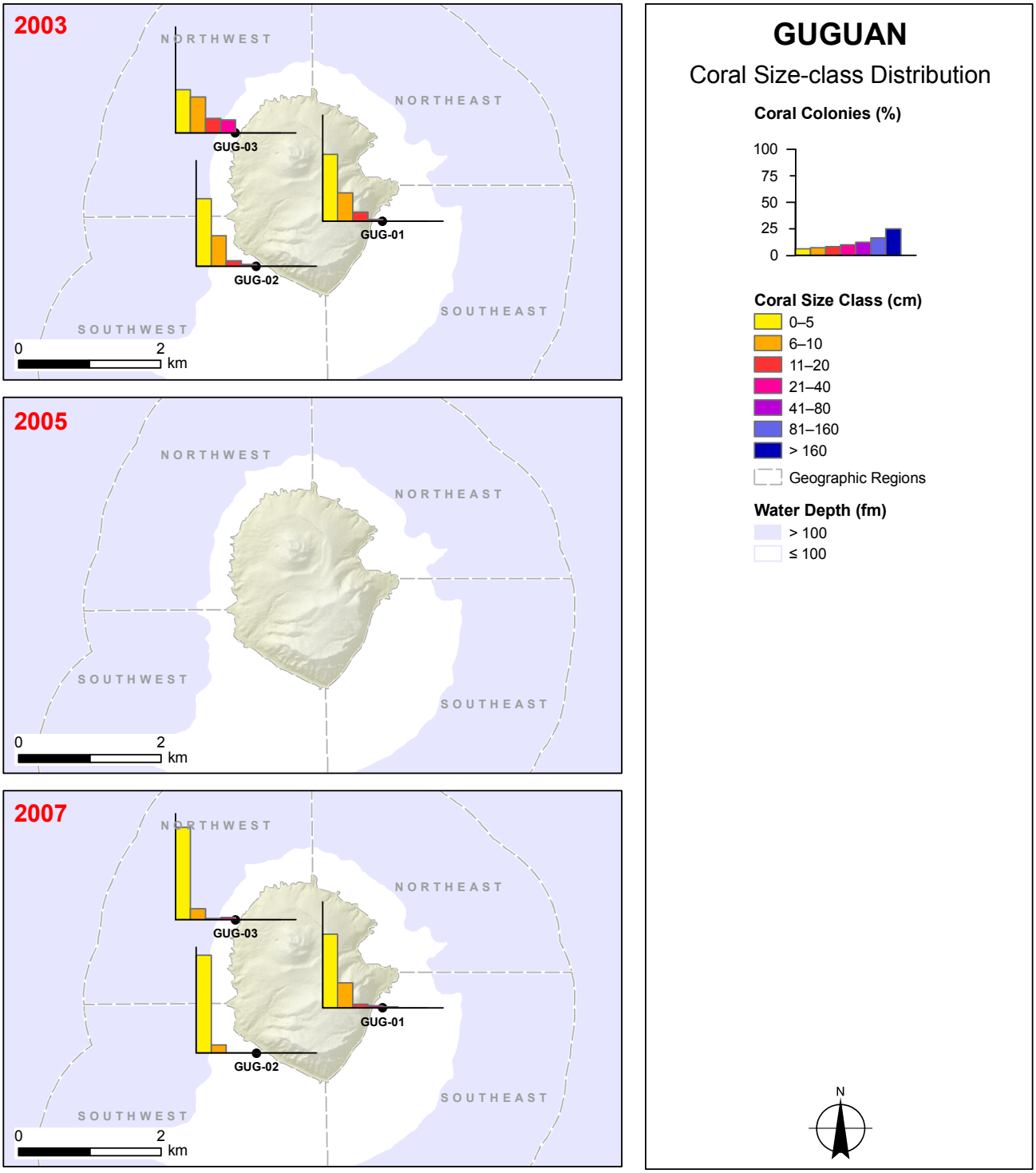


Figure 11.5.1g. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Guguan during MARAMP 2003 and 2007. Guguan was not surveyed for coral size-class distribution in 2005. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in both survey years to size corals.

During MARAMP 2003 and 2007, the majority of coral colonies were in the smallest size class (0–5 cm) with about twice as many small corals observed in 2007 as seen in 2005 (Fig. 11.5.1h). The overall mean proportions of colonies at Guguan that fell in the smallest size class increased, from 55.3% in 2003 to 83% in 2007, as did the values for each of the 3 sites surveyed in both years. Concordantly, the overall mean proportion of colonies in all other size classes decreased between 2003 and 2007, as did all site-specific proportions. This observed shift toward the smallest size class may be a result of recruitment, fragmentation of existing colonies, or both. Minor variation between overall and site-specific size-class distributions recorded in 2003 and 2007 likely result from chance differences in the placement of individual quadrats.

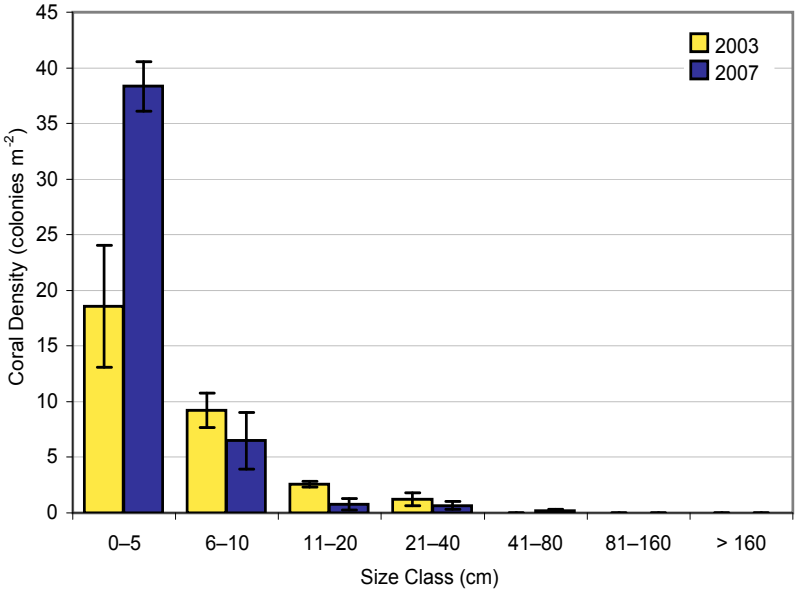


Figure 11.5.1h. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats at Guguan during MARAMP 2003 and 2007. Guguan was not surveyed for coral size-class distribution in 2005. The quadrat method was used in both survey years to size corals. Error bars indicate standard error (± 1 SE) of the mean.

11.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted at 3 sites on forereef habitats at Guguan, covering a total area of 700 m^2. Surveys detected 8 cases of disease, translating to an overall mean prevalence of 0.04% (SE 0.02). Coral-colony counts at all REA sites at Guguan were conducted using the quadrat method, resulting in high coral-colony densities and, therefore, low disease prevalence values, relative to the levels found at sites at other islands surveyed using the belt-transect method.

One disease condition was observed at Guguan: an infestation by the encrusting sponge *Terpios*. Of the 3 sites surveyed, only GUG-03 contained disease (Fig. 11.5.2a). Cases of *Terpios* infestation were detected on a variety of massive and encrusting corals, including *Goniastrea*, *Favia*, *Porites*, and *Pavona*. No signs of predation scars from crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails were observed at the sites surveyed.

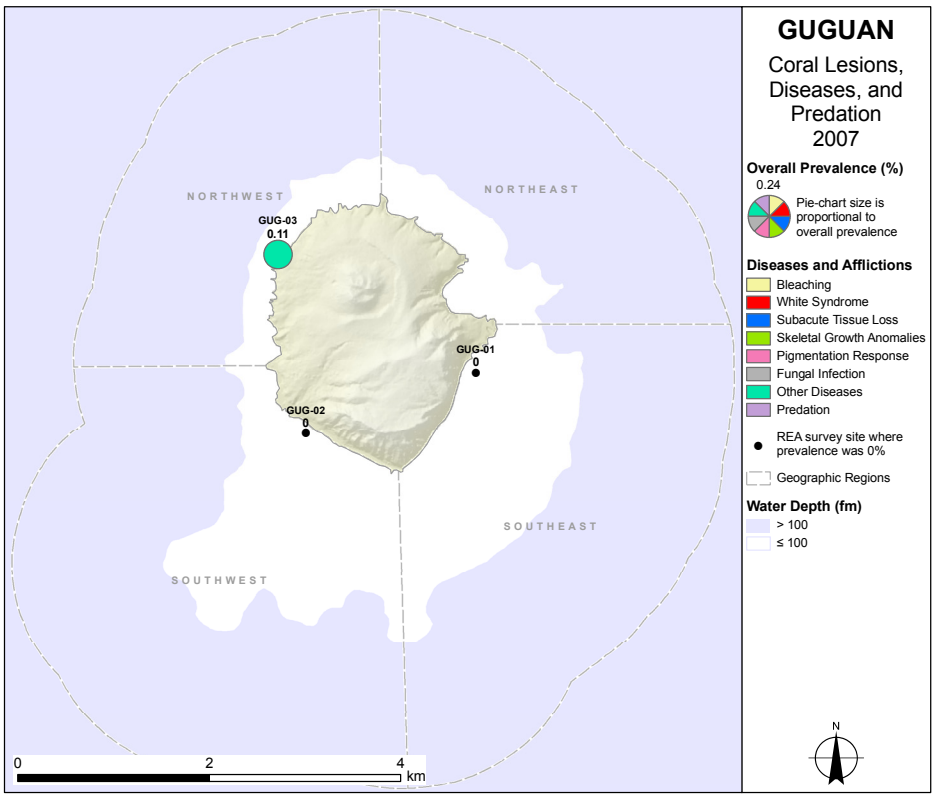


Figure 11.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Guguan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site.

11.6 Algae and Algal Disease

11.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Guguan was 45% (SE 2.3). Obsservations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 64%, within a range of 50.1%–75%, occurred in the northwest region (Fig. 11.6.1a, top left panel) over habitat predominantly of continuous reef and medium-high to high complexity. The second-highest mean macroalgal cover from a towed-diver survey was 59%, recorded in the northeast region. The survey with the lowest mean macroalgal cover of 26%, within a range of 10.1%–50%, occurred along the central part of the west coast of Guguan.

TOAD surveys completed at Guguan during MARAMP 2003 were conducted at depths of 40–270 m. Analyses of TOAD video footage obtained from 2 surveys in the southwest region suggested very few macroalgae in that area (Fig. 11.6.1a, top left panel). Macroalgae were more common in a third survey, which occurred also in the southwest region and between the other 2 surveys, with cover in a range of 20%–100%, at least as seen in a quarter of video frames.

From MARAMP 2005 towed-diver surveys, mean macroalgal cover on forereef habitats at Guguan was 10% (SE 3.4). As a result of a large, northwestern swell and 20-kt winds, only 3 towed-diver surveys were attempted, all in the southwest and northwest regions. Only 1 survey occurred in waters shallow enough to record benthic composition data for the majority of its survey segments. This survey ran along the central part of the west coast in both the northwest and southwest region, recording mean macroalgal cover of 3.1%, within a range of 0%–10% (Fig. 11.6.1a, middle left panel).

From MARAMP 2007 towed-diver surveys, mean macroalgal cover on forereef habitats around Guguan was 20% (SE 1.4). The survey with the highest mean macroalgal cover of 23%, within a range of 10.1%–40%, occurred in the southwest region over habitat of medium to medium-high complexity (Fig. 11.6.1a, bottom left panel). The lowest mean macroalgal cover from a towed-diver survey was 13.7%, recorded around the northern coast crossing the border between the northwest and northeast regions.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats at Guguan were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover from these surveys ranged from 0% to 8.8% with an overall mean of 4% (SE 2.6). The REA survey with the highest macroalgal cover occurred in the southwest region at REA site GUG-02 (Fig. 11.6.1b). No macroalgae were recorded in the northwest region at GUG-03.

Turf-algal cover from these REA benthic surveys in 2007 ranged from 51% to 80.4% with an overall mean of 62% (SE 9.4).The survey with the highest turf-algal cover occurred in the northwest region at GUG-03 (Fig. 11.6.1b). The lowest turf-algal cover was recorded in the southwest region at GUG-02.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Guguan was 17% (SE 1.3). The survey with the highest mean crustose-coralline-red-algal cover of 30%, within a range of 5.1%–40%, occurred in the northwest region (Fig. 11.6.1a, top right panel). The lowest mean cover of crustose coralline red algae from a towed-diver survey was 4.7%, within a range of 1.1%–20%, recorded around the southern coast crossing the border between the southeast and southwest regions.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats at Guguan was 15% (SE 4.4). The only towed-diver survey with observations from more than 5 segments was completed along the central part of the west coast with mean crustose coralline-red-algal cover of 2.5%, within a range of 1.1%–5% (Fig. 11.6.1a, middle right panel).

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Guguan was 13% (SE 1.1). The survey with the highest mean crustose-coralline-red-algal cover of 18.5%, within a range of 5.1%–40%, occurred around the northern coast crossing the border between the northwest and northeast regions

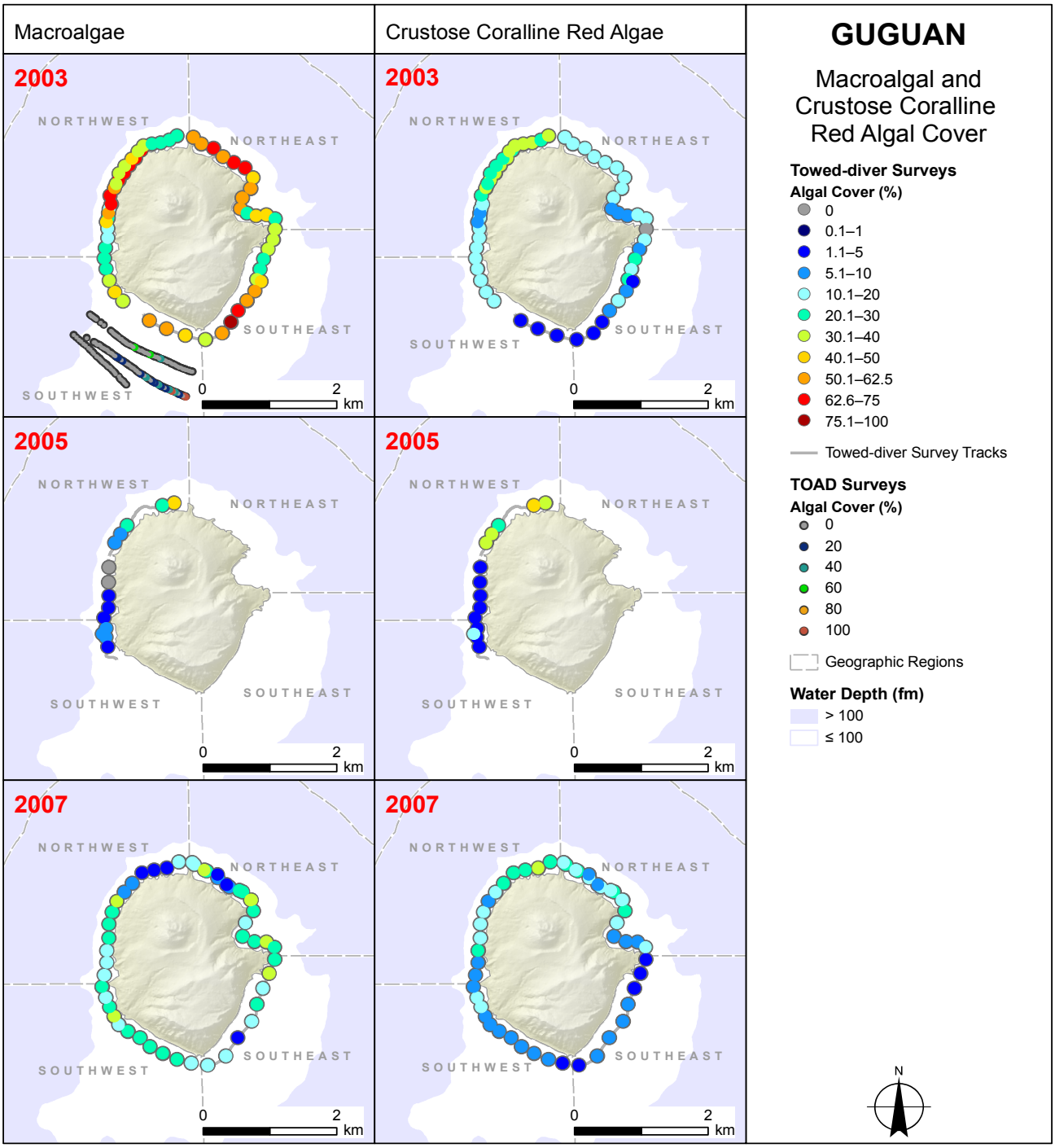


Figure 11.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Guguan during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

(Fig. 11.6.1a, bottom right panel). The lowest mean cover of crustose coralline red algae from a towed-diver survey was 6.2%, recorded in the southeast region.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats around Guguan were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 2.9% with an overall mean of 2% (SE 0.9). The REA survey with the highest crustose-coralline-red-algal cover occurred in the southeast region at GUG-01 (Fig. 11.6.1b). No crustose coralline red algae were recorded at GUG-03 in the northwest region.

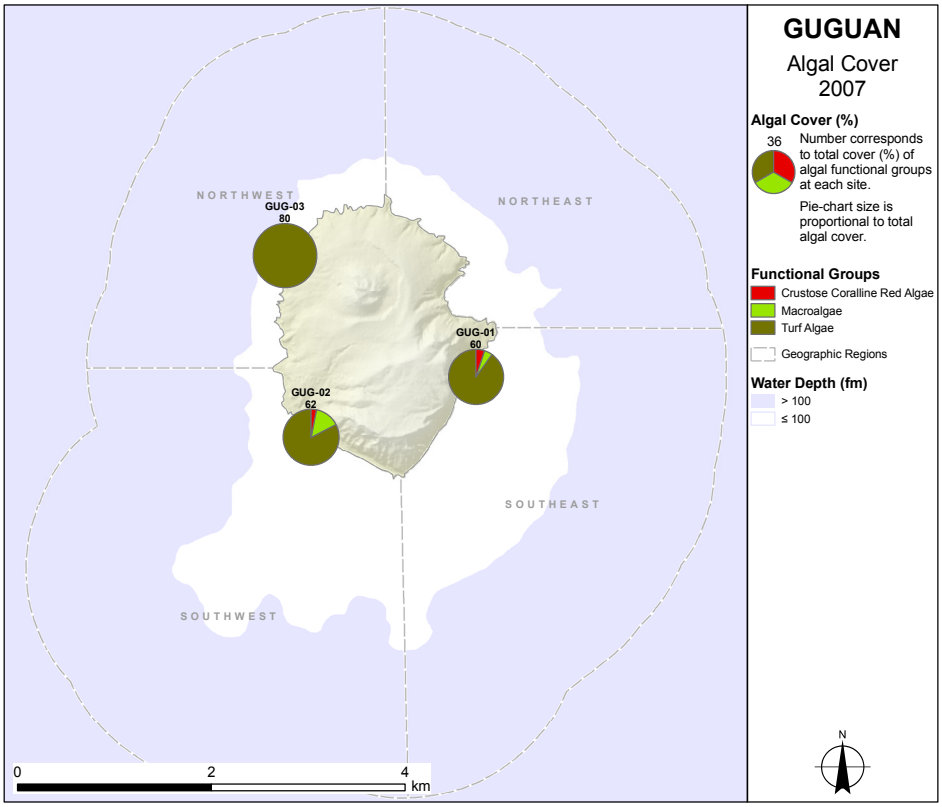


Figure 11.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method around Guguan during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, overall mean cover of macroalgal populations around Guguan, based on towed-diver surveys of forereef habitats, was higher in 2007 than in 2005 (Fig. 11.6.1c). Mean macroalgal cover ranged from 45% (SE 2.3) in 2003 to 10% (SE 3.4) in 2005 and 20% (SE 1.4) in 2007. When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Between survey years, no towed-diver-survey area consistently had the highest or lowest macroalgal cover. The highest macroalgal cover of 64% from a towed-diver survey in 2003 was recorded in the northwest region. Yet surveys in the same vicinity in 2005 and 2007 recorded much lower macroalgal cover with means of 3% and 20%; this decrease is likely a result of the inclusion of turf algae in 2003.

Islandwide estimates of crustose coralline red algae around Guguan, based on towed-diver surveys of forereef habitats, decreased slightly from MARAMP 2003 to 2007 (Fig. 11.6.1c). Mean cover varied from 17.1% (SE 1.3) in 2003 to 12.9% (SE 1.1) in 2007. For the 3 MARAMP survey years, the highest mean crustose-coralline-red-algal cover from a towed-diver survey occurred in the northwest region. In 2003 and 2007, the lowest mean crustose-coralline-red-algal cover occurred along the southern shoreline.

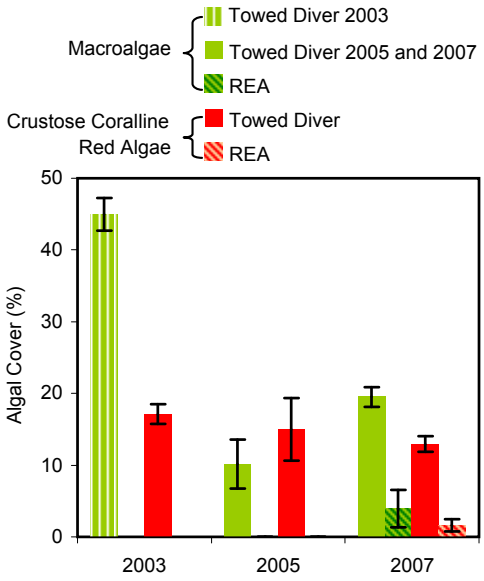


Figure 11.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Guguan during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys includes turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 3 sites on forereef habitats at Guguan. In the field, 9 macroalgal genera (1 red, 1 brown and 7 green), containing at least 9 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. GUG-03 in the northwest region had the highest macroalgal generic diversity with 6 genera, containing 6 species, documented in the field. The lowest macroalgal generic diversity was found in the southeast and southwest regions at GUG-01 and GUG-02, each with 3 species representing 3 genera recorded.

Species of the calcified, red algal genus *Amphiroa* were the most common component of macroalgal communities at Guguan in 2003, occurring in 27.8% of sampled photoquadrats. However, this overall average is misleading as the distribution of the genus *Amphiroa* was not uniform, occurring in 75% of sampled photoquadrats at GUG-02 in the southwest region but in only 8.3% and 0% of sampled photoquadrats at GUG-03 and GUG-01 in the northwest and southeast regions (Fig. 11.6.1d, top panel). Species of the calcified, green algal genus *Halimeda* were found in 13.9% of sampled photoquadrats overall, and in 16.7% and 25% of sampled photoquadrats at GUG-01 and GUG-03. The brown algal genus *Lobophora* was the only other algal genus recorded at more than 1 site at Guguan, although it was seen in only 8.3% of sampled photoquadrats. Of the 6 remaining macroalgal species tentatively identified in the field, most were observed at only 1 site and in low occurrence, making spatial patterns of distribution difficult to determine for most macroalgae at Guguan.

Turf algae and crustose coralline red algae were both exceptionally common in 2003, occurring in 97.2% and 77.8% of photoquadrats sampled at Guguan (Fig. 11.6.1d, top panel). Turf-algal communities were ubiquitous at all sites with site-specific occurrence values of 91.7%–100%. Crustose coralline red algae, occurring in 66.7%–100% of sampled photoquadrats, were found at all sites and were nearly as abundant as turf algae. Cyanobacteria, less common but still observed at all sites, were found in 38.9% of sampled photoquadrats.

During MARAMP 2005, REA benthic surveys were conducted at 1 site on forereef habitat at Guguan. In the field, 5 macroalgal genera (1 red, 3 green, and 1 brown), containing at least 5 species, as well as 2 additional algal functional groups—turf algae, and crustose coralline red algae—were observed.

Species of the green algal genus *Dictyosphaeria* were the most abundant macroalgae at Guguan in 2005, occurring in 33.3% of sampled photoquadrats. Species of the green algal genera *Caulerpa* and *Rhipidosiphon* were both common and each occurred in 25% of sampled photoquadrats. Species of the brown algal genus *Dictyota* also were notably abundant, occurring in 16.7% of sampled photoquadrats. Turf algae and crustose coralline red algae, both exceptionally common, were observed in 100% and 91.7% of sampled photoquadrats (Fig. 11.6.1d, middle panel).

During MARAMP 2007, REA benthic surveys were conducted at 3 sites on forereef habitats at Guguan. In the field, 14 macroalgal genera (5 red, 7 green, and 2 brown), containing at least 14 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. Algal diversity at Guguan was similar at all sites. At GUG-03 in the northwest region, 8 genera, containing 8 species, were documented in the field. At GUG-01 and GUG-02, in the southeast and southwest regions, 7 species representing 7 genera were recorded at each site.

The genera *Lobophora* and the calcified, red alga *Jania* were equally abundant at Guguan in 2007 (Fig. 11.6.1d, bottom panel), each occurring in 66.7% of sampled photoquadrats. Interestingly, both genera occurred in 100% of photoquadrats sampled at GUG-03 in the northwest region; however, *Lobophora* was twice as abundant as *Jania* at GUG-01 in the southeast region and, conversely, *Jania* was twice as abundant as *Lobophora* at GUG-02 in the southwest region. Species of the genera *Dictyota* and *Halimeda* were the only other algal species recorded at all 3 sites surveyed at Guguan. A fairly even distribution at Guguan was observed for these 2 genera, which were found in 10% and 56.7% of sampled photoquadrats. The red algal genera *Peyssonnelia* and *Portieria* each occurred in 33.3% of the photoquadrats sampled at GUG-01 and were not observed at other sites. Species of 3 additional genera were recorded only at GUG-02: *Amphiroa*, *Boodlea*, and

Tolypiocladia, occurring in 25%, 8.3%, and 8.3% of photoquadrats sampled at that site. Three more genera were recorded only at GUG-03: *Bryopsis, Tydemania*, and *Ventricaria* (now recognized as a species of *Valonia*), occurring in 16.7%, 16.7%, and 33.3% of sampled photoquadrats.

Turf algae, crustose coralline red algae, and cyanobacteria all were exceptionally common in 2007, occurring in 91.6%, 88.9%, and 55.6% of sampled photoquadrats at Guguan (Fig. 11.6.1d, bottom panel). These 3 functional groups were observed at all sites surveyed. Occurrence values for turf algae and crustose coralline algae were ≥ 83.3% at a given site and for cyanobacteria ranged from 50% to 66.7%.

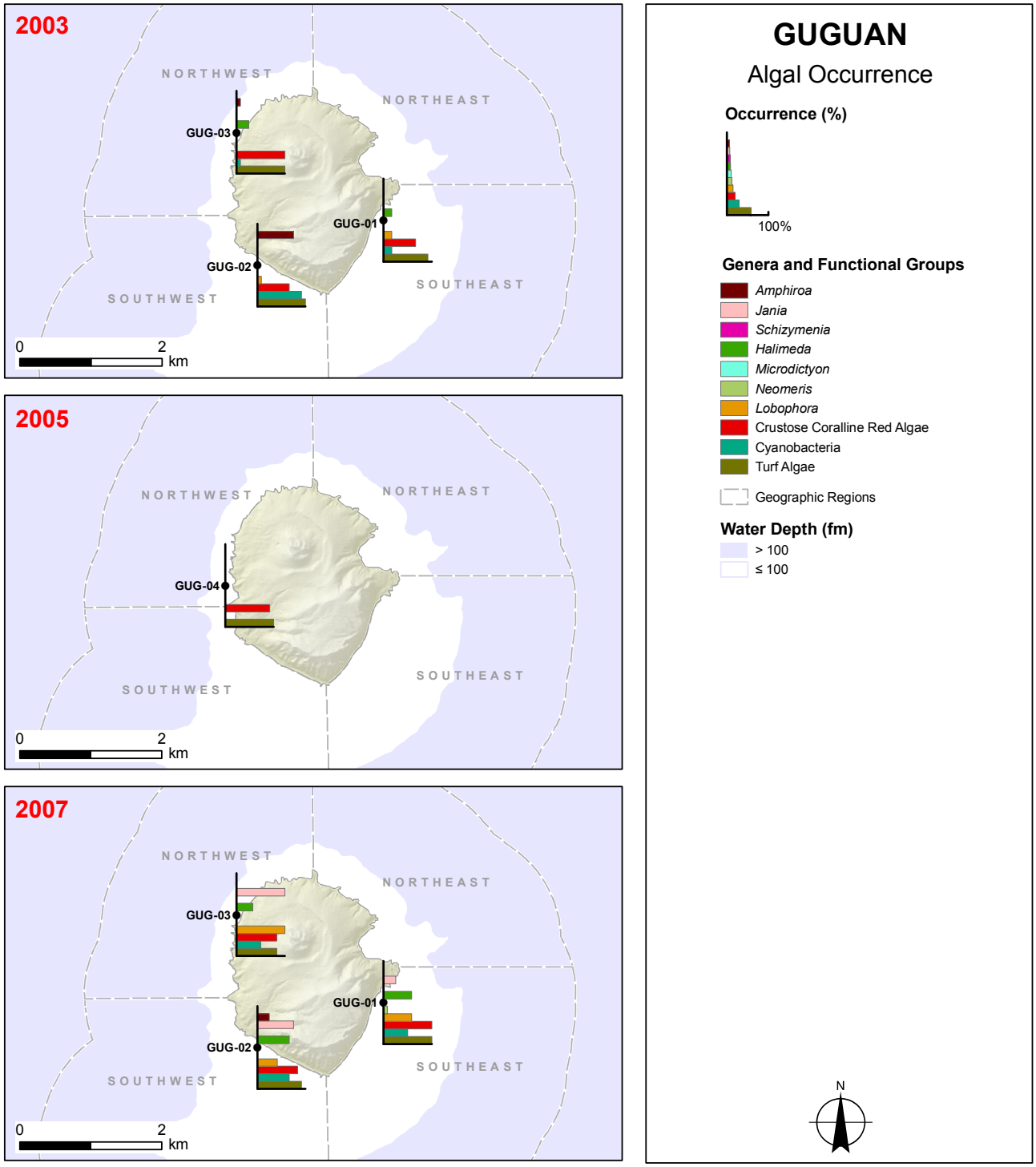


Figure 11.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Guguan during MARAMP 2003, 2005, and 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

The number of macroalgal genera recorded on forereef habitats at Guguan increased from 9 during MARAMP 2003 to 15 during MARAMP 2007. Only 6 genera that were present in 2003 were also recorded in 2007, and 8 genera observed in 2007 were not seen in 2003. Similarly, 3 genera that were recorded in 2003 were not observed in 2007. Differences in survey effort and other factors likely can account for this increase in estimated macroalgal diversity (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Only 5 distinct macroalgal genera were recorded in 2005, when only a single site was surveyed at Guguan.

The genera *Halimeda* and *Lobophora* were minor benthic components in 2003 but substantial components in 2007, occurring in 13.9% and 8.3% of photoquadrats sampled at Guguan in 2003 but in 56.7% and 60% of sampled photoquadrats in 2007 (Fig. 11.6.1e). Although *Lobophora* was not recorded at GUG-03 in the northwest region in 2003, this genus was found in every single photoquadrat at this same site in 2007. Similarly, the genus *Jania* was not recorded in 2003 or 2005, but this genus was observed in high abundance in 2007 when compared to results from earlier survey years, with site-specific occurrence values of 25%, 75%, and 100% at the 3 sites surveyed. Genera commonly encountered in low abundance during all survey years included *Bryopsis*, *Caulerpa*, *Dictyosphaeria*, and *Dictyota*. Four additional genera were commonly recorded in low abundance in 2007 only: *Peyssonnelia*, *Portiera, Tydemania*, and *Ventricaria (Valonia*). The genus *Amphiroa* was observed in 27.8% of photoquadrats sampled in 2003 at Guguan but in only 10% of sampled photoquadrats in 2007.

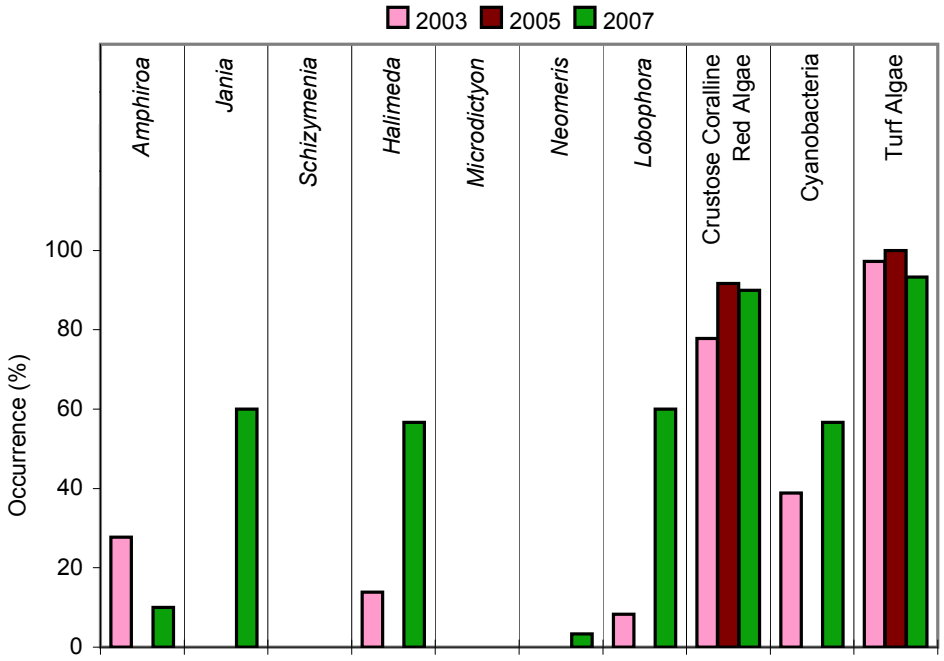


Figure 11.6.1e. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Guguan during MARAMP 2003, 2005 and 2007.

11.6.2 Coralline-algal-disease Surveys

During MARAMP 2007, REA coralline-algal-disease surveys were conducted in concert with coral-disease assessments at 3 sites on forereef habitats at Guguan. These surveys covered a total reef area of ~ 700 m^2 and detected only 1 case of coralline lethal orange disease. Disease was found only at GUG-03 in the northwest region (Fig. 11.6.2a).

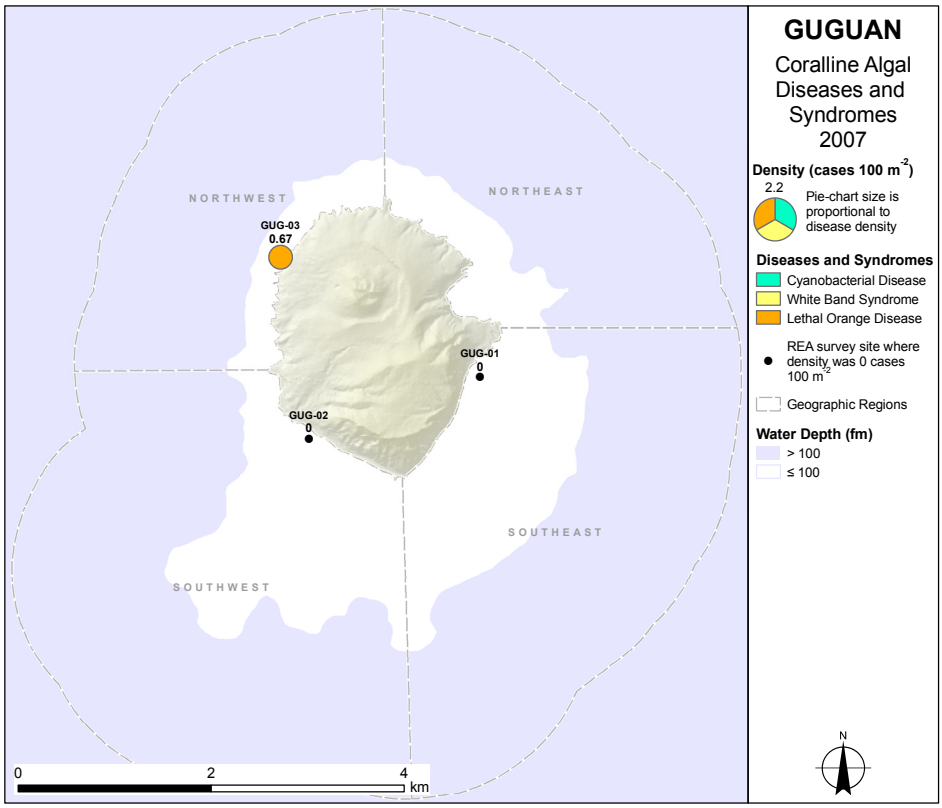


Figure 11.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats at Guguan during MARAMP 2007. The color-coded portions of the pie chart indicate disease-specific density.

11.7 Benthic Macroinvertebrates

11.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Guguan through benthic REA and towed-diver survey methods during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 3 REA surveys and 6 towed-diver benthic surveys were conducted. In 2005, because of weather constraints, only 1 REA survey and 2 towed-diver benthic surveys were conducted on the west coast of Guguan. In 2007, 2 REA surveys and 5 towed-diver benthic surveys were performed around Guguan. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, both REA and towed-diver surveys suggested low daytime macroinvertebrate abundance on forereef habitats around Guguan compared to the rest of the Mariana Archipelago. Minor fluctuations in observed densities between sampling periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density on forereef habitats around Guguan—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Fig. 11.7.1b, d, f, and h).

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at all 3 REA sites surveyed and in 5 of the 6 towed-diver surveys conducted around Guguan (Fig. 11.7.1a, top panel). The sample mean density of giant clams from REA surveys was 8.33 organisms 100 m^{-2} (SE 6.84), and the islandwide mean density from towed-diver surveys was 0.08 organisms 100 m^{-2} (SE 0.01). Survey results suggest giant clams were most abundant at REA site GUG-02 in the southwest region with 22 organism 100 m^{-2}. Among all towed-diver surveys around this island, the survey completed in the

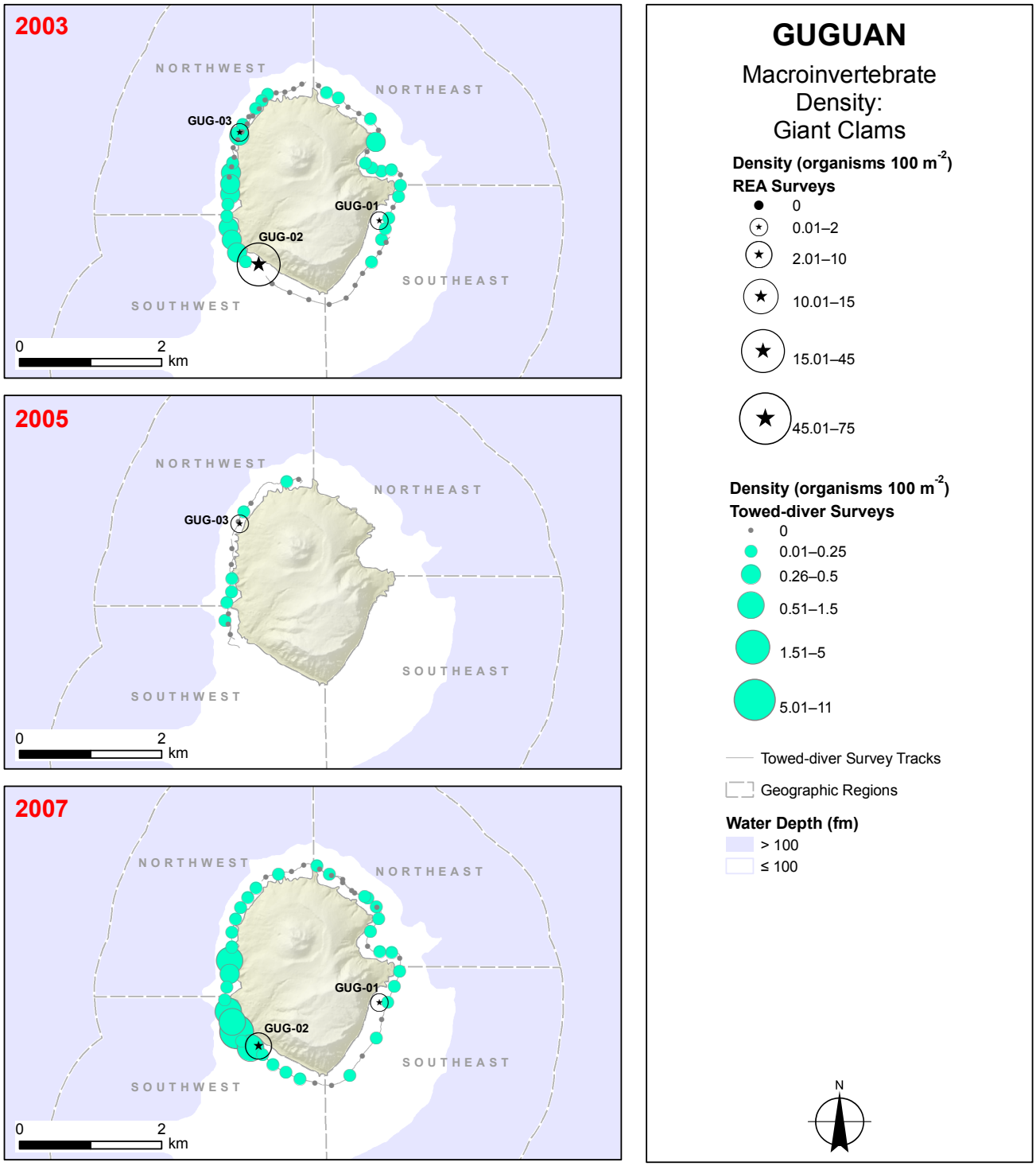


Figure 11.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Guguan during MARAMP 2003, 2005, and 2007.

southwest region had the highest mean density of giant clams with 0.29 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.48 organisms 100 m^{-2}. The second-greatest mean density of giant clams from towed-diver surveys was 0.06 organisms 100 m^{-2}, recorded along the eastern shore; segment densities ranged from 0 to 0.21 organisms 100 m^{-2}.

During MARAMP 2005, giant clams were observed at the 1 REA site that was surveyed and in all 3 towed-diver surveys conducted on the west coast of Guguan (Fig. 11.7.1a, middle panel). The giant clam density at GUG-03 was 1 organism 100 m^{-2}, and the overall mean density from towed-diver surveys was 0.04 organisms 100 m^{-2} (SE 0.01). Among all towed-diver surveys around this island, the survey completed in the northwest region had the highest mean density with 0.04 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.12 organisms 100 m^{-2}.

During MARAMP 2007, giant clams were observed at both of the REA sites surveyed and in all 5 towed-diver surveys conducted around Guguan (Fig. 11.7.1a, bottom panel). The sample mean density of giant clams from the 2 REA surveys was 1.67 organisms 100 m^{-2} (SE 1.33), and the islandwide mean density from towed-diver surveys was 0.16 organisms 100 m^{-2} (SE 0.05). Survey results suggest giant clams were most abundant at GUG-02 in the southwest region with 3 organisms 100 m^{-2}. Among all towed-diver surveys around this island, the survey completed in the southwest region had the highest mean density of giant clams with 0.5 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.47 organisms 100 m^{-2}. The towed-diver survey along the western shore had the second-greatest mean density with 0.16 organisms 100 m^{-2}; segment densities for this survey ranged from 0.47 to 0.69 organisms 100 m^{-2}.

During MARAMP 2003 and 2007, the highest densities of giant clams from towed-diver surveys were recorded along the west coast of Guguan. The overall observed mean density of giant clams at Guguan was higher in 2003 and 2007 than in 2005 (Fig. 11.7.1b). Minor fluctuations in density are not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

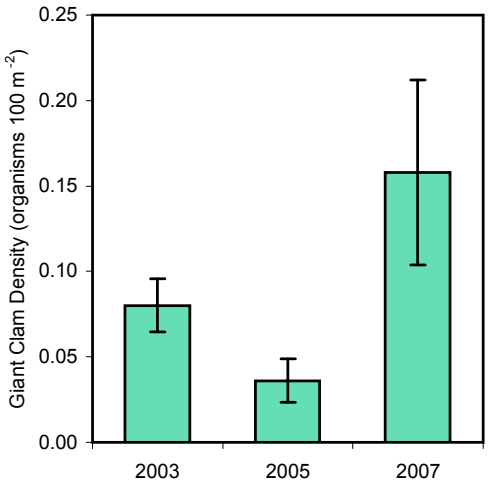


Figure 11.7.1b. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Guguan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Crown-of-thorns Seastars

During MARAMP 2003, no crown-of-thorns seastars (*Acanthaster planci*) were observed at the 3 REA sites surveyed at Guguan, and just 1 of the 6 towed-diver surveys had recordings of COTS (Fig. 11.7.1c, top panel). This towed-diver survey was completed along the eastern shore and had a mean COTS density of 0.001 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.06 organisms 100 m^{-2}.

During MARAMP 2005, no COTS were observed at the 1 REA site surveyed at Guguan, but both towed-diver surveys had recordings of COTS with an overall mean density of 0.04 organisms 100 m^{-2} (Fig. 11.7.1c, middle panel). The towed-diver survey conducted in the northwest region had the highest mean COTS density with 0.07 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.25 organisms 100 m^{-2}.

During MARAMP 2007, no COTS were observed at the 2 REA sites surveyed or in the 5 towed-diver surveys conducted around Guguan (Fig. 11.7.1c, bottom panel).

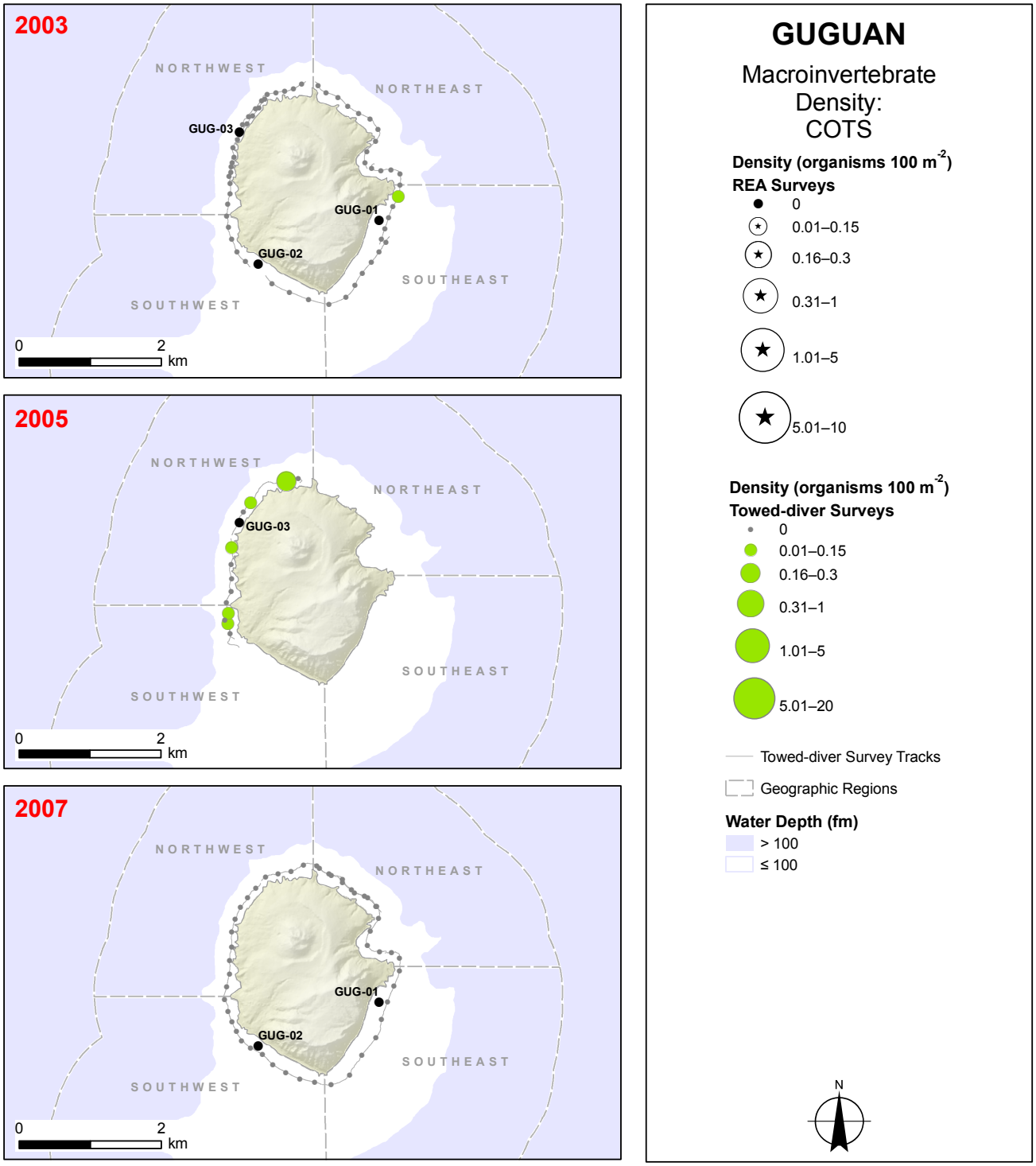


Figure 11.7.1c. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Guguan during MARAMP 2003, 2005, and 2007.

During the 3 MARAMP survey years, few observations of COTS were made during towed-diver benthic surveys conducted around Guguan (Fig. 11.7.1d). Despite the limited number of towed-diver surveys conducted in 2005, COTS densities were greater in 2005 than in 2003 and 2007. This variation in COTS density is not necessarily indicative of changes in the population structure of COTS (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). COTS density naturally fluctuates with food availability and successful recruitment events (Birkeland and Lucas 1990; Fabricius et al. 2010; and Yamaguchi 1987).

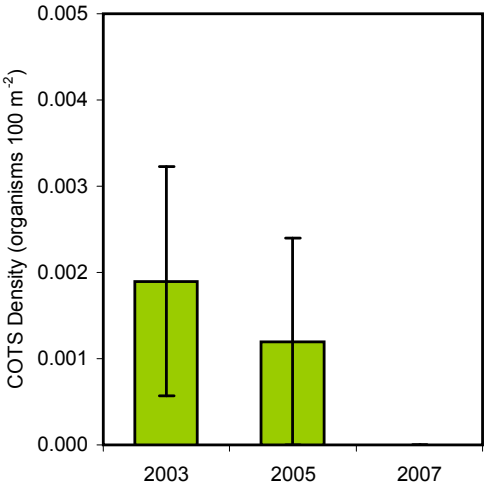


Figure 11.7.1d. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Guguan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Cucumbers

During MARAMP 2003, no sea cucumbers were observed at the 3 REA sites surveyed at Guguan, but 5 of the 6 towed-diver surveys had recordings of sea cucumbers (Fig. 11.7.1e, top panel) with an islandwide mean density of 0.04 organisms 100 m^{-2} (SE 0.01). Among all towed-diver surveys around this island, the survey completed in the southwest region had the highest mean density of sea cucumbers with 0.12 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.55 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.03 organisms 100 m^{-2}, recorded in the northeast region; segment densities ranged from 0 to 0.58 organisms 100 m^{-2}.

During MARAMP 2005, no sea cucumbers were observed at the 1 REA site surveyed at Guguan, and only 1 of the 2 towed-diver surveys conducted had recordings of sea cucumbers (Fig. 11.7.1e, middle panel). The mean density of sea cucumbers from this survey was 0.01 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.07 organisms 100 m^{-2}.

During MARAMP 2007, sea cucumbers were observed at 1 of the 2 REA sites surveyed and in all 5 towed-diver surveys conducted around Guguan (Fig. 11.7.1e, bottom panel). GUG-01 had a density of sea cucumbers of 0.33 organisms 100 m^{-2}, which consisted entirely of species of the genus *Actinopyga.* The islandwide mean density of sea cucumbers from towed-diver surveys was 0.06 organisms 100 m^{-2} (SE 0.01). Among all towed-diver surveys around this island, the survey completed along the western shoreline had the highest mean density of sea cucumbers with 0.17 organisms 100 m^{-2}; segment densities ranged from 0 to 0.58 organisms 100 m^{-2}.

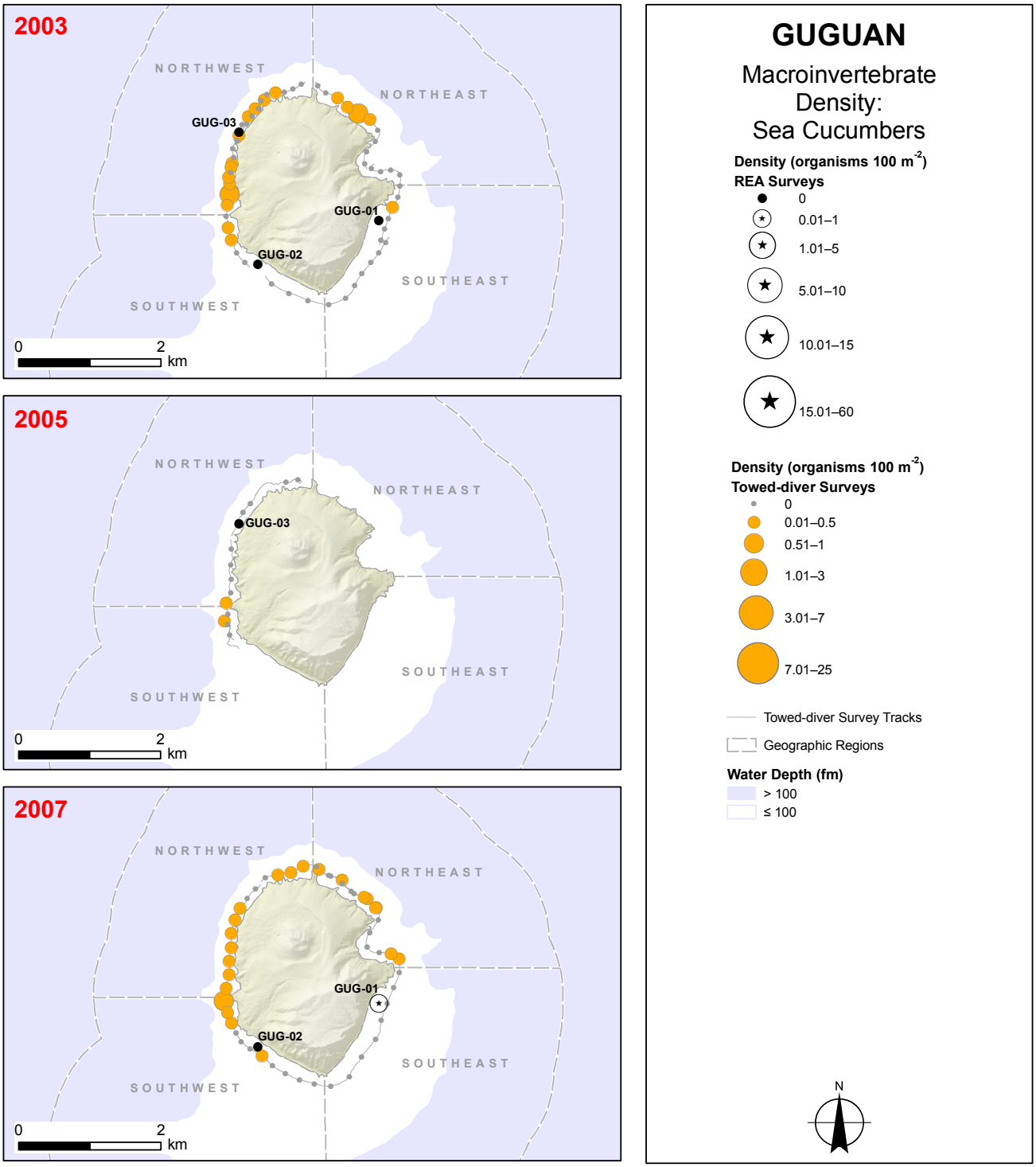


Figure 11.7.1e. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Guguan during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggested low daytime abundance of sea cucumbers around Guguan during MARAMP 2003, 2005, and 2007, relative to the rest of the Mariana Archipelago (Fig. 11.7.1f). Fluctuations in observed densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

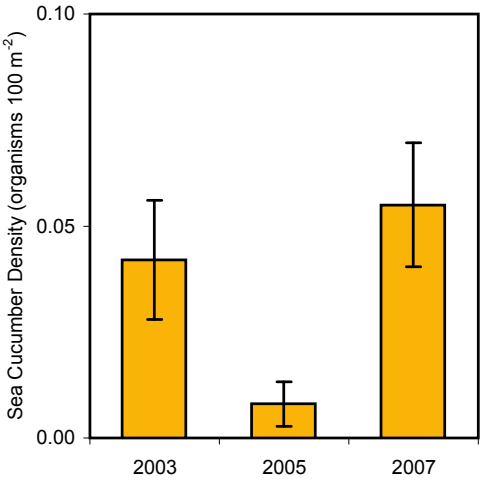


Figure 11.7.1f. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Guguan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean

Sea Urchins

During MARAMP 2003, sea urchins were observed at all 3 REA sites surveyed and in 4 of the 6 towed-diver surveys conducted around Guguan (Fig. 11.7.1g, top panel). The sample mean density for REA surveys was 68 organisms 100 m^{-2} (SE 15.39), and the islandwide mean density of sea urchins from towed-diver surveys was 0.08 organisms 100 m^{-2} (SE 0.04). Survey results suggest that sea cucumbers were most abundant at GUG-02 in the southwest region with a mean density of sea urchins of 98 organisms 100 m^{-2}, and 96% of the species of sea urchins recorded at this site were rock-boring urchins from the genus *Echinostrephus*. Other genera observed at GUG-02 were *Echinometra* and *Echinothrix.* GUG-03 had the second-greatest density with 59 organisms 100 m^{-2}; of the sea urchin species recorded at this site, 69% were of the genus *Diadema,* and the remaining species were of the genus *Echinothrix.*

Among all towed-diver surveys conducted around Guguan in 2003, the survey completed around the eastern point of this island had the highest mean density of sea urchins at 0.38 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.34 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 0.06 organisms 100 m^{-2}, recorded along the center of the west coast; segment densities ranged from 0 to 0.35 organisms 100 m^{-2}.

During MARAMP 2005, no sea urchins were observed at the 1 REA site surveyed or in the 3 towed-diver surveys conducted along the west coast of Guguan (Fig. 11.7.1g, bottom panel).

During MARAMP 2007, sea urchins were observed at both REA sites surveyed and in all 5 towed-diver surveys conducted around Guguan (Fig. 11.7.1g, bottom panel). The sample mean density from REA surveys was 8.67 organisms 100 m^{-2} (SE 3.33), and the islandwide mean density of sea urchins from towed-diver surveys was 2.71 organisms 100 m^{-2} (SE 0.72). GUG-01 had the highest density of sea urchins with 12 organisms 100 m^{-2}, which consisted entirely of species of the genus *Echinostrephus*.

Among all towed-diver surveys conducted around Guguan in 2007, the survey completed in the southeast region had the highest mean density of sea urchins at 8.66 organisms 100 m^{-2}; segment densities from this survey ranged from 0.49 to 23.05 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 2.48 organisms 100 m^{-2}, recorded along the northern shoreline; segment densities ranged from 0 to 16.98 organisms 100 m^{-2}.

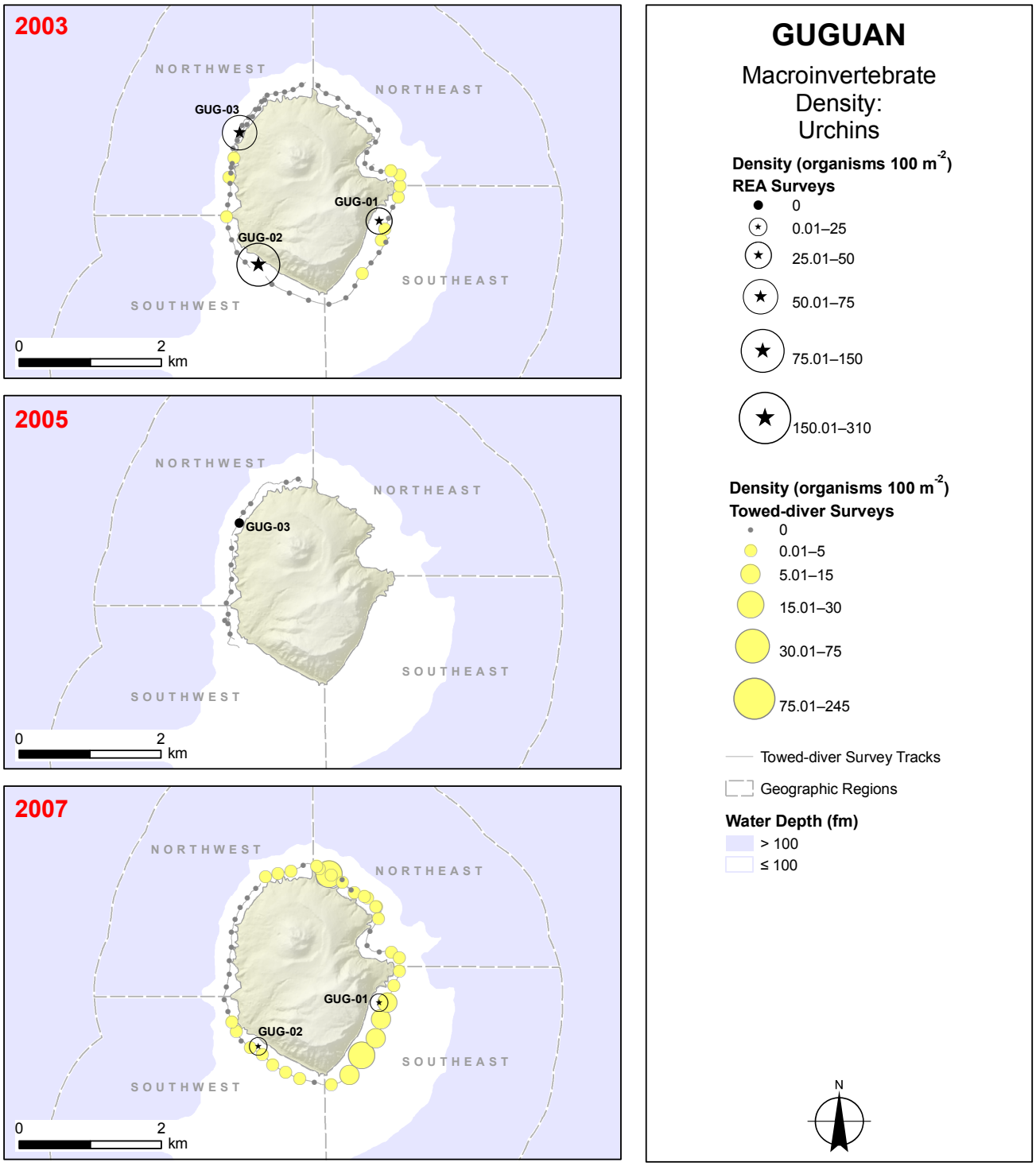


Figure 11.7.1g. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Guguan during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggested low daytime abundance of sea urchins around Guguan during MARAMP 2003, 2005, and 2007, compared to the rest of the Mariana Archipelago, with density values higher in 2007 than in 2003 (Fig. 11.7.1h). Fluctuations in densities between MARAMP years are not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

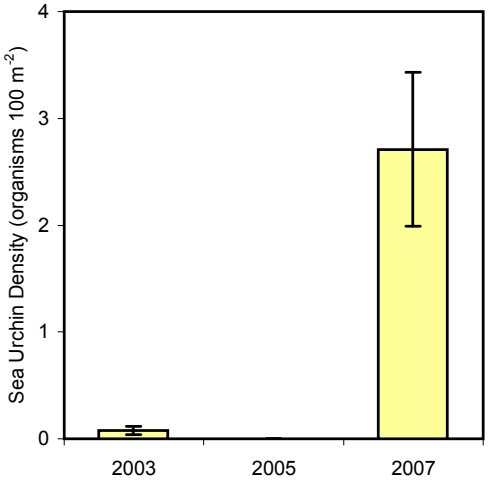


Figure 11.7.1h. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Guguan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

11.8 Reef Fishes

11.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 6 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Guguan. The overall estimated mean biomass of large fishes, calculated as weight per unit area, was 0. 56 kg 100 m^{-2} (SE 0.12), a low value compared to other survey areas in the Mariana Archipelago. Biomass values for large fishes were highest in the northwest region, where reef sharks (Carcharhinidae), nurse sharks (Ginglymostomatidae), and snappers (Lutjanidae) were common (Fig. 11.8.1a, top panel). Snappers and sharks together accounted for the greatest proportion (68%) or 0.38 kg 100 m^{-2} of islandwide mean large-fish biomass. Snappers alone contributed 45% of overall mean biomass of large fishes, and the twinspot snapper (*Lutjanus bohar*) and the black and white snapper (*Macolor niger*) were the dominant snapper species by biomass, accounting for 0.15 kg 100 m^{-2} and 0.07 kg 100 m^{-2} of islandwide mean large-fish biomass. The whitetip reef shark (*Triaenodon obesus*) was the major shark species in terms of biomass, contributing 0.07 kg 100 m^{-2} of overall mean large-fish biomass. During this survey period, 8 sharks were observed: 6 whitetip reef sharks, 1 grey reef shark (*Carcharhinus amblyrhynchos*), and 1 tawny nurse shark (*Nebrius ferrugineus*).

During MARAMP 2005, 3 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats at Guguan. Because of weather constraints, surveys were limited to the west side of this island. The overall mean biomass of large fishes was 0.61 kg 100 m^{-2} (SE 0.31), a value similar to the biomass recorded in 2003. Biomass values for large fishes were highest along the center of the west coast, where sharks contributed a majority of overall mean large-fish biomass (Fig. 11.8.1a, middle panel). Nurse sharks and reef sharks contributed 65% of overall mean biomass of large fishes. The tawny nurse shark alone contributed 50% of overall large-fish biomass. During this survey period, 6 sharks were observed: 3 grey reef sharks, 2 whitetip reef sharks, and 1 large (225 cm in TL) tawny nurse shark. Jacks (Carangidae) composed the family with the second-highest biomass, contributing 9% of overall large-fish biomass.

During MARAMP 2007, 5 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Guguan. The overall mean biomass of large fishes was 0.31 kg 100 m^{-2} (SE 0.12), lower than estimates made in 2003 and 2005. Biomass values for large fishes were distributed fairly evenly around this island; however, they were highest in the southern end of the northeast region where sharks and snappers were common (Fig. 11.8.1a, bottom panel). Reef sharks and snappers together accounted for the greatest proportion (69%) or 0.21 kg 100 m^{-2} of the overall mean biomass of large fishes. The grey reef shark was the shark species with the highest biomass, contributing 0.05 kg 100 m^{-2} of overall large-fish biomass. Parrotfishes (Scaridae) also were commonly observed and accounted for 14% of overall large-fish biomass, and the redlip parrotfish (*Scarus rubroviolaceus*) was the major biomass contributor. During this survey period, 11 sharks were observed: 6 whitetip reef sharks, 4 grey reef sharks, and 1 blacktip reef shark (*Carcharhinus melanopterus*).

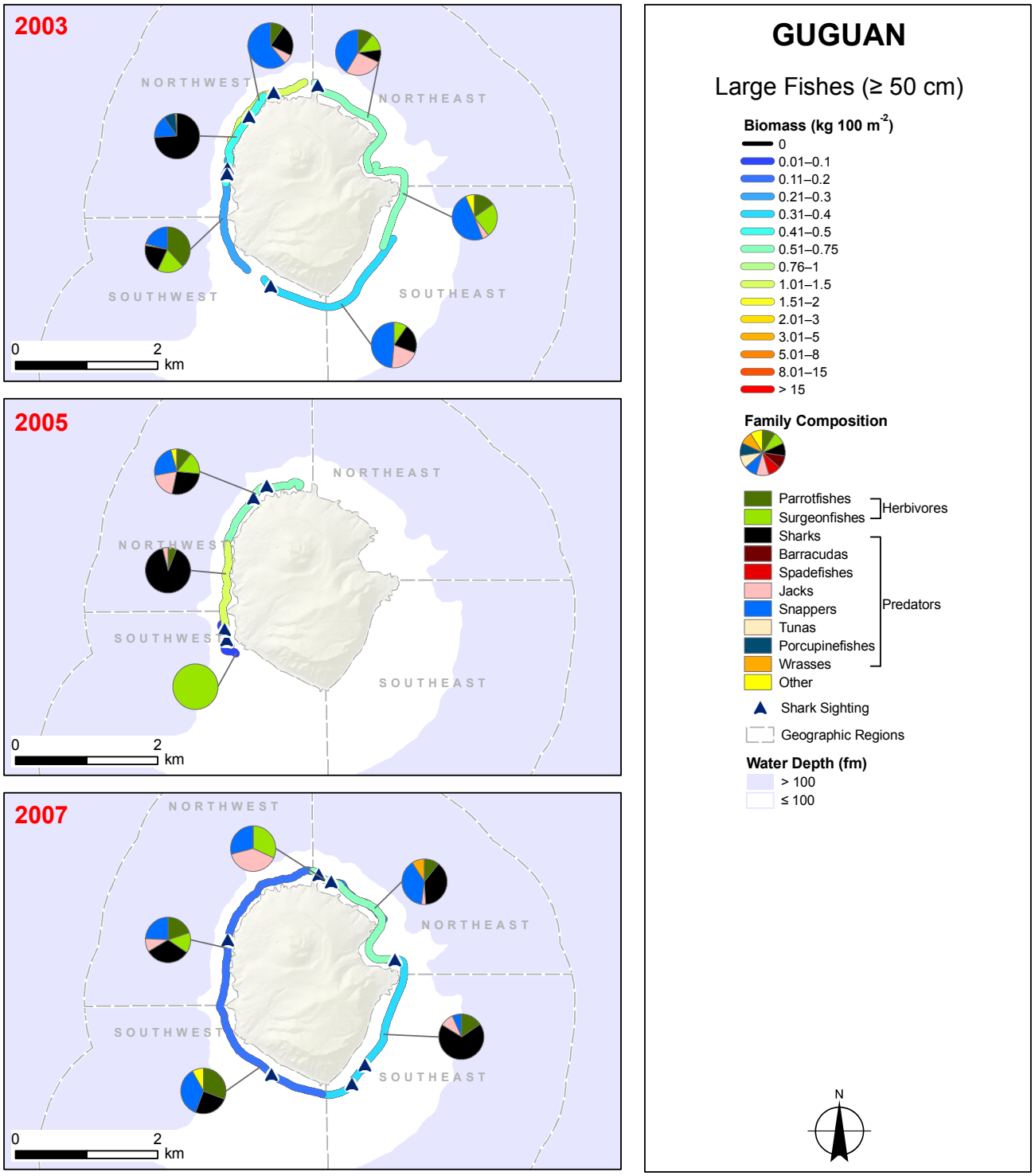


Figure 11.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Guguan during MARAMP 2003, 2005, and 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside the survey area over which it is shown.

Overall mean biomass of large fishes from towed-diver surveys of forereef habitats was moderate for the 3 MARAMP survey years, compared to results from other islands of the Mariana Archipelago. Large-fish biomass values were slightly lower in 2007, with an overall mean of 0.31 kg 100 m^{-2} (SE 0.12), than in 2003 (Fig. 11.8.1b) with an overall mean of 0.56 kg 100 m^{-2} (SE 0.12). Sharks consistently contributed large proportions to overall large-fish biomass during the 3 MARAMP survey periods. Snappers were common during surveys conducted in 2003 and 2007, and the twinspot snapper and the black and white snapper were the species that contributed the greatest proportion of snapper biomass. Notable

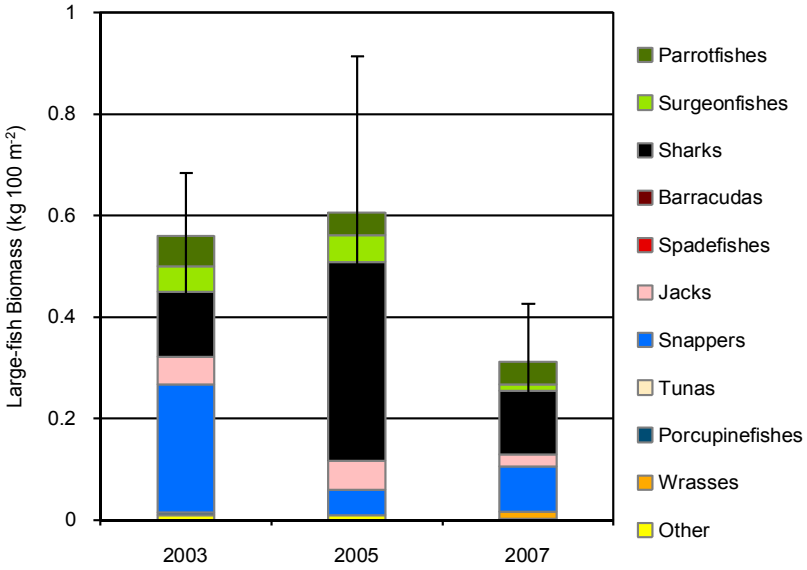


Figure 11.8.1b. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Guguan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

observations around Guguan included a single sighting of the humphead wrasse (*Cheilinus undulatus*) in 2007 and sightings of giant trevally (*Caranx ignobilis*) in 2005 and 2007.

Total Fish Biomass and Species Richness

Total fish biomass for the 3 REA sites surveyed at Guguan during MARAMP 2003 was high, compared to other sites in the Mariana Archipelago, with an overall sample mean of 16.72 kg 100 m^{-2} (SE 1.43). The highest biomass of 19.18 kg 100 m^{-2} was observed in the southwest region at GUG-02, where 2 whitetip reef sharks were recorded (Fig. 11.8.1c, top panel). Surgeonfishes accounted for the largest proportion (24%) or 3.86 kg 100 m^{-2} of total fish biomass at Guguan. The whitecheek surgeonfish (*Acanthurus nigricans*) was the dominant surgeonfish species by biomass, contributing 29% of surgeonfish biomass. The whitetip reef shark was the only shark species observed in 2003, accounting for 2.34 kg 100 m^{-2} of total fish biomass.

Based on REA surveys conducted during MARAMP 2003, species richness at Guguan was fairly consistent among the 3 sites surveyed with a range of 46–53 species 100 m^{-2}. The highest diversity was observed at GUG-03 in the northwest region (Fig. 11.8.1c, top panel). Wrasses (Labridae) and surgeonfishes composed the 2 most represented families with 18 and 15 species recorded. The ornate wrasse (*Halichoeres ornatissimus*) was the most abundant wrasse species, while the orangespine unicornfish (*Naso lituratus*) was the most abundant surgeonfish species. A recent large recruitment of the orangespine surgeonfish contributed to its dominance of counts with more than 150 individuals 100 m^{-2} observed. Damselfishes (Pomacentridae) also were abundant, and Vanderbilt's chromis (*Chromis vanderbilti*) was the most common damselfish with 41 individuals 100 m^{-2} recorded.

Total fish biomass for the 2 REA sites surveyed in forereef habitats at Guguan during MARAMP 2005 was high, compared to other sites in the Mariana Archipelago, with a sample mean of 18.18 kg 100 m^{-2} (SE 1.33). The highest biomass of 19.51 kg 100 m^{-2} was observed in the northwest region at GUG-03 (Fig. 11.8.1c, middle panel). Surgeonfishes accounted for the largest proportion (45%) or 8.16 kg 100 m^{-2} of the total fish biomass. The whitecheek surgeonfish and striated surgeonfish (*Ctenochaetus striatus*) were the 2 main surgeonfish species by biomass, contributing 38% and 24% of surgeonfish biomass. During this survey period, 2 sharks were observed: 1 whitetip reef shark and 1 tawny nurse shark.

Based on REA surveys conducted during MARAMP 2005, species richness at Guguan was moderate at both surveyed sites with 37 and 39 species 100 m^{-2} (Fig. 11.8.1c, bottom panel). Similar to observations made in 2003, wrasses and surgeonfishes composed the 2 most represented families with 19 and 15 species recorded. The ornate wrasse was the most abundant wrasse species with 7 individuals 100 m^{-2} observed, and the whitebar surgeonfish (*Acanthurus leucopareius*) was the most abundant surgeonfish species with 22 individuals 100 m^{-2} recorded. Damselfishes dominated counts and made up the most abundant taxon overall, and the midget chromis (*Chromis acares*) was the most abundant damselfish species with 57 individuals 100 m^{-2} recorded.

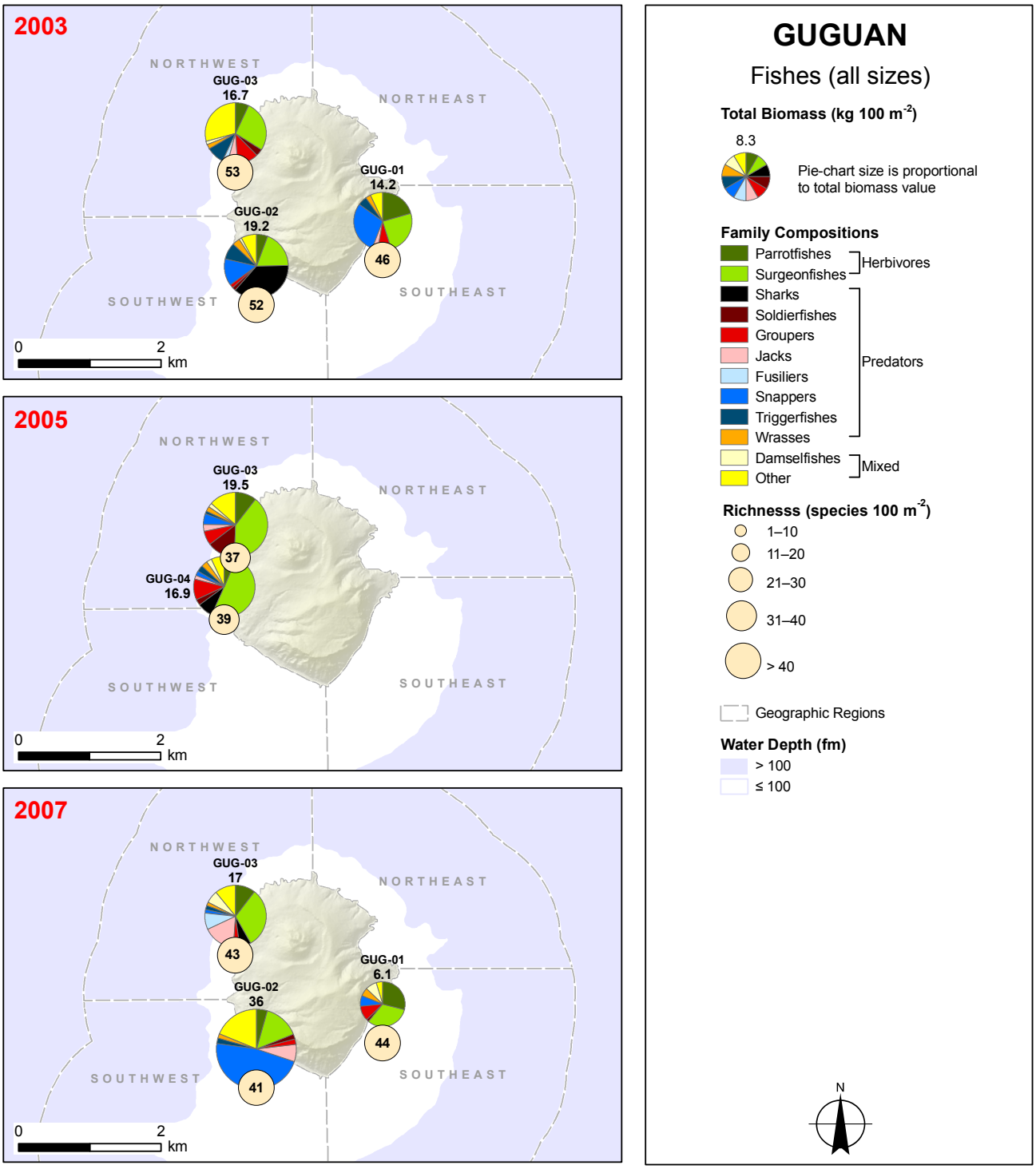


Figure 11.8.1c. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Guguan during MARAMP 2003, 2005, and 2007.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Guguan during MARAMP 2007 was high, compared to other sites in the Mariana Archipelago, with an overall sample mean of 19.70 kg 100 m^{-2} (SE 8.73). The highest biomass of 35.98 kg 100 m^{-2} was observed in the southwest region at GUG-02, where snappers were common (Fig. 11.8.1c, bottom panel). Snappers and surgeonfishes accounted for 30% and 21% of total fish biomass. The twinspot snapper was the major snapper species by biomass at 4.94 kg 100 m^{-2}. The whitecheek surgeonfish was the dominant surgeonfish species by biomass, accounting for 32% to the total surgeonfish biomass.

Based on REA surveys conducted during MARAMP 2007, species richness at Guguan was moderate and consistent among the 3 sites surveyed with a range of 41–44 species 100 m^{-2}. Similar to observations made in 2003 and 2005, wrasses and surgeonfishes composed the 2 most represented families with 23 and 15 species recorded. The ornate wrasse was the most abundant wrasse species, while the whitecheek surgeonfish was the most abundant surgeonfish species. Damselfishes again composed the most abundant taxon overall, and the midget chromis dominated counts with 240 individuals 100 m^{-2} observed.

No persistent spatial patterns were observed for total fish biomass at Guguan during the 3 MARAMP survey periods. However, GUG-02 in the southwest region had the highest mean total fish biomass for surveys conducted in 2003 and 2007 (this site was not surveyed in 2005 because of weather constraints). Compared to estimates made for the rest of the Mariana Archipelago, overall estimates of total fish biomass for Guguan were among the highest levels found. Total fish biomass was consistent between MARAMP survey years (Fig. 11.8.1d) with an overall sample mean of 18.20 kg 100 m^{-2} (SE 0.86) across the 3 survey periods. Surgeonfishes were abundant and accounted for large portions of total fish biomass in each survey year. The orangespine unicornfish, the whitecheek surgeonfish, and the striated surgeonfish contributed the largest proportions of surgeonfish biomass.

Guguan had the highest overall levels of species richness found in the Mariana Archipelago, with a range of 37–53 species 100 m^{-2} over the 3 MARAMP survey years. No clear, consistent spatial patterns were observed for species richness. Wrasses and surgeonfishes composed the 2 most represented families with an average of 21 and 15 species recorded. Damselfishes were abundant, and the midget chromis and Vanderbilt's chromis dominated damselfish counts.

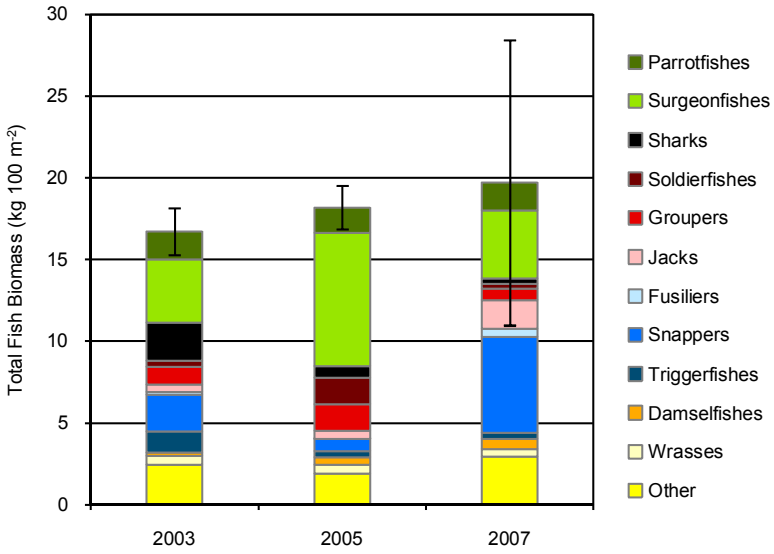


Figure 11.8.1d. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Guguan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

11.9 Marine Debris

11.9.1 Marine Debris Surveys

During MARAMP 2003, 2005, and 2007, no marine debris was recorded in the towed-diver surveys of forereef habitats conducted around Guguan.

11.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Guguan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparison," including archipelago-wide reef condition indices with ranks for Guguan as well as the other 13 islands covered in this report.

Located in the center of the Mariana Arc, Guguan is characterized by a low elevation and less steep slopes, relative to the topography seen at its neighbor islands. This island consists of 2 volcanoes, with a plain that gently slopes down to the shoreline, except in the south where steep, unstable cliffs are found. The topography created by the presence of the 2 volcanoes naturally delineates the northern and southern submarine seascapes (see Figure 11.3.1b in Section 11.3.1: "Acoustic Mapping"), as well as all that lies between them (Fig. 11.10a).

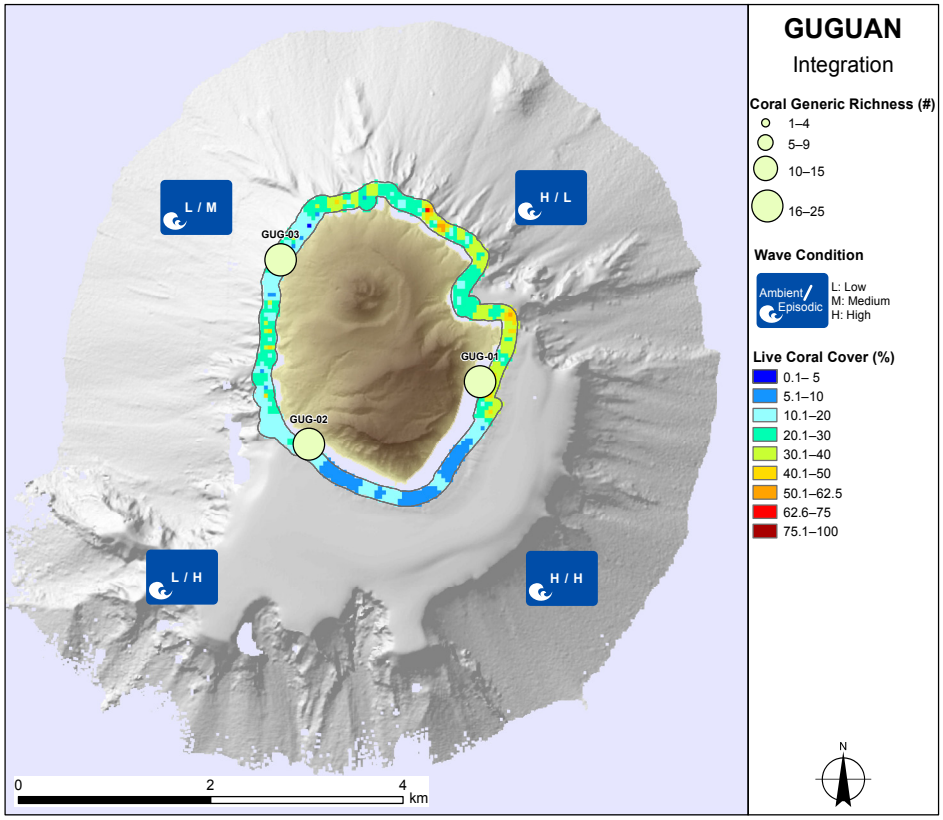


Figure 11.10a. Cover (%) observations of live hard corals from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Guguan during MARAMP 2003, 2005, and 2007. Values of coral cover represent interpolated values from the 3 survey years, and values of coral generic richness represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region. Underlying these data in grey scale is the hillshade bathymetry.

The area north of Guguan is marked by steep submarine slopes (see Figure 11.3.1c in Section 11.3.1: "Acoustic Mapping") with hard substrate of moderate to high complexity (see Figure 11.3.3a in Section 11.3.3: "Habitat Characterization"). The habitat there has a mixture of pavement and spur-and-groove reef with patches of boulders strewn throughout. This area generally supported the highest cover estimates from towed-divers surveys for live hard corals and crustose coralline red algae of all areas surveyed around Guguan, and REA site GUG-03, in the northwest region, had the highest macroalgal diversity recorded during REA surveys across the 3 MARAMP survey years (Fig. 11.10a).

The seascape to the east of Guguan changed drastically from the north to the south. The northeast region was characterized as high-relief, spur-and-groove reef with sections of nearly vertical walls and overall high complexity (see Figure 11.3.3a in Section 11.3.3: "Habitat Characterization"). During a towed-diver survey exiting the eastern-facing bay and heading south, habitat was characterized as continuous reef of medium complexity and farther south transitioned to boulders and sand (Fig. 11.3.3a). Towed-diver surveys conducted on the eastern reefs of Guguan reported high values (up to 50%) of live coral cover in 2003 and moderate values in 2007 (see Figure 11.5.1a in Section 11.5.1: "Coral Surveys"). Furthermore, among all REA sites surveyed in 2007, GUG-01 had the highest levels of coral cover, density, and generic richness (Figs. 11.5.1b and e).



Figure 11.10b. Reef habitat off northern Guguan. *NOAA photo by Robert Schroeder*

South of Guguan, 2 submarine terraces extend ~ 2 km out from the shoreline (see Figure 11.3.1b in Section 11.3.1: "Acoustic Mapping"). A shallow shelf at depths of 25–50 m gives way to a deeper shelf that slopes to depths of 80–130 m. These shelves are fringed by the steepest sloping bathymetry surrounding Guguan, with slopes > 50° (Fig. 11.3.1c). The terraces were characterized as predominantly large sand flats with sections of patch reef and boulders, and towed-diver surveys conducted there generally reported the lowest cover values for live hard corals and crustose coralline red algae, compared to survey results from other areas surveyed at Guguan.

Habitat west of Guguan was characterized as spur-and-groove reef of medium-high complexity (see Figure 11.3.3a in Section 11.3.3: "Habitat Characterization") with the occurrence of vertical walls increasingly common toward the northwest. Compared to other survey areas at Guguan, western reefs supported high values of live coral cover (up to 62.5%) recorded



Figure 11.10c. Reef habitat off northern Guguan. *NOAA photo by Robert Schroeder*

during towed-diver surveys conducted in 2003, but coral cover there was lower in subsequent years (see Figure 11.5.1a in Section 11.5.1: "Coral Surveys"). The highest densities of giant clams at Guguan in 2003 and 2007 were found in the southwest region during towed-diver and REA surveys (Fig. 11.10c; also see Figure 11.7.1a in Section 11.7.1: Benthic Macroinvertebrate Surveys").

Fish biomass was moderately high at Guguan in comparison to the levels observed at other islands of the Mariana Archipelago. Relative to other northern islands, overall mean biomass of large fishes (≥ 50 cm in TL) was low for the 3 MARAMP survey years, although sharks were observed during each survey period (see Figure 11.8.1b in Section 11.8.1: "Reef Fish Surveys"). In contrast, total fish biomass at Guguan from REA surveys for fishes of all sizes and species was among the highest levels recorded in the Mariana Archipelago. No clear temporal changes were observed for total fish biomass between the 3 MARAMP survey years (Fig. 11.8.1d). Guguan had the greatest estimated species richness of reef fishes recorded in the Mariana Archipelago.

11.11 Summary

MARAMP integrated ecosystem observations include a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Guguan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Guguan chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Guguan, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Guguan as well as some of the key natural processes and anthropogenic activities influencing these ecosystems:

- Positioned in the middle of the Mariana Arc, Guguan is the third-smallest island in the Mariana Archipelago with a land area of only 4 km^2.

- Guguan is formed from 2 volcanoes, with the younger of them found in the north. Compared to its neighbor islands, Alamagan and Sarigan, Guguan has a relatively low elevation and less steep slopes.

- Since Guguan likely has not been inhabited and remains relatively undisturbed, it is unique among islands in the Mariana Archipelago in that it supports a diverse range of habitats with a variety of wildlife species. Since 1978, the CNMI Constitution has prohibited inhabitation of Guguan as part of a protected reserve.

- Northern Guguan is surrounded by fairly uniform, smooth flanks, apart from the shallowest depths (< 300 m) where narrow ridges are present. Towed-diver surveys recorded spur-and-of groove habitats of medium to high complexity with predominantly hard substrate and low sand cover.

- South of Guguan, the seabed is characterized by irregularly shaped shelves. A, flat, shallow shelf of hard substrate is located at depths of 25–50 m, and a deeper shelf of soft substrate is located at depths of 80–130 m.

- Overall, the topography of the seafloor around Guguan, characterized by steep slopes to the north and west and an extensive shelf to the south, appears to be very similar to the seascape surrounding the neighbor island of Sarigan.

- Wave model output shows ambient trade wind swells impacting the northeast and southeast regions. Episodic wave energy from storm tracks impact the southwest and southeast regions and to a lesser extent the northwest region.

- Temperature data from STRs deployed at depth of 6 m at a single mooring site on the west side of the island show frequent intraseasonal fluctuations. Recorded temperatures, for example, dropped nearly 3°C in July 2004 for ~ 1 week before sharply increasing to typical summer temperatures. Additionally, temperature values exceeded the coral bleaching threshold in September 2006; however, the duration of this event was < 1 d.

- The overall sample mean for live coral cover was 15.4% from the 3 REA sites surveyed at Guguan in 2007. From towed-diver surveys, islandwide mean cover of live hard corals was 23% in 2003 and 27% in 2007. The overall mean was 10% in 2005, when only 2 towed-diver surveys along the west coast were completed at this island.

- In 2007, 3 REA sites at Guguan were surveyed for the occurrence of disease and predation, and 8 disease cases were detected, all of them at REA site GUG-03 in the northwest region. The overall mean prevalence of disease sites was 0.04% (SE 0.02). Only one disease condition was recorded: an infestation by species of the encrusting sponge Terpios.

- Islandwide mean macroalgal cover, based on towed-diver surveys, was 20% in 2007. Between MARAMP survey years, no towed-diver-survey area consistently had the highest or lowest macroalgal cover.

- Cover of crustose coralline red algae was similar for the 3 MARAMP years, with the highest level observed in the northwest region. Coralline lethal orange disease was the only algal syndrome encountered at Guguan, and only a single case was recorded in the northwest region.

- Overall mean biomass of large fishes during the 3 MARAMP survey years was moderately low relative to estimates made for other northern islands in the Mariana Archipelago but higher than values found at all of the southern islands. However, results from REA surveys for fishes of all sizes and species show that total fish biomass at Guguan, with an overall sample mean of 18.20 kg 100 m^{-2} (SE 0.86) across the 3 survey periods, was among the highest levels found in the Mariana Archipelago.

- Notable observations of large fishes included a sighting of a humphead wrasse (Cheilinus undulatus) in 2007 and sightings of giant trevally (Caranx ignobilis) in 2005 and 2007.

- No COTS were observed in 2007; however, low densities were recorded in 2003 and 2005.

- Overall observed densities of sea cucumbers were low around Guguan during the 3 MARAMP survey years. Comparatively, giant clams were common, especially on the west side, where they were abundant. Sea urchins mostly were observed on the east side. Islandwide observed densities of sea urchins were higher in 2007 than in 2003.

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12 ALAMAGAN

12.1 Introduction

The island of Alamagan is located at ~ 17°36′ N, 145°50′ E in the middle of the Mariana Arc, 52 km south of Pagan and 32 km north of Guguan. This island is ~ 4 km wide and 4.8 km long, with a land area of 12.96 km^2 (Fig. 12.1a). As with all of the other northern islands in the Mariana Archipelago, Alamagan is a volcanic peak, the emergent tip of a much larger, mainly submarine volcano that is ~ 15 km in diameter. The highest elevation of this island is 744 m on the rim of its 350-m deep crater (Fig. 12.1b). The remainder of this island is typically characterized by steep slopes, with flatter areas extending north and south that result from lava flows. Historically, Alamagan has been inhabited by small human populations, mainly within 2 villages, including Songsong on the southern side of this island. In 2000, a homestead site was observed at Patida camp on the northwestern side of this island (Cruz et al. 2000).

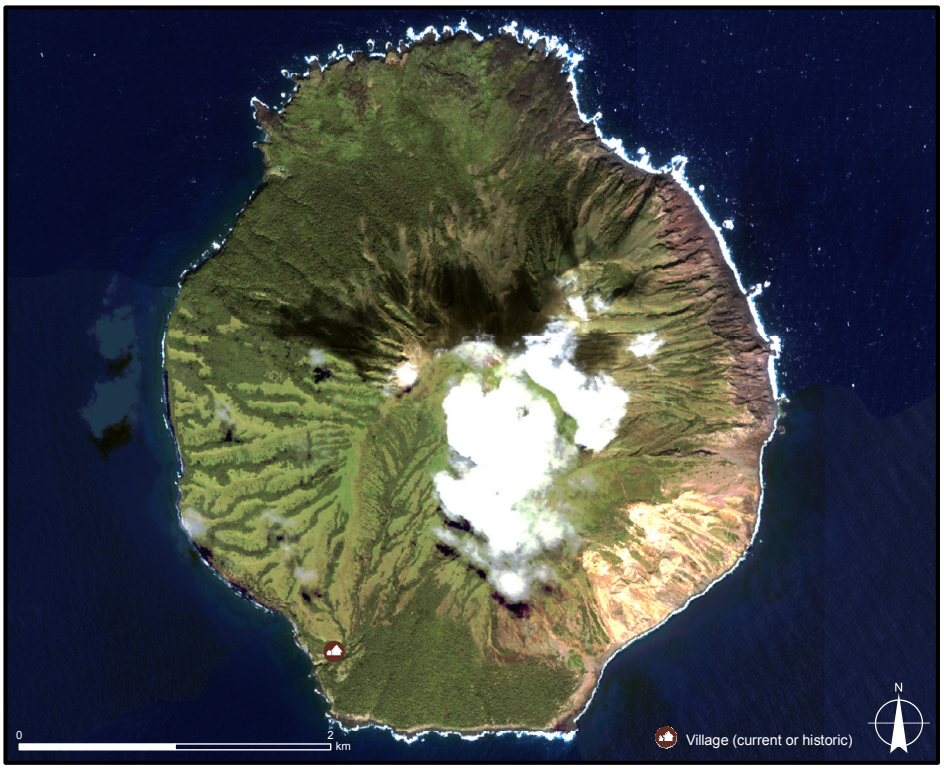


Figure 12.1a. Satellite image of Alamagan (IKONOS Carterra Geo Data, 2003).



Figure 12.1b. Alamagan viewed from the northeast, as seen from the NOAA Ship *Hi`ialakai* in 2007. *NOAA photo*

12.1.1 History and Demographics

Evidence of historic occupation by Chamorro people was discovered by Georg Fritz, the first German administrator of the Northern Mariana Islands, when visiting this island in 1901 (Spennemann 2006). This island has been sporadically populated in fairly small numbers, varying with changes in economic factors and the risk posed by possible eruptions from Alamagan or other nearby volcanoes. During the early 1900s, a populated Alamagan was leased by the Germany to the Pagan Gesellschaft, a trading organization, for copra production (Spennemann 1999b). Copra production was the mainstay of the German economy in the Marshall Islands and in much of Micronesia during this time (Spennemann 1999b). A series of typhoons between 1904 and 1907 resulted in a 50% reduction in copra production (Spennemann 1999b).

Copra production and inhabitation of this island continued, although a shortage of copra on Alamagan in 1962 reduced the number of residents to the extent that it was necessary to close the Alamagan Public Elementary School because of a lack of students (University of Hawaii 2009). Since then, residents of Alamagan have been evacuated numerous times, including in 2003, because of the threat of volcanic eruptions (Siebert and Simkin 2002–). Alamagan is part of the Northern Islands Municipality of the Commonwealth of the Northern Mariana Islands (CNMI). For this municipality, the 2000 U.S. Census recorded an official population of 6 persons, but the 2010 U.S. Census recorded no persons (U.S. Bureau of the Census 2003, 2011a).

Alamagan is one the islands where land could be designated for village and homesteading programs. The *Northern Islands Homestead Act of 2008*, which was signed into law by the Governor of the CNMI in January 2010, recognizes that residents of the "islands north of Saipan" have no formal homesteads, allows residents to have agricultural lots and facilities, encourages resettlement by former residents, and initiates and promotes economic development. This legislation, CNMI Public Law 16-50, may increase the population on Alamagan in coming years.

12.1.2 Geography

Bandeera Peak, the volcano located east of the center of this steeply sloping island, has a summit crater that is ~ 950 m by 600 m and 350-m deep. The steepest slopes of this volcano are east of this crater (Fig. 12.1.2a), and steep slopes of bare lava lie southeast of this crater (University of California San Diego 2009). The slopes on the west side of Alamagan are cut by deep gorges and are more gradual here than on other sides (University of California San Diego 2009). The north-

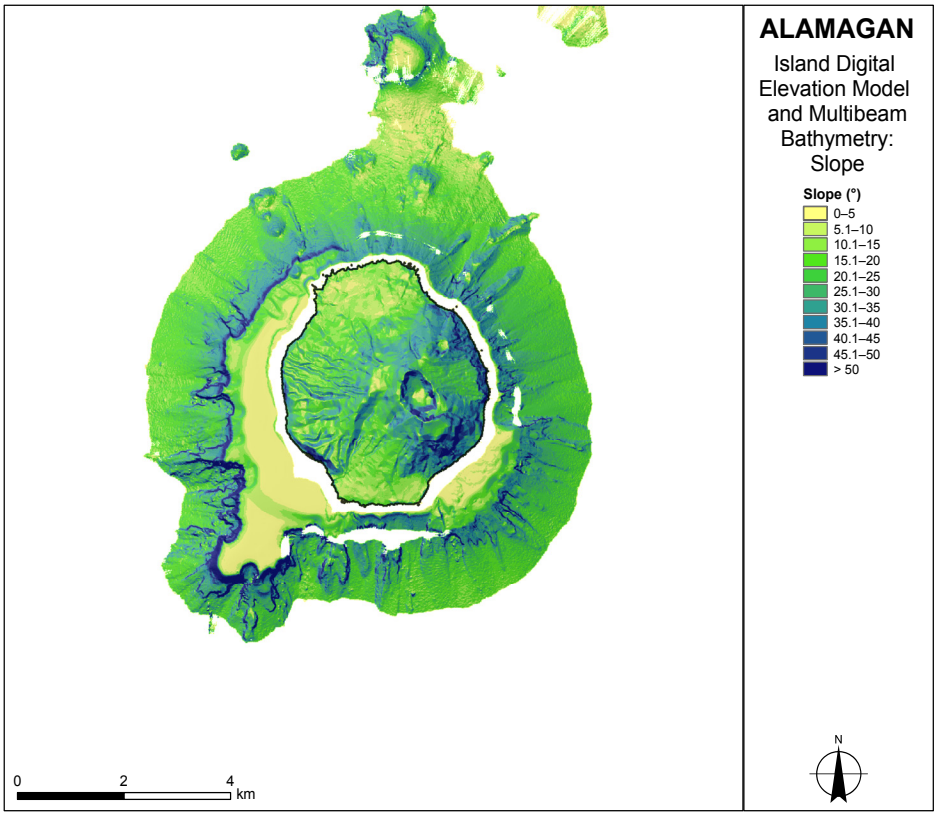


Figure 12.1.2a. Combined slope map using the digital elevation model and bathymetric data for Alamagan (grid cell size: 10 m).

ern and southern coasts of Alamagan have been extended by lava flows that have created low-angle lava platforms (Fig. 12.1.2b). The southwestern flank of Alamagan is cut by a graben, an elongated (1.6 × 1 km), relatively depressed crustal unit bounded by faults on both sides (Siebert and Simkin 2002–). No beaches were found around Alamagan, and this island is surrounded by sea cliffs.

The last known eruption at Alamagan, dated from pyroclastic flow deposits, occurred at 1077 ± 87 years BP or ~ AD 870 (Moore and Trusdell 1993; Siebert and Simkin 2002–); however, active steam fumaroles were observed during scientific surveys conducted on this island in 2000 (Cruz et al. 2000). The first known eruption of a volcano in the Mariana Archipelago, based on radiocarbon dating, was of Alamagan in AD 540 (Siebert and Simkin 2002–).

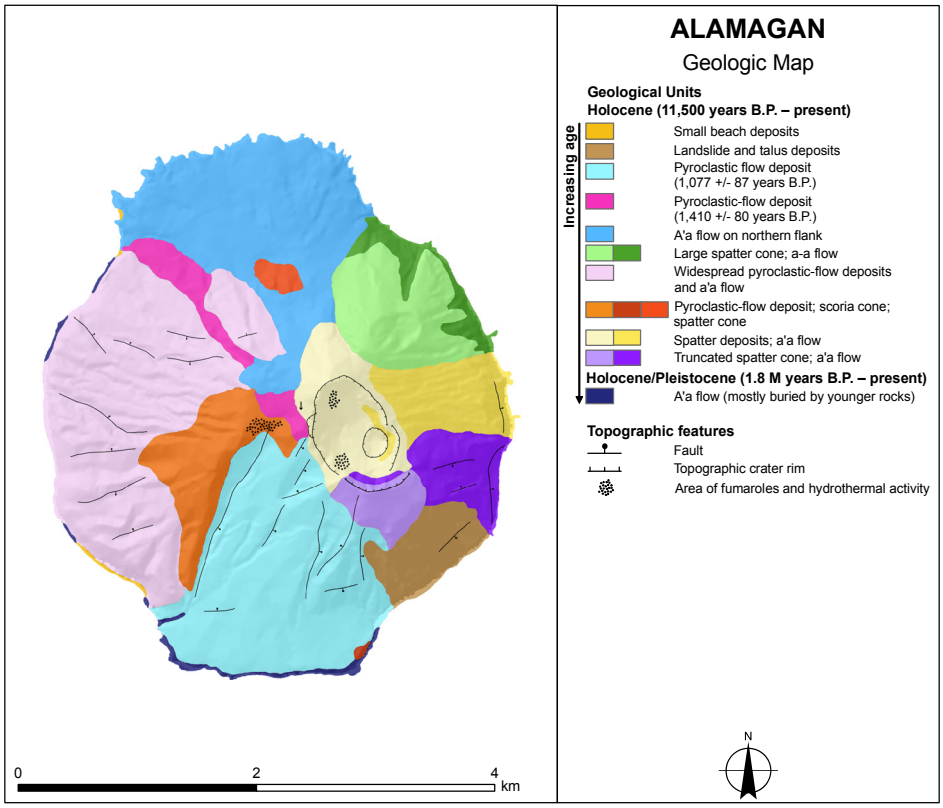


Figure 12.1.2b. Geologic map of Alamagan (adapted from Moore and Trusdell 1993).

The pattern of vegetation on Alamagan is typical of the less volcanically active, northern volcanic islands of the Mariana Archipelago. Sword grass (*Miscanthus floridulus*) dominates the upper (elevations > 150 m) ash slopes of this volcano, the upper-middle slopes support sparse woody vegetation and tree ferns, and dense woody thickets are found within ravines and in lowland areas (Cruz et al. 2000; Mueller-Dombois and Fosberg 1998). Flatter areas have been planted with coconut groves. Native forests are confined to ravines on the southern and western slopes of Alamagan, and the forest cover on this island in general is low (Cruz et al. 2000). The southeastern lava slopes are devoid of vegetation (Fig. 12.1.2c), and landslides on this part of the island have disturbed vegetation. Compared to other islands in the CNMI, Alamagan has low abundance and density of native plant species (Cruz et al. 2000).

No information is available regarding the distribution of groundwater resources at Alamagan, although warm freshwater springs are present on the northern part of this island's west coast (Cruz et al. 2000). Surface water is thought to be absent except during rainy weather (Mueller-Dombois and Fosberg 1998).

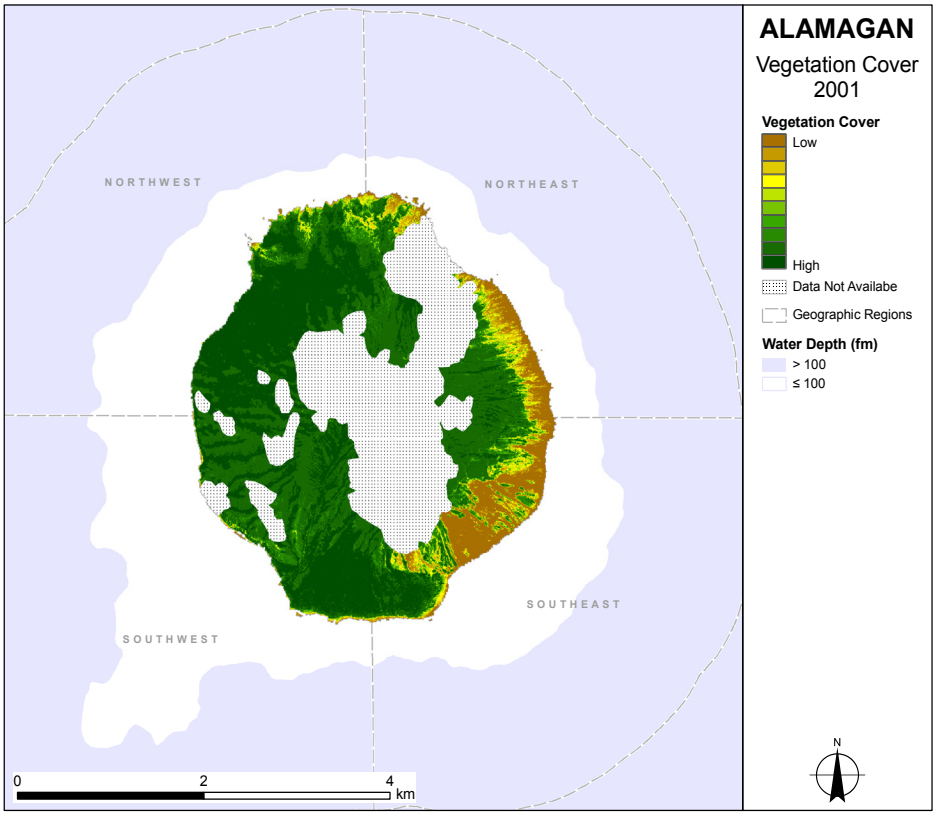


Figure 12.1.2c. Vegetation cover on Alamagan, derived using the Normalized Difference Vegetation Index from a satellite image (grid cell size: 4 m; IKONOS Carterra Geo Data, 2001). Hatched lines indicate areas where data are not available because cloud cover obscures the satellite image.

12.1.3 Environmental Issues on Alamagan

Alamagan has relatively low abundance and density of native plant species. Several important species of birds reside on this island, including the Micronesian starling (*Aplonis opaca*), Micronesian honeyeater (*Myzomela rubrata*), and an estimated population of 30 of the Micronesian megapode (*Megapodius laperouse*), which is listed federally as endangered and locally as threatened or endangered (U.S. Fish and Wildlife Service; Berger et al. 2005). Alamagan has the only well-established population, outside of Saipan, of the nightingale reed warbler (*Acrocephalus luscinia*), also listed federally as endangered and locally as threatened or endangered (U.S. Fish and Wildlife Service; Berger et al. 2005). The Mariana fruit bat (*Pteropus mariannus mariannus*), an endemic subspecies listed federally as threatened and locally as threatened or endangered (U.S. Fish and Wildlife Service; Berger et al. 2005), is present on this island, although the size of this population is unknown. Of the 3 northern islands (Alamagan, Asuncion, and Sarigan) that harbor substantial populations of the endemic Slevin's skink (*Emoia slevini*), Alamagan has the densest population (Cruz et al. 2000).

Native wildlife is threatened by the presence of feral cows, pigs, and goats, which are common on this island and can cause extensive damage to vegetation and destroy seedlings. Rats, although present, are lower in number than on other islands of the CNMI (Cruz et al. 2000).

As one of the few islands of the CNMI that has had a resident, if small, human population, Alamagan does not have the same isolation compared to the remote islands that have not been inhabited.

12.2 Survey Effort

Biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing coral reef ecosystems around the island of Alamagan since 2003. The spatial extent and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around

Alamagan are delineated in Figure 12.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around this island. Potential reef habitat is represented by a 100-fm contour shown in white on this map.

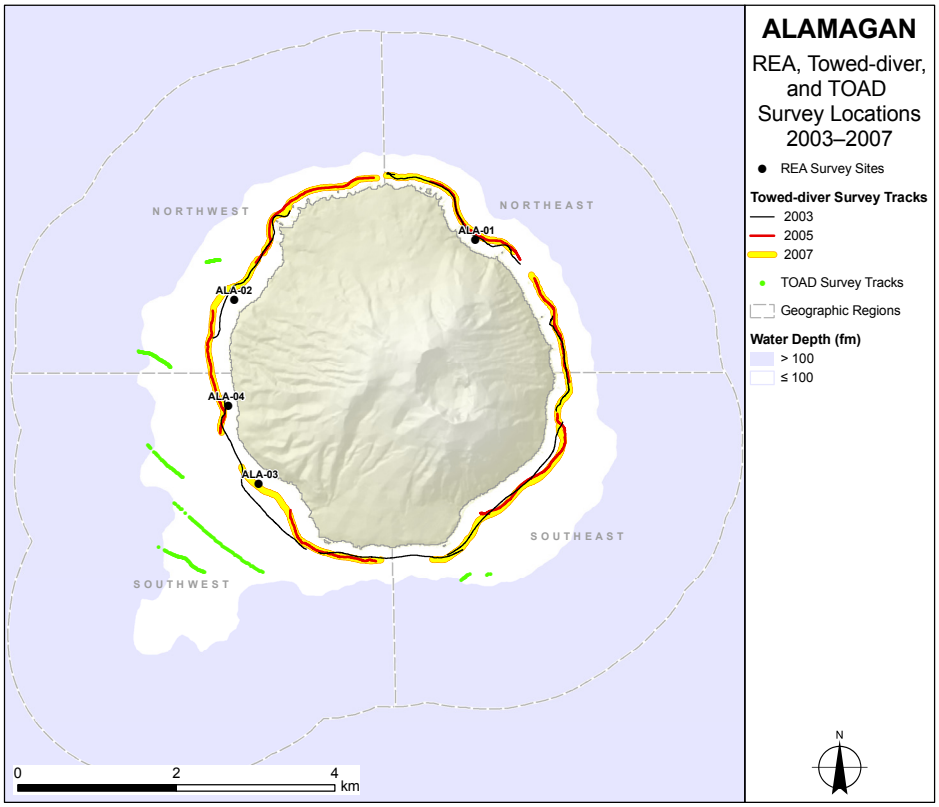


Figure 12.2a. Locations of REA, towed-diver, and TOAD benthic surveys conducted around Alamagan during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 4 geographic regions: northeast, southeast, southwest, and northwest.

Benthic habitat mapping data were collected around Alamagan using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around this island with multibeam sonar covered a total area of 2228 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live-hard-coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 12.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Alamagan was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 12.5–12.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 12.2a, along with their mean depths and total areas and length.

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Alamagan were collected using (1) subsurface temperature recorders (STRs) designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water samples were collected during MARAMP 2007 (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 12.2b. Results are discussed in Section: 12.4: "Oceanography and Water Quality."

Table 12.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Alamagan during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	3	3	3
	Mean Depth (m)	12.3 (SD 2.1)	12.3 (SD 2.1)	12.3 (SD 2.1)
Benthic	Number of Surveys	3	3	3
	Mean Depth (m)	12.3 (SD 2.1)	12.3 (SD 2.1)	12.3 (SD 2.1)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	6	6	6
	Total Survey Area (ha)	12.1	10.1	13.2
	Mean Depth (m)	14.2 (SD 1.5)	15.9 (SD 1)	16.3 (SD 1.3)
TOAD		**2003**		
	Number of Surveys	6		
	Total Length (km)	3.59		

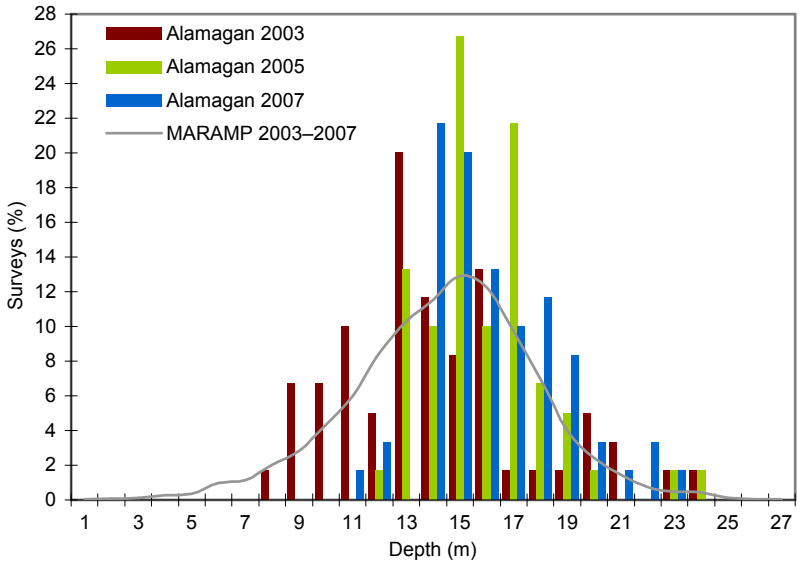
Table 12.2b. Numbers of STRs deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Alamagan during MARAMP 2003, 2005, and 2007. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	**2003**	**2005**		**2007**		**2009**	**Lost**
	Deployed	**Retrieved**	**Deployed**	**Retrieved**	**Deployed**	**Retrieved**	
STR	1	–	1	1	2	2	1
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	14	15		16			45
Deepwater Casts	–	3		1			4
Water Samples		**2005**		**2007**			**Total**
		–		4			4

Towed-diver Surveys: Depths

Figures 12.2b and c illustrate the locations and depths of towed-diver-survey tracks around Alamagan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

Figure 12.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted around Alamagan during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.



During MARAMP 2003, 6 towed-diver surveys were conducted along the forereef slopes around most of Alamagan (Figs. 12.2b and c, top panel). The mean depth of all survey segments was 14.2 m (SD 1.5), and the mean depths of individual surveys ranged from 12.9 m (SD 3.2) to 17 m (SD 6.1).

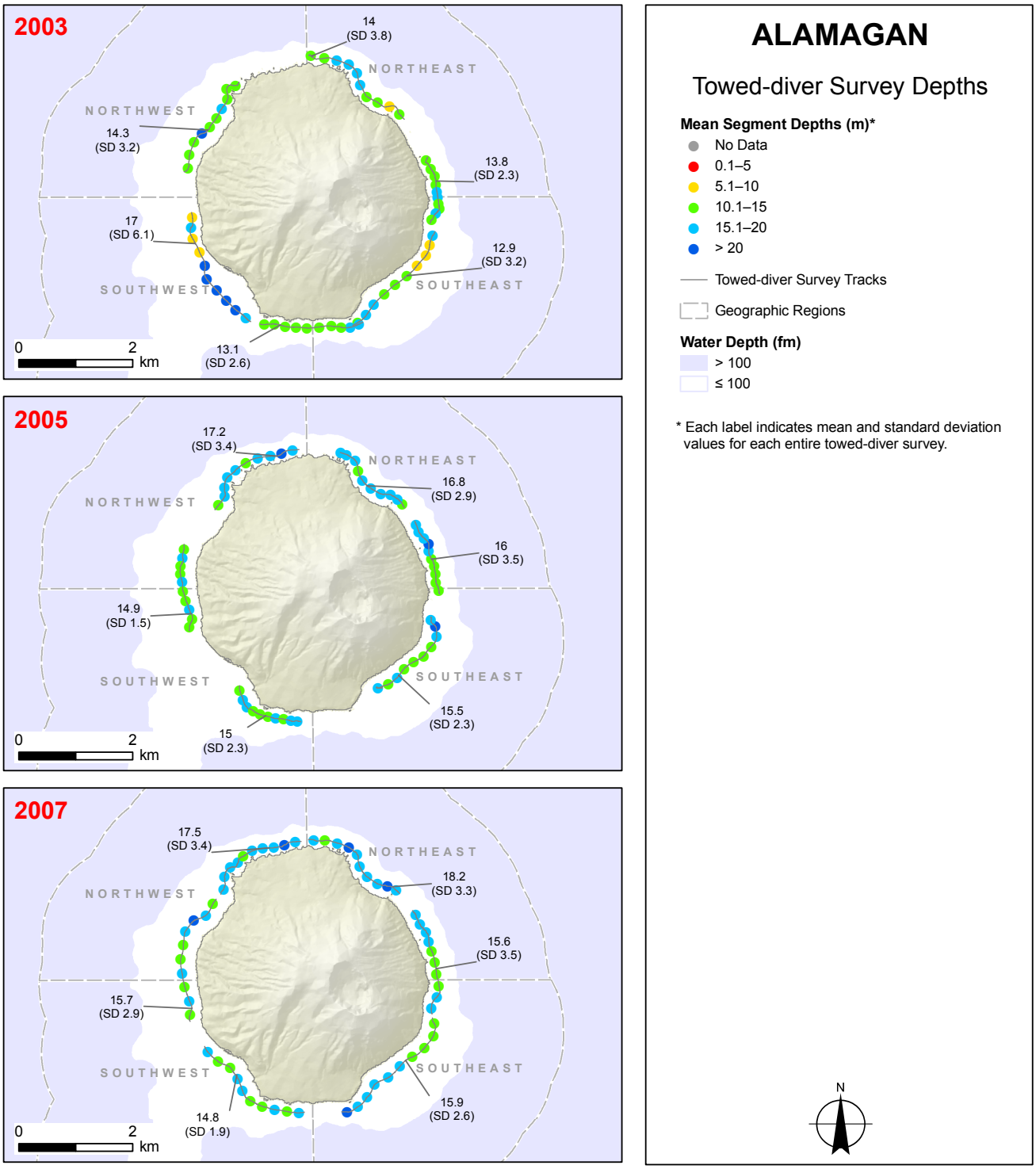


Figure 12.2c. Depths and tracks of towed-diver surveys conducted around Alamagan during MARAMP 2003, 2005, and 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

During MARAMP 2005, 6 towed-diver surveys were conducted along the forereef slopes around most of Alamagan (Figs. 12.2b and c, middle panel). The mean depth of all survey segments was 15.9 m (SD 1), and the mean depths of individual surveys ranged from 14.9 m (SD 1.5) to 17.2 m (SD 3.4).

During MARAMP 2007, 6 towed-diver surveys were conducted along most of the forereef slopes of Alamagan (Figs. 12.2b and c, bottom panel). The mean depth of all survey segments was 16.3 m (SD 1.3), and the mean depths of individual surveys ranged from 14.8 m (SD 1.9) to 18.2 m (SD 3.3).

12.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys of around the island of Alamagan were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 15–2300 m. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted depths of 4–282 m.

12.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 12.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around the islands of Alamagan, Sarigan, Anatahan, Guguan, and Zealandia Bank during MARAMP 2007 encompassed a total area of 2228 km^2. Multibeam data were obtained to depths of 1000–1700 m west of Alamagan, but additional data to 2300 m was obtained east of Alamagan, during transits to and from this island.

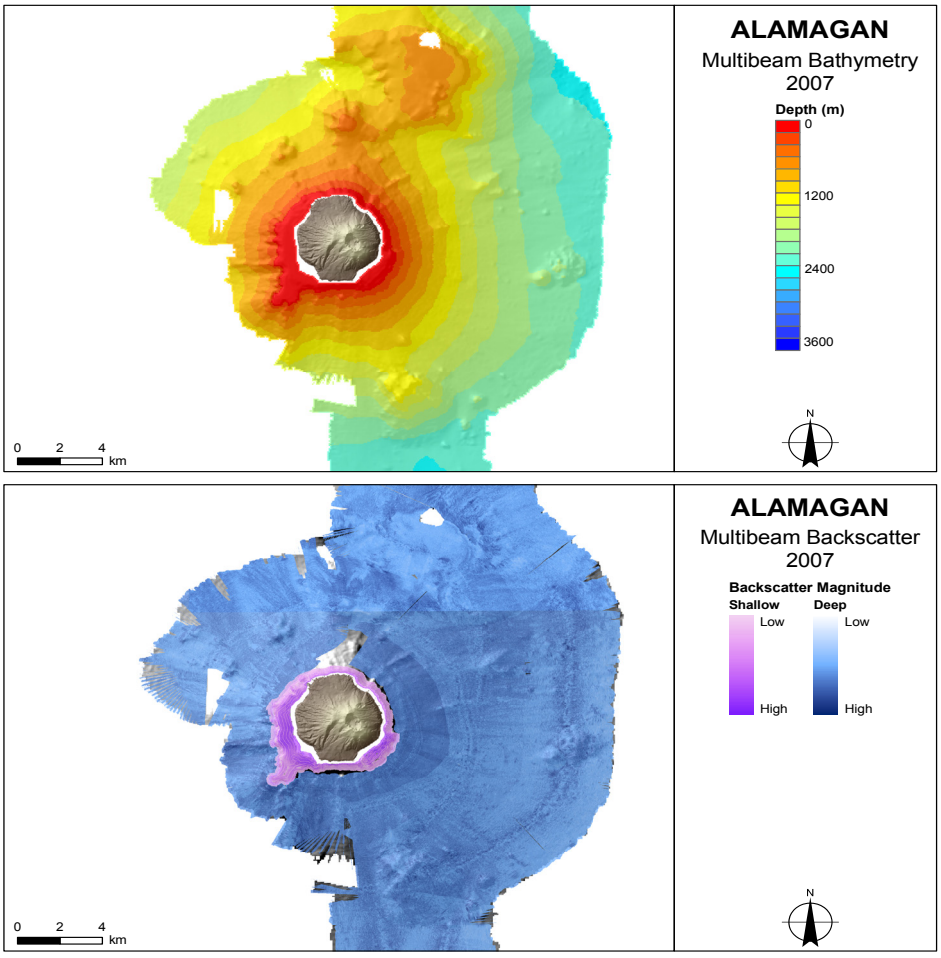


Figure 12.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Alamagan during MARAMP 2007 at depths of 15–2300 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

Multibeam bathymetry acquired around Alamagan reveals part of the flanks of the Alamagan volcano (Fig. 12.3.1a, top panel). The acquired data do not entirely cover the flanks, but data obtained east of Alamagan suggest that the seabed descends to ~ 2000 m within 6.5 km from the coast and continues to descend, albeit less steeply, beyond this point. These low-resolution data also reveal a small shelf extending from the southwest of this island. North of Alamagan, a small pinnacle is visible, with a larger bank further northeast. Smaller peaks are shown elsewhere around this island.

As described in Chapter 2: "Methods and Operational Background," Section 2.2: "Benthic Habitat Mapping and Characterization," multibeam backscatter intensity can provide information about the roughness and hardness of the seafloor. Backscatter data acquired around Alamagan show some variation in intensity that may relate to variation in the acoustic nature of the seabed, although noticeable artifacts also are observed. East of this island, the shallowest swath of backscatter data (Fig. 12.3.1a, bottom panel) is noticeably darker than the deeper swaths, which may be a result of changes in the settings during data acquisition. Low-intensity backscatter—observed on the bank northeast of Alamagan, in contrast to edges of the bank, where backscatter intensity is higher—may indicate the presence of soft sediments on the bank top. The pinnacle between the bank and Alamagan and other pinnacles on the eastern flanks are represented by high-intensity backscatter, suggesting that hard substrates may be at or close to the seabed surface here. Around southwestern Alamagan, high-intensity backscatter also is shown on the shallow shelf.

High-Resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in nearshore (depths of 0–800 m) waters around Alamagan were combined into a grid at 10-m resolution for the identification of fine-scaled features (Fig. 12.3.1b). These high-resolution data were used to derive maps of slope (Fig. 12.3.1c), rugosity (Fig. 12.3.1d), and bathymetric position index (BPI) zones (Fig. 12.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Alamagan.

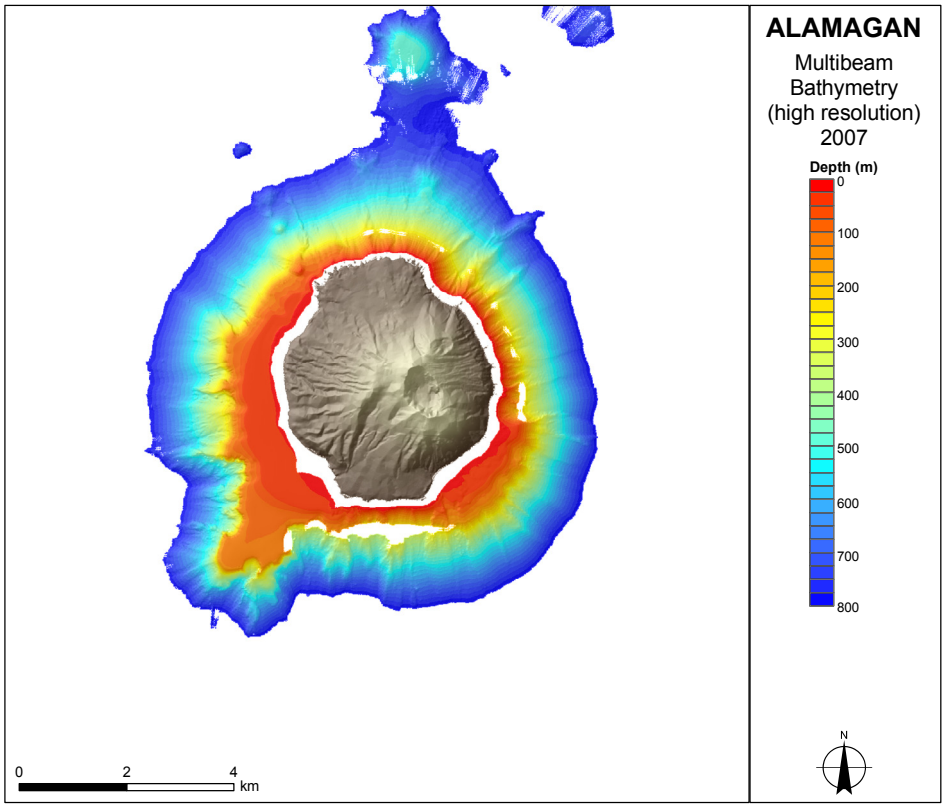


Figure 12.3.1b. High-resolution multibeam bathymetry collected around Alamagan during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives.

Around northern and northeastern Alamagan, the slope map and BPI analysis highlight many ridges that incise moderately steep (20°–25°) flanks. All of the ridges in this area are narrow and steep-sided, with high rugosity values recorded on the sides.

Southeast of Alamagan, the most significant topographic feature depicted on the map of BPI zones is a narrow shelf, the surface of which is shown in the slope and rugosity maps to have a somewhat complex texture, which suggests coral habitat

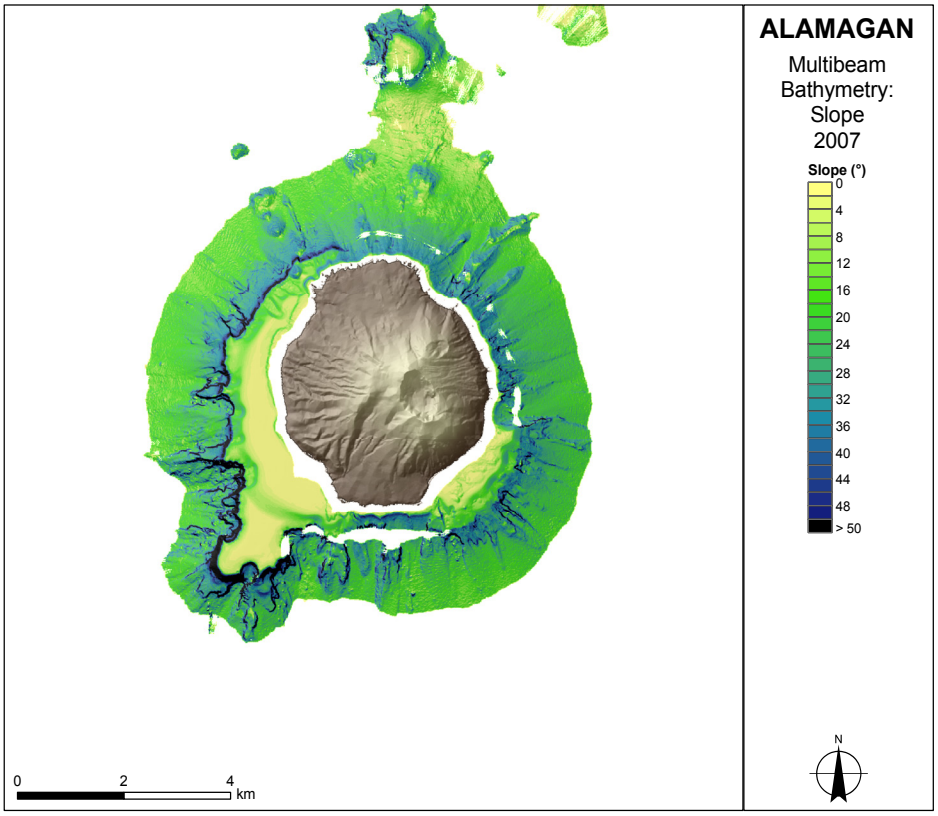


Figure 12.3.1c. Slope (°) of 10-m bathymetric grid around Alamagan. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades.

or may result from onshore landslide deposits. Below the shelf, the smooth moderately sloping (15°–20°) seabed gives way to more steeply sloping flanks incised with ridges, similar in character to the flanks northeast of this island.

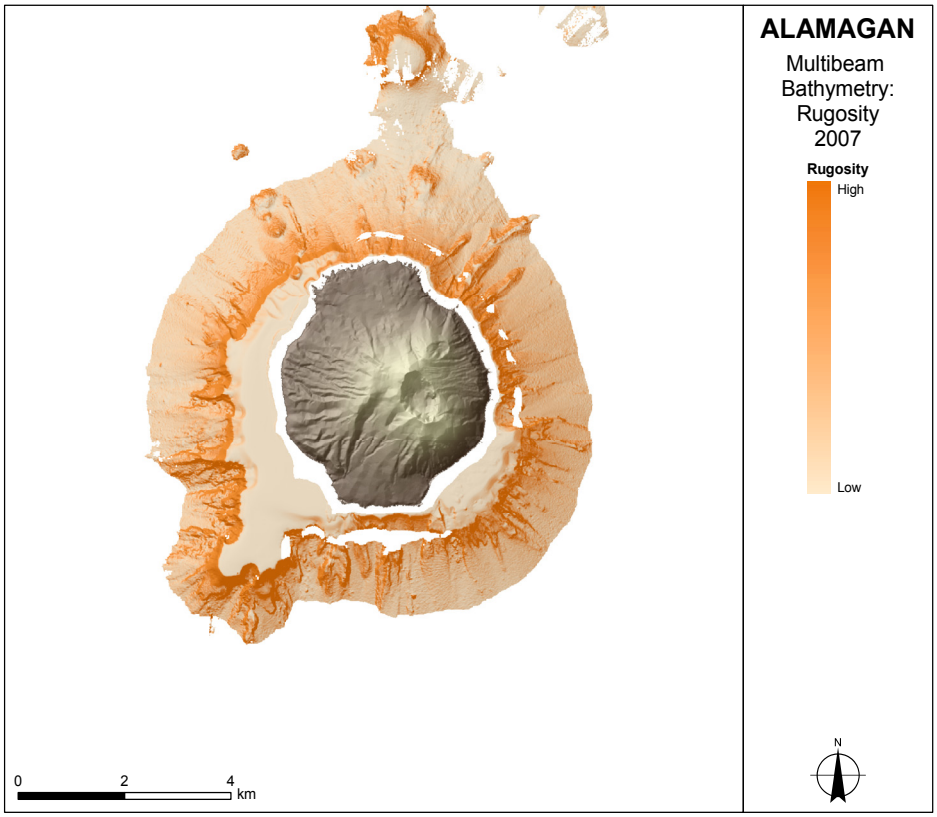


Figure 12.3.1d. Rugosity of 10-m bathymetric grid around Alamagan. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

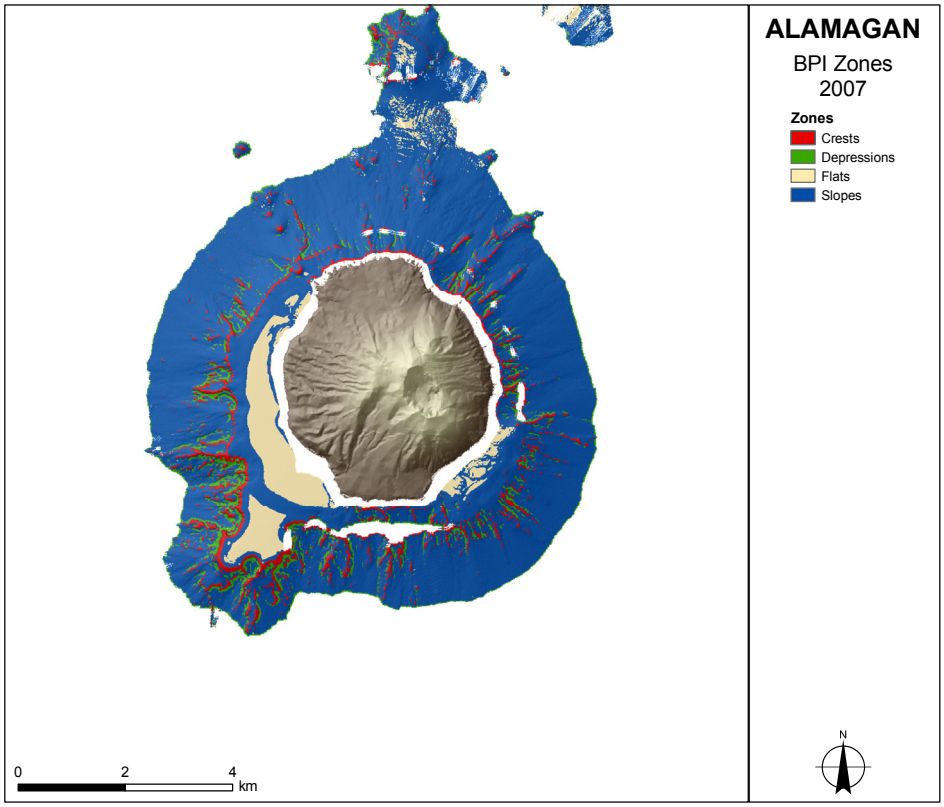


Figure 12.3.1e. BPI zones of 10-m bathymetric grid around Alamagan derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—have been used in this analysis.

A more extensive shelf area is present around western Alamagan at depths of 25–40 m. In the southwest, a second, deeper shelf is present at depths of 80–120 m and extends for a further 1.5 km. Both shelves are characterized by very smooth, flat surfaces and create extensive flat zones in a seabed otherwise dominated by slopes. The shelves are edged by very steep slopes (> 50°); in deeper water, the flanks are more moderately steep and characterized by medium-high rugosity values.

Directly north and south of Alamagan, no such shelf areas are present. South of Alamagan the onshore lava platform creates an extension to the coast below which the seabed slopes steeply. North of this island, the coastline has been similarly extended by a lava flow. Offshore, north of Alamagan, a topographic high is revealed by the high-resolution bathymetry, arising to a depth of ~ 480 m. Small flat areas are defined by the BPI analysis on top of this peak, surrounded by steep, high-rugosity slopes with some ridge features.

High-Resolution Multibeam Backscatter and Derivatives

The high-resolution backscatter data acquired around Alamagan were affected by some artifacts, such as higher backscatter values recorded within the shallower part of the outer swath versus the deeper part. Backscatter data can be affected by steep slopes, sonar settings, sea state during data acquisition, or other factors discussed in more detail in Chapter 2: "Methods and Operational Background," Section 2.2.2 "Acoustic Mapping." Track parallel artifacts visible on the shelf southwest of Alamagan were exaggerated in the hard–soft analysis. The resulting hard-soft substrate map was therefore clipped to exclude these data.

Despite data quality issues, a number of clear patterns are shown in the backscatter intensity recorded around this island, particularly where more complete coverage was achieved (Fig. 12 3.1f). Around north and northeast Alamagan, some of the more prominent ridge features were associated with high-intensity backscatter values indicative of hard substrates. The shallow shelf areas around the south and west of this island were all characterized by high-intensity backscatter, categorized through the hard–soft analysis as being dominated by hard substrates. Along the southern edge of the southeastern shelf, a band of low-intensity backscatter is associated with a channel shown in the bathymetry. This channel is highlighted in the hard–soft substrate map as being an area of soft substrate on an otherwise hard-substrate shelf (Fig. 12.3.1g). The deeper shelf southwest of Alamagan appeared to have lower backscatter intensity, although it may have been affected to some extent by the deeper water being surveyed, and artifacts in these data make interpretation difficult. Around northwestern Alamagan, low backscatter values were recorded in a number of channels visible in the multibeam bathymetry, and the hard–soft analysis suggests that the seabed here is likely to be characterized by soft sediments.

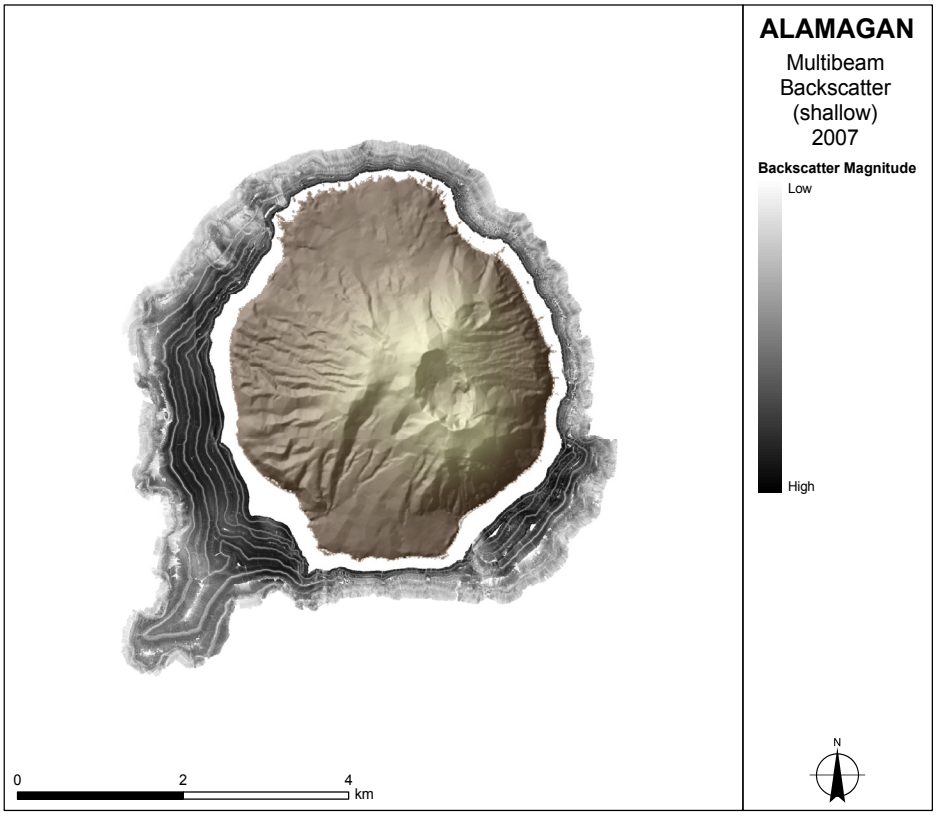


Figure 12.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) collected around Alamagan during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

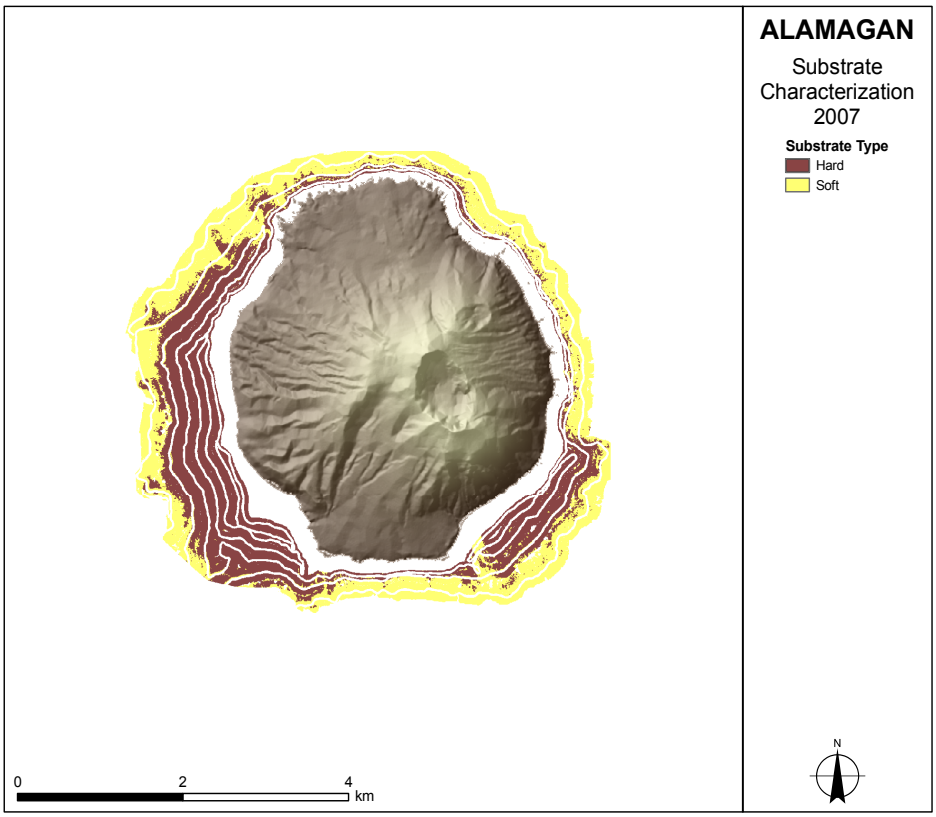


Figure 12.3.1g. Hard and soft substrates (grid cell size: 5 m) based upon an unsupervised classification of multibeam bathymetry and backscatter data acquired around Alamagan in 2007. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

12.3.2 Optical Validation

During MARAMP 2003, 6 TOAD optical-validation surveys, covering a distance of 3.6 km, were conducted around Alamagan at depths of 45–280 m (Fig. 12.3.2a). Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live coral cover.

Covering a distance of 35 km in depths of 4–28 m, 18 towed-diver optical-validation surveys were conducted around Alamagan during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

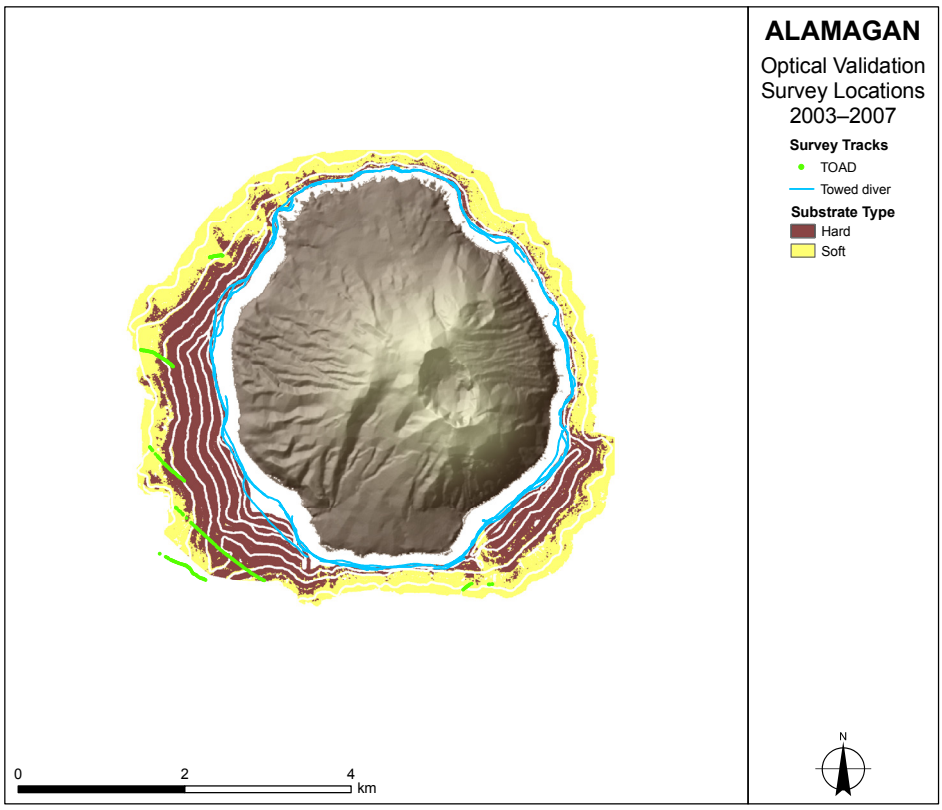


Figure 12.3.2a. Towed-diver tracks from surveys conducted around Alamagan during MARAMP 2003, 2005, and 2007 and TOAD camera-sled tracks for MARAMP 2003. Survey tracks are displayed over the multibeam hard–soft substrate map. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

12.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Alamagan are discussed in this section. These descriptions are organized by the 4 geographic regions around Alamagan.

Around northeastern Alamagan, very low sand cover was observed during towed-diver surveys with cover predominantly < 10% (Fig 12.3.3a, top panel). Habitat complexity observed during towed-diver surveys ranged from medium to high (Fig 12.3.3a, middle panel). This high level of complexity reflects the ridges visible on the bathymetry that provide high relief. Towed-diver surveys characterized this habitat as containing steep reef slopes, boulders with corals, and perpendicular ridges. This hard substrate area coincides with the onshore geology of northern and eastern Alamagan, which is dominated by lava flows (Moore and Trusdell 1993). Live coral cover was estimated at 10.1%–40% (Fig 12.3.3a, bottom panel).

Across the shallow shelf southeast of Alamagan, towed-diver surveys found habitats of boulders on sand,and high-relief spur-and–groove formations. Habitat complexity within this region was recorded as lower than the level observed northeast of Alamagan, ranging from medium-low to medium-high, because no ridges providing high relief were present. Towed-diver surveys recorded higher sand cover than the levels seen in the northeast region (generally 10.1%–40%), including one patch of 85% cover on the southwestern edge of the shelf. This area coincided with a band of low-intensity backscatter and a channel on the edge of the shelf. Observed live coral cover was lower here than further north, with cover predominantly of 5.1%–20%.

An area of low-complexity habitat observed on the shelf southwest of Alamagan was characterized by sand cover of 50.1%–100% and low (< 10%) live coral cover. Parallel surveys conducted closer inshore recorded slightly higher habitat complexity and lower cover of sand, suggesting that sand cover over the shelf area could be spatially variable. The presence of sand in this area coincides with onshore beach deposits, otherwise rare around Alamagan (Moore and Trusdell 1993). Multibeam backscatter data collected over the shelf area revealed predominantly high-intensity backscatter, although some areas of slightly lower intensity were mapped. These data normally would suggest the presence of hard substrates at the seabed surface. This apparent contradiction between the acoustic data and diver observations may be a result of divers observing a thin veneer of sand overlying harder substrates.

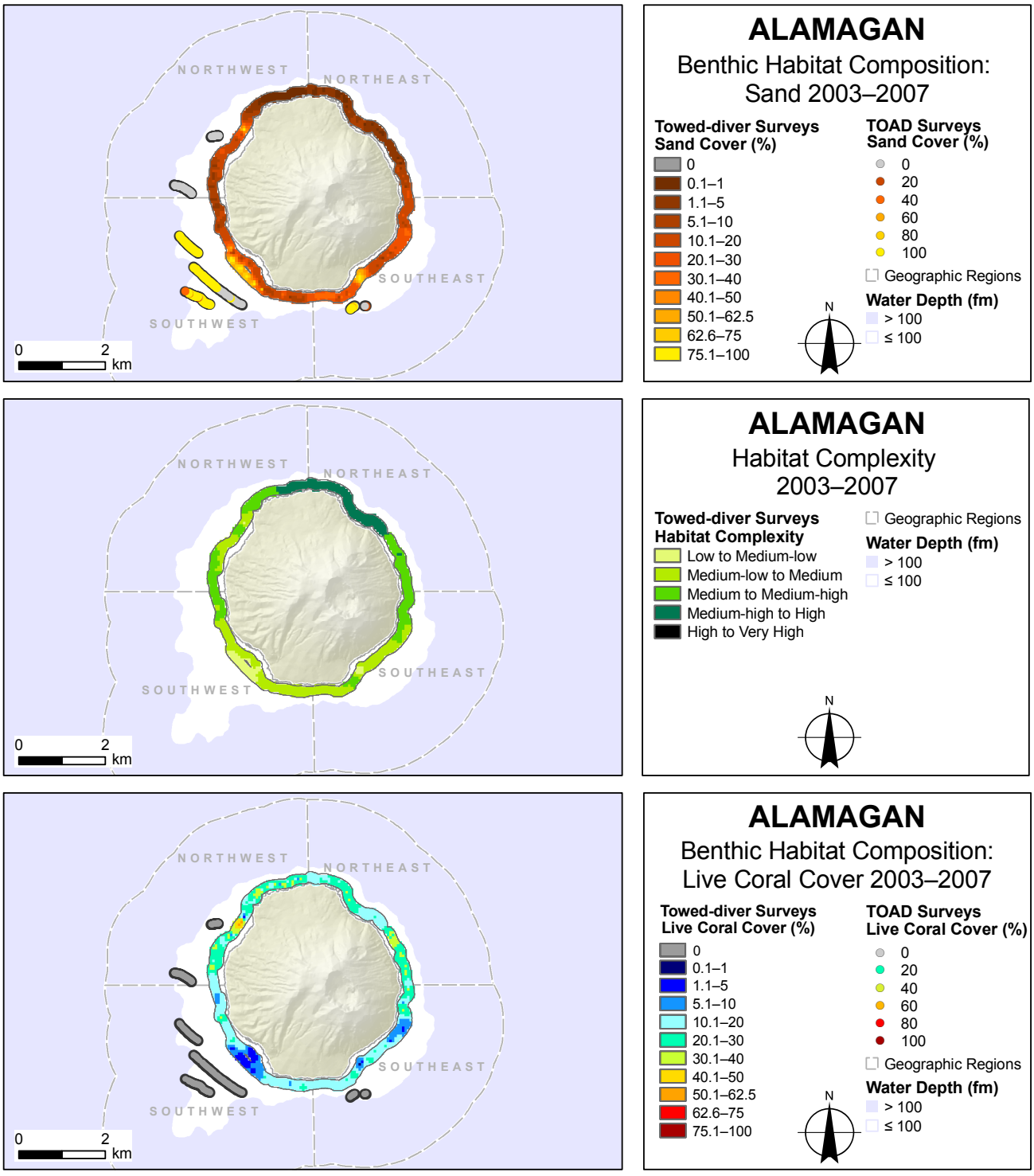


Figure 12.3.3a. Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) live-hard-coral cover (%) from towed-diver surveys conducted and analyses of TOAD video collected around Alamagan during MARAMP 2003, 2005, and 2007.

Within the rest of the southwest region, habitat complexity observed during towed-diver surveys was medium-low to medium, with moderately low cover of sand (< 30%) and live hard corals (10.1%–20%). These data suggest that the seabed here is predominantly composed of hard substrates but supports low levels of live corals. Towed-diver surveys described habitats as consisting of rolling reef, moderate reef slope and boulder fields. Onshore geology in this area is dominated by pyroclastic flow deposits, which include weakly consolidated pumice and boulders (Moore and Trusdell 1993).

Analyses of video obtained from TOAD surveys conducted on the deeper of the two shelf areas southwest of Alamagan revealed predominantly sandy habitats, with benthic substrate observed in video frames from 2 entire surveys and half of the third classified as 100% sand cover. No live corals were observed during video analyses. This absence of coral cover is in apparent contradiction to the hard–soft analysis, which depicts this shelf area as one composed of hard substrates. This difference may result from a hard shelf area being overlain by a thin veneer of soft sediment, visible on the TOAD video, but of insufficient thickness to influence the backscatter return.

In the northwest region, towed-diver surveys conducted along the shelf revealed habitat complexity of medium-low to medium-high, with fairly low sand cover (< 20%), although one small patch of high sand cover was observed, coinciding with an area of low-intensity backscatter. Live coral cover was patchy, varying between 1% and 75.1%–100%. Habitats were characterized as continuous reef with patches of boulder and rubble. Analyses of video footage from 2 TOAD surveys suggested no cover of sand or live corals. For both surveys, the substrate was classified as unconsolidated sediment devoid of live fauna.

12.4 Oceanography and Water Quality

12.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 14 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the island of Alamagan on September 12. Temperature, salinity, and density values varied both spatially and vertically. Spatial comparisons of water properties at a depth of 10 m suggest moderate ranges in temperature (0.41°C), salinity (0.18 psu), and density (0.26 kg m^{-3}) values around Alamagan. Recorded temperatures were lower and, concurrently, salinity and density were higher in the northeast region (casts 5–8) than in other regions (Fig. 12.4.1a). Vertical comparisons of CTD profiles (Fig. 12.4.1b) also reveal moderate ranges in temperature (0.6°C), salinity (0.3 psu), and density (0.4 kg m^{-3}) values. As seen in spatial comparisons, temperature, salinity, and density values in the northeast region (casts 5–8) were markedly different compared to all other cast locations around Alamagan. These observed differences in temperature and salinity values in the northeast region likely result from upwelling of subsurface waters, although the physical oceanographic forcing mechanism behind this upwelling is unknown without further information.

2005 Spatial Surveys

During MARAMP 2005, 15 shallow-water CTD casts were conducted in nearshore waters around Alamagan on September 16. Temperature, salinity, density, and beam transmission values varied both spatially and vertically. Spatial comparisons of water properties at a depth of 10 m suggest little spatial heterogeneity with small ranges in temperature (0.07°C), salinity (0.04 psu), density (0.03 kg m^{-3}), and beam transmission (< 1%) values (Fig. 12.4.1c). Vertical comparisons of CTD profiles (Fig. 12.4.1d) reveal similarly small ranges in temperature (0.2°C), salinity (0.1 psu), density (0.1 kg m^{-3}), and beam transmission (< 1%) values around Alamagan. Recorded temperatures were slightly cooler in the southeast region (casts 12–14) than at other cast locations around this island.

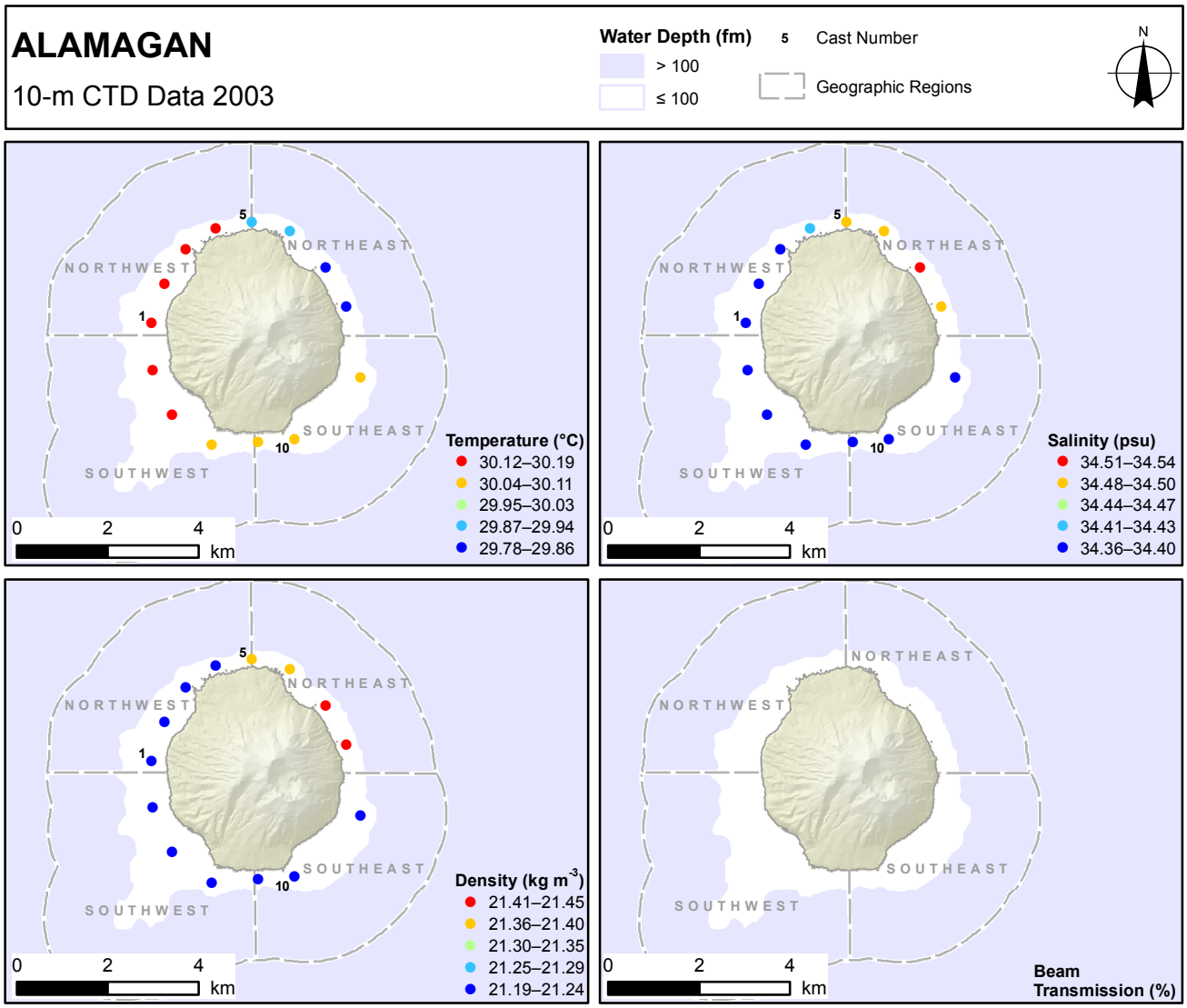
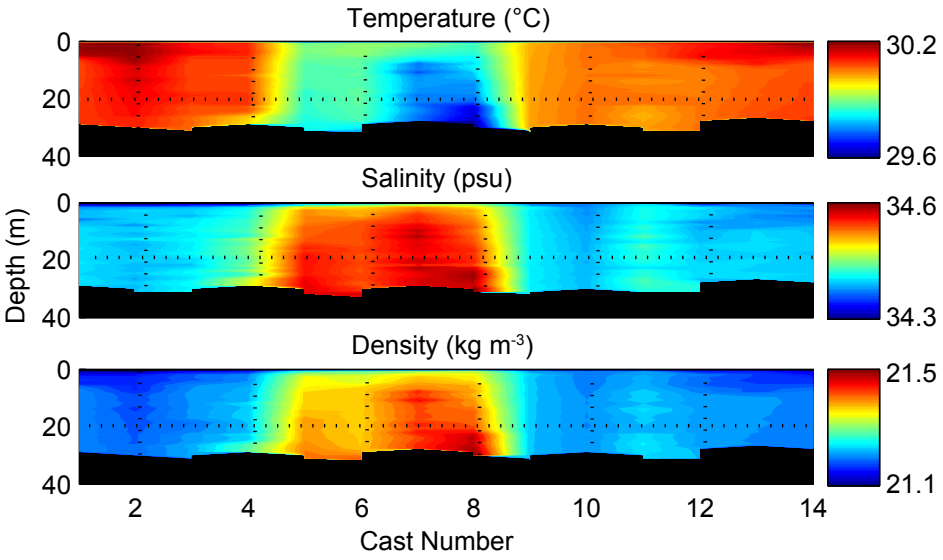


Figure 12.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts around Alamagan on September 12 during MARAMP 2003.

Figure 12.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Alamagan on September 12 during MARAMP 2003, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–14 in a clockwise direction around Alamagan. For cast locations and numbers around this island in 2003, see Figure 12.4.1a.



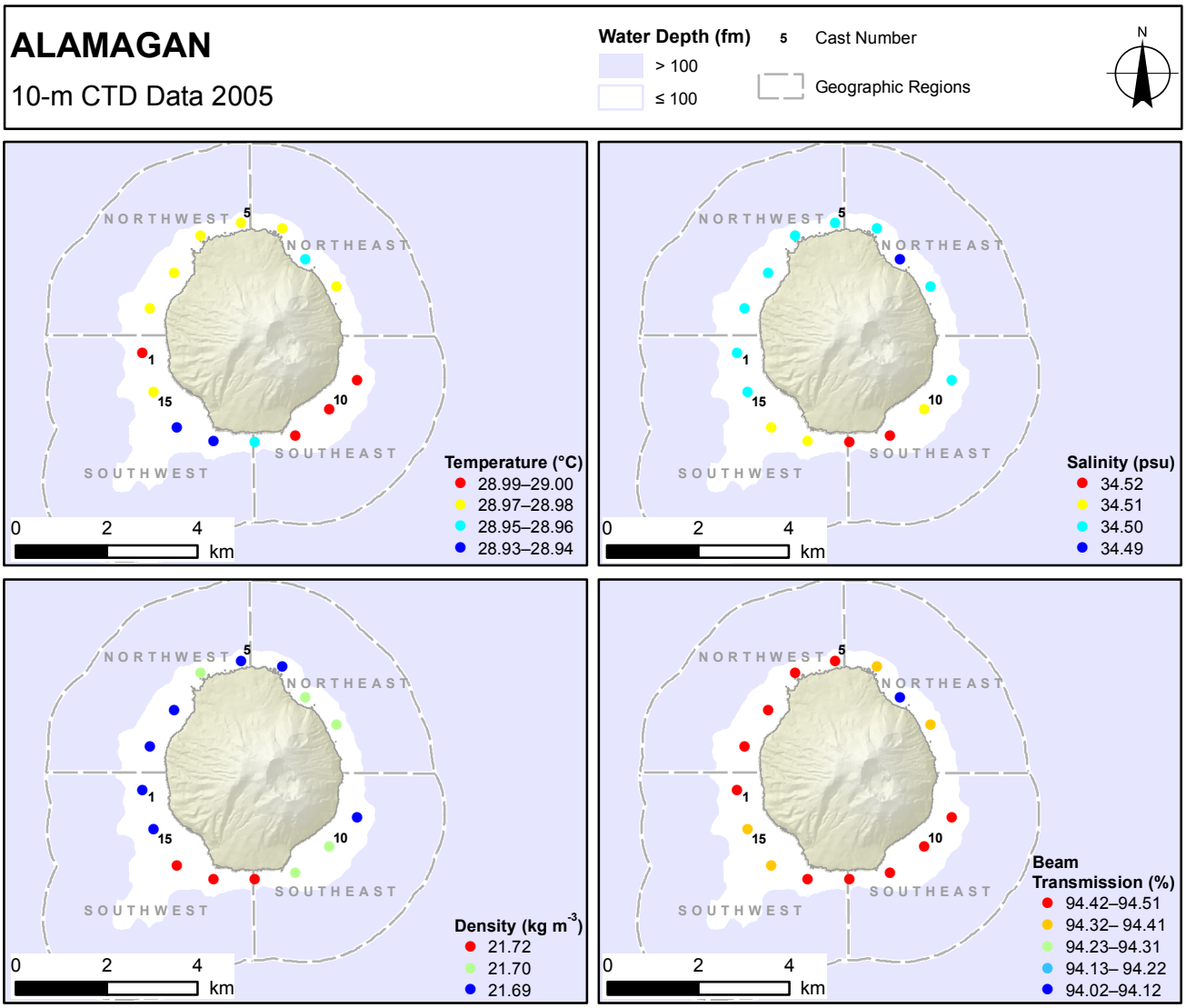


Figure 12.4.1c. Values of *(top left)* water temperature, (*top right*) salinity, (*bottom left*) and density (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Alamagan on September 16 during MARAMP 2005.

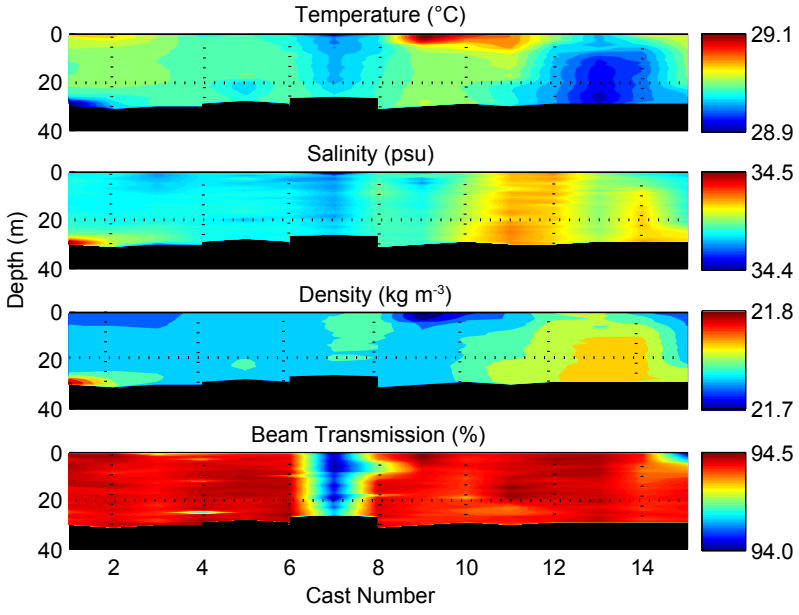


Figure 12.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Alamagan on September 16 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–15 in a clockwise direction around Alamagan. For cast locations and numbers around this island in 2005, see Figure 12.4.1c.

2007 Spatial Surveys

During MARAMP 2007, 16 shallow-water CTD casts were conducted in nearshore waters around Alamagan on May 28. Temperature, salinity, density, and beam transmission values varied both spatially and vertically. Spatial comparisons of water properties at a depth of 10 m suggest moderate variability in temperature (0.67°C) values and small ranges in salinity (0.05 psu), density (0.19 kg m^{-3}), and beam transmission (< 1%) values. Two cool areas, relative to other cast locations around Alamagan, were recorded in the northeast (cast 7) and northwest (cast 5) regions. In general, waters were slightly cooler in the northwest and southwest regions than in the northeast and southeast regions (Fig. 12.4.1e). Vertical comparisons of CTD profiles (Fig. 12.4.1f) reveal an east–west gradient in stratification, with stratified conditions observed in the northeast and southeast regions (casts 6–12) and well-mixed waters found in the northwest and southwest regions (casts 1–5, 14–16). A broad range in water temperature (1.3°C) values, moderate ranges in salinity (0.2 psu) and density (0.5kg m^{-3}) values, and a small range in beam transmission (< 1%) values were recorded.

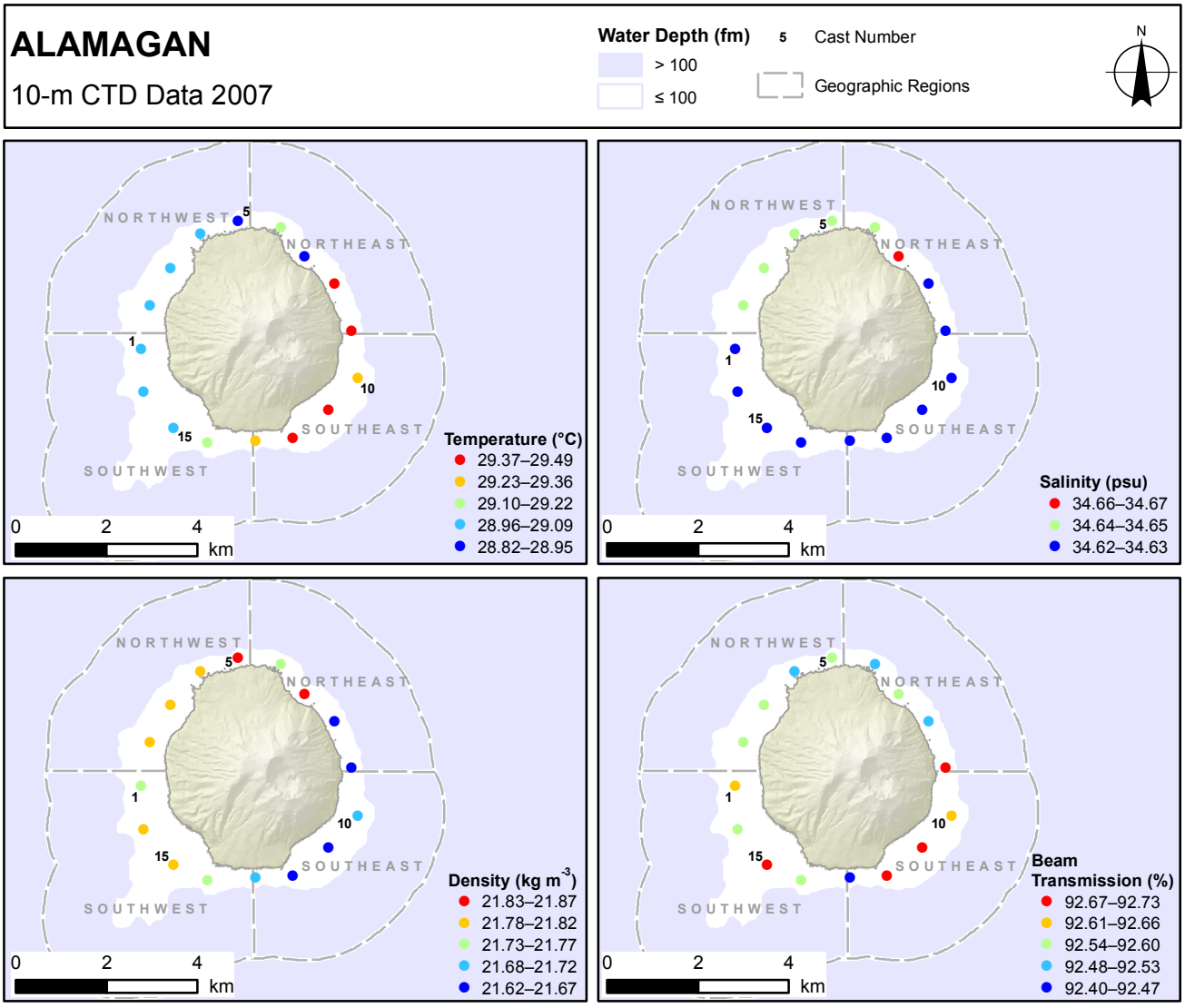


Figure 12.4.1e. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Alamagan on May 28 during MARAMP 2007.

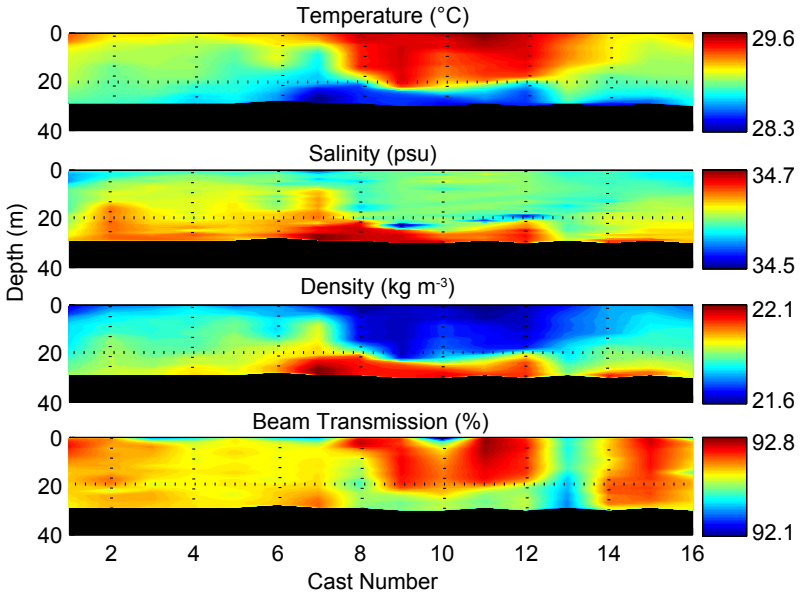


Figure 12.4.1f. Shallow-water CTD cast profiles to a 30-m depth around Alamagan on May 28 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–16 in a clockwise direction around Alamagan. For cast locations and numbers around this island in 2007, see Figure 12.4.1e.

Water samples were collected in concert with shallow-water CTD casts at 4 select locations at Alamagan to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.058–0.074 µg L^{-1}; total nitrogen (TN), 0.003–0.055 µM; nitrate (NO_3^-), 0.002–0.050 µM; nitrite (NO_2^-), 0.001–0.006 µM; phosphate (PO_4^{3-}), 0.035–0.040 µM; and silicate ($Si[OH]_4$), 1.13–1.29 µM. In general, water-quality parameters were low in 2007, typical of the Western Pacific Warm Pool's oligotrophic, oceanic surface layers. The highest Chl-*a* values were observed in the northeast and southwest regions, while the highest values of total nitrogen, nitrate, nitrite, and silicate were found in the northwest and southwest regions (Fig. 12.4.1g). Levels of phosphate and silicate were relatively homogenous in all 4 regions.

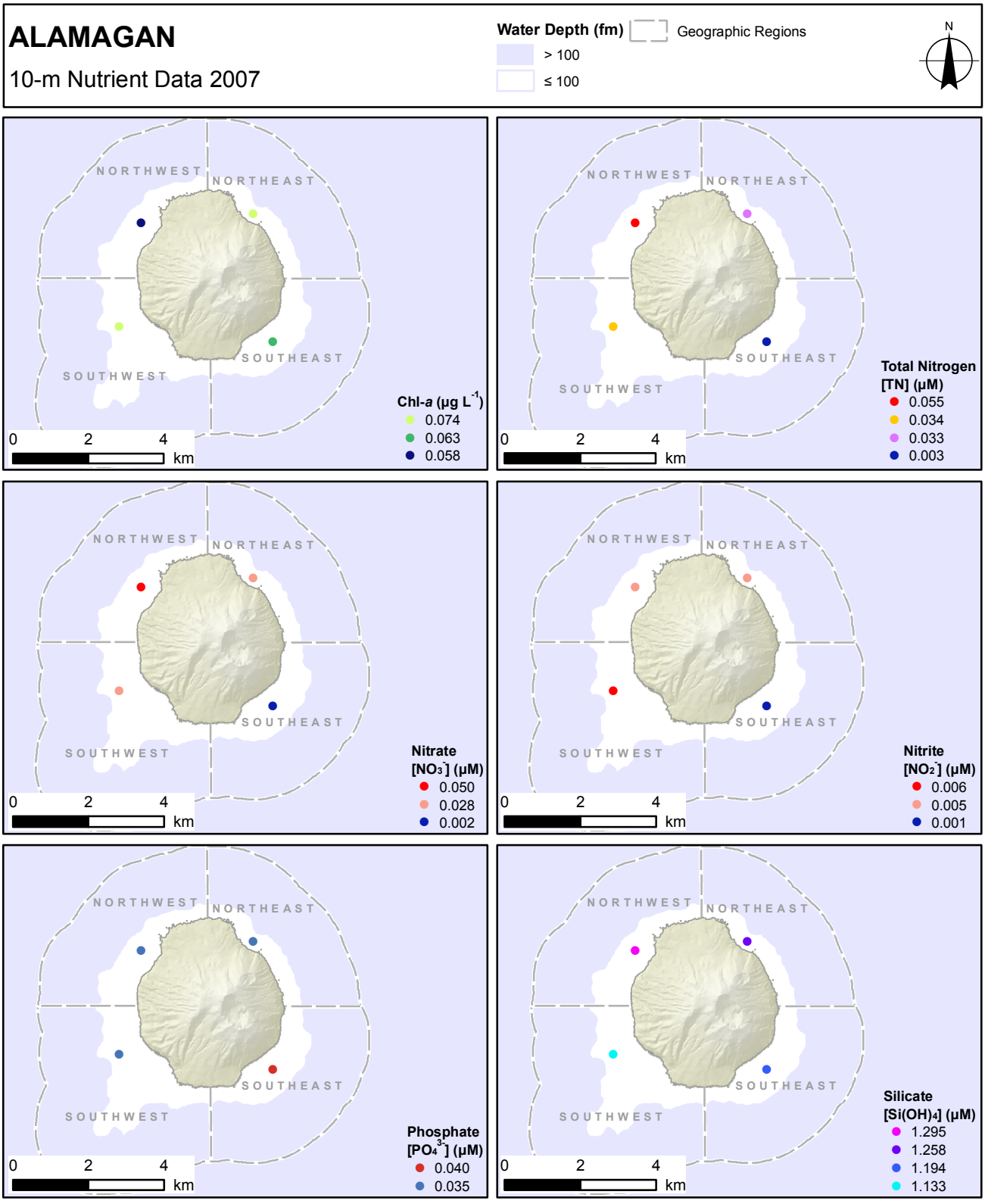


Figure 12.4.1g. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Alamagan on May 28 during MARAMP 2007.

Temporal Comparison

Temporal comparisons of shallow-water CTD data collected during MARAMP 2003, 2005, and 2007 suggest a dynamic physical oceanographic environment. In 2003 and 2005, moderate and little, respectively, variability was observed both spatially and vertical variability. In comparison, in 2007, variance in water properties was greater in vertical comparisons than in spatial comparisons. Data from both MARAMP 2003 and 2007 show east–west patterns in temperature values, although differences in temperature were greater in 2007, and the pattern observed in 2005 was the reverse of the one seen in 2007. Recorded temperatures were much lower in 2007 than in either of the previous 2 MARAMP survey years. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May, and MARAMP 2003 and 2005 occurred in September.

12 4.2 Time-series Observations

Between 2003 and 2007, subsurface temperature recorders (STRs) were moored at Alamagan to collect time-series observations of temperature, a key oceanographic parameter influencing reef conditions (Fig. 12.4.2a). The locations, depths, time frames, and other details about these deployments are provided in Figures 12.4.2a and b.

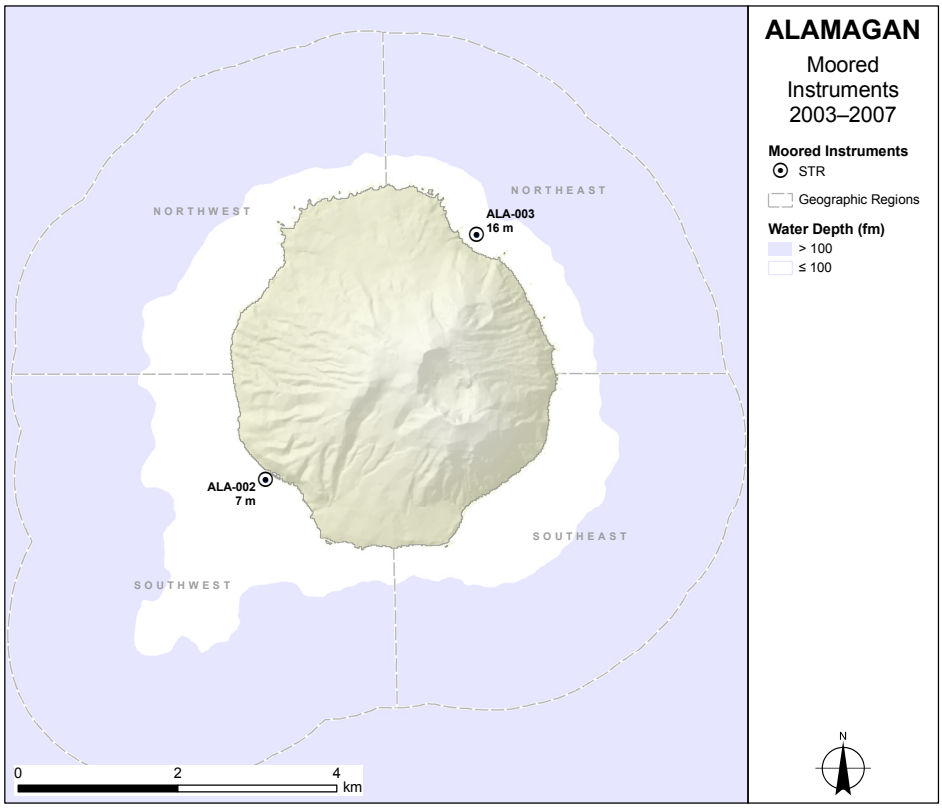


Figure 12.4.2a. Locations and depths of the STRs deployed at Alamagan during MARAMP 2003, 2005, and 2007.

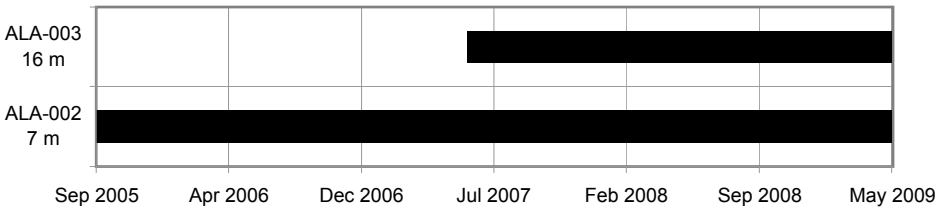


Figure 12.4.2b. Deployment timelines and depths of the STRs moored at Alamagan during the period from September 2005 and May 2009. A solid bar indicates the period for which data were collected by a single STR (ALA-003) or a series of STRs (ALA-002) deployed and retrieved at each mooring site. For more information about deployments and retrievals, see Table 12.2b in Section 12.2: "Survey Effort."

Temperature data from an STR moored at a depth of 7 m in the southwest region during the period from September 2005 to May 2007 exhibit seasonal temperature variability ~ 4°C between summer and winter months (Fig. 12.4.2c). Water temperatures reached ~ 30°C during the months of June–October and fell to a low of ~ 25°C during the months of January–May. Daily temperature excursions of ~ 0.2°C were recorded throughout this temperature time series, owing to diel heating and cooling of the water column. Temperatures in September 2006 reached the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean, although this event was relatively brief, lasting less than 1 d.

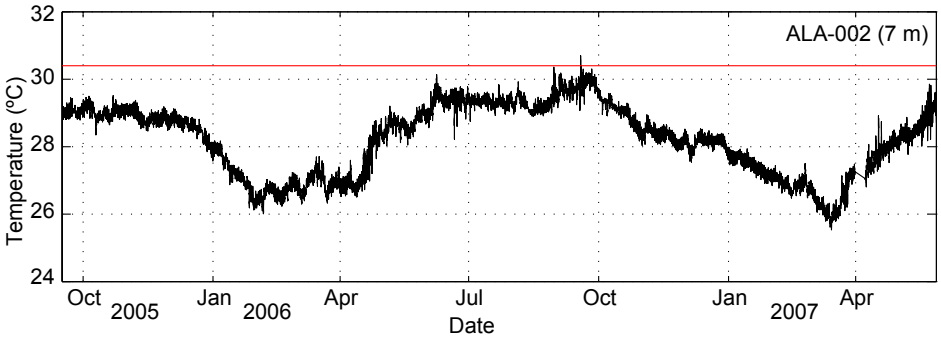


Figure 12.4.2c. Time-series observations of temperature over the period between September 2005 and May 2007 collected from 1 STR deployed at a depth of 7 m at mooring site ALA-002 (see Figure 12.4.2a for mooring locations). The red line indicates the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

12.4.3 Wave Watch III Climatology

Seasonal wave climatology for Alamagan (Fig. 12.4.3a) was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008, and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). The wave regime near Alamagan during typhoon season was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (~ 80°–100°). Superimposed with these short-period swells were large (> 5 m), long-period (12–16 s) wave events from the south (160°–190°) and south-southeast (200°–210°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate (2.5–3.5 m) wave heights could occur from any direction and likely were associated with episodic, medium-sized, or distant storms. The wave climate outside the typhoon season (February–June) also was characterized by frequent (> 30 d per season) and short-period (~8 s) trade wind swells with relatively small (~ 2 m) wave heights originating from the east. Infrequent (< 5 d per season), long-period (12–14 s) swells with moderate (~2–3 m) wave heights also occurred during this time and could originate from any direction.

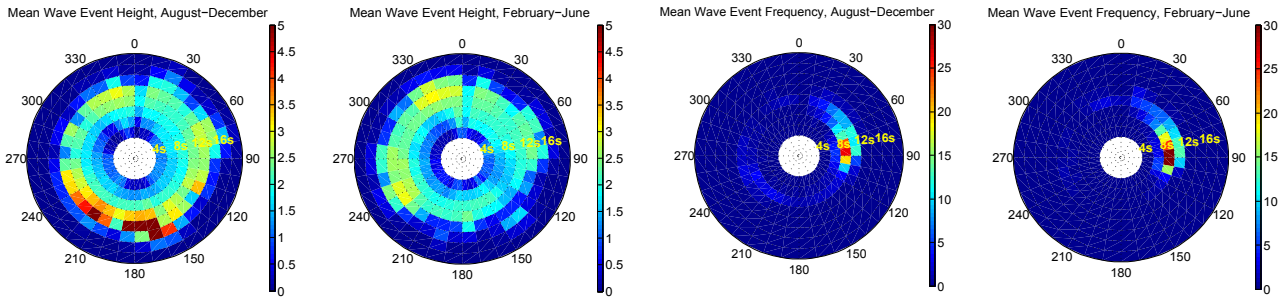


Figure 12.4.3a. NOAA Wave Watch III directional wave climatology for Alamagan from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Alamagan (17°36′ N, 145°50′ E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

12.5 Corals and Coral Disease

12.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Alamagan was 18% (SE 1.4). Coral cover was variable around Alamgan, with the lowest value reported in the southwest region (Fig. 12.5.1a, top panel).

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Alamagan was 17% (SE 1.5). Coral cover was variable around this island, with a localized area of high cover, relative to other survey areas at Alamagan, observed in the northeast region over 9 survey segments with a mean of 31% (Fig. 12.5.1a, middle panel). Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 0.4% (SE 0.04) of coral cover observed on forereef habitats around Alamagan appeared stressed. Estimates of stressed-coral cover from towed-diver surveys was low for the majority of reefs surveyed around Alamagan in 2005.

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Alamagan was 22% (SE 1.6). Coral cover was variable around Alamagan, with the highest coral cover found in the northwest region, for 8 segments with a mean of 38% (Fig. 12.5.1a, bottom panel). Overall, 1% (SE 0.57) of coral cover observed on forereef habitats around this island appeared stressed in 2007. Estimates of stressed-coral cover from towed-diver surveys conducted in 2007 were low for the majority of reefs surveyed around this island.

During MARAMP 2007, 3 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats around Alamagan. Site-specific estimates of live-hard-coral cover from these surveys ranged from 16.7% to 33.3% with an overall sample mean of 23.5% (SE 5). Coral cover was highest at REA site ALA-03 in the southwest region and lowest at ALA-01 in the northeast region (Fig. 12.5.1b, bottom panel).

During MARAMP 2003, 3 REA benthic surveys using the quadrat method on forereef habitats at Alamagan documented 379 coral colonies within a survey area of 11.25 m^2. Site-specific coral-colony density ranged from 32 to 36.3 colonies m^{-2} with an overall sample mean of 33.7 colonies m^{-2} (SE 1.3) at Alamagan. The highest colony density was recorded at ALA-01 in the northeast region, and the lowest colony density was observed at ALA-02 in the northwest region (Fig. 12.5.1b, top panel).

During MARAMP 2005, 3 REA benthic surveys using the quadrat method on forereef habitats at Alamagan documented 646 coral colonies within a survey area of 12 m^2. Site-specific coral-colony density ranged from 50.8 to 55.6 colonies m^{-2} with an overall sample mean of 53.8 colonies m^{-2} (SE 1.5). The highest colony density was recorded at ALA-02 in the northwest region, and the lowest colony density was observed at ALA-01 in the northeast region (Fig. 12.5.1b, middle panel).

During MARAMP 2007, 3 REA benthic surveys using the quadrat method on forereef habitats at Alamagan documented 583 coral colonies within a survey area of 12 m^2. Site-specific coral-colony density ranged from 41 to 53.8 colonies m^{-2}, with an overall sample mean of 48.6 colonies m^{-2} (SE 3.9). Similar to survey results in 2005, the highest colony density was recorded at ALA-02 in the northwest region, and the lowest colony density was observed at ALA-01 in the northeast region (Fig. 12.5.1b, bottom panel).

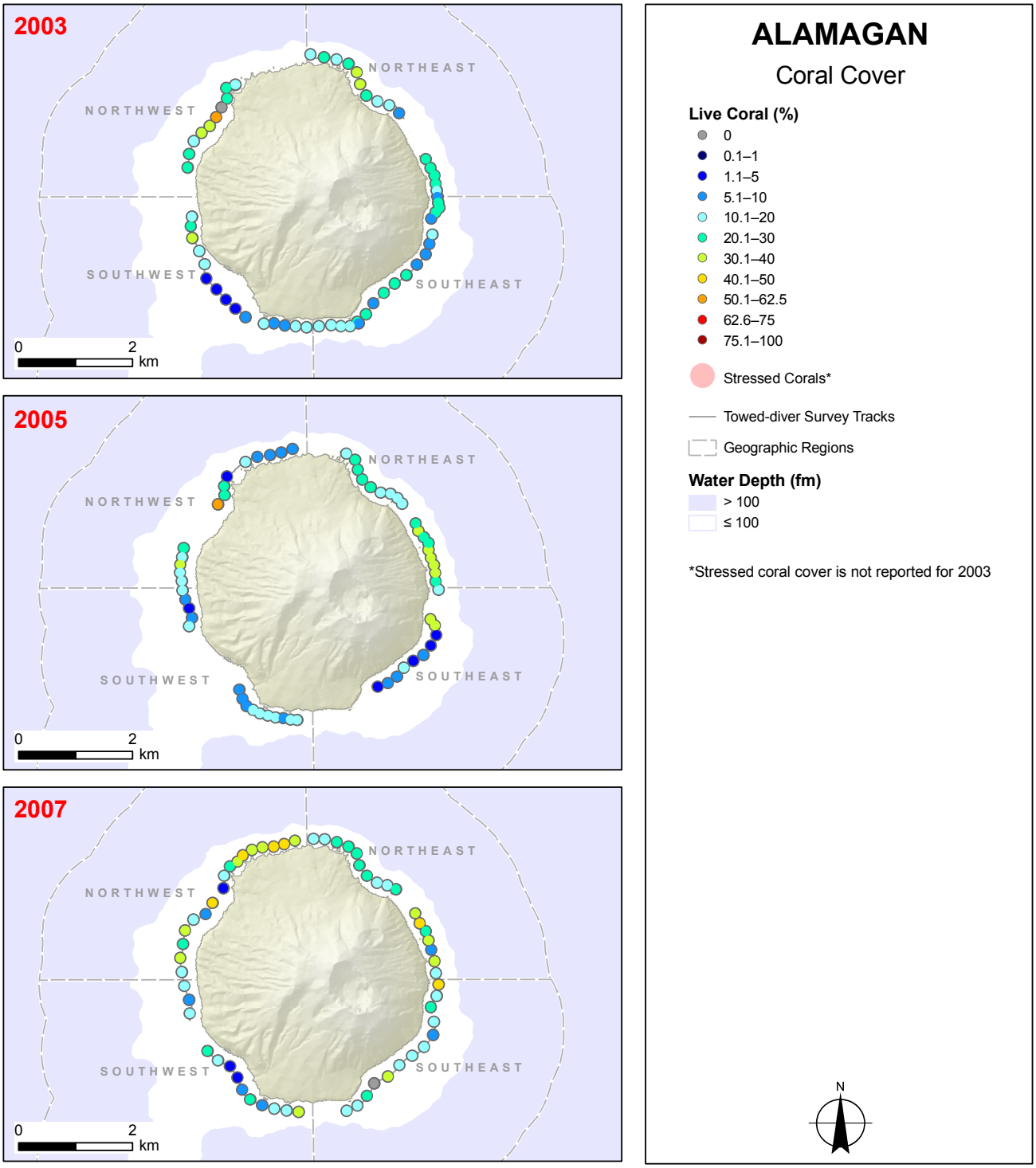


Figure 12.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted around Alamagan during MARAMP 2003, 2005, and 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols are shown only for segments where stressed-coral cover was > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005 and 2007.

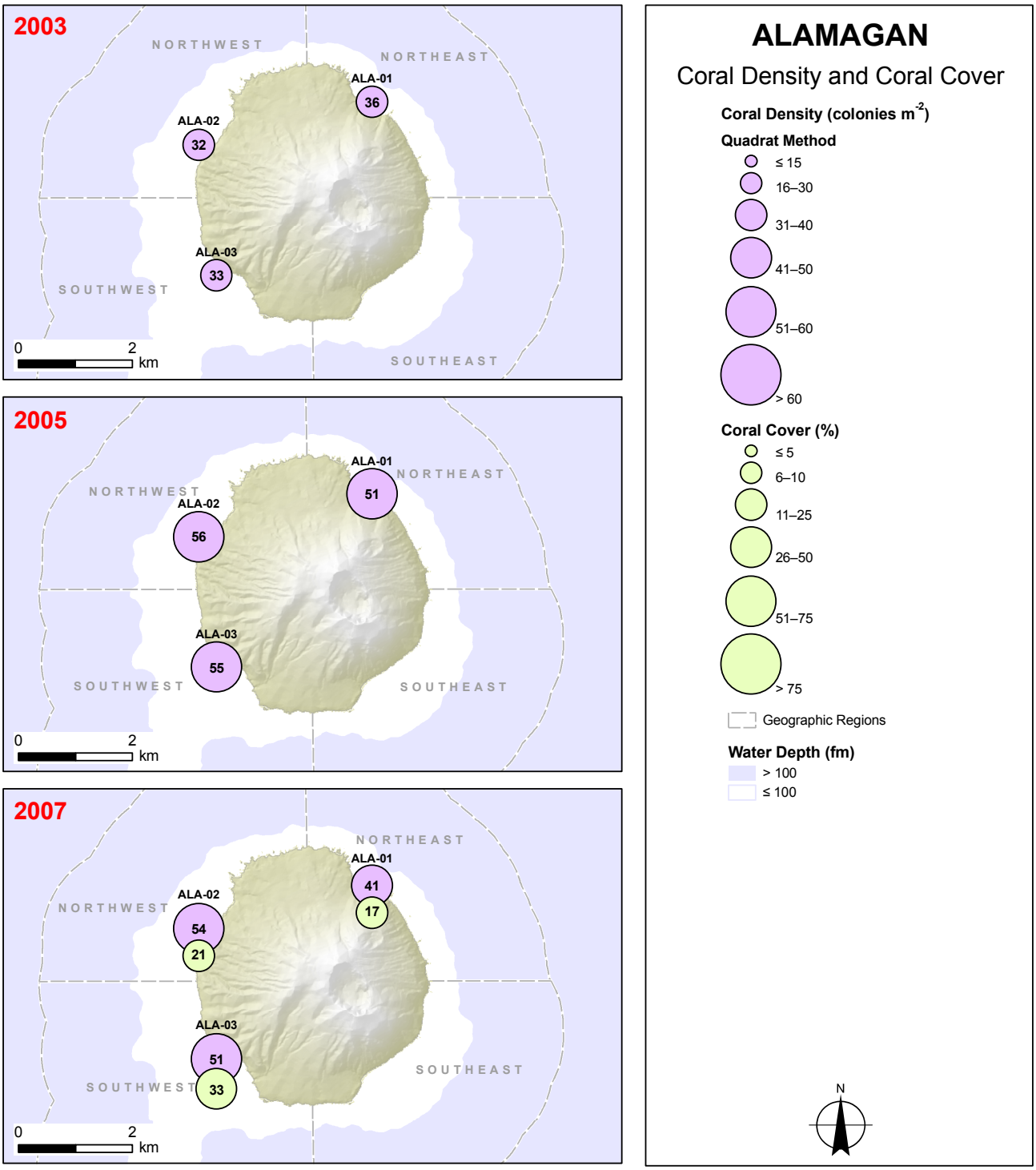


Figure 12.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Alamagan during MARAMP 2003, 2005, and 2007 and cover (%) observations of live corals from REA benthic surveys during MARAMP 2007. Values are provided within each symbol. The quadrat method was used to assess coral-colony density.

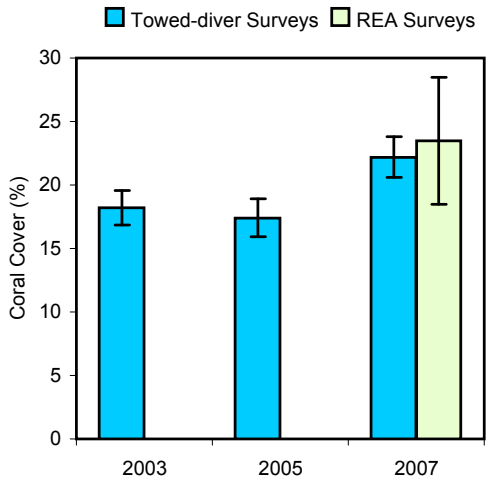


Figure 12.5.1c. Temporal comparison of mean live-coral-cover (%) values from REA and towed-diver benthic surveys conducted on forereef habitats around Alamagan during MARAMP 2003, 2005, and 2007. No REA coral-cover surveys using the line-point-intercept method were conducted around Alamagan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

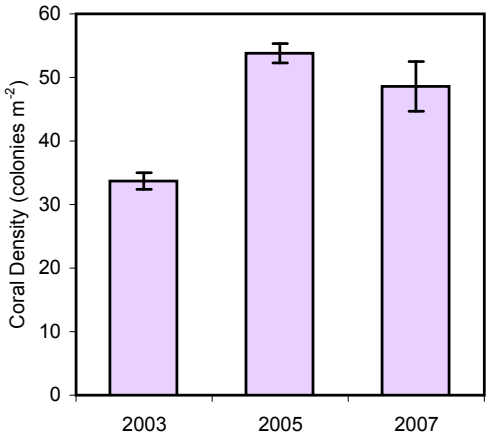


Figure 12.5.1d. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Alamagan during MARAMP 2003, 2005, and 2007. The quadrat method was used in the 3 survey years to measure coral-colony density. Error bars indicate standard error (± 1 SE) of the mean.

Islandwide mean cover of live hard corals, estimated from towed-diver surveys of forereef habitats, varied little between MARAMP survey years, ranging from 18% (SE 1.4) and 17% (SE 1.5) in 2003 and 2005 to 22% (SE 1.6) in 2007 (Fig. 12.5.1c). The spatial variation between the 3 MARAMP towed-diver survey efforts reasonably accounts for the relatively small variation in mean live-coral-cover values between survey years. Estimates of coral cover from REA surveys were similar to towed-diver survey results, with an overall sample mean of 23.5% (SE 5) for the 3 REA sites surveyed in 2007.

The overall sample mean of coral-colony density from REA benthic surveys of forereef habitats at Alamagan, using the quadrat method, increased from 33.7 colonies m^{-2} (SE 1.3) in 2003 to 53.8 colonies m^{-2} (SE 1.5) in 2005 and 48.6 colonies m^{-2} (SE 3.9) in 2007 (Fig. 12.5.1d). Variation in overall and site-specific density distributions between MARAMP survey years may result from chance differences in quadrat placement, increased recruitment, or fragmentation of existing colonies.

Coral Generic Richness and Relative Abundance

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Alamagan during MARAMP 2003, and 21 coral genera were observed at Alamagan. Generic richness ranged from 12 to 18 with a mean of 15.3 (SE 1.8) coral genera per site. The highest generic diversity was seen at ALA-03 in the southwest region, and the lowest generic diversity was recorded at ALA-02 in the northwest region (Fig. 12.5.1e, top panel). *Favia*, *Pavona*, and *Astreopora* were the most numerically abundant genera, contributing 15.7%, 15.2%, and 14% of the total number of colonies enumerated at Alamagan in 2003. All other genera individually accounted for < 10% of the total number of colonies. The genus *Astreopora* dominated the coral fauna at ALA-02, contributing 26.7% of the total number of colonies recorded at that site. The genus *Pavona* dominated at ALA-03 in the southwest region and the genus *Favia* dominated at ALA-01 in the northeast region, contributing 24.4% and 13.2% to the total number of colonies observed at their respective sites.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Alamagan during MARAMP 2005, and 23 coral genera were observed at Alamagan. Generic richness ranged from 14 to 21 with a mean of 16.7 (SE 2.2) coral genera per site. The highest generic diversity was seen at ALA-01 in the northeast region, and the lowest generic diversity was observed at ALA-02 in the northwest region (Fig. 12.5.1e, middle panel). *Astreopora*, *Pavona*, and *Favia* were the most numerically abundant genera, contributing 18.7%, 16.9%, and 14.4% of the total number of colonies enumerated at Alamagan in 2005. All other genera individually accounted for < 10% to the total number of colonies. The genus *Astreopora* dominated the coral fauna at ALA-03 in the southwest region, contributing 24% of the total number of colonies recorded at that site, as well as at ALA-02, contributing 21.2% of the total colonies at that site. The genus *Montipora* dominated the coral fauna at ALA-01, contributing 18.7% of the total number of colonies observed at that site.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Alamagan during MARAMP 2007, and 23 coral genera were observed at Alamagan. Generic richness ranged from 14 to 19 with a mean of 17.3 (SE 1.7) genera per site. The highest generic diversities were seen at ALA-01 and ALA-03 in the northeast and southwest regions, and the lowest generic diversity was observed at ALA-02 in the northwest region (Fig. 12.5.1e, bottom panel). Similar to survey results in 2003 and 2005, *Astreopora, Favia, and Pavona* were the most numerically abundant genera, contributing 17.1%, 15.5%, and 15.6% of the total number of colonies enumerated at Alamagan in 2007. All other genera individually

accounted for < 10% of the total number of colonies. The genus *Astreopora* dominated the coral fauna at ALA-02, contributing 25.1% of the total number of colonies recorded at that site, while *Montipora* (15.9%) and *Favia* (18.6%) were the dominant genera at ALA-01 and ALA-03, respectively.

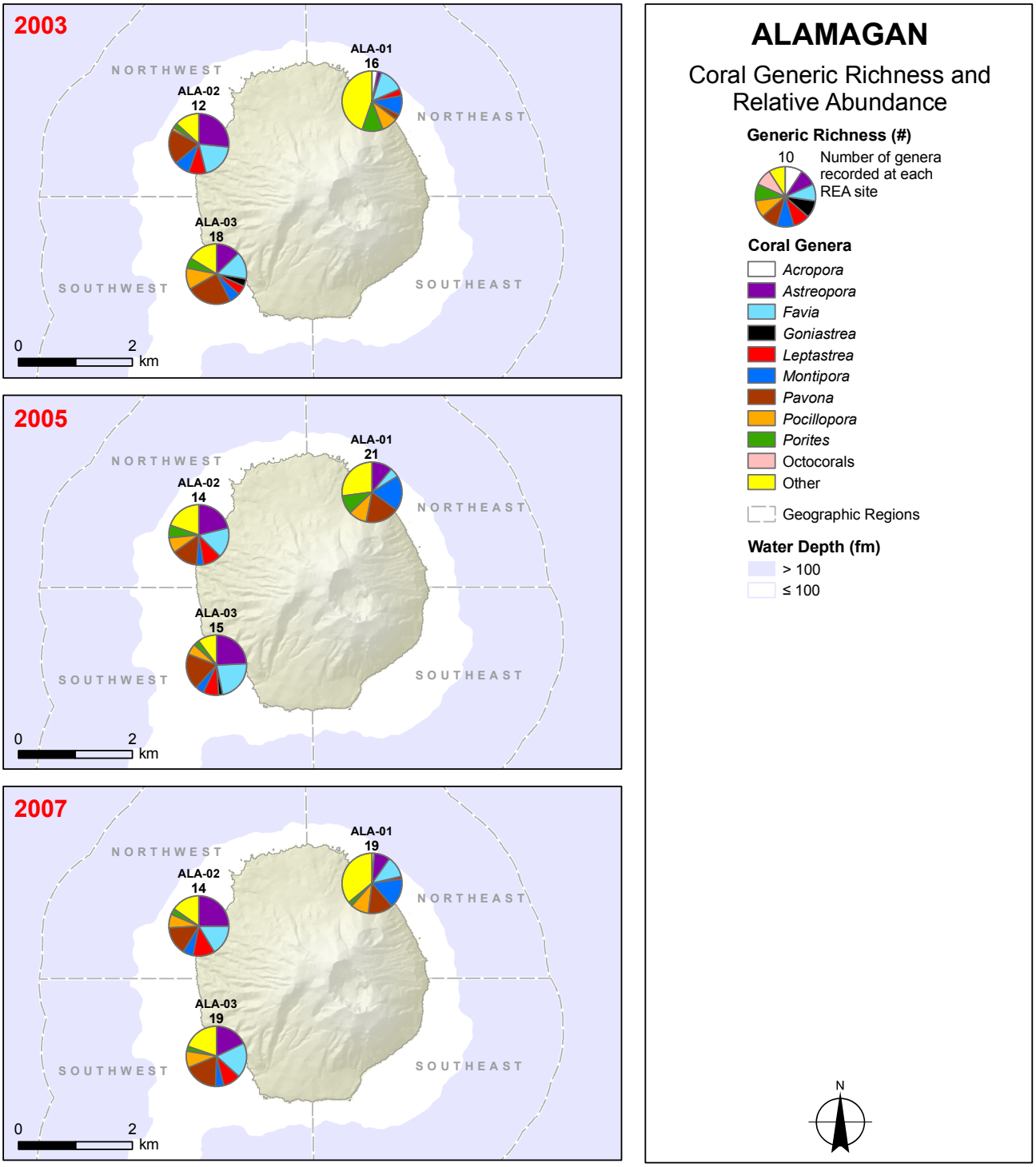


Figure 12.5.1e. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Alamagan during MARAMP 2003, 2005, and 2007. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in the 3 survey years to survey coral genera.

Site-specific estimates of generic richness across the 3 MARAMP survey years ranged from 12 to 21 on forereef habitats at Alamagan. Overall sample means of generic richness remained similar between the 3 survey years with 15.3 (SE 1.8) in 2003, 16.7 (SE 2.2) in 2005, and 17.3 (SE 1.7) in 2007 (Fig. 12.5.1f). There were more genera observed at Alamagan in 2005 and 2007 than in 2003 overall and at individual sites. The quadrat method was used during the 3 survey years to assess generic richness.

Across the 3 MARAMP survey years, 25 coral genera were observed on forereef habitats at Alamagan. The genera *Astreopora*, *Pavona*, and *Favia* were important components of the coral fauna at Alamagan, contributing > 10% of the total number of colonies enumerated in the 3 survey years. The genus *Astreopora* was the most numerically abundant taxon in 2005 and 2007 and the third-most abundant taxon in 2003, contributing 18.7%, 17.1%, and 14% of the total number of colonies enumerated in each survey year. The genus *Favia* was the most numerically abundant taxon in 2003 and the third-most abundant taxon in 2005 and 2007, accounting for 15.7%, 14.4%, and 15.5% of the total number of colonies enumerated in each survey period. The genus *Pavona* was the second-most numerically abundant taxon in the 3 survey years, contributing 15.2%, 16.9%, and 15.6% of the total number of colonies enumerated. All other taxa individually contributed < 10% of the total number of colonies enumerated across the 3 survey years.

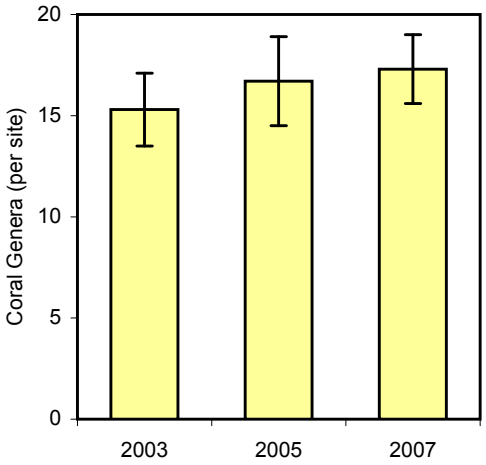


Figure 12.5.1f. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Alamagan during MARAMP 2003, 2005, and 2007. The quadrat method was used in the 3 survey years to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

Coral Size-class Distribution

During MARAMP 2003, 3 REA benthic surveys of forereef habitats were conducted at Alamagan using the quadrat method. The coral size-class distributions from these surveys shows that the majority (60.8%) of corals had maximum diameters ≤ 5 cm. The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 27.7%, 8.2%, 2.9% and 0.5% of colonies recorded. No colonies with maximum diameters > 80 cm were recorded. At each REA site, a majority (> 52%) of corals were in the smallest size class (0–5 cm; Fig. 12.5.1g, top panel).

During MARAMP 2005, 3 REA benthic surveys of forereef habitats were conducted at Alamagan using the quadrat method. The coral size-class distributions from these surveys shows that the majority (69.7%) of corals had maximum diameters ≤ 5 cm. The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 19.7%, 9.6%, and 1.1% of colonies recorded. No colonies with maximum diameters > 40 cm were recorded. At each REA site, a majority (> 60%) of corals were in the smallest size class (0–5 cm; Fig. 12.5.1g, middle panel).

During MARAMP 2007, 3 REA benthic surveys of forereef habitats were conducted at Alamagan using the quadrat method. The coral size-class distributions from these surveys shows that the majority (65.1%) of corals had maximum diameters ≤ 5 cm. The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 24.4%, 6.3%, 4% and 0.2% of colonies recorded. No colonies with maximum diameters > 80 cm were recorded. At each REA site, a majority (> 56%) of corals were in the smallest size class (0–5 cm; Fig. 12.5.1g, bottom panel).

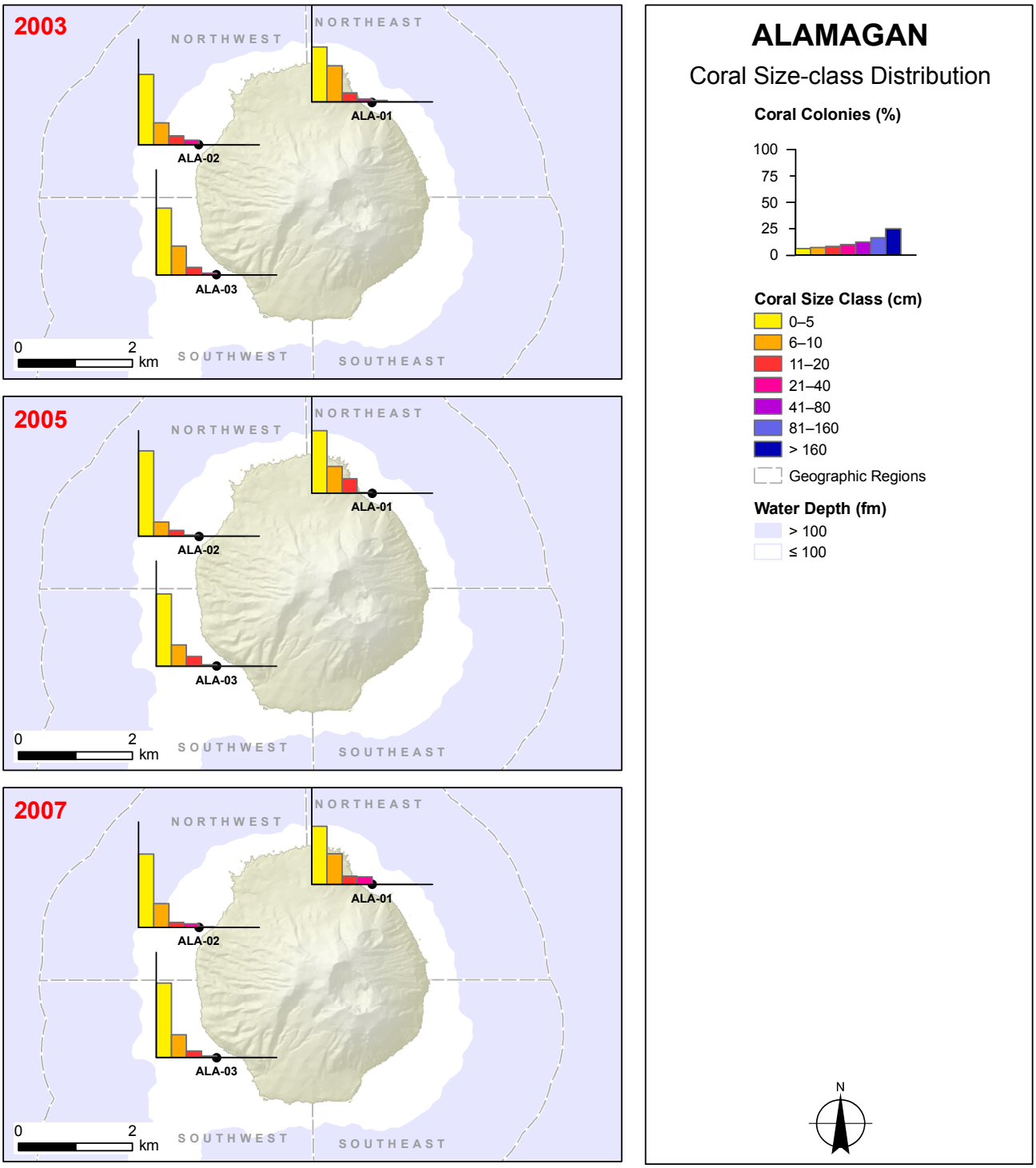
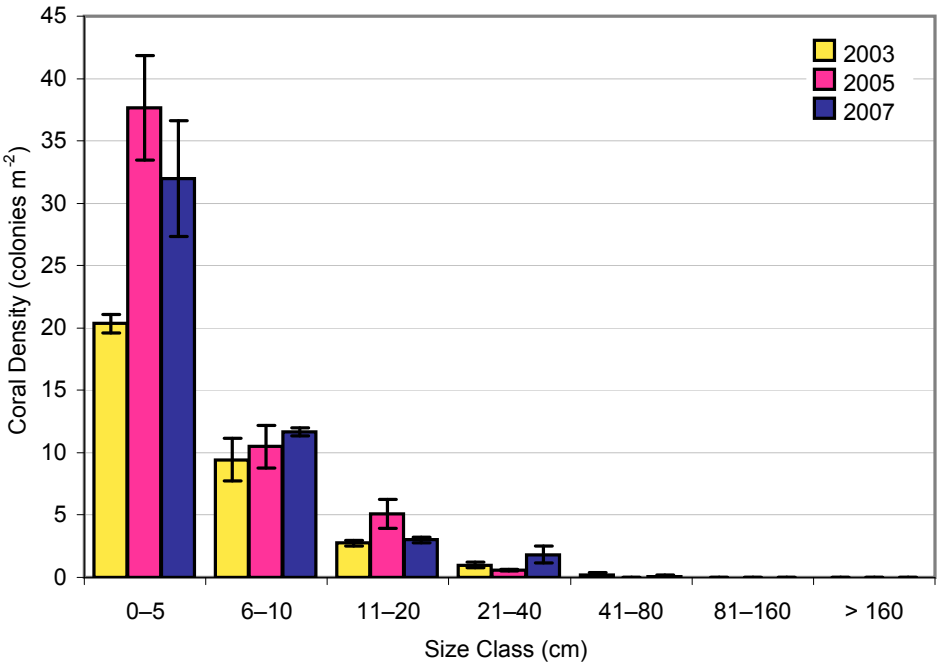


Figure 12.5.1g. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Alamagan during MARAMP 2003, 2005 and 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in the 3 survey years to size corals.

Site-specific distributions of coral size classes reflect inherent biases in the quadrat method used to census and size corals. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. For more on this survey method, see Chapter 2: "Methods and Operational Background," Section 2.4.5: "Corals and Coral Disease."

In each of 3 MARAMP survey years, the number of coral colonies censused on forereef habitats at Alamagan was > 20 colonies m^{-2} in the smallest size class (0–5 cm; Fig. 12.5.1h). The overall sample mean proportion of colonies that fell in the smallest size class varied between MARAMP survey years, as did site-specific size-class distributions. Concordantly, the overall sample mean and site-specific proportions of colonies in all other size classes fluctuated between years. That coral colonies fell in the smallest size class with greater frequency than in other size classes is likely an outcome of recruitment or fragmentation of existing colonies, while minor variation between survey years in overall and site-specific size-class distributions likely results from chance differences in individual quadrat placements.

Figure 12.5.1h. Mean coral-colony densities (colonies m^{-2}) by size-class from REA benthic surveys of forereef habitats conducted at Alamagan during MARAMP 2003, 2005, and 2007. The quadrat method was used in all 3 years to size corals. Error bars indicate standard error (± 1 SE) of the mean.



12.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted at 3 sites on forereef habitats at Alamagan, covering a total area of 900 m^2. Six cases of disease were detected, translating to an overall mean prevalence of 0.01% (SE 0.01). Coral-colony counts at all REA sites at Alamagan were conducted using the quadrat method, resulting in high coral-colony densities and, therefore, low disease prevalence values, relative to the levels found at sites at other islands surveyed using the belt-transect method.

Two major disease conditions and other syndromes were observed at Alamagan (Fig. 12.5.2a). The most abundant disease state was bleaching, followed by subacute tissue loss and other syndromes, particularly infestation and overgrowth by the encrusting sponge *Terpios*. All 3 sites contained disease; however, low prevalence values were observed (Fig. 12.5.2b). Four cases of bleaching were recorded at ALA-02 and ALA-03 on coral species of the genera *Plesiastrea*, *Echinopora*, and *Platygyra*. At both ALA-01 and ALA-03, only 1 case of tissue loss and 1 case of sponge overgrowth were detected on colonies of *Goniastrea*. No signs of predation scars from crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails, such as snails from the genus *Drupella*, were documented at Alamagan.

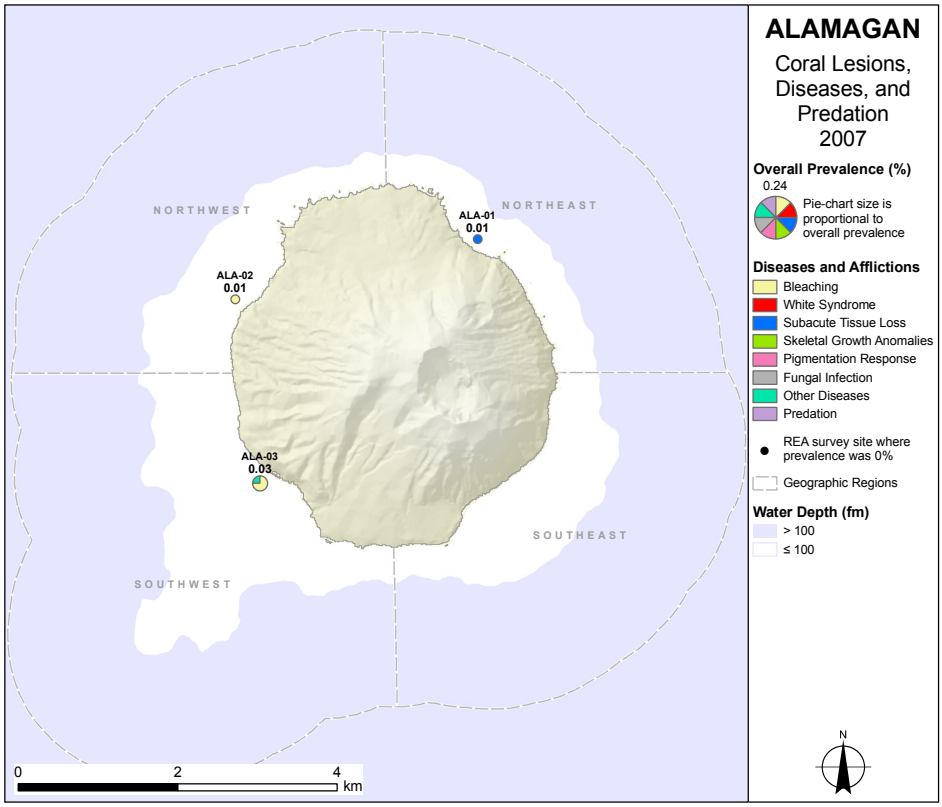


Figure 12.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Alamagan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie charts indicate disease-specific prevalence.

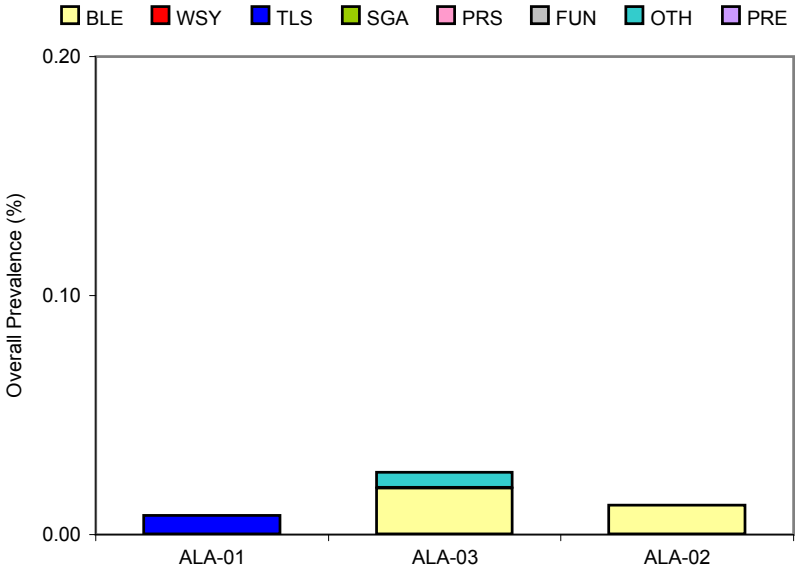


Figure 12.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Alamagan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infections; OTH: algal and cyanophyte infections and other lesion of unknown etiology; PRE: predation by crown-of-thorns seastars or corallivorous snails.

12.6 Algae and Algal Disease

12.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Alamagan was 41% (SE 2.3). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 52% occurred on the east side of this island and crossed the border between the northeast and southeast regions (Fig. 12.6.1a, top left panel). During this survey, habitat complexity was medium and the habitat types observed consistently were rubble (noted on more than half of the segments from this 5-min survey) and pavement. The 3 next-greatest values of mean macroalgal cover were found on the east and south sides of this island. The survey completed on the south side across the border of the southeast and southwest regions had a mean macroalgal cover of 45%, and the other 2 surveys conducted on the east side, in the southeast and northeast regions, each had a mean cover of 44%. The lowest mean macroalgal cover of 27% was recorded during the survey completed entirely in the southwest region.

TOAD surveys completed at Alamagan during MARAMP 2003 were conducted at depths of 45–280 m. Analyses of TOAD video footage obtained from 6 surveys suggested that there were almost no macroalgae in the northwest and southeast regions at least as seen in a majority of images; only 2 analyzed video frames showed any macroalgae at all, with cover of 20%. In contrast, analyses of video footage collected southwest of Alamagan suggested that, although much of the areas surveyed had little or no macroalgae, some of the areas surveyed had macroalgal cover of 20%–100%, with the highest macroalgal cover occurring at depths of 70–97 m. (Fig. 12.6.1a, top left panel).

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Alamagan was 26% (SE 2.7). The survey with the highest mean macroalgal cover of 52% occurred in the southern part of the southwest region (Fig. 12.6.1a, middle left panel). For 9 of the 10 segments of this survey, habitat complexity was described as medium-low or medium. The second-greatest macroalgal cover of 45% was observed in the southern part of the northeast region, and the lowest mean macroalgal cover of 1% was recorded in the southeast region.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats around Alamagan was 16% (SE 1.6). The survey with the highest mean macroalgal cover of 29% occurred on the east side of this island and crossed the border between the northeast and southeast regions (Fig. 12.6.1a, bottom left panel). Habitat in this area was documented mostly as medium or medium-high, and species of the calcified green macroalgal genus *Halimeda* were observed on each of the first 6 survey segments. The lowest mean macroalgal cover of 9% was recorded during a survey in the northwest region, and continuous reef and a moderate slope were noted for most of this survey's segments.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats at Alamagan were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 2.9% to 12.7% with an overall sample mean of 9% (SE 3.1). The survey with the highest macroalgal cover occurred in the northwest region at REA site ALA-02 (Fig. 12.6.1b). The lowest macroalgal cover was recorded in the southwest region at ALA-03.

Turf-algal cover from these REA surveys ranged from 43.1% to 56.9% with an overall sample mean of 50% (SE 4). The highest turf-algal cover of 56.8% occurred at ALA-01 in the northeast region (Fig. 12.6.1b). Turf-algal cover was 50% in the southwest region at ALA-03 and 43.1% in the northwest region at ALA-02.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Alamagan was 7% (SE 1.1). The survey with the highest crustose-coralline-red algal cover of 25% occurred in the northern part of the northeast region (Fig. 12.6.1a, top right panel). The lowest crustose-coralline-red-algal cover of 1% was recorded during 2 surveys: 1survey completed from the southeast to the southwest region, and 1 survey completed entirely in the southwest region. The 2 next-lowest values for mean cover were 2% and 3%, found during surveys completed in the northwest region and in the northern part of the southwest region.

Analyses of TOAD video footage obtained from the 6 surveys conducted during MARAMP 2003 suggested that there were no crustose coralline red algae in the surveyed areas, at least as observable from images.

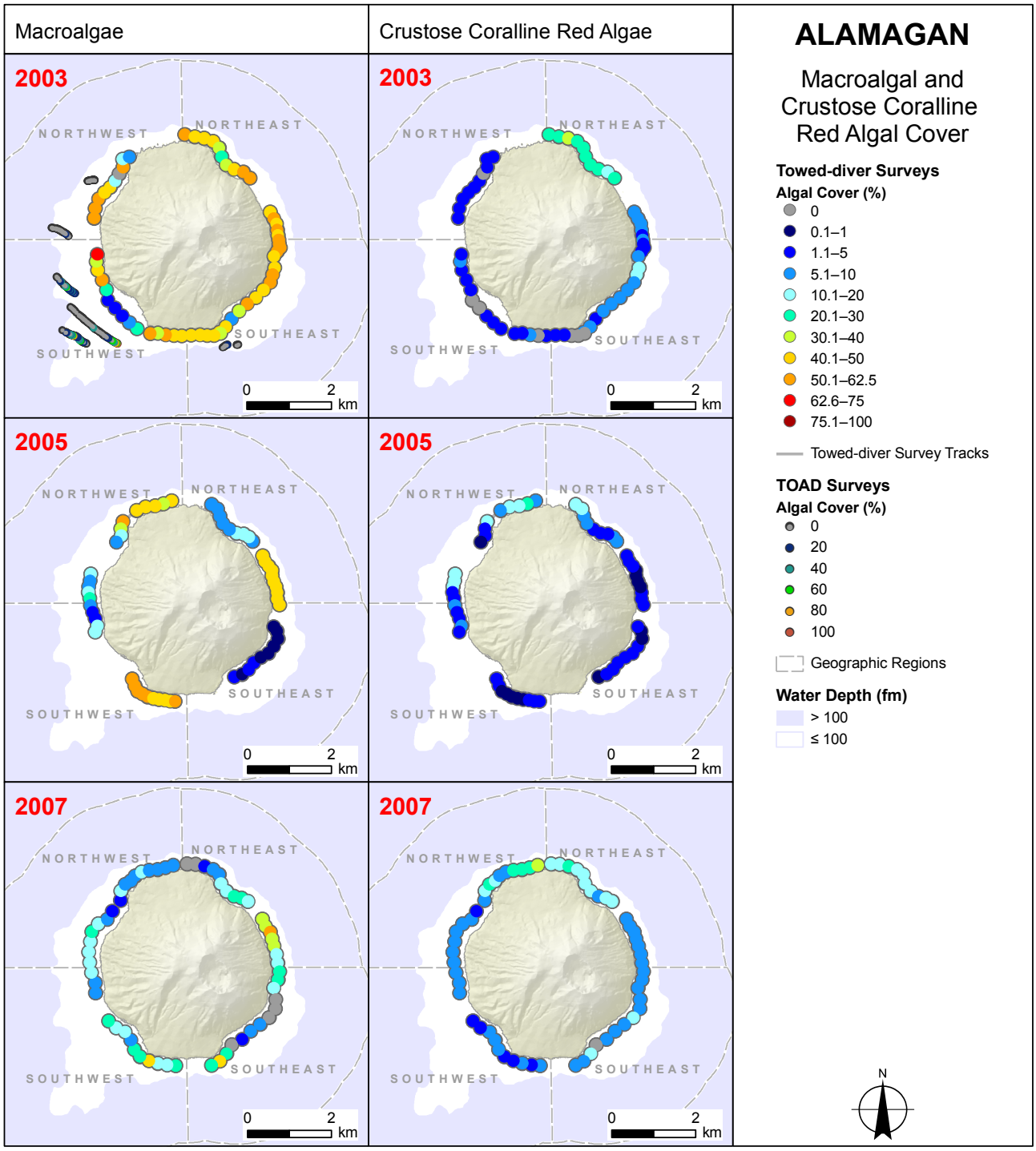


Figure 12.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Alamagan during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Alamagan was 5% (SE 0.7). The survey with the highest crustose-coralline-red-algal cover of 10% occurred in the northern part of the northwest region (Fig. 12.6.1a, middle right panel). The lowest mean cover for crustose coralline red algae was 2%, recorded during each of 3 surveys in the southwest, northeast, and southeast regions.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Alamagan was 10% (SE 0.9). The survey with the highest crustose-coralline-red-algal cover of 19% occurred in the northern part of the northwest region (Fig. 12.6.1a, bottom right panel). For this survey, the habitat was described as continuous reef of mostly medium-high complexity. The lowest mean cover for crustose coralline red algae of 5% was recorded in the southwest region.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats around Alamagan were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red algal cover ranged from 3.9% to 6.9% with an overall sample mean of 5% (SE 0.9). The survey with the highest mean cover of crustose coralline red algae occurred in the northeast region at ALA-01 (Fig. 12.6.1b). The lowest crustose-coralline-red-algal cover was recorded at ALA-02 in the northwest region.

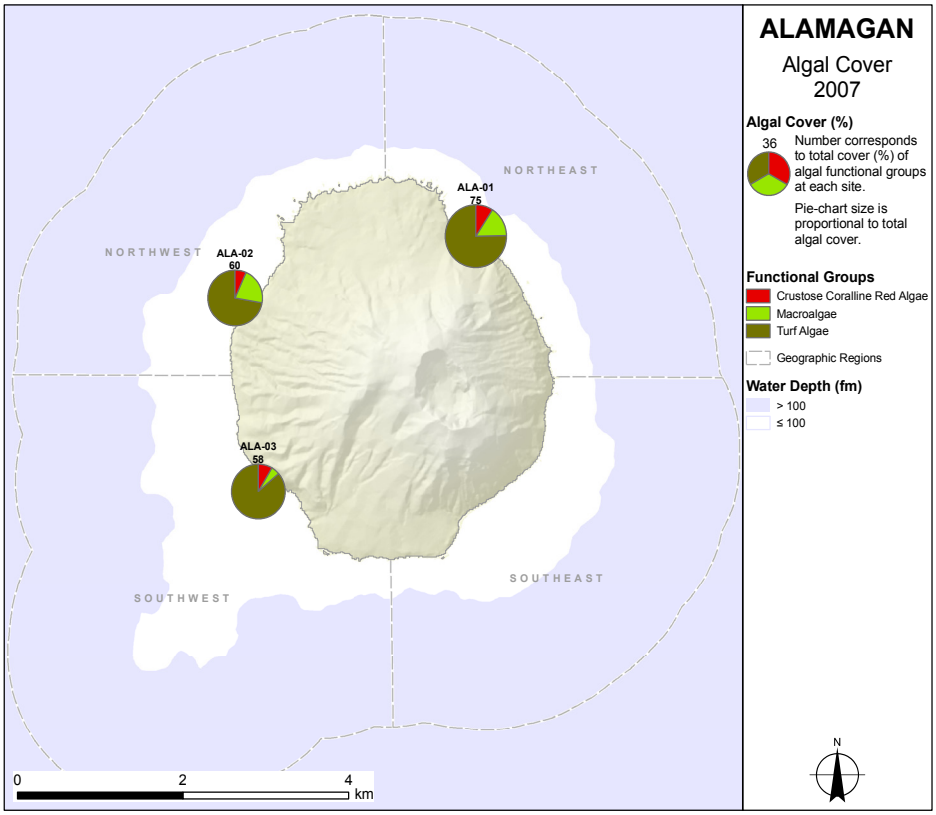


Figure 12.6.1b. Observations of algal cover (%) from REA benthic survey of forereef habitats conducted using the line-point-intercept method at Alamagan during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, islandwide mean cover of macroalgal populations around Alamagan, based on towed-diver surveys of forereef habitats, appeared to decrease from 26% (SE 2.7) in 2005 to 16% (SE 1.6) in 2007 (Fig. 12.6.1c). When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in macroalgal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Some of the highest levels of macroalgal cover found around Alamagam were observed consistently on the east side of this island exhibited. During each MARAMP survey year, a towed-diver survey crossed the border of the northeast and southeast regions, recording the highest macroalgal cover in 2003 and 2007 and the second-greatest value in 2005.

Crustose-coralline-red-algal populations around Alamagan, based on towed-diver survey of forereef habitats, had average cover values ≤ 10% during each of the 3 MARAMP survey years (Fig. 12.6.1c). Islandwide mean cover of crustose coralline red algae increased to 10% (SE 0.9) in 2007, when surveys were conducted in May, from 5% (SE 0.7) in 2005 and 7% (SE 1.1) in 2003.

The lowest mean cover of crustose coralline red algae around Alamagan was found consistently in the southern part of the southwest region during towed-diver surveys in each of the 3 survey years. The highest mean crustose-coralline-red algal cover was recorded in the northeast region in 2003 but in the northern part of the northwest region in 2005 and 2007.

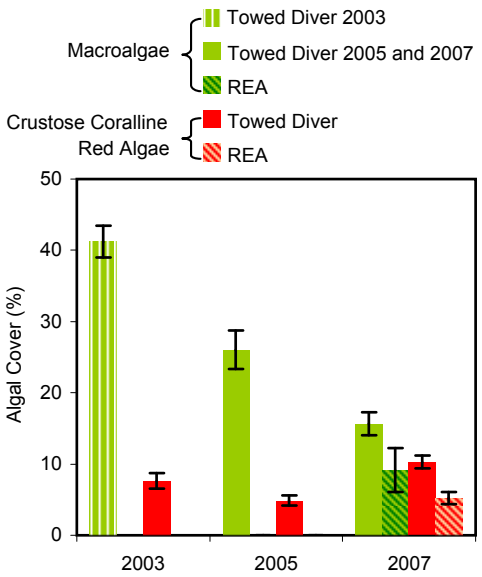


Figure 12.6.1c. Temporal comparison of algal-cover values (%) from surveys conducted on forereef habitats around Alamagan during MARAMP 2003, 2005, and 2007. Macroalgal cover from towed-diver surveys includes turf algae only in 2003. No REA algal-cover surveys using the line-point-intercept method were conducted in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 3 sites on forereef habitats at Alamagan. In the field, 9 macroalgal genera (3 red, 5 green, and 1 brown), containing at least 10 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. ALA-01 in the northeast region had the highest macroalgal generic diversity with 7 genera, containing 7 species, documented in the field. The lowest macroalgal generic diversity was found in the southwest region at ALA-03 with 3 species representing 3 genera recorded.

Species of the green algal genera *Chlorodesmis* and *Halimeda* were equally abundant and the most dominant taxa at Alamagan in 2003, occurring in 52.8% of the sampled photoquadrats. Of the 10 macroalgal species tentatively identified in the field, only a select few showed any spatial patterns of distribution. *Halimeda taenicola* and species of *Chlorodesmis* frequently were found at 2 sites on the west side of Alamagan, occurring in 50% and 83.3% of photoquadrats sampled at ALA-02 and in 100% and 75% of photoquadrats sampled at ALA-03 (Fig. 12.6.1d, top panel). At ALA-01 in the northeast region, the red algal genus *Amphiroa* and the brown algal genus *Lobophora* were recorded in 33.3% and 41.7% of sampled photoquadrats. Species of the green algal genera *Dictyosphaeria* and *Neomeris,* the red algal genus *Jania,* and an unknown species of *Halimeda* also were observed at ALA-01, all occurring in 8.3% of sampled photoquadrats. Species of the green algal genus *Caulerpa* were not recorded at ALA-01 but were found in 8.3% of photoquadrats sampled at both ALA-02 and ALA-03 in the northwest and southwest regions.

Turf algae and crustose coralline red algae both were exceptionally common in 2003, occurring in 100% and 66.7% of photoquadrats sampled at Alamagan (Fig. 12.6.1d, top panel). Turf-algal communities were ubiquitous at all sites, and although crustose coralline red algae occurred at all sites, the occurrence of this functional group varied within a range of 50%–58.3% at ALA-01 and ALA-02 in the northern regions and 91.7% at ALA-03 in the southwest region. Cyanobacteria, found in 16%–70.8% of sampled photoquadrats, were relatively common.

During MARAMP 2005, REA benthic surveys were conducted at 3 sites on forereef habitats at Alamagan. In the field, 12 macroalgal genera (6 red, 4 green, and 2 brown), containing at least 12 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. ALA-02 in the northwest region had the highest macroalgal generic diversity with 8 genera, each containing only 1 species, documented in the field. The lowest macroalgal generic diversity was found at ALA-03 in the southwest region with 6 species representing 6 genera recorded.

Species of the genus *Halimeda* were the most common macroalgae observed at this island in 2005, occurring in 55.6% of all sampled photoquadrats. Of the 12 macroalgal species tentatively identified in the field, only a select few showed any spatial patterns of distribution. Species of the genus *Halimeda* were recorded only at ALA-02 and ALA-03, in 75% and

91.7% of photoquadrats sampled at these sites (Fig. 12.6.1d, middle panel). The genus *Jania* also was common, occurring in 100% of sampled photoquads at ALA-03 in the southwest region and 33.3% at ALA-01 in the northeast region. At ALA-01, the red algal genus *Asparagopsis* and the brown algal genus *Dictyota* were recorded in 58.3% and 41.7% of the sampled photoquadrats. Species of *Amphiroa* and *Chlorodesmis* were observed at fairly high abundance at ALA-02, occurring in 50% and 58.3% of the photoquads sampled at that site. *Caulpera* and *Neomeris* were the only algal genera recorded at all sites in 2005, occurring in 8.3% and 16.7% of photoquadrats sampled.

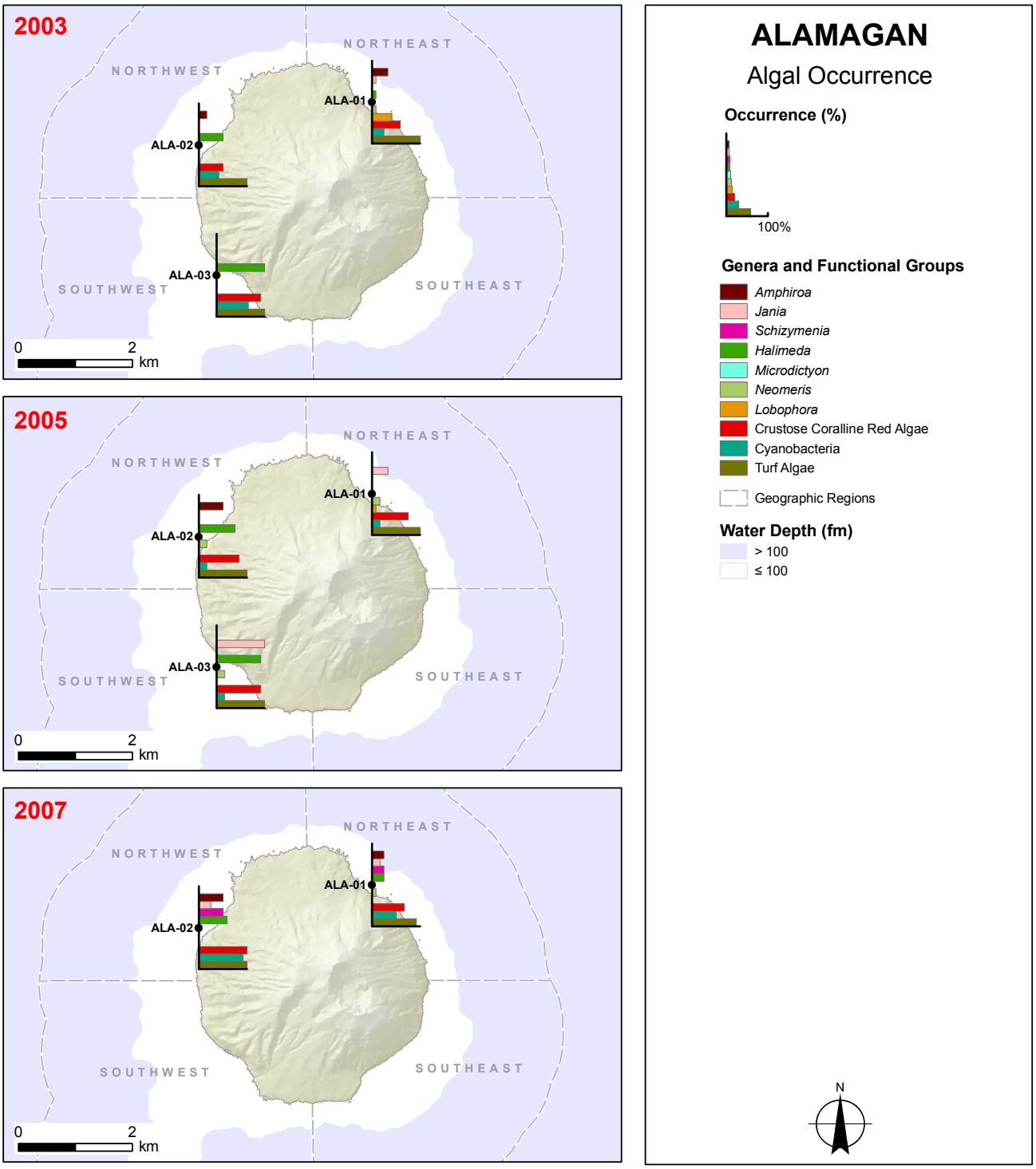


Figure 12.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Alamagan during MARAMP 2003, 2005, and 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

Turf algae and crustose coralline red algae were both exceptionally common in 2005, occurring in 100% and 83.3% of photoquadrats sampled at Alamagan. Cyanobacteria, in contrast, were found only in 16.7% of sampled photoquadrats.

During MARAMP 2007, REA benthic surveys were conducted at 2 sites on forereef habitats at Alamagan. In the field, 12 macroalgal genera (5 red, 5 green, and 2 brown), containing at least 12 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. ALA-01 in the northeast region had the highest macroalgal generic diversity with 11 genera, containing 11 species, documented in the field. Obeserved macroalgal generic diversity was lower at the other site, ALA-02 in the southwest region, with 8 species representing 8 genera recorded.

Species of the genera *Asparagopsis* and *Halimeda* were common at both sites surveyed at Alamagan in 2007, occurring in 50% and 41.7% of sampled photoquadrats (Fig. 12.6.1d, bottom panel). Of the 12 species recorded, 7 were found at both sites surveyed in 2007. Since only 2 sites were surveyed and both fell in the northern regions, distinctive spatial patterns of distribution were difficult to determine for most macroalgae at Alamagan. *Asparagopsis* was the most abundant macroalgal genus, occurring in 58.3% and 41.7% of photoquadrats sampled at ALA-01 and ALA-02. The genus *Halimeda* also was fairly abundant, occurring in slightly more than twice as many sampled photoquadrats at ALA-02 (58.3%) than at ALA-01 (25%). A similar pattern of distribution was found for the red algal genera *Schizymenia* and *Amphiroa*, both occurring in 50% of sampled photoquadrats at ALA-02 but only half that amount at ALA-01. Another green algal genus, *Boodlea*, was recorded in 41.7% of sampled photoquadrats at ALA-02, but, at ALA-01, this genus was observed only in a single photoquadrat with an occurrence of 8.3%. Other species recorded in low abundance were from the genera *Bornetella*, *Caulerpa*, *Culteria*, *Dictyota*, *Jania*, *Neomeris*, and *Peyssonnelia.*

Turf algae, crustose coralline red algae, and cyanobacteria all were exceptionally common in 2007, occurring in 95.8%, 83.3%, and 70.8% of photoquadrats sampled at Alamagan (Fig. 12.6.1d, bottom panel). Turf algae and crustose coralline red algae both occurred in 100% of sampled photoquads at ALA-02 but in fewer photoquadrats (91.7% and 66.7%) sampled at ALA-01. Cyanobacteria were twice as common at ALA-02 than at ALA-01, where they were found in 91.7% and 50% of sampled photquadrats.

The number of macroalgal genera recorded on forereef habitats at Alamagan increased from 9 genera during MARAMP 2003 to 12 genera during MARAMP 2005 and 2007, despite the fact that one less site was sampled in 2007 than in 2005 and 2003. Although 12 genera were observed in 2005 and 2007, the composition of the algal diversity is quite dissimilar between these MARAMP survey years. Difference in season and other factors likely can account for this difference in generic composition (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Further, it is likely that different seasonal flora were documented in 2005 and 2007 and that actual algal diversity over a given yearly cycle is greater than the 12 genera recorded both in 2005 and 2007.

Schizymenia, a red algal genus with obvious blade morphology, was not recorded at Alamagan in either 2003 or 2005 but in 2007 was found in 50% and 25% of photoquadrats sampled at ALA-01 and ALA-02 in the northeast and northwest regions. The genus *Boodlea*, found in 41.7% of sampled photoquadrats at ALA-02, is another example of previously unobserved alga appearing in relatively high abundance in 2007. Species of the genus *Halimeda* consistently had high occurrence values in the 3 survey years with overall sample means of 41.6%–55.6% (Fig. 12.6.1e). The occurrence of species of *Amphiroa* rose from 16.7% in 2003 and 2005 to 37.5% in 2007. Similarly, *Asparagopsi*s was recorded in 8.3% of sampled photoquadrats in 2003 but in 50% of sampled photoquadrats in 2007. Additionally, the abundance of *Jania* varied between MARAMP survey periods, occurring in only 2.7% of photoquadrats sampled in 2003 but in 44% and 20.8% of sampled photoquadrats in 2005 and 2007.

Turf algae and crustose coralline red algae occurred in 95.8%–100% and 66.7%–83.3% of photoquadrats sampled at Alamagan during MARAMP 2003, 2005, and 2007. No patterns showing changes over time in the abundance of these functional groups were obvious.

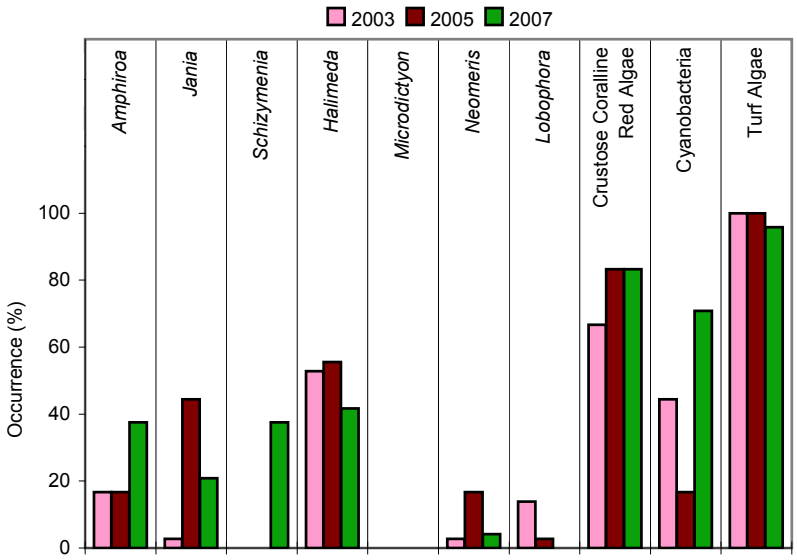


Figure 12.6.1e. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional group conducted on forereef habitats at Alamagan during MARAMP 2003, 2005 and 2007.

12 6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral disease assessments at 3 sites on forereef habitats at Alamagan. These surveys covered a total reef area of ~ 900 m^{-2}. No cases of coralline-algal disease were detected.

12.7 Benthic Macroinvertebrates

12.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Alamagan through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

During each of the 3 MARAMP survey years, 3 REA benthic surveys and 6 towed-diver surveys were conducted around Alamagan. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, both REA and towed-diver surveys revealed low daytime macroinvertebrate abundance on forereef habitats around Alamagan, compared to the rest of the Mariana Archipelago. Minor fluctuations in densities between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density on forereef habitats around Alamagan—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 12.7.1b, d and f).

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at all 3 REA sites surveyed and in all of the 6 towed-diver surveys conducted around Alamagan. The overall mean density of giant clams from REA surveys was

3.67 organisms 100 m^{-2} (SE 1.20), and the islandwide mean density from towed-diver surveys was 0.07 organisms 100 m^{-2} (SE 0.01). Survey results suggest giant clams were most abundant at REA site ALA-03 in the southwest region with 6 organisms 100 m^{-2} (Fig. 12.7.1.a, top panel). Among all towed-diver surveys around this island, the 2 surveys completed in the western regions had the highest mean densities of giant clams with 0.12 and 0.1 organisms 100 m^{-2}; segment densities from these surveys ranged from 0 to 0.58 organisms 100 m^{-2}.

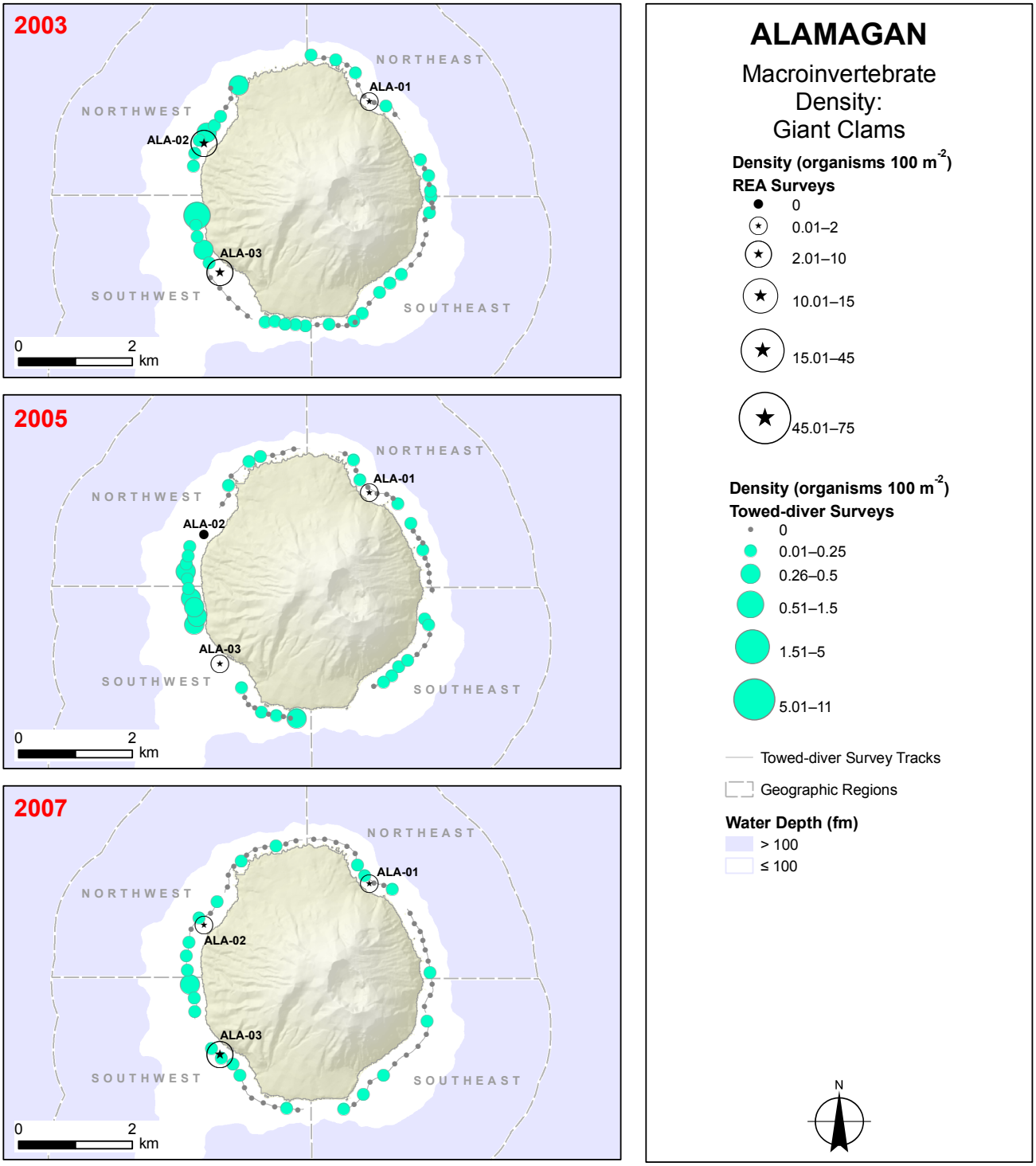


Figure 12.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Alamagan during MARAMP 2003, 2005, and 2007.

During MARAMP 2005, giant clams were observed at 2 of the 3 REA sites surveyed and in all 6 towed-diver surveys conducted around Alamagan. The overall mean density of giant clams from REA surveys was 1 organism 100 m^{-2} (SE 0.58), and the islandwide mean density from towed-diver surveys was 0.08 organisms 100 m^{-2} (SE 0.01). Survey results suggest giant clams were most abundant at ALA-02 in the northwest region with 2 organisms 100 m^{-2} (Fig. 12.7.1.a, middle panel). Among all towed-diver surveys around this island, the survey completed along the central western coast had the highest mean density of giant clams with 0.23 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.38 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.08 organisms 100 m^{-2}, recorded in the southwest region; segment densities ranged from 0 to 0.34 organisms 100 m^{-2}.

During MARAMP 2007, giant clams were observed at all 3 REA sites surveyed and in all 6 towed-diver surveys conducted around Alamagan. The overall mean density of giant clams from REA surveys was 1.22 organisms 100 m^{-2} (SE 0.73), and the islandwide mean density from towed-diver surveys was 0.03 organisms 100 m^{-2} (SE 0.01). Survey results suggest giant clams were most abundant at ALA-03 in the southwest region with 2.67 organisms 100 m^{-2} (Fig. 12.7.1a, bottom panel). Among all towed-diver surveys around this island, the survey completed along the central western coast had the highest mean density of giant clams with 0.08 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.28 organisms 100 m^{-2}.

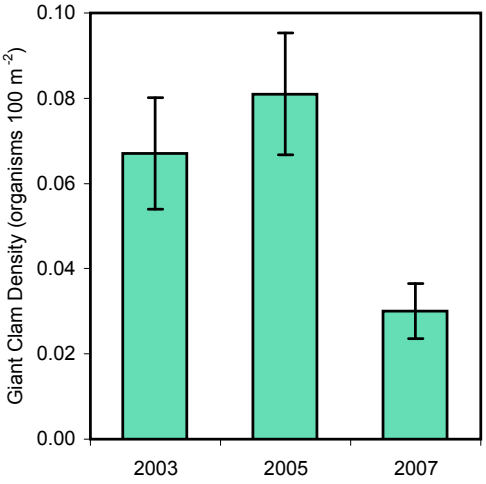


Figure 12.7.1b. Temporal comparison of giant clam mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Alamagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested low abundance of giant clams around Alamagan during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago (Fig. 12.7.1b). Although densities were low, during each of the 3 survey years, the highest densities of giant clams resided along the western shore of this island. Minor fluctuations in density were observed, but this variation is not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Crown-of-thorns Seastars (COTS)

During MARAMP 2003, 2005, and 2007, no crown-of-thorns seastars (*Acanthaster planci*) were observed at the 3 REA sites surveyed or in the 6 towed-diver surveys conducted around Alamagan.

Sea Cucumbers

During MARAMP 2003, no sea cucumbers were observed at the 3 REA sites surveyed around Alamagan, but 4 of the 6 towed-diver surveys had recordings of sea cucumbers with an islandwide mean density of 0.006 organisms 100 m^{-2} (SE 0.003). Among all towed-diver surveys around this island, the survey completed in the southwest region had the highest mean density of sea cucumbers with 0.02 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.09 organisms 100 m^{-2} (Fig. 12.7.1c, top panel).

During MARAMP 2005, again no sea cucumbers were observed at the 3 REA sites surveyed around Alamagan, but 3 of the 6 towed-diver surveys had recordings of sea cucumbers with an islandwide mean density of 0.012 organisms 100 m^{-2} (SE 0.004). Consistent with results from 2003, the towed-diver survey completed in the southwest region had the highest mean density of sea cucumbers with 0.03 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.08 organisms 100 m^{-2} (Fig. 12.7.1c, middle panel).

During MARAMP 2007, again no sea cucumbers were observed at the 3 REA sites surveyed around Alamagan, but 4 of the 6 towed-diver surveys had recordings of sea cucumbers with an islandwide mean density of 0.013 organisms 100 m^{-2} (SE 0.005). Among all towed-diver surveys around this island, the survey completed in the southeast region had the highest mean density of sea cucumbers with 0.03 organisms 100 m^{-2}; segment densities ranged from 0 to 0.26 organisms 100 m^{-2} (Fig. 12.7.1c. bottom panel).

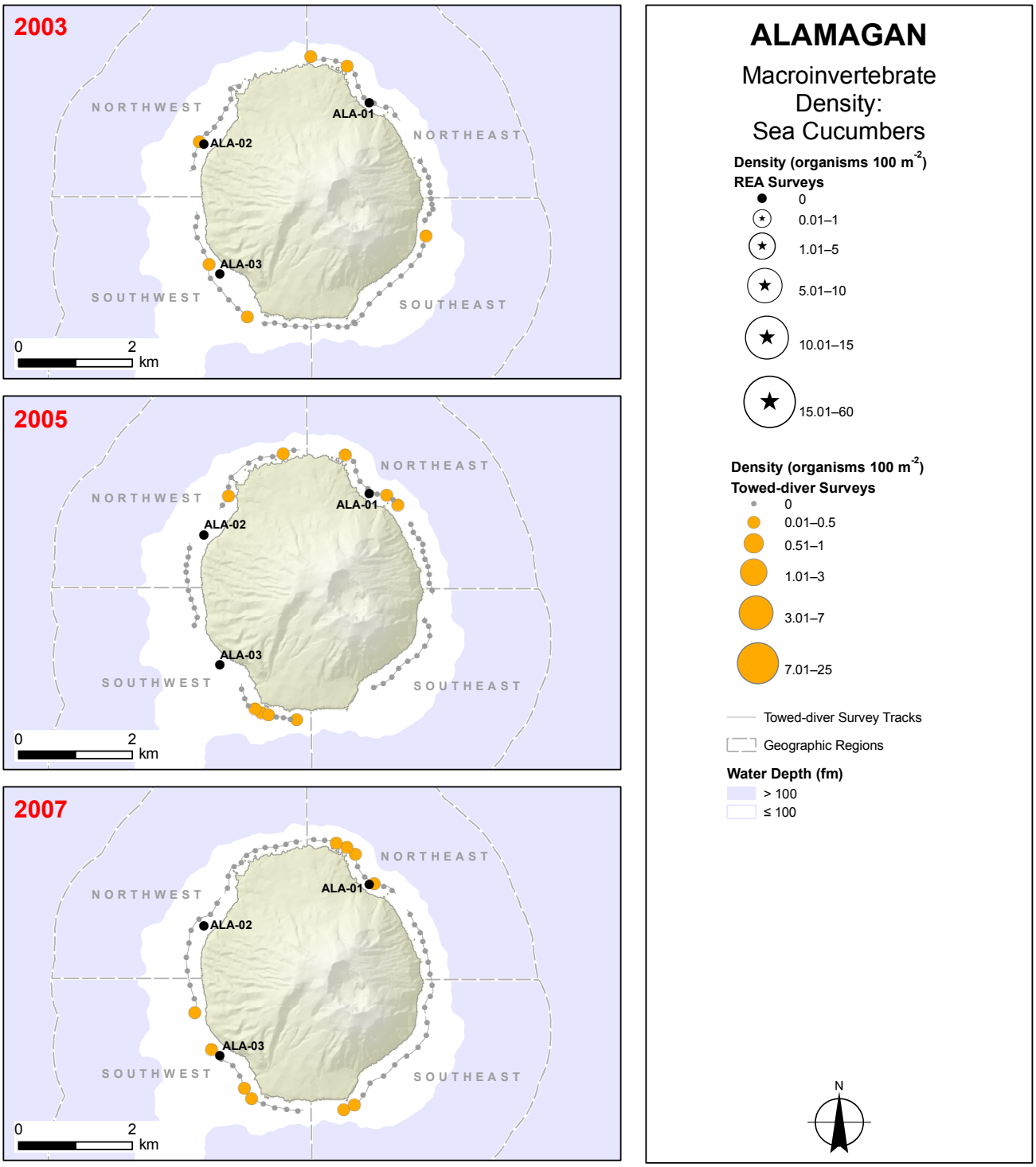


Figure 12.7.1c. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Alamagan during MARAMP 2003, 2005, and 2007.

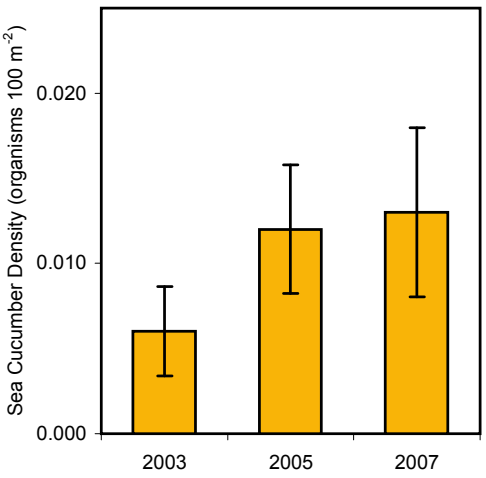


Figure 12.7.1d. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Alamagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested low daytime abundance of sea cucumbers around Alamagan during MARAMP 2003, 2005, and 2007, relative to the rest of the Mariana Archipelago (Fig. 12.7.1d). Minor fluctuations in density were observed, but this variation is not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

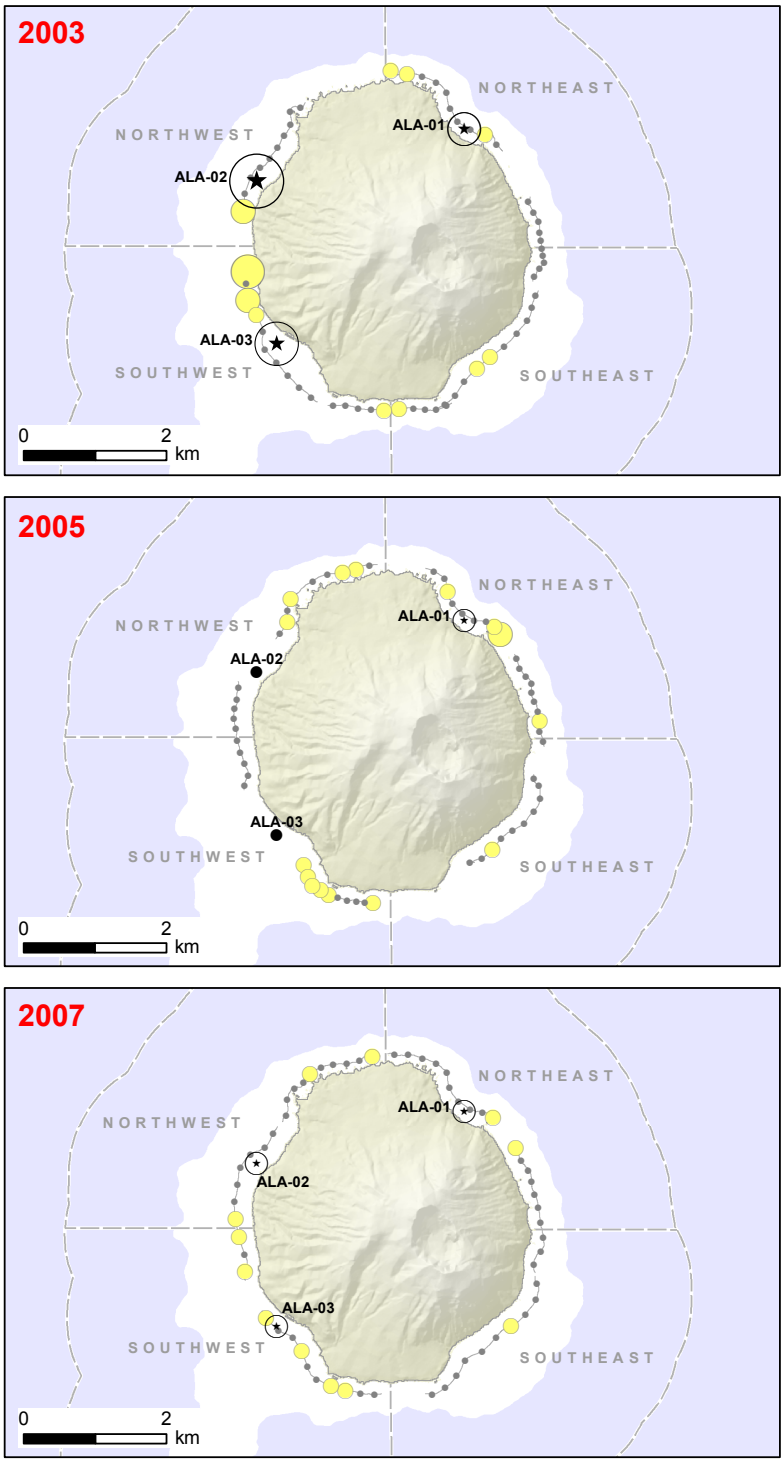
Sea Urchins

During MARAMP 2003, sea urchins were observed at all 3 REA sites surveyed and in 5 of the 6 towed-diver surveys conducted around Alamagan (Fig. 12.7.1e, top panel). The overall mean density of sea urchins from REA surveys was 63.67 organisms 100 m^{-2} (SE 19.77), and the islandwide mean density from towed-diver surveys was 0.64 organisms 100 m^{-2} (SE 0.37). Survey results suggest that sea urchins were most abundant at ALA-02 in the northwest region with a mean density of 100 organisms 100 m^{-2}. All observations were of the rock-boring genus *Echinostrephus*. *Echinostrephus* also was the dominant urchin at ALA-03 and ALA-01. The highest diversity was found at ALA-01, with 3 urchin genera: *Echinostrephus, Echinothrix,* and *Echinometra.* Overall, 95% of the urchins observed were from the genus *Echinostrephus.*

Among all towed-diver surveys conducted around Alamagan in 2003, the survey completed in the southwest region had the highest mean density of sea urchins at 2.81 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 19.93 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 0.83 organisms 100 m^{-2}, recorded in the northwest region; segment densities ranged from 0 to 8.23 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed at 1 of the 3 REA sites surveyed and in 5 of the 6 towed-diver surveys conducted around Alamagan. In the northeast region, ALA-01 had a density of 7 organism 100 m^{-2}. The genera *Echinostrephus, Echinometra,* and *Echinothrix* were observed, with 57% of the urchins observed from the genus *Echinothrix*. The islandwide mean density of sea urchins from towed-diver surveys was 0.26 organisms 100 m^{-2} (SE 0.11). Among all towed-diver surveys conducted around Alamagan, the survey completed in the northeast region had the highest mean density of 1.14 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 5.46 organisms 100 m^{-2} (Fig. 12.7.1e, middle panel).

During MARAMP 2007, sea urchins were observed at all 3 REA sites surveyed and in all 6 towed-diver surveys conducted around Alamagan. The overall mean density of sea urchins from REA surveys was 9.33 organisms 100 m^{-2} (SE 7.83), and the islandwide mean density from towed-diver surveys was 0.03 organisms 100 m^{-2}. Survey results suggest that sea urchins were most abundant at ALA-02 in the northwest region with a mean density of 25 organisms 100 m^{-2} (Fig. 12.7.1e, bottom panel). All observed urchins at REA sites were of the genus *Echinostrephus.* Among all towed-diver surveys around this island, the surveys completed along the northern part of Alamagan and in the southeast region had the highest mean densities of 0.05 and 0.04 organisms 100 m^{-2}; segment densities from these surveys ranged from 0 to 0.43 organisms 100 m^{-2}.



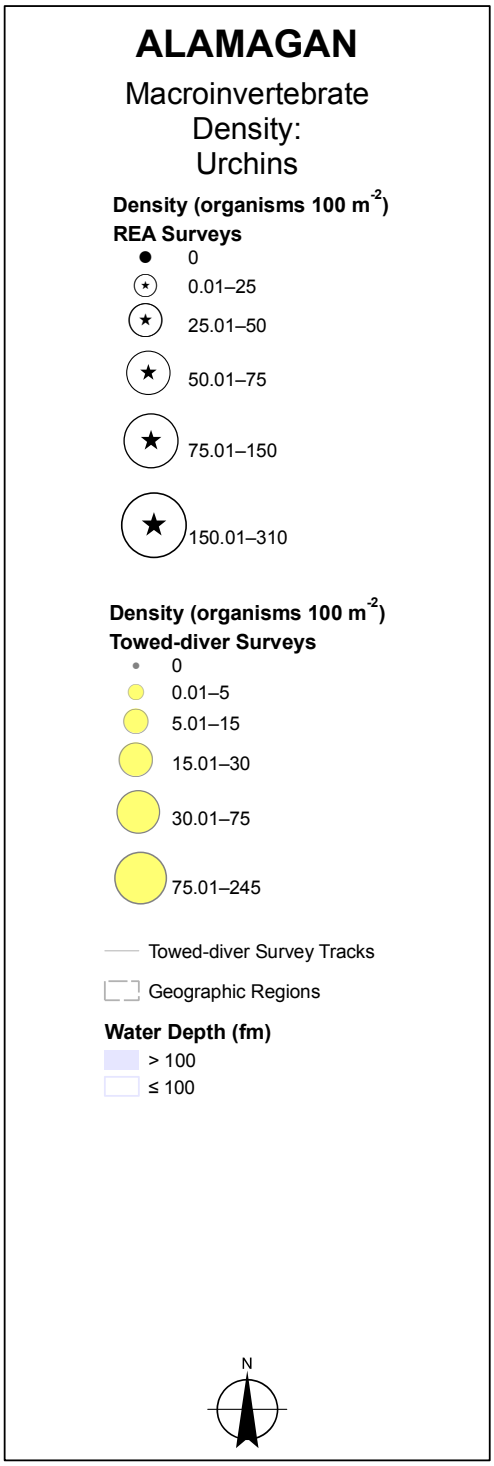


Figure 12.7.1e. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Alamagan during MARAMP 2003, 2005, and 2007.

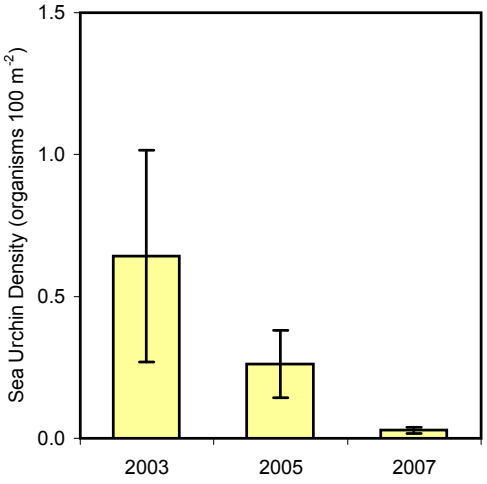


Figure 12.7.1f. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Alamagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested extremely low daytime abundance of sea urchins around Alamagan during MARAMP 2003, 2005, and 2007, relative to the rest of the Mariana Archipelago (Fig. 12.7.1f). Minor fluctuations in density were observed, but this variation is not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

12.8 Reef Fishes

12.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 6 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Alamagan. The overall estimated mean biomass of large fishes around this island, calculated as weight per unit area, was 1.06 kg 100 m^{-2} (SE 0.13). Observed large-fish biomass was highest in the northeast region, where sharks and snappers were abundant (Fig. 12.8.1a, top panel). Nurse sharks (Ginglymostomatidae), reef sharks (Carcharhinidae), and snappers (Lutjanidae) together contributed the greatest proportion (70%) or 0.75 kg 100 m^{-2} of overall mean large-fish biomass. Of those families, the tawny nurse shark (*Nebrius ferrugineus*) and grey reef shark (*Carcharhinus amblyrhynchos*) were the most abundant species, accounting for 0.19 kg 100 m^{-2} and 0.17 kg 100 m^{-2} of overall mean biomass of large fishes. Snappers contributed 32% of overall mean large-fish biomass, and the twinspot snapper (*Lutjanus bohar*) was the dominant snapper species by biomass.

During MARAMP 2005, 6 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Alamagan. The overall estimated mean biomass of large fishes around this island was 0.93 kg 100 m^{-2} (SE 0.10). Observed large-fish biomass was distributed fairly evenly around this island (Fig. 12.8.1a, middle panel). Reef sharks contributed the greatest proportion (57%) or 0.52 kg 100 m^{-2} to overall mean large-fish biomass. The whitetip reef shark (*Triaenodon obesus*) was the largest contributor, accounting for 0.28 kg 100 m^{-2} of large-fish biomass, and grey reef sharks contributed 0.25 kg 100 m^{-2} of overall mean large-fish biomass. Parrotfishes (Scaridae) also were observed regularly, contributing 13% to overall mean large-fish biomass. The ember parrotfish (*Scarus rubroviolaceus*) was the most abundant parrotfish species, contributing 0.09 kg 100 m^{-2} to parrotfish biomass. Of note was a single sighting of a humphead wrasse (*Cheilinus undulatus*) during a survey in the northwest region.

During MARAMP 2007, 6 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Alamagan. The overall estimated mean biomass of large fishes was 0.70 kg 100 m^{-2} (SE 0.15). Observed large-fish biomass was highest in the western regions, where sharks were common (Fig. 12.8.1a, bottom panel). Reef sharks and nurse sharks contributed more than any other group, together accounting for 42 % or 0.29 kg 100 m^{-2} of overall mean large-fish biomass. The whitetip reef shark and tawny nurse shark were the largest contributors to overall mean large-fish biomass with 0.11 and 0.14 kg 100 $m^{-2,}$ respectively. Snappers and surgeonfishes (Acanthuridae) also were common during this survey period. The twinspot snapper alone accounted for 20% of overall mean biomass of large fishes, and the sleek surgeonfish (*Naso hexacanthus*) contributed 16% of overall mean large-fish biomass.

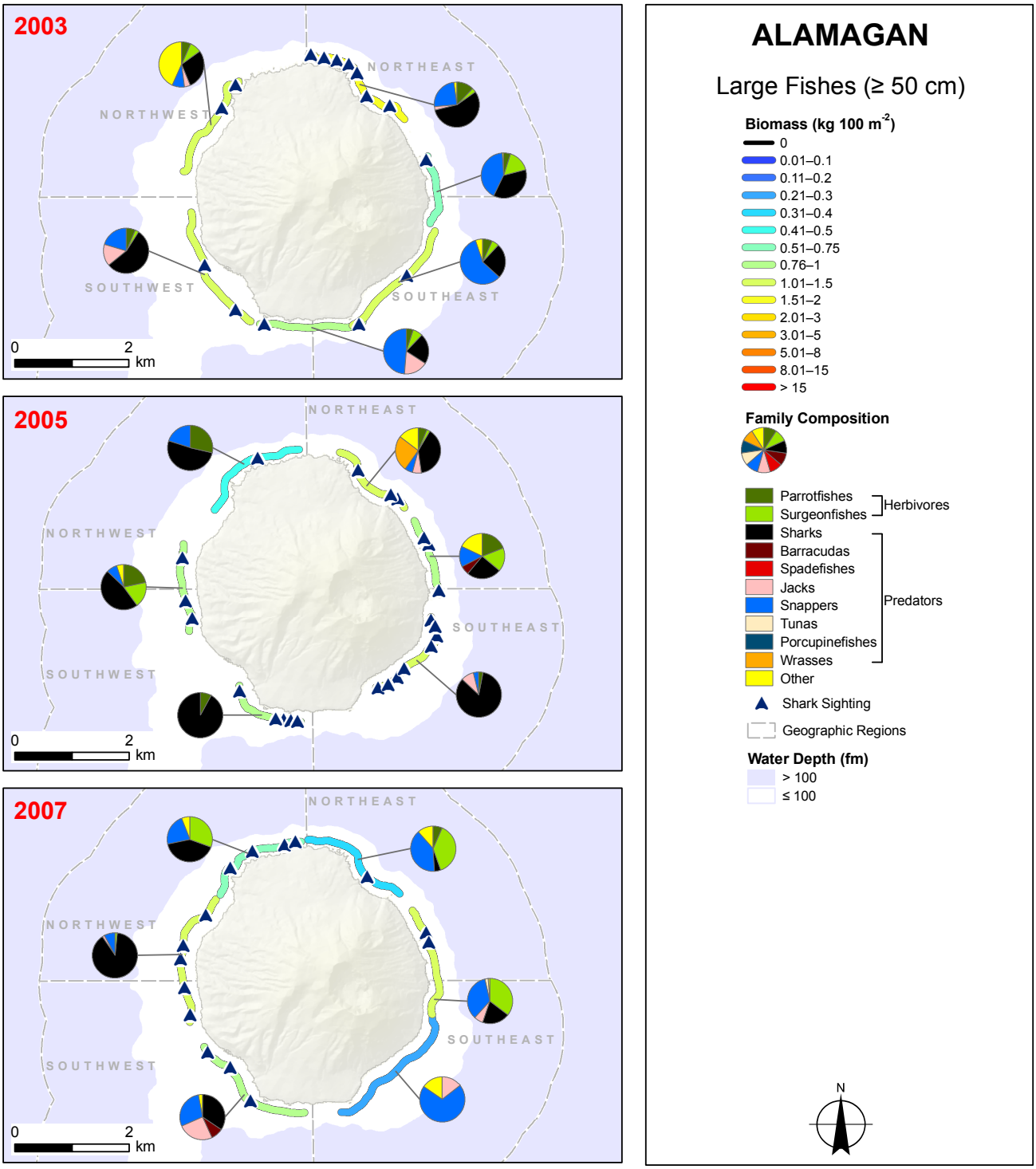


Figure 12.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Alamagan during MARAMP 2003, 2005, and 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

Large-fish biomass from towed-diver surveys of forereef habitats did not show any clear temporal patterns and was generally around the average for the unpopulated northern islands in the Mariana Archipelago, varying between 1.06 kg 100 m^{-2} in 2003 and 0.70 kg 100 m^{-2} in 2007 (Fig. 12.8.1b). Reef sharks and nurse sharks were common during each of the 3 MARAMP years and contributed an average of 46% of the overall estimated mean for large-fish biomass. The whitetip reef shark and tawny nurse shark were the most abundant shark species during MARAMP 2003 and 2005, and the grey reef shark was the most frequently encountered shark species during MARAMP 2007. Snappers also were common during each

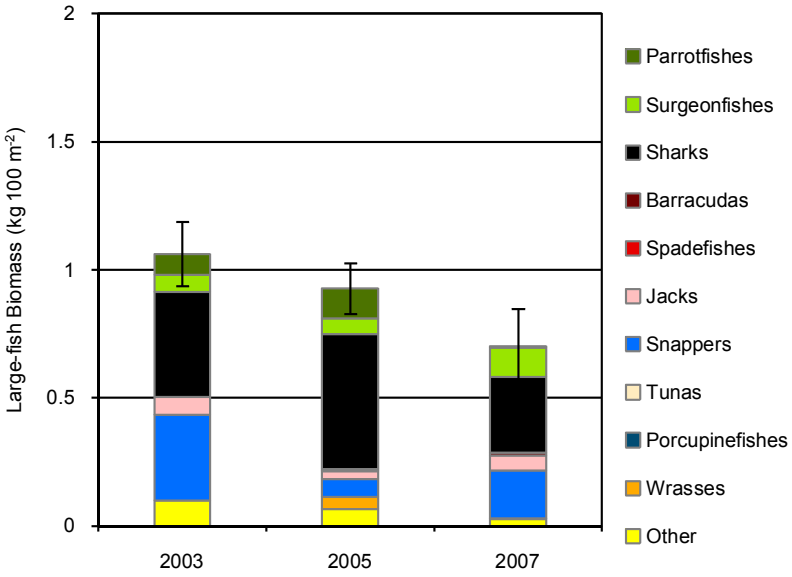


Figure 12.8.1b. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys conducted in forereef habitats around Alamagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

of the 3 MARAMP survey periods, with the twinspot snapper as the most abundant snapper species. Notable observations included a single sighting of the humphead wrasse in 2005 and sightings of the dogtooth tuna (*Gymnosarda unicolor*) and black-margin barracuda (*Sphyraena qenie*) in 2007.

Total Fish Biomass and Species Richness

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Alamagan during MARAMP 2003 was moderate compared to other sites in the Mariana Archipelago, with an overall sample mean of 5.75 kg 100 m^{-2} (SE 0.59). The highest biomass of 6.50 kg 100 m^{-2} was observed at REA site ALA-02 in the northwest region, where surgeonfishes, triggerfishes (Balistidae), and snappers were common (Fig. 12.8.1c, top panel). No sharks were observed during this survey period. Surgeonfishes, parrotfishes, and triggerfishes contributed the greatest proportions to total fish biomass: 22%, 15%, and 14%. The orangespine unicornfish (*Naso lituratus*) was the dominant surgeonfish (0.35 kg 100 m^{-2}), and the pinktail triggerfish (*Melichthys vidua*) was the dominant triggerfish (0.50 kg 100 m^{-2}). Nearly all parrotfish biomass was split almost equally between Forsten's parrotfish (*Scarus forsteni*) and the ember parrotfish (*S. rubroviolaceus*).

Based on REA surveys conducted during MARAMP 2003, species richness at Alamagan was moderately high with a range of 42–47 species 100 m^{-2}. The highest diversity was found at ALA-03 in the southwest region (Fig. 12.8.1c, top panel). Wrasses (Labridae), damselfishes (Pomacentridae) and surgeonfishes were the most diverse families, with 21, 14, and 13 species recorded in 2003. Surgeonfishes were the most abundant taxa, and the orangespine unicornfish dominated counts with 112 individuals 100 m^{-2} observed. Damselfishes were the second-most abundant taxa, and the Vanderbilt's chromis (*Chromis vanderbilti*) was the most common species with 94 individuals 100 m^{-2} recorded. The ornate wrasse (*Halichoeres ornatissimus*) was the most abundant wrasse species.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Alamagan during MARAMP 2005 was high compared to other sites in the Mariana Archipelago, with an overall sample mean of 16.80 kg 100 m^{-2} (SE 10.35). The highest biomass of 37.33 kg 100 m^{-2} was observed at ALA-03 in the southwest region, where 3 humphead wrasse and a tawny nurse shark were observed (Fig. 12.8.1c, middle panel). Wrasses contributed the greatest proportion (54%) or 9.13 kg 100 m^{-2} of the total fish biomass. Reef sharks and surgeonfishes contributed 10% and 9%, respectively, to total fish biomass. The humphead wrasse accounted for over 97% of wrasse biomass. Two sharks were observed during the survey period, a whitetip reef shark and a tawny nurse shark.

Based on REA surveys conducted during MARAMP 2005, species richness at Alamagan was moderate with a range of 27–33 species 100 m^{-2}. The highest species richness was found at ALA-01 in the northeast region (Fig. 12.8.1c, middle panel). Consistent with observations made during MARAMP 2003, wrasses, damselfishes, and surgeonfishes were the most diverse families with 18, 13 and 13 species recorded. The ornate wrasse was the most abundant wrasse species with 22 individuals 100 m^{-2} observed, while the brown surgeonfish (*Acanthurus nigrofuscus*) was the most abundant surgeonfish species with 8 individuals 100 m^{-2} observed. Damselfishes were the most abundant fish taxa overall, and the midget chromis (*Chromis acares*) dominated counts with 127 individuals 100 m^{-2} recorded at Alamagan.

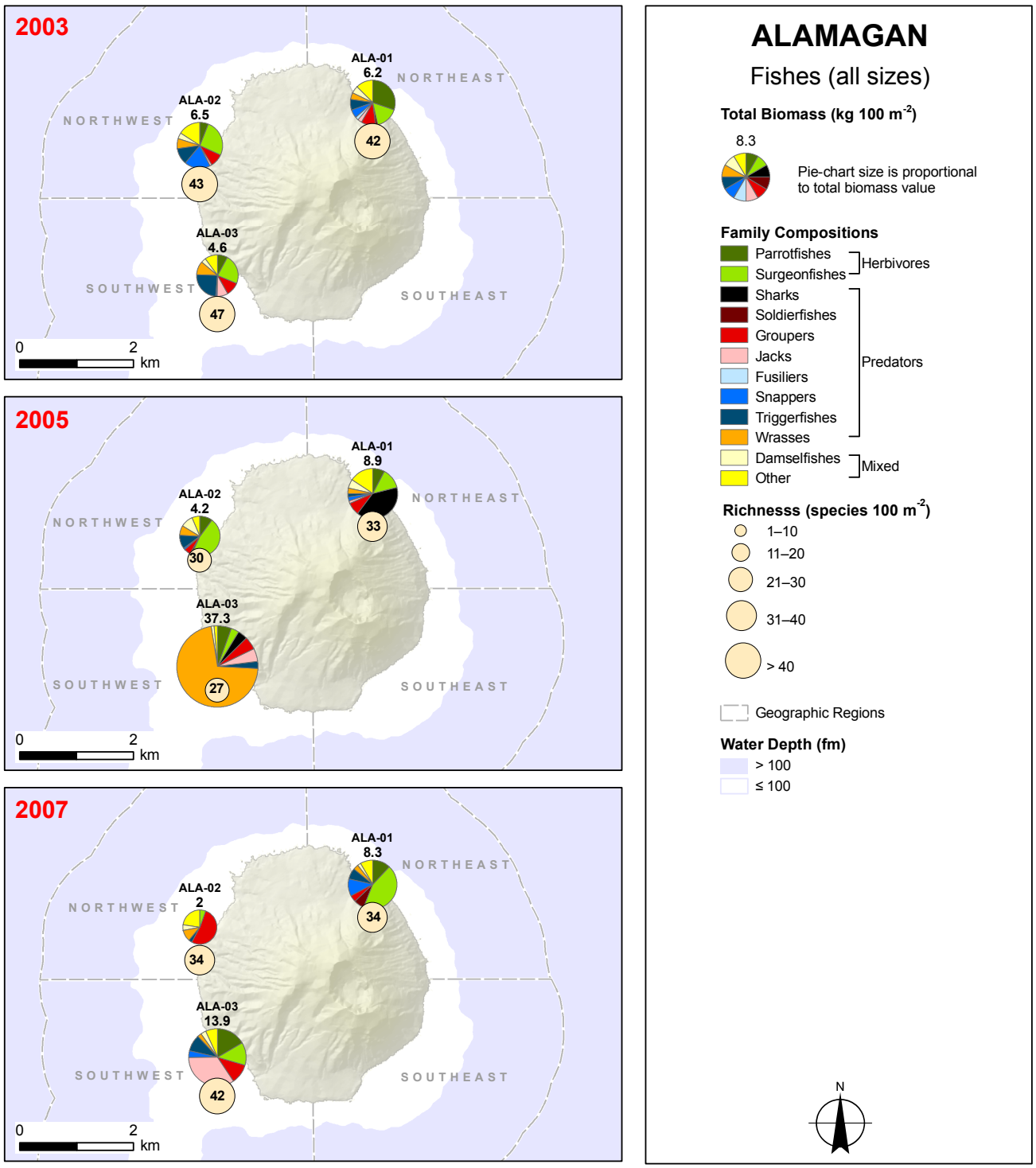


Figure 12.8.1c. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Alamagan during MARAMP 2003, 2005, and 2007.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Alamagan during MARAMP 2007 was moderate compared to other sites in the Mariana Archipelago, with an overall sample mean of 8.06 kg 100 m^{-2} (SE 3.44). The highest fish biomass of 13.92 kg 100 m^{-2} was found at ALA-03, where a school of bigeye trevally (*Caranx sexfaciatus*) was observed (Fig. 12.8.1c, bottom panel). Surgeonfishes and jacks contributed the greatest proportions (23% and 20%) of total fish biomass. The bluespine unicornfish (*Naso unicornis*), brown surgeonfish, and orangespot surgeonfish (*Acanthurus olivaceus*) dominated surgeonfish biomass with 0.47, 0.43, and 0.34 kg 100 m^{-2}. The bigeye trevally accounted for the greatest proportion (77%) or 1.25 kg 100 m^{-2} of jack biomass.

Based on REA surveys conducted during MARAMP 2007, species richness at Alamagan was moderate with a range of 34–42 species 100 m^{-2}. The highest diversity was observed at ALA-03 in the southwest (Fig. 12.8.1c, bottom panel). Consistent with survey results from 2003 and 2005, wrasses, surgeonfishes, and damselfishes were the most diverse families with 21, 15, and 14 species observed. The ornate wrasse was the most abundant wrasse species, while the brown surgeonfish was the most abundant surgeonfish species. Damselfishes again were the most abundant fish taxa overall, and the midget chromis dominated counts with 179 individuals 100 m^{-2}.

No clear spatial pattern was evident for total fish biomass at Alamagan between the 3 MARAMP survey periods; however, ALA-03 in the southwest region had the highest mean total fish biomass for surveys conducted in 2005 and 2007. Additionally, no clear temporal patterns were observed during the 3 survey periods (Fig. 12.8.1d), but the highest overall mean total fish biomass of 16.80 kg 100 m^{-2} was recorded in 2005, when 3 humphead wrasse were observed at ALA-03. A similarly high biomass estimate was recorded for ALA-03 in 2007, when a school of bigeye trevally was observed. Surgeonfishes also were common, but no single species consistently dominated counts during the 3 survey periods.

Species richness was relatively uniform at Alamagan in each of the 3 MARAMP surveys years and ranged from 27–47 species 100 m^{-2}. Consistent with survey results at other islands in the Mariana Archipelago, wrasses, damselfishes, and surgeonfishes were the most diverse families, with an average of 20, 14 and 14 species recorded. Damselfishes dominated counts, with the Vanderbilt's chromis and midget chromis as the most abundant damselfish species.

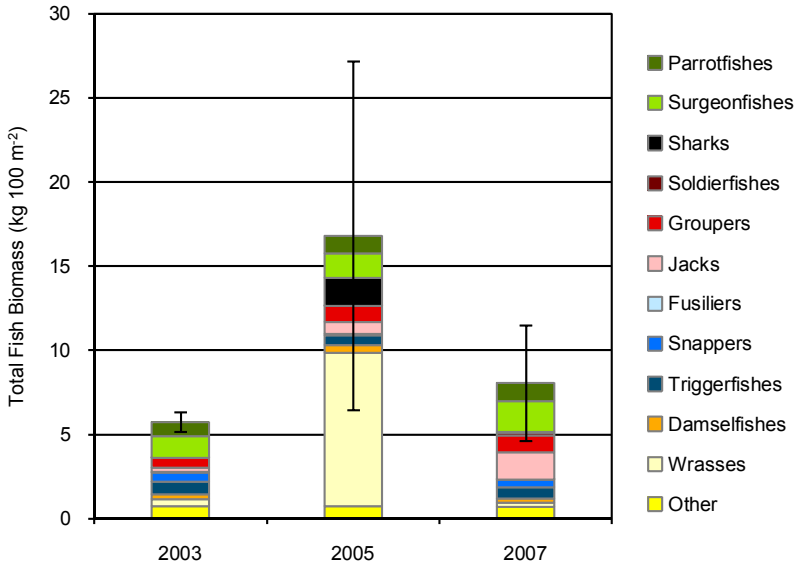


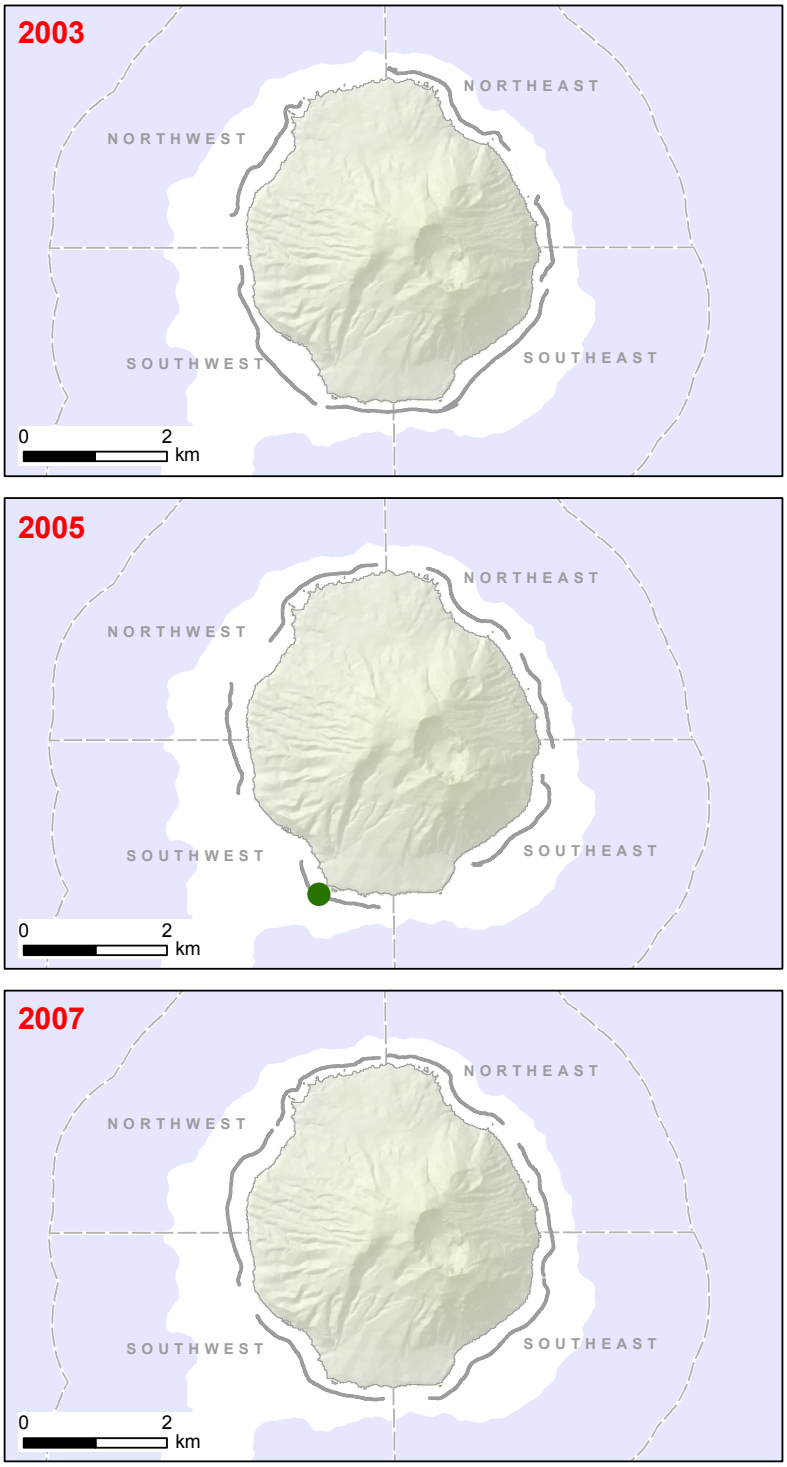
Figure 12.8.1d. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Alamagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

12.9 Marine Debris

12.9.1 Marine Debris Surveys

During MARAMP 2003 and 2007, no marine debris was observed during the 6 towed-diver surveys of forereef habitats conducted around the island of Alamagan (Fig. 12.9.1a, top and bottom panel). During MARAMP 2005, 1 sighting of derelict fishing gear was recorded in the 6 towed-diver surveys conducted around this island (Fig. 12. 9.1a, middle panel). Monofilament line was observed in the southwest region. No munitions, wrecks, or other man-made objects were identified during the 3 MARAMP survey years.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by towed divers in their observer comments.



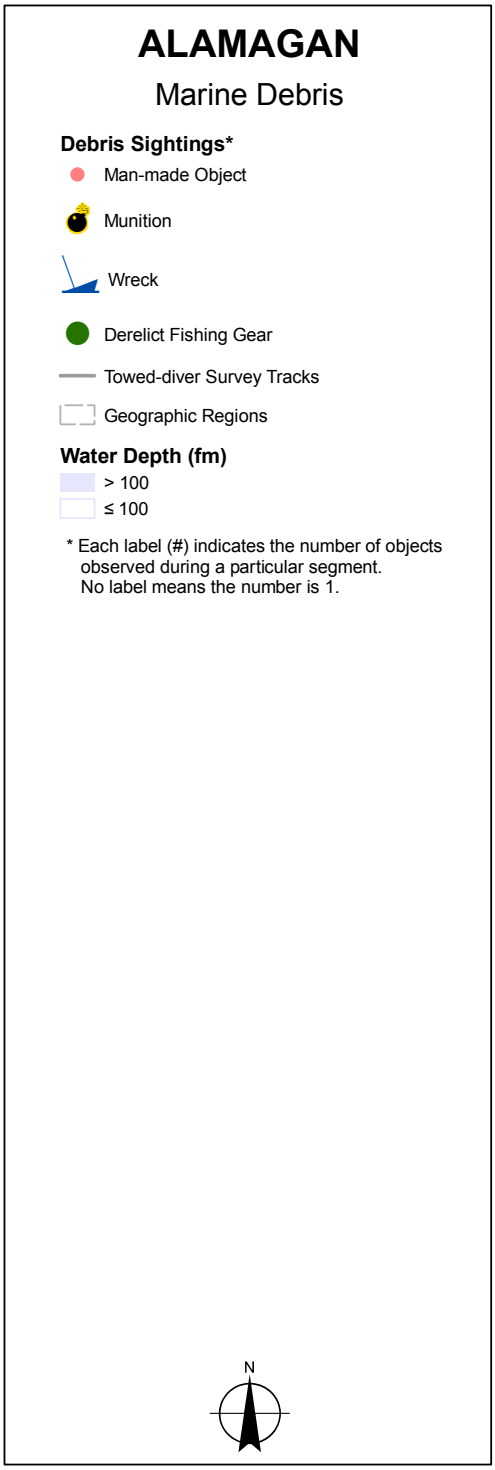


Figure 12.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Alamagan during MARAMP 2003, 2005, 2007. No debris sites were identified in 2003 and 2007. Symbols indicate the presence of specific debris types.

12.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Alamagan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Alamagan as well as the other 13 islands covered in this report.

North and northeast of Alamagan, the submarine topography is characterized by steep-sided, narrow ridges and channels that radiate out from this island. The submarine ridges in the northeast region of Alamagan are particularly pronounced, matched by steep slopes onshore (Fig. 12.1.2a in Section 12.1.2: "Geography"), and adjacent to older volcanic strata associated with the main crater and a large spatter cone (Fig. 12.1.2b). Around the northern side of Alamagan, which has been affected by lava flow, submarine ridges are less pronounced. This gently sloping lava platform extends this island's coastline northward and can be distinguished on the slope map as an area of low slopes north of this island (Fig. 12.1.2a). The seascape found north and northeast of Alamagan is shaped by not only these steep-sided ridges but also numerous boulders that litter the seabed and create holes and crevices, resulting in the highest habitat complexity observed around Alamagan (Fig. 12.3.3a in Section 12.3.3: "Habitat Characterization"). As observed during towed-diver surveys, these ridges ran from shallow waters and ended in deep drop-offs. The substrate in this area, based on towed-diver surveys, was predominantly hard with a small amount of sand present between boulders (Fig. 12.3.3a) and supported live-hard-coral cover primarily of 10.1%–40% throughout this area (Fig. 12.10a).

The rest of Alamagan—the southwest and southeast regions and the southern part of northwest region—can be divided into 4 areas, with different volcanic and numerous physical factors influencing the benthic communities in each of them.

On the west side of Alamagan, the onshore topography is characterized by deep ravines. This area has some of the oldest volcanic strata, and the landscape has been shaped by erosion (Fig. 12.10a). In the shallow waters around the southern part of the northwest region and the northern part of the southwest region, the seascape is dominated by an extensive shelf area of hard substrate covered in place with surface sand. For most segments of the towed-diver surveys completed across this shelf, cover of live corals was moderately low with 1.1%–30%, compared to results from other islands surveyed in

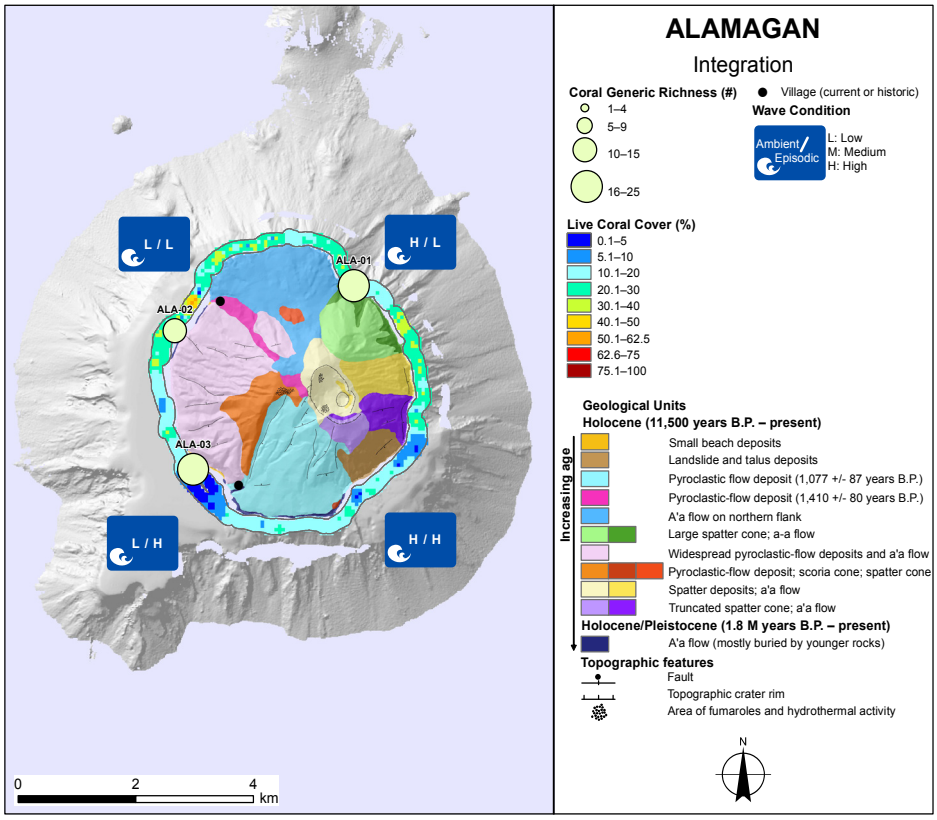


Figure 12.10a. Cover (%) observations of live hard corals from towed-diver benthic surveys and generic richness from REA benthic surveys conducted around Alamagan during MARAMP 2003, 2005 and 2007. Values of coral cover represent interpolated values from the 3 survey years, and generic richness values represent averages of data from the 3 survey years. Color-coded areas on the island indicate different geologic units. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region. Underlying these data in grey scale is the hillshade bathymetry.

the Mariana Archipelago (Fig. 12.10a). The lowest level of live coral cover on this shelf was observed in areas covered by sand. Still, the highest live coral cover found around Alamagan was observed in the northwest region. In a 200-m stretch close to the edge of this shelf, abundant coral colonies of the genus *Porites* resulted in live coral cover of 40.1%–62.5% (Figs. 12.10a and b).

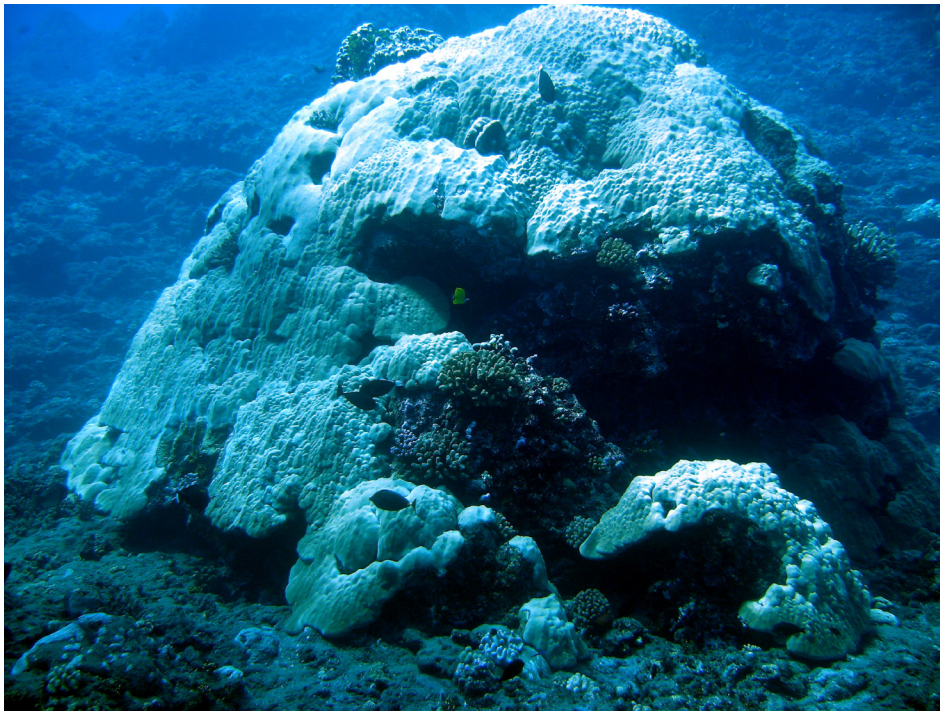


Figure 12.10b. A large colony of corals of the genus *Porites* at Alamagan. *NOAA photo by Robert Schroeder*

On the east side of Alamagan, onshore geology is composed of a similarly old volcanic unit in the form of a truncated spatter cone and an associated fragmented, rough, spiky lava flow. However, in contrast to west Alamagan, the volcanic strata in this area are covered with more recent landslide deposits (Fig. 12.10a), contributing to the complex texture shown by the bathymetry and derived products for this area (see Fig. 12.3.1c and other maps in Section 12.3.1: "Acoustic Mapping"). Resultes from towed-diver surveys suggested a habitat of medium-low to medium-high complexity, consisting of mostly boulders interspersed with sand presumably derived from landslide deposits. The boulders were colonized by encrusting corals. In the southeast region, towed-diver surveys showed that coral cover (< 20%) and macroalgal cover in 2005 and 2007 was low compared to results from other areas surveyed around Alamagan (Fig. 12.10a; Fig. 12.6.1a in Section 12.6.1: "Algal Surveys").

South of Alamagan, the seascape is heavily influenced by a pyroclastic flow deposit that occurred at ~ AD 870. This flow was responsible for the gentle slopes observed on the southern part of this island (Fig. 12.1.2a in Section 12.1.2: "Geography"). A deep graben, which is a block of rock that lies between 2 faults and has moved downward to form a depression, constrained this flow in this area and channeled it in a southwest direction (Fig. 12.1.2b) before it fanned out and extended Alamagan's coastline. This island's seascapes were similarly affected by this flow. The absence of a shallow shelf in this area may be a result of this pyroclastic flow overtopping the shelf that was observed in other areas around Alamagan. The flow in this area resulted in a seabed characterized by steep slopes at depths ≥ 30 m (Fig. 12.3.1c in Section 12.3.1: "Acoustic Mapping"). In this area, habitat complexity ranged from medium-low to medium and live coral cover was low (< 20%) over most survey segments. Macroalgae were a more dominant component of the substrate in this area, with macroalgal cover of 10.1%–62.5% (Fig. 12.6.1a in Section 12.6.1: "Algal Surveys"). Towed-diver surveys described habitats as rolling reef ending at a steep drop-off, and the location of survey tracks suggested that this rolling reef may have occurred on the edge of a very narrow shelf. This edge is just shown on the bathymetry and slope maps for Alamagan (Figs. 12.3.1b and c in Section 12.3.1: "Acoustic Mapping"), and this narrow shelf is perhaps all that remains of a larger shelf that has been covered by the pyroclastic flow deposits described previously.

The overall estimated biomass of large fishes around Alamagan, based on towed-diver surveys, was comparable to the biomass found around most other northern islands in the Mariana Archipelago and higher than the biomass recorded around the neighboring islands of Pagan, Guguan, and Sarigan across the 3 MARAMP survey periods. The greatest contribution

to large-fish biomass around Alamagan came from reef sharks (Carcharhinidae; Fig. 12.10c) and nurse sharks (Ginglymostomatidae), both of which were regularly observed during the 3 survey years (Fig. 12.8.1a in Section 12.8.1: "Reef Fish Surveys"). Fish species richness was moderately high at Alamagan, ranging from 27–47 species per site across the 3 survey periods, compared to levels seen at other areas in the Mariana Archipelago (Fig. 12.8.1c in Section 12.8.1: "Reef Fish Surveys"). The diversity of the fish community at Alamagan may result from the relative isolation of Alamagan, which is more than 250 km from Saipan, the nearest populated island.

Figure 12.10c. Whitetip reef shark (*Triaenodon obesus*) at Alamagan. *NOAA photo by Robert Schroeder*



12.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Alamagan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Alamagan chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Alamagan, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Alamagan as well as some of the key natural processes and anthropogenic activities influencing these ecosystems:

- Alamagan is located in the middle of the Mariana Archipelago. With a land area of 12.96 km^2, this island is about one-tenth the size of Saipan.

- The highest point on this island is Bandeera Peak, formed by a deep crater and surrounded by steep slopes with flatter areas extending north and south as a result of lava flows. No beaches are found around Alamagan, and this island is surrounded by sea cliffs. The last known eruption at Alamagan was at ~ AD 870.

- Historically, small human populations have inhabited Alamagan, mainly within 2 villages. In 2000, a homestead site was observed on the northwestern side of this island. Populations are expected to increase in the future because legislation enacted in 2010 encourages repatriation of this island.

- Many steep-sided, narrow ridges incise the moderately steep submarine flanks observed north and northeast of Alamagan. Towed-diver surveys described these habitats as hard substrate of medium to high complexity with steep reef slopes, ridges, and boulders.

- Southeast of Alamagan, a small shelf is present and has a surface of complex texture, possibly indicating a spur-and-groove habitat. West of Alamagan, a more extensive shelf area is present at depths of 25–40 m. Southwest of Alamagan, a second, deep shelf is present at depths of 80–120 m. Towed-diver surveys revealed that habitats on the shelves south and southeast of Alamagan were of lower complexity and had higher sand cover than habitats observed farther north.

- Wave model output shows ambient trade wind swells impacting the northeast and southeast regions. Episodic wave energy from storm tracks impacts the southwest and the southeast regions.

- For the 3 REA sites surveyed at Alamagan during MARAMP 2007, the overall sample mean of live-hard-coral cover was 23.5%. Across the 3 MARAMP survey years, islandwide mean coral cover from towed-diver surveys was 17%–22%, a high level compared to values recorded at other islands in the Mariana Archipelago.

- At the 3 REA sites surveyed at Alamagan in 2007, 6 cases of coral disease were detected, resulting in an overall mean prevalence of 0.01%. The most numerically abundant disease state was bleaching, followed by subacute tissue loss and other syndromes, particularly infestation and overgrowth by species of the encrusting sponge *Terpios*. No signs of predation scars from crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails were documented at REA sites, and crown-of-thorns seastars have never been observed at Alamagan during MARAMP surveys.

- Giant clams were fairly common around Alamagan, but sea cucumber densities were extremely low during each of the 3 MARAMP survey years.

- Overall mean large-fish biomass around Alamagan, from towed-diver surveys, was close to the average values observed for the unpopulated, northern islands across the 3 MARAMP survey years. Biomass of large fishes around Alamagan varied from 1.06 100 m^{-2} in 2003 to 0.70 100 m^{-2} in 2007.

- Total fish biomass, based on REA surveys, was moderately high in each of the 3 survey periods, compared with levels observed in the rest of the Mariana Archipelago, and specifically in 2005 with a value of 16.80 kg 100 m^{-2}. The highest total fish biomass in 2005 and 2007 was found in the southwest region at ALA-03, where 3 humphead wrasses were recorded in 2005 and a large school of bigeye trevally was seen in 2007.

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13 PAGAN

13.1 Introduction

One of the most active volcanic islands in the Mariana Archipelago, Pagan is located at 18°07′ N, 145°48′ E, 52 km north of Alamagan and 65 km south of Agrihan. Two large stratovolcanoes, or tall, cone-shaped volcanoes with layered internal structure, formed this island, and a low-lying, narrow isthmus connects them (Fig. 13.1a). Pagan extends north to south for 17 km and is 7 km across at its widest point. With a land area of 47.75 km^2, Pagan is the fourth largest island of the Commonwealth of the Northern Mariana Islands (CNMI). The highest elevation on this island, at 570 m, is the peak of Mount Pagan, which dominates the northern part of this island (Fig. 13.1b). South Pagan has a maximum elevation of 548 m.



Volcanic activity on Pagan has been recorded fairly regularly since the 17th century, with all of the verified activity originating from Mount Pagan volcano (Siebert and Simkin 2002–). The largest known eruption occurred in 1981 and forced the evacuation of this island's residents. Lava flows from this eruption dominate the landscape of northern Pagan. More recently, Mount Pagan erupted in December 2006 and August 2010 and possibly in April 2009, and thermal emissions have been observed in subsequent years (Siebert and Simkin 2002–).

Figure 13.1a. Satellite image of Pagan, labeled to show Shomushon Village and Pagan Airstrip (© 2006 DigitalGlobe Inc. All rights reserved).



Figure 13.1b. Mount Pagan, as seen from the NOAA Ship *Hi'ialakai* in 2007. *NOAA photo*

13.1.1 History and Demographics

Evidence of historic occupation of Pagan by the Chamorro people was discovered by Georg Fritz, the first German administrator, when visiting this island in 1901 (Spennemann 2006). Fritz found basalt latte sets, sling stones and cultivated plants, all evidence of Chamorro culture. During the early 1900s, Pagan, populated at the time, was leased by the German government to the Pagan Gesellschaft for copra production. Copra production was the mainstay of the German economy in the Marshall Islands and in much of Micronesia; however, a series of typhoons in 1905 and 1907 resulted in a 50% reduction in production for several years (Spennemann 1999b).

After World War I, Pagan was awarded to Japan for administrative authority, as were the other islands of the Northern Mariana Islands. During World War II, more than 4000 Japanese troops and 1000 laborers were stationed on Pagan until their surrender to U.S. Army representatives in September 1945 (Rottman 2002). Following that war, a small U.S. Navy installation was established on Pagan. The main settlement on Pagan was a village called Shomushon on the northwestern coast of Pagan (Fig. 13.1a), but this village was destroyed by flooding and debris flows after the 1981 eruption (Trusdell et al. 2006). In 1981, the eruption of Mount Pagan volcano prompted the evacuation of this island's 53 residents (Siebert and Simkin 2002–). Since then, inhabitation on Pagan has been sporadic, with 6–10 persons observed during Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) cruises.

Part of the Northern Islands Municipality of the CNMI, Pagan is one of the islands where land could be designated for village and homesteading programs. The *Northern Islands Homestead Act of 2008*, which was signed into law by the Governor of the CNMI in January 2010, may increase the population in coming years. This legislation, CNMI Public Law 16-50, recognizes that residents of the "islands north of Saipan" have no formal homesteads, allows residents to have agricultural lots and facilities, encourages resettlement by former residents, and initiates and promotes economic development.

13.1.2 Geography

Two stratovolcanoes originally formed Pagan, and more recent volcanoes have developed within these large calderas (Siebert and Simkin 2002–). The northern caldera is 7 km wide and contains a low-lying crater within which 2 lakes have formed. Lagona Lake, also known as Laguna Sanhiyon, near the west coast and an interior lake near the western foot of Mount Pagan hold the only nonstream water present in the northern islands of the CNMI (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). From this large caldera, Mount Pagan emerges. South Pagan has an elongated summit with 4 distinct craters (Siebert and Simkin 2002–).

Large calderas form the northern and southern sections of this island, and relatively few steep slopes are present on Pagan (Fig. 13.1.2a). The highest slopes on northern Pagan are found on the inner walls of the craters. The narrow isthmus that separates the two parts of this island is dominated by a narrow ridge with very steep slopes on either side. South Pagan has steep slopes around South Point. Although much of the coastline of Pagan is rocky, several beaches allow easy access to this island.

The geology of northern Pagan is characterized by lava flows and deposits from eruption events (Fig. 13.1.2b). The oldest rocks are lava flows from the Holocene Epoch (11,700 years to present) on the northwestern and eastern flanks of Mount Pagan that have not been capped by more recent deposits (Trusdell et al. 2006). South of the large northern caldera, Holocene tuff deposits are also found. West of the Mount Pagan summit, a large maar (or shallow crater resulting from an eruption caused by groundwater mixing with magma) contains deposits from pyroclastic flows varying in age from 50 to 600 years (Trusdell et al. 2006). On the northeastern and southern flanks of Mount Pagan, lava flows originating from an 1872–1873 eruption are present, although many of them have been topped by lava flows from the large eruption in 1981 (Trusdell et al. 2006).

The geology of the isthmus and southern Pagan has not been as extensively studied as the geology of northern Pagan. However, geologic investigations conducted in 1954 indicated that the isthmus and southern peninsula are characterized by geologic strata originating before the large calderas were created, while South Pagan volcano is dominated by lavas originating after the large calderas were created (Fosberg and Corwin 1958).

The eruption in 1981 included lava flows on the northeastern and northwestern flanks of the Mount Pagan volcano. Flows on the southwestern flank reached within 1 km of the village of Shomushon and covered half of Pagan Airstrip (Figs. 13.1.2b and 13.1a; Trusdell et al. 2006). This eruption resulted in extensive ash fall over Pagan and the neighboring island of Agrihan, ~ 65 km north of Pagan. Volcanic activity was recorded through the late 1980s and early 1990s, and more

recently, eruptions with ash fall and plumes were observed in December 2006 and August 2010, a possible eruption with steam plumes was recorded in April 2009, and thermal emissions were detected in the subsequent years (Siebert and Simkin 2002–).

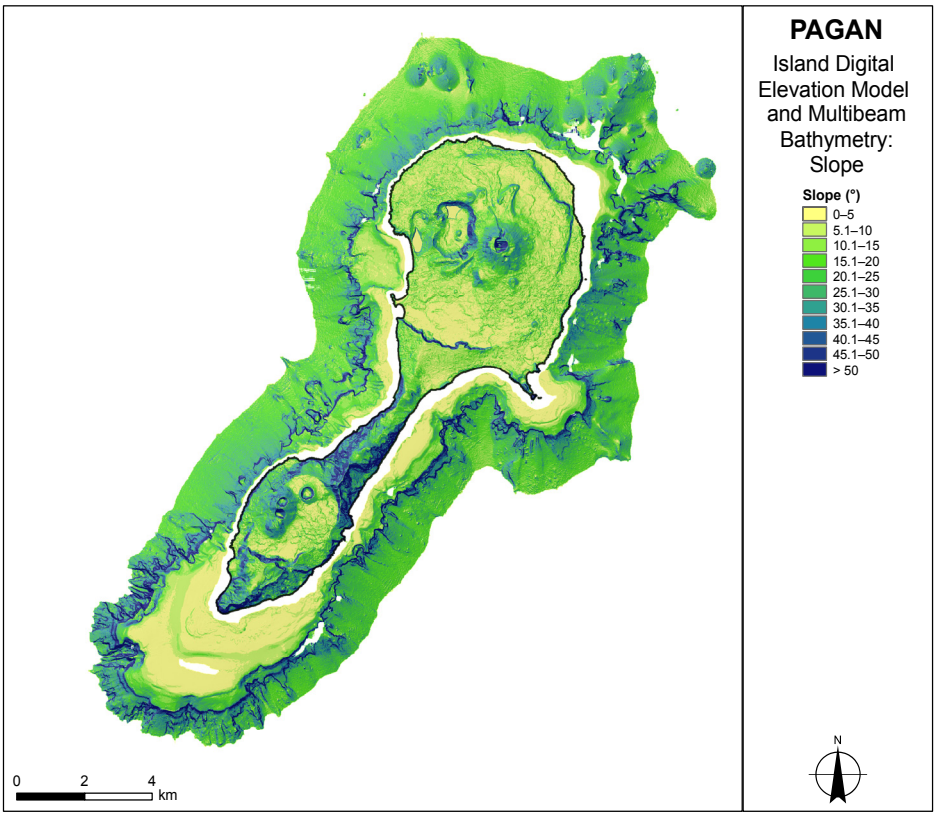


Figure 13.1.2a. Combined slope map using the digital elevation model and bathymetry data for Pagan (grid cell size: 10 m).

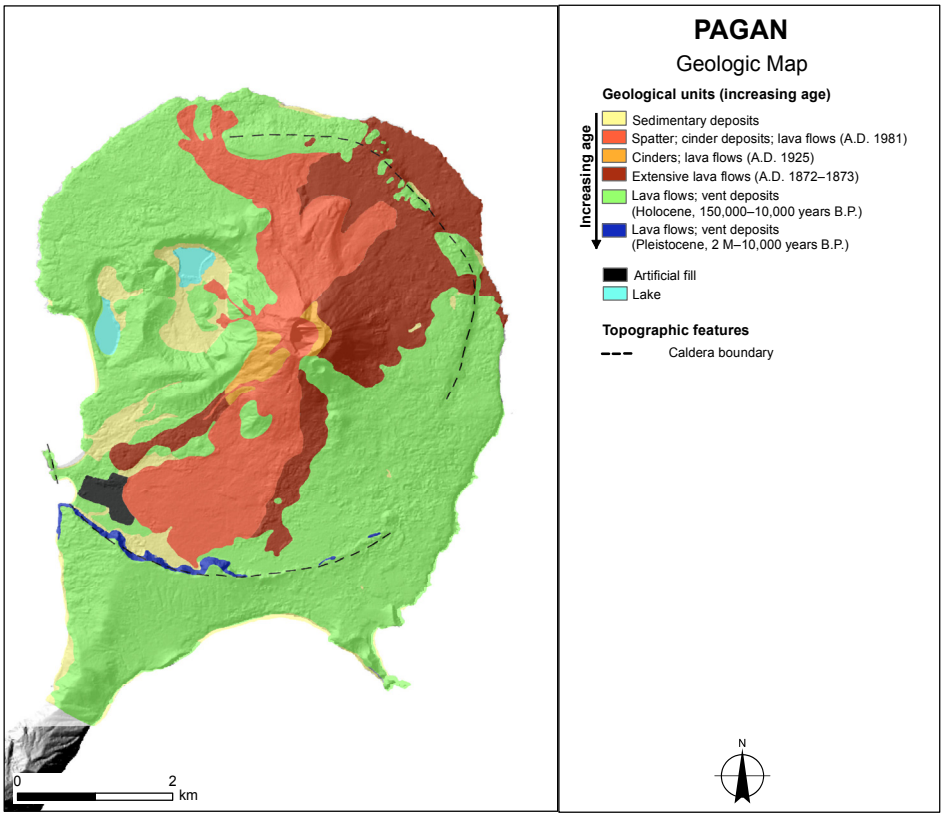


Figure 13.1.2b. Geologic map of Mount Pagan (adapted from Trusdell et al. 2006).

Except for areas covered by the most recent lava flows and volcanic deposits, the majority of Pagan is vegetated. Where recent volcanic material is vegetated, it supports pioneer vegetation, such as sword grass (*Miscanthus floridulus*) that is able to survive on a porous substrate. Around this island's 2 lakes, marshy areas and thickets of broad-leaved trees are present. Forest habitats on Pagan are fragmented and have suffered degradation from feral animals. Forests are present in valleys and ravines, on either side of the lava flows on the northern flanks of Mount Pagan, and on the western slopes of this island's isthmus (Cruz et al. 2000; Mueller-Dombois and Fosberg 1998). Small native patches remain, but forests primarily are composed of non-native species, including abundant *Casuarina equisetifolia*, an invasive tree (Cruz et al. 2000). Other introduced or non-native species on Pagan include the coconut palm (*Cocos nucifera*), tangan-tangan (*Leuceana leucocephala*), and physic nut (*Jatropha curcas*; Cruz et al. 2000).

Little information is available regarding the distribution of groundwater resources on Pagan. The 2 lakes in the northern caldera are filled with brackish water, and local groundwater supplies feed fumaroles (vent from which steam or hot gases escape) on Mount Pagan (Evans et al. 1987).

13.1.3 Environmental Issues on Pagan

One of the biggest environmental concerns on Pagan is the impact of feral animals on the native forests of this island (Cruz et al. 2000). Grazing by feral animals has removed natural vegetation and created a lack of a seedling understory, preventing future regeneration and resulting in dry soil and increased erosion.

The remaining, vulnerable patches of native forest on Pagan are important as habitat for native wildlife. Pagan supports a number of native birds, including the Micronesian starling (*Aplonis opaca*), Micronesian honeyeater (*Myzomela rubrata*), and a small population of the Micronesian megapode (*Megapodius laperouse*), a bird listed both as an endangered species Federally (U.S. Fish and Wildlife Service) and as a threatened or endangered species locally (Berger et al. 2005). The Mariana fruit bat (*Pteropus mariannus mariannus*), an endemic subspecies listed Federally as threatened (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), is present on this island with an estimated population of 1500 individuals in 2000 (Cruz et al. 2000).

Surveys conducted by the Division of Fish and Wildlife (DFW) of the CNMI Department of Lands and Natural Resources around planned homestead sites in 2000 indicated that no species of concern were located in the potential homestead areas and that northern Pagan was well suited to agriculture and ecotourism. Harvesting of natural resources from the coral reef ecosystems around Pagan would need to be managed to ensure sustainable use. In contrast to northern Pagan, southern Pagan supports a number of species of concern, and management of the feral animals in this area has been recommended by the CNMI DFW. Other potential environmental issues that may require management are erosion and sedimentation that could result from commercial ash mining in the future. The successful applicant likely would be required to develop harbor facilities and construct housing and associated infrastructure. Development of this new industry could change the economic and natural landscape of Pagan (Cruz et al. 2000).

13.2 Survey Effort

Extensive biological, physical, and chemical observations collected under MARAMP have documented the conditions and processes influencing coral reef ecosystems around the island of Pagan since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around Pagan are delineated in Figure 13.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Pagan. Potential reef habitat around this island is represented by a 100-fm contour shown in white on this map.

Benthic habitat mapping data were collected around Pagan using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around Pagan and Agrihan with multibeam sonar covered a total area of 2511 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 13.3: "Benthic Habitat Mapping and Characterization."

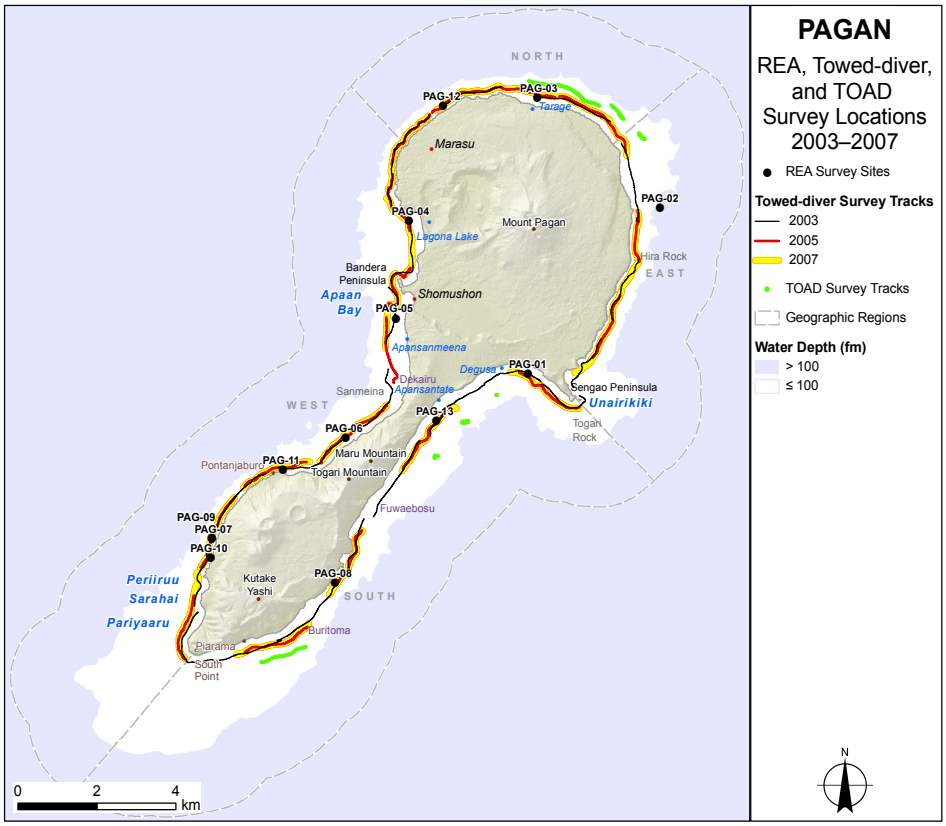


Figure 13.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Pagan during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 4 geographic regions: north, east, south, and west.

Information on the condition, abundance, diversity, and distribution of biological communities around Pagan was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 13.5–13.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 13.2a, along with their mean depths and total areas and length.

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Pagan were collected using (1) two types of moored instruments designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure

Table 13.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Pagan during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	7	9	9
	Mean Depth (m)	11.5 (SD 1.7)	12.6 (SD 1.7)	12.6 (SD 1.7)
Benthic	Number of Surveys	10	9	9
	Mean Depth (m)	11.9 (SD 1.8)	12.6 (SD 1.7)	12.6 (SD 1.7)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	21	17	16
	Total Survey Area (ha)	38.7	30.9	33.6
	Mean Depth (m)	12.9 (SD 1.7)	15 (SD 1)	14.8 (SD 1.3)
TOAD		**2003**		
	Number of Surveys	7		
	Total Length (km)	5.48		

of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007. Results from some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 13.2b. Results are discussed in Section: 13.4: "Oceanography and Water Quality."

Table 13.2b. Numbers of oceanographic instruments deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Pagan during MARAMP 2003, 2005, and 2007. Two types of instruments were moored around Pagan: sea-surface temperature (SST) buoy and subsurface temperature recorder (STR). Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
SST	1	1	1	1	1	–	1
STR	1	1	1	1	3	3	–
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	37	40		25			102
Deepwater Casts	–	9		1			10
Water Samples		**2005**		**2007**			**Total**
		5		7			12

Towed-diver Surveys: Depths

Figures 13.2b–e illustrate the locations and depths of towed-diver-survey tracks around Pagan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

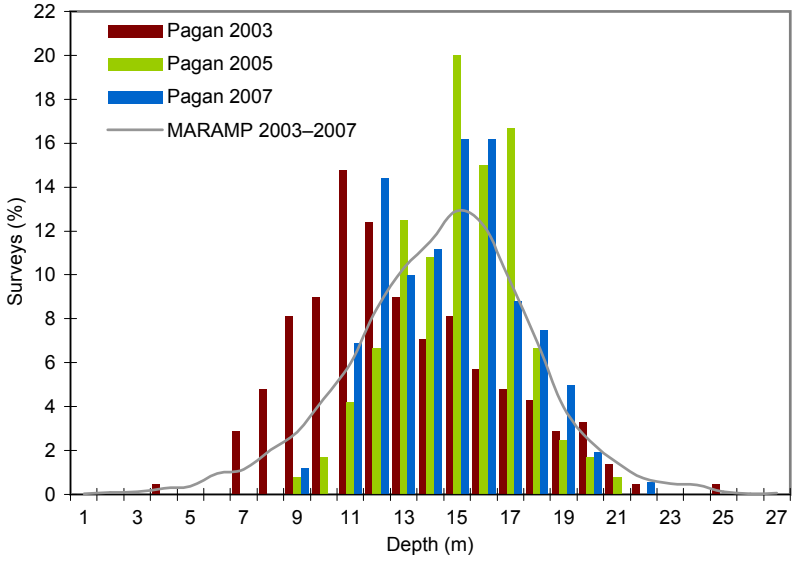


Figure 13.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

During MARAMP 2003, 21 towed-diver surveys were conducted along the forereef slopes around Pagan (Figs. 13.2b and c). The mean depth of all survey segments was 12.9 m (SD 1.7), and the mean depth of individual surveys ranged from 10.1 m (SD 2.9) to 16 m (SD 4.7).

During MARAMP 2005, 17 towed-diver surveys were conducted along the forereef slopes around Pagan (Figs. 13.2b and d). The mean depth of all survey segments was 15 m (SD 1), and the mean depths of individual surveys ranged from 12.5 m (SD 1.5) to 16.1 m (SD 2). Depths were not recorded for 4 surveys in the north region and for 1 survey in the west region because of an equipment malfunction.

During MARAMP 2007, 16 towed-diver surveys were conducted along the forereef slopes around Pagan (Figs. 13.2b and e). The mean depth of all survey segments was 14.8 m (SD 1.3), and the mean depths of individual surveys ranged from 12.6 m (SD 1.6) to 17.7 m (SD 3.1).

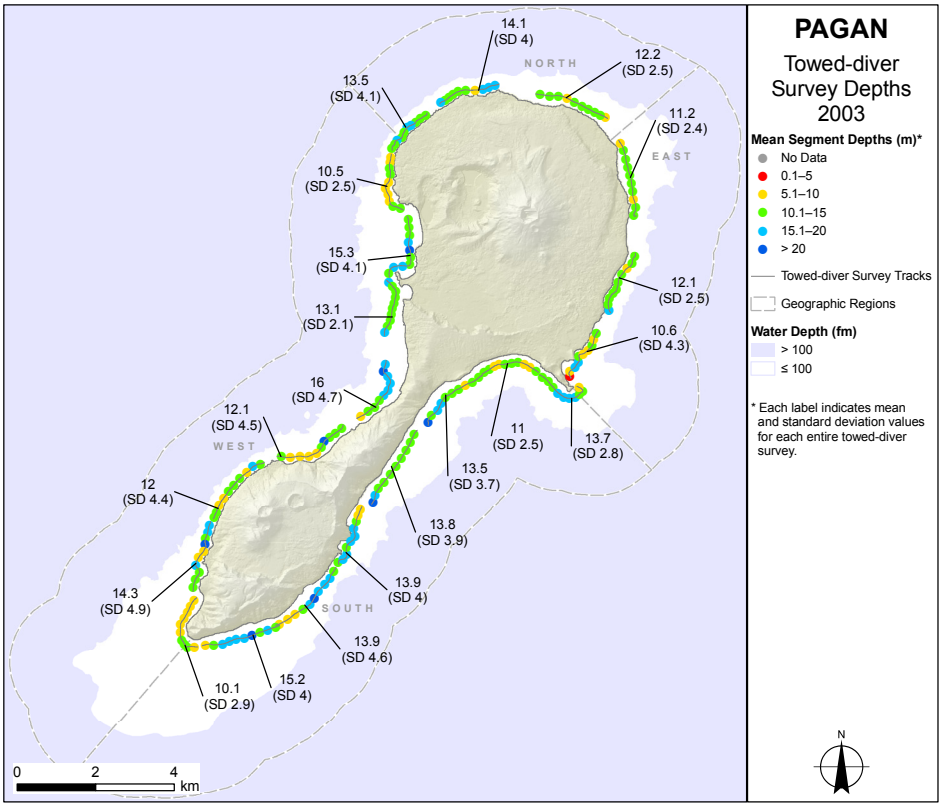


Figure 13.2c. Depth and tracks of towed-diver surveys conducted on forereef habitats around Pagan during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

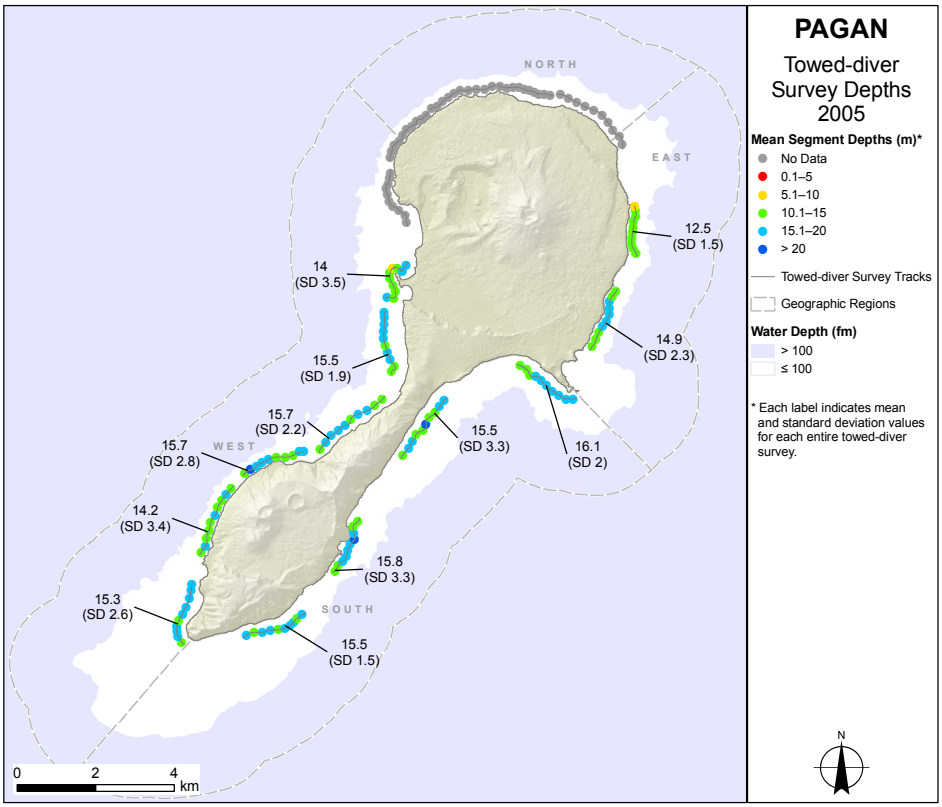


Figure 13.2d. Depths and tracks of towed-diver surveys conducted on forereef habitats around Pagan during MARAMP 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

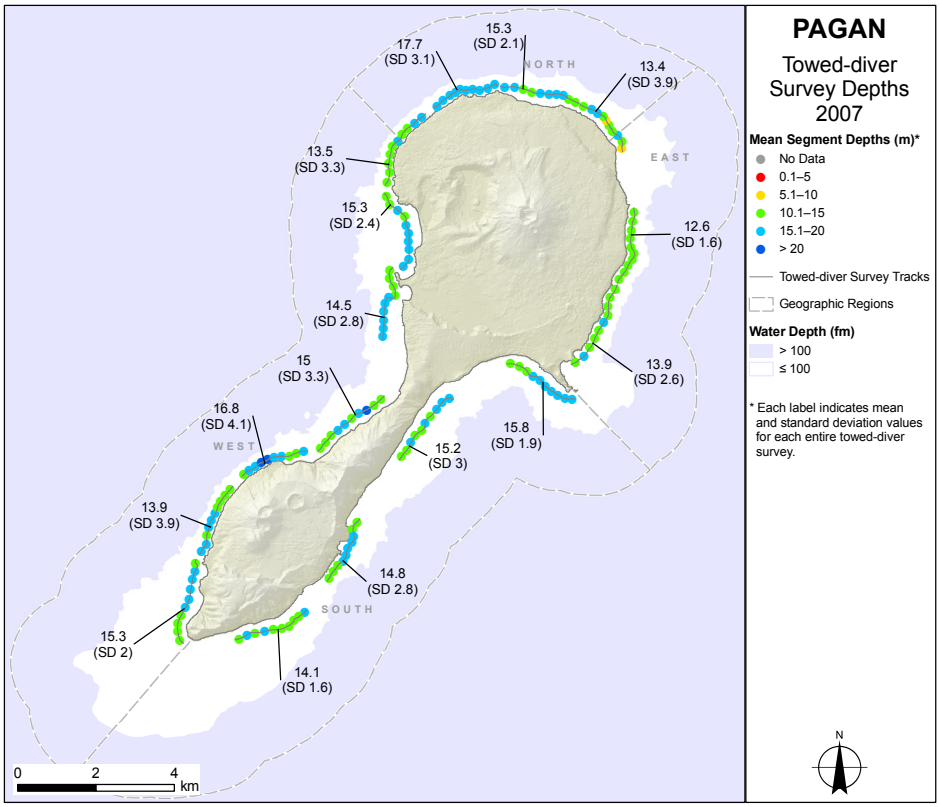


Figure 13.2e. Depths and tracks of towed-diver surveys conducted on forereef habitats around Pagan during MARAMP 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

13.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Pagan were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 7–2800 m with almost complete coverage around Pagan, except on the northeast corner. Coverage there began several hundred meters farther offshore than elsewhere as a result of rough sea conditions. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of < 5–100 m.

13.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 13.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around Pagan and Agrihan during MARAMP 2007 encompassed an area of 2511 km^2.

Multibeam bathymetry acquired around Pagan looks similar to the onshore topography of this island, which is dominated by Mount Pagan in the north and a second, smaller volcano in the south. The bathymetry reveals the steeply sloping flanks of Mount Pagan that descend from the coastline to depths > 2000 m. Numerous ridges and pinnacles are depicted by the bathymetry north of Pagan. Around southern Pagan, the seafloor topography is similar to the northern topography, with steep slopes that extend to depths > 3000 m, again punctuated with ridges and pinnacles. A large, shallow shelf area is shown around southern Pagan and extends for ~ 3 km from South Point (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). East of Pagan around Sengao Peninsula, a smaller shelf area is shown, and wide channels on either side of this shelf are formed by ridges extending northeast and southeast. East of the narrow isthmus that joins the north and south of Pagan, another shelf is revealed, forming 1 of the 2 anchorage areas present at Pagan; the second is located west of the isthmus. Aside from these 3 shelf areas, there is little shallow seabed around Pagan.

Several distinctive features are revealed by the multibeam backscatter data acquired around Pagan. Around northern Pagan, the various ridges and pinnacles shown in the bathymetry were characterized by high-intensity backscatter, indicating hard substrates. High backscatter values also were observed along the shelf edge around southern Pagan. A large area of

low-intensity backscatter, indicative of softer substrates, was present within and below the wide channel found south of Sengao Peninsula, suggesting this channel may form a conduit for the downward transport of soft sediments. Another large bay with low backscatter values lies north of the Bandera Peninsula, just downslope from 2 lakes formed in craters west of Mount Pagan, again suggesting a possible conduit for transport of sediments.

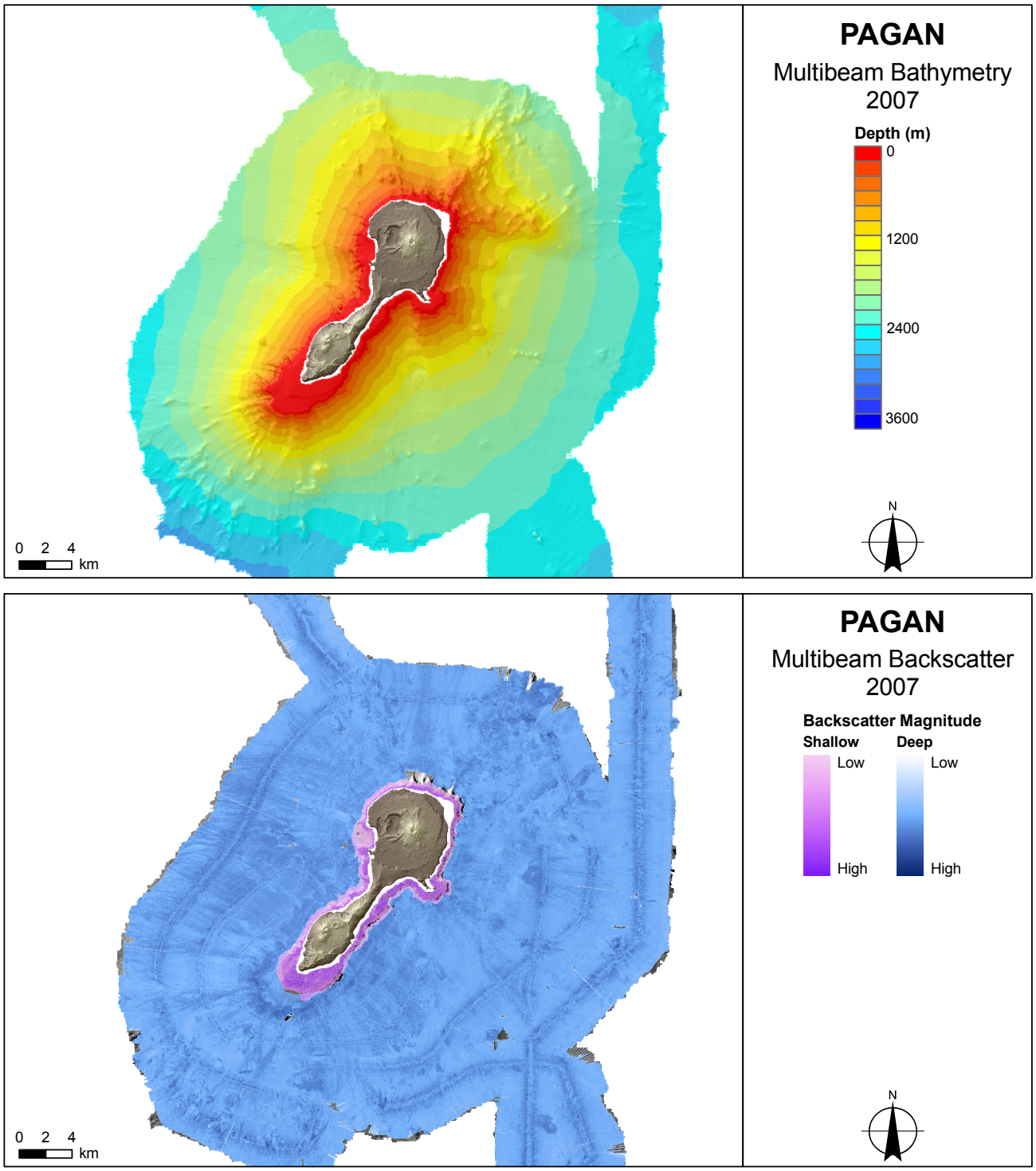


Figure 13.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Pagan during MARAMP 2007 at depths of ~ 7–2800 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

High-resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in nearshore (depths of 0–800 m) waters around Pagan were combined into a grid at a 10-m resolution to allow for the identification of fine-scaled features (Fig. 13.3.1b). These high-resolution data were also used to derive maps of slope (Fig. 13.3.1c), rugosity (Fig. 13.3.1d), and bathymetric position index (BPI) zones (Fig. 13.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Pagan.

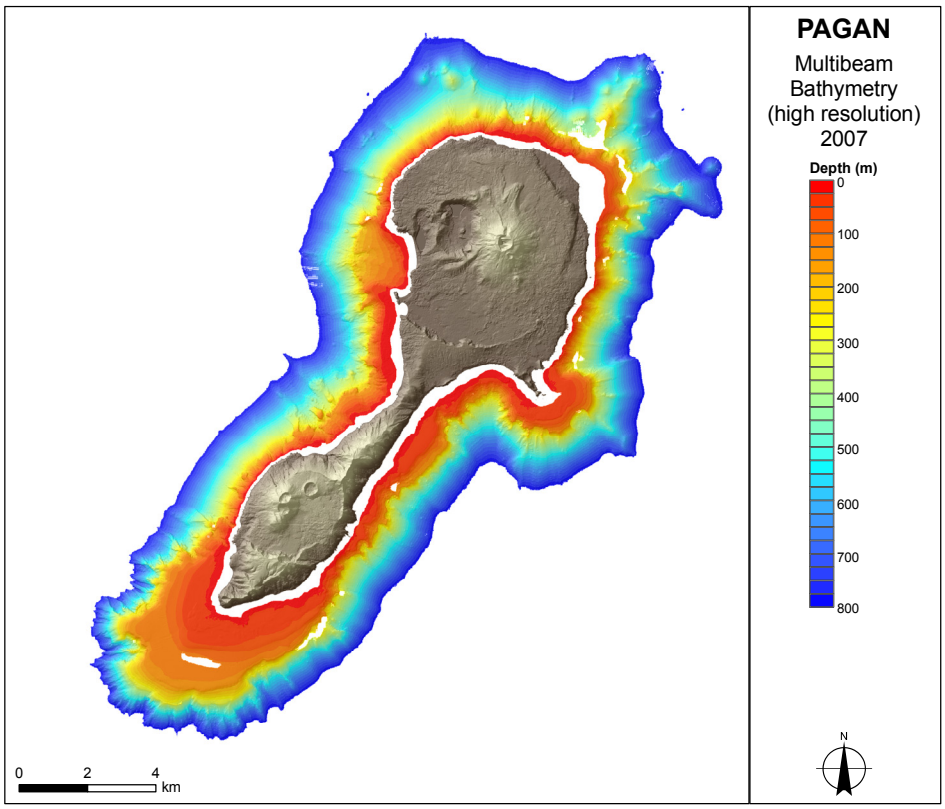


Figure 13.3.1b. High-resolution multibeam bathymetry collected by CRED around Pagan during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives.

The high-resolution multibeam bathymetry north of Pagan reveals a predominantly smooth seabed, characterized by moderate to steep slopes. The steepest slopes are found toward the east, where slopes > 50° are observed along the edge of shelf and ridge features and around a number of cones that are shown north of Pagan at a depth of 500–700 m (Fig. 13.3.1c). These topographic features also support the highest levels of rugosity (Fig. 13.3.1d). The BPI terrain analysis supports these observations and indicates that "slopes" are the dominant zone in this area (Fig. 13.3.1e).

East of Pagan, the high-resolution bathymetry reveals a similarly steeply sloping seafloor, although additional topographic complexity is provided by the numerous ridges that extend from the flanks of Mount Pagan. Observed slopes were generally 15°–20°, although very steep slopes > 50° were present at around a depth of 140–160 m. Additional steep slopes > 50° were observed on either side of the narrow ridges, which also support the highest levels of rugosity. BPI analysis highlights the complex nature of the seafloor in this area, which is characterized by a mixture of slopes, crests, and depressions.

South of Pagan, the seabed character is somewhat different from the one in the north, and the bathymetry data show a series of shallow shelves, with successively deeper areas of flat seabed at depths down to 150 m. The shelf area around the Sengao Peninsula on the eastern shore has a depth of ~ 40 m and extends along the coast toward Fuwaebosu. Slope, rugosity, and BPI analyses suggest that the shelf is smooth and flat. Below the shelf, the slope and BPI zone maps reveal that the seabed is moderately sloping down to a depth of 130–140 m, at which point it becomes steeper with slopes > 50°. The seabed descends steeply, forming ridges and canyons in several places, most noticeably north and south of the Sengao Peninsula.

Around South Point, the seabed is characterized by the presence of an extensive, shallow shelf, which extends for nearly 3 km out from South Point and is composed of 2 terraces at depths of ~ 50 and 125 m. Both terraces are low-rugosity, flat zones. High-resolution bathymetry and slope maps show mound-like features on this shallow shelf, features that may indicate coral reef habitats (Fig. 13.3.1c). No optical data were obtained in this area to validate this hypothesis, and further

investigation of this area is merited. Below this shelf, the seabed is characterized by highly rugose slopes > 50°, with steep-sided ridges forming canyons.

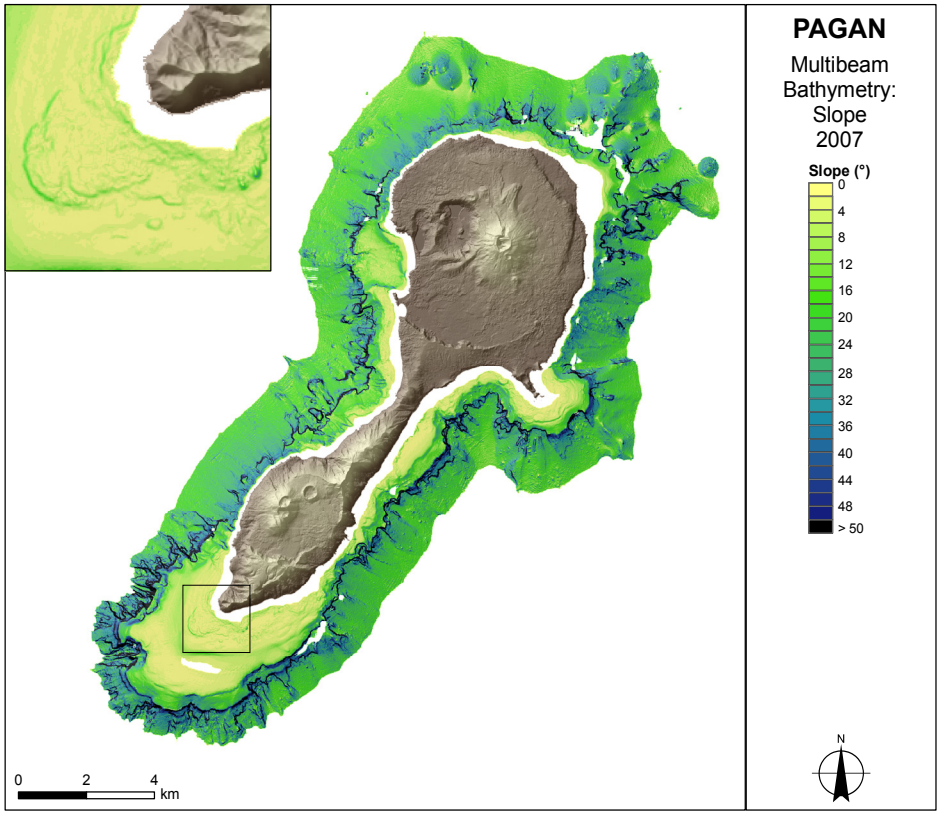


Figure 13.3.1c. Slope (°) of 10-m bathymetric grid around Pagan. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades. Inset map shows complex bathymetry at a depth of 15–40 m on the shelf around South Point.

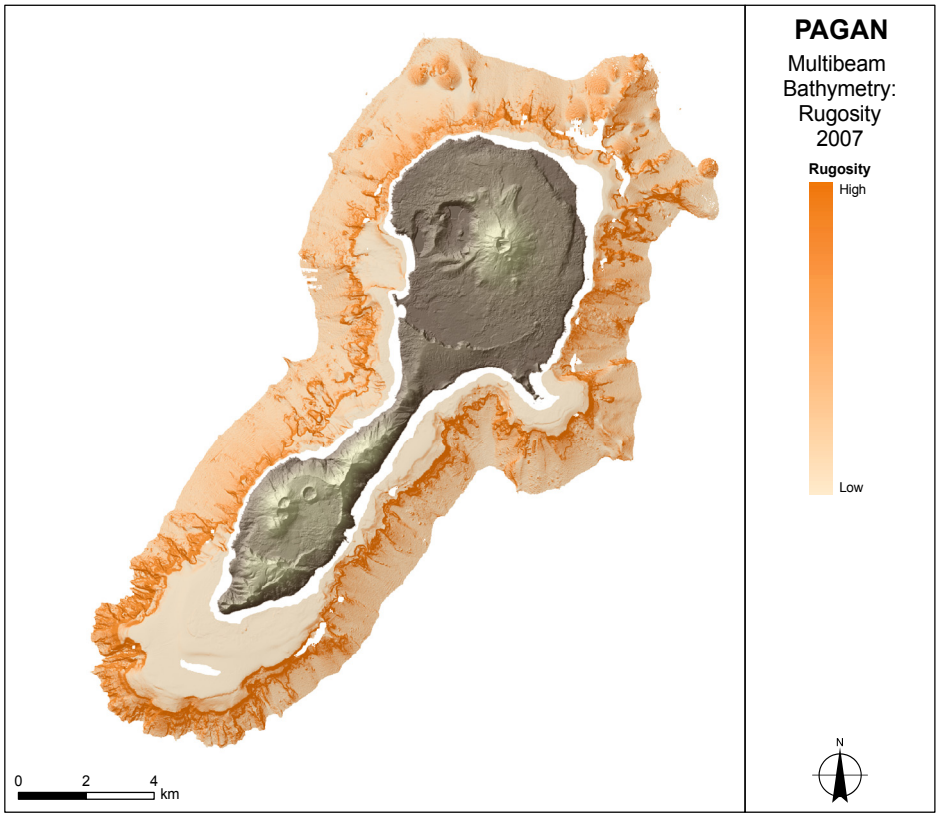


Figure 13.3.1d. Rugosity of 10-m bathymetric grid around Pagan. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

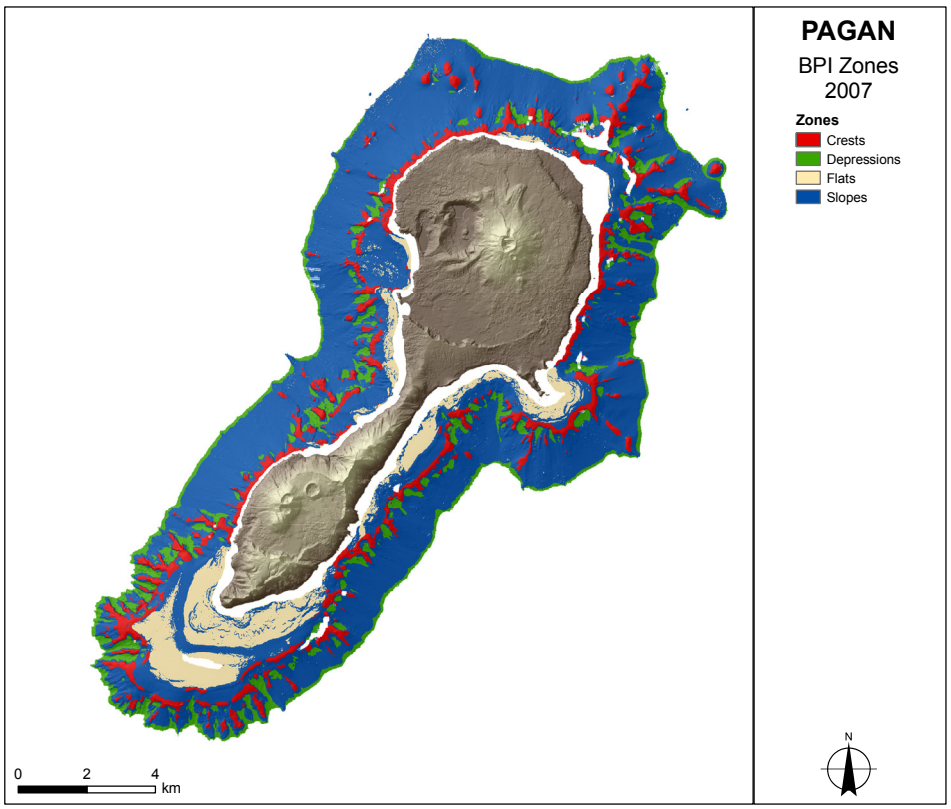


Figure 13.3.1e. BPI zones of 10-m bathymetric grid around Pagan derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

West of Pagan, narrow shelves are present within Apaan Bay and north of Bandera Peninsula. The shelf north of Bandera Peninsula is bordered by a large area of gentle slopes and flats, forming a large bay. Below these shelf areas, the seabed topography is similar to elsewhere around Pagan, with moderate slopes at depths < 200 m, a zone of very steep slopes (> 50°) at depths of 200–250 m, and then a steeply sloping seabed at depths > 250 m.

High-resolution Multibeam Backscatter and Derivatives

The quality of the backscatter data acquired around Pagan was impacted to some extent by the very steep slopes present around much of this island, and time constraints that resulted in data being acquired at speeds slightly faster than the optimum rate. These issues resulted in some loss of data quality, such as gaps in the data coverage. Despite these constraints, the high-resolution data do provide some clear patterns in the acoustic characteristics of the seabed around this island (Fig. 13 3.1f) that can be related to other seabed characteristics such as topography and slope.

North and east of Pagan, high backscatter values are shown in the shallowest areas (Fig. 13 3.1f), and lower backscatter values are shown below the shelf break, which is demarcated by the narrow band of steeply (> 50°) sloping seabed. These backscatter data and the hard–soft classification (Fig. 13.3.1g) suggest that soft sediments are present on the deeper slopes and hard substrates are present on the shallow flats and slopes, although the backscatter intensity may be influenced to some degree by the slopes themselves, vessel speed, or the instrument settings during data collection.

South and east of Pagan, higher backscatter values indicate hard substrates for the shallow shelf areas around Sengao Peninsula, along the southeast coast, and near South Point. These results show the importance of the extensive shelf around South Point that provides a suitable substrate to support coral reef habitat. Below this shelf, the sloping seabed has predominantly low backscatter values, suggesting that soft substrates might be present there.

Along the southeastern coast of Pagan, the hard–soft classification map shows several small areas of soft sediments associated with valleys in the seabed. An area of soft sediment is indicated by low backscatter values along the inner margin of a shallow shelf, adjacent to the reef edge, and along the more gradually sloping base.

Southwest of Pagan, backscatter values are predominantly low, suggesting the predominance of soft substrates. Shallow shelves, where hard substrates tend to be found, were not observed in this area. In contrast, west of Pagan, around Apaan

Bay, high backscatter values are shown along a shallow shelf area. The hard–soft map shows patches of soft sediments that correspond to channels revealed in the multibeam bathymetry. The accumulation of sediment in these areas may relate to sediment inputs from surface-water runoff from this volcanic island. The hard–soft analysis also suggests areas of soft

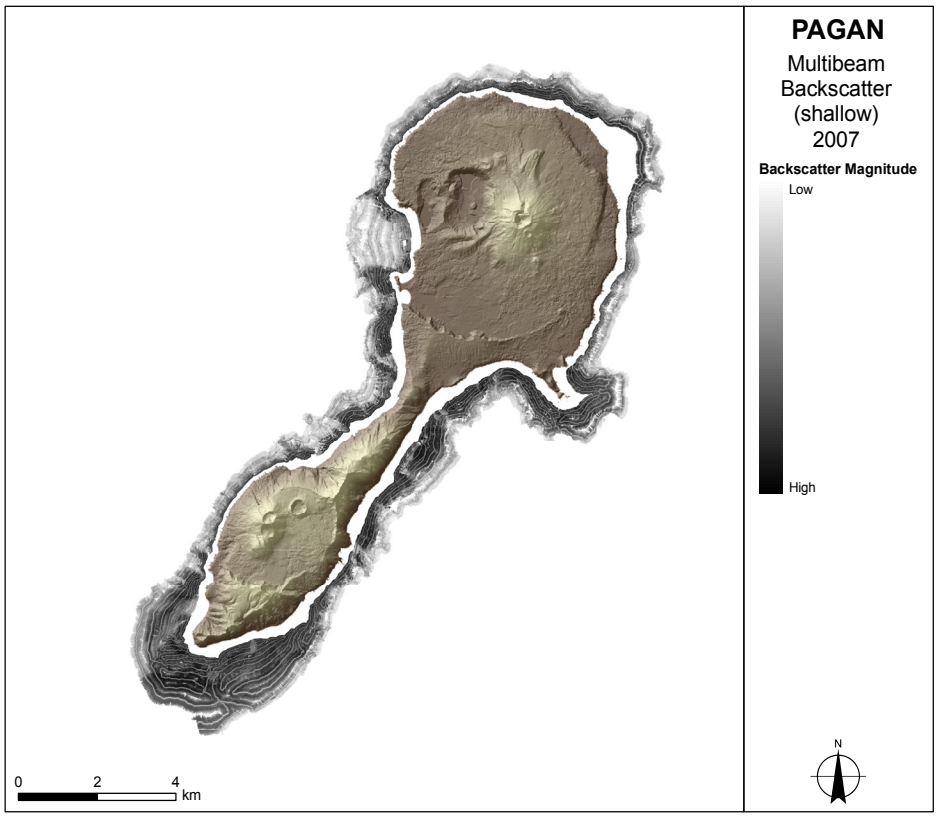


Figure 13.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 10 m) collected around Pagan during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

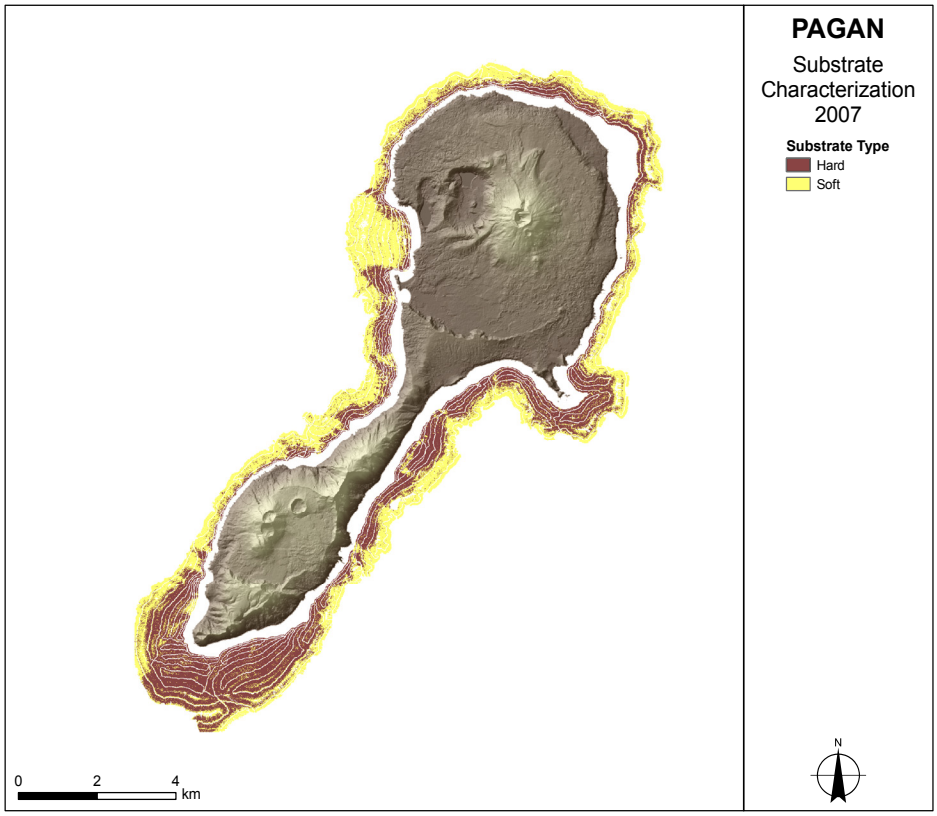


Figure 13.3.1g. Hard and soft substrates (grid cell size: 10 m) based upon an unsupervised classification of multibeam bathymetry and backscatter data acquired around Pagan in 2007. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

sediments within the small bay south of Bandera Peninsula and the larger bay to the north. Onshore, adjacent to this larger bay, 2 lakes are present within the maar, a shallow, flat-floored crater created by explosive volcanic eruptions shown on the topographic maps, west of Mount Pagan. The lower of these 2 lakes, Lagona Lake, is only tens of meters away from shore and may contribute soft sediments to the bay below.

13.3.2 Optical Validation

During MARAMP 2003, 8 TOAD optical-validation surveys were conducted at Pagan at depths < 100 m (Fig. 13.3.2a). Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live-hard-coral cover.

Covering a distance of 103 km at depths of 4–25 m, 54 towed-diver optical-validation surveys of forereef habitats, were conducted around Pagan during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

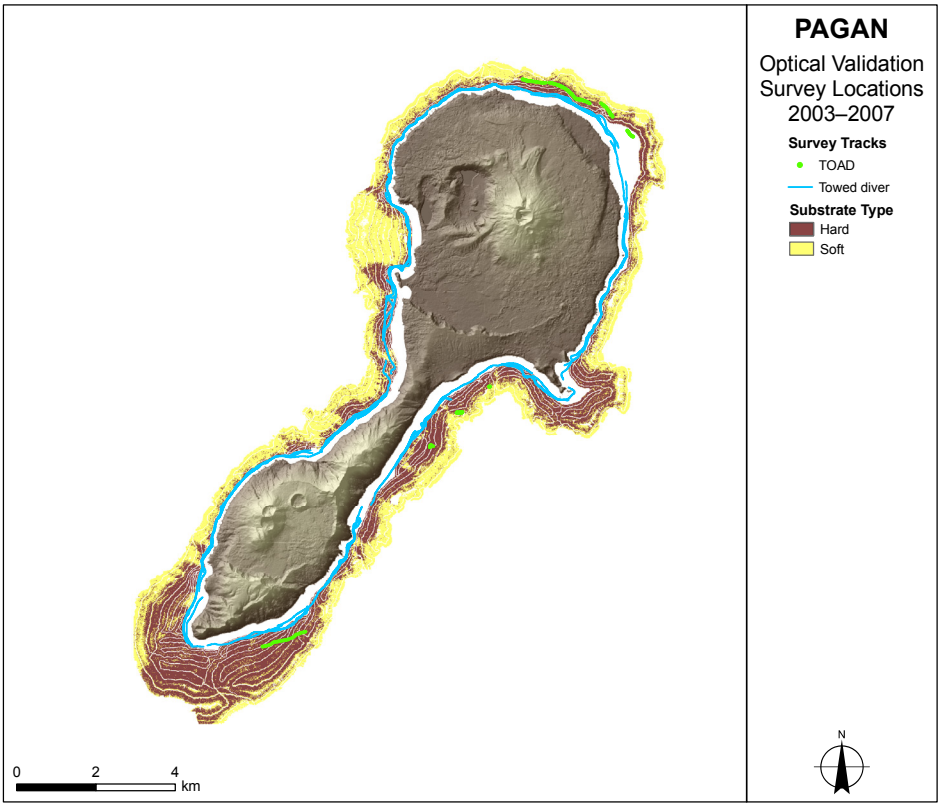


Figure 13.3.2a. Towed-diver tracks from surveys of forereef habitats conducted around Pagan during MARAMP 2003, 2005, and 2007, and TOAD camera-sled tracks for MARAMP 2003. Survey tracks are displayed over the multibeam hard–soft substrate map. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

13.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Pagan are discussed in this section. These descriptions are organized by the 4 geographic regions around Pagan. Optical-validation surveys conducted around Pagan during MARAMP 2003, 2005, and 2007 showed clear differences between the seabed surveyed around the northern and eastern flanks of Mount Pagan, the southern and western flanks of Mount Pagan, the narrow central region of Pagan, and South Point. In general, habitats in the north and east regions consisted of hard substrates (Fig. 13.3.3a), were fairly complex (Fig. 13.3.3b), and supported a moderate cover of live corals (Fig. 13.3.3c). In contrast, south and west of Mount Pagan, the seabed was characterized by low-complexity, soft-sediment habitats that supported very low levels of live coral cover. On either side of the narrow center of Pagan, habitats were hard substrate of medium complexity with moderate amounts of live coral cover. Around South Point, sand was again more common, and habitat complexity was lower than in other areas around this island. Overall, live coral cover around Pagan was low to medium compared to the rest of the Mariana Archipelago, with the highest concentrations of live coral cover observed at the tip of Sengao Peninsula on the east side of this island. These general conclusions are discussed in more detail in the rest of this section.

In the north region, predominantly hard substrates with low sand cover were observed during towed-diver surveys. In the western half of this geographic region, very low sand cover was recorded, and the habitats encountered were characterized by medium to high complexity and live coral cover of 10.1%–30%. In the eastern half, sand cover was higher, reaching 75.1%–100% in one small area. Habitat complexity there was lower than in the western half, and live coral cover was also lower, generally ranging from 1.1%–20%. The habitats present included spur-and-groove reefs, slopes, ridges, hard pavement, and boulders. Optical data collected in deeper water (depths of 50–100 m) using the TOAD suggest mainly hard substrates, with a section of 100% sand cover northeast of Tarage in the north region. Very low live coral cover was recorded at these depths, with only isolated video frames showing live corals.

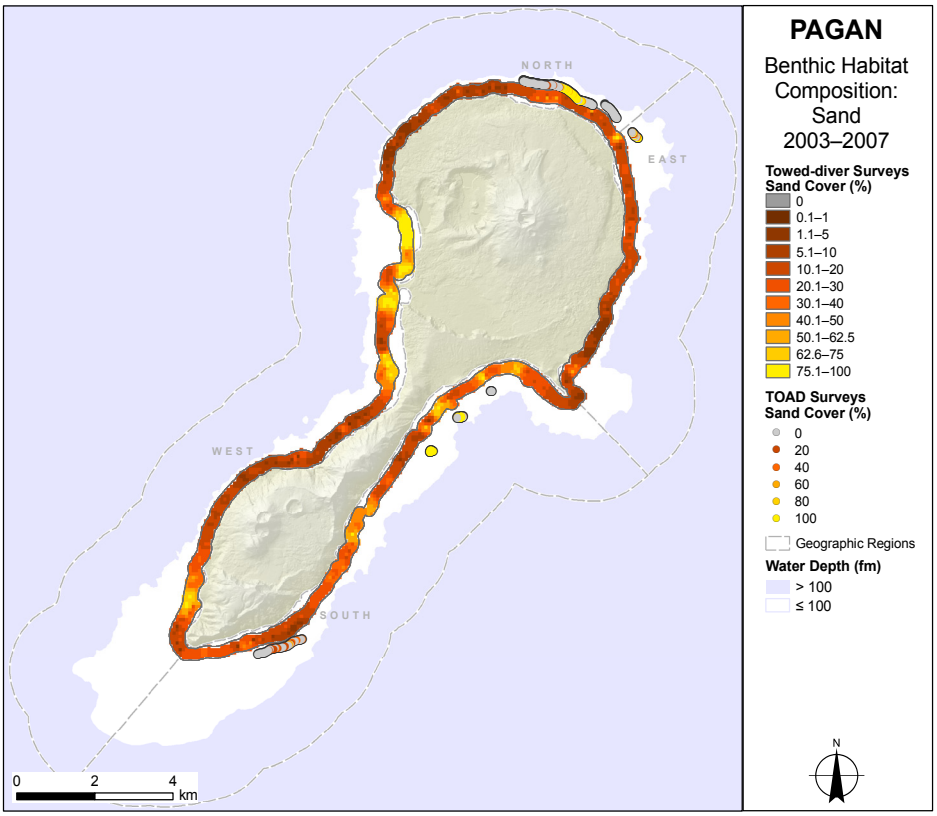


Figure 13.3.3a. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Pagan during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggest that habitats in the east region had slightly more sand than areas farther north, with cover generally in a range of 5.1%–20%. Habitat complexity was predominantly medium to high, and live coral cover of 5.1%–40% was observed. Habitats encountered were described as a mixture of spur-and-groove reef, rocky reef, and pavement, with boulders frequently forming part of the habitat. Results from the single short TOAD survey conducted in this region suggested patchy sand cover and very few live corals, although 2 video frames showed live corals at depths of ~ 55 and 80 m.

In the south region, sand was a more dominant component of the seabed habitat with high cover recorded around Degusa and east of Buritoma. TOAD surveys also documented high cover of sand offshore from Apansantate, although this area is classified as hard substrate in the hard–soft map (Fig. 13.3.1g), suggesting that the sand is likely to be a thin veneer with acoustically reflective substrates beneath. Based on towed-diver surveys, habitat complexity in this area was low to medium, but live coral cover was not very dissimilar to the more complex habitats encountered north of Pagan. Live coral cover from towed-div surveys was variable, with cover of up to 40% recorded in several locations. Analyses of video footage obtained in deeper water during TOAD surveys indicate very few live corals, with cover of 20% in some video frames at depths up to ~ 75 m. Habitats observed in this region included pavement flats, patch reefs, boulders in sand, and continuous reefs.

Around South Point, towed-diver surveys suggested some variability in the distribution of sand cover. High sand cover was recorded in the narrow bay just north of South Point (Fig. 13.3.3a), corresponding to a sand channel identified in the hard–soft substrate map (Fig. 13.3.1g). Hard substrates were recorded at South Point itself and at Piarama, both in the shallow waters surveyed by towed divers and in the slightly deeper waters surveyed with the TOAD. Towed-diver surveys conducted around South Point revealed habitats of medium to medium-high complexity and generally low live coral cover

of 1.1%–30%. Analyses of video footage acquired during TOAD surveys indicate very low live coral cover at a depth of 30–40 m, with a small number of video frames showing 20% live coral cover.

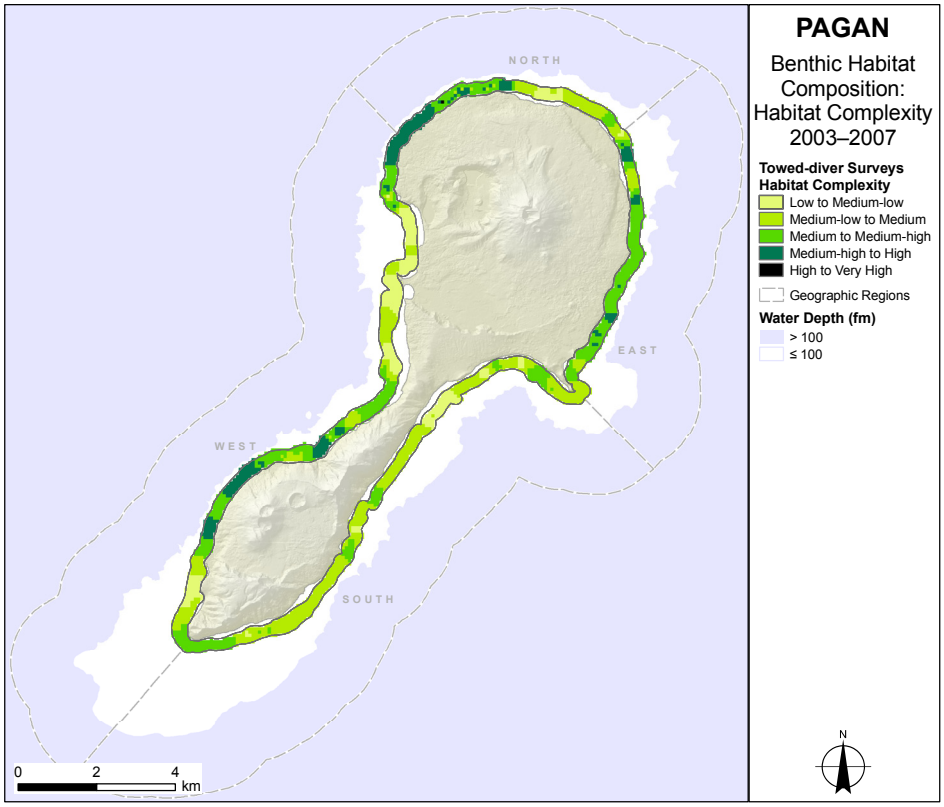


Figure 13.3.3b. Observations of benthic habitat complexity from towed-diver surveys of forereef habitats conducted around Pagan during MARAMP 2003, 2005, and 2007.

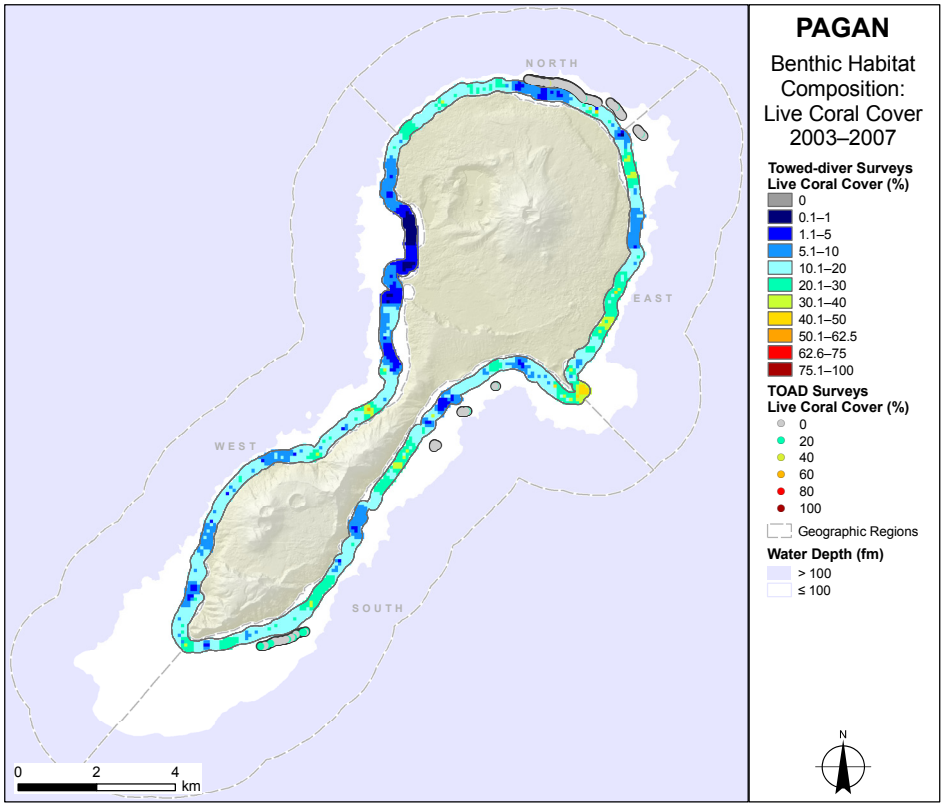


Figure 13.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Pagan during MARAMP 2003, 2005, and 2007.

Around southwestern Pagan, around the flanks of the southern volcano and on either side of the narrow isthmus of Pagan, habitats observed during towed-diver surveys were characterized by predominantly hard substrates of medium to high complexity and in general supported live coral cover of 1.1%–20%, with cover of up to 40% recorded in one location.

The seabed observed on the southwestern flanks of Mount Pagan was somewhat different than the one seen on the northern and eastern flanks, as it was predominantly sandy, with very low live coral cover and low to medium habitat complexity. Towed-diver surveys conducted within the bays north and south of Bandera Peninsula suggest habitats characterized by high cover of sand and very low cover of live corals. These corresponded to areas of soft sediment identified on the hard–soft substrate map (Fig. 13.3.1g).

13.4 Oceanography and Water Quality

13.4.1 Hydrographic Data

2003 Spatial Surveys

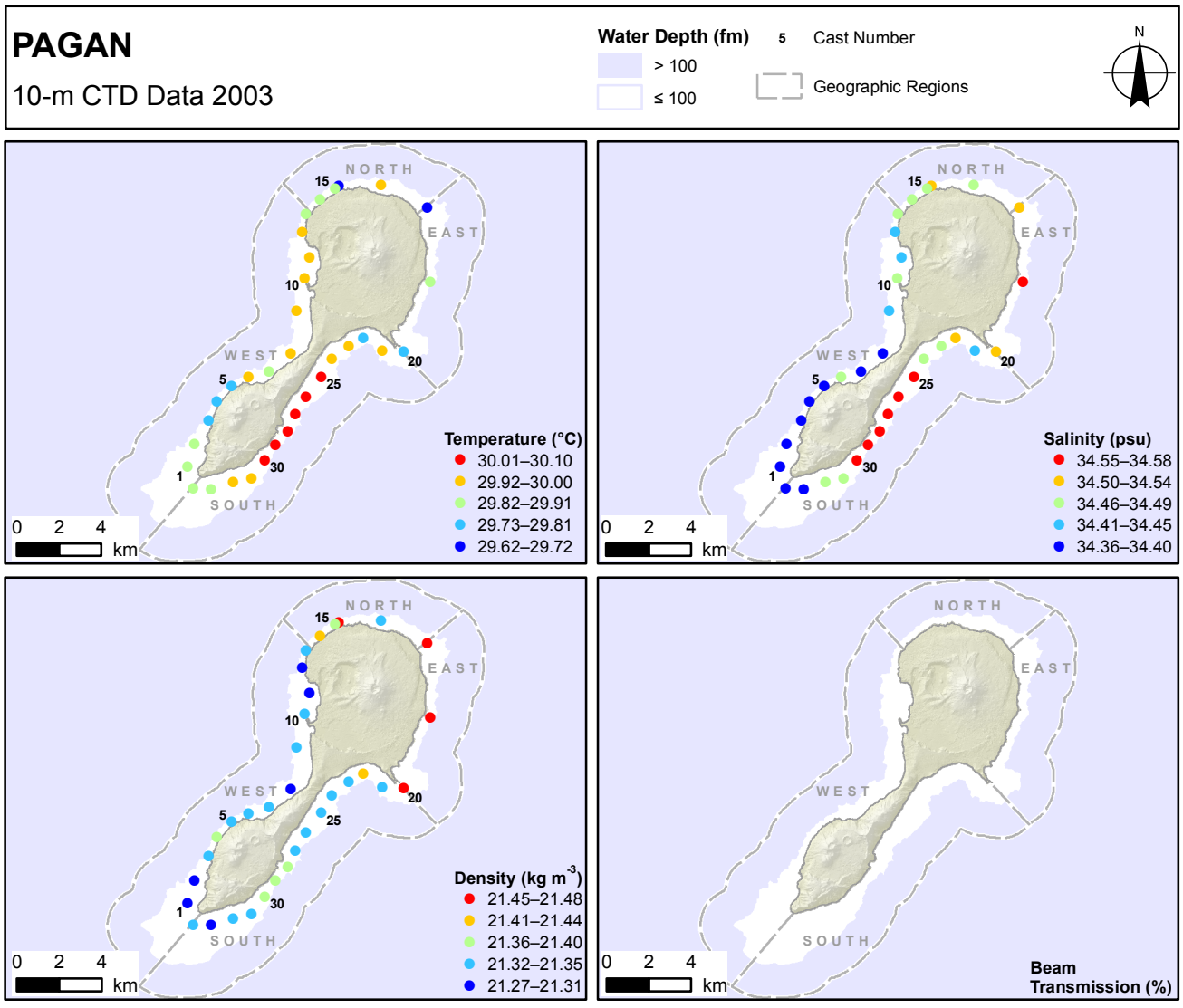


Figure 13.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts around Pagan during MARAMP 2003, with casts 20 and 22 done on August 25, casts 16–19 done on August 26, casts 13–15 done on September 6, casts 1–12 done on September 7, casts 21, 23, 24, and 31–34 done on September 8, and casts 25–30 done on September 12.

During MARAMP 2003, shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the island of Pagan over the period of August 25–September 12. Temperature, salinity, and density values from 34 of these casts varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest moderate variability around this island, with temperature differences measured up to 0.48°C (Fig. 13.4.1a). The warmest temperature (30.1°C) and highest salinity (34.58 psu) values were recorded in the south region (casts 25–30). Vertical comparisons of CTD profiles reveal water properties with a broad range in temperature (1.3°C), salinity (0.7 psu), and density (0.7 kg m^{-3}) values (Fig. 13.4.1b). These large ranges could have resulted from temporal separation in sampling. These measured ranges in water properties also could result from enhanced mixing, with deeper waters or localized upwelling observed in the east region (cast 18) relative to other areas of this island. Additionally, a well-mixed and warm (30.1°C) water column was seen in the south region (casts 25–30).

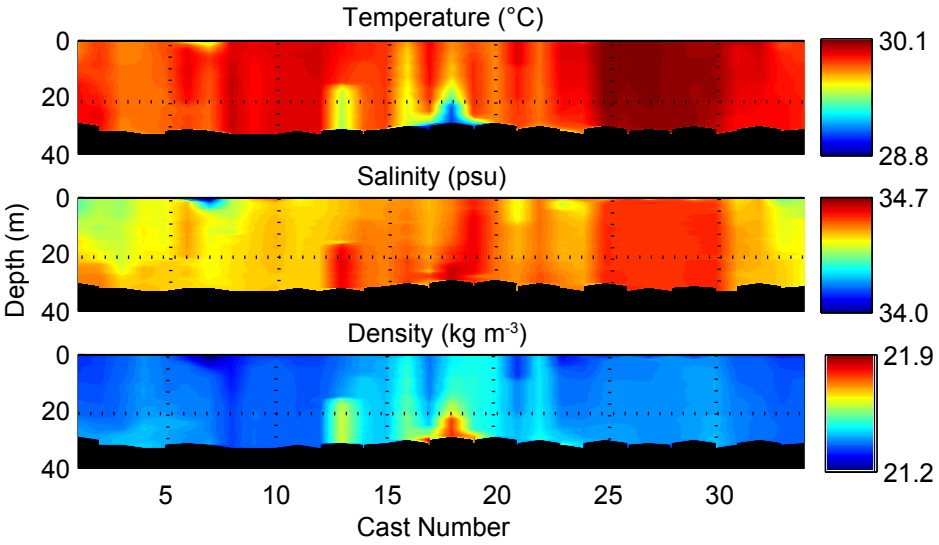


Figure 13.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Pagan during MARAMP 2003, August 25–26, September 6–8, and September 12, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–34 in a clockwise direction around Pagan. Casts 20 and 22 were completed on August 25, casts 16–19 were done on August 26, casts 13–15 were done on September 6, casts 1–12 were done on September 7, casts 21, 23, 24, and 31–34 were done on September 8, and casts 25–30 were done on September 12. For cast locations and numbers around this island in 2003, see Figure 13.4.1a.

2005 Spatial Surveys

During MARAMP 2005, shallow-water CTD casts were conducted in nearshore waters around Pagan over the period of September 6–8. Temperature, salinity, density, and beam transmission values from 39 of these casts varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest low variability around Pagan, with temperature differences measured up to 0.31°C (Fig. 13.4.1c). Cool (28.77°C–28.83°C) waters were recorded in the south region (casts 32–39), with low salinity (34.29–34.38 psu), low density (21.61–21.66 kg m^{-3}), and high beam transmission (> 94.19%) values compared to waters monitored at other cast locations at Pagan. Vertical comparisons of CTD profiles (Fig. 13.4.1d) reveal a well-mixed water column in most cast locations; however, at select locations, the water column was highly stratified (casts 29–31). Additionally, a cold, less saline and clear (low beam transmission) water mass was observed at the upper surface southeast of Pagan (casts 34–39), likely indicative of a rain event that occurred during data collection.

Water samples were collected in concert with shallow-water CTD casts at 5 select locations at Pagan in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.125–0.225 µg L^{-1}; total nitrogen (TN), 0.084–0.226 µM; nitrate (NO_3^-), 0.069–0.205 µM; nitrite (NO_2^-), 0.014–0.021 µM; phosphate (PO_4^{3-}), 0.022–0.04 µM; and silicate [$Si(OH)_4$], 1.364–1.705 µM. Concentrations of Chl-*a* were highest in the north and west regions, whereas total nitrogen, nitrate, and nitrite were greatest in the south region (Fig. 13.4.1e). Silicate and phosphate varied concurrently, with higher values measured to the north and lower values to the south.

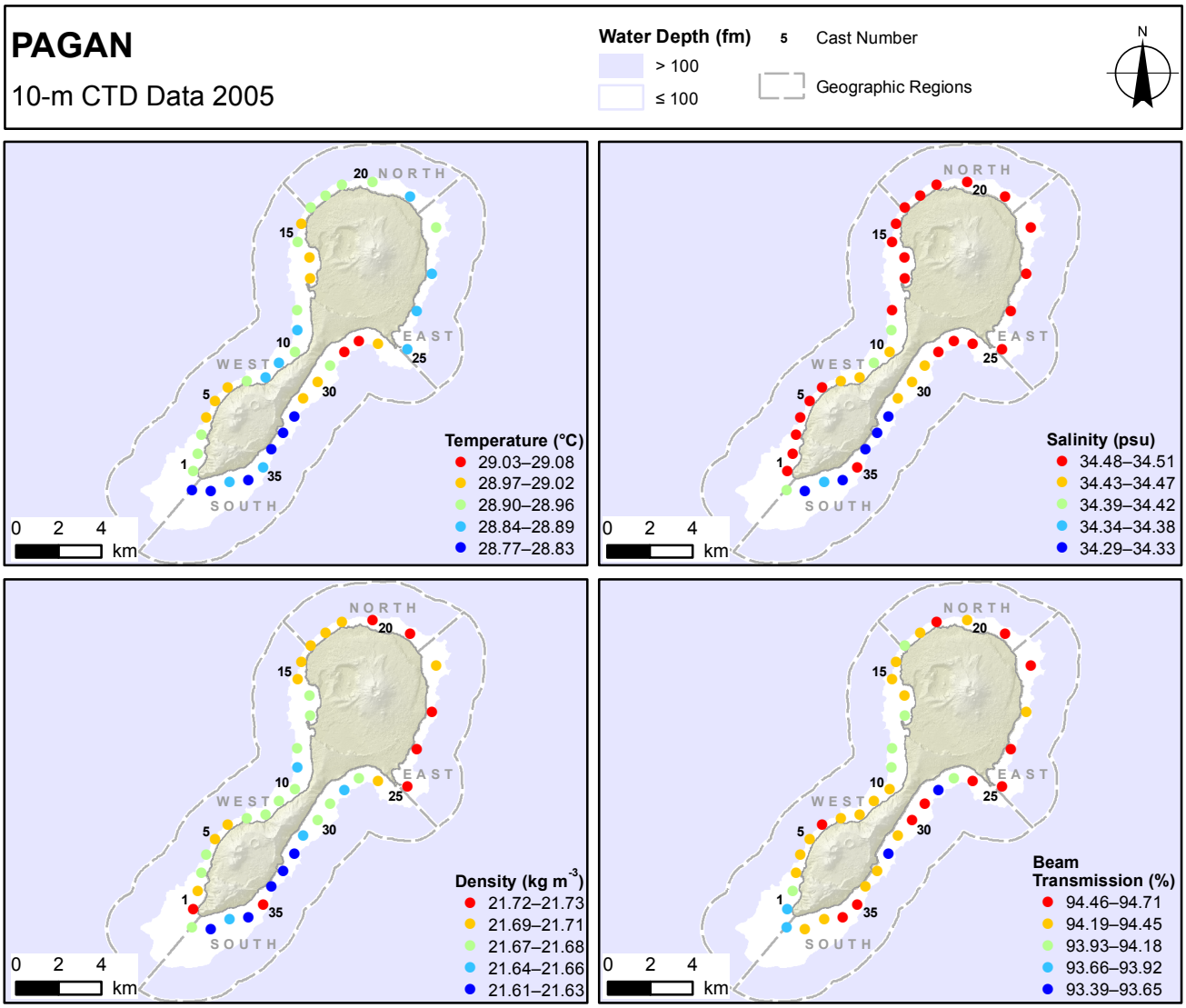


Figure 13.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Pagan on September 6–8 during MARAMP 2005.

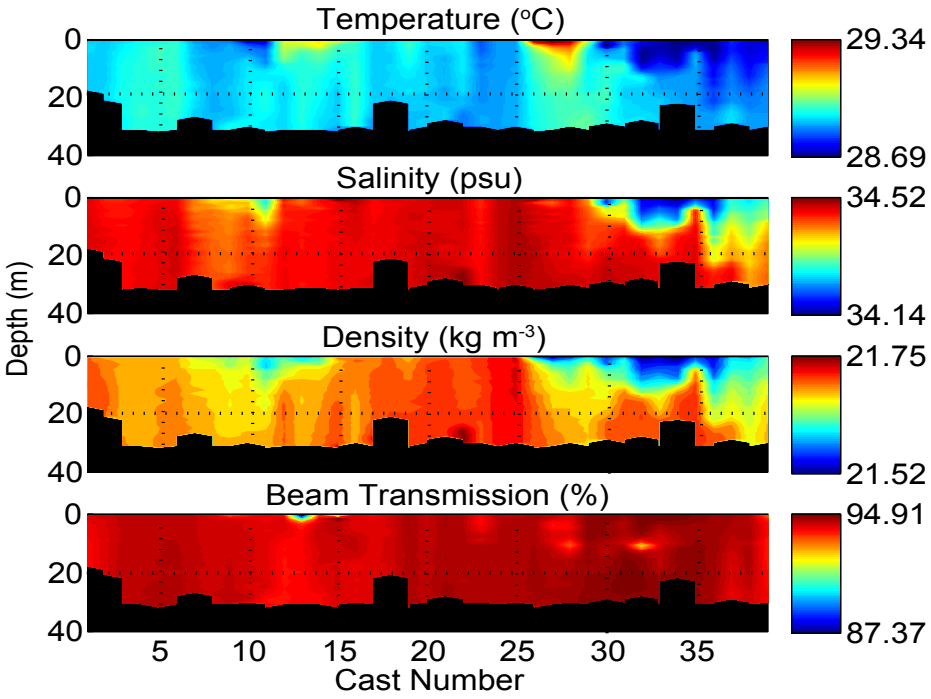


Figure 13.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Pagan on September 6–8 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–39 in a clockwise direction around Pagan. For cast locations and numbers around this island in 2005, see Figure 13.4.1c.

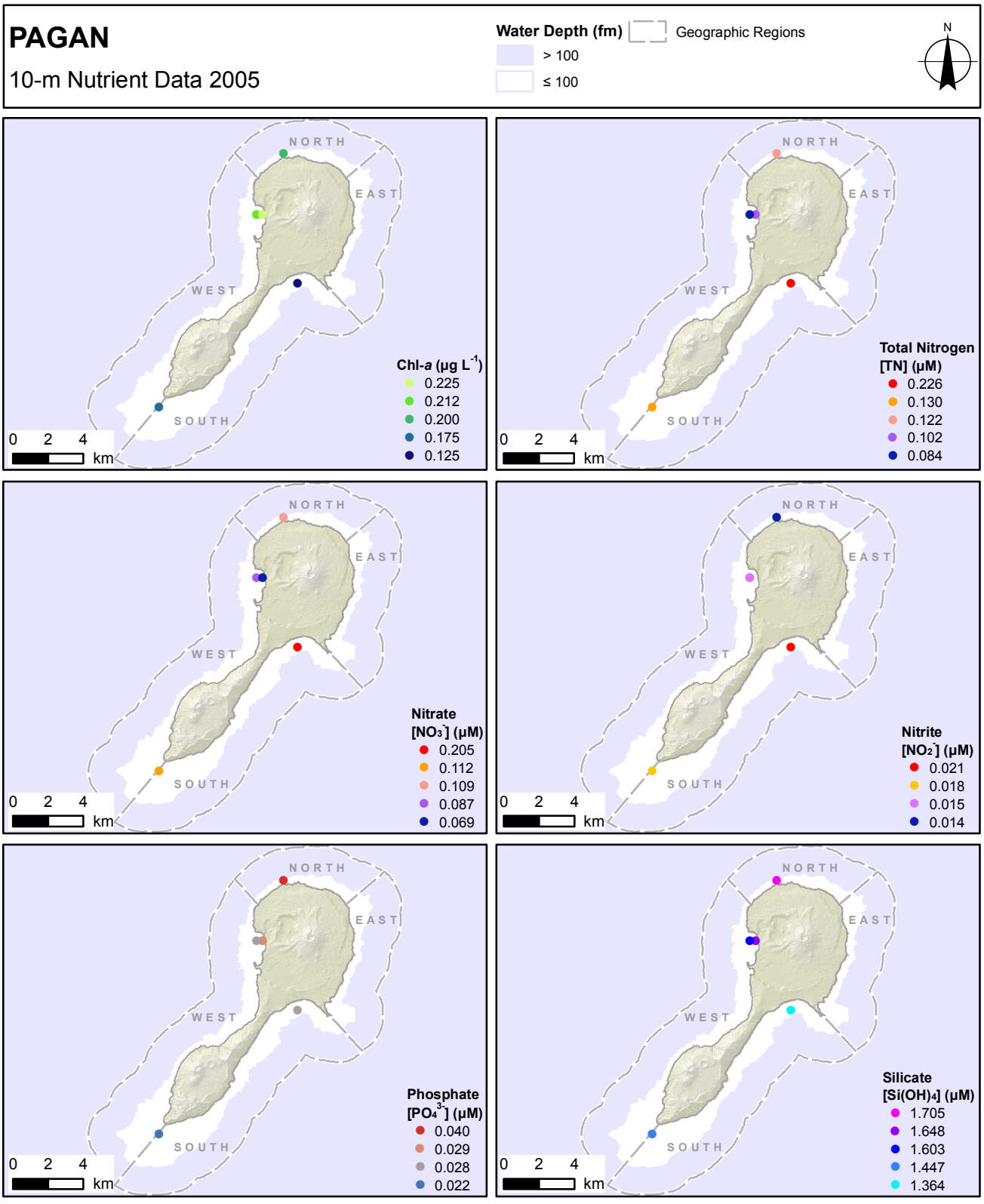


Figure 13.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Pagan on September 6–8 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, shallow-water CTD casts were conducted in nearshore waters around Pagan over the period of June 4–6. Temperature, salinity, density, and beam transmission values from 23 of these casts varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest moderate variability around Pagan, with temperature differences measured up to 0.6°C (Fig. 13.4.1f). Warm (29.77°C) water was recorded in the west region (casts 1–3), with low salinity (34.49 psu), low density (21.46 kg m^{-3}), and high beam transmission (92.25%) values compared to waters monitored at other cast locations at Pagan. In general, waters surrounding the west and north regions were warmer than waters in the east and south regions. Vertical comparisons of CTD profiles reveal water properties with a broad range in water temperature (1.3°C) and moderate ranges in salinity (0.3 psu), density (0.6 kg m^{-3}), and beam transmission (1.7%) values (Fig. 13.4.1g). The observed ranges in temperature and salinity values may result from enhanced mixing with deeper waters or localized upwelling seen at discrete locations around this island (casts 5, 6–8, 13–17).

Water samples were collected in concert with shallow-water CTD casts at select locations at Pagan in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: Chl-*a*, 0.028–0.307 µg L^{-1}; total nitrogen (TN), 0.023–0.133 µM; nitrate (NO_3^-), 0.004–0.104 µM; nitrite (NO_2^-), 0.019–0.029 µM; phosphate (PO_4^{3-}), 0.034–0.043 µM; and silicate [$Si(OH)_4$], 1.999–2.463 µM. Based on data from 6 sample locations, the highest concentra-

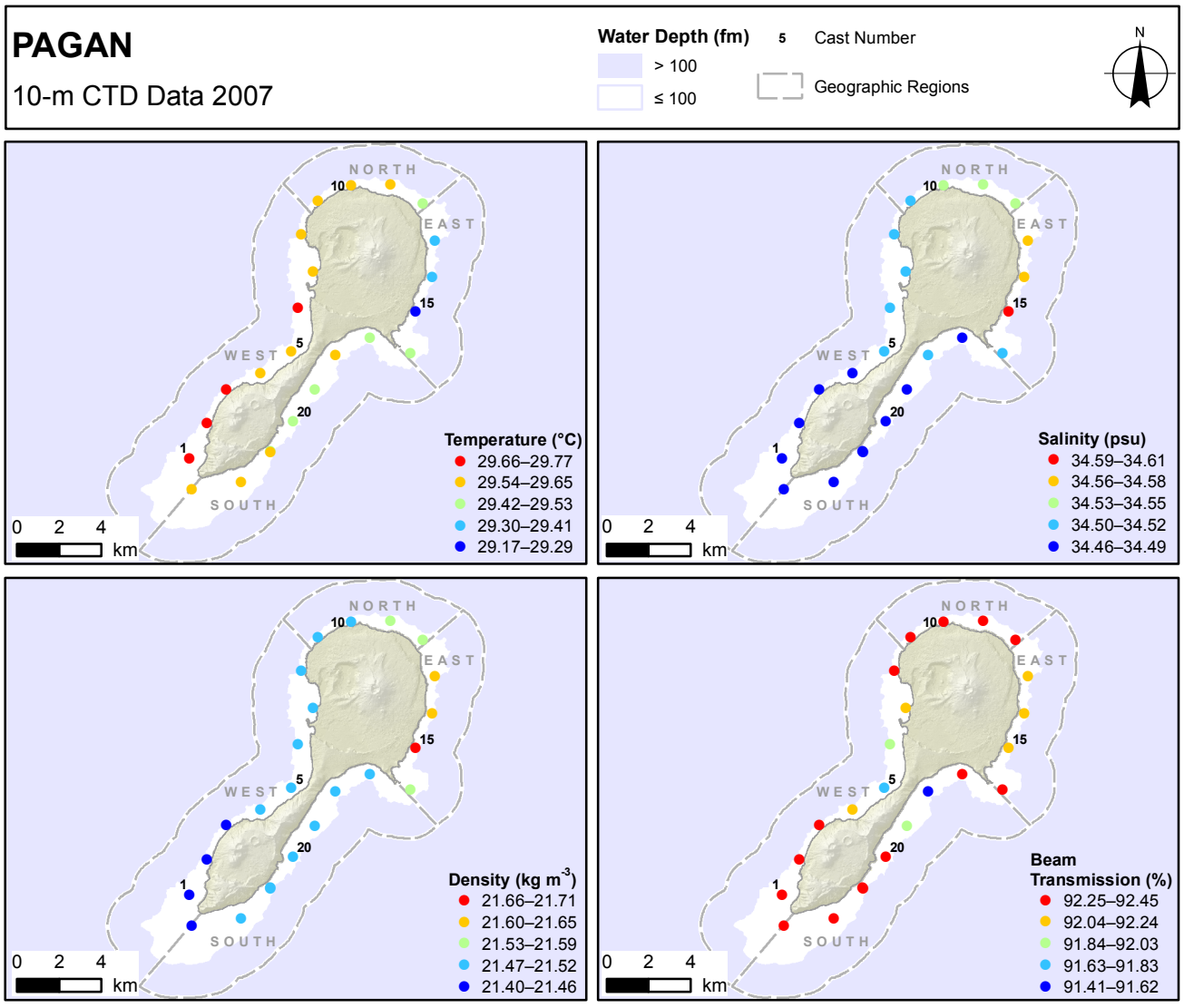


Figure 13.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Pagan on June 4–6 during MARAMP 2007.

tions of most water-quality parameters were recorded near the large bay north of Bandera Peninsula west of Mount Pagan in the west region (Fig. 13.4.1h; for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). Chl-a concentrations also were high at this location, but the highest level was observed in the south region near Apansantate. The lowest values of total nitrogen, nitrate, nitrite, and silicate all were found at the southern tip of Pagan.

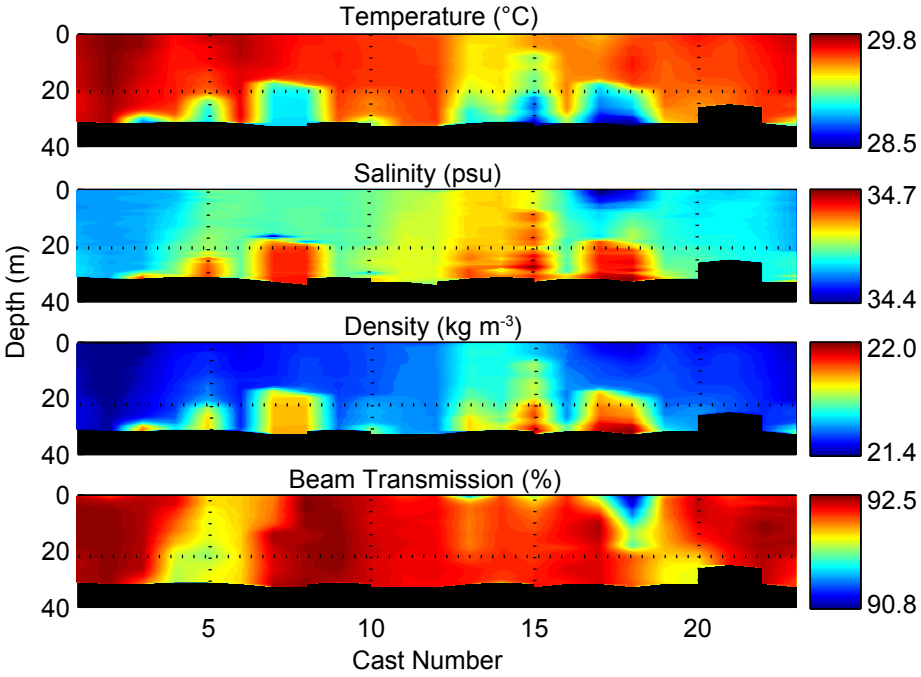


Figure 13.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Pagan on June 4–6 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%).Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–23 in a clockwise direction around Pagan. For cast locations and numbers around this island in 2007, see Figure 13.4.1f.

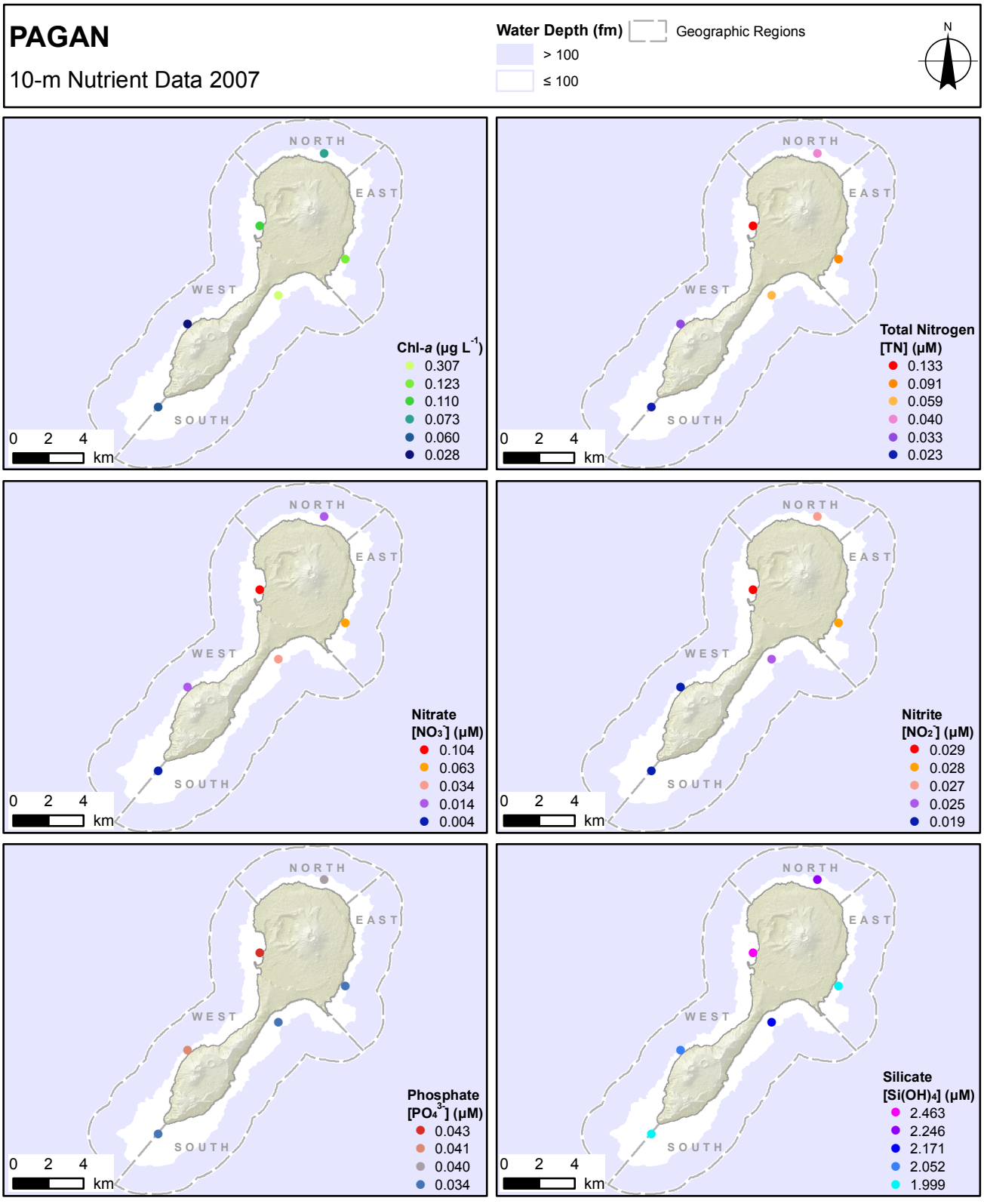


Figure 13.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Pagan on June 4–6 during MARAMP 2007.

Temporal Comparison

Comparisons between survey periods of shallow-water CTD data collected around Pagan during MARAMP 2003, 2005, and 2007 suggest a dynamic physical environment with few hydrographic similarities between visits. During MARAMP 2005 and 2007, temperature, salinity, and density values generally were lower along the east side of Pagan than along the west side. Beam transmission data do not show any spatial similarities between survey periods, although the maximum value did decrease with each subsequent survey as did the minimum temperature recorded. Stratification and cold-water intrusions originating from below a depth of 30 m are far more prominent in data collected in 2007 than in data from 2003 and 2005, when the water column showed increased homogeneity around this island. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May and June, and MARAMP 2003 and 2005 occurred in September and October. This change was made to avoid the typhoon season and reduce the probability of weather disruptions.

Water-quality data obtained during MARAMP 2005 and 2007 suggest that nutrient concentrations were variable spatially and temporally at Pagan. Spatial patterns for most measured parameters varied between these survey years, except for phosphate, which had relatively similar values in both years. The maximum silicate value was greater in 2007 (2.46 µM) than in 2005 (1.7 µM). Whether these differences resulted from a seasonal effect or some other process is unknown at this time. MARAMP 2005 occurred during a period of seasonally high precipitation, while MARAMP 2007 occurred during a period of seasonally low precipitation, likely affecting local water chemistry (for more precipitation information, see Chapter 3: "Archipelagic Comparisons," Section 3.3.1: "Seasonal Climatologies").

13.4.2 Time-series Observations

Between 2003 and 2007, two types of moored instruments were deployed at Pagan to collect time-series observations of key oceanographic parameters influencing reef conditions. The locations, depths, time frames, and other details about these deployments are provided in Figures 13.4.2a and b.

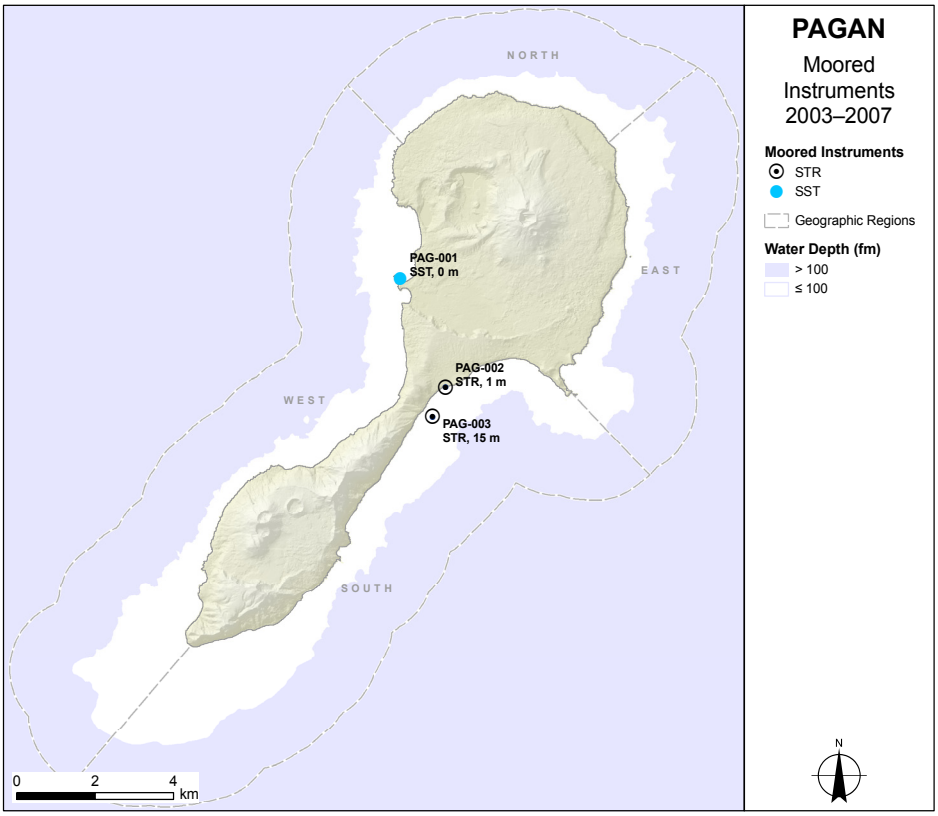


Figure 13.4.2a. Locations, depths, and types of oceanographic instrument moorings deployed at Pagan during MARAMP 2003, 2005, and 2007. Two types of instruments were moored at Pagan: sea-surface temperature (SST) buoy and subsurface temperature recorder (STR).

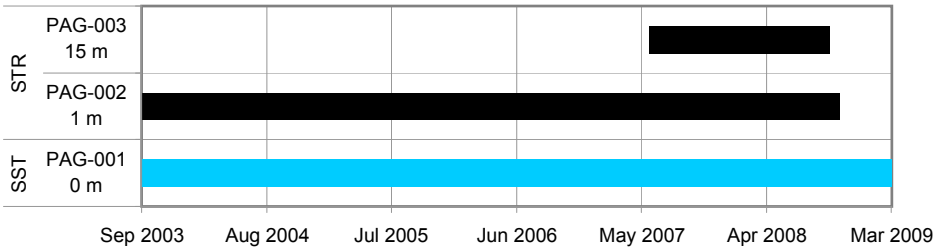


Figure 13.4.2b. Deployment timelines and depths of oceanographic instruments moored at Pagan during the period from September 2003 to March 2009. A solid bar indicates the period for which temperature data were collected by a single instrument or a series of them deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 13.2b in Section 13.2: "Survey Effort."

Satellite-derived (Pathfinder) sea-surface temperature (SST) and in situ temperature observations suggest that the seasonal maximum for water temperatures around Pagan was usually reached in late August or September; the monthly maximum climatological mean from Pathfinder-derived SST data was 29.3°C (Fig. 13.4.2c[a]). Winter minima occurred in February with a monthly minimum climatological mean of 26.6°C. In situ SST and satellite-derived SST were relatively similar throughout this time series, with a few instances of differences of 0.1°C–0.5°C observed. SST data show that water temperatures around Pagan in August 2005 rose above the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean. Still, given the relatively short duration and small magnitude of this period of elevated temperature, widespread mass coral bleaching likely did not occur. It's important to note that satellite-derived SST represents the upper few millimeters of oceanographic temperatures within the region of an island, as opposed to site- or reef-specific temperatures.

Periods of elevated mean wave heights of 2–4 m were usually more frequent during winter (Fig. 13.4.2c[b]). The largest episodic events of wave heights > 4 m, however, tended to happen during periods of warm sea temperatures. Warm sea temperatures typically occurred during the period of August–December, when wave heights of > 4 m are generally associated with typhoons. This pattern was especially noticeable during the summer of 2004 with the passages of Typhoons Tingting and Chaba.

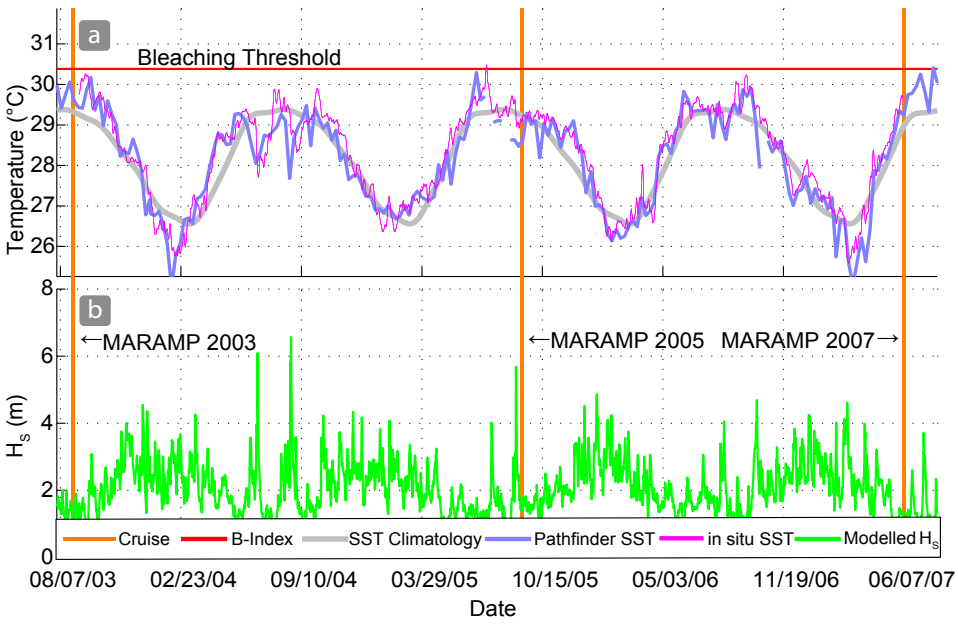


Figure 13.4.2c. Time-series observations of (*a*) SST and (*b*) wave height around Pagan for the period between August 2003 and June 2007. Remotely sensed data (SST climatology and weekly Pathfinder-derived SST) and modeled significant wave height (H_s) derived from Wave Watch III are shown with CRED in situ temperature data from SST buoys (see Fig. 13.4.2a for the buoy location). The 2 high points in the modeled wave height in the summer of 2004 show the occurrences of Typhoons Tingting and Chaba. The horizontal red and vertical orange bars represent the bleaching threshold and the MARAMP research cruise dates, respectively.

A subsurface temperature recorder (STR) mooring site was established south of Mount Pagan in 2003 at Pagan. Data from STRs deployed at this site at a depth of 1 m in the south region show a seasonal temperature variability of 4°C–6°C (Fig. 13.4.2d). Water temperatures occasionally reached maximums of ~ 32°C during the months of June–October and fell to minimums of ~ 25°C during the months of January–May. Temperature at this shallow location exceeded the coral bleaching threshold of 30.4°C each year at multiple times through the summer months of July–August. Interestingly, temperature values during the summer of 2006 were not significantly higher than values recorded in previous years, as was observed in most other temperature time series for mooring sites at other islands in the CNMI, although the period above the coral bleaching threshold may have been more extended. Diurnal temperature fluctuations of ~ 0.8°C were observed throughout this time series.

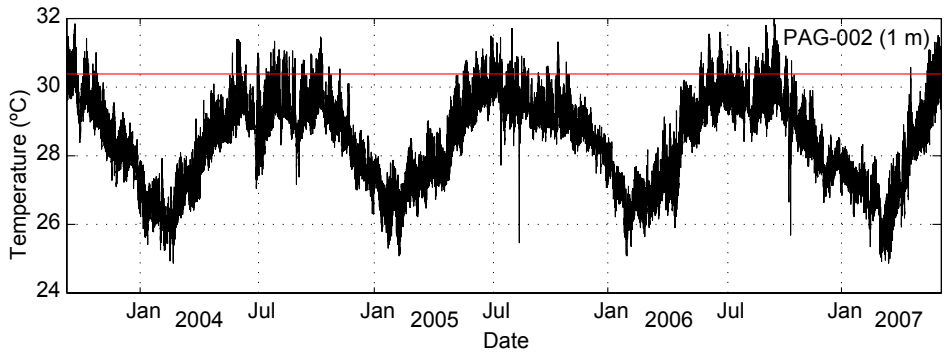


Figure 13.4.2d. Time-series observations of temperature over the period between August 2003 and June 2007 collected from 1 STR mooring site at a depth of 1 m at Pagan (see Figure 13.4.2a for the mooring location). The red line indicates the satellite-derived coral bleaching threshold, which is defined as 1°C above the maximum climatological mean.

13.4.3 Wave Watch III Climatology

Seasonal wave climatology for Pagan (Fig. 13.4.3a) was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008, and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (90°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the south (180°), although they could originate from a broad directional source (120°–200°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–4.5 m) occurred from the west and southwest (240°–270°) and likely were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) was also characterized by frequent (> 30 d per season) and short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season) and long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this time and originated from the southwest (240°) and the northwest (330°).

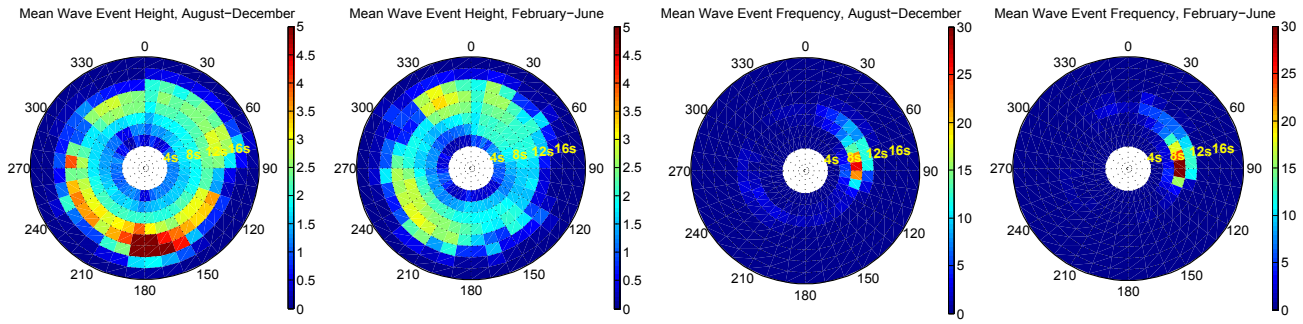


Figure 13.4.3e. NOAA Wave Watch III directional wave climatology for Pagan from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Pagan (18° N, 145°42′ E). Mean significant wave height (*far left & left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right & far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 out of 150 days of that season.

13.5 Corals and Coral Disease

13.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Pagan was 19% (SE 0.8). Coral cover was variable in all regions with the highest cover recorded near Togari Rock, in the area bordering the south and east regions, with a mean of 46% for 8 survey segments (Fig. 13.5.1a; for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). Localized areas of high coral cover also were observed north of Fuwaebosu in the south region with a mean of 35% over 4 segments. Coral cover was lowest in the west region north of Bandera Peninsula where sand was the predominant habitat.

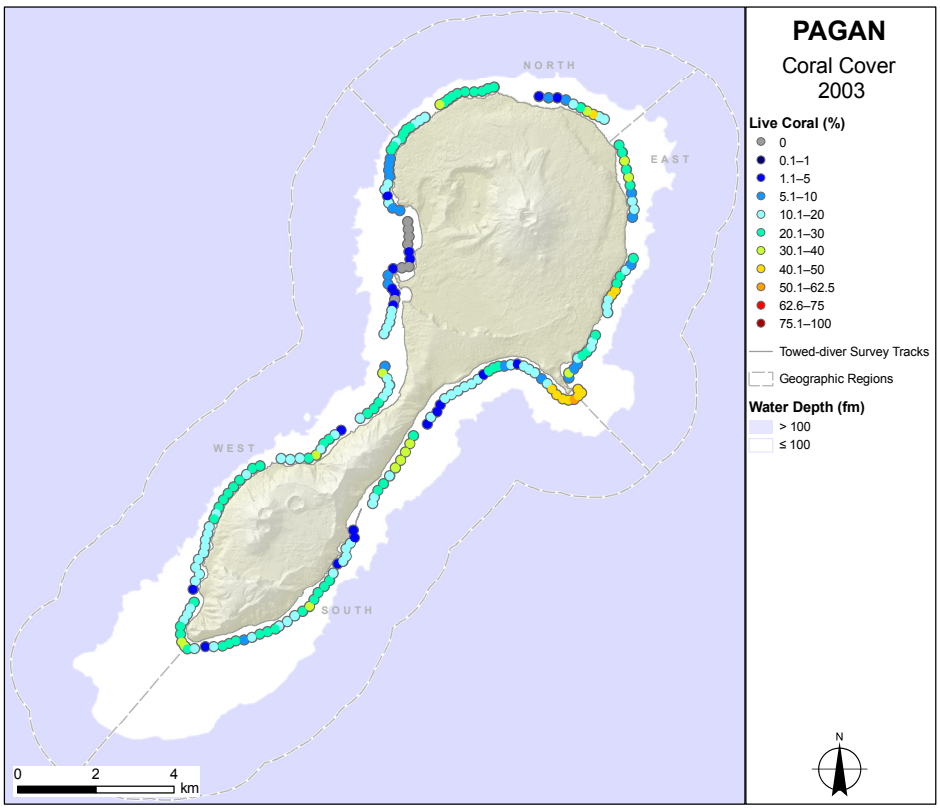


Figure 13.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2).

During MARAMP 2003, 7 REA benthic surveys using the quadrat method on forereef habitats at Pagan documented 882 coral colonies within a total survey area of 26.25 m^2. Site-specific colony density ranged from 25.6 to 50.1 colonies m^{-2} with an overall sample mean of 33.6 colonies m^{-2} (SE 3.4). The highest colony density was recorded at PAG-07 in the west region, and the lowest colony density was observed at PAG-06, also in the west region (Fig. 13.5.1b).

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Pagan was 10% (SE 0.8). The highest coral cover was observed in the east region with a mean of 36% for 8 segments (Fig. 13.5.1c). A localized area of high coral cover was noted southwest of Sanmeina in the west region with a range of 50%–62.5% over a single survey segment. Coral cover was low in all other regions, compared to other areas surveyed in the Mariana Archipelago.

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 3.2% (SE 0.6) of coral cover observed on forereef habitats around Pagan appeared stressed in 2005. Occurrence of stressed-coral cover from towed-diver surveys was low for the majority of

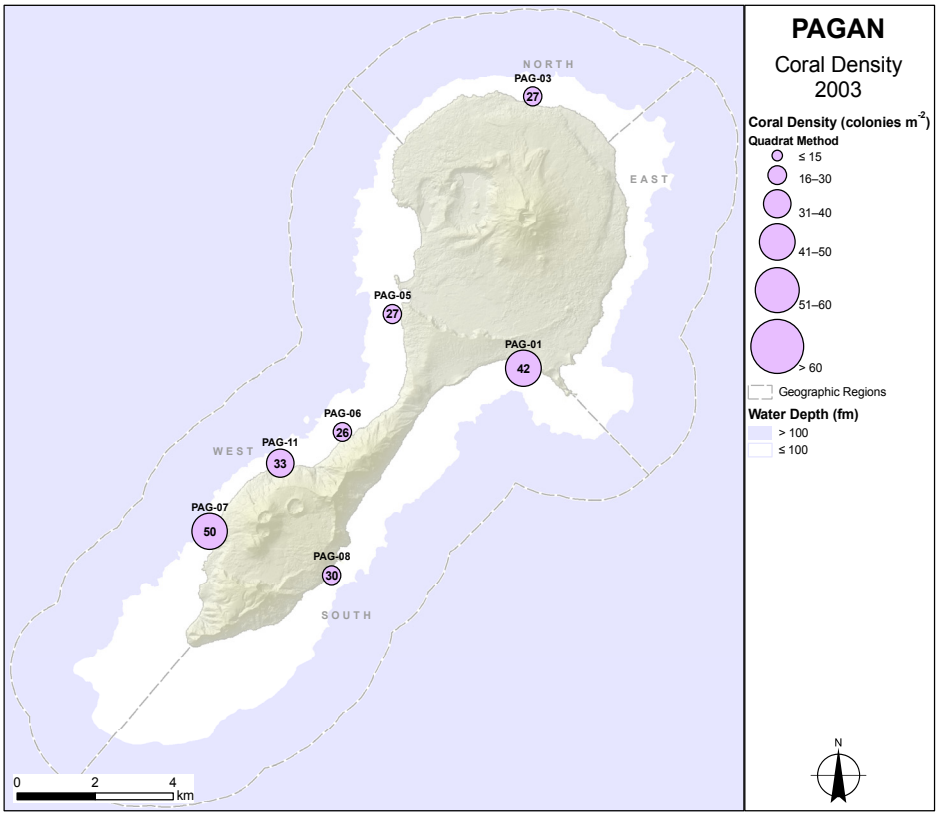


Figure 13.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003. Values are provided within each symbol. The quadrat method was used in 2003 to assess coral-colony density.

segments in the south and west regions. Relative to other areas surveyed around Pagan, high levels of stressed-coral cover were observed north of Togari Rock in the south region, around Hira Rock in the east region, and in the north region (Fig. 13.5.1c). Predation scars from crown-of-thorns seastars (*Acanthaster planci*) were noted in many areas with elevated levels of stressed-coral cover. For more about crown-of-thorns seastars (COTS) around Pagan, see Section 13.7.1: "Benthic Macroinvertebrate Surveys".

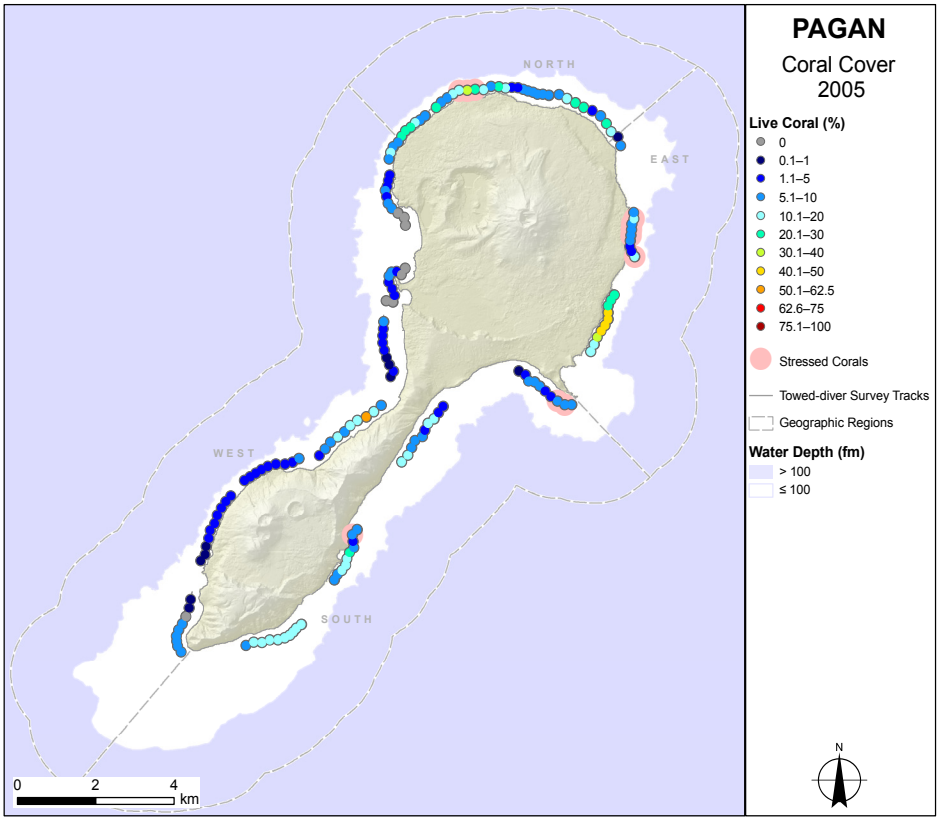


Figure 13.5.1c. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005.

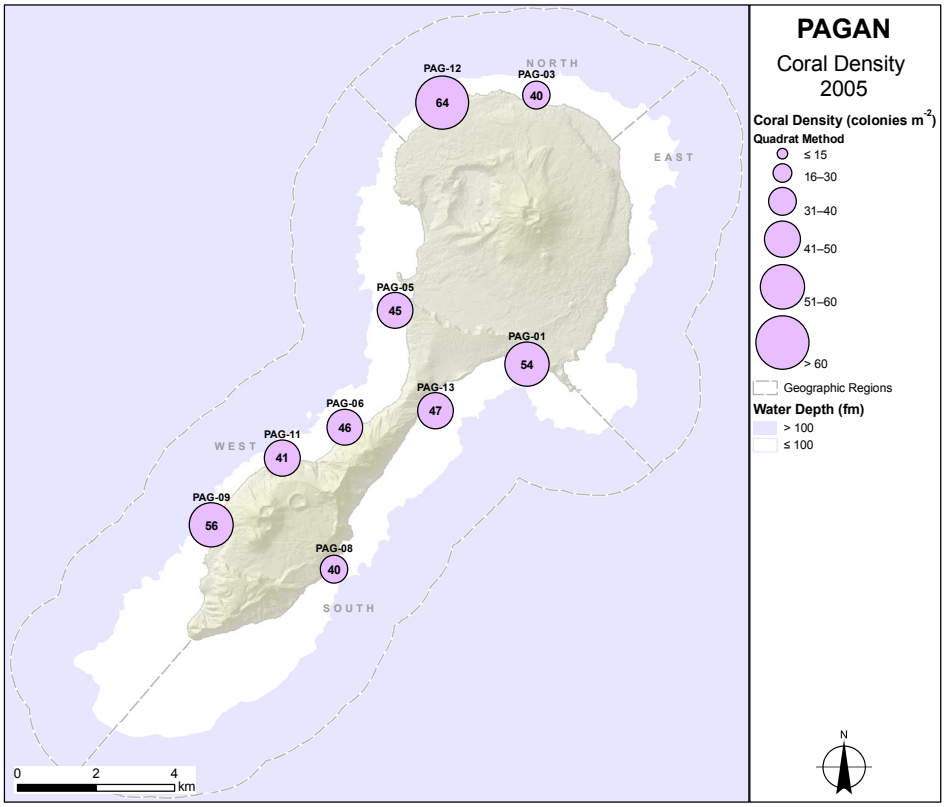


Figure 13.5.1d. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2005. Values are provided within each symbol. The quadrat method was used in 2005 to assess coral-colony density.

During MARAMP 2005, 9 REA benthic surveys using the quadrat method on forereef habitats at Pagan documented 1735 coral colonies within a total survey area of 36 m^2. Site-specific colony density ranged from 39.5 to 64.3 colonies m^{-2}, with an overall sample mean of 48.2 colonies m^{-2} (SE 2.8). The highest colony density was recorded at PAG-12 in the north region, and the lowest colony density was observed at PAG-08 in the south region (Fig 13.5.1d).

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Pagan was 12% (SE 0.7). The highest coral cover was observed north of Fuwaebosu in the south region with a mean of 24% over 7 segments (Fig. 13.5.1e). A localized area of high coral cover, relative to other areas surveyed at Pagan, was recorded southwest of Sanmeina in the west region with a range of 50–62.5% over a single survey segment and large stands of *Porites rus* and *Euphyllia ancora* noted. Coral cover was low in all other regions, compared to levels observed elsewhere in the Marina Archipelago; however, despite low coral cover, large colonies of the genus *Porites* with diameters as great as 3 m were observed outside of the surveyed areas in several locations in the east and south regions.

Overall, 2% (SE 0.3) of coral cover observed on forereef habitats around Pagan appeared stressed in 2007 (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Occurrence of stressed-coral cover, as observed in towed-diver surveys, was low for the majority of segments in the south and west regions. As in 2005, relatively high levels of stressed-coral cover were observed near Togari Rock, around Hira Rock, and in the north region (Fig. 13.5.1e). Predation scars from COTS were noted in many surveys areas with elevated levels of stressed-coral cover.

During MARAMP 2007, 9 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Pagan. Site-specific estimates of live-hard-coral cover ranged from 3.9% to 20.6% (Fig. 13.5.1f) with an overall sample mean of 10.6% (SE 1.7). Live coral cover was highest at PAG-13 south of Apansantate in the south region and lowest at PAG-09 in the west region.

During MARAMP 2007, 9 REA benthic surveys using the quadrat method on forereef habitats at Pagan documented 1712 coral colonies within a total survey area of 36 m^2. Site-specific colony density ranged from 34.5 to 77.8 colonies m^{-2} with an overall sample mean of 47.6 colonies m^{-2} (SE 4.2). The highest colony density was recorded at PAG-12 in the north region, and the lowest colony density was observed at PAG-03 in the north region near Tarage (Fig. 13.5.1f).

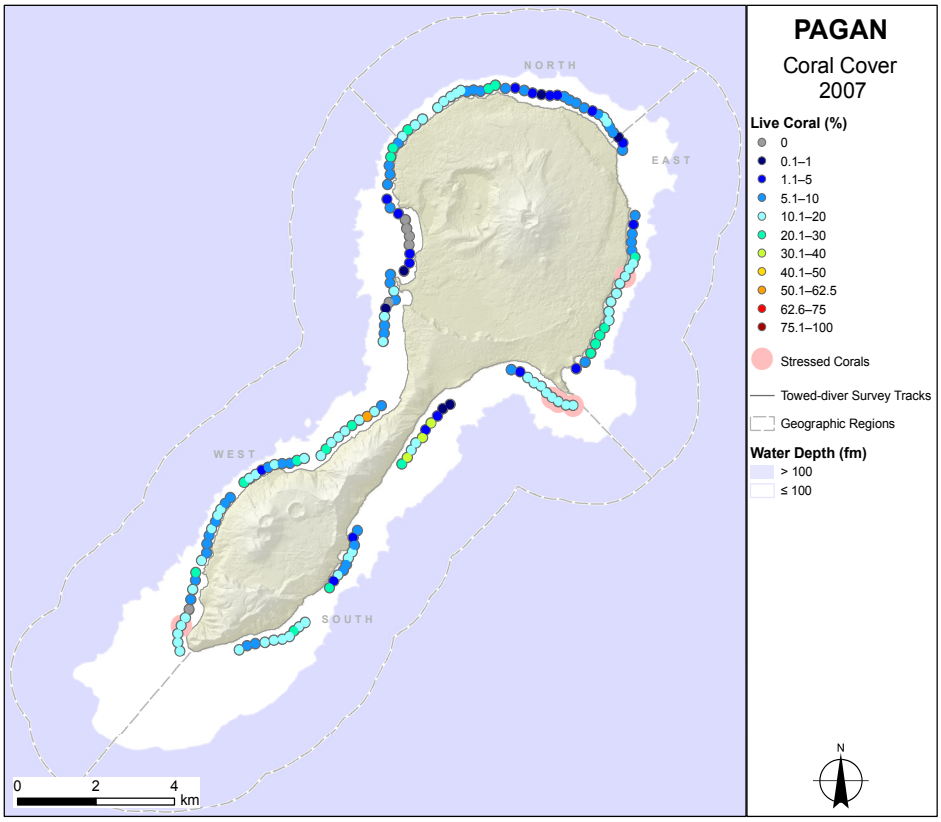


Figure 13.5.1e. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2007.

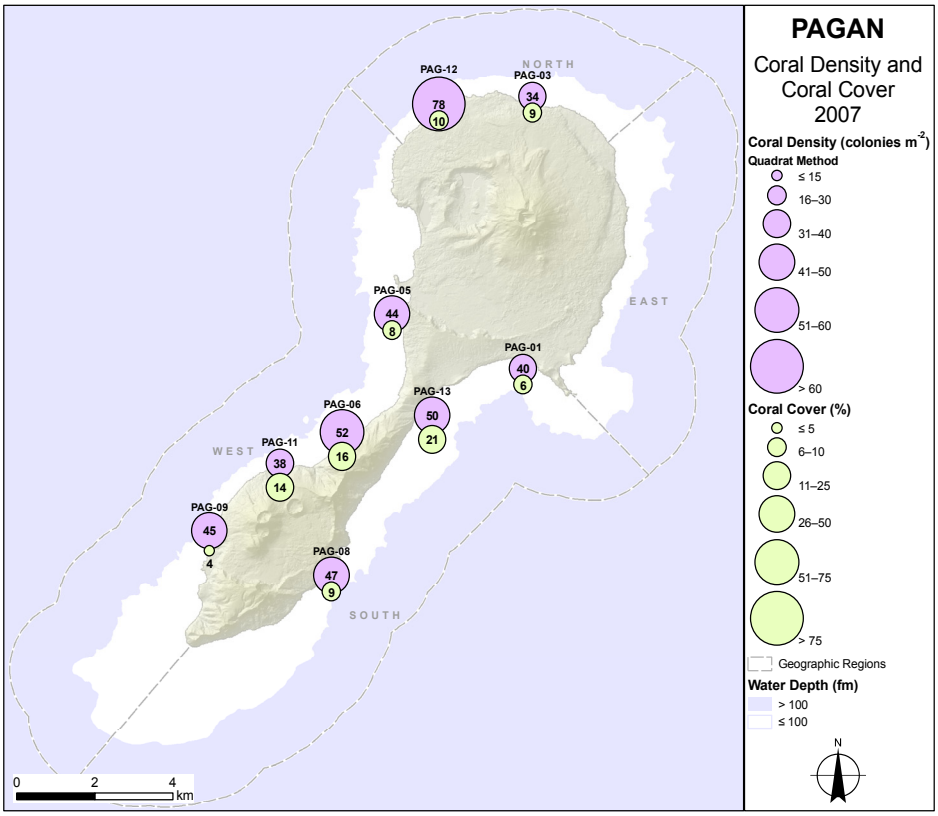


Figure 13.5.1f. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. Values are provided within or below each symbol. The quadrat method was used in 2007 to assess coral-colony density.

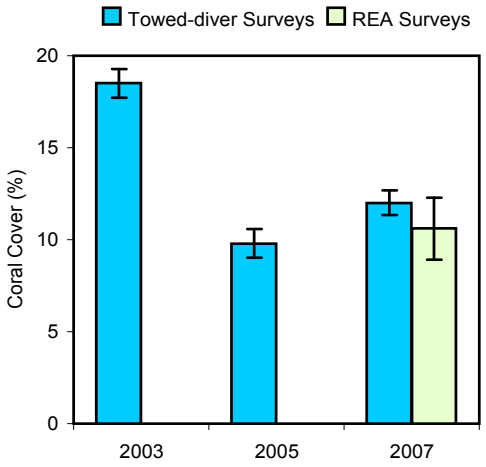


Figure 13.5.1g. Temporal comparison of mean live coral cover (%) from REA and towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted at Pagan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Islandwide mean cover of live corals, estimated from towed-diver surveys of forereef habitats, varied between MARAMP survey years, ranging from 19% (SE 0.8) in 2003 to 10% (SE 0.8) in 2005 and 12% (SE 0.7) in 2007 (Fig. 13.5.1g). Coral cover in 2005 was about half the level observed in 2003. The lower cover in 2005 likely is not a reflection of spatial variation in survey effort, since the areas with the highest estimates of coral cover in 2003, most notably an area adjacent to Togari Rock bordering the south and east regions and an area north of Fuwaebosu in the south region, mostly were resurveyed in 2005. Instead, in these survey areas, along with survey areas in the east region, declines in coral cover were observed from 2003 to 2005.

COTS predation and other stressors may have contributed to the decreases in observed coral cover in these survey areas. In the south region north of Fuwaebosu, the second-greatest mean density of COTS in 2003 was recorded. In 2005, the majority of observed COTS was concentrated in the east region and in the southern half of the south region, with the third-greatest mean density of COTS recorded in the east region north of Hira Rock, where stressed-coral cover > 10% was recorded. In both 2005 and 2007, stressed-coral cover > 10% also was observed in the area adjacent to Togari Rock.

REA benthic surveys target hard-bottom communities, whereas towed-diver surveys include a wider array of substrate types. In good agreement with the overall mean from towed-diver surveys in 2007, site-specific estimates of coral cover averaged 10.6% (SE 1.7), within a range of 3.9% to 20.6%, for the 9 REA sites surveyed at Pagan in 2007 (Fig. 13.5.1g; Pagan was not surveyed for coral cover using the line-point-intercept method in 2003 or 2005).

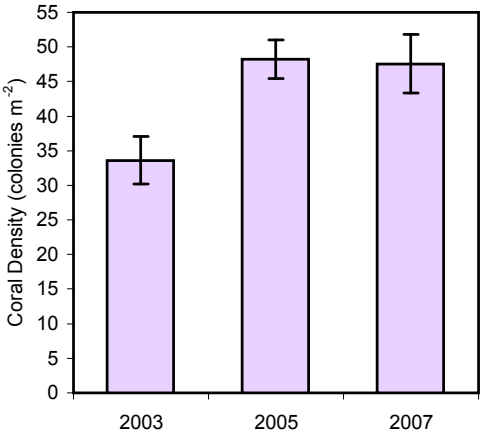


Figure 13.5.1h. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Pagan during MARAMP 2003, 2005, and 2007. The quadrat method was used in all three survey years to measure coral-colony density. Error bars indicate standard error (± 1 SE) of the mean.

The quadrat method was used for REA benthic surveys conducted at Pagan during each of the 3 MARAMP survey years. Overall mean coral-colony density from REA benthic surveys of forereef habitats at 9 sites at Pagan (Fig. 13.5.1h) increased from 33.6 colonies m^{-2} (SE 3.4) in 2003 to 48.2 colonies m^{-2} (SE 2.8) in 2005; the overall sample mean in 2007 was 47.6 colonies m^{-2} (SE 4.2). A similar temporal pattern was observed at the 6 sites surveyed in all 3 survey years: PAG-01 and PAG-08 in the south region, PAG-03 in the north region, and PAG-05, PAG-06, and PAG-11 in the west region. Across these 6 sites, mean colony density was 30.9 colonies m^{-2} (SE 2.4) in 2003, 44.4 colonies m^{-2} (SE 2.3) in 2005, and 42.6 colonies m^{-2} (SE 2.7) in 2007. This rise in observed colony density between 2003 and 2005 could be a result of increased recruitment, fragmentation of existing colonies, or both.

Coral Generic Richness and Relative Abundance

Seven REA benthic surveys of forereef habitats were conducted using the quadrat method at Pagan during MARAMP 2003. At least 36 coral genera were observed at Pagan. Generic richness ranged from 11 to 17 with a mean of 14 (SE 0.9) coral genera per site (Fig. 13.5.1i). The highest generic diversity was seen at PAG-06 in the west region, and the lowest generic diversity was recorded at PAG-03 in the north region near Tarage.

Pavona, *Favia*, and *Astreopora* were the most numerically abundant genera, contributing 21%, 15.8%, and 15.6% to the total number of colonies enumerated at Pagan during MARAMP 2003. All other genera individually contributed < 10% to the total number of colonies. *Pavona* dominated the coral fauna at 3 sites in the west region: PAG-05 south of Bandera Peninsula, PAG-06, and PAG-07, contributing 33%, 24%, and 34.6% to the total number of colonies (Fig. 13.5.1i). *Favia* dominated the coral fauna at PAG-08 in the south region and PAG-03 in the north region, contributing 25.9% and 18.4% to the total number of colonies. *Astreopora* dominated at PAG-01 in the north region and PAG-11 near Pontanjaburo in the west region, contributing 34.4% and 22% to the total number of colonies.

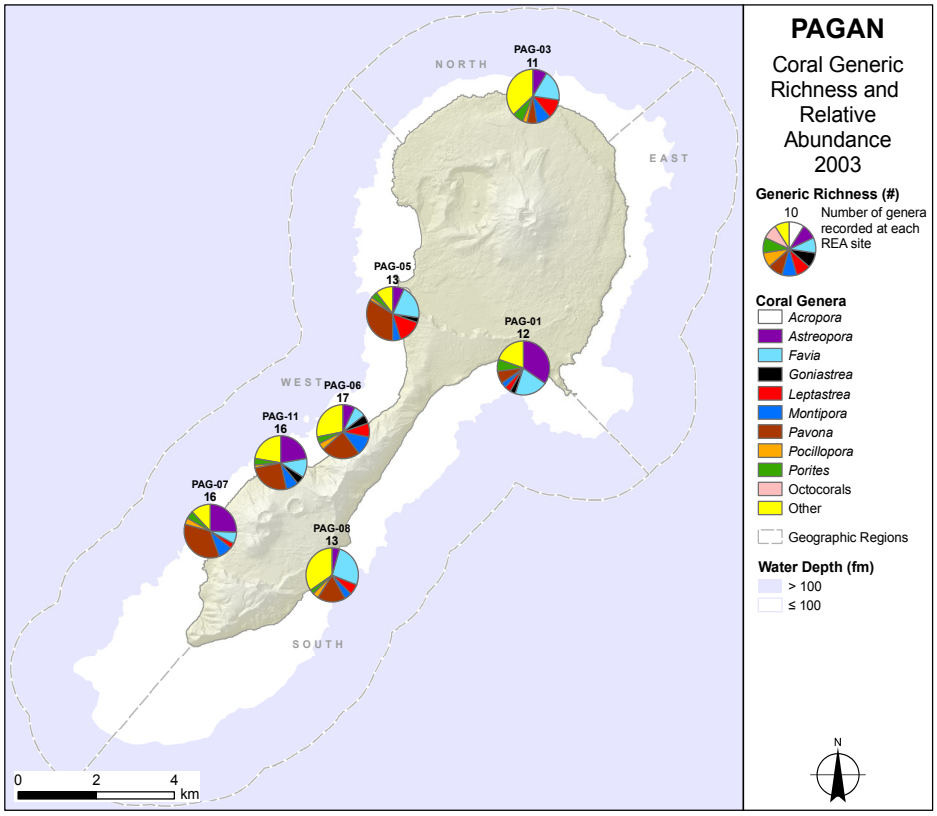


Figure 13.5.1i. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to survey coral genera.

Nine REA benthic surveys of forereef habitats were conducted using the quadrat method at Pagan during MARAMP 2005. At least 28 coral genera were observed at Pagan. Generic richness ranged from 13 to 20 with a mean of 16.8 (SE 0.8) coral genera per site (Fig. 13.5.1j). The highest generic diversity was seen at PAG-13 in the south region near Apansantate, and the lowest generic diversity was recorded at PAG-08, farther south in the south region.

Favia, Pavona, and *Astreopora* were the most numerically abundant genera, contributing 20.8%, 17.9%, and 12.5% to the total number of colonies enumerated at Pagan during MARAMP 2005. All other genera individually contributed < 10% to the total number of colonies. *Pavona* dominated at PAG-06, PAG-09, and PAG-11, all in the west region, and PAG-12 in the north region (Fig. 13.5.1j), contributing 31.9%, 28.1%, 23.6%, and 27.6%, respectively, to the total number of colonies. *Favia* dominated the coral fauna at PAG-01 and PAG-08 in the south region and PAG-05 in the west region south of Shomushon, contributing 31.2%, 39.2%, and 26.7% to the total number of colonies. *Astreopora* dominated at PAG-13 in the south region, contributing 23.4% to the total number of colonies. *Pocillopora* dominated at PAG-03 in the north region near Tarage, contributing 24.4% to the total number of colonies.

Figure 13.5.1j. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2005. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2005 to survey coral genera.

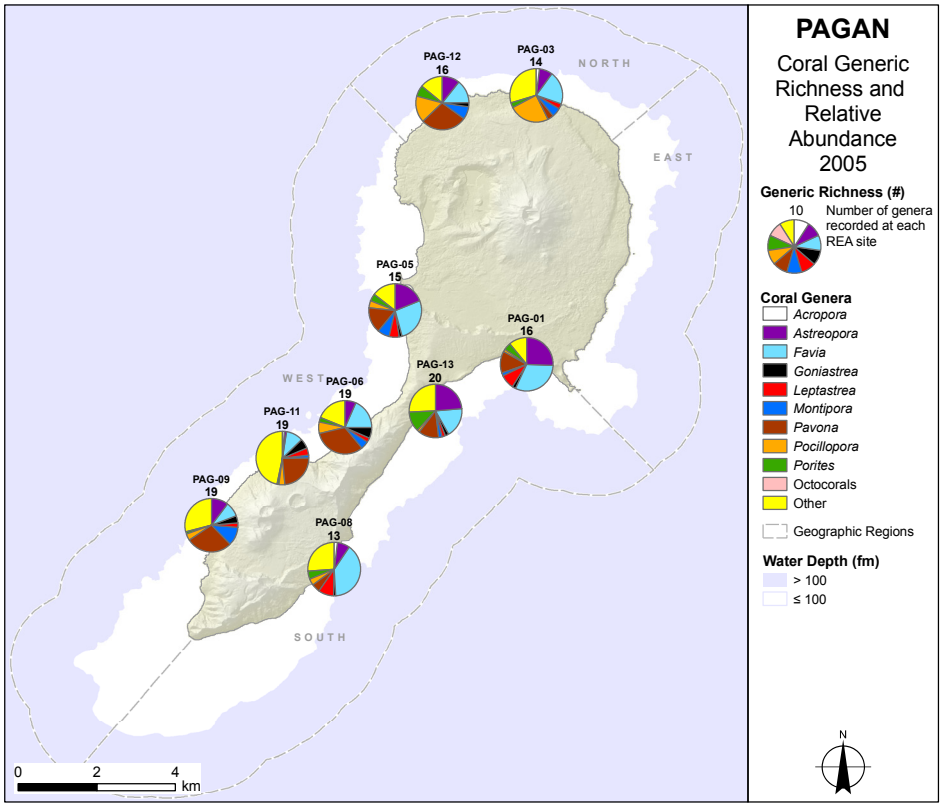
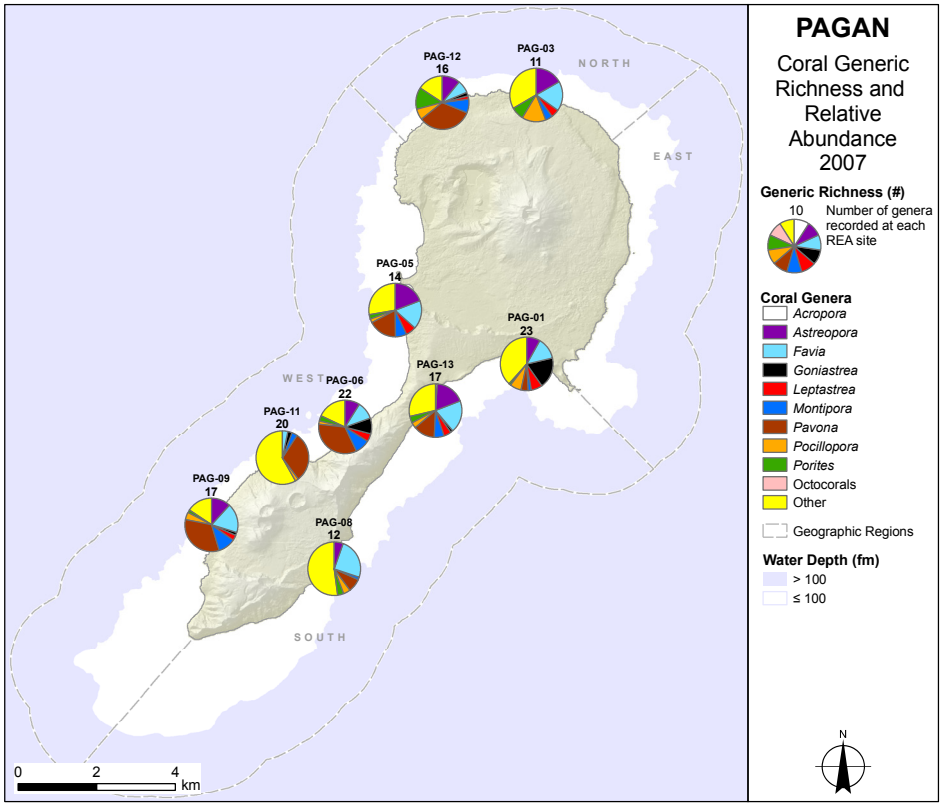


Figure 13.5.1k. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2007 to survey coral genera.



Nine REA benthic surveys of forereef habitats were conducted using the quadrat method at Pagan during MARAMP 2007. At least 30 coral genera were observed. Generic richness ranged from 11 to 23 with a mean of 16.9 (SE 1.4) coral genera per site (Fig. 13.5.1k). The highest levels of generic diversity were seen at PAG-01 and PAG-06 in the south and west regions, and the lowest generic diversity was recorded at PAG-03 near Tarage in the north region.

Pavona, Favia, and *Astreopora* were the most numerically abundant genera, contributing 19.2%, 14.7%, and 11% to the total number of colonies enumerated at Pagan during MARAMP 2007. All other genera individually contributed < 10% to the total number of colonies. As in 2005, *Pavona* dominated the coral fauna at PAG-06, PAG-09, and PAG-11, all in the west region, and PAG-12 in the north region (Fig. 13.5.1k), contributing 33.3%, 33%, 30.3%, and 33.1%, respectively, to the total number of colonies. *Favia* dominated at PAG-03 in the north region and PAG-08 and PAG-13 in the south region, contributing 18.1%, 24.6%, and 19.6% to the total number of colonies. *Astreopora* dominated at PAG-05 south of Shomushon in the west region and PAG-13 south of Apansantate in the south region, contributing 19.2% and 18.1% to the total number of colonies. *Goniastrea* dominated at PAG-01 in the south region, contributing 18.9% to the total number of colonies.

Site-specific estimates of generic richness across the 3 MARAMP survey years ranged from 11 to 23 coral genera per site on forereef habitats at Pagan. Overall mean generic-richness values (Fig. 13.5.1l) increased from 14 (SE 0.9) in 2003 to 16.8 (SE 0.8) in 2005. Generic richness in 2007 was 16.9 (SE 1.4). A similar temporal pattern was seen at the 6 sites surveyed in all 3 survey years: PAG-01 and PAG-08 in the south region, PAG-03 in the north region, and PAG-05, PAG-06, and PAG-11 in the west region. Across these 6 sites, mean generic richness increased from 13.7 (SE 0.9) in 2003 to 16 (SE 1) coral genera per site in 2005 and was 17 (SE 2.2) in 2007. This rise between 2003 and 2005 is not a result of recording additional genera at Pagan in 2005 but of recording more genera at individual sites in 2005 than in 2003.

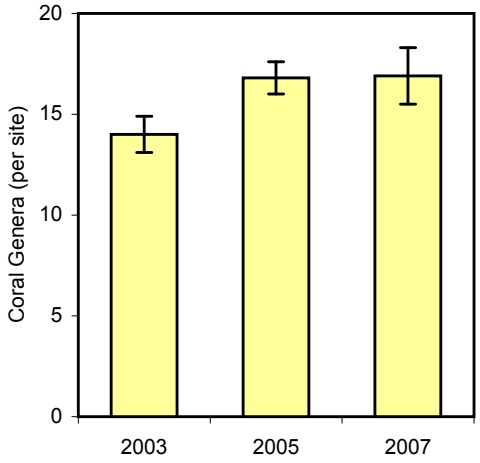


Figure 13.5.1l. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Pagan during MARAMP 2003, 2005, and 2007. The quadrat method was used in all three survey years to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

Across the 3 MARAMP survey years, 32 coral genera were observed on forereef habitats at Pagan. *Pavona*, *Favia*, and *Astreopora* were important components of the coral fauna, contributing > 10% to the total number of colonies enumerated in all 3 survey years. *Pavona* was the most numerically abundant taxon in 2003 and 2007 and the second-most abundant taxon in 2005, contributing 21%, 19.2%, and 17.9% to the total number of colonies enumerated in these MARAMP survey years. *Favia* was the most numerically abundant taxon in 2005 and the second-most abundant in 2003 and 2007, contributing 21%, 16.1%, and 14.8% to the total number of colonies. *Astreopora* was the third-most numerically abundant taxon in the 3 MARAMP years, contributing 15.6%, 12.5%, and 11% to the total number of colonies enumerated in 2003, 2005, and 2007. All other taxa contributed < 10% to the total number of colonies in the 3 survey years.

Coral Size-class Distribution

During MARAMP 2003, 7 REA benthic surveys of forereef habitats were conducted at Pagan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (64.7%) of corals had maximum diameters ≤ 5 cm (Fig. 13.5.1m). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 25.9%, 7.1%, and 2.3% of colonies recorded. No colonies with maximum diameters > 40 cm were recorded. At each REA site, a majority (> 59%) of corals were in the smallest size class (≤ 5 cm), except for a site in the west region, PAG-06, where 49% of corals were in this size class.

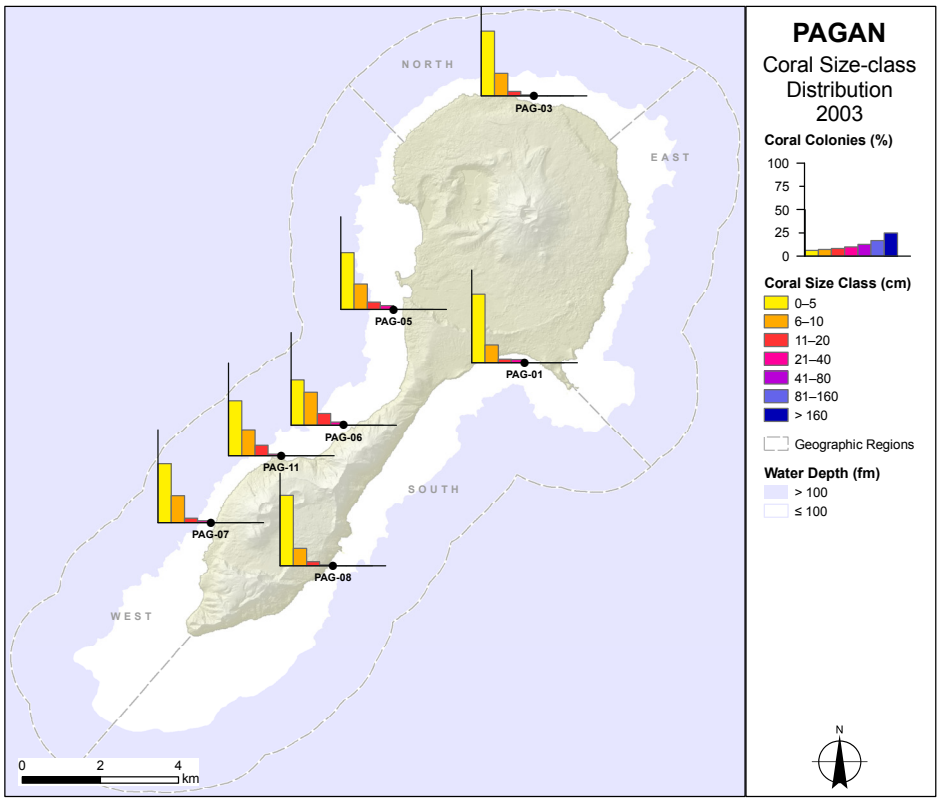


Figure 13.5.1m. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.

During MARAMP 2005, 9 REA benthic surveys of forereef habitats were conducted at Pagan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (79.6%) of corals had maximum diameters ≤ 5 cm (Fig. 13.5.1n). The next 3 size classes (6–10, 11–20, and 21–40) accounted for 15.7%, 3.4%, and 1.1%, of colonies recorded, and 0.1% of corals had maximum diameters > 40 cm. At each REA site, a majority (> 72%) of corals were in the smallest size class (≤ 5 cm).

During MARAMP 2007, 9 REA benthic surveys of forereef habitats were conducted at Pagan using the quadrat method. The coral size-class distribution from these surveys shows that the majority (80.8%) of corals had maximum diameters ≤ 5 cm (Fig. 13.5.1o). The next 3 size classes (6–10, 11–20, and 21–40) accounted for 15.9%, 2.5%, and 0.7% of colonies recorded, and 0.1% of corals had maximum diameters > 40 cm. At each REA site, a majority (> 67%) of corals were in the smallest size class (≤ 5 cm).

Site-specific and overall distributions of estimated coral size classes on forereef habitats at Pagan are affected by the inherent bias in the quadrat method, which was used to census and size corals in each of the 3 MARAMP survey years. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. For more on this survey method, see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease."

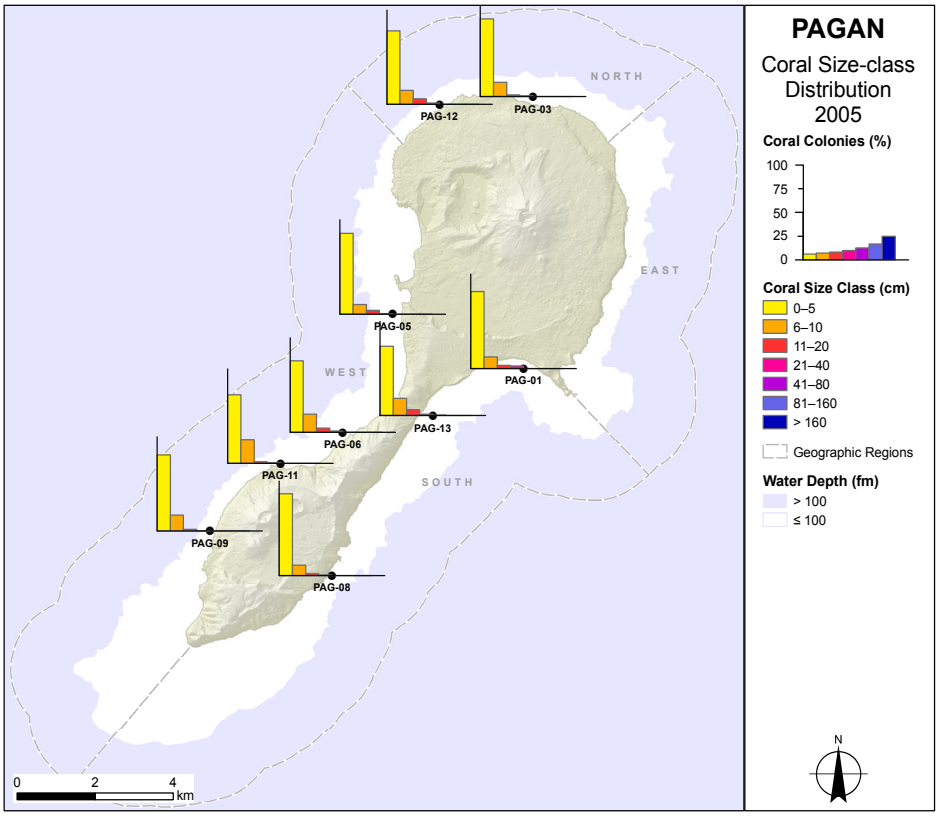


Figure 13.5.1n. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2005. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2005 to size corals.

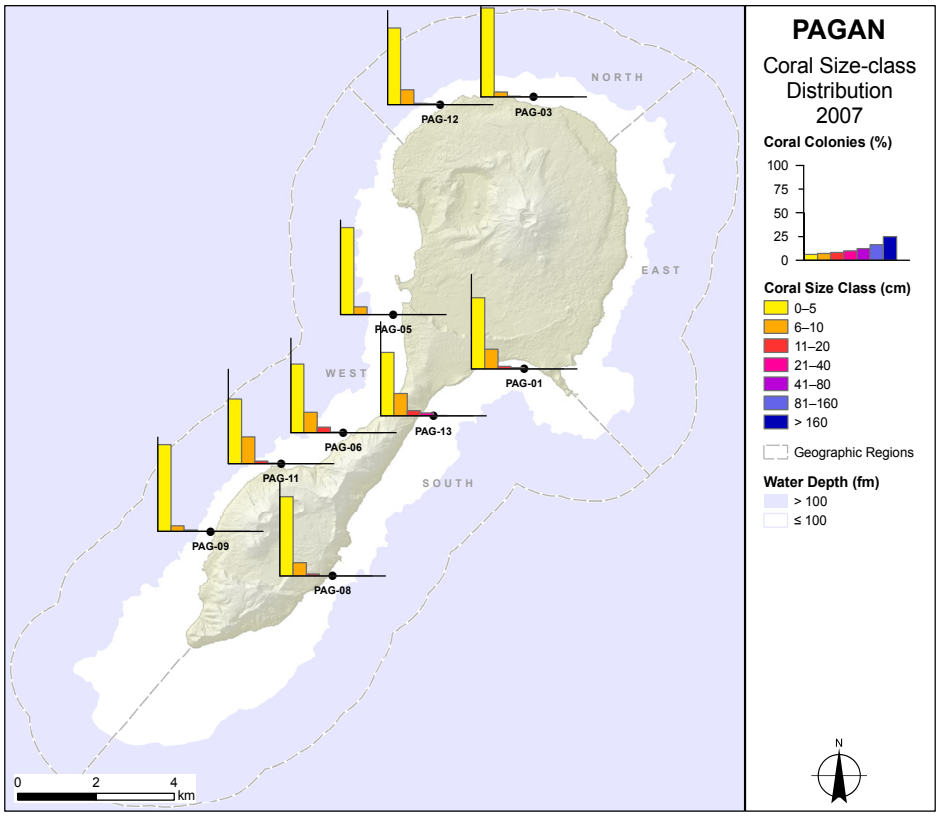


Figure 13.5.1o. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2007 to size corals.

In the 3 MARAMP survey years, the density of coral colonies was > 22 colonies m^{-2} in the smallest size class (Fig. 13.5.1p). The overall mean proportion of colonies in the smallest size class (≤ 5 cm) increased from 64.7% in 2003 to 79.6% in 2005. Similarly, the proportion of colonies in the smallest size class at each of the sites surveyed in both 2003 and 2005 (PAG-01, PAG-03, PAG-05, PAG-06, PAG-08, and PAG-11) was higher in 2005 than in 2003. The increase in coral colony density between 2003 and 2005 in the smallest size class may be a result of recruitment, fragmentation of existing colonies, or both. Minor variations in islandwide and site-specific size-class distributions between surveys in 2005 and 2007 likely are consequences of chance differences in placement of quadrats.

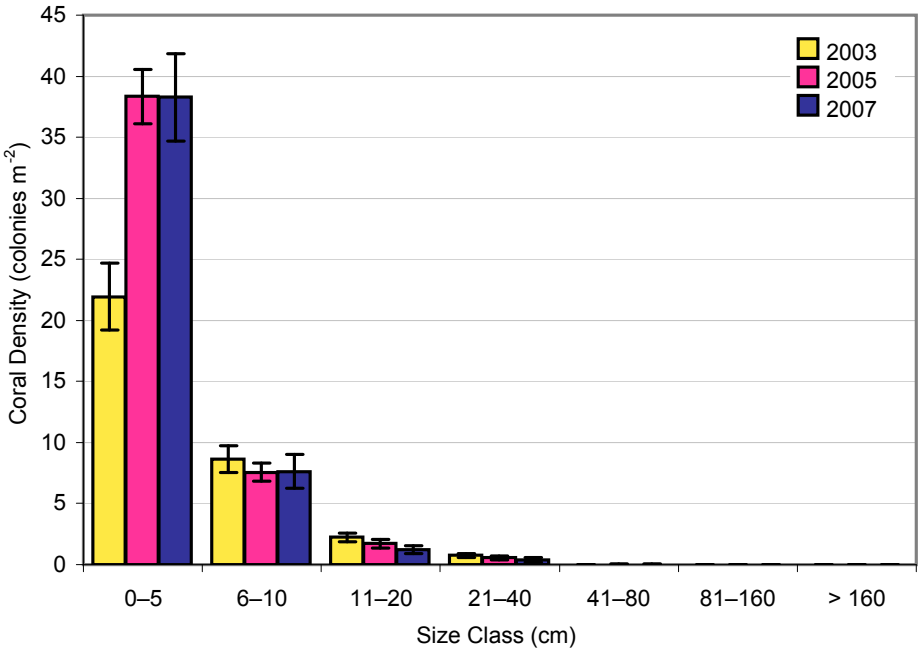


Figure 13.5.1p. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003, 2005, and 2007. The quadrat method was used to size corals in the 3 survey years. Error bars indicate standard error (± 1 SE) of the mean.

13.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted at 9 sites on forereef habitats at Pagan, covering an area of 2700 m^2. Surveys detected 28 cases of disease, translating to an overall mean prevalence of 0.02% (SE 0.01), excluding predation. Coral-colony counts at all REA sites at Pagan were conducted using the quadrat method, resulting in higher than expected coral-colony densities and, therefore, lower disease prevalence values, relative to the levels found at sites at other islands surveyed using the belt-transect method. Two major disease conditions were observed at Pagan: fungal infections and other syndromes of unknown etiology. Fungal infections accounted for more than 90% of disease cases, and more than 95% of afflictions involving fungal infections were observed on corals of the genus *Cyphastrea*. Other disease-hosting coral genera included *Porites* and *Galaxea*. Among the 9 sites surveyed, only 3 of them contained disease: PAG-03 near Tarage in the north region, PAG-08 in the south region, and PAG-11 near Pontanjaburo in the west region. PAG-08 in the south region contained 85% of disease cases and had the greatest overall disease-prevalence value of 0.20% (Fig. 13.5.2a; the values of overall prevalence shown in this figure include predation). Prevalence values at PAG-03 in the north region near Tarage and PAG-11 in the west region near Pontanjaburo did not exceed 0.02%.

Only a few cases of coral predation attributable to COTS or corallivorous snails, such as snails from the genus *Drupella*, were observed at Pagan, particularly at PAG-12 in the north region, affecting corals of the genera *Favia*, *Goniastrea*, and *Pocillopora* and amounting to a prevalence value of 0.01%. The mean overall prevalence of predation for Pagan was 0.001% (SE 0.0005). As with fungal infections, the positive bias of the quadrat method in measuring coral density contributed to this lower overall mean prevalence value for predation at Pagan.

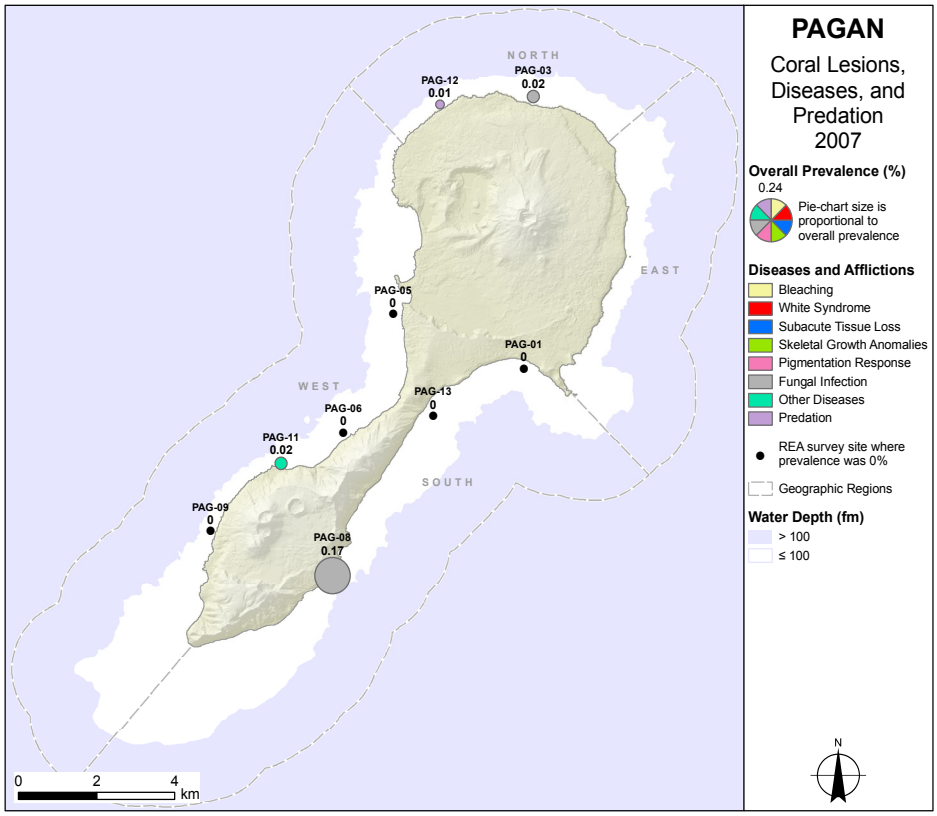


Figure 13.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie charts indicate disease-specific prevalence.

13.6 Algae and Algal Disease

13.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Pagan was 46% (SE 1.2). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 64%, within a range of 30.1%–75%, occurred in the northernmost part of the west region (Fig. 13.6.1a, top left panel). Occasionally interspersed with sand flats of low complexity, habitats in this area primarily contained low-relief, spur-and-groove pavement with rock boulders and were classified as medium to high complexity. During 4 adjacent surveys in the west region, from South Point up to the coast adjacent to Maru Mountain (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"), spur-and-groove reefs exhibited higher values of macroalgal-cover than did reefs in most other survey areas around Pagan. The 2 middle surveys reported cover levels among the highest found around Pagan with means of 59% and 58%. Habitat complexity in these areas ranged from medium-low to high, and complexity values were inversely correlated with sand-cover levels. Surveys along the pavement reefs in the west and north regions, where habitat complexity ranged from medium-high to high, also recorded relatively high values of macroalgal cover with means of 55% and 54%. In contrast, the survey areas surrounding Bandera Peninsula in the west region exhibited low macroalgal cover relative to other survey areas in the rest of the west region. This area was characterized by large sand flats with small sections of reef. In the east region, the majority of surveys recorded fairly consistent values for macroalgal cover, with localized areas of high cover observed off Hira Rock and to the north of Sengao Peninsula with means of 56% and 49%, relative to other survey areas around Pagan. The habitats of these localized areas were unique among the areas surveyed in the east region, consisting of increased spur-and-groove structure with sections of bedrock and rock boulders of medium to high complexity.

TOAD surveys completed at Pagan during MARAMP 2003 were conducted at depths of 15–100 m. Analyses of TOAD video footage obtained from a survey conducted in the east region, at depths of 32–27 m, suggested that macroalgal cover was high there, with cover of 60%–100% seen in nearly half of the video frames analyzed from that survey (Fig. 13.6.1a, top left panel). Two TOAD surveys in the south region also suggested high levels of macroalgal cover: a very short survey conducted east of Pagan's isthmus at depths of 84–92 m and a survey conducted further south at depths of 30–40 m. Analyses of video footage from the remaining 4 TOAD surveys recorded little or no macroalgae.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Pagan was 18% (SE 1.6). The survey with the highest mean macroalgal cover of 63%, within a range of 30.1%–100%, occurred west of Tarage in the north region (Fig. 13.6.1a, middle left panel) over habitat that consisted of pavement of medium-low complexity. Two surveys east of Tarage in the north region and one survey north of Hira Rock in the east region recorded greater than average macroalgal cover for survey areas around Pagan, with means of 31%, 26%, and 31%. These 3 surveys were conducted over boulder and continuous reef habitats where complexity ranged from medium-low to high. A survey in the northernmost part of the west region also reported moderate macroalgal cover, with a mean of 27%, in comparison to other areas surveyed around Pagan. Over the northern portion of this survey area, characterized as continuous reef and boulder habitat, mean macroalgal cover of 20.1%–75% was observed, whereas for the southern portion, no macroalgae were documented over habitat primarily of sand. Several other surveys recorded above average macroalgal cover, compared to other areas surveyed around Pagan, including 2 of the surveys conducted along the southeastern coast, with means of 22% and 19%, and 2 of the surveys conducted along the southwestern coast, each with a mean of 19%. The habitat observed during the 2 surveys on the southeastern coast consisted of patch reefs of medium-low to medium complexity among sand flats. The habitat seen during surveys on the southwestern coast was continuous reef with sections of rock boulders and a medium to high complexity. Large variations occurred between surveys conducted in the southern portion of the west region, where macroalgal-cover values alternated between 19% and < 4% for every other survey. This fluctuation possibly could be a result of interobserver bias as well as the presence of sandy flat terrain. It is important to note that habitat complexity and sand cover also appear to vary in the southern portion of the west region, around Sanmeina at the top of the isthmus, and Periiruu Sarahai in the southern portion of the west region. In both cases, noticeable decreases in habitat complexity and increases in sand habitat were noted (see Fig. 13.3.3a and b in Section 13.3: Benthic Mapping and Characterization"). These habitat differences also may be at least partially responsible for observed variations in macroalgal cover between towed-diver surveys. Observations of what appeared to be volcanic ash were recorded along the southwestern coast.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats for Pagan was 17% (SE 1.1). The survey with the highest mean macroalgal cover of 39%, within a range of 20.1%–62.5%, occurred off Piarama in the south region (Fig. 13.6.1a, bottom left panel). The habitat in this area was continuous reef of medium complexity and dominated by species of the red algal genus *Asparagopsis*. Reports of species of the brown alga *Padina,* the green alga *Halimeda,* and cyanobacteria were also noted. Another survey in the south region, located in the vicinity of Apansantate, also recorded greater than average macroalgal cover, relative to other survey areas around Pagan, with a mean of 33%.

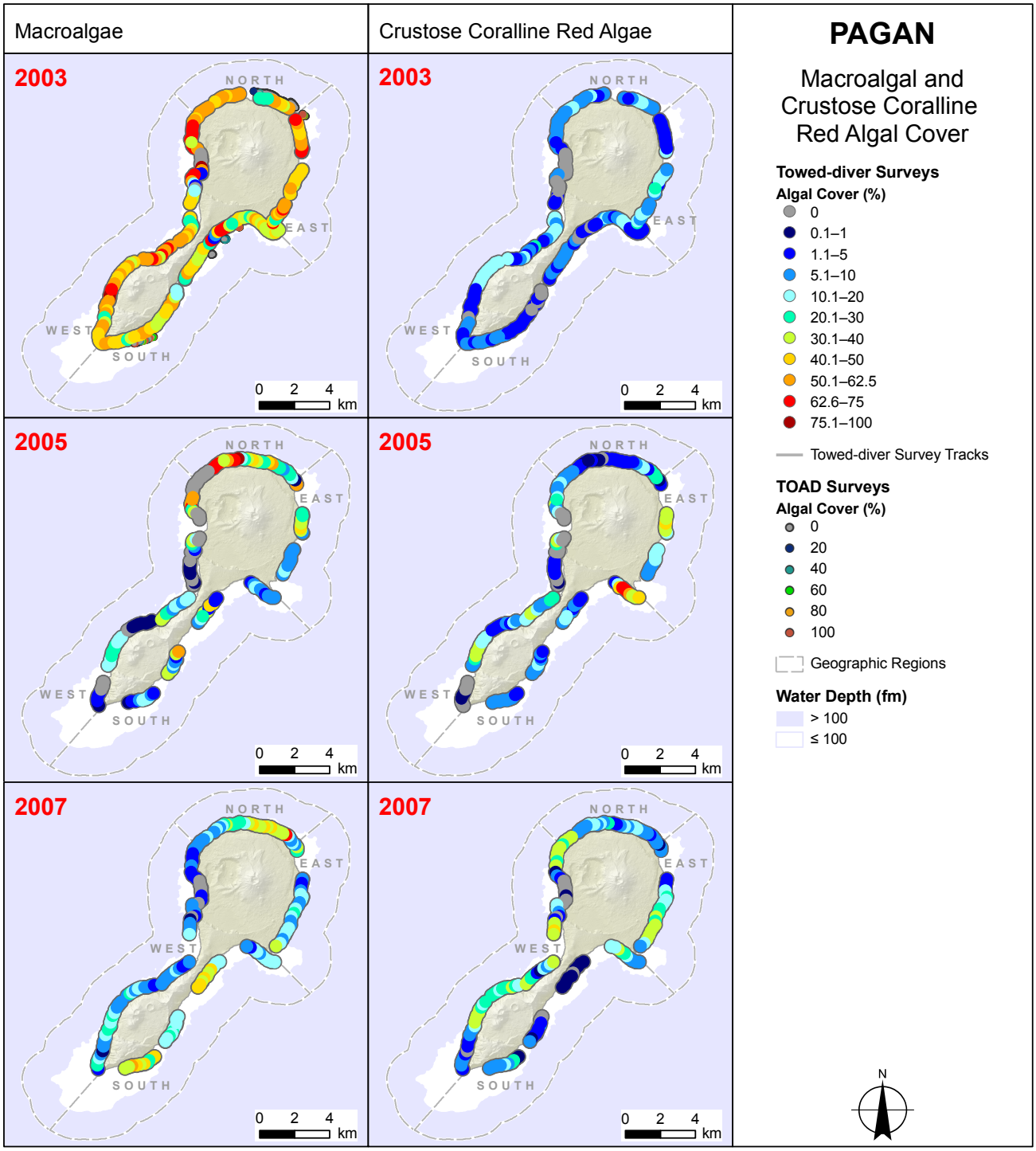


Figure 13.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segments with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

In this survey area, a series of patch reefs and continuous reef of medium-low to medium complexity were the dominant habitat types, and taxa there consisted primarily of species of *Asparagopsis* in combination with species of *Padina*, the red alga *Liagora*, the green algae *Halimeda* and *Caulerpa*, and cyanobacteria. Three adjacent surveys conducted in the north region, moving east along continuous reef habitat of medium-low to medium-high complexity, reported elevated values of macroalgal cover, compared to most other areas surveyed at this island, with means of 20%, 36% and 24%. This habitat was dominated by species of *Asparagopsis, Padina*, the green algae *Halimeda* and *Neomeris*, and cyanobacteria. The remainder of towed-diver surveys reported low levels of macroalgal cover, with the lowest values associated with large sand flats.

During MARAMP 2007, 9 REA benthic surveys of forereef habitats at Pagan were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 0% to 27.5% with an overall mean of 5% (SE 2.9). The survey with the highest macroalgal cover occurred in the north region at PAG-03 near Tarage (Fig. 13.6.1b). The second-highest macroalgal cover of 7.8% was observed in the south region at PAG-13 near Apansantate. For all other survey areas, macroalgal cover was < 3%, and no macroalgal cover was recorded at PAG-11 in the west region.

Turf-algal cover from these REA benthic surveys ranged from 46.1% to 80.4% with an overall mean of 67% (SE 3.8). The highest turf-algal cover was observed in the south region at PAG-08 and in the west region at PAG-05 south of Bandera Peninsula (Fig. 13.6.1b). Relative to results from other sites surveyed at Pagan, high turf-algal cover was also found at PAG-11 in the west region with 72.5%. The lowest turf-algal cover occurred at PAG-03 near Tarage in the north region.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Pagan was 7% (SE 0.4). The survey with the highest mean crustose-coralline-red-algal cover of 15%, within a range of 10.1%–20%, occurred southwest of Pontanjaburo in the west region (Fig. 13.6.1a, top right panel), where the habitat consisted of pavement and rock boulders of medium-high to high complexity. Just north of this area, 2 adjacent surveys recorded greater than average values of crustose-coralline-red-algal cover, relative to other survey areas around Pagan, with means of 8% and 11%. Habitats in these areas consisted of pavement with sections of continuous and spur-and-groove reef of medium-low to high complexity; areas of high complexity corresponded with the spur-and-groove areas. Additionally, the survey area to the south of Hira Rock in the east region also reported mean cover of crustose coralline red algae of 11%. The medium-complexity habitat in this area consisted of rock boulders.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae around Pagan was 12% (SE 1.1). The survey with the highest mean crustose-coralline-red-algal cover of 42%, within a range of 1.1%–75%, occurred on the reefs between Degusa and Togari Rock in the south region (Fig. 13.6.1a, middle right panel), where the habitat consisted of pavement reef of medium-low to medium-high complexity. The survey conducted to the north of Hira Rock in the east region reported mean crustose-coralline-red-algal cover of 35%. Habitat in this area was characterized as rock boulders of medium to medium-high complexity along a moderate slope. Two surveys conducted in the west region recorded greater than average values of crustose-coralline-red-algal cover, relative to other survey areas around Pagan, with means of 18% and 22%. Habitats in these areas were continuous reef with sections of rock boulders and spur-and-groove structure of predominantly medium-high complexity. Observations of what appeared to be volcanic ash were recorded on both reef areas. The remainder of towed-diver surveys reported below average levels of crustose-coralline-red-algal cover.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae around Pagan was 14% (SE 1.0). The survey with the highest mean crustose-coralline-red-algal cover of 33%, within a range of 20.1%–40%, occurred along the northwest coast of Pagan, crossing the border of the west and north regions (Fig. 13.6.1a, bottom right panel), where the habitat of medium-high to high complexity consisted of continuous reef and boulders. Almost all of the surveys conducted in the west region reported greater than average values of crustose-coralline-red-algal cover, relative to other areas surveyed around Pagan, except for the southernmost survey and the survey conducted north of Bandera Peninsula, in areas of large sand flats, where low values of crustose-coralline-red-algal cover were observed. Along the southwestern coast, mean values of crustose-coralline-red-algal cover of 24% and 26% were recorded during the survey conducted near Pontanjaburo and the adjacent survey to the south. The habitats in these survey areas consisted of continuous or irregular rocky reef of medium to medium-high complexity. Relatively low levels of crustose-coralline-red-algal cover were observed in the east region. The area between Hira Rock and Sengao Peninsula, a continuous reef habitat of medium to high complexity, exhibited the greatest cover values recorded in the east region with a mean of 28%. The adjacent survey to the south and around Sengao Peninsula reported mean crustose-coralline-red-algal cover of 15%.

During MARAMP 2007, 9 REA benthic surveys of forereef habitats at Pagan were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 11.8% with an overall mean of 4% (SE 1.5). The survey with the highest mean cover of crustose coralline red algae occurred in the west region at PAG-11 (Fig. 13.6.1b). The second-highest mean crustose-coralline-red-algal cover of 10.8% was observed at PAG-12 in the north region. No crustose coralline red algae were recorded at both PAG-08 and at PAG-13 in the south region.

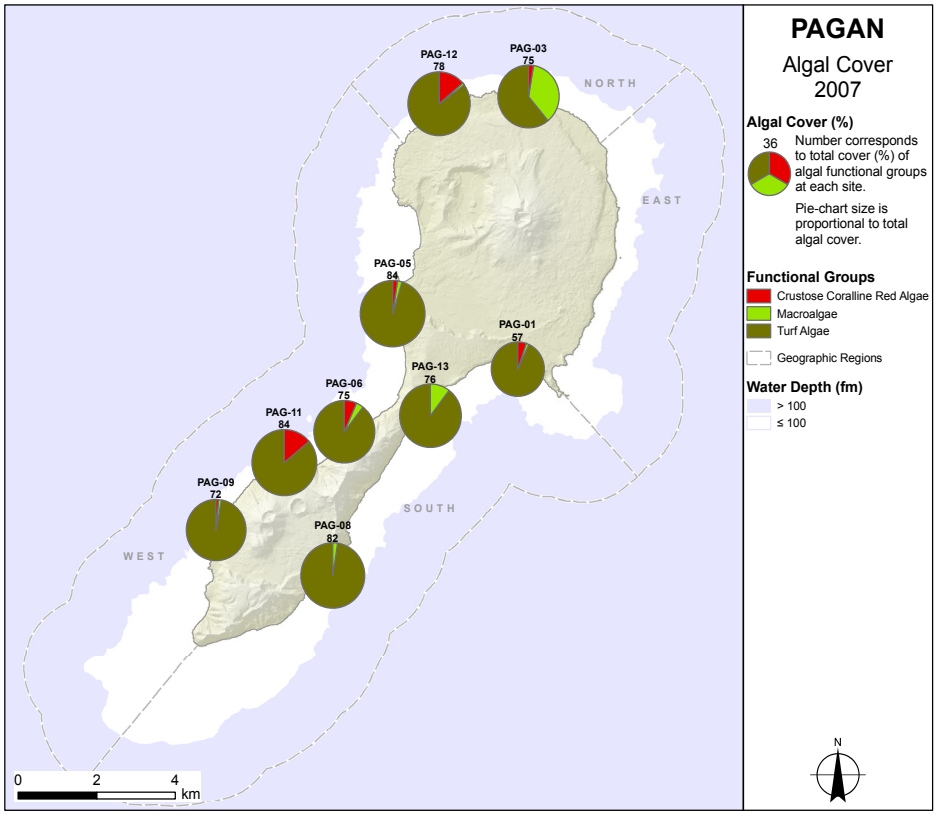


Figure 13.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method at Pagan during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total cover are provided above each symbol.

Algal Cover: Temporal Comparison

Islandwide mean cover of macroalgal populations around Pagan, based on towed-diver surveys of forereef habitats, varied between MARAMP survey years by as much as 29%. In general, the greatest level of macroalgal cover was observed on reefs in the north region. The most abundant macroalgal genera in this region were *Halimeda*, *Caulerpa*, *Neomeris*, *Padina*, *Asparagopsis*, and *Liagora.* When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Overall macroalgal cover around Pagan appeared to decrease from 46% in 2003 to 18% in 2005, but this reduction in observed cover is likely a result of the change in survey method. The greatest variability between observations in these 2 survey years occurred in the west region, where mean cover values decreased from 45% to 10% across 8 surveys. Less variability was recorded in the east and south regions, although declines in observed macroalgal cover were reported in all surveys. The only increase observed from 2003 to 2005 occurred in the north region with a rise in mean macroalgal cover from 55% to 63%. From MARAMP 2005 to 2007, overall macroalgal cover essentially remained the same (Fig. 13.6.1c). The survey area with the greatest variability between 2005 and 2007 values, with a drop in mean cover from 63% to 20%, occurred in the north region west of Tarage. In addition, mean macroalgal cover values near Hira Rock in the east region decreased from 32% in 2005 to 9% in 2007. In contrast, the survey conducted near Piarama in the southernmost area of the south region reported a large increase in mean macroalgal cover from 7% to 39%.

Crustose-coralline-red-algal cover around Pagan, based on towed-diver surveys of forereef habitats, varied as much as 7% in average cover of the benthos between MARAMP survey years. Populations of crustose coralline red algae most commonly inhabited areas medium to medium-high complexity.

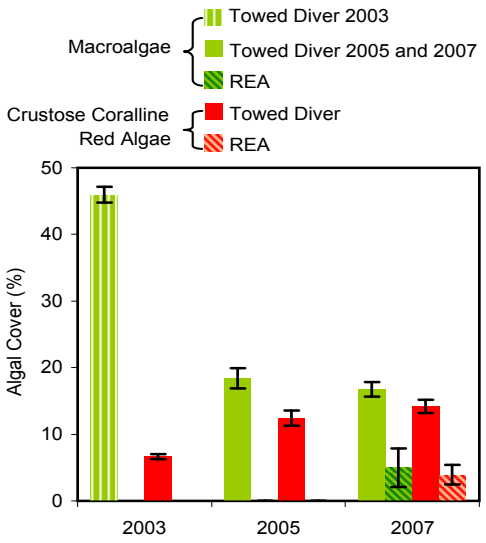


Figure 13.6.1c. Temporal comparison of algal-cover (%) valvues from surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted at Pagan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

An islandwide mean increase of 6% in observed cover of crustose coralline red algae occurred between MARAMP 2003 and 2005 (Fig. 13.6.1c). The greatest variability around Pagan between all MARAMP survey years was recorded in 3 surveys areas: near Hira Rock in the east region, along the southern coast of the Sengao Peninsula in the south region, and north of Periiruu in the west region with increases in cover values of 24%, 35%, and 20%. Between MARAMP 2005 and 2007, the greatest difference was observed in a survey area in the south region along the southern coast of Sengao Peninsula with a drop in mean cover from 42% in 2005 to 15% in 2007. In contrast, the survey area north of this peninsula reported an increase in mean crustose-coralline-red-algal cover from 11% in 2005 to 28% in 2007. For the survey area near Pontanjaburo an increase in mean cover from 5% in 2005 to 24% in 2007 was recorded, and a survey area crossing the border between the west and north regions reported an increase in cover from 9% to 33%.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae are lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islandds of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 8 sites on forereef habitats at Pagan. In the field, 15 macroalgal genera (5 red, 8 green, and 2 brown), containing at least 18 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. PAG-08, located in the south region, had the highest macroalgal generic diversity with 7 genera, containing 7 species, documented in the field. The lowest macroalgal generic diversity was found at PAG-01, located east of Degusa in the south region, with 4 species representing 4 genera recorded.

Species of the calcified red algal genus *Amphiroa* were some of the most common components of algal communities at Pagan in 2003, occurring in 47.9% of photoquadrats sampled and at all sites surveyed except PAG-03 and PAG-04 in the north and west regions (Fig. 13.6.1d). The calcified algal genus *Neomeris* was also extremely common with occurrence values of > 50% at all sites except PAG-01 in the south region and PAG-07 in the west region, where it occurred in 8.3% and 0% of sampled quadrats. The genus *Halimeda* was less common, occurring in 15.6% of all sampled photoquadrats and in 0%–83.3% of photoqudrats sampled at individual sites. Also less common was the green algal genus *Dictyosphaeria,* occurring in 0%–66.7% of sampled photoquadrats at 5 of the 8 sites surveyed at Pagan. At the genus level, most of the other 11 taxa tentatively identified occurred only at 1 or 2 sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Pagan.

Turf algae were exceptionally common in 2003, occurring in 82% of photoquadrats sampled at Pagan. Observed at all sites except PAG-04 in the west region, turf algal communities were found in 83.3%–100% of sampled photoquadrats (Fig. 13.6.1d). Crustose coralline red algae and cyanobacteria were less common, occurring in 31.3% and 37.5% of sampled photoquadrats.

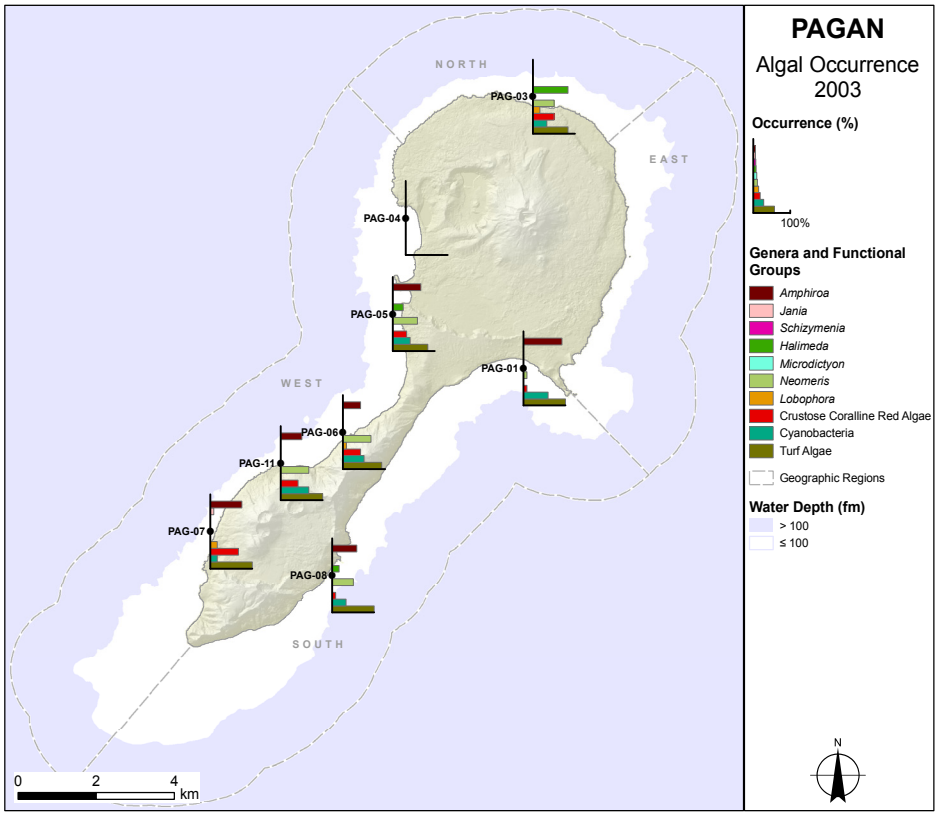


Figure 13.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2005, REA benthic surveys were conducted at 9 sites on forereef habitats at Pagan. In the field, 21 macroalgal genera (10 red, 9 green, and 2 brown), containing at least 21 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, branched nongeniculate calcified red algae, and cyanophytes—were observed. PAG-13, located near Apansantate in the south region, had the highest macroalgal generic diversity with 12 genera, containing 12 species, documented in the field. The lowest macroalgal genera diversity was found in the south region at PAG-08 with 3 species representing 3 genera recorded.

Species of the genera *Amphiroa* and *Halimeda* were the dominant components of the macroalgal community at Pagan in 2005, occurring in 36.1% and 29.6% of sampled photoquadrats. Species of *Amphiroa* were found in 25%–75% of sampled photoquadrats at most sites but were absent from PAG-03 and PAG-12 in the north region and PAG-08 in the south region (Fig. 13.6.1e). Species of *Halimeda* were observed in 8.3%–100% of sampled photoquadrats at most sites but were absent from PAG-01 in the south region and PAG-06, PAG-09, and PAG-11 in the west region. No discernible spatial distributional patterns were found for either genus. At the genus level, most of the 21 taxa tentatively identified occurred only at a few sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Pagan. In an exception, however, the green algal species *Ventricaria ventricosa* was documented at all sites, except PAG-08 in the south region, occurring in 8.3%–33.3% of sampled photoquadrats.

Turf algae, crustose coralline red algae, and cyanobacteria were all exceptionally common in 2005, occurring in 96%, 75%, and 23% of photoquadrats sampled at Pagan. Communities of turf algae and crustose coralline red algae, ubiquitous at all sites, were found in 75%–100% and 50%–91.7% of sampled photoquadrats (Fig. 13.6.1e). Cyanobacteria were prominent components of the algal community at all sites, except PAG-03 and PAG-08 in the north and south region, occurring in 8.3%–41.7% of sampled photoquadrats. Nongeniculate coralline red algae were found only at PAG-09 in the west region, occurring in 8.3% of sampled photoquadrats.

During MARAMP 2007, REA benthic surveys were conducted at 9 sites on forereef habitats at Pagan. In the field, 30 macroalgal genera (16 red, 10 green, and 4 brown), containing at least 31 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. PAG-13, located near Apansantate in the south region, had the highest macroalgal generic diversity with 15 genera, containing 15 species, documented in the field. The lowest macroalgal generic diversity was also found in the south region at PAG-01, also in the south region, with 5 species representing 5 genera recorded.

Species of the red algal genera *Jania* and *Amphiroa*, the brown algal genera *Lobophora* and *Dictyota*, and the green algal genera *Neomeris* and *Halimeda* were common components of algal communities at Pagan in 2007, occurring in 76.9%, 44.4%, 47.2%, 28.7%, 37.0%, and 26.9% of sampled photoquadrats, respectively. The dominant macroalgal genus at most sites, *Jania* was found in 41.7%–91.7% of sampled photoquadrats (Fig. 13.6.1f). At the genus level, most of the 30 taxa

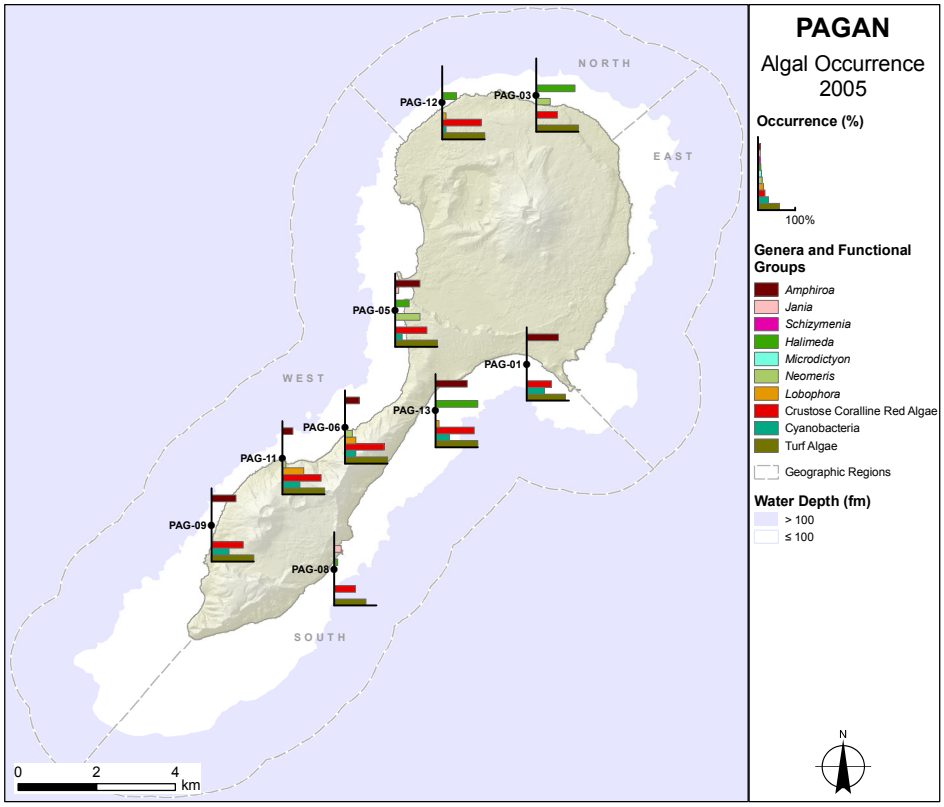


Figure 13.6.1e. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

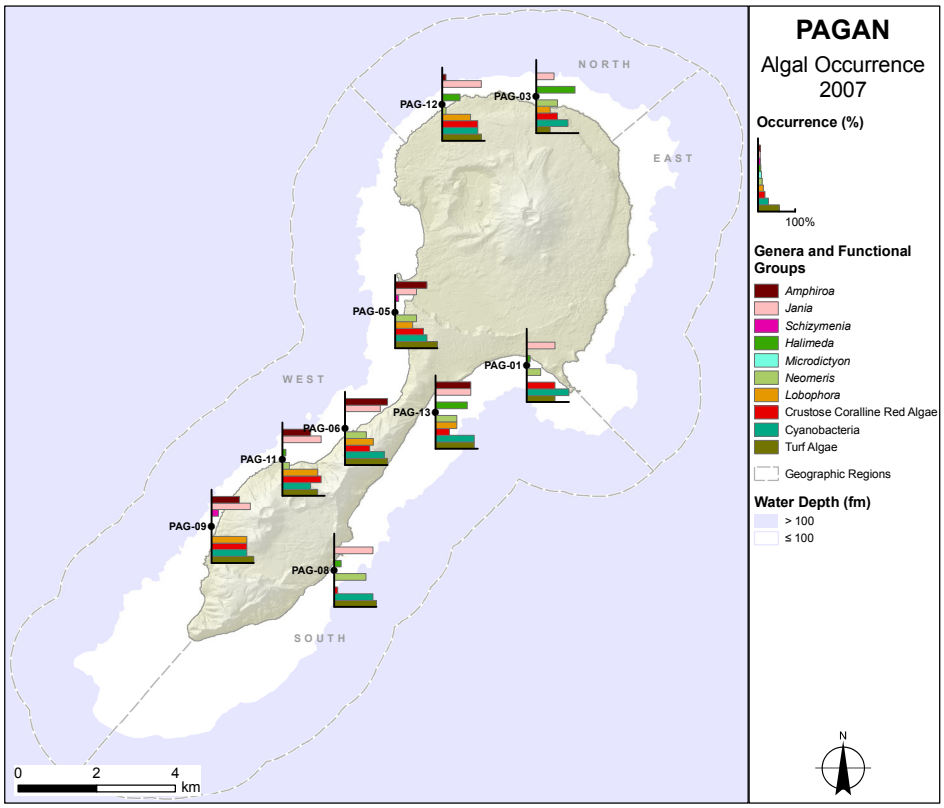


Figure 13.6.1f. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Pagan during MARAMP 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

tentatively identified occurred only at a few sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Pagan. However, some exceptions were found. Species of *Amphiroa* were documented at all sites in the south region except for PAG-08, occurring in 66.7%–100% of sampled photoquadrats at those sites. Species of *Halimeda* were common at several sites, occurring in 8.3%–91.7% of photoquadrats sampled at PAG-03 and PAG-12 in the north region; PAG-01, PAG-08, and PAG-13 in the south region; and PAG-11 in the west region; however, they did so without a distinct spatial pattern of distribution. Species of the calcified algal genus *Jania* were ubiquitous at all sites, and species of *Neomeris* were documented at all sites except PAG-09 in the west region. Also, species of the genus *Lobophora* occurred at all sites except PAG-01 and PAG-08 in the south region.

Turf algae, crustose coralline red algae, and cyanobacteria were all exceptionally common in 2007, occurring in 85%, 60%, and 84% of photoquadrats sampled at Pagan. Although crustose-coralline-red-algal communities were common, this functional group was observed in 8.3%–91.7% of photoquadrats sampled at the REA sites surveyed at this island (Fig. 13.6.1f). Turf algae and cyanobacteria were found in 33.3%–100% and 66.7%–100% of sampled photoquadrats.

The number of macroalgal genera recorded during MARAMP surveys conducted on forereef habitats at Pagan increased from 15 in 2003 to 21 in 2005 and 30 in 2007. Differences in survey effort and other factors likely can account for this increase in estimated macroalgal diversity (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). One additional site was surveyed in 2005 and 2007, compared to the number surveyed in 2003. The overall occurrence of macroalgal genera did not fluctuate greatly between the 3 MARAMP survey years. The genera *Amphiroa, Neomeris*, and *Halimeda* were consistently prominent components of the macroalgal community at Pagan during the 3 survey years, with average occurrence ranges of 36.1%–47.9%, 13%–37.5%, and 15.6%–29.6% (Fig. 13.6.1g). However, no distinct change (increasing or decreasing) in occurrence was seen for any of these genera. Species of *Jania*, *Lobophora*, and *Dictyota* steadily increased in occurrence across the 3 survey periods, and species of *Jania* and *Lobophora*, found in 76.9% and 47.2% of photoquadrats sampled in 2007, were the dominant components of the macroalgal community in 2007.

Turf algae, crustose coralline red algae, and cyanobacteria occurred in 82.3%–96.3%, 31.3%–75%, and 23.1%–84.3% of photoquadrats sampled at Pagan during MARAMP 2003, 2005, and 2007 (Fig. 13.6.1g). No clear changes in abundance of these functional groups were observed between MARAMP survey years.

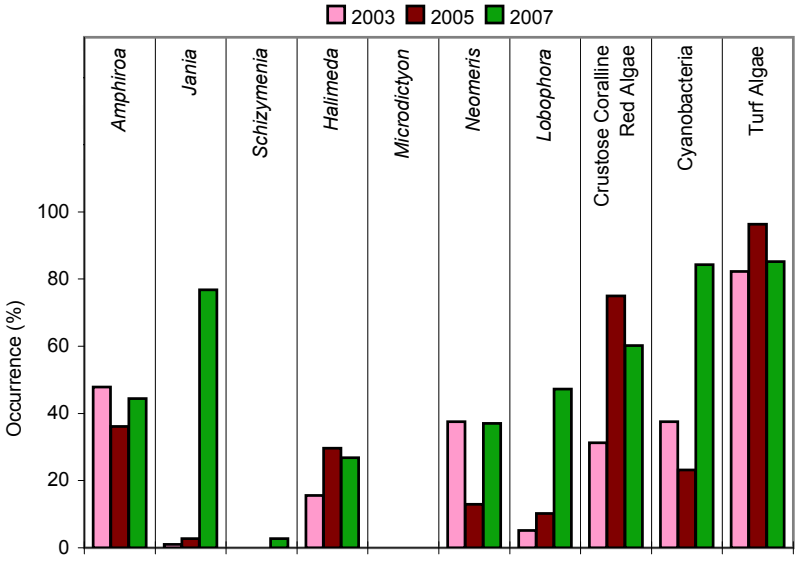


Figure 13.6.1g. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Pagan during MARAMP 2003, 2005, and 2007.

13.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 9 sites on forereef habitats at Pagan, covering a total reef area of 2700 m^2. Disease of coralline algae was found only at PAG-01, located east of Degusa in the south region. At this site, 2 cases of coralline lethal orange disease were enumerated with a density of 0.67 cases 100 m^{-2} (Fig. 13.6.2a), translating to a mean overall density of 0.07 cases 100 m^{-2}.

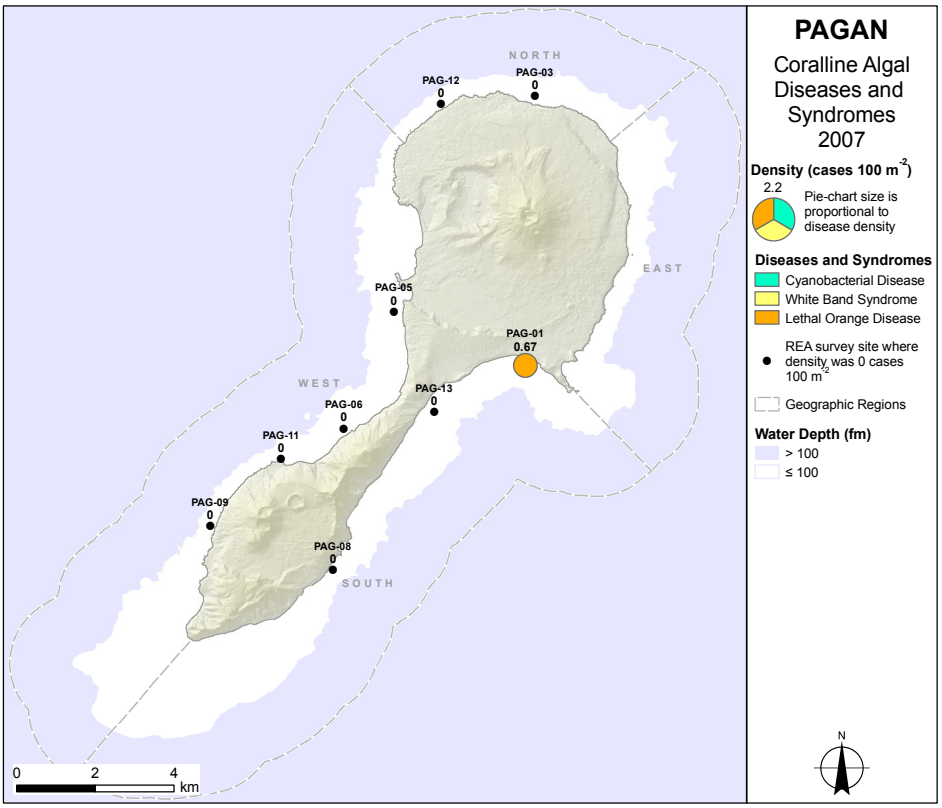


Figure 13.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats at Pagan during MARAMP 2007. The color-coded portions of the pie charts indicate disease-specific density.

13.7 Benthic Macroinvertebrates

13.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Pagan through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 7 REA surveys and 21 towed-diver benthic surveys were conducted around Pagan. In 2005, 9 REA surveys and 17 towed-diver benthic surveys were completed. And in 2007, 8 REA surveys and 16 towed-diver benthic surveys were conducted. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, towed-diver surveys suggested low daytime macroinvertebrate abundance on forereef habitats around Pagan compared to the rest of the Mariana Archipelago. Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density on forereef habitats around Pagan—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 13.7.1d, h, l, and p).

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at all 7 REA sites surveyed and in 13 of the 21 towed-diver surveys conducted around Pagan (Fig. 13.7.1a). The overall mean density of giant clams from REA surveys was 4 organisms 100 m^{-2} (SE 1.7), and the islandwide mean density from towed-diver surveys was 0.026 organisms 100 m^{-2} (SE 0.004). Survey results suggest giant clams were most abundant at REA site PAG-01, located east of Degusa in the south region, with 13 organisms 100 m^{-2} and at PAG-05, located south of Bandera Peninsula in the west region, with a density of 7 organisms 100 m^{-2} (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). Among all towed-diver surveys around this island, the survey completed between Degusa and Apansantate in the south region had the highest mean density of giant clams with 0.14 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.311 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.115 organisms 100 m^{-2}, recorded in the west region between Bandera Peninsula and Dekairu in Apaan Bay; segment densities ranged from 0 to 0.327 organisms 100 m^{-2}.

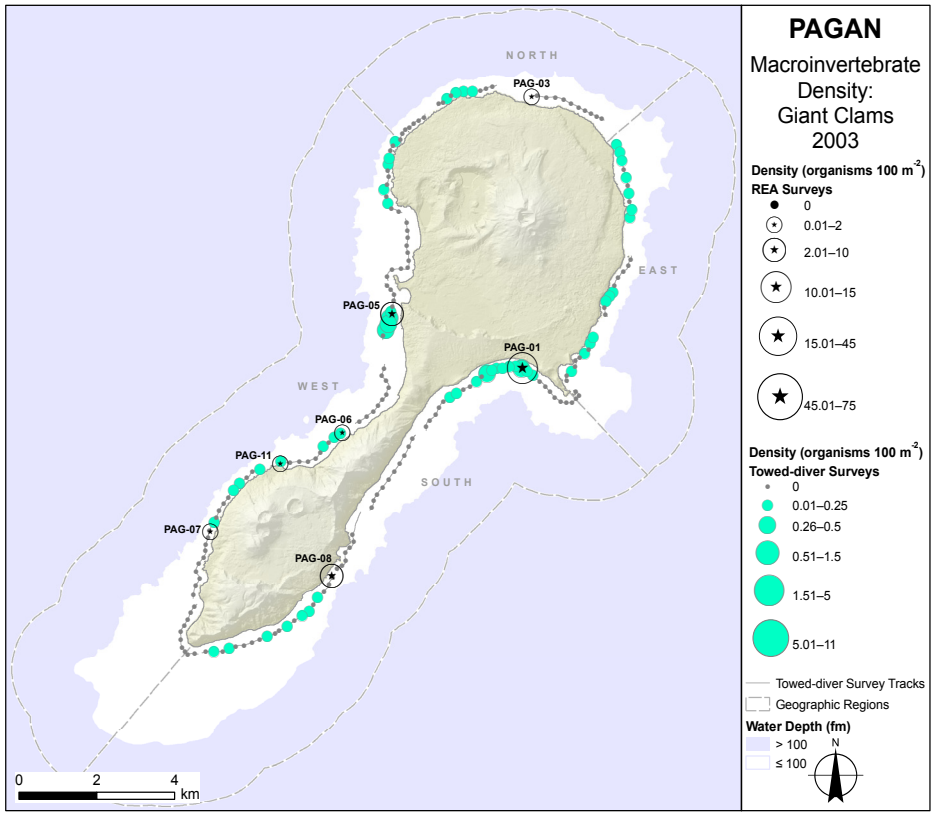
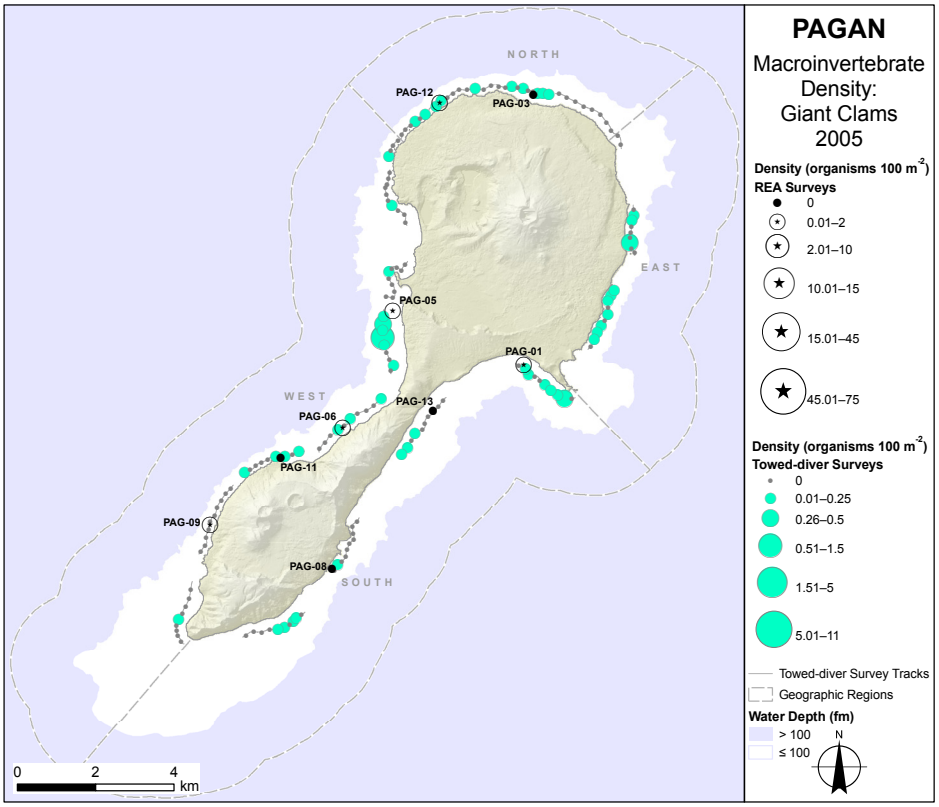


Figure 13.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003.

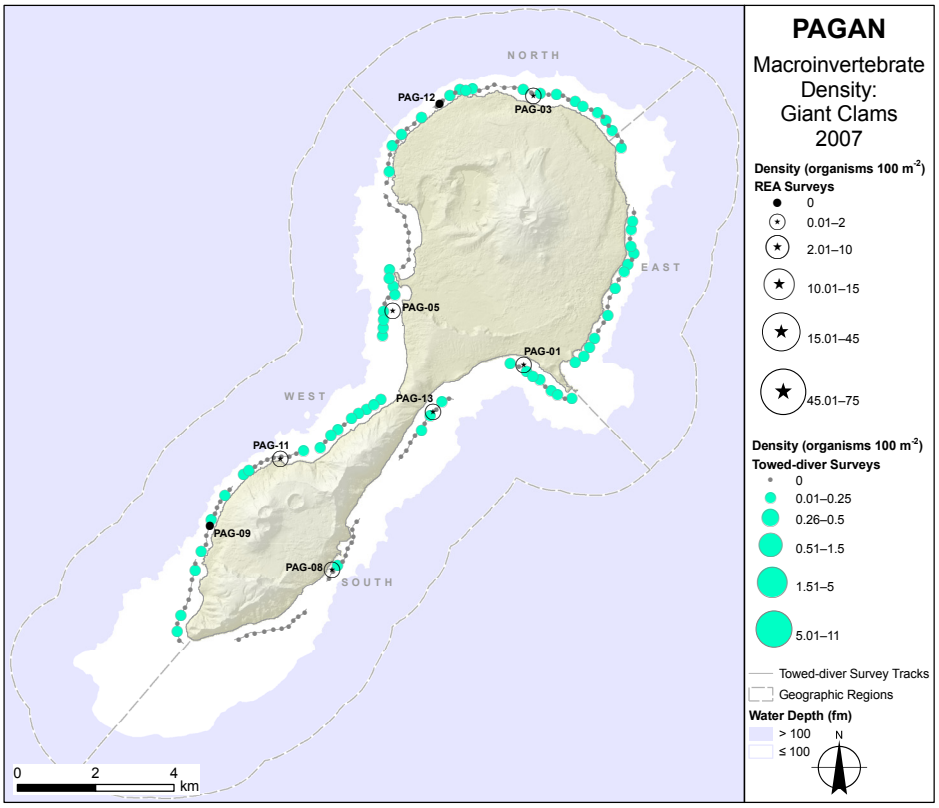
During MARAMP 2005, giant clams were observed at 5 of the 9 REA sites surveyed and in 16 of the 17 towed-diver surveys conducted around Pagan. The overall mean density of giant clams from REA surveys was 0.778 organisms 100 m^{-2} (SE 0.278), and the islandwide mean density from towed-diver surveys was 0.037 organisms 100 m^{-2} (SE 0.007). Survey results suggest that giant clams were most prevalent at PAG-01 in the south region and PAG-05 in the west region with 2 organisms 100 m^{-2} (Fig. 13.7.1b). Among all towed-diver surveys around this island, the survey completed in the west region between Bandera Peninsula and Dekairu in Apaan Bay had the highest mean density of giant clams with 0.171 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.701 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.093 organisms 100 m^{-2}, recorded in the east region north of Hira Rock; segment densities ranged from 0 to 0.494 organisms 100 m^{-2}.

Figure 13.7.1b. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005.



During MARAMP 2007, giant clams were observed at 6 of the 8 REA sites and in 14 of the 16 towed-diver benthic surveys conducted around Pagan. The overall mean density of giant clams from REA survey was 0.542 organisms 100 m^{-2} (SE 0.17), and the islandwide mean density from towed-diver surveys was 0.033 organisms 100 m^{-2} (SE 0.004).

Figure 13.7.1c. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007.



Survey results suggest giant clams were most abundant at PAG-13 near Apansantate in the south region with 1.333 organisms 100 m^{-2} (Fig. 13.7.1c). Among all towed-diver surveys around this island, the survey completed between Togari Rock and Degusa in the south region had the highest mean density of giant clams with 0.079 organisms 100 m^{-2}; segment densities for this survey ranged from 0 to 0.213 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.075 organisms 100 m^{-2}, recorded in the west region between Bandera Peninsula and Dekairu; segment densities ranged from 0 and 0.241 organisms 100 m^{-2}.

Towed-diver surveys suggested low abundance of giant clam around Pagan during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago (Fig. 13.7.1d). Minor fluctuations in densities were observed, but this variation is not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

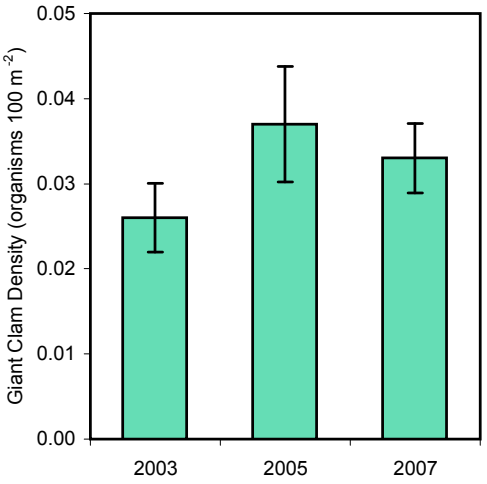


Figure 13.7.1d. Temporal comparison of mean densities (organisms m^{-2}) of giant clam from towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Crown-of-thorns Seastars

During MARAMP 2003, crown-of-thorns seastars (*Acanthaster planci*) were observed at 1 of the 7 REA sites surveyed and in 5 of the 21 towed-diver surveys conducted around Pagan. PAG-06 in the west region had 1 organism 100 m^{-2}. The islandwide mean density of COTS from towed-diver surveys was 0.002 organisms 100 m^{-2} (SE 0.001). Among all towed-diver surveys around this island, the survey completed in the north region had the highest mean density of COTS with 0.016 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.119 organisms 100 m^{-2} (Fig. 13.7.1e). The second-greatest mean density of COTS from a towed-diver survey was 0.010 organisms 100 m^{-2}, recorded just north of Fuwaebosu in the south region; segment densities ranged from 0 to 0.061 organisms 100 m^{-2}.

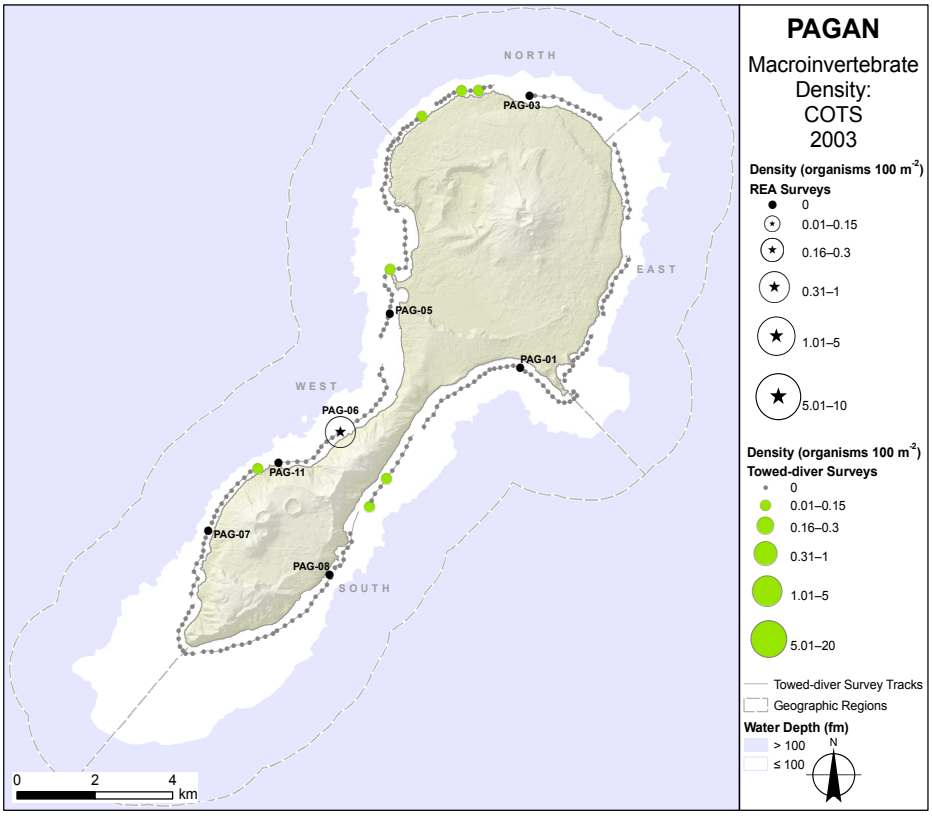


Figure 13.7.1e. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003.

During MARAMP 2005, no COTS were observed at the 9 REA sites surveyed around Pagan; however, high numbers of COTS were recorded in all but 1 of the 17 towed-diver surveys. The majority of COTS observed were concentrated in the east region and in the southern half of the south region. The islandwide mean density of COTS from towed-diver surveys was 0.24 organisms 100 m^{-2} (SE 0.05). Among all towed-diver surveys around this island, the survey completed in the south region between South Point and Buritoma in the south region had the highest mean density with 0.89 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 5.22 organisms 100 m^{-2} (Fig. 13.7.1f). The second-greatest mean density of COTS from a towed-diver survey was 0.75 organisms 100 m^{-2}, recorded between Buritoma and Fuwaebosu in the south region; segment densities ranged from 0 to 4.16 organisms 100 m^{-2}. The survey in the east region just north of Hira Rock had the third-greatest mean density with 0.68 organisms 100 m^{-2}; segment densities ranged from 0 to 2.86 organisms 100 m^{-2}.

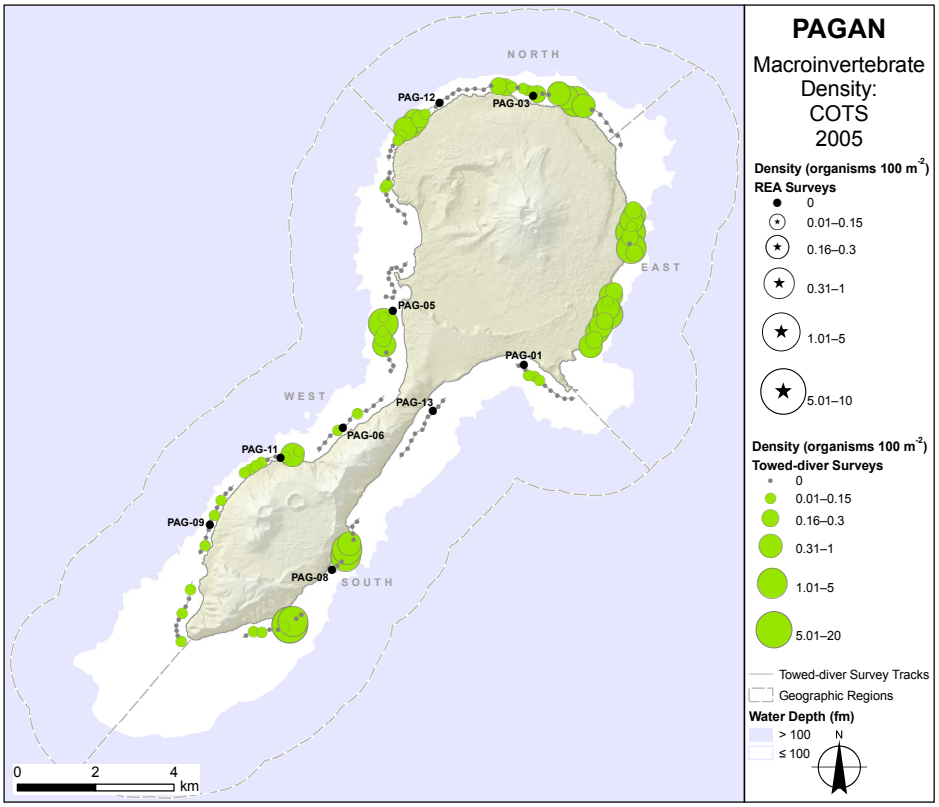


Figure 13.7.1f. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005.

During MARAMP 2007, COTS were observed at 3 of the 8 REA sites surveyed and in all 16 towed-diver surveys conducted around Pagan. The overall mean density of COTS from REA surveys was 0.33 organisms 100 m^{-2} (SE 0.15), and the islandwide mean density from towed-diver surveys was 0.08 organisms 100 m^{-2} (SE 0.01). The same COTS density was found at PAG-03 and PAG-12 in the north region and PAG-11 in the west region: 0.33 organisms 100 m^{-2} (Fig. 13.7.1.g). Among all towed-diver surveys around this island, the survey completed in the west region south of Dekairu had the highest mean density with 0.2 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.74 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.17 organisms 100 m^{-2}, recorded in the east region north of Hira Rock; segment densities ranged from 0.09 to 0.44 organisms 100 m^{-2}. The survey in the south region between Togari Rock and Degusa had the third-greatest density with 0.17 organisms 100 m^{-2}; segment densities ranged from 0 to 0.82 organisms 100 m^{-2}.

Towed-diver surveys suggested low daytime densities of COTS during MARAMP 2003 and 2007 but high COTS densities during MARAMP 2005 around Pagan, compared to the rest of the Mariana Archipelago (Fig. 13.7.1h). This temporal pattern from towed-diver surveys suggests a potential recruitment pulse of COTS to Pagan between MARAMP 2003 and 2005. A greater percentage of forereef habitats was surveyed in 2003 than in other years, with 21 towed-diver surveys, yet these surveys recorded virtually no COTS with an islandwide mean density of 0.002 organisms 100 m^{-2}. The mean density of COTS observed from towed-diver surveys conducted around Pagan increased to 0.24 organisms 100 m^{-2} in 2005 and then declined to 0.08 organisms 100 m^{-2} by 2007.

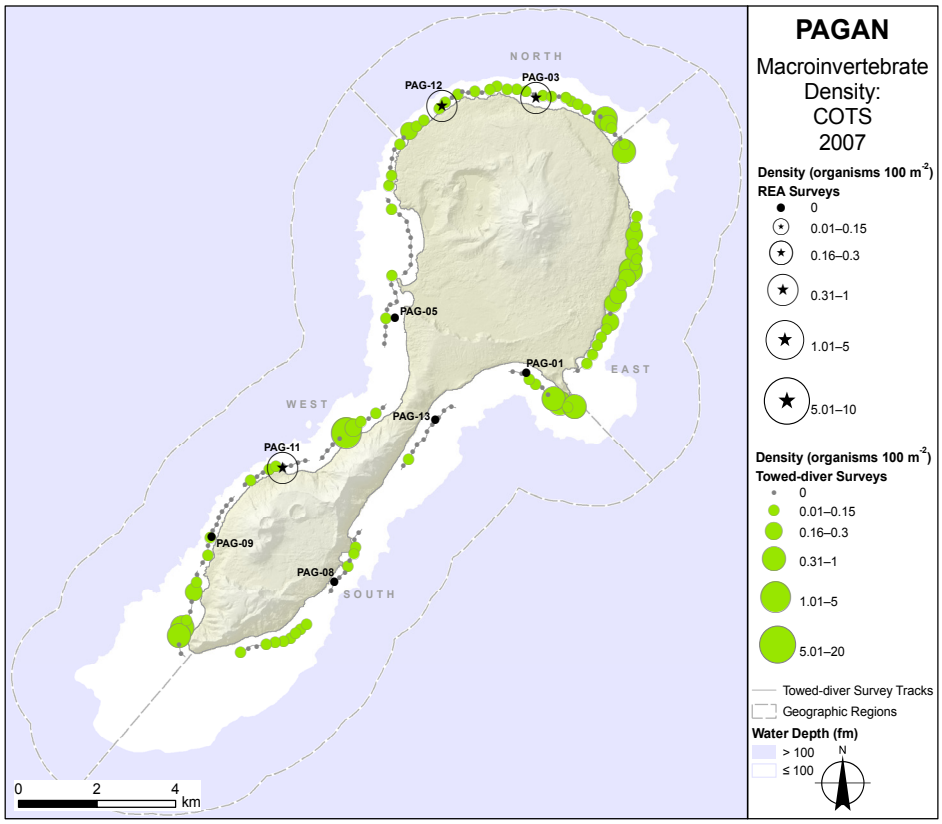


Figure 13.7.1g. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007.

Given that these corallivorous seastars can decimate a reef, understanding whether their observed densities signify an outbreak is important. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure established for using scuba divers to conduct MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms km^{-2} (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of density and considering each towed-diver survey as an individual reef area, localized areas with relatively high densities of COTS that suggest that they were undergoing an outbreak were found during MARAMP 2005 and 2007.

The aforementioned density criterion was met for 7 towed-diver surveys, conducted in the south, east, and north regions during MARMP 2005, with mean COTS densities of 0.24–0.87 organisms 100 m^{-2}. The south region had the greatest concentration of COTS in 2005. In 2007, 3 towed-diver surveys had densities > 0.15 organisms 100 m^{-2}, all located on reefs along the northern half Pagan. However, COTS densities from these surveys, with means of 0.17–0.21 organisms 100 m^{-2}, were lower than values recorded in 2005.

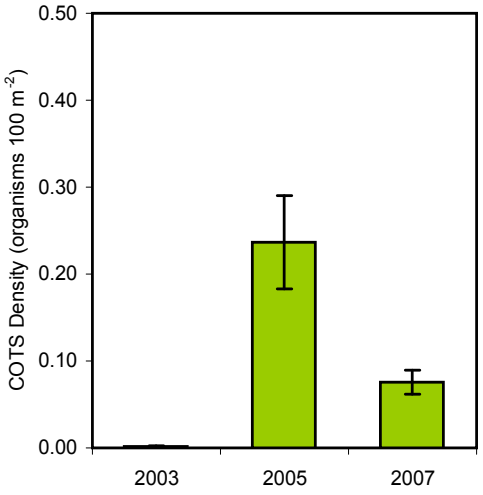


Figure 13.7.1h. Temporal comparison of COTS mean densities (organisms m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at 4 of the 7 REA sites surveyed and in 20 of the 21 towed-diver surveys conducted around Pagan. The overall mean density of sea cucumbers from REA surveys was 8.71 organisms 100 m^{-2} (SE 7.89), and the islandwide mean density from towed-diver surveys was 1.22 organisms 100 m^{-2} (SE 0.16). Survey results suggest that sea cucumbers were most abundant at PAG-01 in the south region east of Degusa with 26 organisms 100 m^{-2} (Fig. 13.7.1i). All the sea cucumbers recorded at this site were species of the genus *Stichopus*. The only other genus observed at REA sites was *Actinopyga*. Among all towed-diver surveys around this island, the survey completed

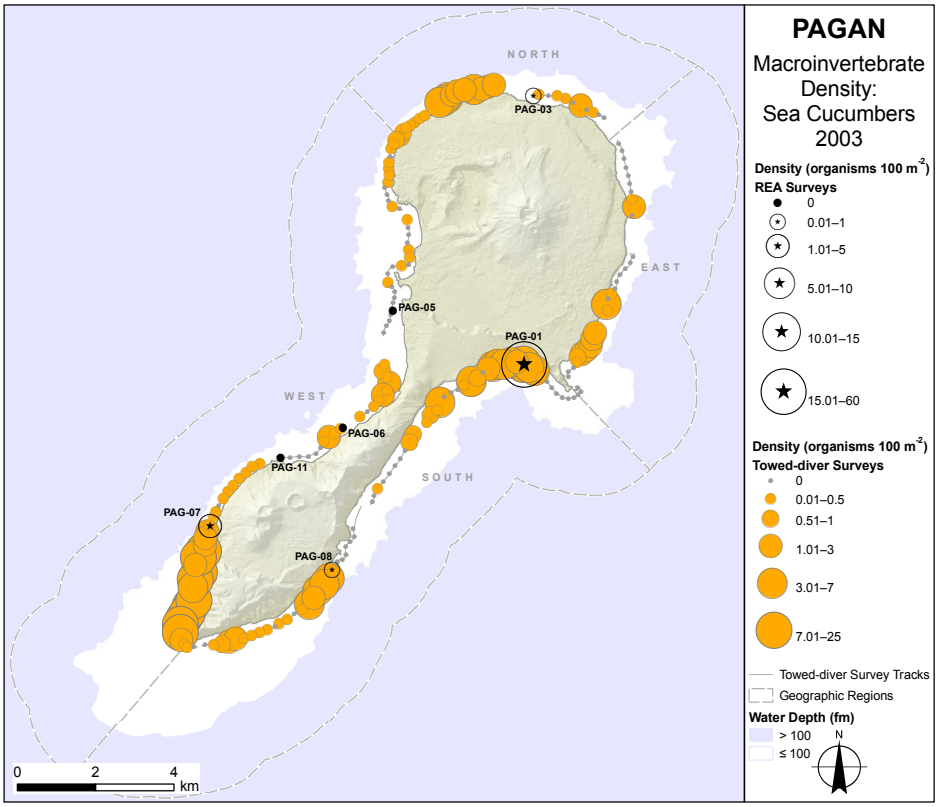


Figure 13.7.1i. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003.

around South Point had the highest mean density of sea cucumbers with 6.06 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 10.51 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 4.64 organisms 100 m^{-2}, recorded north of South Point near Sarahai in the west region; segment densities ranged from 0 to 9.58 organisms 100 m^{-2}.

During MARAMP 2005, sea cucumbers were observed at 5 of the 9 REA sites surveyed and in all 17 towed-diver surveys conducted around Pagan (Fig. 13.7.1j). The overall mean density of sea cucumbers from REA surveys was 4 organisms 100 m^{-2} (SE 2.09), and the islandwide mean density from towed-diver surveys was 0.38 organisms 100 m^{-2} (SE 0.06). Species from the genus *Stichopus* represented 86% of sea cucumbers recorded in 2005 at Pagan during REA surveys, and species of the genera *Actinopyga*, *Holothuria*, and *Bohadschia* were also observed. Survey results suggest sea cucumbers were most prevalent at PAG-01 east of Degusa in the south region with 26 organisms 100 m^{-2}, all of them from the genus *Stichopus*. Among all towed-diver surveys around this island, the survey completed in the east region north of Sengao Peninsula had the highest mean density of sea cucumbers with 1.62 organisms 100 m^{-2}; segment densities from this survey ranged from 0.29 to 2.25 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 1.49 organisms 100 m^{-2}, recorded in the south region between Degusa and Togari Rock; segment densities ranged from 0 to 4.17 organisms 100 m^{-2}.

During MARAMP 2007, sea cucumbers were observed at 6 of the 8 REA sites surveyed and in all 16 of the towed-diver surveys conducted around Pagan. The overall mean density from REA surveys was 4.71 organisms 100 m^{-2} (SE 2.31), and the islandwide mean density of 0.81 organisms 100 m^{-2} (SE 0.1). Species from the genus *Stichopus* represented 90% of sea cucumbers recorded in 2007 at Pagan during REA surveys. Survey results suggest sea cucumbers were most abundant at PAG-12 in the north region with 16.33 organisms 100 m^{-2} (Fig. 13.7.1k), and 96% of them were species from the genus *Stichopus*. Species from the genera *Holothuria* and *Pearsonothuria* were also observed at PAG-12. PAG-01 in the south region east of Degusa had the second-greatest mean density with 13.67 organisms 100 m^{-2}. Species of the genus *Stichopus* accounted for 95% of sea cucumbers observed at this site, and species of the genera *Bohadschia* and *Pearsonothuria* were also recorded.

Among all towed-diver surveys conducted around Pagan in 2007, the survey completed in the south region, east of Piarama, had the highest mean density of sea cucumbers with 2.07 organisms 100 m^{-2}; segment densities from this survey ranged

from 0 to 9.74 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 1.87 organisms 100 m^{-2}, recorded in the north region near Tarage; segment densities ranged from 0.57 to 3.37 organisms 100 m^{-2}.

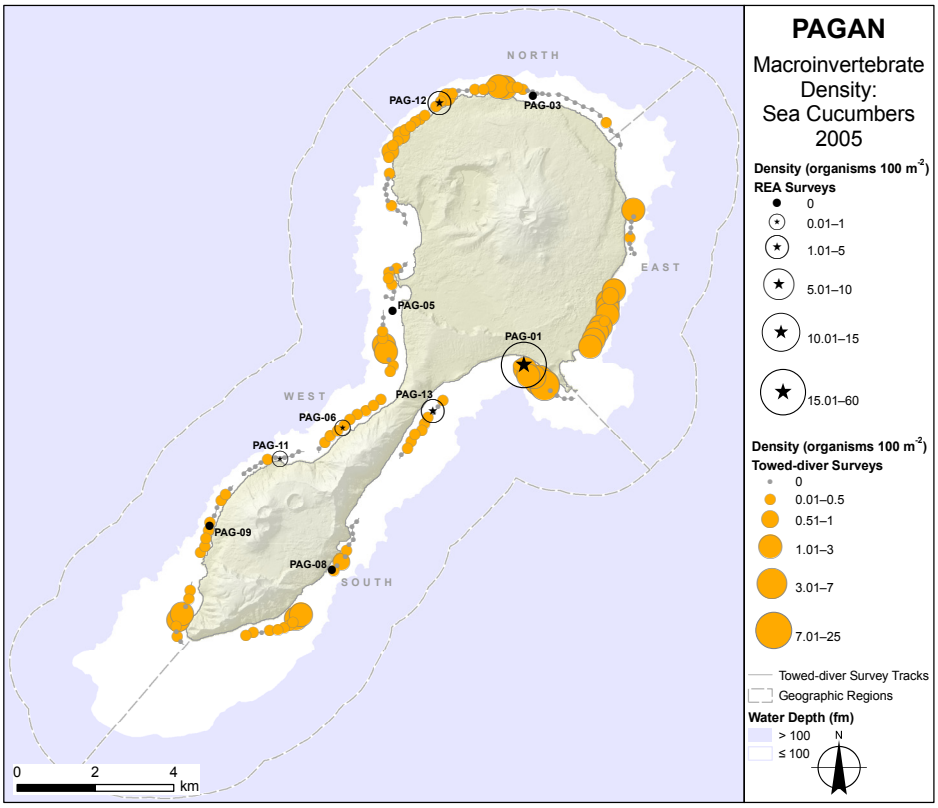


Figure 13.7.1j. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005.

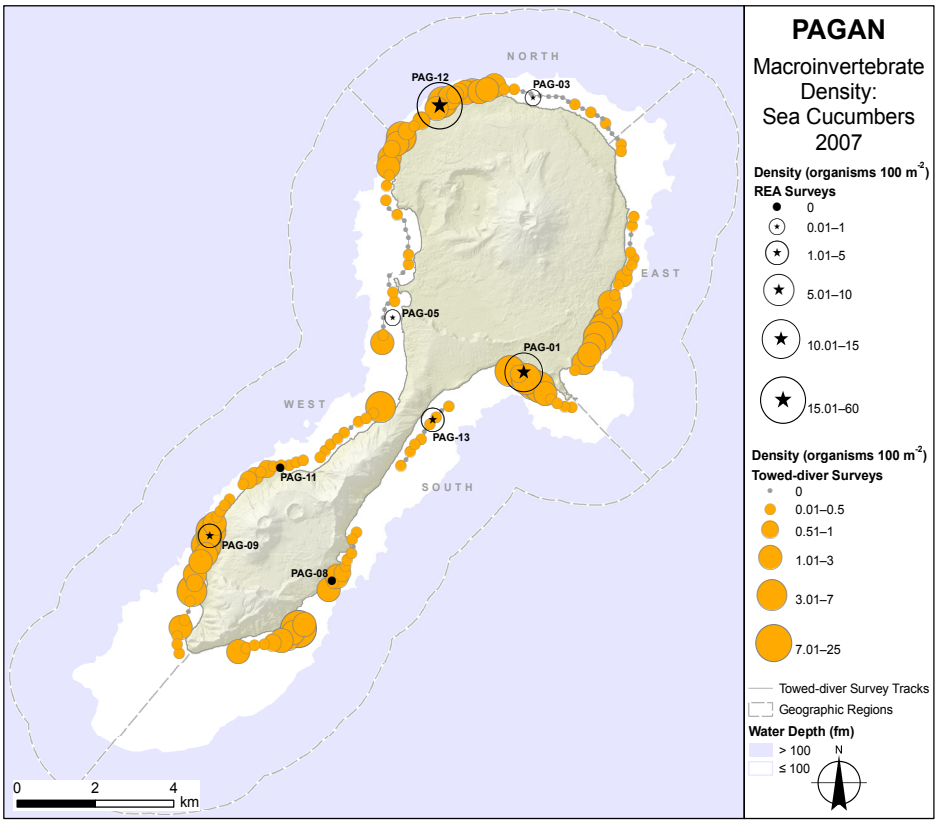


Figure 13.7.1k. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007.

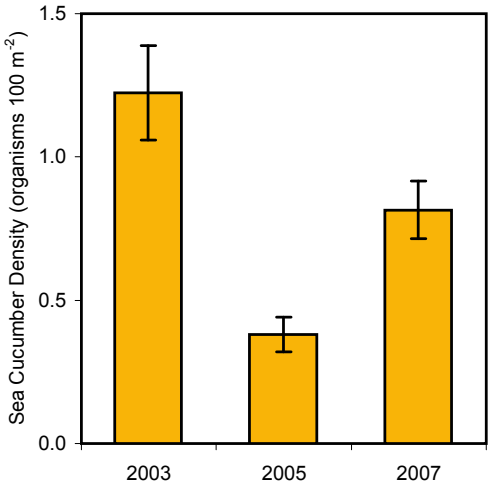


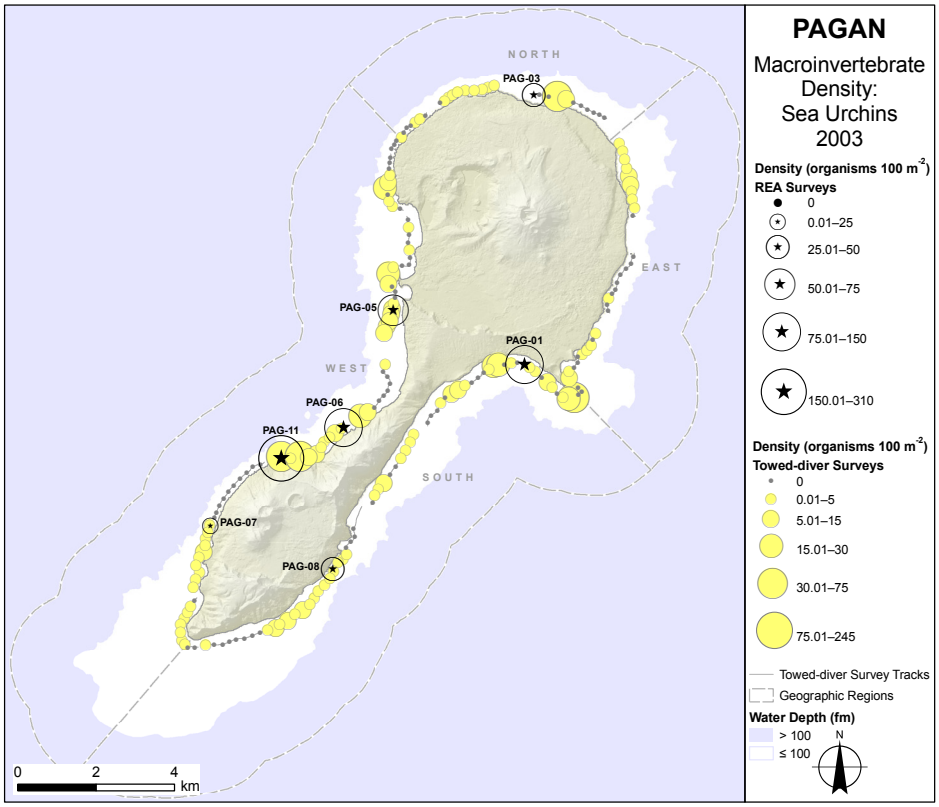
Figure 13.7.1l. Temporal comparison of mean densities (organisms m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested that daytime abundance of sea cucumbers was more or less uniformly distributed around Pagan during the 3 MARAMP survey years. The overall observed mean density of sea cucumbers around Pagan decreased from 2003 to 2005 and then increased from 2005 to 2007 (Fig. 13.7.1l). These changes may result from differences in survey effort or other factors and are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). The number of towed-diver surveys decreased from 21 in 2003 to 17 and 16 in 2005 and 2007. Also, towed-diver surveys covered more habitat around the southern tip of Pagan in 2003 than in 2005 and 2007; this area had the greatest density of sea cucumbers with 6.06 organisms 100 m^{-2}.

Sea Urchins

During MARAMP 2003, sea urchins were observed at all 7 REA sites surveyed and in 20 of the 21 towed-diver surveys conducted around Pagan. The overall mean density of sea urchins from REA surveys was 80.43 organisms 100 m^{-2} (SE 27.81), and the islandwide mean density from towed-diver surveys was 3.08 organisms 100 m^{-2} (SE 0.48). Survey results suggest that sea urchins were most abundant at PAG-11 near Pontanjaburo in the west region with 226 organisms 100 m^{-2} (Fig. 13.7.1m). Rock-boring urchin species of the genus *Echinostrephus* accounted for 95% of the observed urchins at this site and species of the genus *Echinothrix*, *Echinometra*, and *Diadema* were recorded in low numbers, compared

Figure 13.7.1m. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003.



to other sites surveyed in the Mariana Archipelago. PAG-01 had the second-greatest density of sea urchins with 112 organisms 100 m^{-2}. Four genera were recorded at this site: *Echinostrephus*, *Echinometra*, *Diadema,* and *Echinothrix.* The rock-boring urchin *Echinostrephus* was also the dominant genus of sea urchins at this site, where it accounted for 93.7% of urchin observations.

Among all towed-diver surveys conducted around Pagan in 2003, the survey completed in the west region, south of Dekairu, had the highest mean density of sea urchins with 11.22 organisms 100 m^{-2}; segment densities from this survey ranged from 2.13 to 32.89 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 9.67 organisms 100 m^{-2}, recorded between Togari Rock and Degusa in the south region; segment densities ranged from 0 to 49.5 organisms 100 m^{-2}.

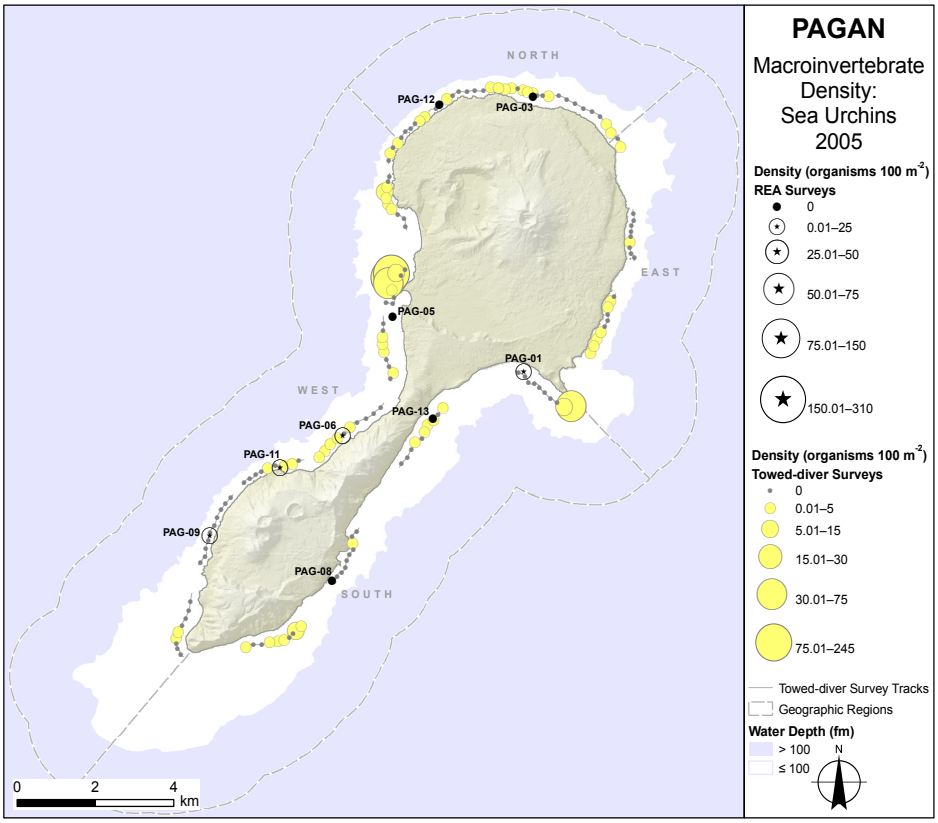


Figure 13.7.1n. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2005.

During MARAMP 2005, sea urchins were observed at 4 of the 9 REA sites surveyed and in 15 of the 17 towed-diver surveys conducted around Pagan. The overall mean density of sea urchins from REA surveys was 0.89 organisms 100 m^{-2} (SE 0.39), and the islandwide mean density from towed-diver surveys was 2.15 organisms 100 m^{-2} (SE 0.82). Survey results suggest sea urchins were most prevalent at PAG-06 in the west region south of Dekairu with 3 organisms 100 m^{-2} (Fig. 13.7.1n). Among all towed-diver surveys around this island, the survey completed around Bandera Peninsula in the west region had the highest mean density of sea urchins with 21.5 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 84.34 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 6.84 organisms 100 m^{-2}, recorded between Togari Rock and Degusa in the south region; segment densities ranged from 3.38 to 38.92 organisms 100 m^{-2}.

During MARAMP 2007, sea urchins were observed at all 8 REA sites surveyed and in all 16 towed-diver surveys conducted around Pagan. The overall mean density of sea urchins from REA surveys was 11.04 organisms 100 m^{-2} (SE 6.44), and the islandwide mean density from towed-diver surveys was 3.9 organisms 100 m^{-2} (SE 0.83). Survey results suggest that sea urchins were most abundant at PAG-03 in the north region near Tarage with 52 organisms 100 m^{-2} (Fig. 13.7.1o). Rock-boring urchins of the genus *Echinostrephus* accounted for 97% of recorded sea urchins at this site. PAG-05 had the second-greatest density of sea urchins with 23.67 organisms 100 m^{-2}. The rock-boring urchin *Echinostrephus* was the dominant urchin at this site, where it accounted for 98.6% of observations. Overall, 3 genera were observed on forereef habitats around Pagan: *Echinostrephus*, *Echinothrix*, and *Diadema.*

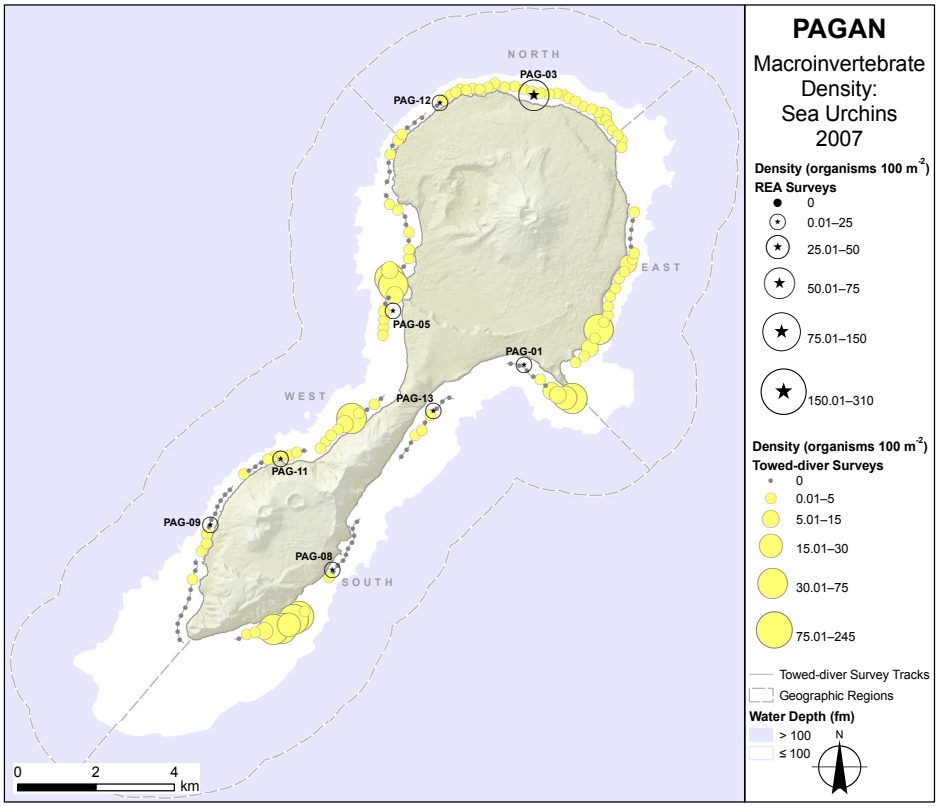


Figure 13.7.1o. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007.

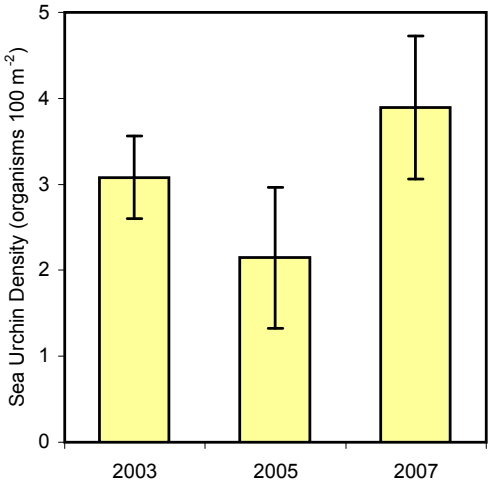


Figure 13.7.1p. Temporal comparison of mean densities (organisms m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Among all towed-diver surveys conducted around Pagan in 2007, the survey completed in the south region near Piarama had the highest mean density of sea urchins with 23.06 organisms 100 m^{-2}; segment densities for this survey ranged from 0 to 55.70 organisms 100 m^{-2}. The second-greatest mean density from a towed-diver survey was 10.14 organisms 100 m^{-2}, recorded in the west region near Bandera Peninsula; segment densities ranged from 0 to 45.85 organisms 100 m^{-2}. The towed-diver survey conducted between Togari Rock and Degusa in the south region had the third-greatest mean density at 8.74 organisms 100 m^{-2}; segment densities ranged from 0 to 49.79 organisms 100 m^{-2}.

Towed-diver surveys suggested low daytime abundance of sea urchins around Pagan, compared to the rest of the Mariana Archipelago. Overall mean sea urchin densities from towed-diver surveys varied slightly between MARAMP survey years (Fig. 13.7.1p). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

13.8 Reef Fishes

13.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 21 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Pagan. The islandwide estimated mean biomass of large fishes, calculated as weight per unit area, was 0.87 kg 100 m^{-2} (SE 0.18), a high value compared to levels found around other islands in the Mariana Archipelago. Values of large-fish biomass were high in most survey areas around Pagan, compared to survey results at other islands in the Mariana Archipelago, and no clear spatial patterns were seen in the distribution of biomass (Fig. 13.8.1a). Reef sharks (Carcharhinidae), nurse sharks (Ginglymostomatidae), and snappers (Lutjanidae) contributed 58% to overall large-fish biomass around Pagan. Sharks alone accounted for 26% or 0.23 kg 100 m^{-2} of large-fish biomass with the tawny nurse shark (*Nebrius ferrugineus*) contributing 78% of shark biomass. During this survey period, 25 sharks were observed: 13 whitetip reef sharks (*Triaenodon obesus*) and 12 tawny nurse sharks. Snappers accounted for 32% of overall large-fish biomass. The twinspot snapper (*Lutjanus bohar*) contributed 66% or 0.18 kg 100 m^{-2} of snapper biomass with 155 individuals recorded in 2003. Jacks (Carangidae) and parrotfishes (Scaridae) also were common, accounting for 9% and 10% of islandwide large-fish biomass. Biomass values for large fishes were highest along the northwestern coast, where sharks, snappers and stingrays (Dasyatidae) commonly were observed.

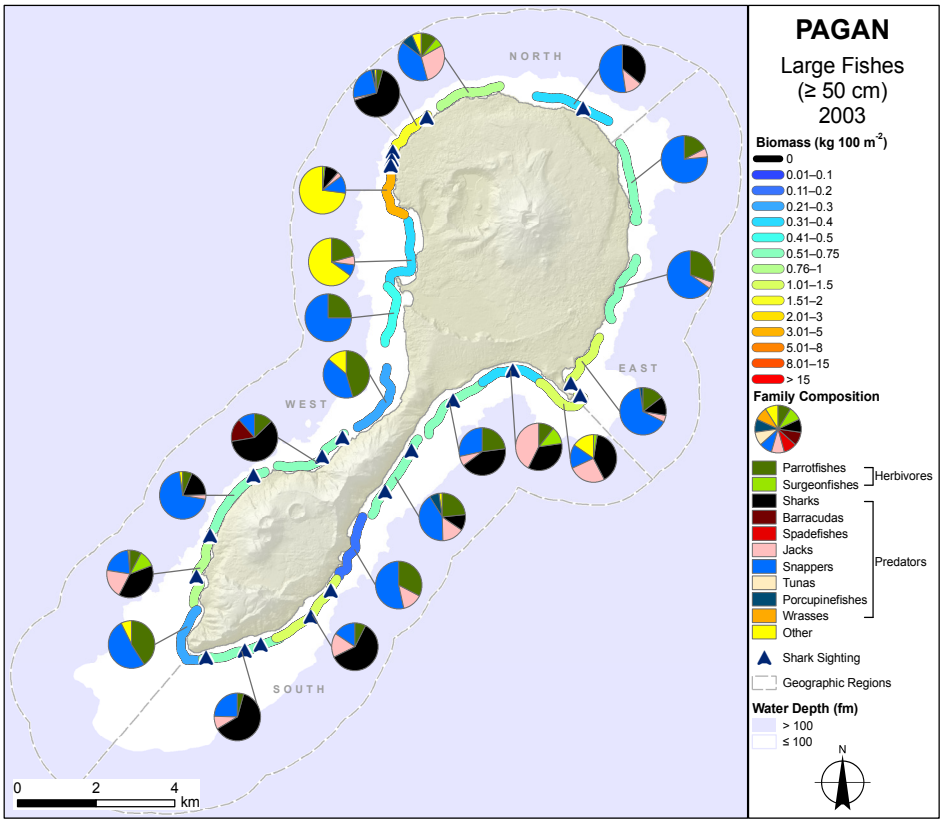


Figure 13.8.1a Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Pagan during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown

During MARAMP 2005, 17 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Pagan. The islandwide estimated mean biomass of large fishes was lower than the value found in 2003 with 0.37 kg 100 m^{-2} (SE 0.08). Sharks accounted for the largest proportion (22%) of overall large-fish biomass. The tawny nurse shark contributed 60% of shark biomass and 0.05 kg 100 m^{-2} to overall large-fish biomass. During this survey period, 14 sharks were observed: 10 whitetip reef sharks, 3 tawny nurse sharks, and 1 blacktip reef shark (*Carcharhinus melanopterus*). Jacks and snappers also were commonly recorded around Pagan, each accounting for 20% of overall large-fish biomass. The bigeye trevally (*Caranx sexfasciatus*) contributed the greatest proportion of jack biomass, with a school of 45 individuals recorded during a single survey along the northwestern coast. Consistent with observations made in 2003, the twinspot snapper was the dominant snapper species by biomass, accounting for 75% of snapper biomass and

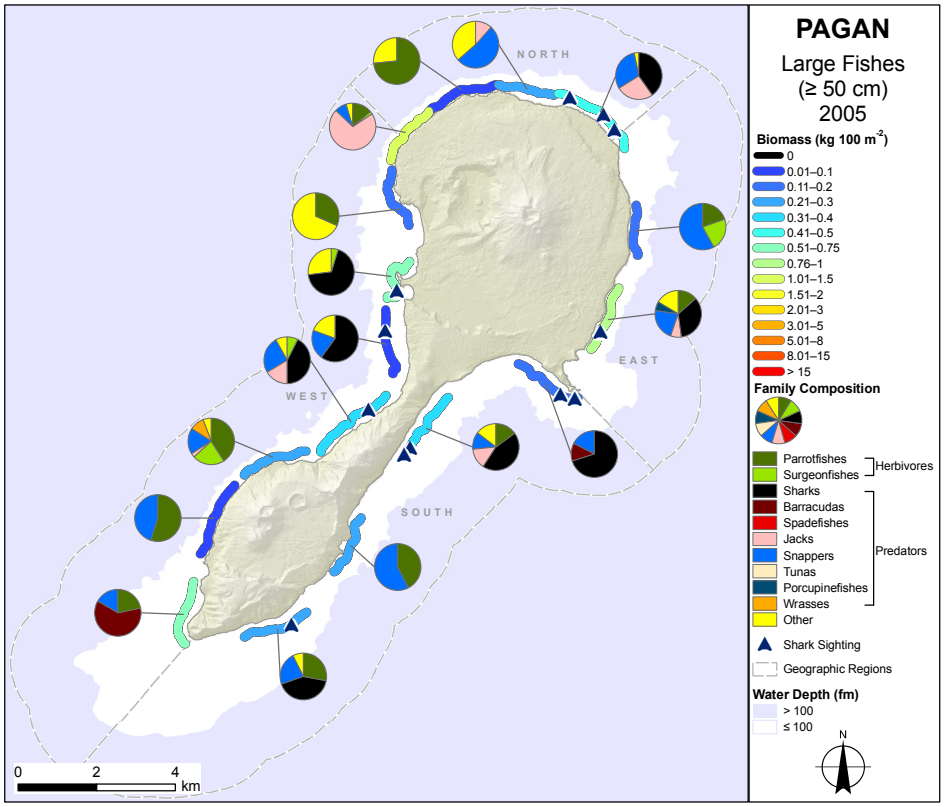


Figure 13.8.1b. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Pagan during MARAMP 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

0.06 kg 100 m^{-2} of overall large-fish biomass. Also similar to survey results from 2003, biomass values for large fishes were highest along the northwestern coast, where the school of bigeye jacks was seen (Fig. 13.8.1b).

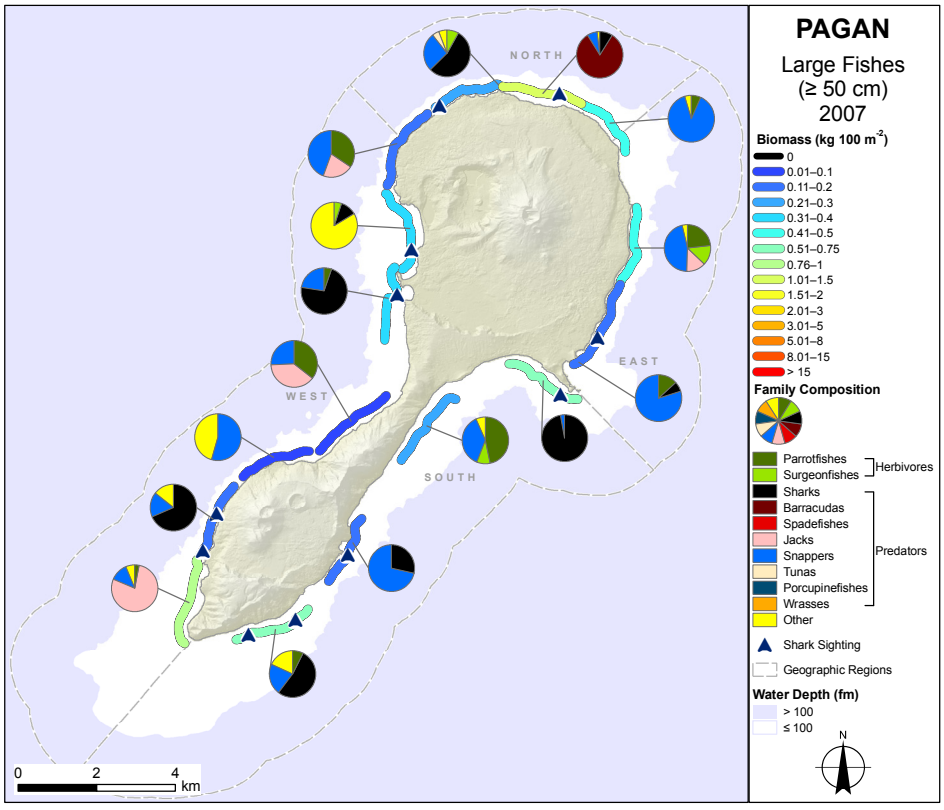


Figure 13.8.1c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys conducted of forereef habitats around Pagan during MARAMP 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

During MARAMP 2007, 16 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Pagan. The islandwide estimated mean biomass of large fishes was 0.41 kg 100 m^{-2} (SE 0.09), similar to survey results from 2005. Consistent with previous survey periods, sharks accounted for the largest proportion (27%) of large-fish biomass. Tawny nurse sharks contributed 79% of shark biomass and 0.09 kg 100 m^{-2} to overall large-fish biomass. During this survey period, 12 sharks were observed, all of them benthic dwelling species: 7 whitetip reef sharks and 5 tawny nurse sharks. Snappers accounted for the second-greatest proportion (25%) of large-fish biomass. The twinspot snapper was the most abundant snapper species, contributing 69% or 0.07 kg 100 m^{-2} of snapper biomass. Barracudas (Sphyraenidae) and jacks also were common, accounting for 18% and 11% of overall large-fish biomass. Biomass values for large fishes were highest in the north region, where a school of Heller's barracuda (*Sphyraena helleri*) was observed during a single survey (Fig. 13.8.1c).

Large-fish biomass from towed-diver surveys of forereef habitats was distributed fairly evenly around Pagan in each of the 3 MARAMP survey years; however, values were slightly elevated in the west and north regions versus other areas surveyed at Pagan. Islandwide mean biomass of large fishes around Pagan was highest in 2003 with 0.87 kg 100 m^{-2} (SE 0.18), dropping to 0.37 kg 100 m^{-2} (SE 0.08) in 2005 and 0.41 kg 100 m^{-2} (SE 0.09) in 2007 (Fig. 13.8.1d). Averaged across the 3 survey years, large-fish biomass around Pagan was 0.55 kg 100 m^{-2} (SE 0.16), below the average for the northern islands of the Mariana Archipelago. Sharks accounted for > 20% of overall large-fish biomass in each of the 3 MARAMP survey years, and benthic dwelling species like whitetip reef sharks and tawny nurse sharks were the most abundant. Snappers also were common, and the twinspot snapper was the major snapper species by biomass in each survey period.

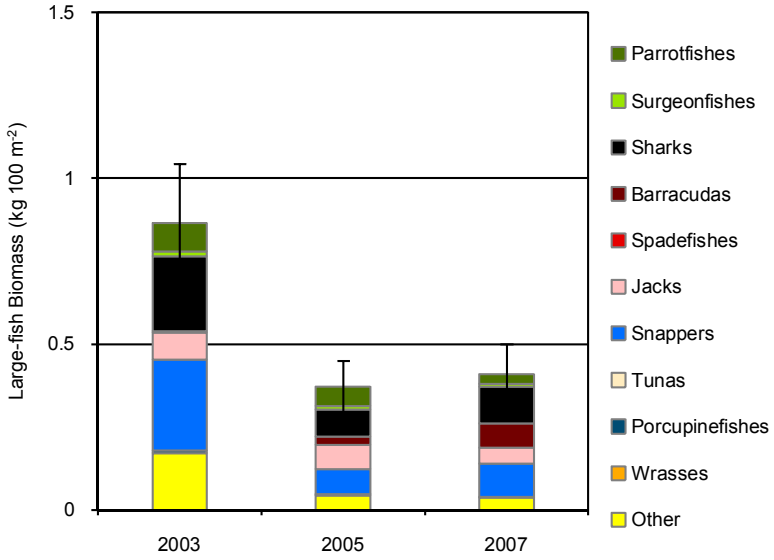


Figure 13.8.1d. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Mean total fish biomass for the 7 REA sites surveyed in forereef habitats at Pagan during MARAMP 2003 was 7.52 kg 100 m^{-2} (SE 3.01). The highest biomass of 25.07 kg 100 m^{-2} was observed at PAG-03 in the north region near Tarage, where 3 whitetip reef sharks were observed. The other sites surveyed at this island had more similar values of 2.03–7.37 kg 100 m^{-2} (Fig. 13.8.1e). Nearly half of the total fish biomass at PAG-03 consisted of snappers and reef sharks. Snappers accounted for the greatest proportion (34%) of total fish biomass at Pagan. The twinspot snapper contributed 69% to snapper biomass and 2.04 kg 100 m^{-2} to total fish biomass. Reef sharks accounted for the second-greatest proportion (13%) of total fish biomass; the whitetip reef shark was the only shark species observed and contributed 1.01 kg 100 m^{-2} to total fish biomass. Surgeonfishes (Acanthuridae) were also common. There was evidence of a large recruitment of orangespine unicornfish (*Naso lituratus*), which accounted for the greatest proportion (33%) of surgeonfish biomass and 0.43 kg 100 m^{-2} of total fish biomass. Many newly recruited orangespine unicornfish appeared to be frail and in a compromised state. At some REA sites, numerous individuals were dead and littered across the seabed.

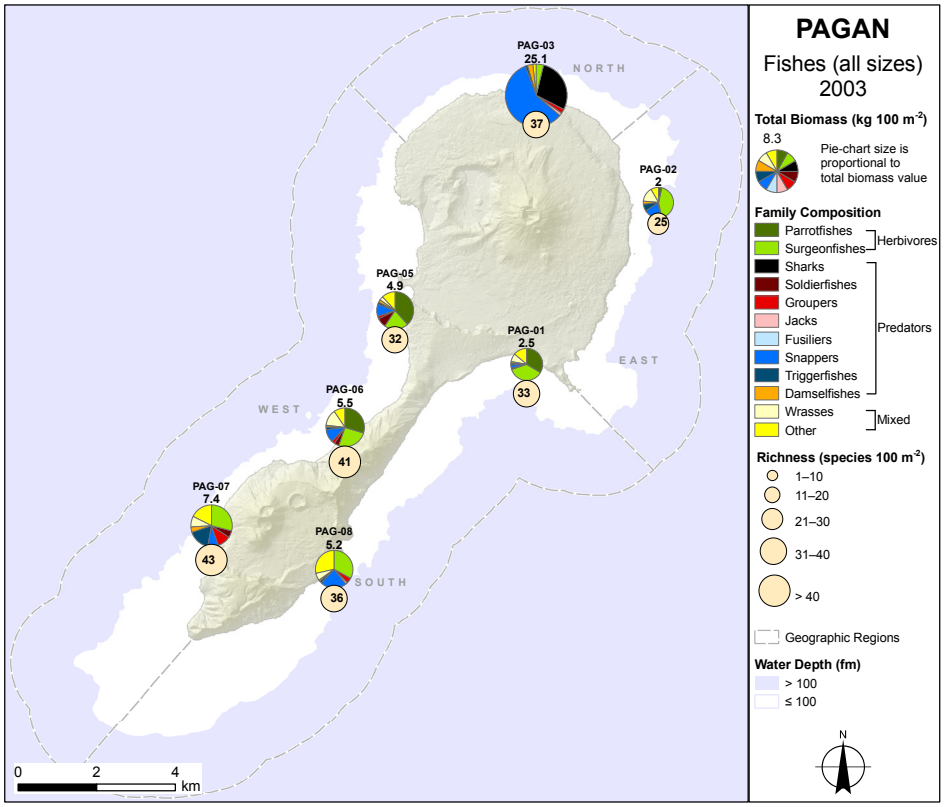


Figure 13.8.1e. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Pagan during MARAMP 2003.

Based on REA surveys conducted during MARAMP 2003, species richness at Pagan ranged from 25 to 43 species 100 m^{-2}. The lowest diversity was seen at PAG-02 in the east region, and the highest diversity was found at PAG-07 in the west region. Wrasses (Labridae) composed the most represented family with 27 species observed. The ornate wrasse (*Halichoeres ornatissimus*) was the most abundant wrasse species. Damselfishes (Pomacentridae) were the most abundant taxa of fishes overall with the Vanderbilt's chromis (*Chromis vanderbilti*) dominating counts at 18 individuals 100 m^{-2}.

Total fish biomass for the 9 REA sites surveyed in forereef habitats at Pagan during MARAMP 2005, with an overall sample mean of 9.28 kg 100 m^{-2} (SE 1.85), was similar to survey results at this island in 2003. The highest biomass of 19.25 kg 100 m^{-2} was found at PAG-06 in the west region (Fig. 13.8.1f). Surgeonfishes accounted for the largest proportion (37%) of total fish biomass. A small tawny nurse shark (100 cm in TL) was the only shark observed in 2005.

Based on REA surveys conducted during MARAMP 2005, species richness at Pagan was similar to the diversity recorded in 2003 with a range of 19–45 species 100 m^{-2}. The highest diversity in 2005 was found in the north region at PAG-12, which was not surveyed in 2003. The lowest diversity was seen at 2 sites: PAG-03 in the north region and PAG-08 in the south region. Wrasses composed the most represented family with 27 species recorded. Similar to observations made in 2003, the ornate wrasse was the most abundant wrasse species. Damselfishes were the most abundant taxa of fishes overall with the midget chromis (*Chromis acares*) dominating counts at 134 individuals 100 m^{-2}.

Total fish biomass for the 9 REA sites surveyed in forereef habitats at Pagan during MARAMP 2007, with an overall sample mean of 9.90 kg 100 m^{-2} (SE 2.29), was similar to biomass values observed in 2003 and 2005. The highest biomass of 25.19 kg 100 m^{-2} was found at PAG-12 in the north region, and the lowest biomass of 3.31 kg 100 m^{-2} was seen at site PAG-03, near Tarage and also in the north region (Fig. 13.8.1g). Similar to observations made in 2005, surgeonfishes accounted for the largest proportion (38%) of total fish biomass. The orangespot surgeonfish (*Acanthurus olivaceus*) accounted for the greatest proportion (37%) of surgeonfish biomass and 1.74 kg 100 m^{-2} of total fish biomass. The orangespine unicornfish also was common, accounting for the second-greatest proportion (18%) of surgeonfish biomass. Sharks were rare with 1 whitetip reef shark observed at PAG-11 in the west region.

Based on REA surveys conducted during MARAMP 2007, species richness at Pagan was similar to the diversity recorded in 2003 and 2005 with a range of 26–48 species 100 m^{-2}. The site with the highest species diversity in 2007, PAG-12 in the north region, also had the highest diversity in 2005. This site also had the highest total fish biomass in 2007. The lowest

diversity was seen in the south region at PAG-08, although this site had the second-greatest total fish biomass. Wrasses composed the most represented family with 29 species recorded. Consistent with observations made in 2003 and 2005, the ornate wrasse was the most abundant wrasse species observed in 2007 with 10 individuals 100 m^{-2}. Damselfishes were the most abundant taxa of fishes with the midget chromis again dominating counts with 87 individuals 100 m^{-2}.

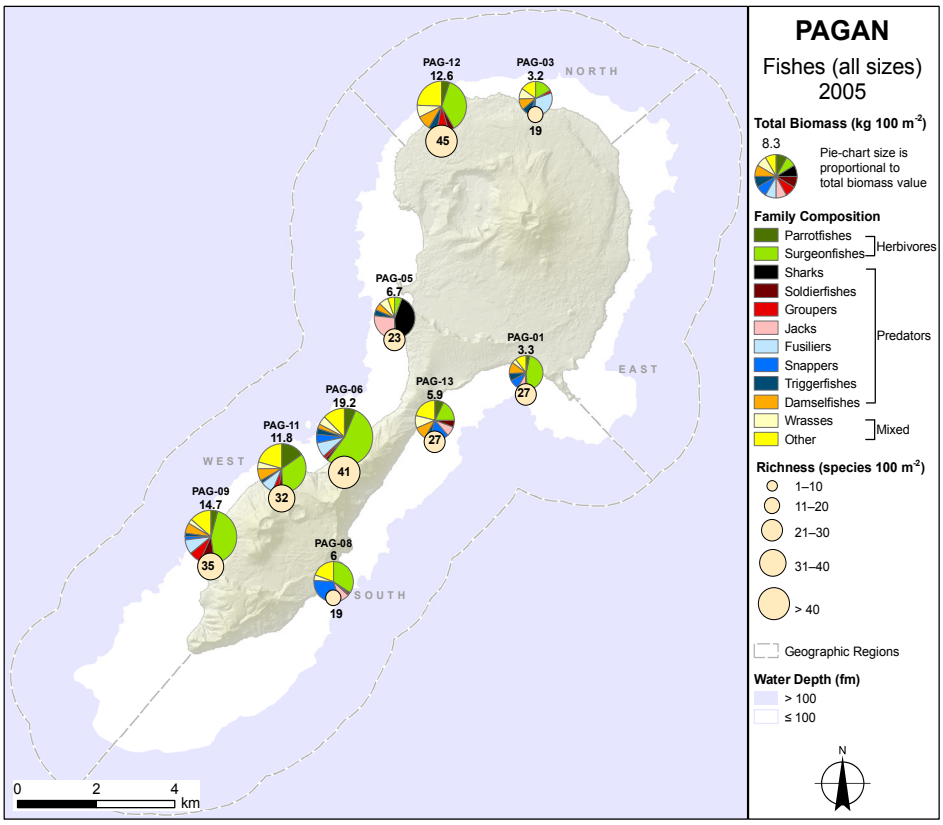


Figure 13.8.1f. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Pagan during MARAMP 2005.

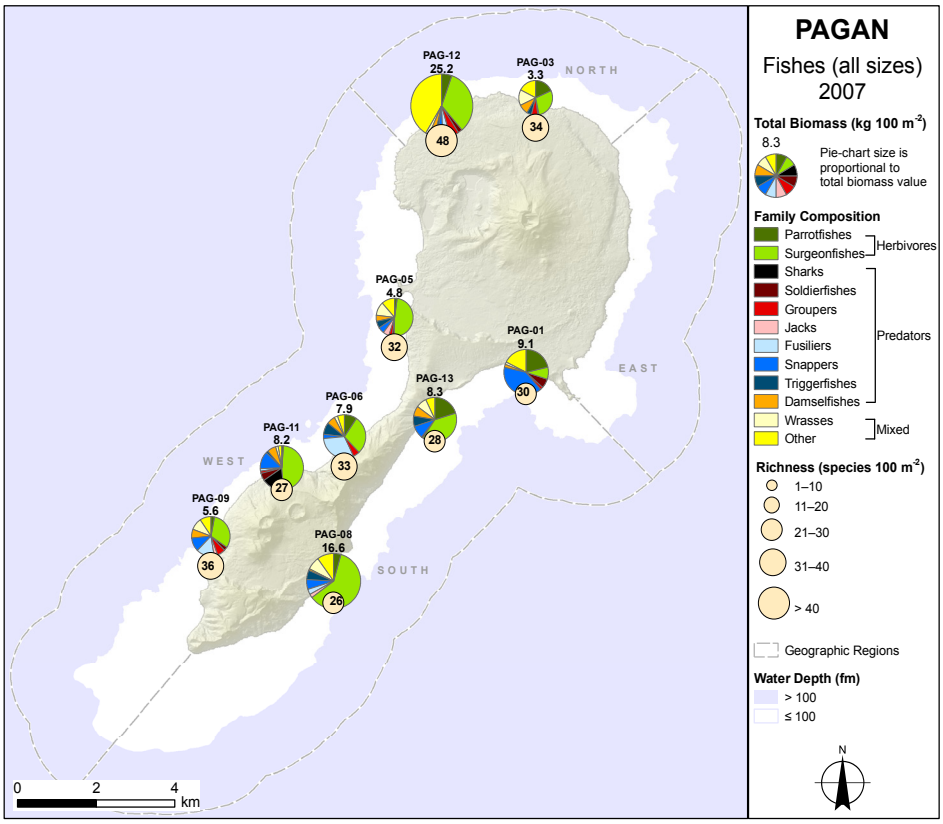


Figure 13.8.1g. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Pagan during MARAMP 2007.

Total fish biomass for all REA sites surveyed at Pagan was consistently high (Fig. 13.8.1h) across the 3 MARAMP years, relative to biomass values observed at other islands in the Mariana Archipelago. Surgeonfishes accounted for the greatest proportion (nearly 40%) of overall total fish biomass from surveys conducted in 2005 and 2007. In 2003, however, fish biomass was dominated by snappers and reef sharks; 3 whitetip reef sharks were observed at PAG-03 in the north region near Tarage. Overall total fish biomass for Pagan, averaged across the 3 survey periods, was 8.90 kg 100 m^{-2} (SE 0.71), more than 3 times the observed biomass values for Guam and Saipan and slightly lower than average for the unpopulated islands of the Mariana Archipelago.

Species richness at Pagan was similar in the 3 MARAMP survey years, with an overall mean of 32.6 species 100 m^{-2} (SE 1.6).Wrasses compopsed the most represented family in each of the 3 survey periods with an average of 27 species recorded per year. The ornate wrasse was consistently the most abundant wrasse species observed. Damselfishes were the most abundant taxa of fishes overall, and the midget chromis and Vanderbilt's chromis were the most abundant damselfish species recorded over the 3 survey years.

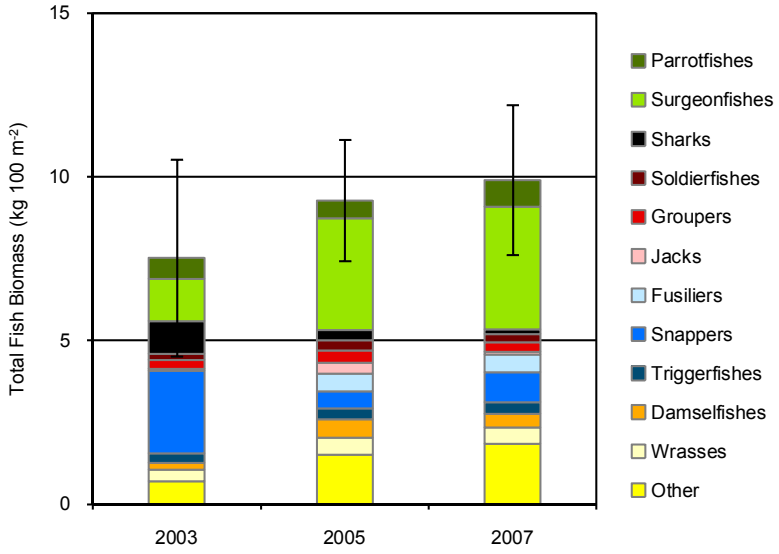


Figure 13.8.1h. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Pagan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

13.9 Marine Debris

13.9.1 Marine Debris Surveys

During MARAMP 2003, 5 sightings of man-made objects and 2 sightings of wrecks were recorded in the 21 towed-diver surveys conducted on forereef habitats around the island of Pagan (Fig. 13.9.1a). Three anchors were observed adjacent to Marasu just north of the border between the north and west regions (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"). An unidentified aluminum structure and a shipwreck were recorded at 2 separate locations along Bandera Peninsula in the west region. An additional wreck, with propeller, engine, and anchor chain, was noted in the west region along this island's isthmus. Farther south in the west region, an unidentified steel object was observed north of Periiruu. No munitions or derelict fishing gear were identified in 2003.

During MARAMP 2005, no marine debris sightings were recorded in the 17 towed-diver surveys conducted on forereef habitats around Pagan.

During MARAMP 2007, 1 sighting of derelict fishing gear and 1 sighting of a wreck were recorded in the 16 towed-diver surveys conducted on forereef habitats around Pagan (Fig. 13.9.1b). One net was noted in the south region along this island's isthmus. A small wreck was recorded in a sandy area of low habitat complexity along Bandera Peninsula in the west region. No additional descriptive information was recorded, aside from the observation that live corals and algae were established on the wreck. No munitions or other man-made objects were identified in 2007.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational

methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments. Still, the location of the shipwreck sighting near Bandera Peninsula was the same in 2003 and 2007.

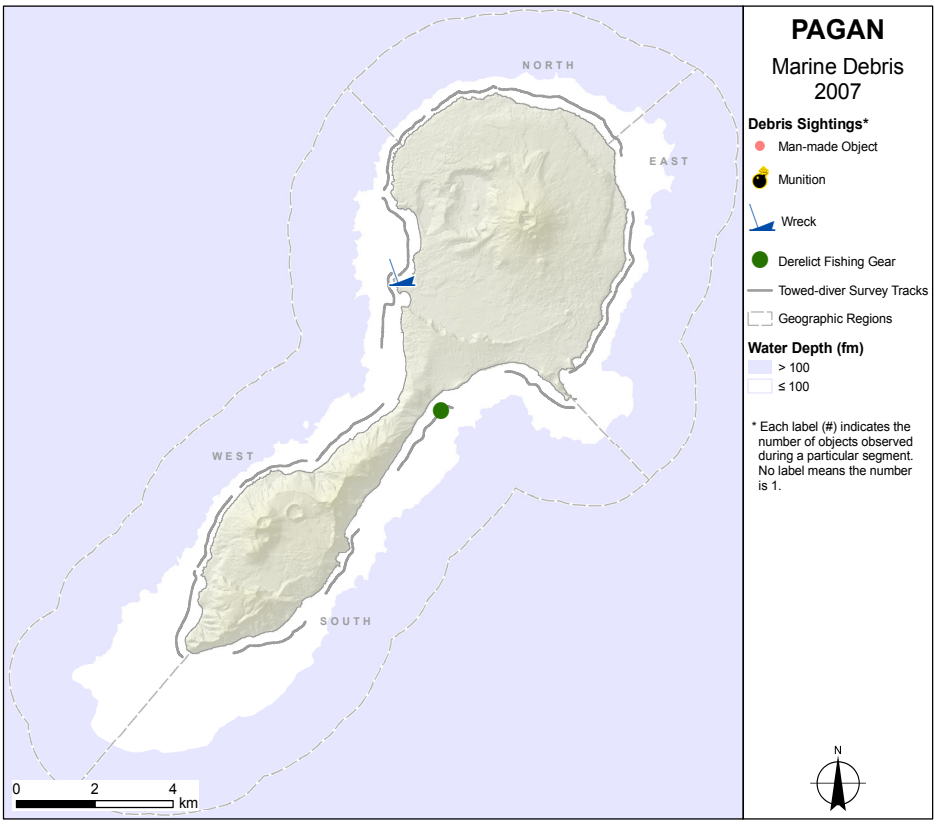


Figure 13.9.1b. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2007. Symbols indicate the presence of specific debris types.

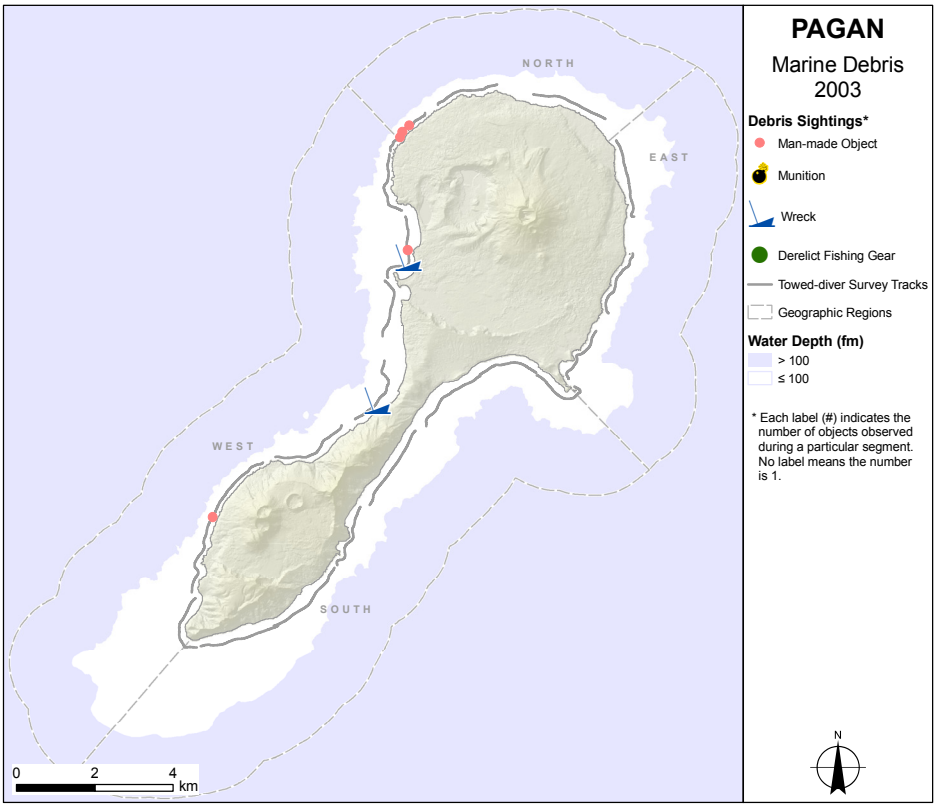


Figure 13.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Pagan during MARAMP 2003. Symbols indicate the presence of specific debris types.

13.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Pagan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations on an archipelagic scale of different ecosystem elements and their potential relationships across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Pagan as well as the other 13 islands covered in this report.

Pagan is one of the most volcanically active islands in the Mariana Archipelago, and recent volcanic activity undoubtedly has shaped the submarine habitats surrounding this island. The seascape around Pagan reflects the onshore topography, which is dominated by Mount Pagan in the north and a smaller volcano in the south (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort").

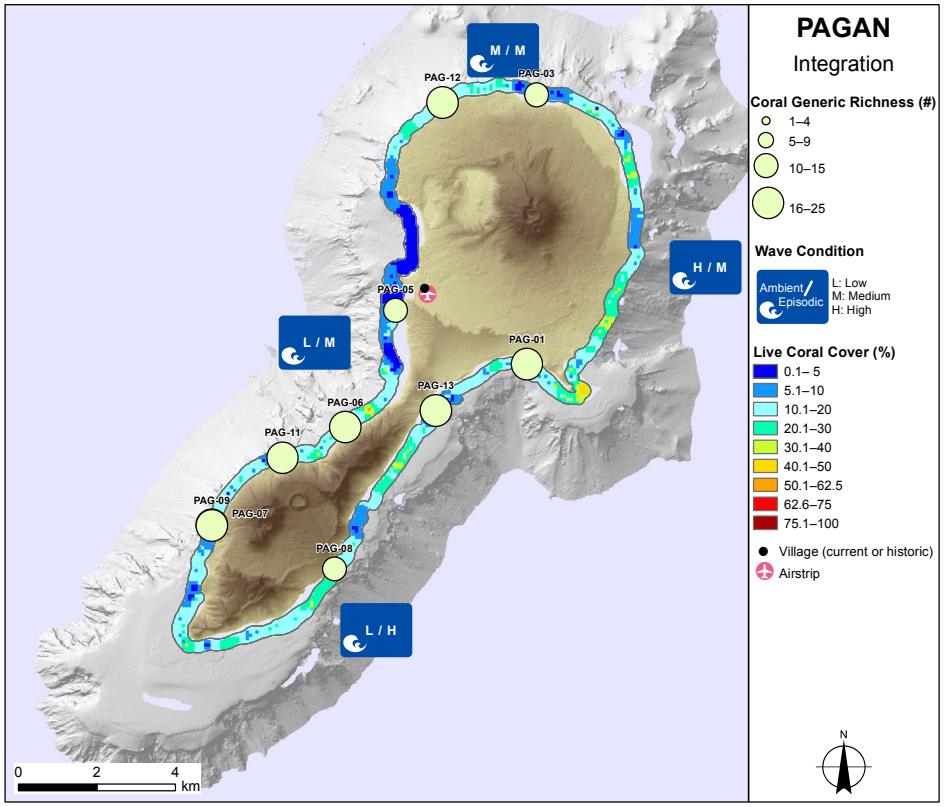


Figure 13.10a. Observations of live-hard-coral cover (%) from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Pagan during MARAMP 2003, 2005, and 2007. Values of coral cover represent interpolated values from the 3 MARAMP survey years, and generic-richness values represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.

The geology of northern Pagan is characterized by lava flows and deposits from different eruptive events. The largest known eruption occurred in 1981, but ongoing volcanic activity has included eruptions in 2006 and 2010 and gas discharges in subsequent years. In the north, bathymetry reveals the flanks of Mount Pagan steeply sloping to depths > 2000 m (see Figure 13.3.1a in Section 13.3.1: "Acoustic Mapping"). Numerous ridges and pinnacles also are present on these slopes. Towed-diver surveys reported spur-and-groove habitat and continuous reef with cover of live hard corals within a range of 0%–30% (Fig. 13.10a). South of Mount Pagan, the reef area around the tip of the Sengao Peninsula near Togari Rock supported the highest coral cover in 2003, within a range of 40.1%–62.5% over 8 segments (see Figure 13.5.1a in Section 13.5.1: "Coral Surveys"). During MARAMP 2005 and 2007, in this area stressed-coral cover > 10% was observed (Figs. 13.5.1c and e) and COTS were fairly common (Fig. 13.10b; see also Figures 13.7.1f and g in Section 13.7: "Benthic Macroinvertebrates"). No clear difference in total fish biomass between the southeastern coast and other areas at Pagan was observed from REA surveys for fishes of all species and sizes (see Figures 13.8.1e, f, and g in Section 13.8.1: "Reef Fish Surveys").

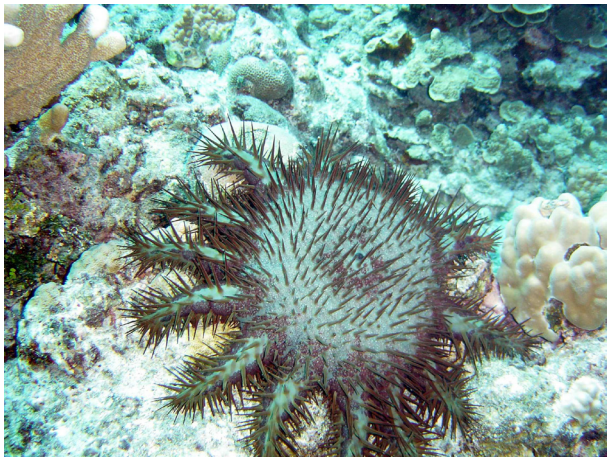


Figure 13.10b. A crown-of-thorns seastar (*Acanthaster planci*) preying on corals at Pagan. *NOAA photo by Robert Schroeder*

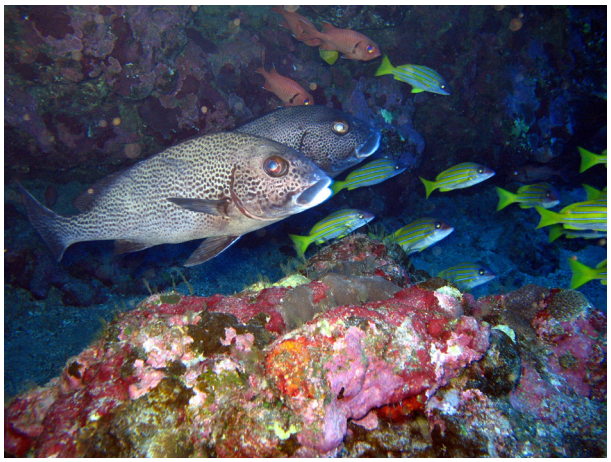


Figure 13.10c. Reef fishes, (*left to right*) the painted sweetlip (*Plectorhinchus picus*), blotcheye soldierfish (*Myripristis* berndti), and common bluestripe snapper (*Lutjanus kasmira*), observed during a survey conducted at Pagan. *NOAA photo by Danny Merritt*

One area west of Mount Pagan was distinctive with a habitat characterized as low complexity and soft sediment that supported very little live coral cover or macroalgal cover (see Figures 13.3.3a and c in Section 13.3.3: "Habitat Characterization" and Figure 13.6.1a in Section 13.6.1: "Algal Surveys"). This area, inside a bay north of Bandera Peninsula, is located just downslope from 2 lakes formed in craters west of Mount Pagan, and, thus, onshore topography provides a possible conduit for transport of sediments there.

Large-fish biomass in the north region and the northern part of the west region, assessed using towed-diver surveys, was fairly similar overall to the biomass values observed in other regions around Pagan. The highest biomass of large fishes found during the 3 MARAMP survey years was from a single survey conducted in 2003 in the northern part of the west region (see Figure 13.8.1a in Section 13.8.1: "Reef Fish Surveys"). Data from REA fish surveys suggested high levels of total fish biomass in the north region, compared to other areas surveyed at Pagan. The highest mean biomass in 2003 was seen at REA site PAG-03 near Tarage in the north region, and the highest mean biomass in 2007 was observed at PAG-12, also in the north region (Fig. 13.10c and Figs. 13.8.1e and g).

A narrow isthmus separates Mount Pagan in northern part of Pagan from the smaller volcano in the southern part. On either side of this isthmus, towed-diver surveys found moderately complex, hard substrate habitat that supported moderate amounts of live coral cover relative to other areas surveyed around Pagan (see Figures 13.3.3a and c in Section 13.3.3: "Habitat Characterization"). The levels of coral-colony density recorded during REA benthic surveys on either side of this isthmus (at sites PAG-06 and PAG-13) also were moderate during the 3 MARAMP survey years, compared to other sites surveyed at this island (see Figures 13.5.1b, d, and f in Section: 13.5.1: "Coral Surveys"). East of this isthmus, a shallow shelf forms one of the two anchorage areas at Pagan (see Figure 13.3.1b in Section 13.3.1: "Acoustic Mapping"); the other is located west of this isthmus. Relatively high live coral cover, within a range of 50.1%–62.5%, was recorded during a single segment of the towed-diver survey conducted along the narrowest portion west of Pagan's isthmus in both 2005 and 2007 (Figs. 13.5.1c and e). This high cover value was attributed to a large field of *Euphyllia ancora* and *Porites rus* observed during the survey. Surrounding areas did not support the same level of live coral cover but instead exhibited the low coral cover typically found around much of Pagan, relative to the rest of the Mariana Archipelago.

The bathymetry around southern Pagan is similar to the bathymetry around the northern part of this island, with steep slopes descending to depths > 3000 m as well as ridges and pinnacles (see Figure 13.3.1a in Section 13.3.1: "Acoustic Mapping"). A large, shallow shelf in the south region extends southwest ~ 3 km from South Point (Fig. 13.3.1c). Mound-like features on this shallow shelf suggest the presence of coral reef habitats; however, the optical-validation data collected on this shelf are insufficient for verifying this possibility. TOAD surveys conducted east of this shelf at depths of 30–40 m suggested low coral cover of 20% in some areas, but these surveys were not extensive (Fig. 13.3.3c). Some of the highest levels of coral-colony density recorded during the 3 MARAMP survey years were seen at PAG-07 and PAG-09, in the southern part of the west region, with 45–56 colonies m^{-2} (see Figures 13.5.1b, d, and f in Section: 13.5.1: "Coral Surveys"). Values of coral cover observed during both REA and towed-diver surveys in this area were low relative to averages recorded around Pagan. Total fish biomass from REA surveys off the southern coasts of Pagan was similar to the total fish biomass values found in other survey areas at Pagan.

Overall, values of coral cover recorded around Pagan were low to moderate in comparison to levels seen at other islands in the Mariana Archipelago. No clear spatial patterns were observed for live coral cover around Pagan across the 3 survey years, other than the near absence of corals in the bay north of Bandera Peninsula. Hydrographic surveys conducted in 2005 and 2007 revealed temperature, salinity and density values that were lower in the east and south regions of Pagan than in the west and north regions. Such a strong east–west pattern was not reflected in surveys of benthic communities around Pagan. Patches of high coral cover were observed relatively infrequently and often not recorded in the same place during different survey years, probably as a result of differences in survey locations and depth between years. Effects of COTS predation may have masked other natural factors in the observed variability in coral distribution around Pagan. COTS were observed in high abundance, compared survey results from the rest of the Mariana Archipelago, in many areas around Pagan in both 2005 and 2007.

13.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Pagan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Pagan chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Pagan, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Pagan as well as some of the key natural processes and anthropogenic activities influencing these ecosystems (for place-names and their locations, see Figure 13.2a in Section 13.2: "Survey Effort"):

- Pagan was formed by 2 large volcanoes, which are separated by a narrow isthmus. With a land area of 47 km^2, it is the fourth largest island of the CNMI.

- Human habitation on Pagan has been sporadic and mainly seasonal since the evacuation of this island's residents in 1981 after the largest documented volcanic eruption of Mount Pagan occurred.

- The seascape around Pagan reflects the onshore topography, which is dominated by Mount Pagan in the north and a second, smaller volcano in the south. Bathymetry reveals the steeply sloping flanks of Mount Pagan descending to depths > 2000 m. Numerous ridges and pinnacles also are present on these slopes. Bathymetry is similar in southern Pagan, with steep slopes descending to depths > 3000 m.

- Habitats in the north and east regions were characterized, during towed-diver surveys conducted at depths of ~ 14 m, as fairly complex with hard substrate. Limited optical data from TOAD surveys, conducted at depths of 50–100 m, suggested mainly hard substrates with patchy sand cover. Analyses of video footage from these TOAD surveys show very little live coral cover, with live corals observed only in isolated video frames.

- In the northern parts of the south and west regions, low-complexity and soft-sediment habitats supported very little live coral cover. On either side of this island's narrow isthmus, habitats were moderately complex and characterized as hard substrate with moderate amounts of live corals. Around South Point, sand cover was more common and habitat complexity lower than in other areas around Pagan. South of Pagan, analyses of TOAD video footage obtained at depths of 15–100 m suggest only few live corals, with estimates of 20% coral cover for some video frames at depths up to ~75 m.

- Wave model output shows that ambient trade wind swells impacted the east and, to a lesser extent, the north. Episodic wave energy from storm tracks impacted the south and, to a lesser extent, the west, north, and east.

- In situ SST data from a buoy deployed off Bandera Peninsula show that water temperatures there rose above the coral bleaching threshold in August 2005. Given the relatively short duration and small magnitude of this period of elevated temperature, widespread mass coral bleaching was unlikely.

- Islandwide mean coral cover from towed-diver surveys during the 3 MARAMP survey years ranged from 10% to 19%. Estimates of live coral cover from the 9 REA sites surveyed at Pagan in 2007, using the line-point-intercept method, ranged from 3.9% to 20.6% with an overall sample mean of 10.6%. The highest coral cover was seen on either side of this island's isthmus at PAG-13 (20.6%) and PAG-06 (16%).

- Coral disease surveys, conducted using the belt-transect method at 9 REA sites around Pagan in 2007, detected 28 cases of coral disease. Overall mean prevalence of coral disease was 0.02%. Fungal infections, accounting for 90% of disease cases recorded at Pagan, and other syndromes of unknown etiology, contributing 10% of cases found, were identified at only 3 of the sites surveyed. More than 95% of the afflictions involving fungal infections were observed on corals of the genus *Cyphastrea*.

- Overall mean macroalgal cover for Pagan, based on towed-diver surveys, was essentially the same in 2005 (18%) and 2007 (17%). The greatest variability between these survey years occurred in the survey area west of Tarage in the north region with a 43% decrease in macroalgal cover. Also, macroalgal cover near Hira Rock in the east region decreased from 32% to 9% between these survey years. In the south region, near Piarama, a large increase in macroalgal cover from 7% to 39% was observed between the same survey periods.

- Between MARAMP 2003 and 2007, islandwide mean crustose-coralline-red-algal cover increased 7%, based on towed-diver surveys. Coralline-algal disease was found in 2007 at only one REA site, PAG-01 east of Degusa in the south region. Two cases of a single affliction, coralline lethal orange disease, were enumerated at this site.

- The overall mean biomass of large fishes from towed-diver surveys was highest in 2003 with 0.87 kg 100 m^{-2}; biomass values were 0.37 kg 100 m^{-2} in 2005 and 0.41 kg 100 m^{-2} in 2007. The lower levels observed in 2005 and 2007 reflect a decline in sightings of sharks and snappers in those years.

- From REA surveys of fishes of all sizes and species, the overall mean total fish biomass for Pagan across the 3 survey periods, at 8.90 kg 100 m^{-2}, was a little lower than the average observed for the unpopulated islands but more than 3 times the biomass values found around Guam and Saipan.

- Giant clams were observed at low levels of abundance around Pagan during the 3 MARAMP survey periods. Sea cucumbers were uniformly distributed around Pagan at moderate daytime densities, relative to survey results from other islands of Mariana Archipelago.

- Based on towed-diver surveys, COTS were virtually non-existent in 2003. During MARAMP 2005, observed COTS densities were much higher than levels recorded in 2003. In several localized areas in all regions around Pagan, COTS densities were high enough to suggest that they may have been experiencing a COTS outbreak. By 2007, population densities had decreased; however, localized areas in the west, south, and east regions had densities suggesting possible outbreaks.

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14 AGRIHAN

14.1 Introduction

The island of Agrihan is located at 18°46′ N, 145°40′ E in the northern part of the Mariana Arc, 65 km north of Pagan and 100 km south of Asuncion. Also known as Agrigan and Grigan, this island is ~ 10 km wide and 7 km long, has a land area of 44.05 km^2, and is one of the largest islands of the Commonwealth of the Northern Mariana Islands (CNMI). The part of Agrihan that is visible above the ocean is the exposed part of a large volcano that rises 4000 m from the surrounding seafloor and is the second-largest volcano of the Mariana Archipelago (Fig 14.1a). Agrihan's summit, at an elevation of 965 m, is the highest point in the CNMI and is surrounded by steep slopes. These slopes are cut by narrow ridges and ravines with occasional volcanic dikes, and many coastal areas are bordered by steep cliffs (Fig 14.1b).

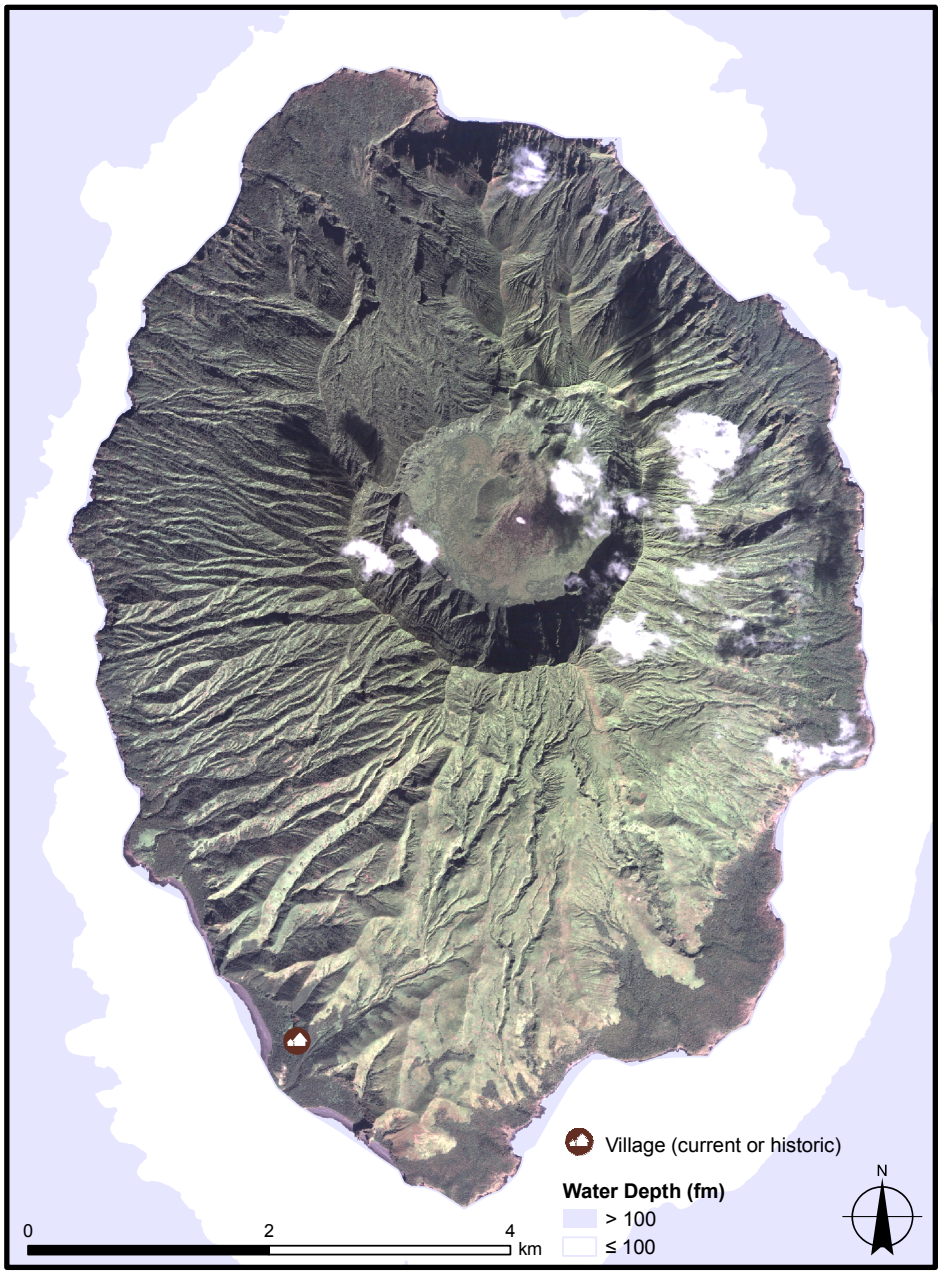


Figure 14.1a. Satellite image of Agrihan, labeled with the village where the only permanent human population north of Saipan in the Mariana Archipelago may reside (© 2005 DigitalGlobe Inc. All rights reserved).



Figure 14.1b. Agrihan as seen from the NOAA Ship *Hi'ialakai* in 2009. *NOAA photo*

14.1.1 History and Demographics

Historically, Agrihan was inhabited by the Chamorro people and notably the site of the last stand of the Chamorro against Spain. In 1810, colonists from Hawai`i and the United States attempted to establish plantations on Agrihan but were expelled from this island by Spain (Encyclopædia Britannica 2009). In 1909, while under administration by Germany, Agrihan (along with Farallon de Pajaros, Maug, Asuncion, Guguan, Sarigan, and Farallon de Medinilla) was leased to the Pagan Gesellschaft, a trading association, for exploitation of bird plumage for a period of 3 years (Spennemann 1999b). During this time, Japanese bird catchers employed on these islands may have been temporarily resident on Agrihan.

Inhabitation has been sporadic during the 20th and 21st centuries, including a U.S. military camp at one time. Volcanic activity, in both 1917 and 1990, prompted evacuation of this island's inhabitants as a precaution against more significant eruptions (Siebert and Simkin 2002–). Subsequently, on southwestern Agrihan, 1 of the 4 original villages has been re-inhabited; Agrihan is thought to have the only permanent human population north of Saipan, although this population is small (Cruz et al. 2000). During surveys conducted by the CNMI Division of Fish and Wildlife in 2000, 6 permanent residents were observed (Cruz et al. 2000). Agrihan is part of the Northern Islands Municipality of the CNMI. For this municipality, the 2000 U.S. Census recorded an official population of 6 persons, but the 2010 U.S. Census recorded no persons (U.S. Bureau of the Census 2003, 2011a).

Resettlement of Agrihan has been encouraged by the CNMI government through the *Northern Islands Homestead Act of 2008* (CNMI Public Law 16-50), which recognizes that residents of the "islands north of Saipan" have no formal homesteads, allows them to have agricultural lots and facilities, and initiates and promotes economic development. The anticipated resettlement of this island may involve increased agriculture, although cultivation would be limited because of the steep slopes and shallow soils of this island.

14.1.2 Geography

The elongated volcanic crater (1 × 2 km) is breached to the northwest, where lava flowed, extending to the coastline and forming a lava delta. This lava flow is shown on the slope map, where it contrasts with the otherwise steep ridges and ravines that dominate Agrihan's topography (Fig. 14.1.2a). The caldera floor contains relatively recent lava flows and 2 cones that may have formed during an eruption in 1917 (Siebert and Simkin 2002–).

The only recorded eruption at Agrihan occurred in 1917 and resulted in the deposition of large blocks of material and volcanic ash on a village located on the southeastern coast. Subsequent volcanic activity has been at a low level, although fumarolic and thermal activity was recorded in 1990 and 1992 (Siebert and Simkin 2002–).

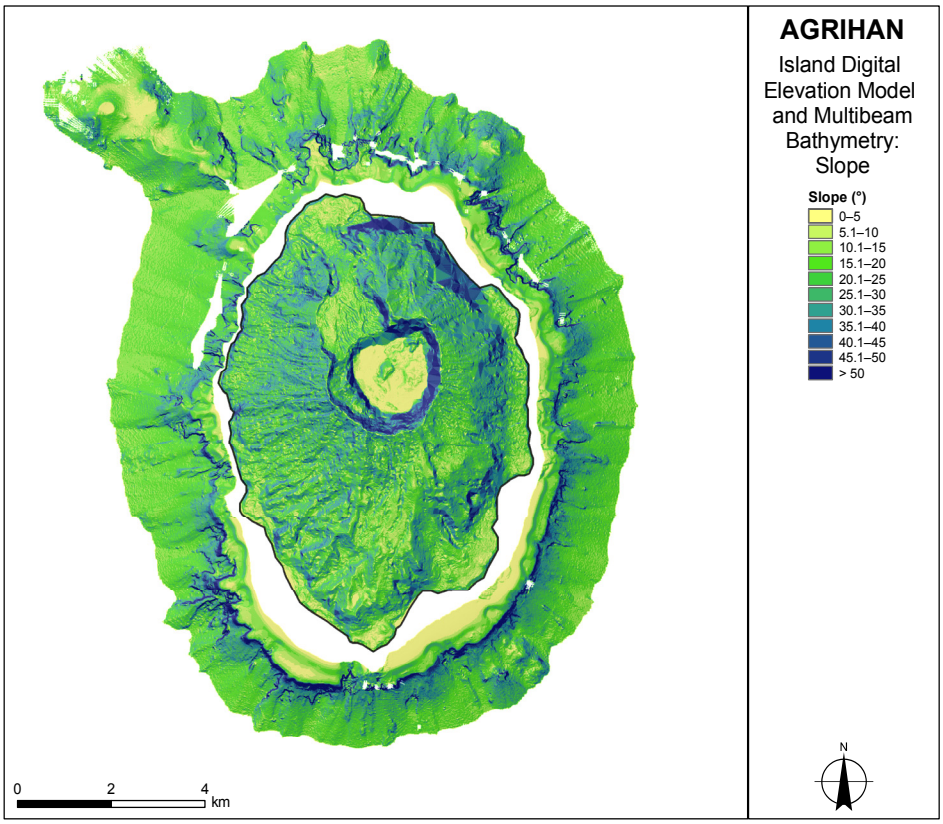


Figure 14.1.2a. Combined slope map using the digital elevation model and multibeam bathymetric data for Agrihan (grid cell size: 10 m).

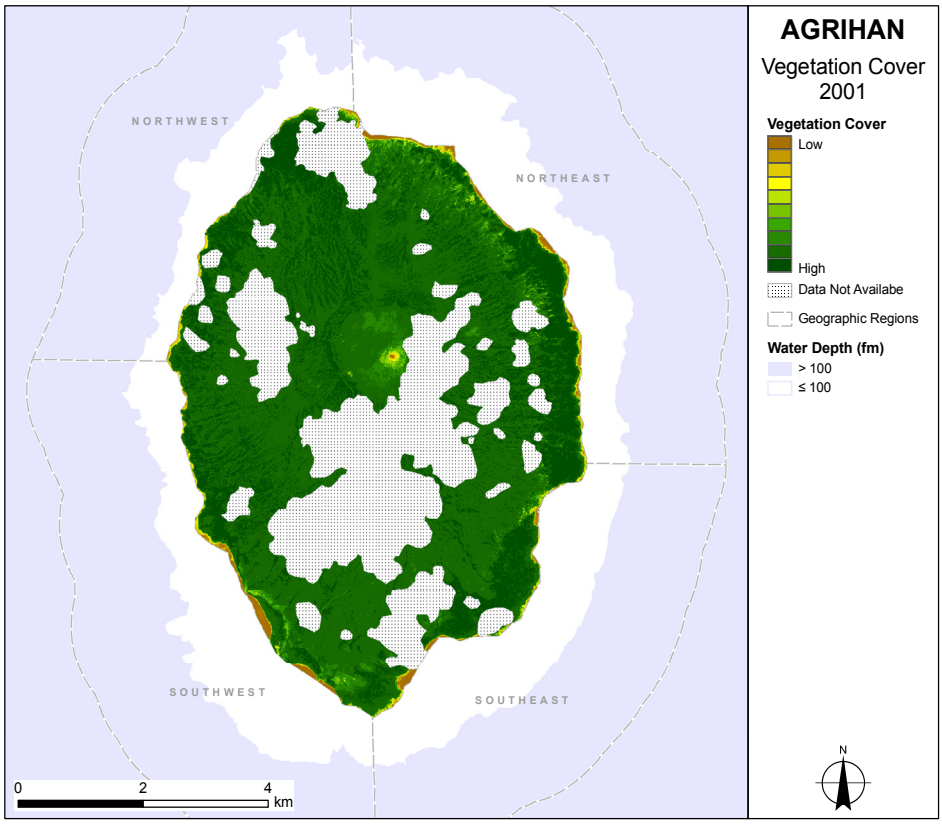


Figure 14.1.2b. Vegetation cover on Agrihan, derived using the Normalized Difference Vegetation Index from a satellite image (grid cell size: 4 m; IKONOS Carterra Geo Data, 2001). Hatched lines indicate areas where data are not available because cloud cover obscures the satellite image.

Geologically, Agrihan is dominated by volcanic deposits, composed largely of loose ash with some interbedded basaltic flows (Mueller-Dombois and Fosberg 1998). Occasional volcanic dikes also are present on the slopes (Cruz et al. 2000).

The majority of this island is vegetated (Fig. 14.1.2b) with vegetation complexes that are typical of the volcanic islands of the CNMI. Steep ash slopes are colonized predominantly by sword grass, with thickets and woods present in the narrow ravines that cut these slopes. Mixed coconut and native forest is present on the northern part of Agrihan, and coastal beaches and bluffs support mixed thickets and woods. At higher elevations, tree ferns also have been observed (Cruz et al. 2000, Mueller-Dombois and Fosberg 1998). As on many other islands that have been subject to human colonization, most of the flat areas of this island have been planted with coconuts. Other cultivated trees also are present in areas that were farmed during administration by Japan. In addition to the introduction of these non-native species, the vegetation on Agrihan has been affected by human activity, such as the clearing of large hillside areas by U.S. military personnel formerly stationed on this island (Cruz et al. 2000). Further damage to native forests has resulted from feral animals, which have caused reduction in the forest understory and erosion (Cruz et al. 2000).

Information regarding the distribution of groundwater resources around Agrihan is not available, and surface water is thought to be absent except during rainy weather (Mueller-Dombois and Fosberg 1998).

14.1.3 Environmental Issues on Agrihan

One of the main environmental concerns on Agrihan is the impact of feral animals on its native forests. Grazing by feral animals, such as pigs and goats, has resulted in the destruction of natural vegetation, including removal of the seedling understory and increased erosion (Cruz et al. 2000). Agrihan has areas of mixed and native forest, which are important in providing a habitat for native wildlife. Rats also are present, although the population size is not known, and form a serious threat to the native bird population (Cruz et al. 2000). Agrihan supports a number of forest birds native to Micronesia, including the Micronesian honeyeater (*Myzomela rubrata*) and Micronesian starling (*Aplonis opaca*). Less common are the white tern (*Gygis alba*), white-throated ground dove (*Gallicolumba xanthonura*), which is locally protected from hunting by regulation, and Micronesian megapode (*Megapodius laperouse*), which is listed federally as endangered and locally as threatened or endangered (Cruz et al. 2000; U.S. Fish and Wildlife Service; Berger et al. 2005). Micronesian megapode were found to be rare in bird surveys on Agrihan and were observed in low numbers within areas planned for homestead lots, which could be a cause for concern (Cruz et al. 2000). Agrihan also supports several groups of the Mariana fruit bat (*Pteropus mariannus mariannus*), an endemic subspecies listed federally as threatened (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), with an estimated population of 1000 bats in 2000 (Cruz et al. 2000).

As one of the few islands of the CNMI that has had and may still have a resident, if small, human population, Agrihan does not have the same isolation as do other remote islands. The encouragement of resettlement of Agrihan, along with the associated development of infrastructure that would be required, could affect the natural resources of this island if unmanaged.

14.2 Survey Effort

Biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing the coral reef ecosystems around the island of Agrihan since 2003. The spatial reach and time frame of these surveys are discussed in this section. The disparate areas around this island are often exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around Agrihan are delineated in Figure 14.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around this island. Potential reef habitat is represented by a 100-fm contour shown in white on this map.

Benthic habitat mapping data were collected around Agrihan using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around Agrihan and Pagan with multibeam sonar covered a total area of 2511 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 14.3: “Benthic Habitat Mapping and Characterization.”

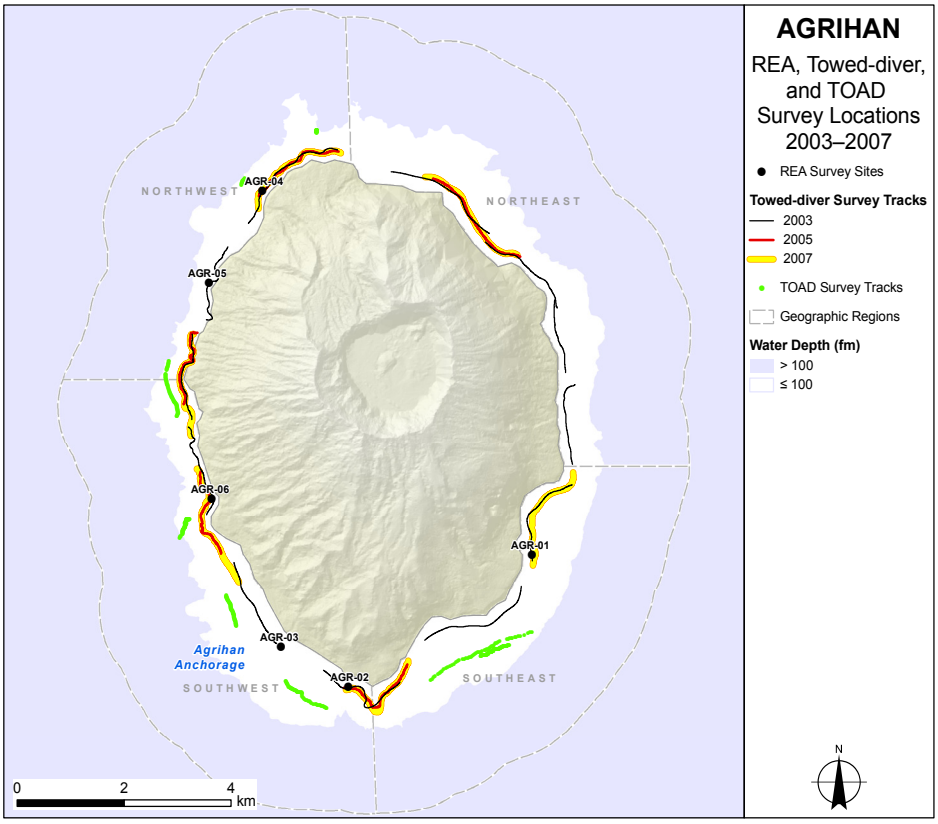


Figure 14.2a. Locations of REA, towed-diver, and TOAD benthic surveys conducted around Agrihan during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 4 geographic regions: northeast, southeast, southwest, and northwest.

Information on the condition, abundance, diversity, and distribution of biological communities around Agrihan was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 14.5–14.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 14.2a, along with their mean depths and total areas or length.

Table 14.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Agrihan during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	6	3	3
	Mean Depth (m)	12.5 (SD 0.8)	12.8 (SD 0.3)	13 (SD 0)
Benthic	Number of Surveys	6	3	3
	Mean Depth (m)	12.5 (SD 0.8)	12.8 (SD 0.3)	13 (SD 0)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	12	5	6
	Total Survey Area (ha)	22.5	9.6	13.1
	Mean Depth (m)	12.6 (SD 1.7)	14.6 (SD 0.9)	14.4 (SD 1.5)
TOAD		**2003**		
	Number of Surveys	8		
	Total Length (km)	5.88		

Table 14.2b. Numbers of STRs deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Agrihan during MARAMP 2003, 2005, and 2007. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

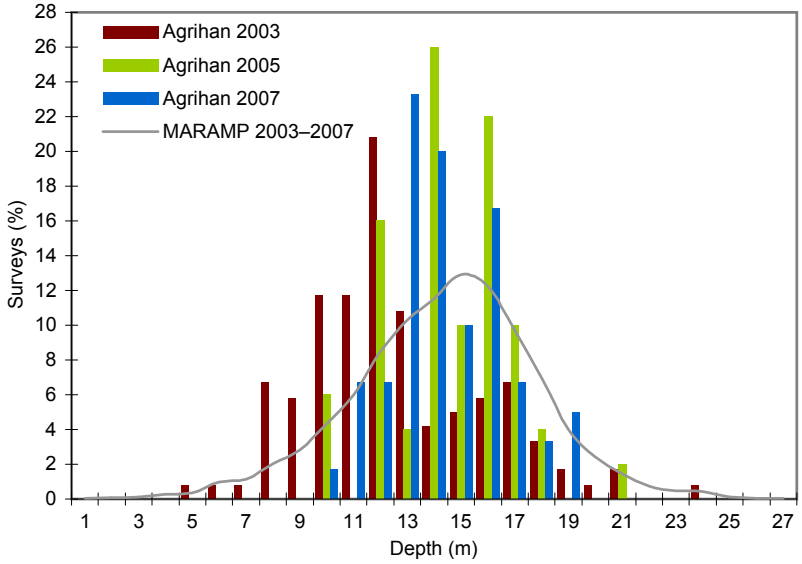
Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
STR	1	1	1	1	1	1	–
CTD Casts	2003	2005		2007			Total
Shallow-water Casts	15	14		15			44
Deepwater Casts	–	3		1			4
Water Samples		2005		2007			Total
		–		3			3

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Agrihan were collected using (1) subsurface temperature recorders (STR) designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water samples were collected during 2007 (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 14.2b, and results are discussed in Section: 14.4: "Oceanography and Water Quality."

Towed-diver Surveys: Depths

Figures 14.2b and c illustrate the locations and depths of towed-diver-survey tracks around Agrihan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

Figure 14.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Agrihan during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005 and 2007.



During MARAMP 2003, 12 towed-diver surveys were conducted along the forereef slopes around Agrihan (Figs. 14.2b and c, top panel). The mean depth of all survey segments was 12.6 m (SD 1.7), and the mean depths of individual surveys ranged from 10.2 m (SD 2.8) to 15.4 m (SD 4).

During MARAMP 2005, 5 towed-diver surveys were conducted along the forereef slopes around parts of Agrihan (Figs. 14.2b and c, middle panel). The mean depth of all survey segments was 14.6 m (SD 0.9), and the mean depths of individual surveys ranged from 13.6 m (SD 2.6) to 15.6 m (SD 1.8).

During MARAMP 2007, 6 towed-diver surveys were conducted along the forereef slopes around most of Agrihan (Figs. 14.2b and c, bottom panel). The mean depth of all survey segments was 14.4 m (SD 1.5), and the mean depths of individual surveys ranged from 12.4 m (SD 2.7) to 16.1 m (SD 2.8).

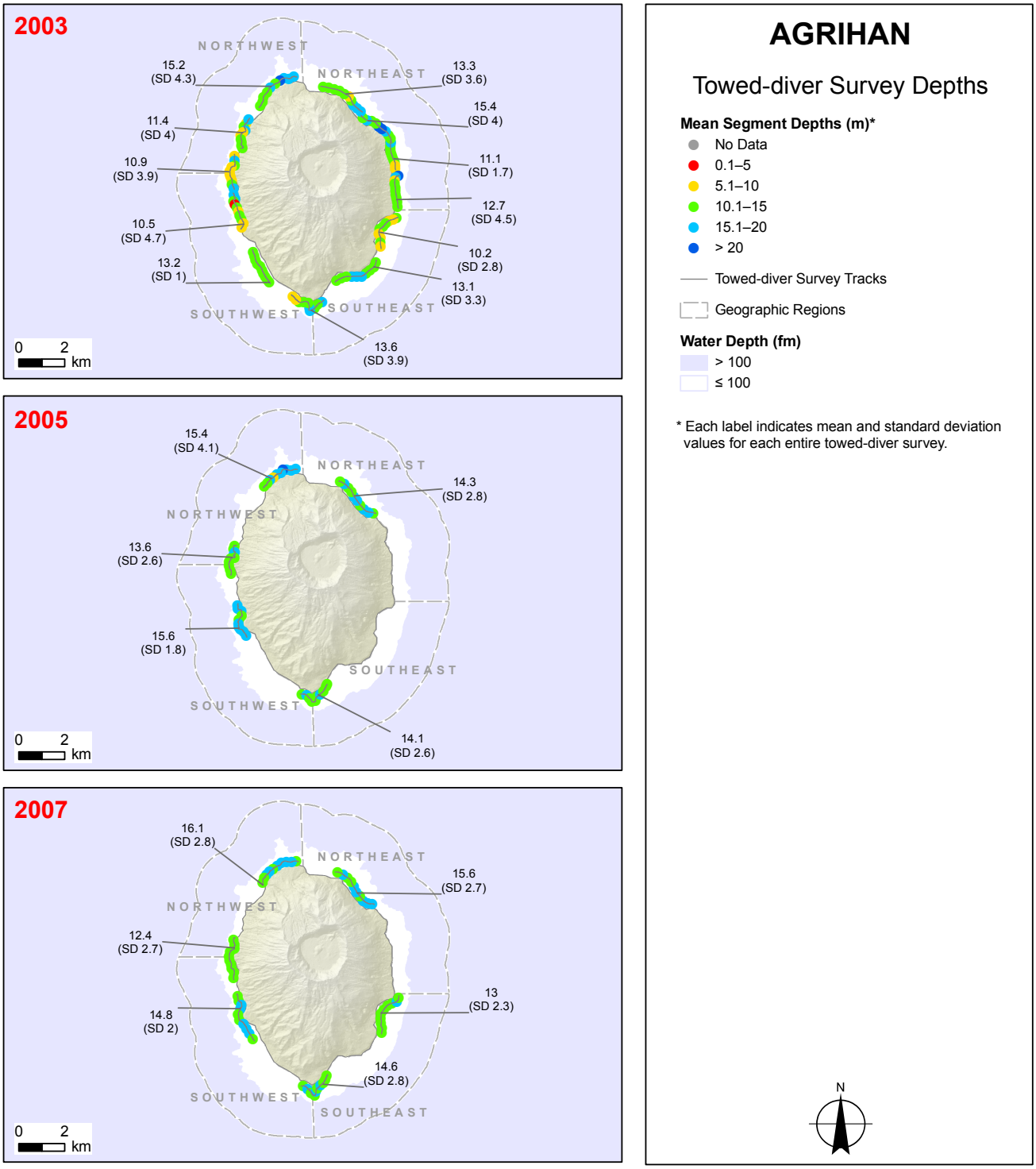


Figure 14.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Agrihan during MARAMP 2003, 2005, and 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

14.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Agrihan were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products from depths of 20–2100 m with almost complete coverage around Agrihan. Optical validation and benthic characterization were conducted in depths of 5–165 m by a combination of diver observation, video analysis, and still image analysis.

14.3.1 Acoustic Mapping

Multibeam bathymetry and backscatter imagery (Fig. 14.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around Agrihan and Pagan during MARAMP 2007 encompasses an area of 2511 km^2.

The multibeam data collected in the deep waters (> 100 m) around Agrihan reveal steep-sided volcanic flanks incised on all sides by submarine channels and canyons (Fig. 14.3.1a, top panel). Blocky material at depths > 500 m primarily was the result of mass wasting (the movement of soil and surface materials by gravity), although some of the larger mounds also may be volcanic in origin. For example, the bathymetric high located ~ 4 km northwest of this island is conical, has a circular peak that reaches a depth of ~ 480 m, and may be a separate volcanic edifice formed on the submarine flanks of Agrihan.

Low-resolution backscatter data acquired around Agrihan show intensity variations that relate to type of seafloor substrate (Fig. 14.3.1a, bottom panel). High-intensity backscatter characterizes the blocks of material present on the submarine flanks and the shallow seafloor adjacent to this island, suggesting areas composed of hard substrate. Around southern

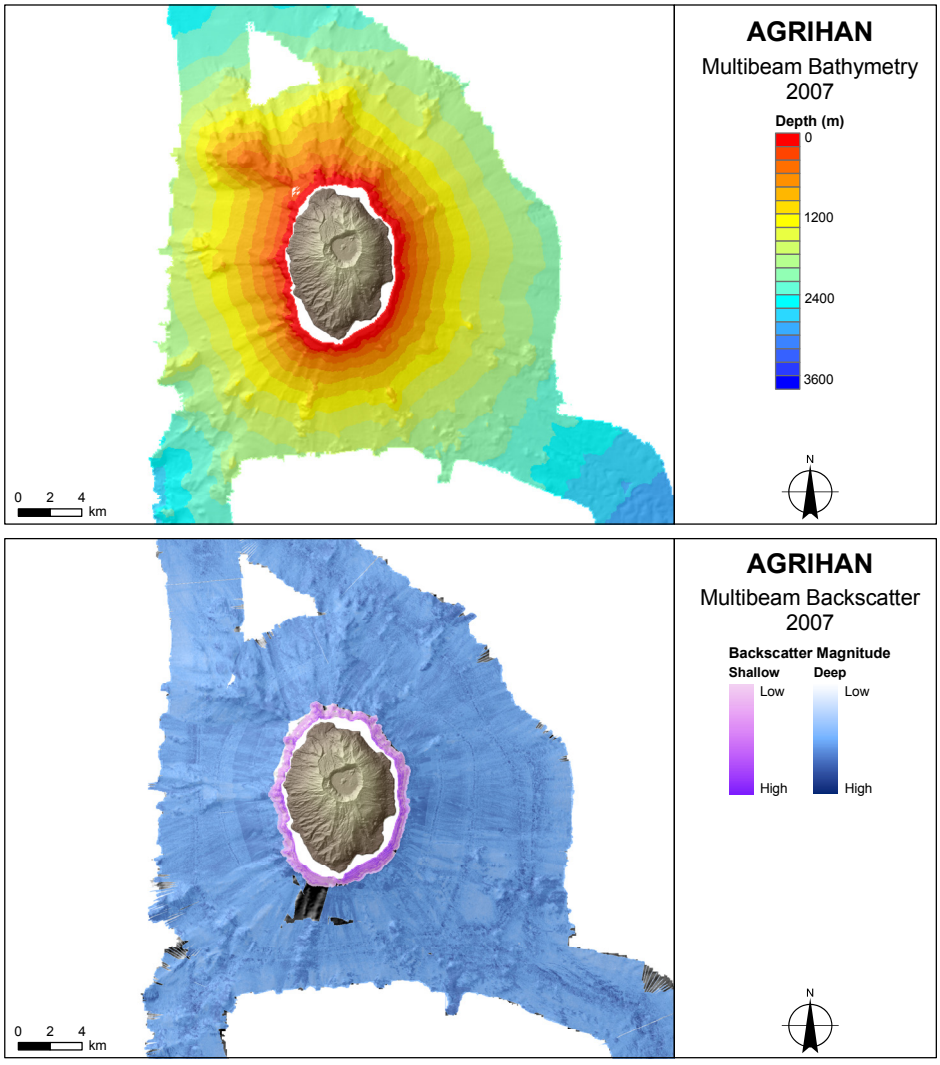


Figure 14.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Agrihan during MARAMP 2007 in depths of 20–2810 m. Shallow backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

Agrihan, several large, low-intensity backscatter areas are present between ridges that radiate away from the volcano and on lower angle portions of the submarine flanks. These areas are sandy or composed of unconsolidated material. Additionally, alternating bands of high and low backscatter are present on the Agrihan flanks and characteristic of slopes incised by canyons and channels.

High-resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in nearshore (depths of 0–800 m) waters around Agrihan were combined into a grid at 10-m resolution to allow for identification of fine-scaled features (Fig. 14.3.1b). These high-resolution data also have been used to derive maps showing slope (Fig. 14.3.1c), rugosity (Fig. 14.3.1d), and Bathymetric Position Index (BPI) zones (Fig. 14.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Agrihan.

The submarine character of Agrihan is fairly consistent within the northeast, southeast, and southwest regions. The slope, BPI, and rugosity maps reveal a flat, low-rugosity area at the shallowest depths (30–40 m) mapped with multibeam within these regions, particularly in the southeast region where a narrow platform is revealed. Below this flat area, the moderately sloping seabed descends to 120–140 m, where very steep slopes of > 50° are observed. The flanks below a depth of 140 m have fairly uniform, low- to moderate-rugosity slopes of ~ 15°–20°. Steep-sided ridges, highlighted by the BPI analysis, incise these flanks (Fig. 14.3.1e).

No shallow, flat areas were observed northwest of Agrihan, but, otherwise, the seafloor is very similar to the other regions. A broad ridge extending for more than 4 km in a northwesterly direction is an extension of the lava flow shown northwest of the crater in the digital elevation model for this island. This uneven topography, shown in the low-resolution multibeam bathymetry (Fig. 14.3.1a, top panel), results from this ridge not having a distinct, linear crest but instead having a number of smaller, sinuous crests. Additionally, at the end of this ridge, a small (~ 300 m in diameter) crater can be seen on both the high-resolution bathymetry and slope maps (Figs. 14.3.1b and c). Rugosity data suggest that the top of this ridge is fairly smooth (Fig. 14.3.1d), and some flat areas are shown in the slope map and BPI analysis (Figs. 14.3.1c and e). The ridge crest and narrow platform southeast of Agrihan are the only flat zones shown in the BPI analysis within the entire mapped area, which is otherwise dominated by slope zones with narrow crests and depressions associated with the many ridges.

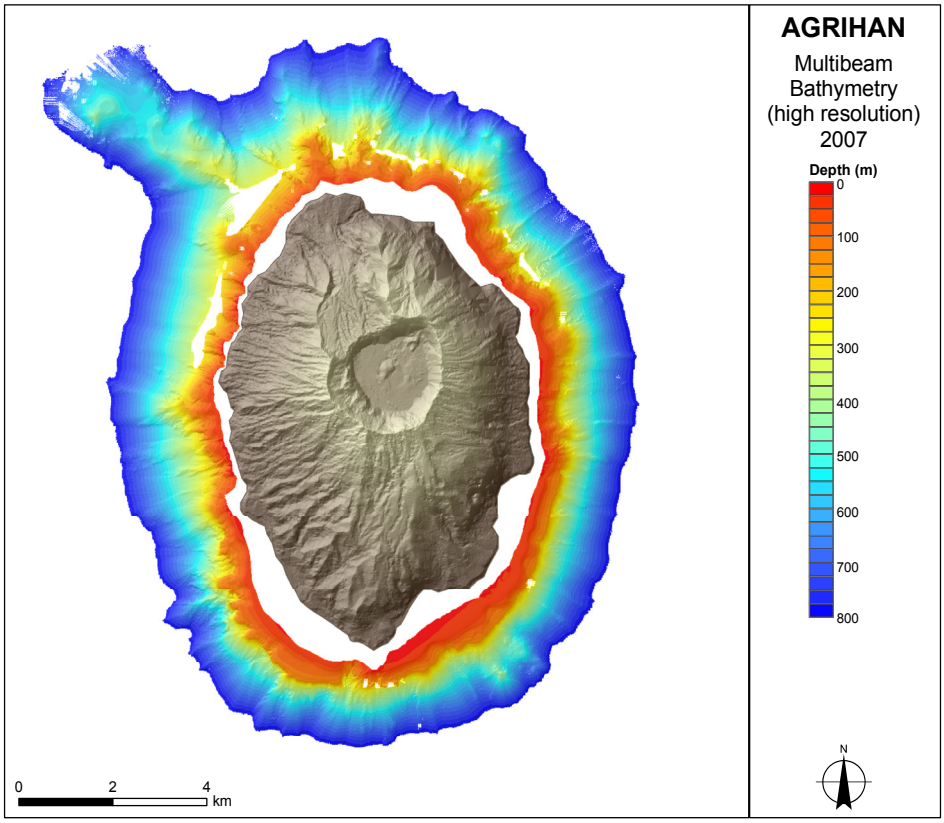


Figure 14.3.1b. High-resolution multibeam bathymetry collected around Agrihan during MARAMP 2007. This 10-m bathymetry grid has been clipped at 800 m and is used as the basis for slope, rugosity, and BPI derivatives.

Figure 14.3.1c. Slope (°) of 10-m bathymetric grid around Agrihan. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades.

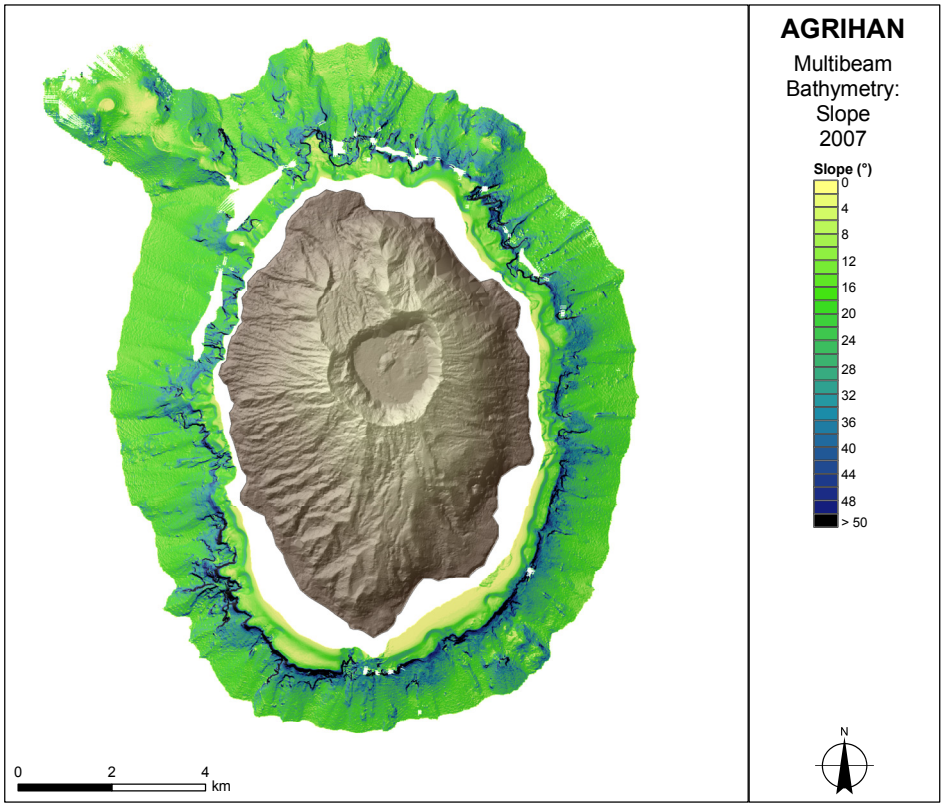
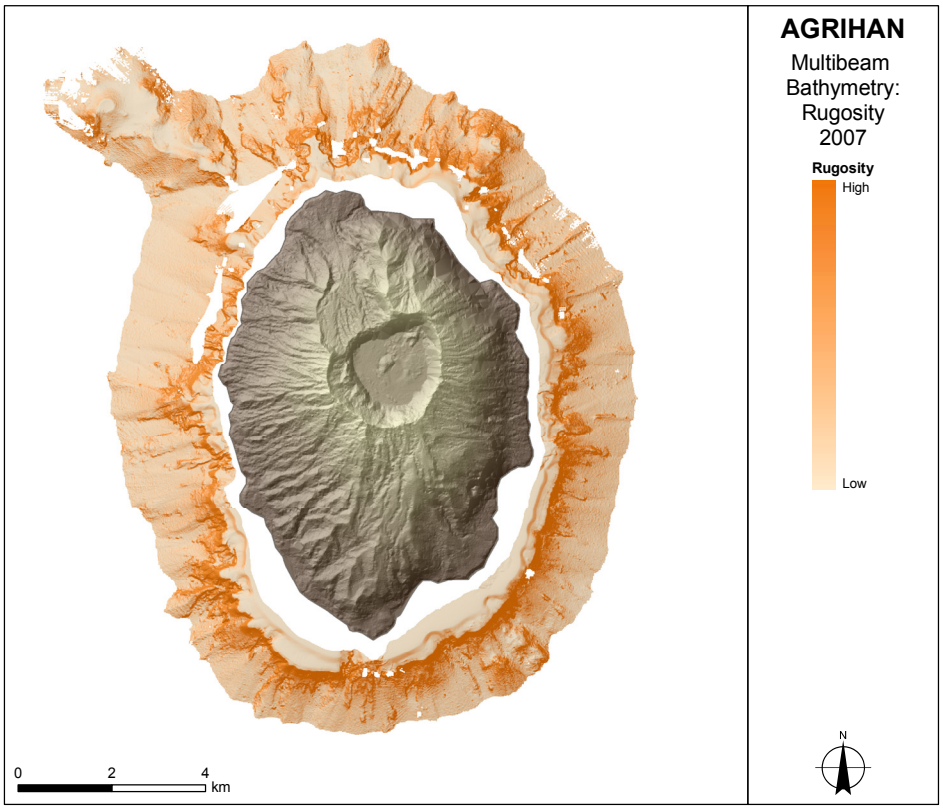


Figure 14.3.1d. Rugosity of 10-m bathymetric grid around Agrihan. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.



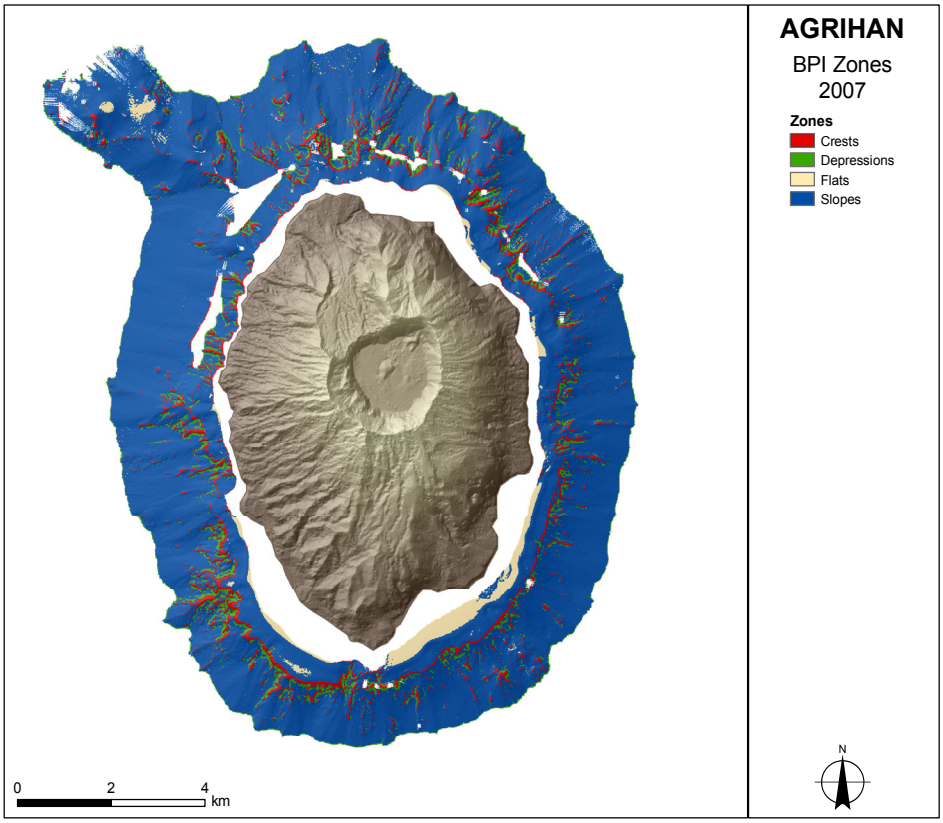


Figure 14.3.1e. BPI zones of 10-m bathymetric grid around Agrihan derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

High-resolution Multibeam Backscatter and Derivatives

The high-resolution backscatter data acquired around Agrihan has some noticeable artifacts, such as gaps in data between inner and outer swaths, but in general the data shows distinct patterns in the variation of backscatter intensity around this island that are strongly linked to the topography (Fig. 14 3.1f). These data also were used in an unsupervised classification (see Chapter 2: "Methods and Operational Background," Section 2.2.2: "Acoustic Mapping") of the substrate to produce hard–soft substrate maps (Fig. 14 3.1g). Although the hard–soft analysis is a useful tool to help interpret the seabed character around Agrihan, insufficient optical ground truth data are available to calculate classification accuracy. Nevertheless, the hard–soft analysis provides some indication of the distribution of different substrate types around this island.

High-intensity backscatter values were observed on the shallow platforms around the northeast, southeast, and southwest coasts of Agrihan, and these areas were classified as hard substrate. On the flanks below, high- and low-intensity backscatter correlated with the presence of ridges and channels. These observations were confirmed by the hard–soft analysis, which classified the ridges as having hard substrates and the channels in between as having soft substrates. Around northwest Agrihan, no shallow platform and fewer areas of high-intensity backscatter are present. High-intensity backscatter characterizes the tops of several short ridges, and they are classified as hard substrates. Seafloor with low-intensity backscatter, classified as soft substrate, is present in channels on the flanks, suggesting down-slope sediment transport.

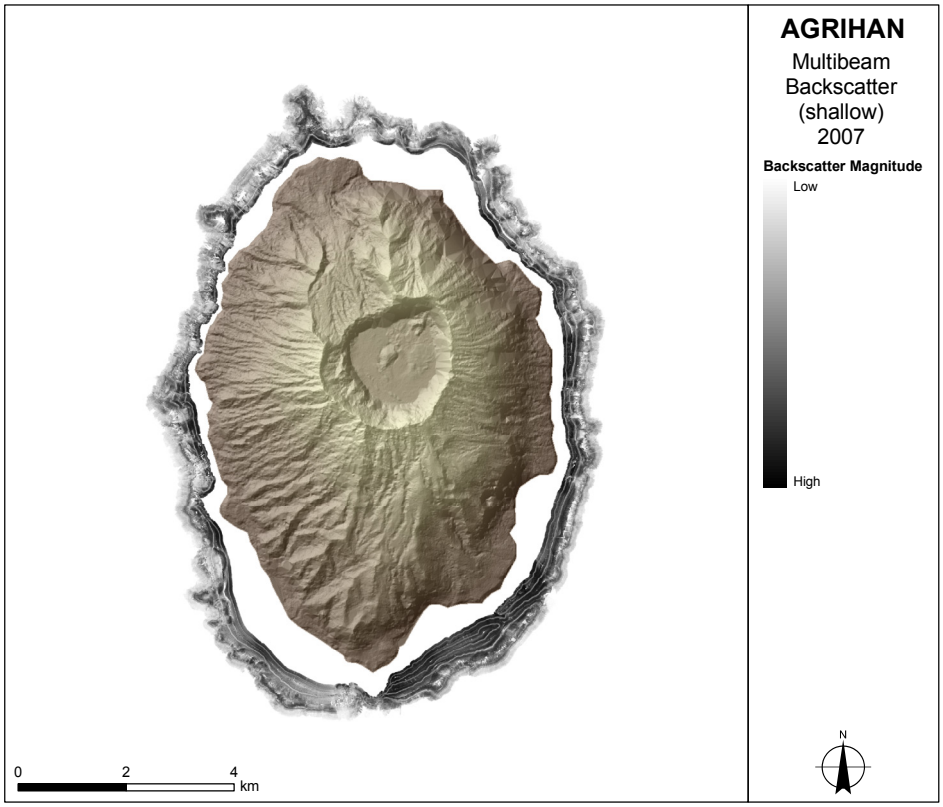


Figure 14.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) collected around Agrihan during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

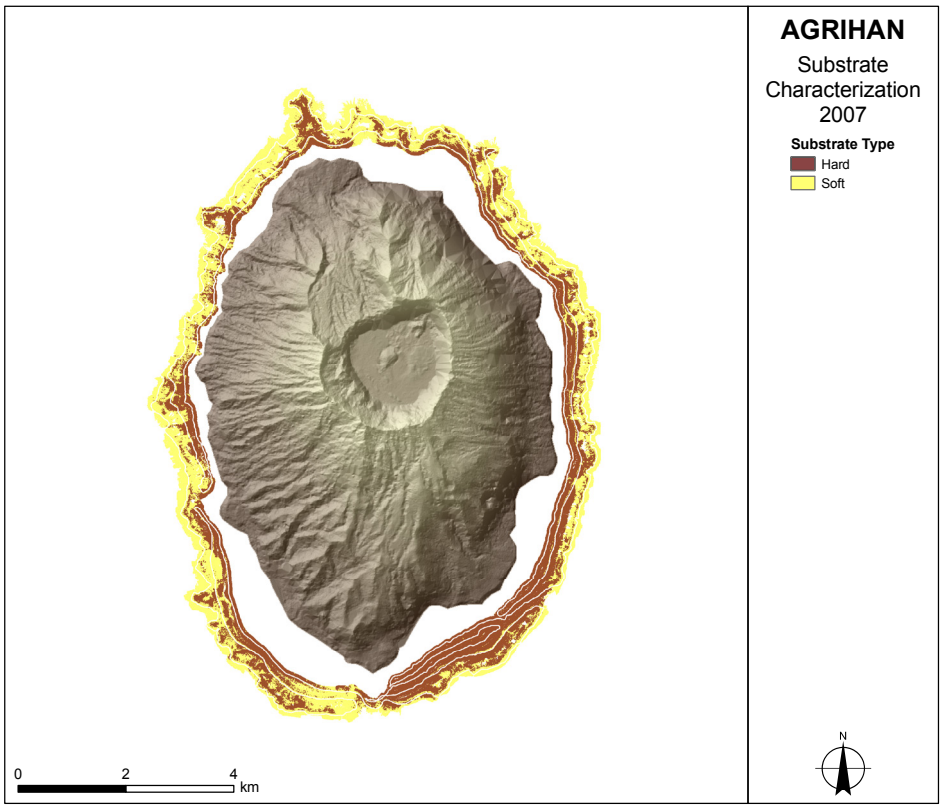


Figure 14.3.1g. Hard and soft substrates (grid cell size: 5 m) at depths of < 350 m based upon an unsupervised classification of multibeam bathymetry and backscatter data acquired around Agrihan between 2003 and 2007. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

14.3.2 Optical Validation

During MARAMP 2003, 8 TOAD optical-validation surveys were conducted around Agrihan, covering a distance of ~ 6 km at depths of 1–220 m (Fig. 14.3.2a). Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live coral cover.

Covering a distance of ~ 45 km at depths of 5–24 m, 23 towed-diver optical-validation surveys of forereef habitats were conducted around Agrihan during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

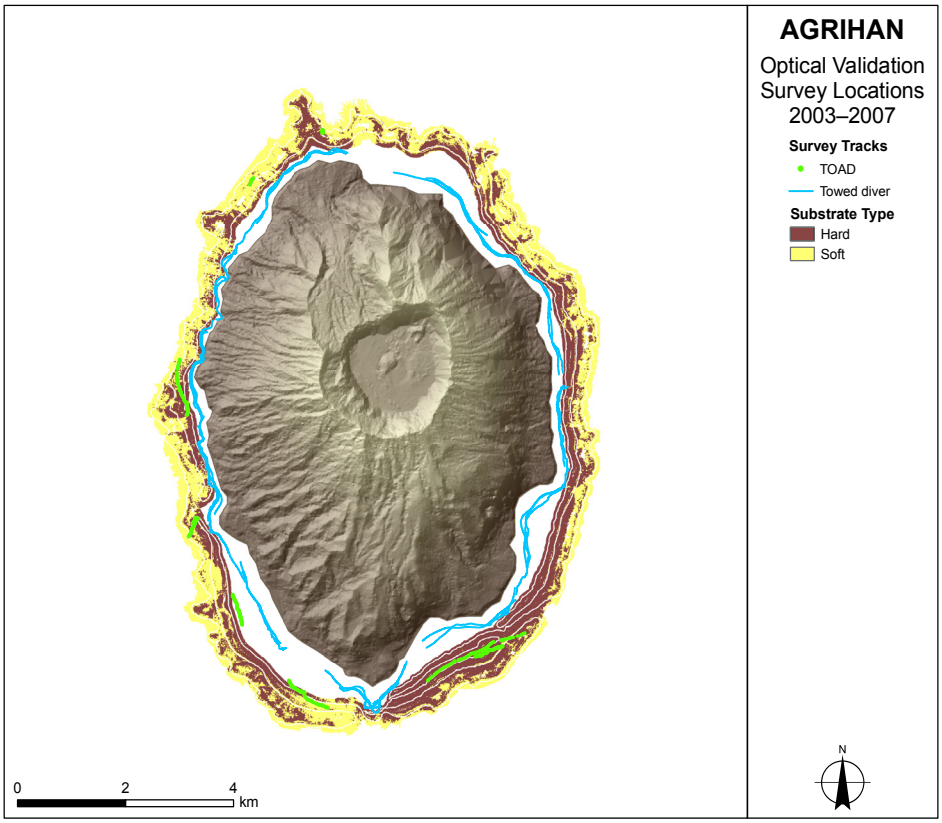


Figure 14.3.2a. Towed-diver tracks from surveys of forereef habitats conducted around Agrihan during MARAMP 2003, 2005, and 2007 and TOAD camera-sled tracks for MARAMP 2003. Survey tracks are displayed over the multibeam hard–soft substrate map. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

14.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Agrihan are discussed in this section. Around west and northwest Agrihan, towed-diver surveys recorded sand cover (Fig.14.3.3a, top panel) that was generally low (< 10%) and habitat of medium to high complexity (Fig.14.3.3a, middle panel**)**. In this area, observed cover of live hard corals (Fig.14.3.3a, bottom panel) also was fairly low at 5.1%–20%, although a higher level of coral cover was recorded adjacent to the onshore lava flow, clearly seen on the island topography northwest of the main caldera. This area, based on towed-diver surveys, was characterized predominantly as continuous reef and ridges with occasional boulder fields. Farther offshore from the lava flow, analyses of video footage obtained from TOAD surveys suggested hard substrates, although no live coral cover was observed. Hard–soft analysis classified this area as soft substrates. This apparent discrepancy could be caused by the different scale at which the TOAD video and bathymetry data are used, with the hard–soft analysis based on a 5-m grid providing a broader picture of the nature of the substrate and the TOAD video imaging a small area of seafloor. On a short ridge north of Agrihan, analyses of video footage from another TOAD survey, revealed a seabed characterized by 100% sand cover, corresponding to an area of soft substrate identified by the hard–soft classification. West of Agrihan, for an area that was mainly classified as hard substrate by the hard–soft analysis, analyses of video footage from a TOAD survey suggested a mixed substrate with a large section of 100% sand cover. This apparent contradiction may be a result of the sand observed on the video being a thin veneer overlying the hard substrates suggested by the acoustic signature.

Northeast of Agrihan, low sand cover < 20% was observed during towed-diver surveys in an area described as including pavement, boulders on sand, and rocky ridges. Recorded habitat complexity was medium-low to high. In the southern half of the northeast region, an area of higher live coral cover of 10.1%–50% was observed adjacent to a flatter area observed on the island topography.

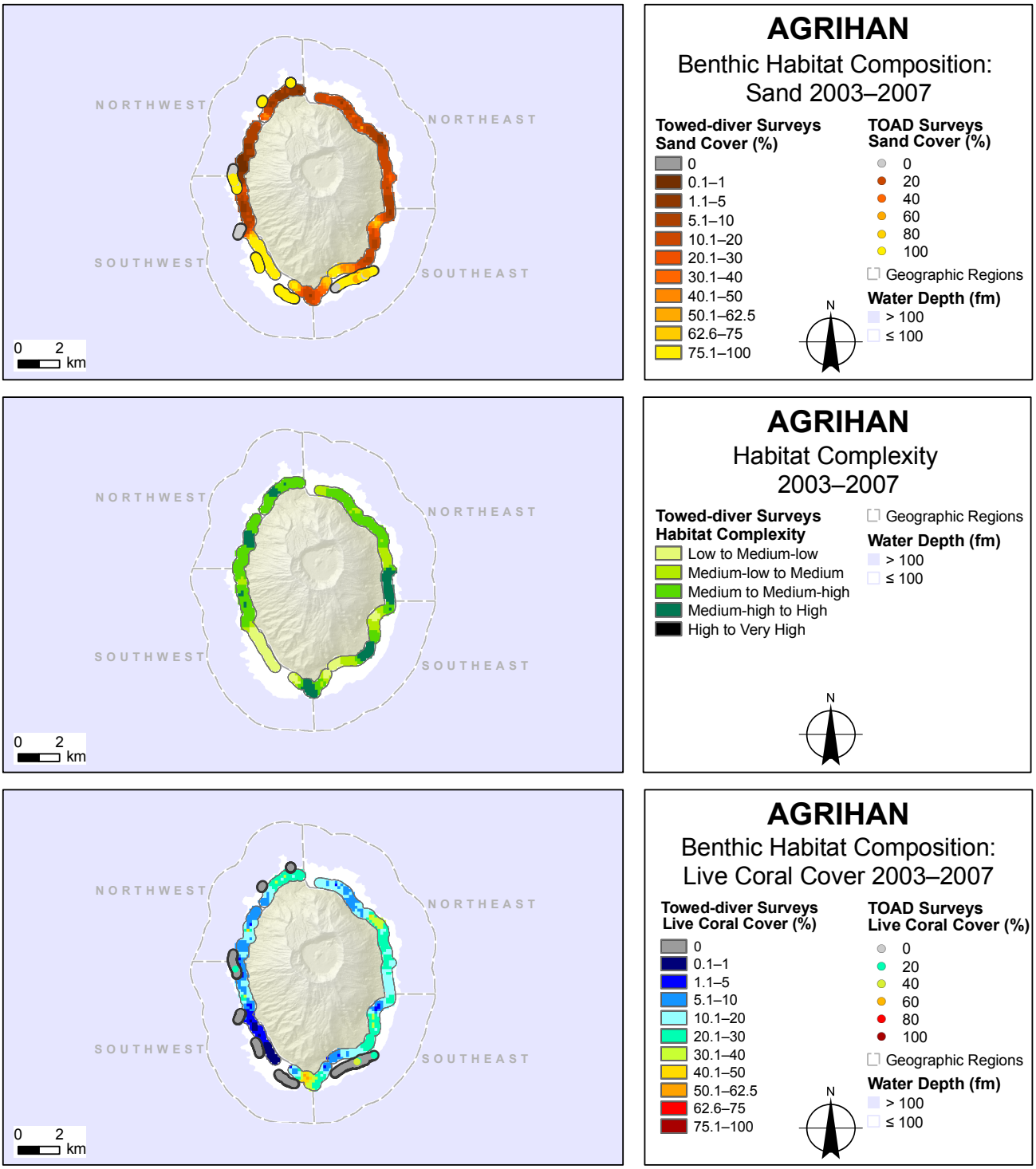


Figure 14.3.3a. Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) live-hard-coral cover (%) from towed-diver surveys of forereef habitats conducted and analyses of TOAD video collected around Agrihan during MARAMP 2003, 2005, and 2007.

Within the southeast region, benthic habitat composition was more variable. Patches of low complexity, sandy habitat supporting low cover of live hard corals were observed within the wide bays on this coastline, with sand cover as high as 75.1%–100% and live coral cover < 10% from towed-diver surveys. The areas between these patches were characterized by more complex habitats, with lower sand cover (< 30%) and higher live coral cover (10.1%–62.5%). These areas were described during towed-diver surveys in some locations as medium-relief, spur-and-groove habitats. In the southeast region, analyses of video footage obtained during 2 adjacent TOAD surveys conducted at depths of 25–70 m revealed that the substrate was primarily sandy, with a majority of analyzed video frames revealing sand cover of 80.1%–100% and a few frames suggesting small amounts of live corals with cover of 20.1%–40%. West of the southern point of Agrihan, seabed composed of 100% sand, again, with no benthic fauna was revealed during analyses of TOAD video acquired during a TOAD survey conducted at depths of 30–45 m.

Southwest of Agrihan, towed-diver surveys characterized a large area as habitat of low to medium-low complexity and sand substrates, with sand cover of 75.1%–100% sand cover and very low live coral cover < 5%. In adjacent deeper waters, analyses of TOAD video collected also revealed substrates with observed sand cover of 100%.

14.4 Oceanography and Water Quality

14.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 15 shallow-water CTD casts were conducted in nearshore waters around the island of Agrihan over the period of August 26–September 6. Temperature, salinity, density, and beam transmission values varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest small differences in temperature (0.2°C), salinity (0.2 psu), density (0.1 kg m^{-3}), and beam transmission (< 1%) values; however, temperature, salinity, density, and beam transmission values were recorded at higher levels in the northwest and northeast regions than in the southwest and southeast regions (Fig. 14.4.1a). Vertical comparisons of CTD profiles reveal moderate differences in temperature (0.7°C), salinity (0.4 psu), density (0.4 kg m^{-3}), and beam transmission (2%) values (Fig. 14.4.1b). Marked intra-island differences in salinity values occurred, with recorded salinity higher in the northwest and northeast regions (casts 2–8) than in the 2 southern regions. Temperature values, however, did not show this same spatial pattern. Instead, temperature observations alternate around this island between well-mixed, nearly homogenous profiles and highly stratified profiles with warm waters overlying cooler waters. Beam transmission data appear to vary concurrently with salinity values, and density data show variability similar to temperature values. These differences in values could have resulted from temporal separation in sampling.

2005 Spatial Surveys

During MARAMP 2005, 14 shallow-water CTD casts were conducted in nearshore waters around Agrihan on September 15. Temperature, salinity, density, and beam transmission values varied both spatially and vertically around this island. Spatial comparisons of water properties at a depth of 10 m suggest little variability around Agrihan with small ranges in temperature (0.2°C), salinity (0.04 psu), density (0.1 kg m^{-3}), and beam transmission (< 1%) values; however, recorded temperatures were slightly warmer in the southeast and southwest regions than in the northeast and northwest regions, indicating small intra-island differences (Fig. 14.4.1c). Vertical comparisons of CTD profiles reveal moderate ranges in temperature (0.4°C) and salinity (0.3 psu) values and slight ranges in density (0.2 kg m^{-3}) and beam transmission (1.1%) values. A shift in water properties occurred between casts 7 and 8 (Fig. 14.4.1d), with warm, well-mixed waters observed in the southeast and southwest regions (casts 8–14) and comparatively cooler, more saline waters in the northwest and northeast regions (casts 1–7).

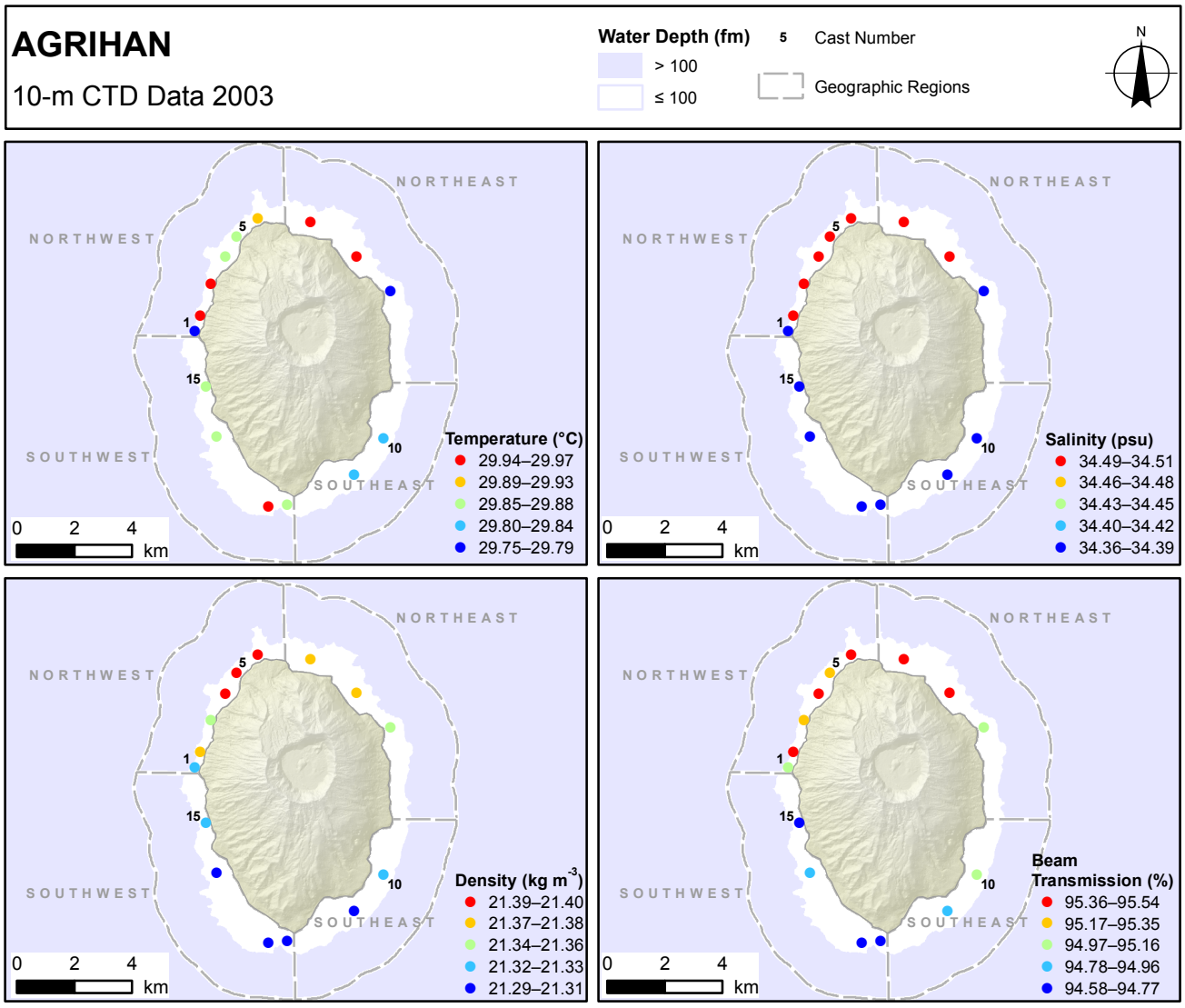


Figure 14.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Agrihan during MARAMP 2003, with cast 9 done on August 26, casts 1 and 10–15 done on August 27, casts 7 and 8 done on September 5, and casts 2–6 done on September 6.

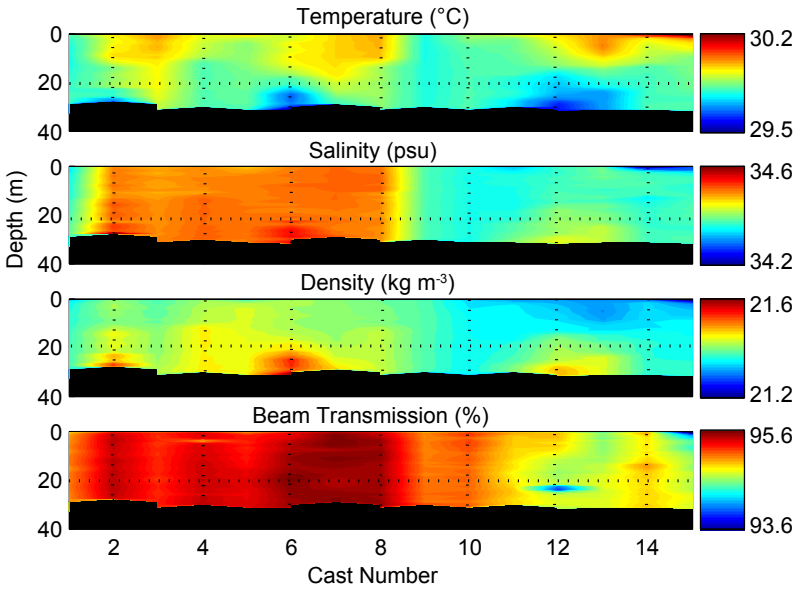


Figure 14.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Agrihan during MARAMP 2003, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–15 in a clockwise direction around Agrihan. Cast 9 was completed on August 26, casts 1 and 10–15 were done on August 27, casts 7 and 8 were done on September 5, and casts 2–6 were done on September 6. For cast locations and numbers around this island in 2003, see Figure 14.4.1a.

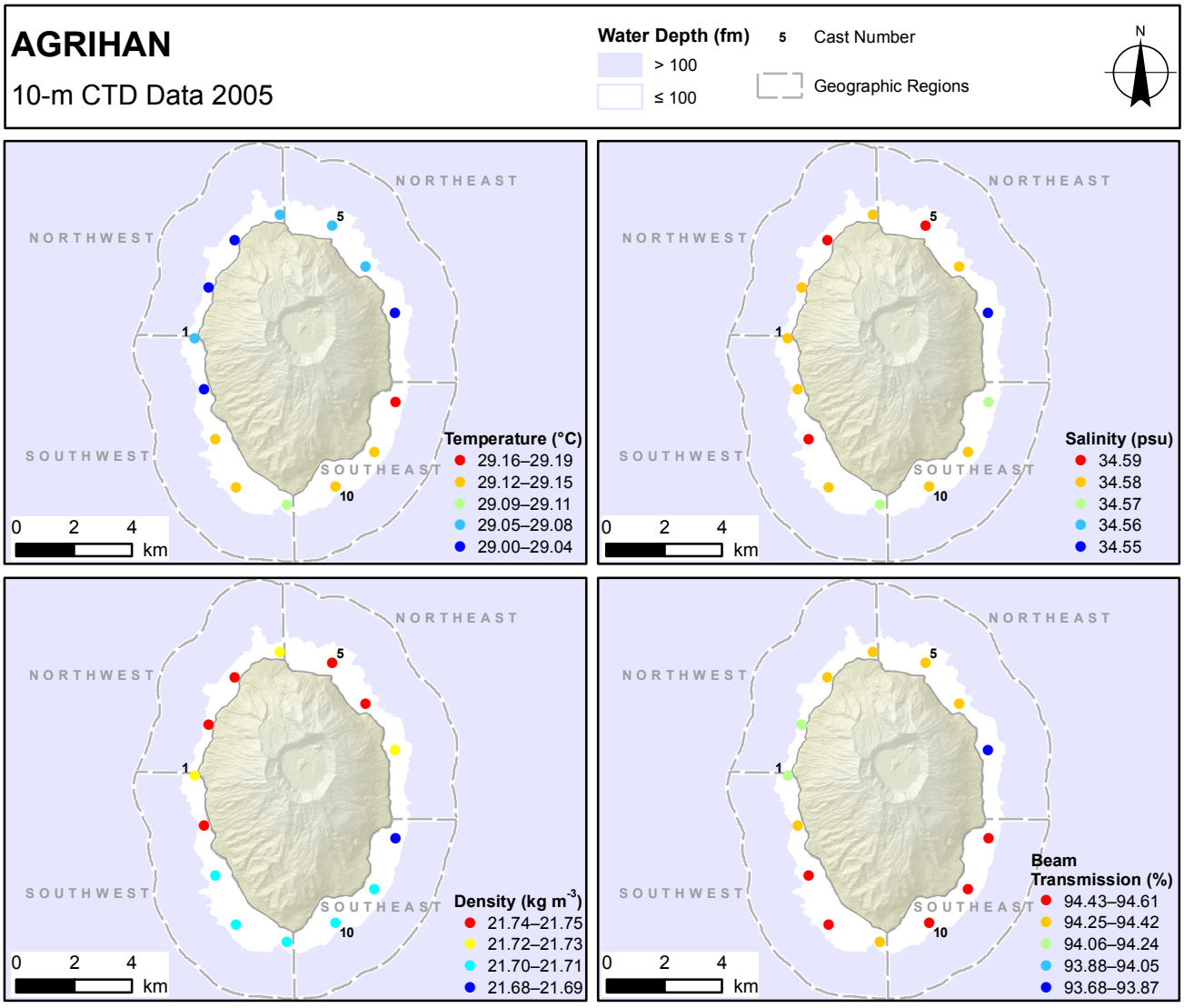


Figure 14.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Agrihan on September 15 during MARAMP 2005.

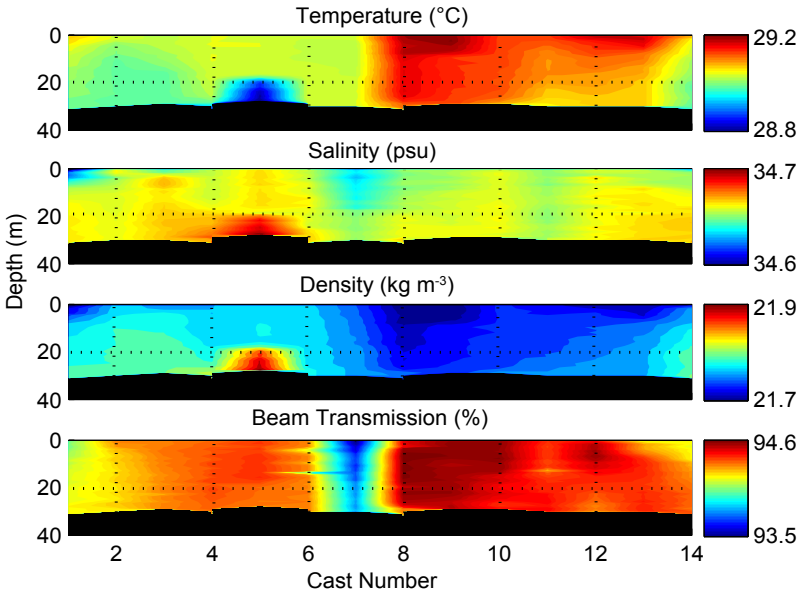


Figure 14.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Agrihan on September 15 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–14 in a clockwise direction around Agrihan. For cast locations and numbers around this island in 2005, see Figure 14.4.1c.

2007 Spatial Surveys

During MARAMP 2007, 15 shallow-water CTD casts were conducted in nearshore waters around Agrihan on May 29. Temperature, salinity, density, and beam transmission values varied both spatially and vertically. Spatial comparisons of water properties at a depth of 10 m show little variability around this island; however, broad ranges in temperature (1.9°C) and density (0.7 kg m^{-3}) values were recorded as a result of a single cast (cast 11) in the southeast region (Fig. 14.4.1e). Vertical comparisons of CTD profiles reveal mostly well-mixed waters, although considerable ranges in temperature (3.2°C) density (1 kg m^{-3}) values combined with moderate ranges in salinity (0.2 psu) and beam transmission (1.4%) values were recorded (Fig. 14.4.1f). The large range in temperature values principally is a result of localized upwelling of deep waters in the southeast region (cast 11) and to a lesser extent in the northwest region (cast 2).

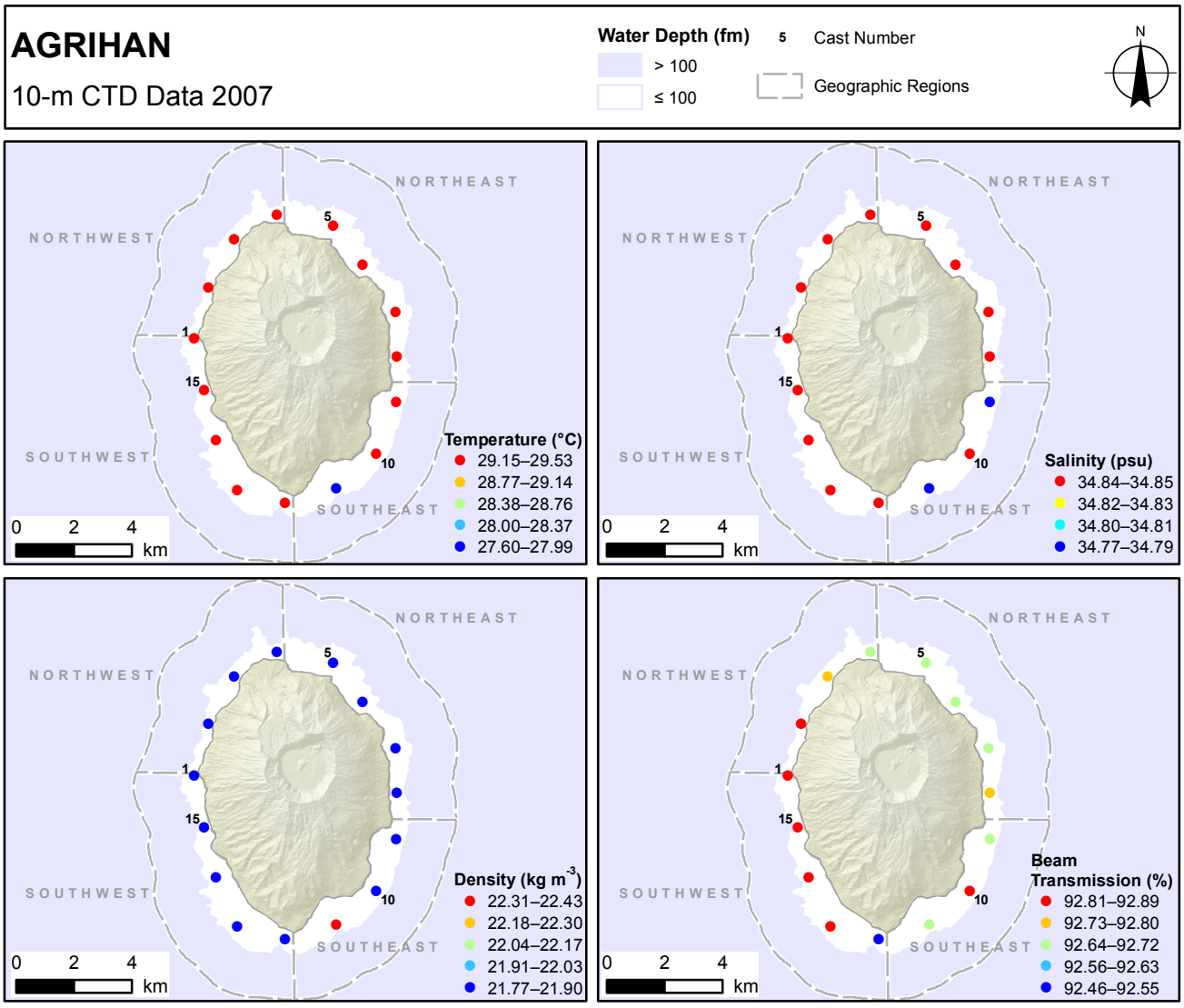


Figure 14.4.1e. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Agrihan on May 29 during MARAMP 2007.

Water samples were collected in concert with shallow-water CTD casts at 3 select locations at Agrihan in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.06–0.09 µg L^{-1}; total nitrogen (TN), 0.02–0.11 µM; nitrate (NO_3^-), 0.01–0.10 µM; nitrite (NO_2^-), 0.005–0.011 µM; phosphate (PO_4^{3-}), 0.01–0.02 µM; silicate [$Si(OH)_4$], 1.21–1.73 µM. The highest values of Chl-*a* were recorded in the northwest region, and the highest values of total nitrogen, nitrate, nitrite, and phosphate were all observed in the southwest region (Fig. 14.4.1g).

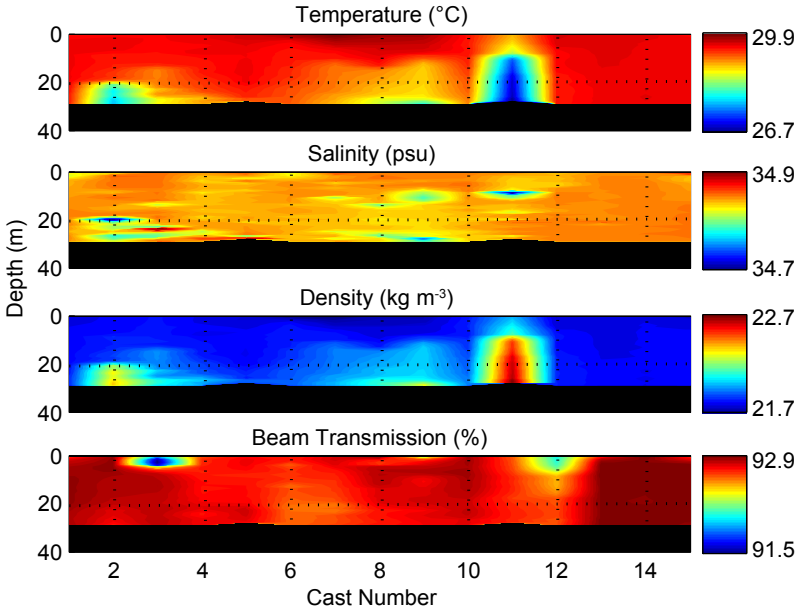


Figure 14.4.1f. Shallow-water CTD cast profiles to a 30-m depth around Agrihan on May 29 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–15 in a clockwise direction around Agrihan. For cast locations and numbers around this island in 2007, see Figure 14.4.1e.

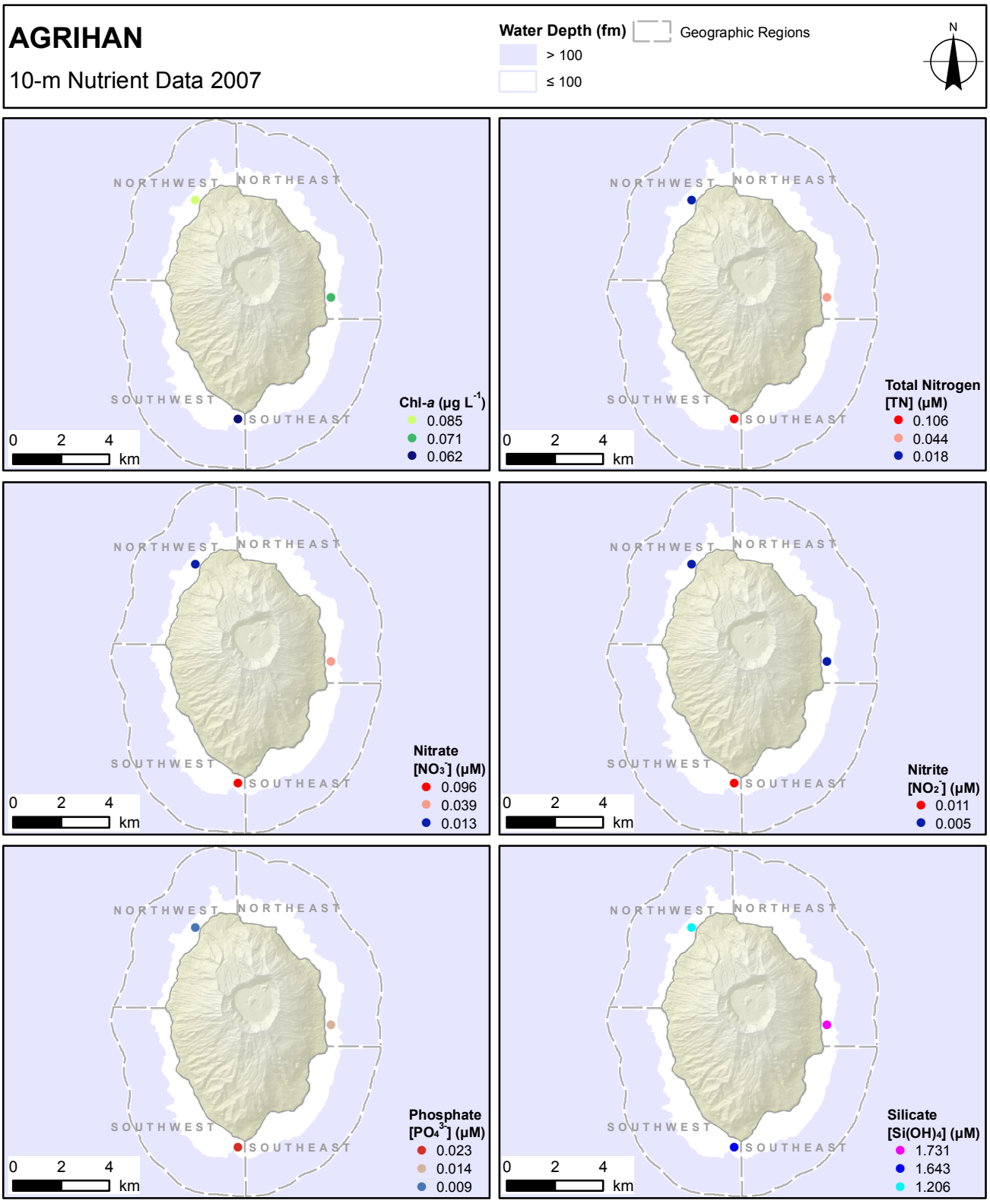


Figure 14.4.1g. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate, at a 10-m depth from water samples collected at Agrihan on May 29 during MARAMP 2007.

Temporal Comparison

Comparisons of shallow-water CTD data from MARAMP 2003, 2005, and 2007 suggested a dynamic physical oceanographic environment. During MARAMP 2003 and 2005 minimal spatial variability and moderate vertical variability were observed, and during MARAMP 2007 substantial spatial variability in water properties was recorded, although intra-island differences were entirely attributed to a single cast location in the southeast region with exceptionally cooler temperatures. Cold water (26.7°C; 3.2°C colder than surface waters) intrusions originating from below a depth of 30 m may be caused by upwelling or internal tide activity. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May, and MARAMP 2003 and 2005 occurred in August and September. This change was made to avoid the typhoon season and reduce the probability of weather disruptions.

14.4.2 Time-series Observations

Between 2003 and 2007, one type of moored instrument was installed at Agrihan, a subsurface temperature recorder (STR), to collect time-series observations of a key oceanographic parameter influencing reef conditions. The location, depth, time frame, and other details about these deployments are provided in Figures 14.4.2a and b.

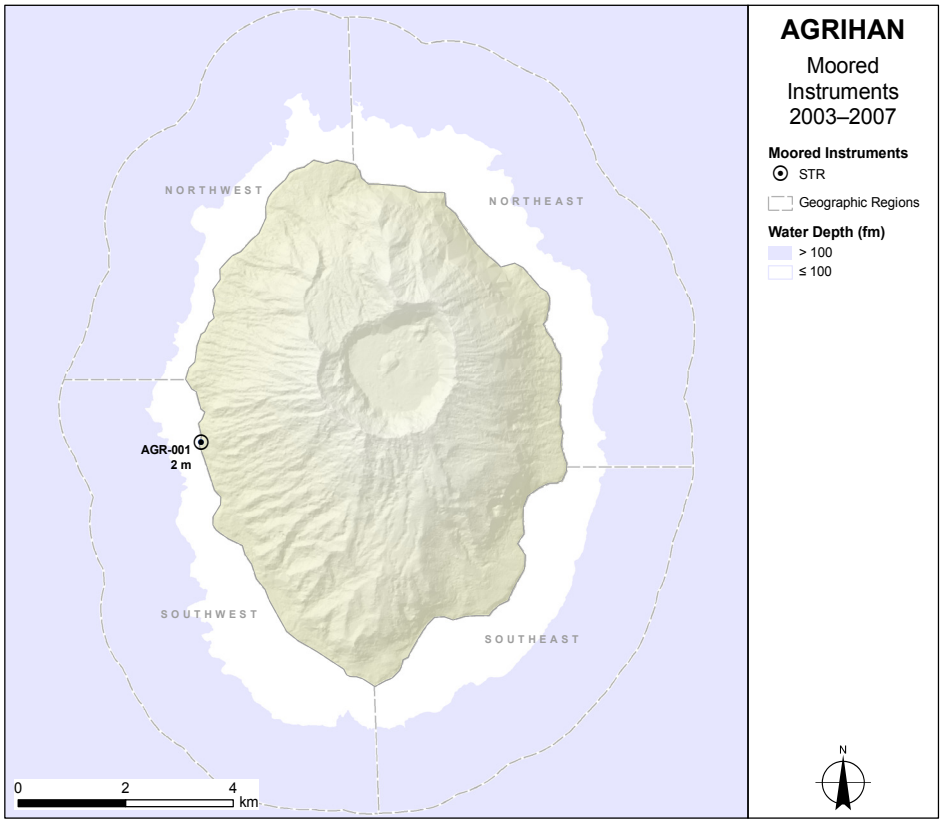


Figure 14.4.2a. Location and depth of the STRs deployed at Agrihan during MARAMP 2003, 2005, and 2007.

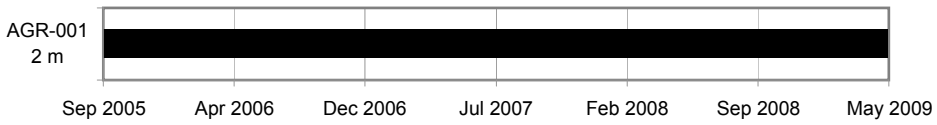
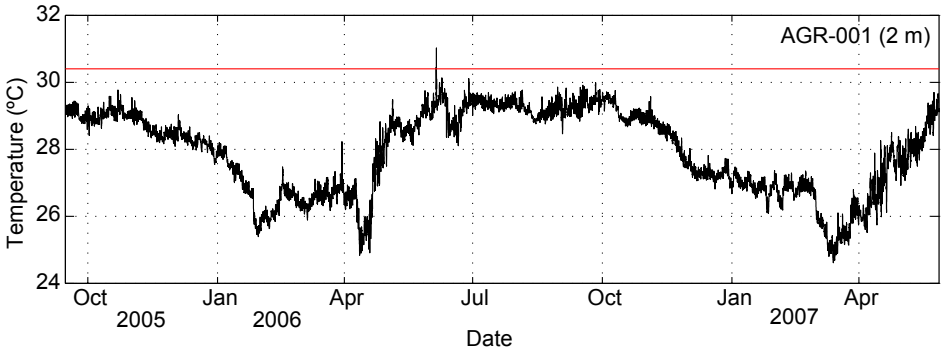


Figure 14.4.2b. Deployment timeline and depth of the STRs installed at Agrihan during the period from September 2005 to May 2009. A solid bar indicates the period for which temperature data were collected by a series of STRs that were deployed and retrieved at the mooring site AGR-001. For more information about deployments and retrievals, see Table 14.2b in Section 14.2: "Survey Effort."

A series of STRs were deployed at a depth of 2 m at the same location at Agrihan, mooring site AGR-001 in the southwest region. Data from these STRs for the period from September 2005 to June 2007 show seasonal temperature variability of ~ 4°C (Fig. 14.4.2c). Water temperatures reached 29°C–30°C during the months of June–October and fell to a low of ~ 27°C during the months of January–May. Temperature values exceeded the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean, for the region in September 2006; however, the duration of this event was less than 1 d. Diurnal temperature fluctuations were ~ 0.25°C throughout this time series.

Figure 14.4.2c. Time-series observations of temperature over the period between September 2005 and June 2007 collected from 1 STR deployed in the southwest region at a depth of 2 m (see Figure 14.4.2a for mooring location). The red line indicates the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.



14.4.3 Wave Watch III Climatology

Seasonal wave climatology for Agrihan (Fig. 14.4.3a) was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008, and seasons were selected to elucidate waves generated by typhoons, which most frequently occur between the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 25 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (90°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the south (180°), although they could originate from a broad directional source (150°–210°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from the west and southwest (240°–270°) and probably were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) was also characterized by frequent (> 30 d per season), short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season), long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this period and originated from the southwest (240°) and the northwest (330°).

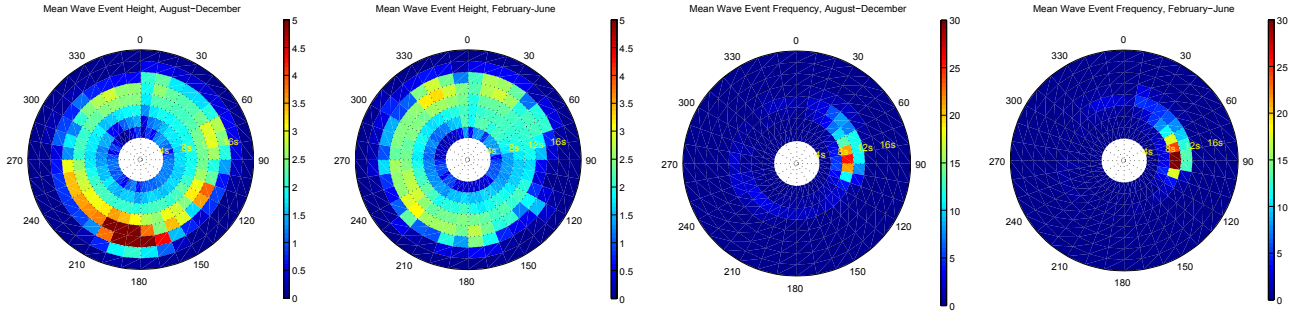


Figure 14.4.3a. NOAA Wave Watch III directional wave climatology for Agrihan from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Agrihan (18° N, 145° E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

14.5 Corals and Coral Disease

14.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Agrihan was 16% (SE 1.3). Coral cover was higher in the east regions than in the west regions (Fig. 14.5.1a, top panel). Localized areas of high coral cover were observed in the southwest region with a mean of 56% for 4 survey segments, in the northeast region with a mean of 34% for 7 segments, and in the southeast region with a mean of 35% for 6 segments.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats at Agrihan was 15% (SE 2.1). Surveys in 2005 were limited to one day, resulting in partial spatial coverage compared to 2003. Coral cover was highest along the southern point of this island with a mean of 33% for 8 survey segments (Fig. 14.5.1a, middle panel). Towed divers recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 5.3% (SE 2.4) of coral cover observed on forereef habitats at Agrihan appeared stressed. The occurrence of stressed-coral cover was low for the majority of areas surveyed at this island, except the northeast region (Fig. 14.5.1a, middle panel), where divers noted predation by crown-of-thorns seastars (*Acanthaster planci*). For more information about crown-of-thorns seastar (COTS) observations at Agrihan, see Section 14.7.1: "Benthic Macroinvertebrate Surveys."

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats at Agrihan was 14% (SE 1.7). As was the case in 2005, surveys were limited to one day, resulting in partial spatial coverage compared to 2003. Coral cover was highest along the southern coastline of this island with a mean of 38% for 4 survey segments and in the northwest region with a mean of 31% for 7 segments (Fig. 14.5.1a, bottom panel). Overall, 1.5% (SE 0.4) of coral cover observed on forereef habitats around Agrihan appeared stressed in 2007. The occurrence of stressed-coral cover was low for the majority of areas surveyed around this island, with elevated levels of stressed-coral cover recorded in 2 areas. In the northeast region, divers noted the presence of COTS and predation scars on corals (Fig. 14.5.1a, bottom panel), and, in the southwest region, divers observed high numbers of COTS (> 100 individuals) and widespread predation scars during a safety stop at the end of a survey.

During MARAMP 2003, 4 REA benthic surveys using the quadrat method on forereef habitats at Agrihan documented 540 coral colonies within a total survey area of 15 m^2. Site-specific colony density ranged from 29.9 to 45.9 colonies m^{-2} with an overall sample mean of 36 colonies m^{-2} (SE 3.6). The highest colony density was recorded at REA site AGR-02 in the southwest region, and the lowest colony density was observed at AGR-04 in the northwest region (Fig. 14.5.1.b, top panel).

During MARAMP 2005, 3 REA benthic surveys using the quadrat method on forereef habitats at Agrihan documented 491 coral colonies within a total survey area of 12 m^2. Site-specific colony density ranged from 14.8 to 59.3 colonies m^{-2}, with an overall sample mean of 40.9 colonies m^{-2} (SE 13.4). The highest colony density was recorded at AGR-02 in the southwest region, and the lowest colony density was observed at AGR-06, farther north in the southwest region (Fig. 14.5.1b, middle panel).

During MARAMP 2007, 3 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Agrihan. Site-specific estimates of live-hard-coral cover from these surveys ranged from 17.7% to 38.2%, with an overall sample mean of 30.7% (SE 6.6). Live coral cover was highest at AGR-02 in the southwest region and lowest at AGR-01 in the southeast region (Fig. 14.5.1b, bottom panel).

During MARAMP 2007, 3 REA benthic surveys using the quadrat method on forereef habitats at Agrihan documented 612 coral colonies within a total survey area of 12 m^2. Site-specific colony density ranged from 40.5 to 56.5 colonies m^{-2}, with an overall sample mean of 51 colonies m^{-2} (SE 5.3). The highest colony density was recorded at both AGR-04 in the northwest region and AGR-02 in the southwest region (Fig. 14.5.1b, bottom panel).

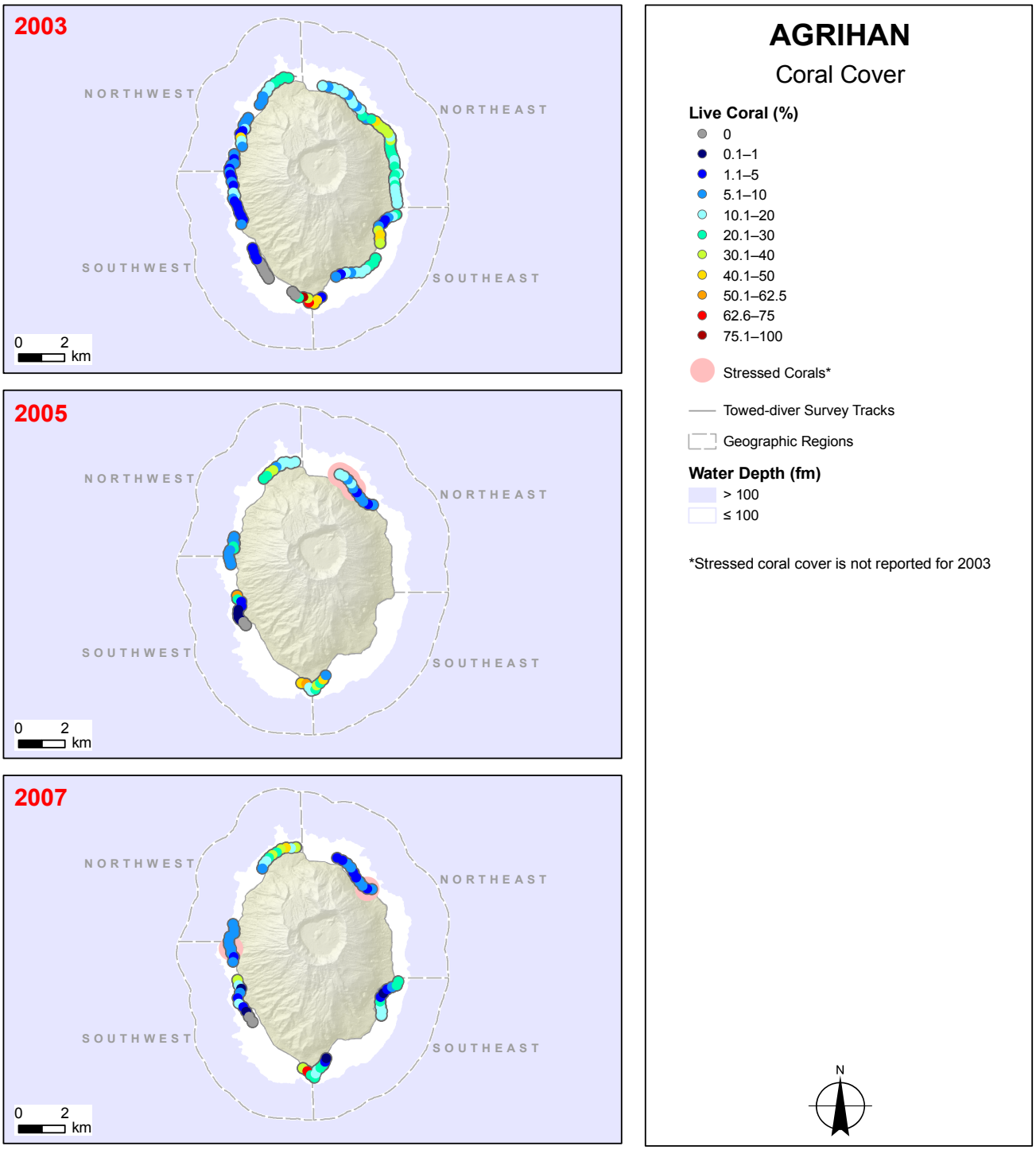


Figure 14.5.1a. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Agrihan during MARAMP 2003, 2005, and 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005 and 2007.

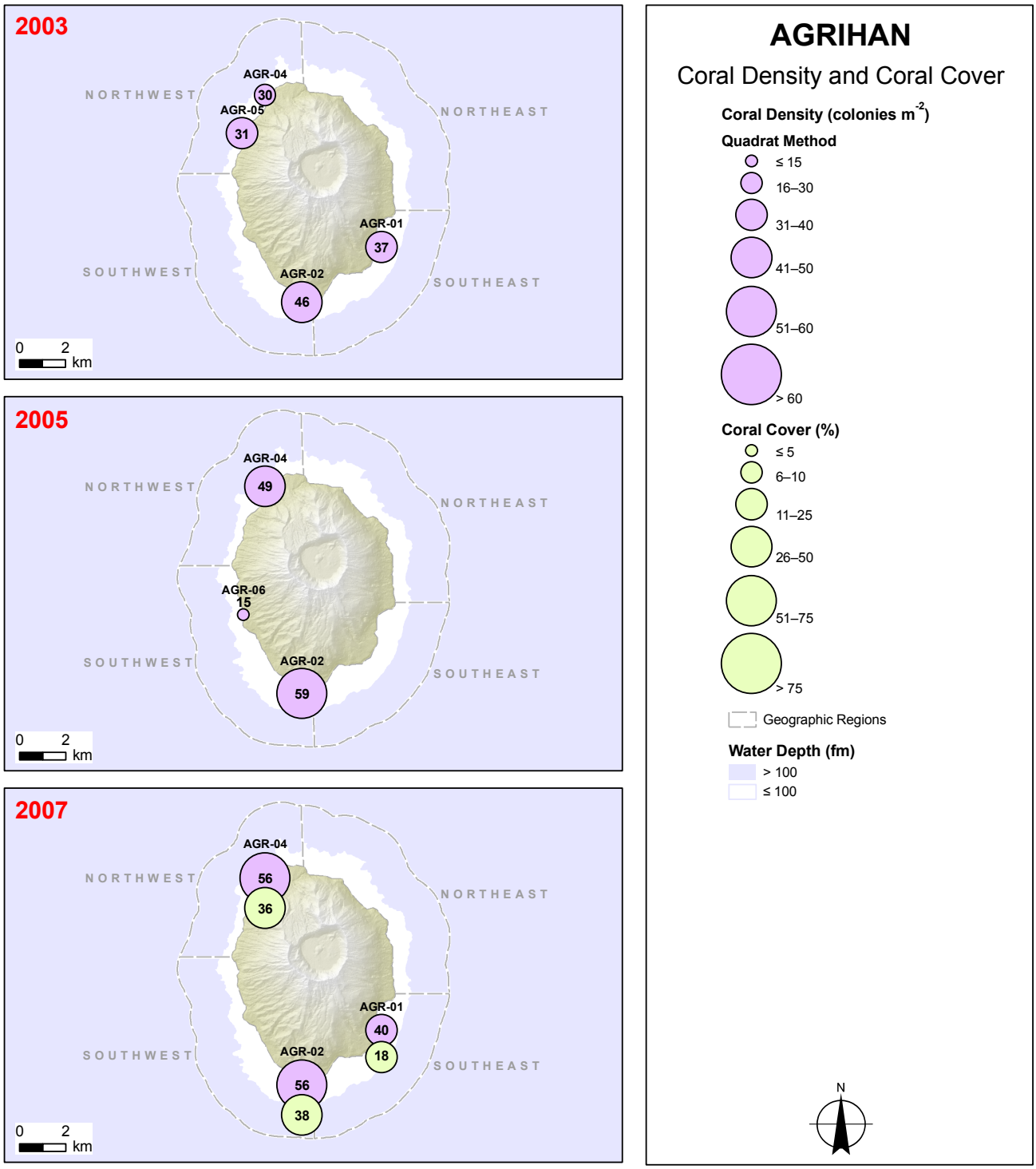


Figure 14.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Agrihan during MARAMP 2003, 2005, and 2007 and cover (%) observations of live corals from REA benthic surveys during MARAMP 2007. Values are provided within or above each symbol. The quadrat method was used to assess coral-colony density.

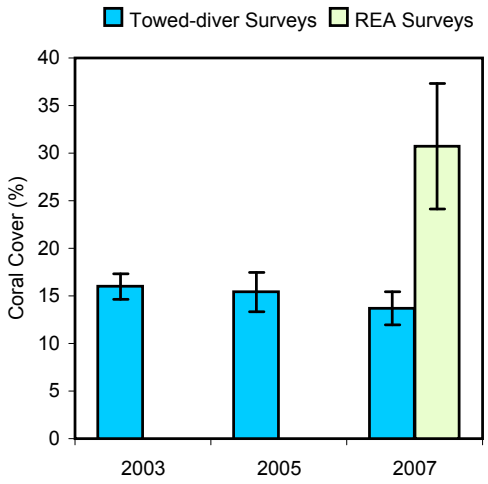


Figure 14.5.1c. Temporal comparison of mean live-coral-cover (%) values from REA and towed-diver surveys conducted on forereef habitats at Agrihan during MARAMP 2003, 2005, and 2007. No REA coral-cover surveys using the line-point-intercept method were conducted around Agrihan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

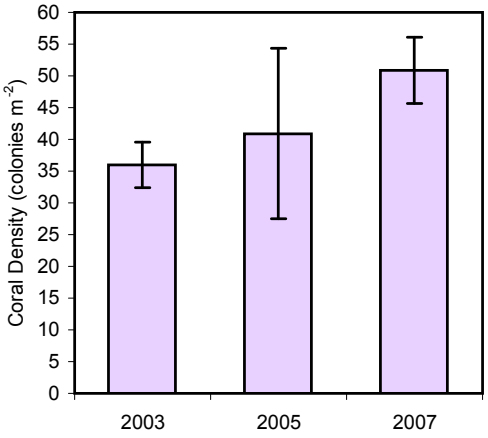


Figure 14.5.1d. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats around Agrihan during MARAMP 2003, 2005, and 2007. The quadrat method was used in the 3 MARAMP survey years to survey coral density. Error bars indicate standard error (± 1 SE) of the mean.

Islandwide mean cover of live corals estimated from towed-diver surveys of forereef habitats was 16% (SE 1.2) in 2003, 15% (SE 2.1) in 2005, and 14% (SE 1.7) in 2007 (Fig. 14.5.1c). Although there was substantial spatial variation between the 3 MARAMP survey years, the overall percentage of live coral cover was similar between survey years. For the 3 sites surveyed using the line-point-intercept method in 2007, the overall sample mean of live coral cover was 30.7% (SE 1.7). Estimates of live coral cover from REA surveys generally exceed those derived from towed-diver surveys because REA surveys target hard-bottom communities whereas towed-diver surveys include more variable substrate types.

The quadrat method was used during each of the 3 MARAMP survey years to assess coral-colony density. Overall mean coral-colony density from REA surveys of forereef habitats at Agrihan was 36 colonies m^{-2} (SE 3.6) in 2003, 40.9 colonies m^{-2} (SE 13.4) in 2005, and 51 colonies m^{-2} (SE 5.3) in 2007 (Fig. 14.5.1d). A similar temporal pattern exists when only the 2 sites surveyed in all of the 3 survey years (AGR-02 and AGR-04) are examined: mean density was 37.9 colonies m^{-2} (SE 8) in 2003, 54 colonies m^{-2} (SE 5.3) in 2005, and 56.3 colonies m^{-2} (SE 0.3) in 2007.

Coral Generic Richness and Relative Abundance

Four REA benthic surveys of forereef habitats were conducted using the quadrat method at Agrihan during MARAMP 2003. At least 22 coral genera were observed. Generic richness ranged from 13 to 17 with a mean of 15.5 (SE 0.8) coral genera per site (Fig. 14.5.1e, top panel). The highest generic diversity values were seen at AGR-05 and AGR-04 in the northwest region, and the lowest generic diversity was recorded at AGR-02 in the southern part of the southwest region. *Pavona*, *Goniastrea*, and *Favia* were the most numerically abundant genera, contributing 30.5%, 14.8%, and 12.1% of the total number of colonies enumerated at Agrihan in 2003. All other genera individually contributed < 10% of the total number of colonies. *Pavona* dominated the coral fauna at all 4 sites, contributing 26.8%, 32%, 30.4%, and 33.1% of the total number of colonies enumerated.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Agrihan during MARAMP 2005. At least 21 coral genera were observed. Generic richness ranged from 8 to 19 with a mean of 15 (SE 3.5) coral genera per site (Fig. 14.5.1e, middle panel). The highest generic diversity was seen at AGR-04 in the northwest region, and the lowest generic diversity was recorded at AGR-06 in the southwest region. *Pavona, Pocillopora, Goniastrea*, and *Leptastrea* were the most numerically abundant genera, contributing 16.2%, 13.9%, 13.7%, and 11.9% of the total number of colonies enumerated at Agrihanin 2005. All other genera individually contributed < 10% of the total number of colonies. *Leptastrea* dominated at AGR-06, accounting for 28.8% of the total number of colonies enumerated at that site. *Pocillopora* and *Porites* were each found to contribute 23.7% of the total number of colonies at AGR-06. *Goniastrea* dominated the coral fauna at AGR-02 and *Pavona* at AGR-04, contributing 23.2% and 21.5% of the total number of colonies recorded at their relevant site.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Agrihan during MARAMP 2007. At least 25 coral genera were observed. Generic richness ranged from 17 to 21 with a mean of 18.7 (SE 1.2) genera per site (Fig. 14.5.1e, bottom panel). The highest generic diversity was seen at AGR-01 in the southeast region, and the lowest generic diversity was recorded at AGR-04 in the northwest region. *Pavona*, *Pocillopora*, and *Goniastrea* were the most numerically abundant genera, contributing 23.9%, 15.0%, and 12.9% of the total number of colonies enumerated at

Agrihan in 2007. All other genera individually contributed < 10% of the total number of colonies. *Pavona* dominated the coral fauna at AGR-04 and AGR-02, contributing 32.3% and 27.7% of the total number of colonies recorded at those sites. *Astreopora* dominated at AGR-01, contributing 17.3% of the total number of colonies enumerated at that site.

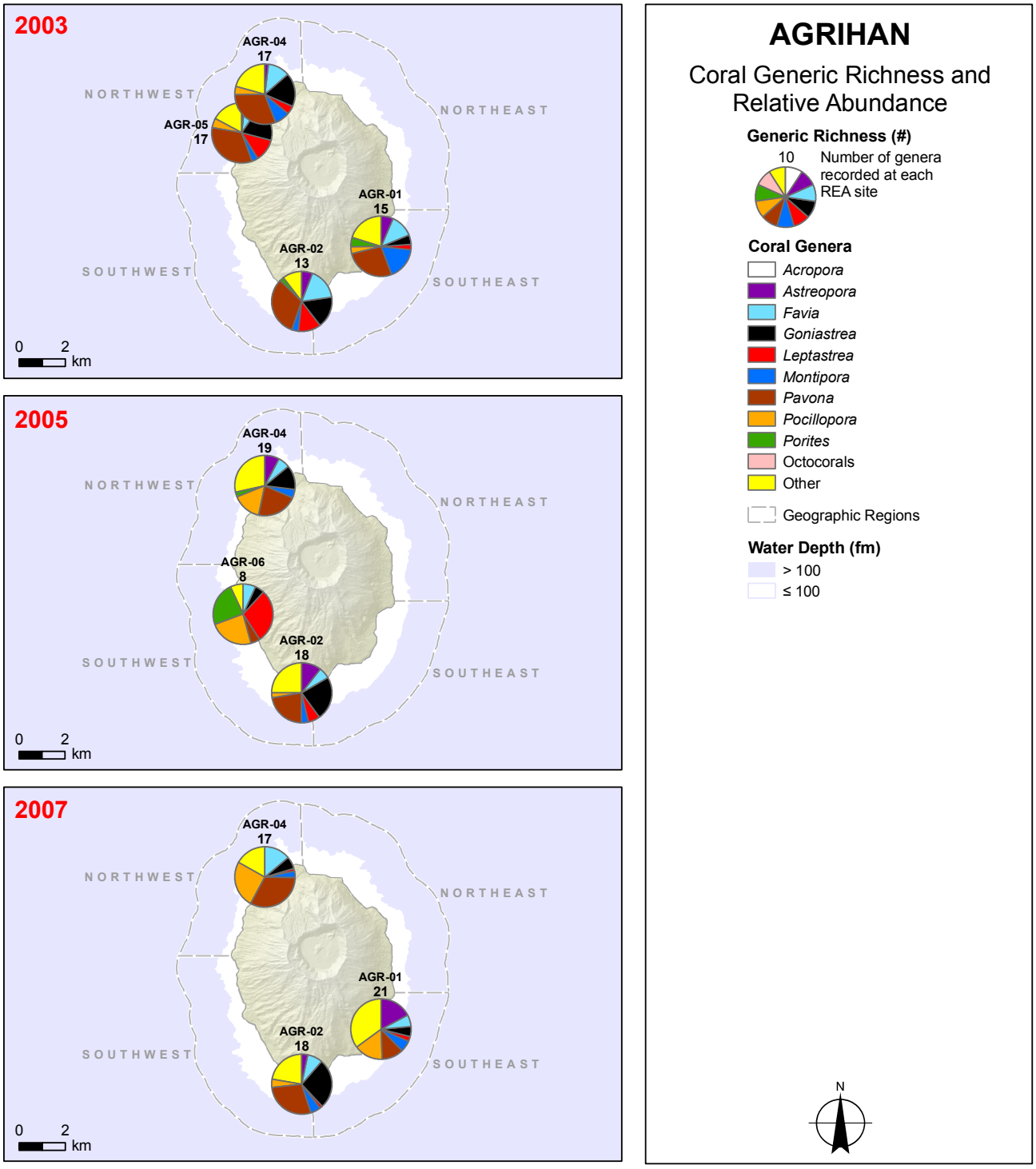


Figure 14.5.1e. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Agrihan during MARAMP 2003, 2005, and 2007. The pie charts indicate percentages of relative abundance of key coral genera.

The quadrat method was used in each of the 3 MARAMP survey years to assess generic richness on forereef habitats at Agrihan. Estimates for the overall sample mean of generic richness remained similar between MARAMP survey years, with 15.5 (SE 0.8) and 15 (SE 3.5) coral genera per site in 2003 and 2005 and 18.7 (SE 1.2) genera per site in 2007 (Fig. 14.5.1f). A different temporal pattern exists when only the 2 sites surveyed in all of the 3 survey years are examined (AGR-02 and AGR-04): mean generic richness increased from 15 (SE 2) genera per site in 2003 to 18.5 (SE 0.5) and 17.5 (SE 0.5) genera per site in 2005 and 2007. The increase in generic richness between 2003 and 2005 is not a result of new or additional genera being recorded at Agrihan in 2005, but to a greater number of genera being recorded at individual sites.

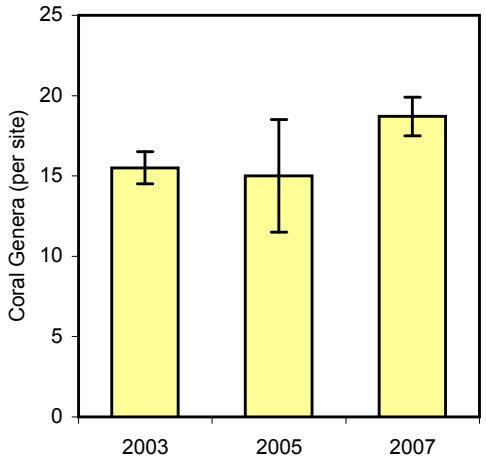


Figure 14.5.1f. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Agrihan during MARAMP 2003, 2005, and 2007. The quadrat method was used in the 3 MARAMP survey years to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

Across the 3 MARAMP survey years, 28 coral genera were observed on forereef habitats at Agrihan. *Pavona* and *Goniastrea* were important components of the coral fauna, accounting for > 10% of the total number of colonies enumerated in the 3 survey years. *Pavona* was the most numerically abundant taxon in each of the 3 survey years, contributing 30.5%, 16.2%, and 23.9% to the total number of colonies. *Goniastrea* was the second-most numerically abundant taxon in 2003, accounting for 14.8% of the colonies recorded that year, while *Pocillopora* was the second-most numerically abundant taxon in 2005 and 2007, contributing 13.9% and 15%, of the total number of colonies enumerated in those years. *Favia* was the third-most numerically abundant taxon in 2003, contributing 12.1% of the colonies, while *Goniastrea* was the third-most abundant taxon represented in 2005 and 2007, contributing 13.7% and 12.9% of the total number of colonies. All other taxa contributed < 12% of the total number of colonies enumerated over the 3 survey years.

Coral Size-class Distribution

During MARAMP 2003, 4 REA benthic surveys of forereef habitats were conducted at Agrihan using the quadrat method. The coral size-class distributions from these surveys show that the majority (61.5%) of corals had maximum diameters ≤ 5 cm (Fig. 14.5.1g, top panel). The next 4 size classes (6–10, 11–20, 21–40 and 41–80 cm) accounted for 30.1%, 7.1%, 3.8%, and 0.6% of colonies recorded. No colonies with maximum diameters > 80 cm were recorded. At all REA sites, a majority of all measured corals (> 64%) were in the smallest size class (0–5 cm), except for at AGR-04, where 49% of corals had maximum diameters ≤ 5 cm.

During MARAMP 2005, 3 REA benthic surveys of forereef habitats were conducted at Agrihan using the quadrat method. The coral size-class distributions from these surveys show that the majority (77.9%) of corals had maximum diameters ≤ 5 cm (Fig. 14.5.1g, middle panel). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 14.4%, 7.9%, 2.8%, and 0.7% of colonies recorded. No colonies with maximum diameters > 80 cm were recorded. At all REA sites, a majority (> 66%) of corals were in the smallest size class (0–5 cm).

During MARAMP 2007, 3 REA benthic surveys of forereef habitats were conducted at Agrihan using the quadrat method. The coral size-class distributions from these surveys show that the majority (64.3%) of corals had maximum diameters ≤ 5 cm (Fig. 14.5.1g, bottom panel). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 24.9%, 8.1%, 2.1%, and 1.3% of colonies recorded. Colonies with maximum diameters > 80 cm contributed 0.5% of colonies recorded. At all REA sites, a majority (> 69%) of corals was in the smallest size class (0–5 cm), except for at AGR-02, where 49.1% of corals had maximum diameters ≤ 5 cm.

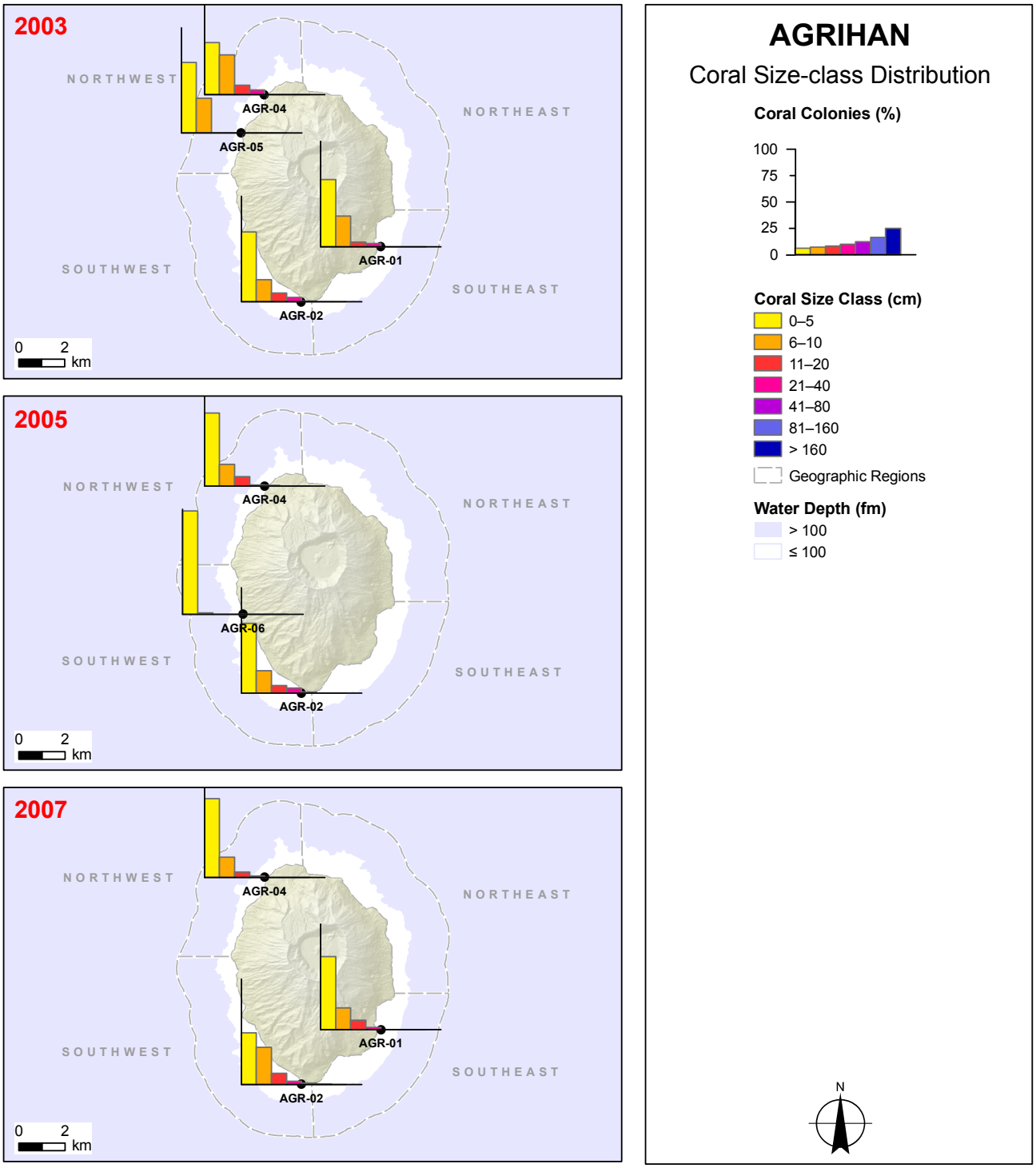
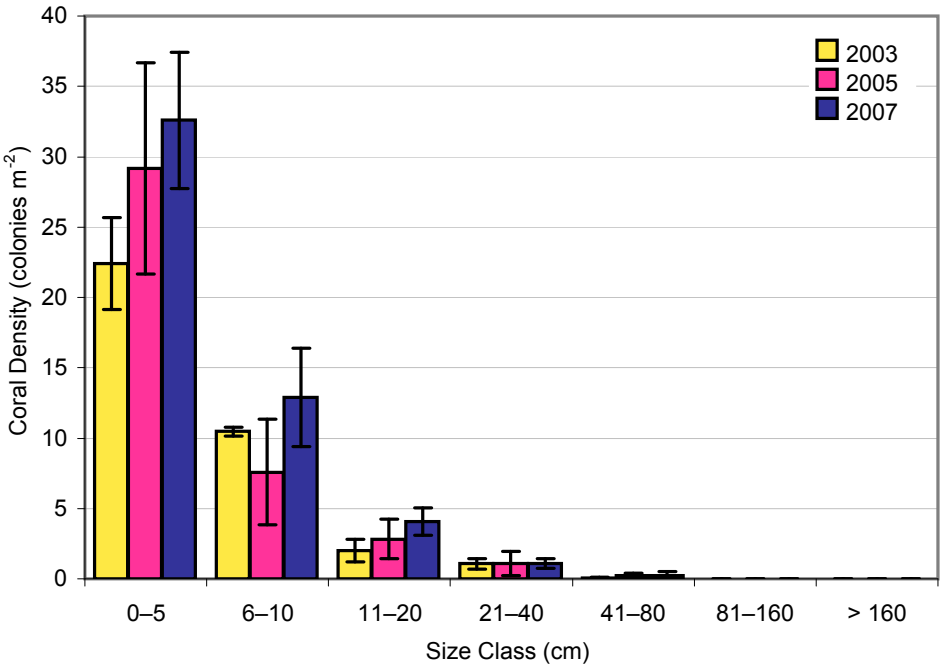


Figure 14.5.1g. Size-class distributions of hard corals from REA benthic surveys conducted on forereef habitats at Agrihan during MARAMP 2003, 2005, and 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used to size corals.

The quadrat method was used to establish size-class distributions on forereef habitats at Agrihan during the 3 MARAMP survey periods. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. For more on these survey methods, see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease."

In each of the 3 MARAMP survey years, the number of colonies in the smallest size class (0–5 cm) was much higher than the number of colonies in the larger size classes (Fig. 14.5.1h). The overall mean proportion of colonies censused on forereef habitats at Agrihan that fell in the smallest size class (0–5 cm) increased from 61.5% in 2003 to 77.9% in 2005 but decreased to 64.3% in 2007. Values for individual sites surveyed in all of the 3 survey years (AGR-02 and AGR-04) were variable between years with mean proportion of colonies with maximum diameters ≤ 5 cm at AGR-02 decreasing between years but increasing at AGR-04. Concordantly, the overall mean proportion of colonies in all other size classes was variable between years, as were all site-specific proportions. The higher frequency of the smallest size class may result from recruitment, fragmentation of existing colonies, or both. Minor variation between overall and site-specific size-class distributions recorded in 2003, 2005 and 2007 likely result from chance differences in the placement of individual quadrats.

Figure 14.5.1h. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Agrihan during MARAMP 2003, 2005, and 2007. The quadrat method was used in each of the 3 survey years to size corals. Error bars indicate standard error (± 1 SE) of the mean.



14.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic disease surveys for coral disease and predation were conducted at 3 sites on forereef habitats at Agrihan, covering a total area of 900 m^2. Surveys detected 5 cases of disease, translating to an overall mean prevalence of 0.01% (SE 0.01). The use of the quadrat method for coral-colony counts at all REA sites at Agrihan resulted in higher-than-expected coral-colony densities, and, therefore, lower-than-expected disease prevalence values.

Three disease conditions were observed at Agrihan. In order of numerical abundance, these conditions were fungal infection, skeletal growth anomalies, and bleaching. All 3 of the sites surveyed contained disease, however, in low prevalence values (Fig. 14.5.2a and b). Disease conditions involving skeletal growth anomalies were observed at AGR-01 and AGRI-04 on corals of the genera *Acropora*, *Goniastrea*, and *Astreopora*. Cases of fungal infections were observed at AGR-02 and AGR-04 on corals of the genera *Astreopora* and *Coscinaraea*. Bleaching conditions were recorded only at AGR-02 on corals of the genus *Platygyra*. Only one case of COTS predation was enumerated at Agrihan; this case was detected at AGU-04 on a colony of the genus *Goniastrea*. For more information about COTS at Agrihan, see Section 14.7.1: "Benthic Macroinvertebrate Surveys."

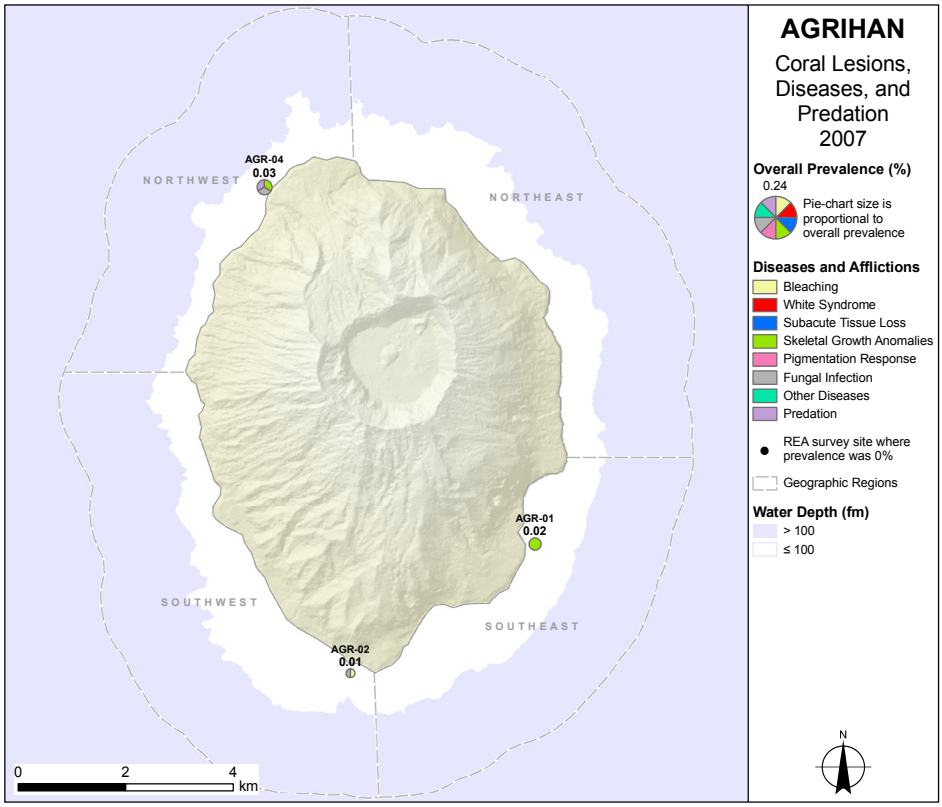


Figure 14.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Agrihan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie chart indicate disease-specific prevalence.

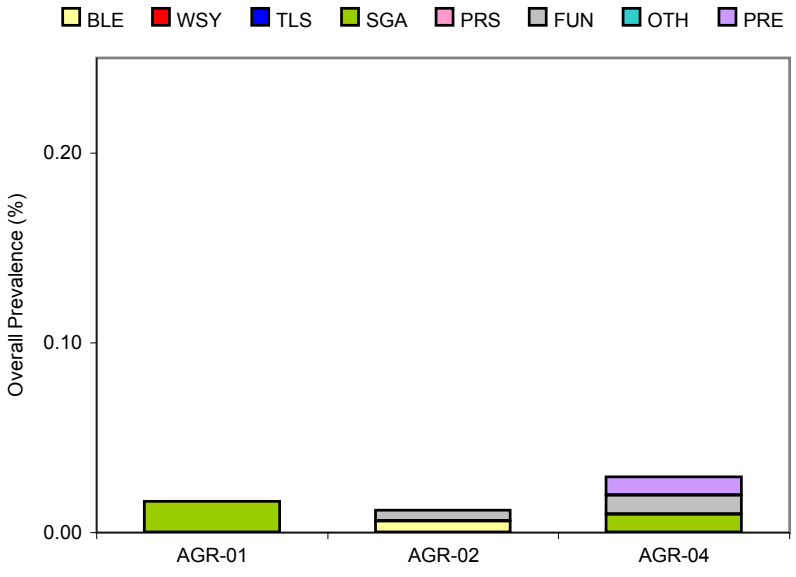


Figure 14.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Agrihan during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesion of unknown etiology; PRE: predation by COTS or corallivorous snails.

14.6 Algae and Algal Disease

14.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Agrihan was 48% (SE 2.2). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 74% occurred along the central part of the west coast in the northwest and southwest regions (Fig. 14.6.1a, top left panel). The habitat in this area had pavement, bedrock, and rubble of medium to medium-high complexity. Other surveys in the southwest and northwest regions also showed high macroalgal cover with means of 66% and 64%. In the southern half of the southwest region, the towed-diver survey with the lowest mean macroalgal cover of 1.7% occurred in the vicinity of Agrihan Anchorage (for place-names and their locations, see Figure 14.2a in Section 14.2: "Survey Effort").

TOAD surveys completed at Agrihan during MARAMP 2003 were conducted at depths of 20–165 m. Analyses of TOAD video footage obtained from 8 surveys suggested that there was almost no macroalgae, at least as seen in a majority of images (Fig. 14.6.1a, top left panel). Macroalgae were present in only a single video frame.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats at Agrihan was 23% (SE 2.8). The survey with the highest mean macroalgal cover of 37% occurred in the northernmost part of the northwest region (Fig. 14.6.1a, middle left panel). Habitat complexity was medium to medium-high in this area. The second-greatest mean macroalgal cover of 33% was found during a survey completed in the northeast region. The survey with the lowest mean macroalgal cover of 2.2% occurred around the southern point of Agrihan over habitat with high complexity.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats at Agrihan was 9% (SE 1.4%). The survey with the highest mean macroalgal cover of 21% occurred in the northeast region (Fig. 14.6.1a, bottom left panel), over medium-complexity habitat that included rock ridges with boulders in between, boulders on sand, and a gentle slope. The lowest macroalgal-cover values, with means of 3.4%–6.6%, were recorded during 3 surveys conducted in the southwest region.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats around Agrihan were conducted using the line-point-intercept method. No macroalgae were observed at any of the REA sites surveyed. Turf-algal cover ranged from 35.3% to 53.9% with an overall mean of 46% (SE 5.5). The highest turf-algal cover was recorded in the southeast region at REA site AGR-01. Relatively high (48%) turf-algal cover also was found at AGR-04 in the northwest region. AGR-02 in the southwest regions had the lowest turf-algal cover (Fig. 14.6.1b).

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Agrihan was 9% (SE 0.6). The survey with the highest mean crustose-coralline-red algal cover of 19% occurred in the southwest region (Fig 14.6.1a, top right panel). The lowest cover values of crustose coralline red algae with means of 0%–3% were recorded during 3 surveys: near Agrihan Anchorage in the southwest region, at the southern tip of this island, and in the northern part of the southeast region.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Agrihan was 6% (SE 0.8). The survey with the highest mean crustose-coralline-red-algal cover of 9% occurred in the northernmost part of the northwest region (Fig. 14.6.1a, middle right panel). The lowest mean crustose-coralline-red algal cover of 2.3% was recorded during surveys in the northeast region and around the southern tip of this island.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae around Agrihan was 10% (SE 1). The survey with the highest mean crustose-coralline-red algal cover of 20% occurred in the northernmost part of the northwest region (Fig. 14.6.1a, bottom right panel). The dominant habitat in this area was of continuous reef and ridges of medium to very high complexity. In comparison with this survey, all other towed-diver surveys conducted at Agrihan in 2005 recorded low levels ($\leq$ 7.5%) of mean crustose-coralline-red-algal cover. The lowest mean crustose-coralline-red algal cover of 3.5% was recorded during a survey in the northwest region.

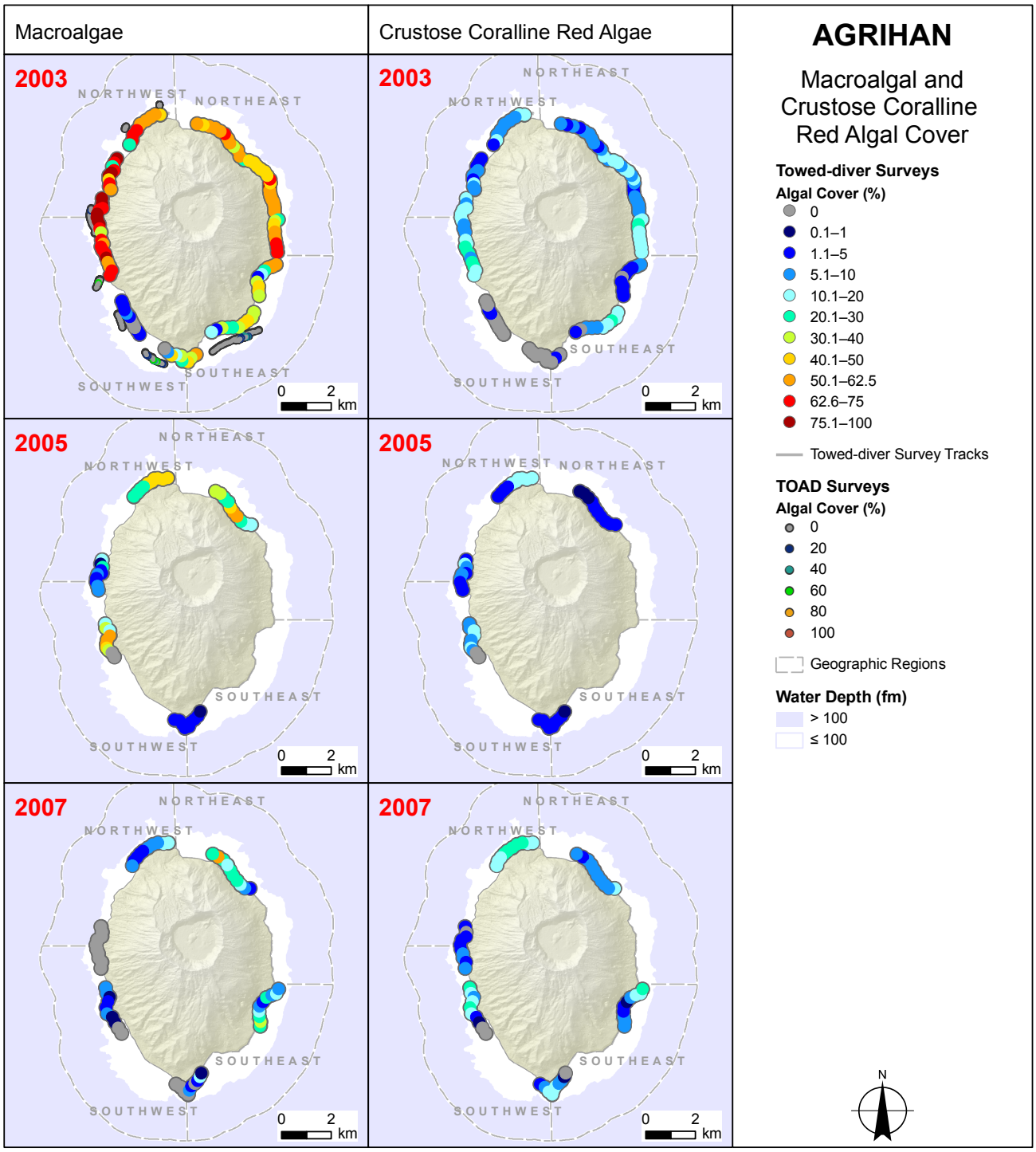


Figure 14.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Agrihan during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats around Agrihan were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 8.8% with an overall mean of 4% (SE 2.6). The survey with the highest cover of crustose coralline red algae occurred in the northwest region at AGR-04 (Fig. 14.6.1b). No crustose coralline red algae were recorded at AGR-02 in the southwest region.

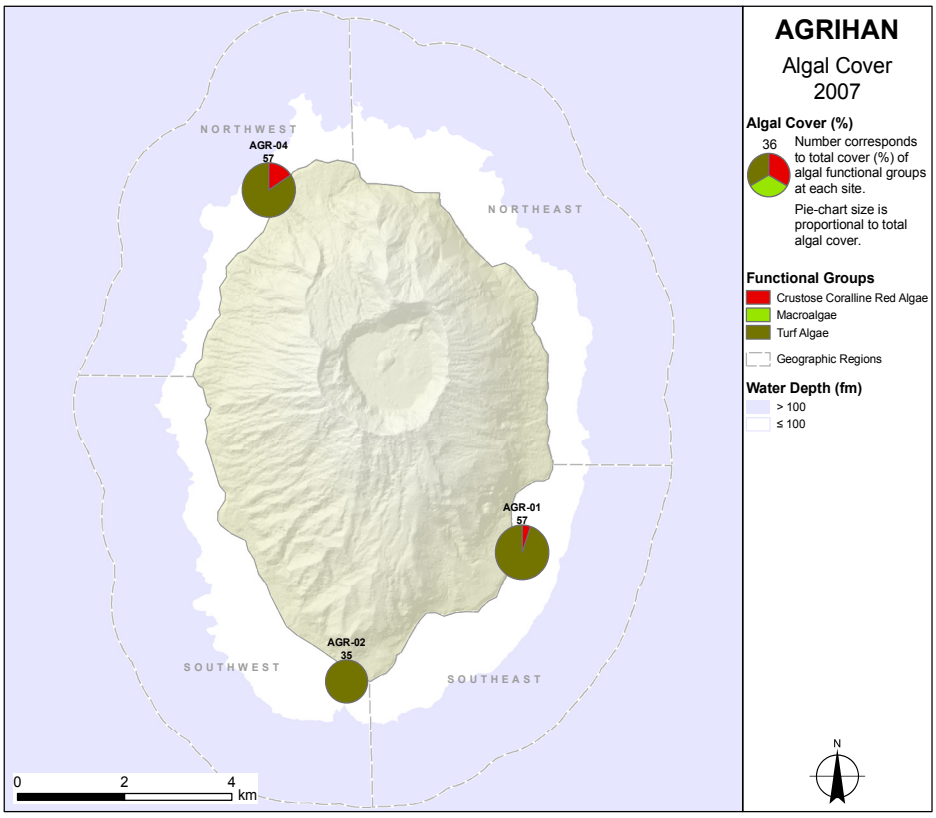


Figure 14.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method at Agrihan during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

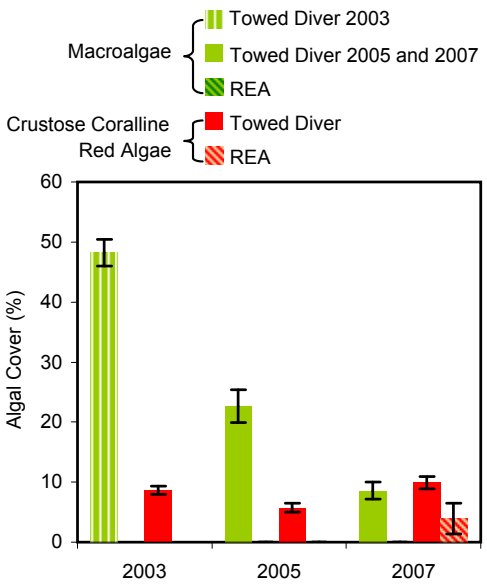


Figure 14.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Agrihan during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA algal-cover surveys using the line-point-intercept method were conducted at Agrihan in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, islandwide mean cover of macroalgal populations around Agrihan, based on towed-diver surveys, decreased considerably from 23% (SE 2.8) in 2005 to 9% (SE 1.4) in 2007 (Fig. 14.6.1c). When considering survey results, keep in mind that turf algae was included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Also, fewer surveys were conducted around Agrihan in 2005 and 2007 (when surveys were limited to one day) than in 2003. Other factors could have contributed to differences in estimates of algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Crustose-coralline-red-algal populations around Agrihan, based on towed-diver surveys of forereef habitats, varied slightly between MARAMP survey years and was ≤ 10% for each of the 3 MARAMP survey years. In 2003, the highest cover of crustose coralline red algae was recorded during a towed-diver survey completed in the southwest region, but, in 2005 and 2007, the highest cover was found during the northernmost survey in the northwest region. Since many surveys documented cover values ≤ 5%, no consistent spatial trend was observed between years for the lowest values of crustose-coralline-red-algal cover.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 6 sites on forereef habitats at Agrihan. In the field, 18 macroalgal genera (6 red, 8 green, and 4 brown), containing at least 18 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. AGR-05 in the northwest region had the highest macroalgal generic diversity with 11 genera, containing 11 species, documented in the field. The lowest macroalgal generic diversities were found at AGR-02 and AGR-06 in the southwest region with 2 species representing 2 genera recorded.

Species of the green algal genus *Neomeris* were common at Agrihan in 2003, occurring in 25% of sampled photoquadrats and at 5 of the 6 sites surveyed (Fig. 14.6.1d, top panel). The highest occurrence of the genus *Neomeris* was found in the northwest region at AGR-04, where it was observed in 50% of sampled photoquadrats. The green alga *Caulerpella ambigua* and species of the calcified green algal genus *Halimeda* were common members of the algal community at AGR-01 in the southeast region. Although the brown algal genus *Lobophora* had the highest overall occurrence (27.8%) of any algal genus seen in the sampled photoquadrats, it was recorded only at AGR-05 and AGR-06 in the northwest and southwest regions, occurring in 83.3% of photoquadrats sampled at each site. Of the remaining 14 taxa tentatively identified, only species of the red algal genus *Amphiroa* were observed at more than 2 sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Agrihan.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2003, occurring in 86.1%, 44.4%, and 23.6% of photoquadrats sampled at Agrihan (Fig. 14.6.1d, top panel). Turf algae were ubiquitous across all sites, while crustose coralline red algae and cyanbacteria were missing only from a single site in the southwest region, AGR-03 or AGR-02, respectively. Both crustose coralline red algae and cyanobacteria had higher occurrence values in the northwest region than in other regions.

During MARAMP 2005, REA benthic surveys were conducted at 3 sites on forereef habitats at Agrihan. In the field, 9 macroalgal genera (2 red, 4 green, and 3 brown), containing at least 9 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, nongeniculate calcified red algae, and cyanophytes—were observed. AGR-06 in the southwest region had the highest macroalgal generic diversity with 7 genera, containing 7 species, documented in the field. The lowest macroalgal generic diversity was found at AGR-02, located farther south in the southwest region, with 6 species representing 6 genera recorded.

Species of the brown macroalgal genera *Lobophora* and *Dictyota* and the red algal genus *Jania* were all ubiquitous at every site surveyed at Agrihan in 2005, occurring in 80.6%, 16.7%, and 63.9% of sampled photoquadrats (Fig. 14.6.1d, middle panel). Species of the green algal genus *Dictyosphaeria,* although found at only 1 site, was observed in 41.7% of photoquadrats sampled at AGR-06. Of the 9 macroalgal species tentatively identified in the field, only a select few showed any pattern of spatial distribution. Species of *Lobophora* were most prevalent in the northwest region, and the lowest occurrence (41.7%) of this genus was found at AGR-02 in the southwest region. Species of *Jania* were less common at AGR-02 than at AGR-04 in the northwest region, occurring in 16.7%–100% of sampled photoquadrats at these 2 sites.

Turf algae and crustose coralline red algae were both abundant in 2005, occurring in 91.7% and 55.6% of photoquadrats sampled at Agrihan (Fig. 14.6.1d, middle panel). Cyanobacteria, found at 2 of the 3 sites surveyed, were a minor component of the algal community at Agrihan, occurring in 8.3%–25% of photoquadrats sampled at AGR-06 in the southwest region and AGR-04 in the northwest region. Nongeniculate, calcified, branched red algae, also a minor component of this algal community, were recorded in 8.3% of photoquadrats sampled at only 1 site, AGR-04.

During MARAMP 2007, REA benthic surveys were conducted at 3 sites on forereef habitats at Agrihan. In the field, 19 macroalgal genera (9 red, 6 green, and 4 brown), containing at least 19 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. AGR-01 in the southeast region had

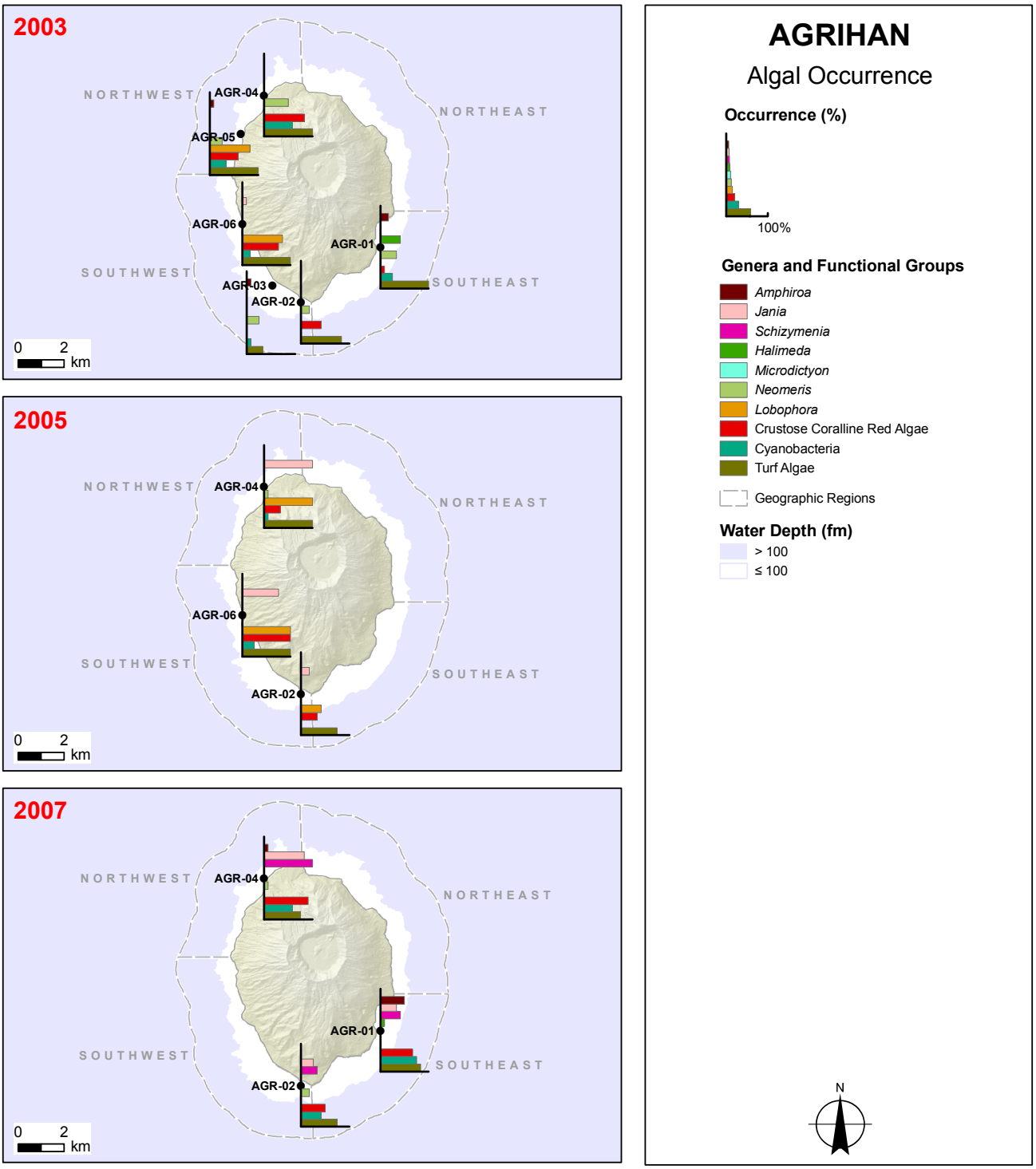


Figure 14.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Agrihan during MARAMP 2003, 2005, and 2007. Occurrence is equivalent to the percentage of photo-quadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

the highest macroalgal generic diversity with 15 genera, containing 15 species, documented in the field. The lowest macroalgal generic diversity was found near the southern tip of this island at AGR-02 in the southwest region with 6 species representing 6 genera recorded.

Species of the red macroalgal genera *Schizymenia* and *Jania* were ubiquitous at every site surveyed at Agrihan in 2007, occurring in 58.3% and 47.2% of sampled photoquadrats (Fig. 14.6.1d, bottom panel). Species of *Dictyota* also were ubiquitous at every site surveyed, occurring in 16.7%–33.3% of sampled photoquadrats at Agrihan. Of the 19 macroalgal genera tentatively identified in the field, 12 were found only at 1 site, making distinctive spatial patterns of distribution difficult to determine for most macroalgae at Agrihan. However, species of *Schizymenia* were observed in more sampled photoquadrats AGR-04 (100%) in the northwest region than at AGR-02 (33.3%) in the southwest region. Species of *Jania* were seen in a similar pattern of distribution, occurring in 83.3% and 25% of sampled photoquadrats at AGR-04 and AGR-02.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2007, occurring in 77.8%, 69.4%, and 58.3% of photoquadrats sampled at Agrihan (Fig. 14.6.1d, bottom panel). Crustose coralline red algae were more prevalent in the northwest region at AGR-04 than in the southwest region at AGR-02, where they were found in 91.7% and 50% of photoquadrats sampled at those sites. No other patterns of spatial distribution were apparent for these functional groups.

The number of macroalgal genera recorded on forereef habitats at Agrihan decreased from 18 to 9 between MARAMP 2003 and 2005 but increased to 19 during MARAMP 2007. Differences in survey effort and other factors likely can account for small changes in estimated macroalgal diversity (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Overall patterns of distribution for common macroalgal genera did not fluctuate dramatically between MARAMP survey years. Species of *Dictyota* were consistently prominent members of the macroalgal community during the 3 survey years, with mean occurrence of 4.2%–22.2% and a slight increasing change in abundance (Fig. 14.6.1d). Species of *Lobophora* also were abundant members of the macroalgal community with occurrence values of 27.7% in 2003 and 80.6% in 2005; however, no members of this genus were documented in 2007. Species of *Jania* showed an increase in occurrence from 1.4% in 2003 to 63.9% in 2005 but a decrease in occurrence to 47.2% in 2007.

Across the 3 MARAMP survey years, crustose coralline red algae occurred in 44.4%–69.4% of photoquadrats sampled at Agrihan, with a slight increase in abundance each year (Fig. 14.6.1d). No temporal trends in abundance were observed on forereef habitats at Agrihan for turf algae or cyanobacteria, which occurred in 77.8%–91.7% and 11.1%–58.3% of sampled photoquadrats in the 3 survey years.

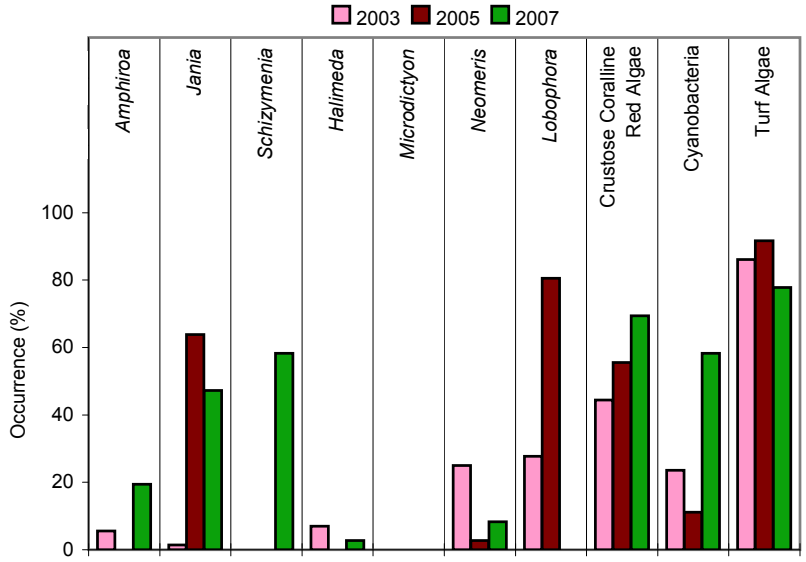


Figure 14.6.1f. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Agrihan during MARAMP 2003, 2005, and 2007.

14.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 3 sites on forereef habitats at Agrihan. These surveys covered a total reef area of 900 m^2. No cases of coralline-algal disease were detected.

14.7 Benthic Macroinvertebrates

14.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Agrihan through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during the REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 6 REA surveys and 12 towed-diver surveys were conducted around Agrihan. In 2005 and 2007, 3 REA surveys and 5 and 6 towed-diver surveys were performed at Agrihan. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, both REA and towed-diver surveys suggested low daytime macroinvertebrate abundance on forereef habitats around Agrihan compared to other surveyed sites in the Mariana Archipelago. Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean benthic macroinvertebrate density around Agrihan—from towed-diver benthic surveys during the MARAMP 2003, 2005, and 2007—are shown later in this section (Figs.14.7.1b, d, f, and h).

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at 2 of the 6 REA sites and in 9 of the 12 towed-diver surveys conducted around Agrihan (Fig. 14.7.1a, top panel). The overall mean density of giant clams from REA surveys was 0.83 organisms 100 m^{-2} (SE 0.65), and the islandwide mean density from towed-diver surveys was 0.03 organisms 100 m^{-2} (SE 0.01). Survey results suggest that giant clams were most abundant at REA site AGR-02 in the southwest region with 4 organisms 100 m^{-2}. Among all towed-diver surveys around Agrihan, a survey completed along the western shore had the highest mean density of giant clams with 0.14 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.67 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.06 organisms 100 m^{-2}, also recorded along the western shoreline; segment densities ranged from 0 to 0.14 organisms 100 m^{-2}.

During MARAMP 2005, giant clams were observed at 1 of the 3 REA sites surveyed and in all 5 towed-diver surveys conducted around Agrihan (Fig. 14.7.1a, middle panel). The density of giant clams at AGR-02 was 1 organism 100 m^{-2}. The overall mean density from towed-diver surveys was 0.04 organisms 100 m^{-2} (SE 0.01). Among all towed-diver surveys around Agrihan, the surveys completed along the western shore had the highest mean densities of giant clams with 0.05 and 0.08 organisms 100 m^{-2}; segment densities from both these surveys ranged from 0 to 0.34 organisms 100 m^{-2}.

During MARAMP 2007, giant clams were observed at all 3 REA sites surveyed and in all 6 towed-diver surveys conducted at Agrihan (Fig. 14.7.1a, bottom panel). The sample mean density of giant clams from REA surveys was 0.56 organisms 100 m^{-2} (SE 0.22), and the overall mean density from towed-diver surveys was 0.04 organisms 100 m^{-2} (SE 0.01). Survey results suggest that giant clams were most abundant at AGR-02 with 1 organism 100 m^{-2}. Among all towed-diver surveys around Agrihan, the surveys completed along the western coast had the highest mean densities of giant clams with 0.06 organisms 100 m^{-2} for both surveys; segment densities for these surveys ranged from 0 to 0.22 organisms 100 m^{-2}.

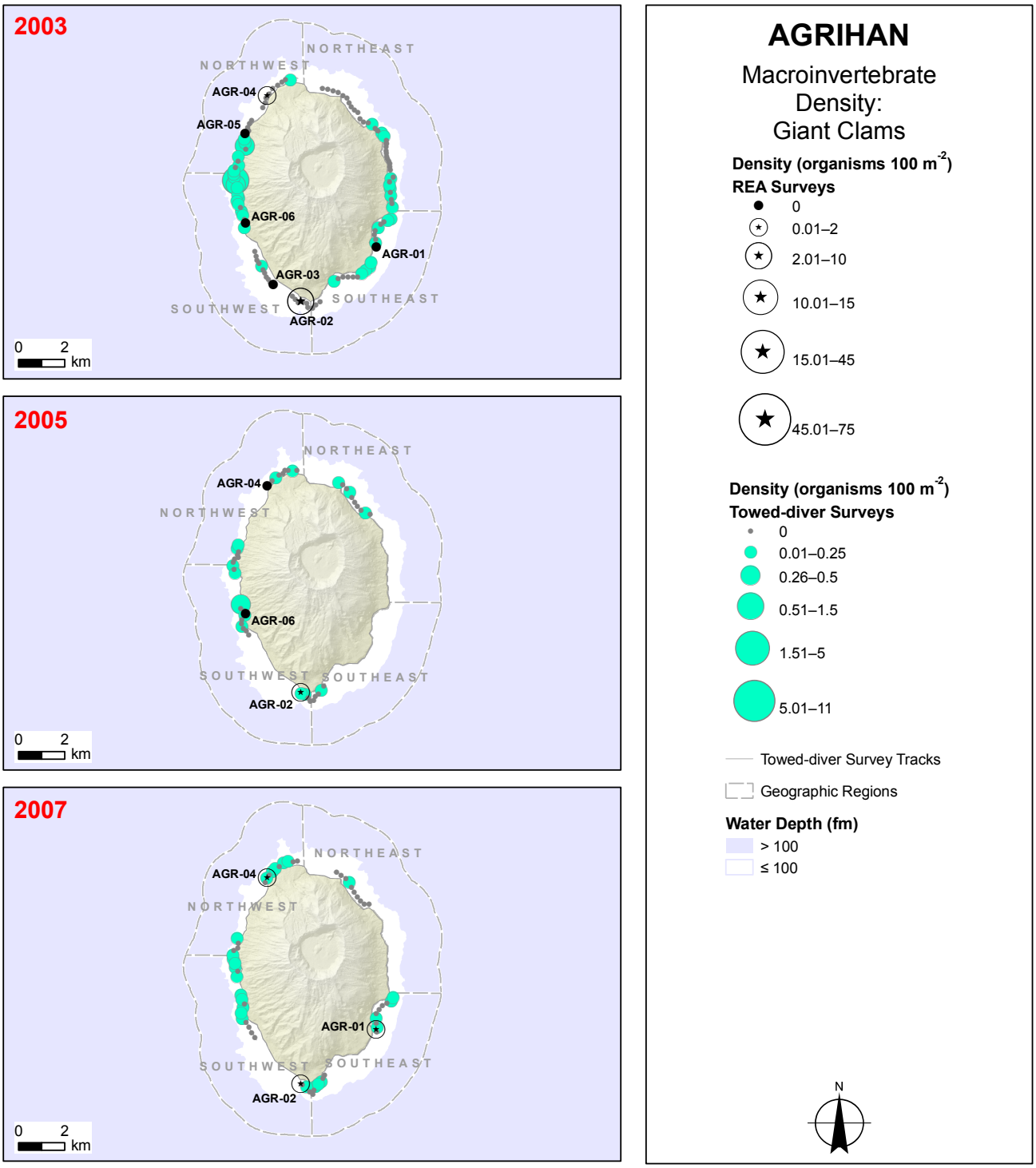


Figure 14.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Agrihan in 2003, 2005, and 2007.

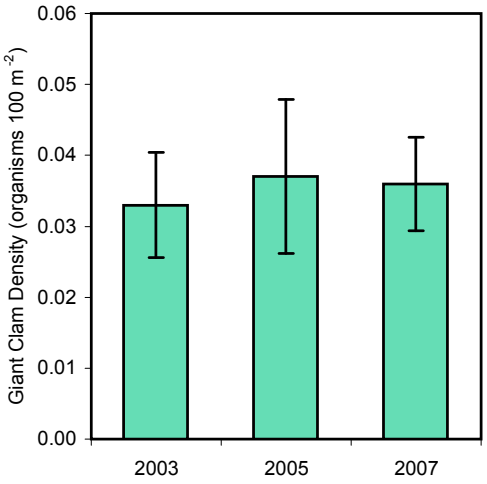


Figure 14.7.1b. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Agrihan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested low abundance of giant clams around Agrihan during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago. The overall observed mean density of giant clams around Agrihan was consistent between survey years (Fig. 14.7.1b), and giant clams were more abundant along the western shoreline than on the east side of this island. However, survey efforts were different between survey years, with fewer towed-diver surveys conducted along the east coast in 2005 and 2007 than in 2003 (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Crown-of-thorns Seastars

During MARAMP 2003, crown-of-thorns seastars (*Acanthaster planci*) were observed only at 1 of the 6 REA sites surveyed and in 1 of the 12 towed-diver surveys conducted around Agrihan (Fig. 14.7.1c, top panel). AGR-01 had a COTS density of 1 organism 100 m^{-2}. The towed-diver survey in the northeast region had a recording of COTS with a mean density of 0.004 organisms 100 m^{-2} (SE 0.517); segment densities from this survey ranged from 0 to 0.042 organisms 100 m^{-2}.

During MARAMP 2005, no COTS were observed at the 3 REA sites surveyed at Agrihan, but 2 of the 5 towed-diver surveys had recordings of COTS, with an overall mean density of 0.06 organisms 100 m^{-2} (SE 0.028). The towed-diver survey completed in the northeast region had the greatest mean density of COTS with 0.286 organisms 100 m^{-2} (Fig. 14.7.1c, middle panel); segment densities from this survey ranged from 0 to 0.966 organisms 100 m^{-2}. The towed-diver survey in the southwest region had a mean density of 0.016 organisms 100 m^{-2}; segment densities ranged from 0 to 0.068 organisms 100 m^{-2}.

During MARAMP 2007, no COTS were observed at the 3 REA sites surveyed at Agrihan, but 4 of the 6 towed-diver surveys had recordings of COTS, with an overall mean density of 0.017 organisms 100 m^{-2} (SE 0.005). Among all towed-diver surveys around Agrihan, the survey completed in the northeast region had the highest mean density with 0.038 organisms 100 m^{-2} (Fig. 14.7.1c, bottom panel); segment densities from this survey ranged from 0 to 0.14 organisms 100 m^{-2}. The 2 surveys conducted along the western coast had mean COTS densities of 0.031 and 0.026 organisms 100 m^{-2}; segment densities from both these surveys ranged from 0 to 0.143 organisms 100 m^{-2}.

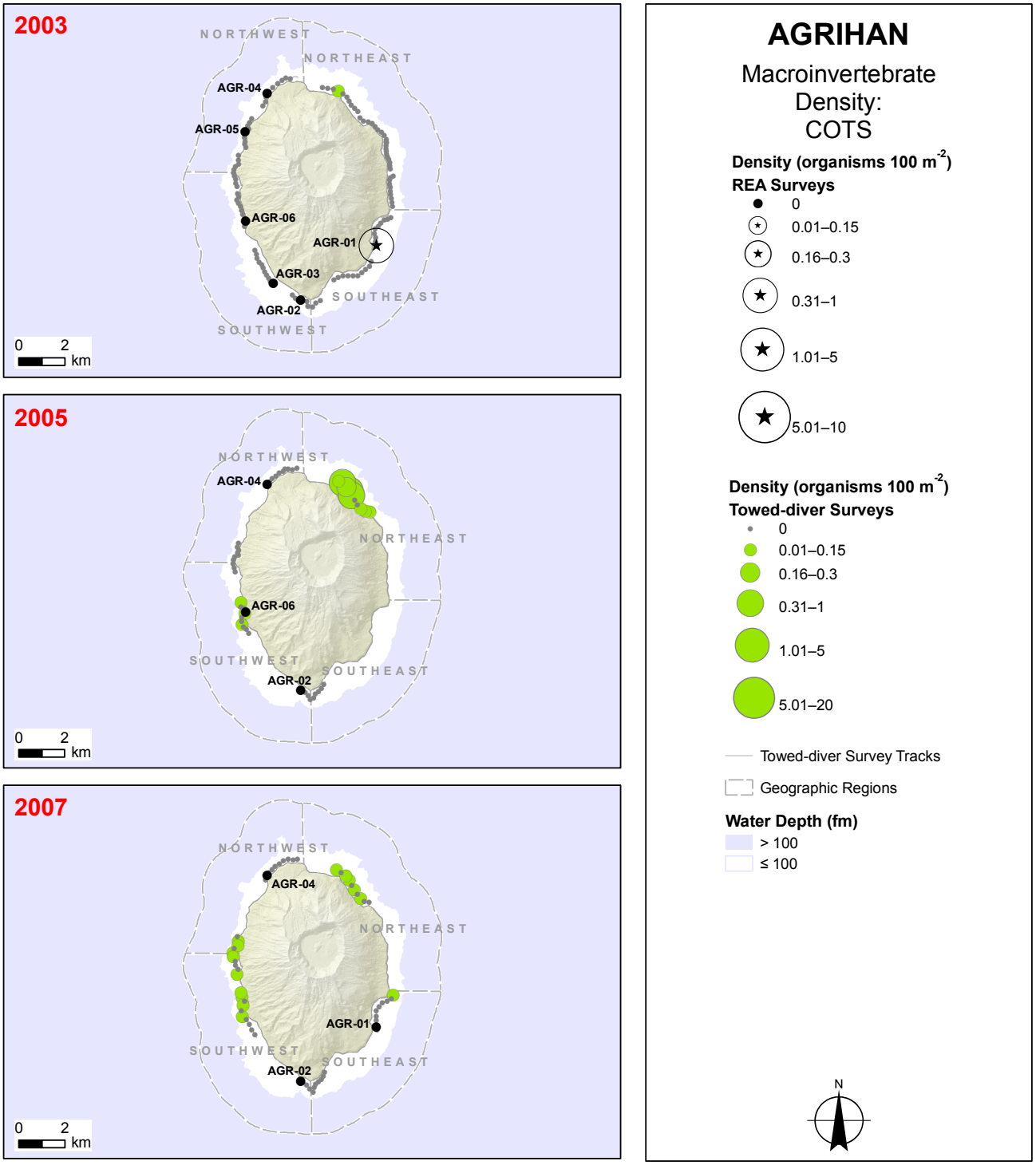


Figure 14.7.1c. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Agrihan during MARAMP 2003, 2005, and 2007.

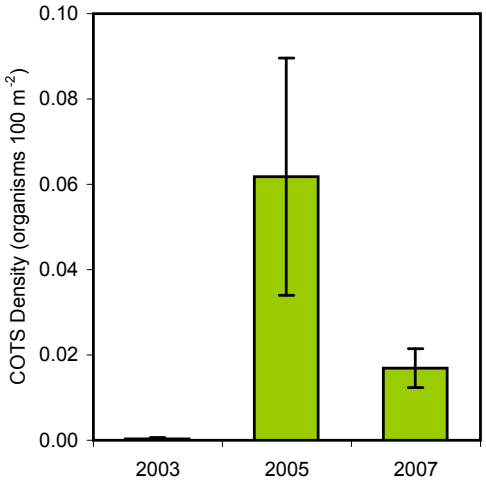


Figure 14.7.1d. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver surveys conducted on forereef habitats around Agrihan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested that COTS densities around Agrihan were higher in 2005 than in 2003 and 2007 (Fig. 14.7.1d). Given that these corallivorous seastars can decimate a reef, understanding whether their observed densities signify an outbreak is important. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure established for using scuba divers to conduct MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms km^{-2} (0.15 organisms 100 m^{-2}), and the level of dead coral present was at least 40%. Using this definition only in terms of density and considering each towed-diver survey as an individual reef area, only one localized area was found with relatively high densities that suggest it was undergoing an outbreak. This area was in the northeastern region where densities from towed-diver surveys during MARAMP 2005 were estimated at 0.29 organisms 100 m^{-2}.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at only 1 of the 6 REA sites surveyed and in 8 of the 12 towed-diver surveys conducted around Agrihan (Fig. 14.7.1e, top panel). The density of sea cucumbers at AGR-01 was 2 organisms 100 m^{-2}; these sea cucumbers were from the genus *Actinopyga*. The overall mean density of sea cucumbers from towed-diver surveys was 0.004 organisms 100 m^{-2} (SE 0.001). Among all towed-diver surveys around Agrihan, the survey completed in the southeast region had the highest mean density with 0.024 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.064 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.01 organisms 100 m^{-2}, recorded along the southwestern shore; segment densities ranged from 0 to 0.101 organisms 100 m^{-2}.

During MARAMP 2005, no sea cucumbers were observed at the REA sites surveyed around Agrihan, but 2 of the 5 towed-diver surveys had recordings of sea cucumbers (Fig. 14.7.1e, middle panel), with an overall mean density of 0.003 organisms 100 m^{-2} (SE 0.002). The 2 towed-diver surveys with observations of sea cucumber were completed along the western shoreline with mean densities of 0.011 and 0.005 organisms 100 m^{-2}; segment densities from these surveys ranged from 0 to 0.058 organisms 100 m^{-2}.

During MARAMP 2007, no sea cucumbers were observed at the REA sites surveyed around Agrihan, but 3 of the 6 towed-diver surveys had recordings of sea cucumbers (Fig. 14.7.1e, bottom panel), with an overall mean density of 0.006 organisms 100 m^{-2} (SE 0.003). Among all towed-diver surveys around Agrihan, the survey completed along the western shore had the highest mean density of sea cucumbers with 0.014 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.143 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers was 0.01 organisms 100 m^{-2}, recorded along the southern shore; segment densities ranged from 0 to 0.06 organisms 100 m^{-2}.

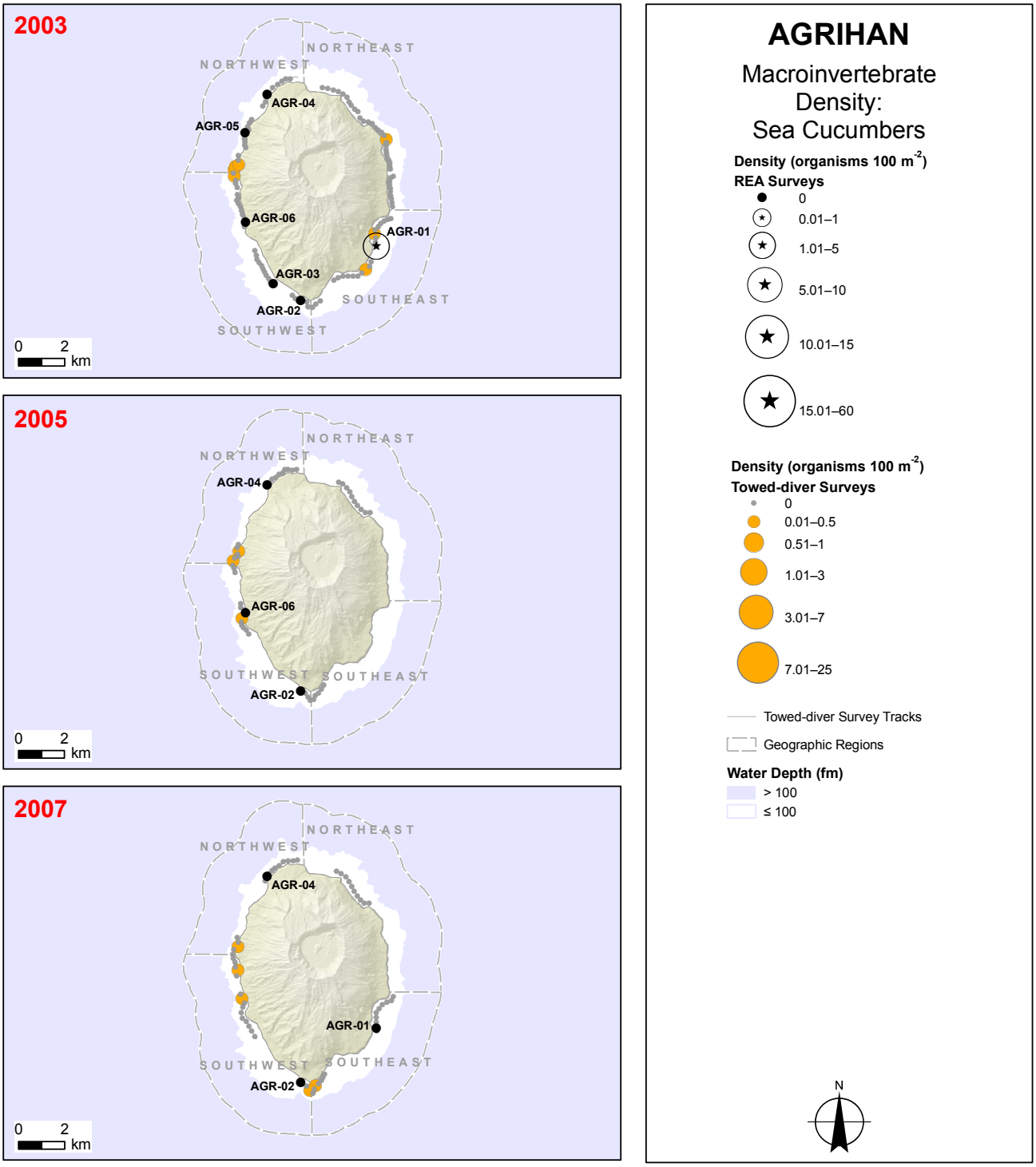


Figure 14.7.1e. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Agrihan during MARAMP 2003, 2005, and 2007.

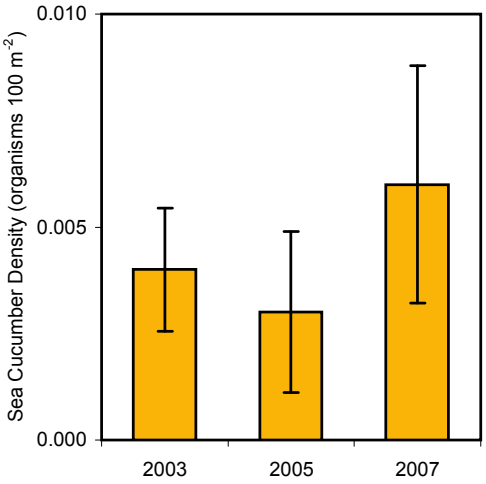


Figure 14.7.1f. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Agrihan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested extremely low daytime abundance of sea cucumbers around Agrihan during MARAMP 2003, 2005, and 2007, relative to the rest of the Mariana Archipelago. The overall observed mean density of sea cucumbers was relatively consistent between MARAMP survey years (Fig. 14.7.1f). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Sea Urchins

During MARAMP 2003, sea urchins were observed at all 6 REA sites surveyed and in 10 of the 12 towed-diver surveys conducted around Agrihan (Fig. 14.7.1g, top panel). The sample mean density from REA surveys was 29.33 organisms 100 m^{-2} (SE 15.76), and the overall mean density from towed-diver surveys was 2.69 organisms 100 m^{-2} (SE 0.52). Survey results suggest that sea urchins were most abundant at AGR-05 in the northwest region with a mean density of 90 organisms 100 m^{-2}. AGR-01 in the southeast region had the second-highest mean density with 66 organisms 100 m^{-2}. Rock-boring urchin species from the genus *Echinostrephus* were the dominant macroinvertebrates at all sites, accounting for 92% of sea urchins recorded at AGR-05 and AGR-01. Other genera observed were *Echinothrix, Echinometra,* and *Diadema*. The highest species diversity was found at AGR-05 with representatives from all 4 genera.

Among all towed-divers surveys conducted around Agrihan in 2003, the surveys completed along the western coast had the greatest mean densities with 7.38 and 5.1 organisms 100 m^{-2}; segment densities froms these surveys ranged from 0 to 38.73 organisms 100 m^{-2}. The third-greatest mean density from a towed-diver was 3.09 organisms 100 m^{-2}; recorded in the southeast region; segment densities from this survey ranged from 0 to 11.16 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed at 1 of the 3 REA sites surveyed and in all 5 towed-diver surveys conducted around Agrihan (Fig. 14.7.1g, middle panel). AGR-06 had a density of 3 organisms 100 m^{-2}; all of these urchins belonged to the genus *Echinothrix.* The overall mean density from towed-diver surveys was 0.48 organisms 100 m^{-2} (SE 0.22). Among all towed-diver surveys around Agrihan, the survey completed in the northeast region had the greatest mean density of 1.34 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 9.94 organisms 100 m^{-2}. The second-greatest mean density of sea urchins was 0.57 organisms 100 m^{-2}, recorded in the northwest region; segment densities ranged from 0 to 3.71 organisms 100 m^{-2}.

During MARAMP 2007, sea urchins were observed at 2 of the 3 REA sites surveyed and in all 6 towed-diver surveys conducted around Agrihan (Fig. 14.7.1g, bottom panel). The sample mean density from REA surveys was 11.89 organisms 100 m^{-2} (SE 8.22), and the overall mean density from towed-diver surveys was 0.40 organisms 100 m^{-2} (SE 0.13). Survey results indicate that sea urchins were most abundant at AGR-04 in the northwest region with a mean density of 27.67 organisms 100 m^{-2}. Species of the rock-boring genus *Echinostephus* accounted for all urchins recorded during REA surveys. Among all towed-diver surveys around Agihan, the survey completed in the southeast region had the greatest mean density of 0.8 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 3.92 organisms 100 m^{-2}. The second-greatest mean density of sea urchins was 0.67 organisms 100 m^{-2}, recorded along the western shoreline; segment densities ranged from 0 to 3.46 organisms 100 m^{-2}.

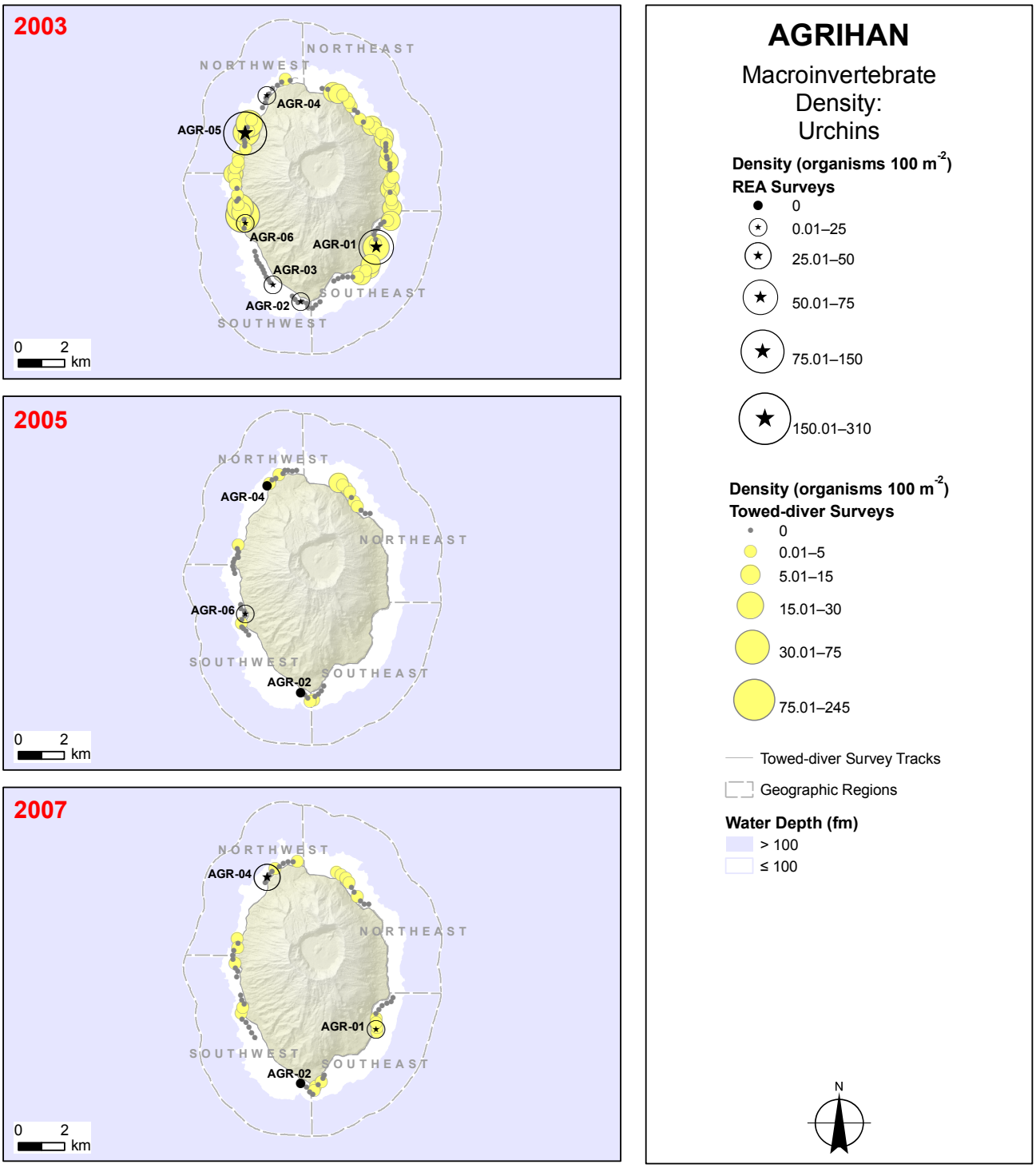


Figure 14.7.1g. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Agrihan during MARAMP 2003, 2005, and 2007.

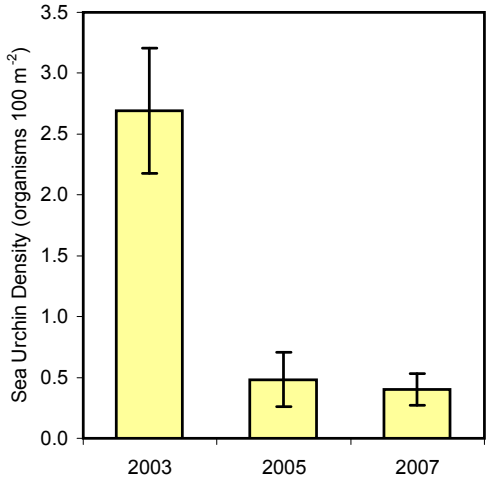


Figure 14.7.1h. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Agrihan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested low daytime abundance of sea urchins around Agrihan during MARAMP 2003, 2005, and 2007, compared to the rest of the Mariana Archipelago. The overall observed mean density of sea urchins around Agrihan was higher in 2003 than in 2005 and 2007 (Fig. 14.7.1h). This variation is not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

14.8 Reef Fishes

14.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 12 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Agrihan. The overall estimated mean biomass of large fishes, calculated as weight per unit area, was 0.84 kg 100 m^{-2} (SE 0.10). Biomass values for large fishes were highest in the northwest region, where sharks, snappers (Lutjanidae), and jacks (Carangidae) were common (Fig. 14.8.1a, top panel). Reef sharks (Carcharhinidae), nurse sharks (Ginglymostomatidae), and snappers together accounted for 70%, or 0.59 kg 100 m^{-2}, of islandwide mean large-fish biomass. Snappers composed the greatest proportion (33%) of islandwide mean large-fish biomass. The twinspot snapper (*Lutjanus bohar*) was the dominant snapper species, contributing 65% or 0.18 kg 100 m^{-2} of snapper biomass. Reef sharks alone accounted for 31% of overall mean biomass of large fishes, with the whitetip reef shark (*Triaenodon obesus*) and grey reef shark (*Carcharhinus amblyrhynchos*) contributing 0.12 kg 100 m^{-2} and 0.14 kg 100 m^{-2} of large-fish biomass.

During MARAMP 2005, 5 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats at Agrihan. The overall estimated mean biomass of large fishes was 0.87 kg 100 m^{-2} (SE 0.08). No clear spatial patterns were seen in the distribution of large-fish biomass at this island (Fig. 14.8.1a, middle panel). Reef sharks and nurse sharks together contributed 55% or 0.48 kg 100 m^{-2} of the overall large-fish biomass. The grey reef shark was the largest component (28%) of overall mean biomass of large fishes. Jacks comprised 19% of overall large-fish biomass. A large school of bigeye trevally (*Caranx sexfaciatus*) was observed in the northwest region.

During MARAMP 2007, 6 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats at Agrihan. The overall estimated mean biomass of large fishes was 1.22 kg 100 m^{-2} (SE 0.85). Biomass values for large fishes, as was seen in 2003, were highest in the northwest region, where sharks and jacks were common (Fig. 14.8.1a, bottom panel). Jacks, reef sharks, and nurse sharks together contributed 88% of overall mean large-fish biomass. Jacks composed the greatest proportion (61%) or 0.74 kg 100 m^{-2} of overall large-fish biomass. As in 2005, a large school of bigeye trevally was observed in the northwest region; consequently, this species accounted for a higher proportion of estimated large-fish biomass than other jacks. Sharks also were frequently seen in 2007 and contributed 27% of overall mean large-fish biomass. The tawny nurse shark (*Nebrius ferrugineus*) and grey reef shark had the highest biomass levels among shark species, contributing 0.12 kg 100 m^{-2} and 0.19 kg 100 m^{-2} of overall mean biomass of large fishes.

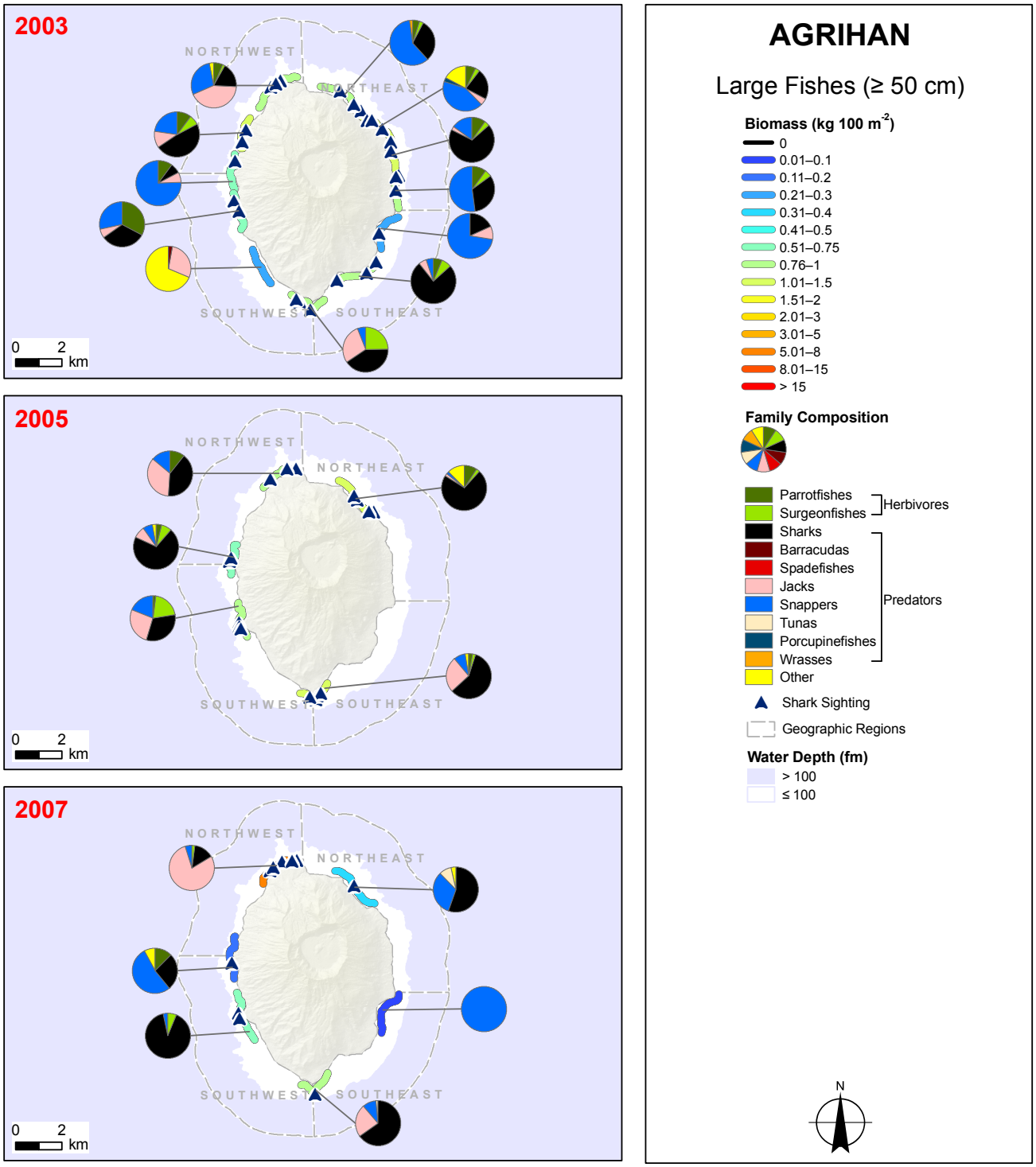


Figure 14.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Agrihan during MARAMP 2003, 2005, and 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

Compared to values recorded at other islands in the Mariana Archipelago, the overall large-fish biomass estimated at Agrihan was about average for observations at unpopulated islands in the Mariana Archipelago (Fig. 14.8.1b). Reef sharks and nurse sharks were common during the 3 MARAMP survey periods. Among shark species, the whitetip reef shark contributed the highest biomass values in 2003 and 2005, while the tawny nurse shark accounted for the highest biomass value in 2007. Snappers and jacks also were common during the 3 survey periods, and the twinspot snapper and bigeye trevally were the most abundant snapper and jack species. Notable observations included a single sighting of the humphead wrasse (*Cheilinus undulatus*) in 2003 and sightings of the dogtooth tuna (*Gymnosarda unicolor*) in 2007.

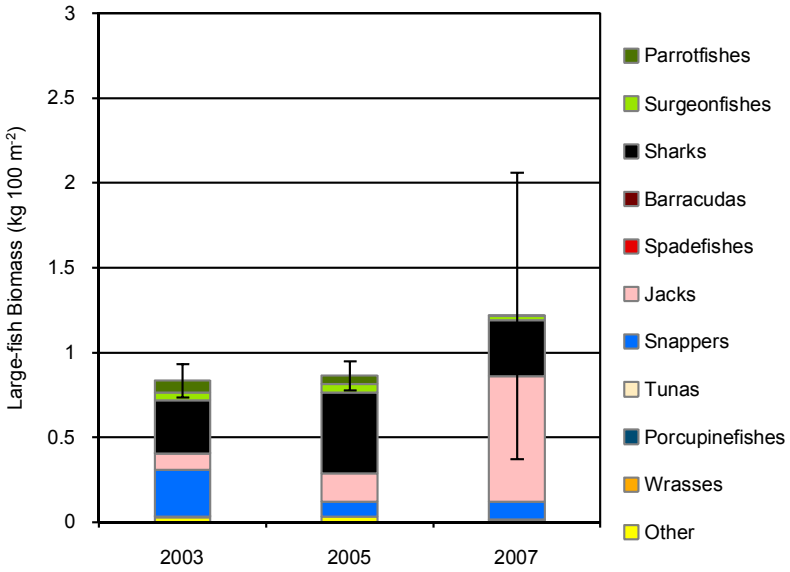


Figure 14.8.1b. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Agrihan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass

Total fish biomass for the 6 REA sites surveyed in forereef habitats at Agrihan during MARAMP 2003 was moderate, compared to other sites in the Mariana Archipelago, with an overall sample mean of 5.85 kg 100 m^{-2} (SE 1.34). The highest biomass was observed at AGR-05 in the northwest region (Fig. 14.8.1c, top panel), where a large school of dark-banded fusilier (*Pterocaesio tile*) was recorded. Surgeonfishes (Acanthuridae) accounted for the greatest proportion (20%) or 1.20 kg 100 m^{-2} of total fish biomass at Agrihan. The whitecheek surgeonfish (*Acanthurus nigricans*) was the largest contributor to surgeonfish biomass, accounting for 24% of surgeonfish biomass. Parrotfishes (Scaridae) accounted for the second-greatest proportion (11%) of total fish biomass. Two grey reef sharks were observed in 2003, both at AGR-03 in the southwest region.

Based on REA surveys conducted during MARAMP 2003, species richness at Agrihan ranged from 4 to 48 species 100 m^{-2}. The lowest diversity was seen at AGR-03 in the southwest region, while the highest diversity was found at AGR-05 in the northwest region (Fig. 14.8.1c, top panel). Among fish families observed at Agrihan, wrasses (Labridae) and surgeonfishes were the most represented with 29 and 15 species recorded. The ornate wrasse (*Halichoeres ornatissimus*) was the most abundant wrasse species, and the orangespine unicornfish (*Naso lituratus*) was the most abundant surgeonfish species. Damselfishes (Pomacentridae) dominated counts with the Vanderbilt's chromis (*Chromis vanderbilti*) and midget chromis (*C. acares*) as the 2 most often seen species.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Agrihan during MARAMP 2005 was moderately high, compared to other sites in the Mariana Archipelago, with an overall sample mean of 14.53 kg 100 m^{-2} (SE 3.67). The highest biomass of 21.87 kg 100 m^{-2} was observed at AGR-04 in the northwest region (Fig. 14.8.1c, middle panel). Reef sharks and surgeonfishes contributed the greatest proportions to total fish biomass at Agrihan. Reef sharks alone composed 19% of overall total fish biomass; 5 whitetip reef sharks were recorded. As in 2003, the whitecheek surgeonfish was the largest contributor (18%) to surgeonfish biomass. Groupers (Serranidae) also were common, with the peacock hind (*Cephalopholis argus*) and darkfin hind (*C. urodeta*) accounting for 78% of grouper biomass.

Based on REA surveys conducted during MARAMP 2005, species richness ranged from 31 to 46 fish species 100 m^{-2}. The highest diversity was found at AGR-04 in the northwest region (Fig. 14.8.1c, middle panel). Wrasses and surgeonfishes again were the most diverse families with 20 and 17 species recorded. The ornate wrasse was the most abundant wrasse species with an overall mean density of 17.60 individuals 100 m^{-2}. The striated surgeonfish (*Ctenochaetus striatus*) was the most abundant surgeonfish, but a number of other species were nearly as abundant: orangespine unicornfish, whitebar surgeonfish (*Acanthurus leucopareius*), brown surgeonfish (*A. nigrofuscus*), and whitecheek surgeonfish. The midget chromis was the most abundant of all species recorded at Agrihan, with an overall mean density of 106.70 individuals 100 m^{-2}.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Agrihan during MARAMP 2007 was fairly high, compared to other sites in the Mariana Archipelago, with an overall sample mean of was 11.32 kg 100 m^{-2} (SE 7.63). The highest biomass of 26.58 kg 100 m^{-2} was observed in the northwest region at AGR-04, where numerous sleek unicornfish

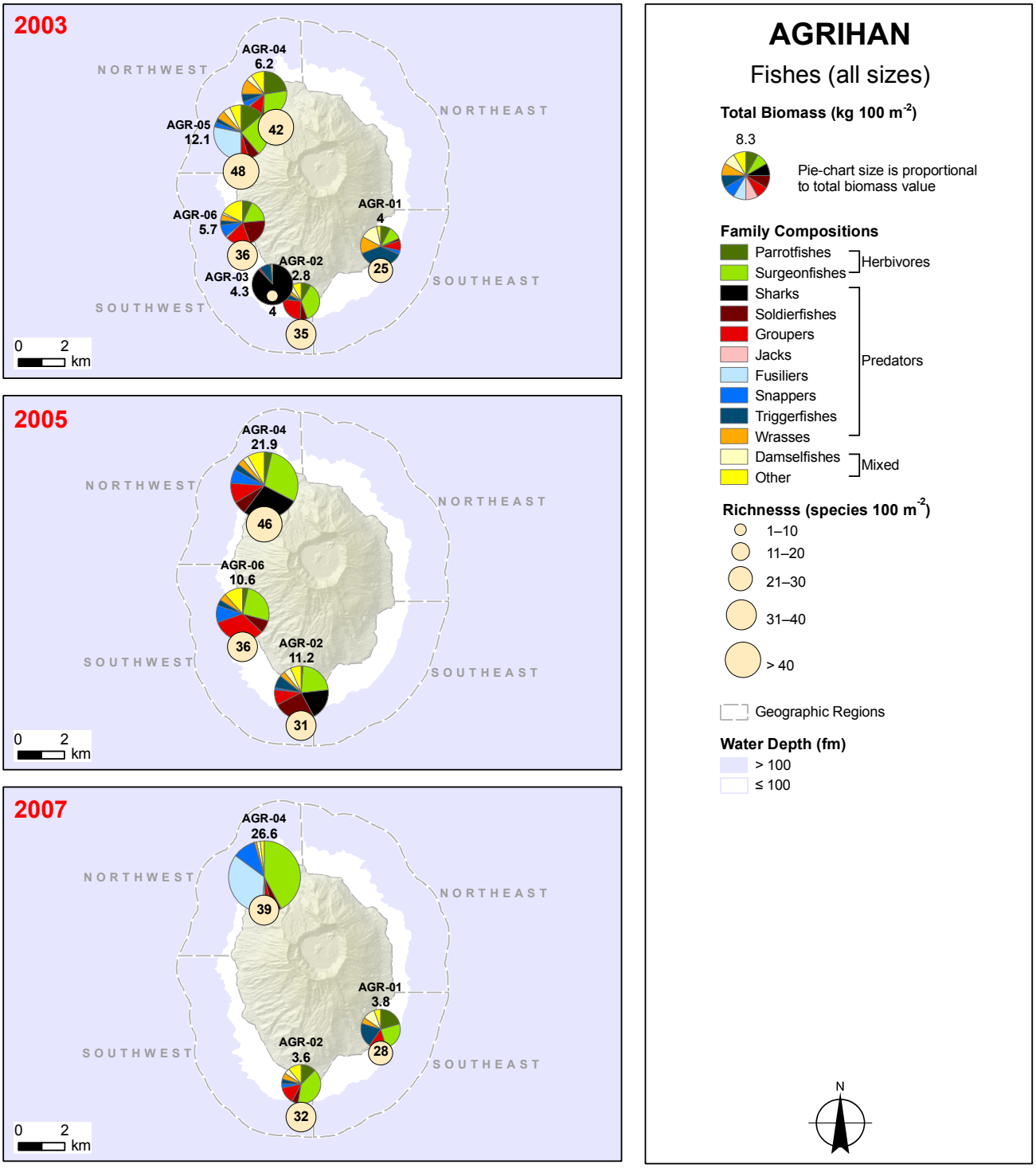


Figure 14.8.1c. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Agrihan during MARAMP 2003, 2005, and 2007.

(*Naso hexacanthus*) and schools of dark-banded fusilier and yellow and blueback fusilier (*Caesio teres*) were recorded (Fig. 148.1c, bottom panel). Surgeonfishes accounted for the greatest proportion (40%) or 4.51 kg 100 m^{-2} of total fish biomass at Agrihan. The sleek unicornfish was the most abundant surgeonfish species, accounting for 46% of surgeonfish biomass. The whitecheek surgeonfish also was commonly recorded, contributing 19% of surgeonfish biomass. No sharks were observed during this survey period.

Based on REA surveys conducted during MARAMP 2007, species richness ranged from 28 to 39 species 100m^{-2}. The highest diversity was found at AGR-04 in northwest region (Fig. 148.1c, bottom panel). Wrasses, damselfishes, and surgeonfishes were the most represented families at Agrihan with 18, 13, and 13 species recorded. The ornate wrasse was the most abundant wrasse species, and the whitebar surgeonfish was the most abundant surgeonfish species. Damselfishes, as in 2003, dominated counts, and the midget chromis was the most abundant of all species with an overall mean density of 134.10 individuals 100 m^{-2}.

During each of the 3 MARAMP survey years, the highest mean total fish biomass from REA surveys conducted in forereef habitats at Agrihan was found in the northwest region. No clear temporal trend was observed, although the overall estimated mean for total fish biomass was highest in 2005, as a result of the observation of 5 whitetip reef sharks at AGR-04 (Fig. 14.8.1d). Surgeonfishes also were abundant, with the whitecheek surgeonfish, orangespine unicornfish, striated surgeonfish, and sleek unicornfish collectively contributing 52%–77% of total surgeonfish biomass over the 3 survey periods.

Site-specific estimates of species richness ranged from 4 to 48 species 100 m^{-2} over the 3 MARAMP survey years, with the highest species richness consistently observed in the northwest region. Wrasses and surgeonfishes were the 2 most diverse families with 22 and 15 species recorded. Damselfishes dominated counts, with the midget chromis and Vanderbilt's chromis as the most abundant damselfish species.

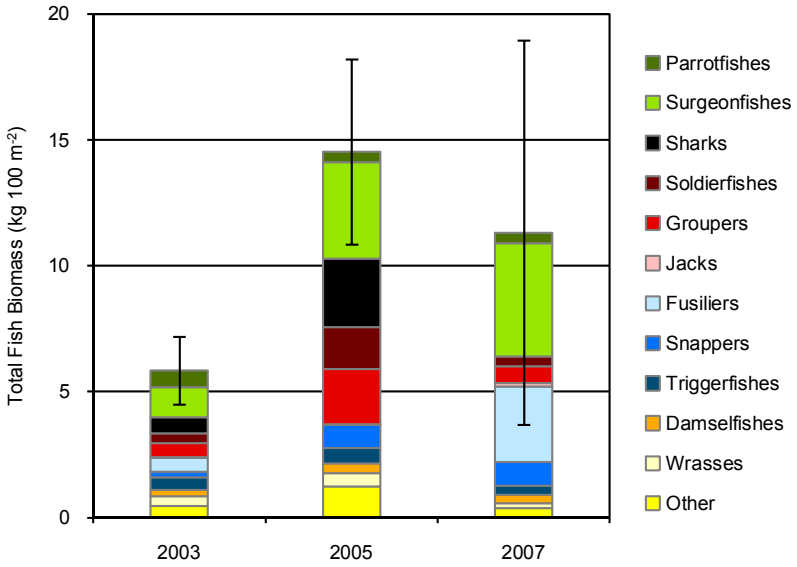


Figure 14.8.1d. Temporal comparison of mean total fish biomass (all species and size classes in kg 100 m^{-2}) values from REA fish surveys of forereef habitats conducted at Agrihan during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

14.9 Marine Debris

14.9.1 Marine Debris Surveys

During MARAMP 2003, no sightings of marine debris were recorded in the 12 towed-diver surveys conducted on forereef habitats around the island of Agrihan. During MARAMP 2005, 2 sightings of derelict fishing gear were documented in the 5 towed-diver surveys conducted on forereef habitats at Agrihan, (Fig. 14.9.1a). Two net fragments were observed near the border between the southeast and southwest regions. During MARAMP 2007, 2 sightings of derelict fishing gear were recorded in the 6 towed-diver surveys conducted on forereef habitats at this island. Net fragments were observed at 1 location in the southeast region, and 1 old fishing line was noted in the northwest region. No munitions, wrecks, or other man-made objects were identified during the 3 MARAMP survey years.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed-divers in their observer comments.

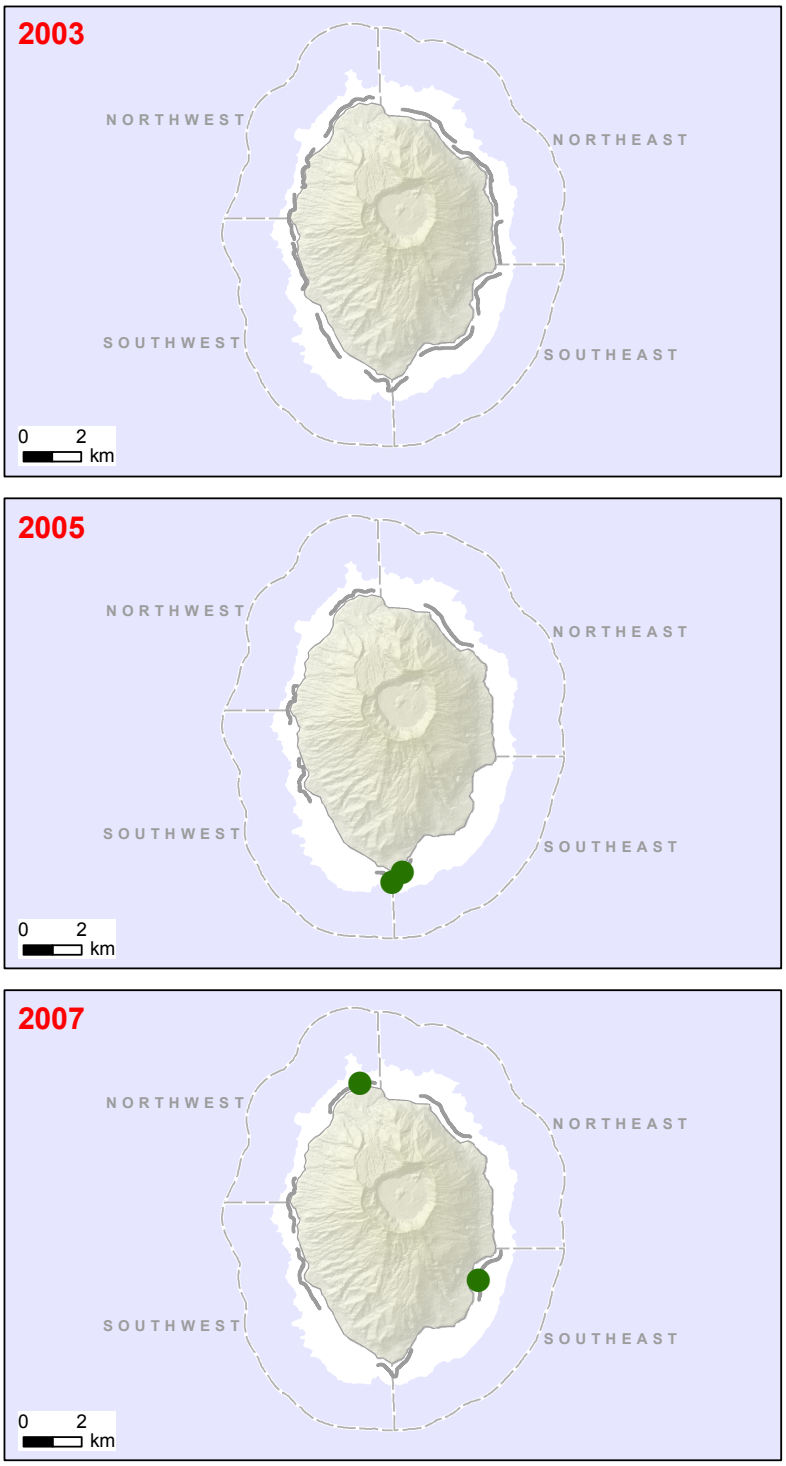


Figure 14.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Agrihan during MARAMP 2005 and 2007. No debris sightings were recorded in 2003. Symbols indicate the presence of specific debris types.

14.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Agrihan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Agrihan and the other 13 islands covered in this report.

Agrihan is the tallest island in the Mariana Archipelago with a maximum elevation of 965 m at the summit crater rim. This island's summit crater is surrounded by steep slopes that continue underwater, dominating the submarine topography. The only historic volcanic eruption recorded at Agrihan occurred in 1917. The lava flow from this eruption breached the summit cone and can be seen both onshore (Figure 14.1.2a, in Section 14.1.2: "Geography"), where it extends the coastline north-northwest of this island, and in adjacent waters, where it created a small, shallow ridge (Figure 14.3.1c, in Section 14.3.1: "Acoustic Mapping"). From observations made during towed-diver surveys, this ridge appeared to support live-hard-coral cover at a slightly higher level (10%–40%) than did the surrounding area during the 3 MARAMP survey years (Figs. 14.10a and b). The habitat in this location was described by towed divers as continuous reef with ridges, some with very high vertical relief and depth changes, and occasional boulder fields.



Figure 14.10a. A northern reef at Agrihan. *NOAA photo by Robert Schroeder*

In the nearshore waters around Agrihan, steep volcanic flanks are interrupted by a shallow shelf at depths of 30–40 m (see Figures 14.3.1b and c in Section 14.3.1: "Acoustic Mapping"). Along southwest Agrihan, the surface of this hard shelf is covered by sand (see Figures 14.3.1g and 14.3.3a in Section 14.3: "Benthic Habitat Mapping and Characterization") and supports little or no cover of live corals or macroalgae (Fig. 14.10b). At the southern tip of this island, in an area where this shelf narrows, high levels of coral cover, relative to other survey areas around Agrihan, were observed during towed-diver surveys in each of the 3 MARAMP survey periods. REA benthic surveys conducted at AGR-02 in the same location had the highest values of coral-colony density and coral cover recorded at REA sites at this island (see Figure 14.5.1b in Section 14.5.1: "Coral Surveys").

On the more exposed east side of Agrihan, the continuing shelf supported low levels of live coral cover, except for one location in the northeast region, where the coastline protrudes slightly and a towed-diver survey ran closer to the shelf edge. Here, coral cover of up to 40% was recorded (Fig. 14.10b, top panel). Elsewhere in the northeast region, live coral cover was low, and high densities of COTS observed in 2005 likely resulted in relatively high levels of stressed-coral cover in this region (see Figure 14.5.1a in Section 14.5.1: "Coral Surveys"). High values of macroalgal cover were recorded on

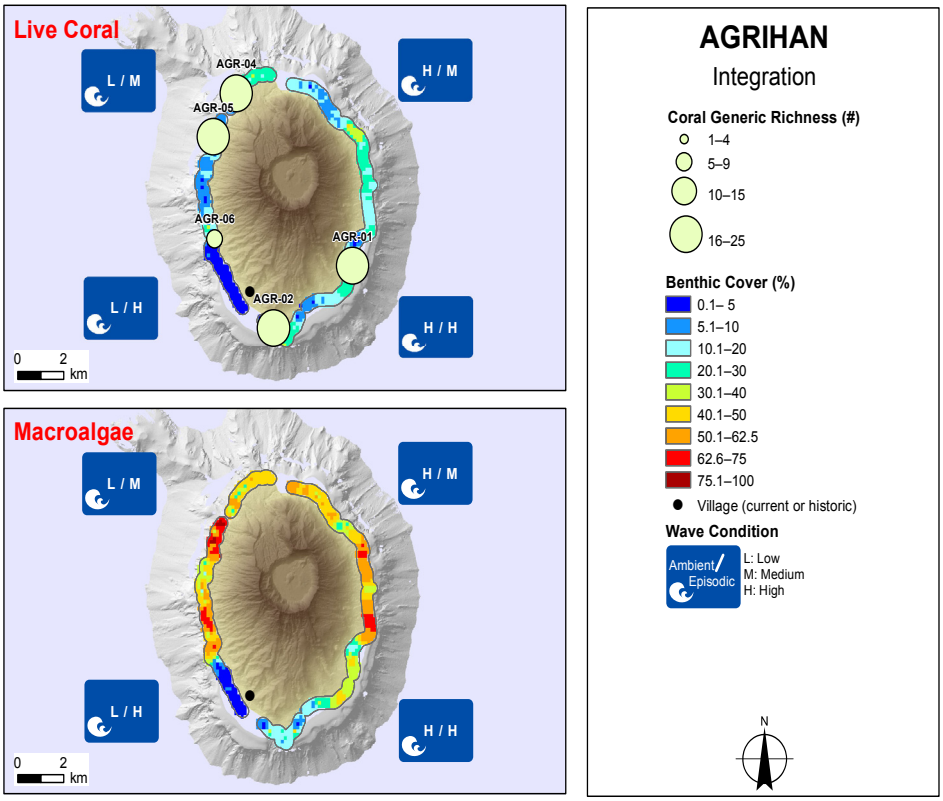


Figure 14.10b. Cover (%) observations of live hard corals and macroalgae from towed-diver benthic surveys and coral generic-richness values from REA benthic surveys conducted on forereef habitats at Agrihan during MARAMP 2003, 2005, and 2007. Values of coral cover and macroalgal cover represent interpolated values from the 3 survey years, and values of coral generic richness represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.

the shelf in the northeast region, compared to other survey areas around southern Agrihan, during towed-diver surveys in each of the 3 survey years. The habitat in this region, as described by towed divers, consisted predominantly of boulders on sand interspersed with pavement.

In the northern section of the southwest region, towed-diver surveys were conducted close to the shelf edge because it runs close to shore. Towed divers found a hard pavement habitat with low sand cover (see Figure 14.3.3a in Section 14.3.3: "Habitat Characterization"), low cover of live corals (predominantly < 30%), and very high macroalgal cover (frequently 75%–100%; Fig. 14.10b, bottom panel), compared to other areas surveyed at Agrihan. Similarly, in the southern part of the northwest region, low cover of live corals and abundant macroalgae were observed, although the habitat type in this area was very different with high-relief, spur-and-groove formations, and boulders collected in channels.

Oceanographic conditions observed around Agrihan showed some spatial variability. Shallow-water CTD casts conducted around this island in 2003 and 2005 suggested that water temperatures were cooler and salinity values were higher in the northern regions than in the well-mixed waters of the southern regions (see Figures 14.4.1a and c in Section 14.4.1: "Hydrographic Data"). This pattern was not seen in 2007, when results from CTD casts in nearshore waters around Agrihan suggested less variation than in previous survey years, apart from one cast location in the southeast region where localized upwelling was observed (Fig. 14.4.1e). Variation between MARAMP survey years may result from differences in season (MARAMP 2007 occurred in May and MARAMP 2003 and 2005 occurred in August and September).

The fish communities observed at Agrihan appeared to have levels of large-fish biomass comparable with estimates for other northern islands in the Mariana Archipelago (see Figure 14.8.1a in Section 14.8.1: "Reef Fish Surveys"; for more details, also see Chapter 3: "Archipelagic Comparisons"). The greatest proportion of overall large-fish biomass was contributed by reef sharks, which were seen regularly during each of the 3 MARAMP survey years. Surgeonfishes also were common, with the whitecheek surgeonfish (*Acanthurus nigricans*), orangespine unicornfish (*Naso lituratus*), striated surgeonfish (*Ctenochaetus striatus*), and sleek unicornfish (*Naso hexacanthus*) collectively constituting 52%–77% of surgeonfish biomass across the 3 survey periods (Fig. 14.10c). With the exception of the low species richness observed at the single REA site that was surveyed only in 2003, fish diversity was relatively high at Agrihan with 25–48 species per site (Fig. 14.8.1c). The superior condition of the fish community at Agrihan, compared to the communities observed at other islands in the Mariana Archipelago, may result from the relative isolation of this island, which is ~ 400 km from Saipan, the nearest densely populated island.

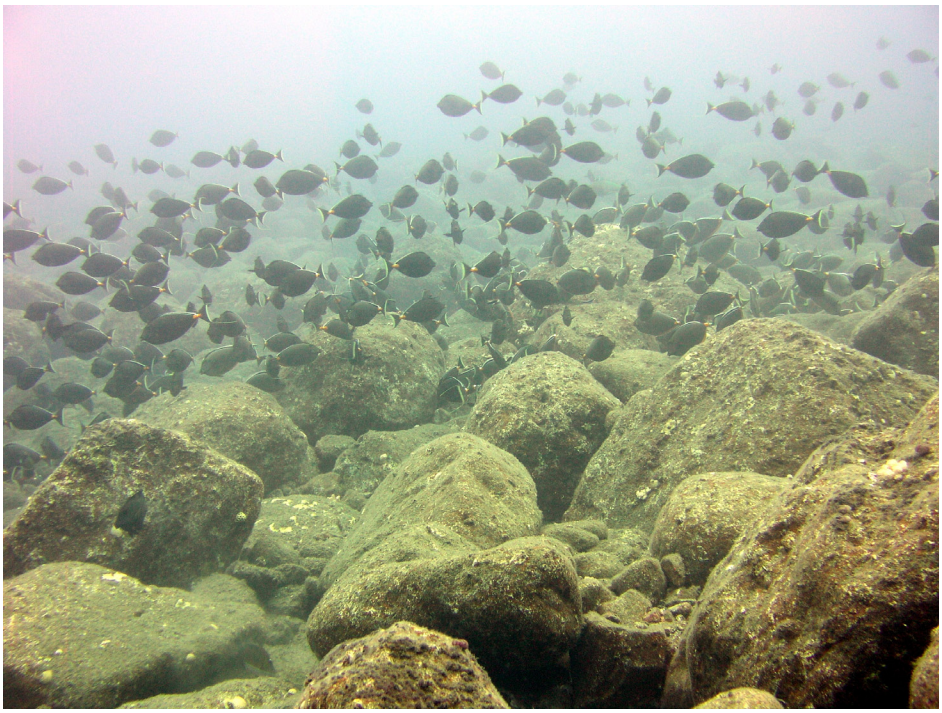


Figure 14.10c. A school of orang-espine unicornfish (*Naso lituratus*) at a boulder habitat at Agrihan. *NOAA photo by Robert Schroeder*

14.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Agrihan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Agrihan chapter are included in the relevant discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Agrihan, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Agrihan and some of the key natural processes influencing these ecosystems:

- Agrihan is 65 km north of Pagan and is one of the largest northern islands in the Mariana Archipelago with a land area of 44.05 km^2.
- Inhabitation of Agrihan has been sporadic over the last 100 years because of volcanic activity. One of the 4 original villages has been resettled, making Agrihan the only island north of Saipan that currently may have a permanent human population.
- As the tallest island in the Mariana Archipelago, with a summit elevation of 965 m, Agrihan is surrounded by steep slopes and sea cliffs.
- Agrihan's seascape is similarly characterized by steep volcanic flanks, which are incised by channels. North-northwest of Agrihan, a lava flow created a submarine ridge and extended the coastline in this area. A shallow shelf is present around this island at depths of 30–40 m.
- Habitats of medium to high complexity were observed in the northwest region and northern part of the southwest region, with low sand cover and primarily low cover of live hard corals compared to levels recorded at other islands in the Mariana Archipelago. Coral cover was higher in the survey area adjacent to the onshore lava flow than in the rest of the northwest region.

- The northeast region of Agrihan had habitats of medium-low to high complexity, including pavement, boulders on sand, and rocky ridges. In the southern part of this region, live coral cover of 10%–50% was recorded adjacent to a flat area observed on the island topography.

- In the southeast region, an area with habitat of low complexity was observed. Sand cover as high as 75%–100% and low cover (< 10%) of live hard corals was recorded during towed-diver surveys of the wide bays of this coastline. That habitat alternated with patches of medium-relief, spur-and groove habitat of higher complexity with lower sand cover (< 30%) and higher live coral cover (10%–62.5%).

- Southwest of Agrihan, a large area had habitat of low to medium-low complexity characterized by high sand cover (75%–100%) and very low coral cover (< 5%).

- Wave model output shows ambient trade wind swells impacting the northeast and southeast regions. Episodic wave energy from storm tracks impacts the southwest and southeast regions and to a lesser extent the northeast and northwest regions.

- Some spatial heterogeneity was seen in 2003 and 2005, with northern waters cooler and more saline than the well-mixed waters in the southern regions. In 2007, water masses around Agrijan were homogeneous, although a large range in water temperatures (3.2˚C) was recorded via nearshore CTD casts. This broad range in temperatures was likely a result of localized upwelling of subsurface waters in the southeast region and to a lesser extent the northwest region.

- Subsurface temperature values from an STR deployed at a depth of 2 m in the southwest region exceeded the coral bleaching threshold in September 2006; however, the duration of this event was < 1 d.

- Observed cover of live hard corals, based on towed-diver surveys, was fairly consistent between the 3 MARAMP survey years, with overall means of 14%–16%. The overall sample mean for live coral cover estimated from REA surveys conducted at 3 sites in 2007 was 30.7%.

- The same 3 REA sites also were surveyed for coral disease in 2007, and overall mean prevalence of disease was 0.01%. Three disease states were recorded: fungal infection, skeletal growth anomalies, and bleaching. Only one case of COTS predation was detected.

- Observations of COTS from towed-diver surveys were virtually nonexistent in 2003. In 2005, observed densities of COTS in the northeast and southwest regions were much higher than densities seen in 2003. A localized area in the northeast region had densities suggesting a possible COTS outbreak. By 2007, population densities had declined.

- During each of the 3 MARAMP survey years, overall observed mean density of sea cucumbers was extremely low and abundance of giant clams was low at Agrihan, compared to densities observed at other islands in the Mariana Archipelago.

- Between MARAMP 2005 and 2007, average cover of macroalgae from towed-diver surveys at Agrihan decreased considerably, by more than 60%. Consistently, in each of the 3 survey years, reefs in the northeast region had the highest macroalgal cover recorded during towed-diver surveys.

- Overall mean crustose-coralline-red-algal cover from towed-diver surveys was < 10% during each of the 3 MARAMP survey years, with little temporal variation. No cases of coralline-algal disease were registered at Agrihan.

- The overall mean large-fish biomass, estimated from towed-diver surveys, was moderate in each of the 3 MARAMP survey years, relative to results from other islands surveyed in the Mariana Archipelago.

- The highest mean biomass from REA surveys for fishes of all sizes was found in the northwest region during the 3 MARAMP survey years. No clear temporal trend was observed, although total mean biomass for Agrihan was highest in 2005 at 14.53 kg 100 m^{-2}, likely a result of the sighting of 5 reef sharks at AGR-04 in the northwest region.

- Mean species richness of reef fishes at Agrihan ranged from 4 to 48 species 100 m^{-2} over the 3 survey years, with the highest species richness consistently observed in the northwest region.

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15 ASUNCION

15.1 Introduction

The island of Asuncion is the third-most northerly island of the 14 islands that make up the Commonwealth of the Northern Mariana Islands (CNMI) and is located at 19°41′ N, 145°24′ E. This island is also known as Asonson, Assongsong, and Asumption. Asuncion is ~ 3 km wide and 3.3 km long and has a land area of 7.86 km^2 (Fig. 15.1a). This island is a steep-sided volcanic cone. The rim of this volcano's crater is the highest point on Asuncion, an elevation of 857 m, and is surrounded by steep slopes that culminate in sea cliffs at the coasts of this island (Fig. 15.1b).



Figure 15.1a. Satellite image of Asuncion (© 2004 DigitalGlobe Inc. All rights reserved).



Figure 15.1b. The steep flanks of Asuncion, as seen from the NOAA Ship *Hi`ialakai* in 2007. *NOAA photo*

15.1.1 History and Demographics

Asuncion is currently unpopulated. As on other islands in the CNMI, Spain in 1695 forced any inhabitants to relocate to Guam (Rogers 1995), and, from then on, Asuncion has been inhabited only intermittently (Mueller-Dombois and Fosberg 1998). In 1909, while under rule by Germany, Asuncion was leased to the Pagan Gesellschaft, a trading association, for exploitation of bird plumage for a period of 3 years, along with Farallon de Pajaros, Maug, Agrihan, Guguan, Sarigan, and Farallon de Medinilla (Spennemann 1999b). During this time, Japanese bird catchers employed on these islands may have resided on Asuncion temporarily, and other fishing or hunting parties also may have resided periodically on this island. Since 1978, the CNMI Constitution has prohibited inhabitation of Asuncion (CNMI Constitution).

Asuncion falls within the Northern Islands Municipality of the CNMI, and the political history of Asuncion follows that of the CNMI as a whole, which is described in more detail in Chapter 1: "Introduction" and Chapter 8: "Saipan," Section 8.1.1: "History and Demographics."

15.1.2 Geography

Asuncion is the steepest of the northern volcanic islands of the Mariana Archipelago (Fig. 15.1.2a). High sea cliffs bound the steepest slopes, located on the northeastern side of Asuncion, and, in contrast, the gentler southwestern slopes are bordered by much lower sea cliffs (Siebert and Simkin 2002–). The southwestern and western flanks are mantled by ash deposits, and landslide scars mark this island's southern flanks.

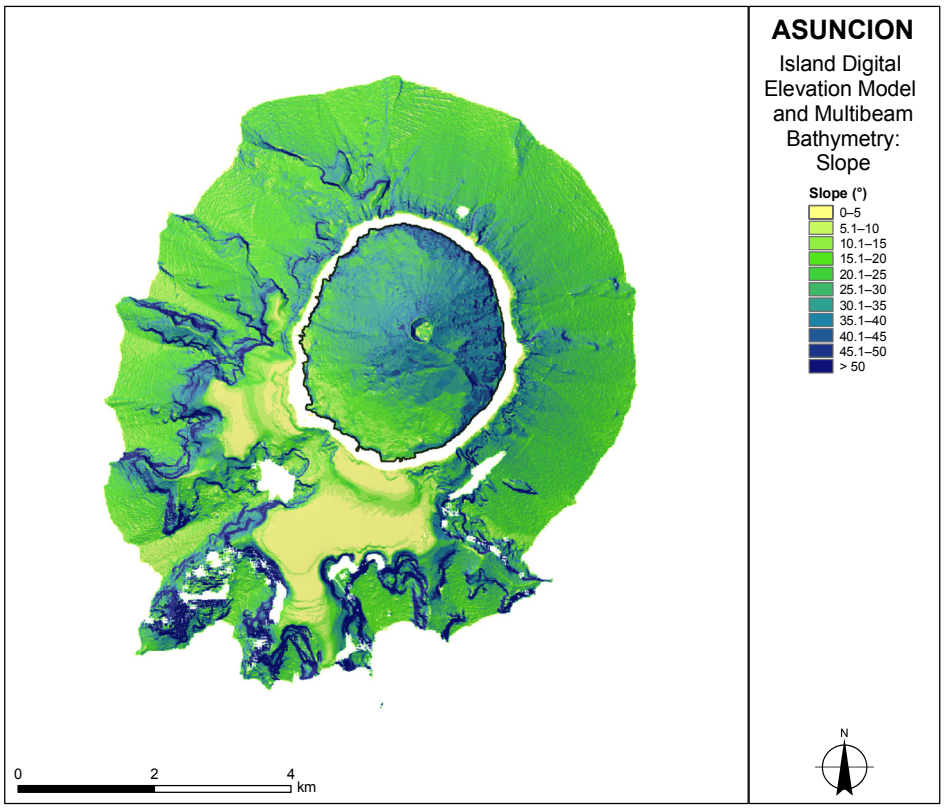


Figure 15.1.2a. Combined slope map using the digital elevation model and bathymetric data for Asuncion (grid cell size: 10 m).

The most recent confirmed volcanic eruption occurred in 1906, producing lava flows that descended down the southeastern and western flanks. Another eruption may have occurred in 1924 but is unconfirmed (Siebert and Simkin 2002–). More recently, volcanologists observed active fumaroles within the summit crater during a visit in 1992 (Siebert and Simkin 2002–).

In comparison to many other islands of the CNMI, Asuncion is abundantly vegetated (Fig. 15.1.2b). Sword grass occurs on its upper slopes, and the lower slopes are heavily forested (Pacific Protected Areas Database). Coconut groves occur on the lowest slopes of the southern and southwestern flanks and on areas of flat land (Mueller-Dombois and Fosberg 1998).

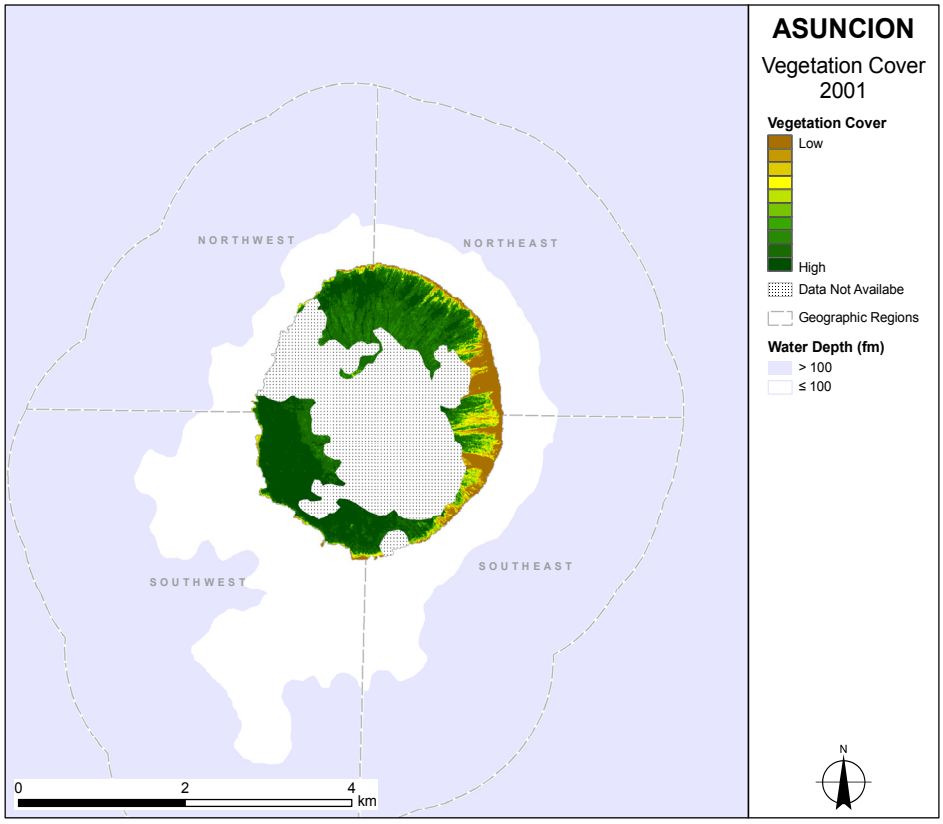


Figure 15.1.2b. Vegetation cover on Asuncion, derived using the Normalized Difference Vegetation Index from a satellite image (grid cell size: 4 m; IKONOS Carterra Geo Data, 2001). Hatched lines display areas where data are not available because cloud cover obscures the satellite image.

15.1.3 Environmental Issues on Asuncion

The native, tropical, dry forest supported on Asuncion is the best developed in the CNMI. The most extensive forest type is scrubby, mixed-broadleaved forest, dominated by species of the deciduous tree genus *Terminalia*. The seeds of these indigenous trees are edible to both humans and animals and are dispersed by fruit bats. Species of *Terminalia* occur on the southern slopes of Asuncion, above the coconut groves on the southern and southwestern flanks and on the lower slopes of the western flanks (World Wildlife Fund 2001).

Asuncion is part of a protected reserve established under Article XIV of the CNMI Constitution and managed by the CNMI Division of Fish and Wildlife. This legislation states that Asuncion is to remain an uninhabited place, and no permanent structures can be built on this island, except for the purposes of preservation and protection of natural resources (CNMI Constitution). Asuncion is preserved as a habitat for birds, wildlife, and plants. Specifically, 25 bird species are protected on this island, including the Micronesian starling (*Aplonis opaca*), the Micronesian honeyeater (*Myzomela rubrata*), and small numbers of the Micronesian megapode (*Megapodius laperouse*), which is listed Federally as endangered and locally as threatened or endangered (Pacific Protected Areas Database; U.S. Fish and Wildlife Service; Berger et al. 2005). The Mariana fruit bat (*Pteropus mariannus mariannus*), an endemic subspecies listed Federally as threatened (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), is also present on this island (Pacific Protected Areas Database). Asuncion is 1 of only 3 northern islands of the CNMI, along with Alamagan and Sarigan, with a substantial population of the endemic Slevin's skink (*Emoia slevini*).

Because of Asuncion's isolated location and lack of inhabitants, local anthropogenic effects around this island likely are few. However, non-native species, including several species of plants and rats, reportedly have been introduced to this island (Pacific Protected Areas Database; U.S. Departement of Agriculture Forest Service 2008). Fishing activity within the CNMI tends to be focused around the southern islands of the Mariana Archipelago, with multiday fishing trips on the islands and banks south of Guguan (Western Pacific Fishery Management Council 2009).

Asuncion is part of the Marianas Trench Marine National Monument, formed by presidential proclamation in January 2009. This Marine National Monument includes 3 units: the Trench Unit, Islands Unit, and Vents Unit. The Islands Unit includes the waters and submerged lands of the islands of Asuncion, Maug, and Farallon de Pajaros.

15.2 Survey Effort

Biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing coral reef ecosystems around the island of Asuncion since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around Asuncion are delineated in Figure 15.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around this island. Potential reef habitat is represented by a 100-fm contour shown in white on this map.

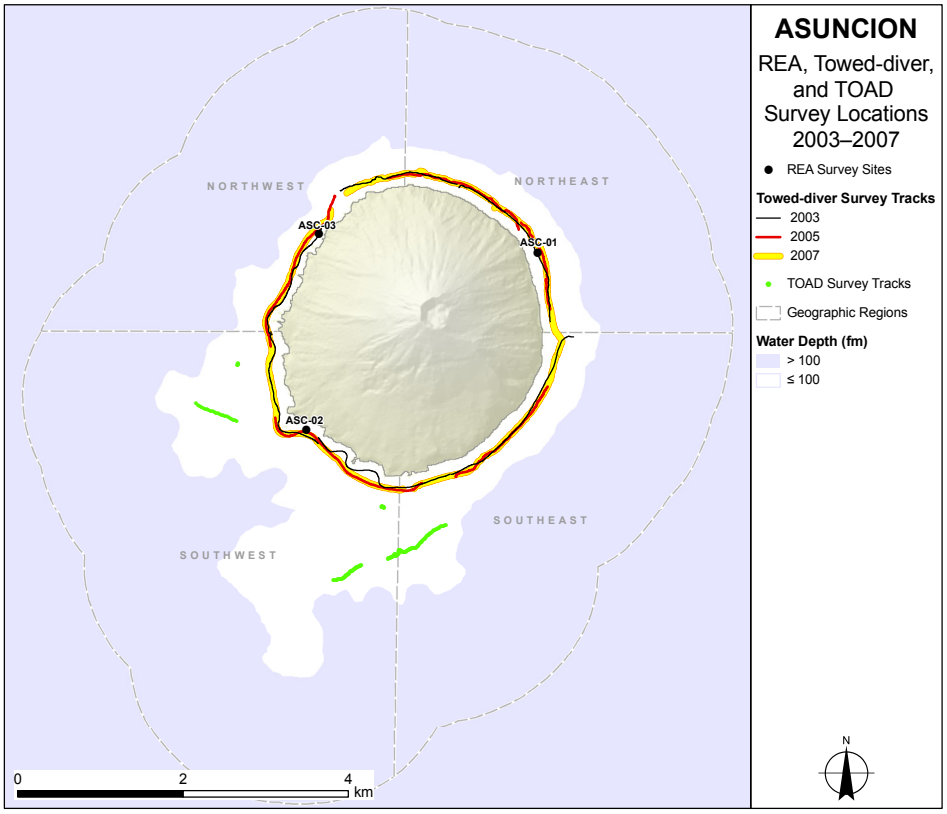


Figure 15.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Asuncion during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 4 geographic regions: northeast, southeast, southwest, and northwest.

Benthic habitat mapping data were collected around Asuncion using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted in 2007 around Asuncion, Maug, Supply Reef, and Farallon de Pajaros with multibeam sonar covered a total area of 3856 km^2. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live-hard-coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 15.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Asuncion was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 15.5–15.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 15.2a, along with their mean depths and total areas and length.

Table 15.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Asuncion during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	3	3	3
	Mean Depth (m)	13.8 (SD 2.3)	13.8 (SD 2.3)	13.8 (SD 2.3)
Benthic	Number of Surveys	3	3	3
	Mean Depth (m)	13.8 (SD 2.3)	13.8 (SD 2.3)	13.8 (SD 2.3)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	6	5	5
	Total Survey Area (ha)	11.1	8.8	11.2
	Mean Depth (m)	11.8 (SD 1)	14.9 (SD 1.6)	13.9 (SD 1.6)
TOAD		**2003**		
	Number of Surveys	5		
	Total Length (km)	1.84		

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Asuncion were collected using (1) subsurface temperature recorders (STRs) designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2007 (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 15.2b. Results are discussed in Section: 15.4: "Oceanography and Water Quality."

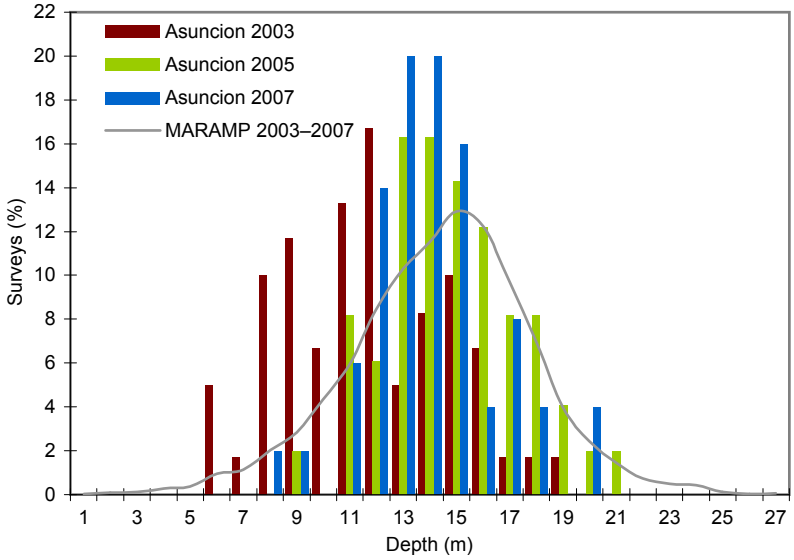
Table 15.2b. Numbers of subsurface temperature recorders (STRs) deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Asuncion during MARAMP 2003, 2005, and 2007. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: Archipelagic Comparisons.

Observation Type	Year						
Instruments	**2003**	**2005**		**2007**		**2009**	**Lost**
	Deployed	**Retrieved**	**Deployed**	**Retrieved**	**Deployed**	**Retrieved**	
STR	1	1	1	1	1	1	–
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	8	–		12			20
Deepwater Casts	–	3		5			8
Water Samples		**2005**		**2007**			**Total**
		–		4			4

Towed-diver Surveys: Depths

Figures 15.2b and c illustrate the locations and depths of towed-diver-survey tracks around Asuncion and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

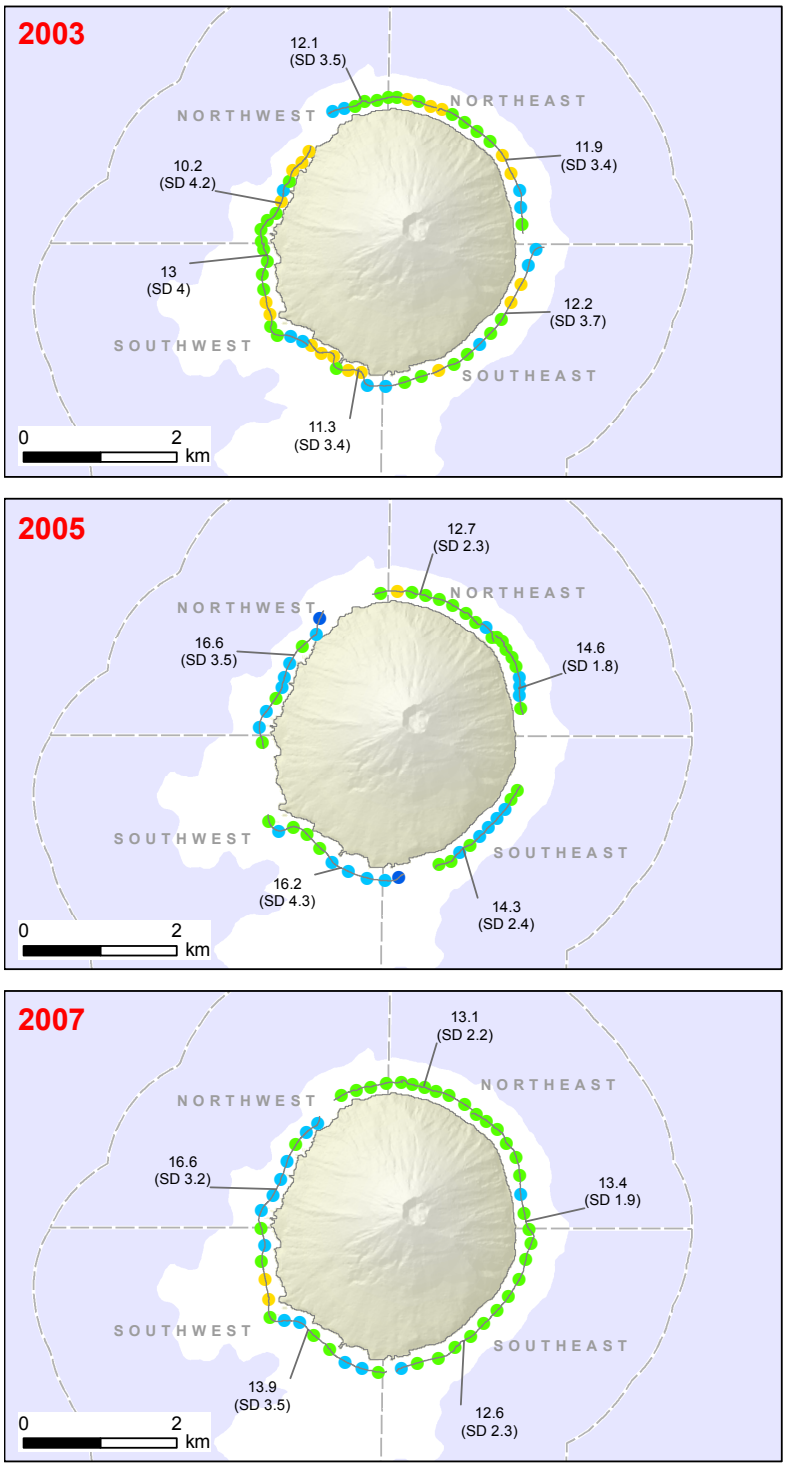
Figure 15.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Asuncion during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.



During MARAMP 2003, 6 towed-diver surveys were conducted along the forereef slopes around Asuncion (Figs. 15.2b and c, top panel). The mean depth of all benthic survey segments was 11.8 m (SD 1), and the mean depths of individual surveys ranged from 10.2 m (SD 4.2) to 13 m (SD 4).

During MARAMP 2005, 5 towed-diver surveys were conducted along the forereef slopes around most of Asuncion (Figs. 15.2b and c, middle panel). The mean depth of all benthic survey segments was 14.9 m (SD 1.6), and the mean depths of individual surveys ranged from 12.7 m (SD 2.3) to 16.6 m (SD 3.5).

During MARAMP 2007, 5 towed-diver surveys were conducted along the forereef slopes around Asuncion (Figs. 15.2b and c, bottom panel). The mean depth of all benthic survey segments was 13.9 m (SD 1.6), and the mean depths of individual surveys ranged from 12.6 m (SD 2.3) to 16.6 m (SD 3.2).



ASUNCION

Towed-diver Survey Depths

Mean Segment Depths (m)*

- No Data
- 0.1–5
- 5.1–10
- 10.1–15
- 15.1–20
- > 20

Towed-diver Survey Tracks

Geographic Regions

Water Depth (fm)

- > 100
- ≤ 100

* Each label indicates mean and standard deviation values for each entire towed-diver survey.

N

Figure 15.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Asuncion during MARAMP 2003, 2005, 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

15.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys the around the island of Asuncion were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 10–2300 m. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of 2–120 m.

15.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery collected by the Coral Reef Ecosystem Division (CRED) around Asuncion, Maug, Supply Reef, and Farallon de Pajaros during MARAMP 2007 encompassed an area of 3856 km^2.

Low-resolution multibeam bathymetry data show the uniformly steep-sided volcanic cone that forms Asuncion (Fig. 15.3.1a, top panel). Data collected by CRED do not entirely cover the flanks of this volcano, extending only to depths of ~ 1300 m east and west of this island. However, data acquired during transits north and south of Asuncion reveal that the flanks continue to descend to ~ 2300 m before reaching deep plateaus that separate Asuncion from Maug, located 41 km northwest of this island, and Agrihan, located 100 km to the southeast. These low-resolution bathymetry data also reveal several canyon and ridge features on the southwestern flanks of Asuncion.

The limited low-resolution backscatter data acquired around Asuncion show numerous artifacts (Fig. 15.3.1a, bottom panel), such as sudden changes in backscatter intensity that do not appear to relate to the seabed topography. As discussed

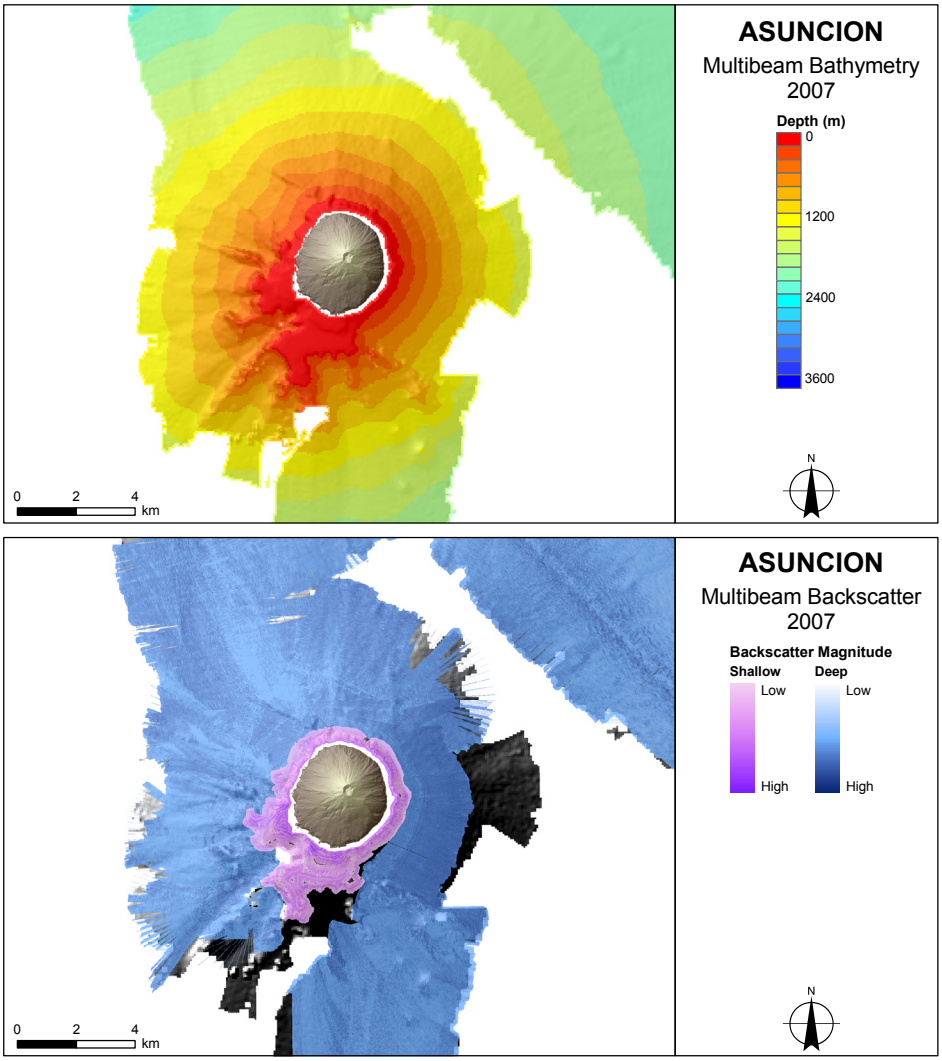


Figure 15.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Asuncion during MARAMP 2007 at depths of 10–2300 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates. Black areas are seen where backscatter data do not fully overlap bathymetry data.

in Chapter 2: "Methods and Operational Background", Section 2.2.2: "Acoustic Mapping: Data Processing," a number of factors aside from the acoustic character of the seabed can affect backscatter intensity. These factors include sonar settings during data acquisition and slope. It is likely that the exceptional steepness of the flanks of Asuncion influenced backscatter results, producing the artifacts noted at the beginning of this paragraph. Some patterns in these data appear less affected by artifacts, including the high-intensity backscatter recorded on the 3 ridges west of Asuncion with low-intensity backscatter recorded between them. These data suggest that exposed rock is present at or near the surface of these ridges and that soft sediments are present on the surrounding flanks.

High-resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in nearshore (depths of 0–800 m) waters around Asuncion were combined into a grid with a 10-m resolution (Fig. 15.3.1b). These data allow for the identification of fine-scaled features. These high-resolution data were used to derive benthic maps showing slope (Fig. 15.3.1c), rugosity (Fig. 15.3.1d), and bathymetric position index (BPI) zones (Fig. 15.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Asuncion.

Within the northeast and much of the southeast regions, the seabed of Asuncion is classified as a slope zone. The crests and depressions shown at the inner and outer edge of the BPI map in these regions are artifacts caused by depth value comparisons of cells at the edge of the data set to adjacent cells that contain no data. Within these regions, the seabed is characterized by flanks with uniformly steep slope values (20°–30°), very little variation in topography, and moderate rugosity levels.

Northwest of Asuncion, the flanks of this volcano are very similar in character to those in the northeast region, apart from the 3 long ridges that extend along the length of this mapped area. These narrow ridges are characterized by steeply sloping (> 50°), high-rugosity sides.

South of Asuncion, the seabed topography is dominated by a large, low-rugosity shelf, which is highlighted as a flat zone in the BPI analysis. This shelf is composed of a number of terraces: a narrow terrace at ~ 30 m, a much larger shelf at 100–120 m that is ~ 1.5 km at its widest point, and a series of successively deeper narrow shelves. Numerous steep-sided ridges descend from the edge of the largest shelf, forming wide channels between ridges. These ridges and channels form the complex pattern of crests and depressions identified on the BPI analysis.

Southwest of Asuncion, a similar series of shelves are shown in the bathymetry, slope, and BPI maps, although these shelves are much less extensive than the previously described shelf south of this island. Again, a series of ridges and canyons fan out from these shelves with slopes > 50°. Below and between these ridges, the flanks of Asuncion are uniformly steep with moderate rugosity levels recorded. Like the larger shelf south of Asuncion, this shelf area is characterized by low levels of rugosity, whereas ridge features have very high rugosity values.

In the shallowest waters surveyed, the BPI analysis identifies reef crests. However, this classification is likely an artifact of the methodology, since no data are available for immediately inshore areas and no comparison can be made to the innermost cells of the grid. Instead, these areas probably should be characterized as slopes.

Figure 15.3.1b. High-resolution multibeam bathymetry collected around Asuncion during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives.

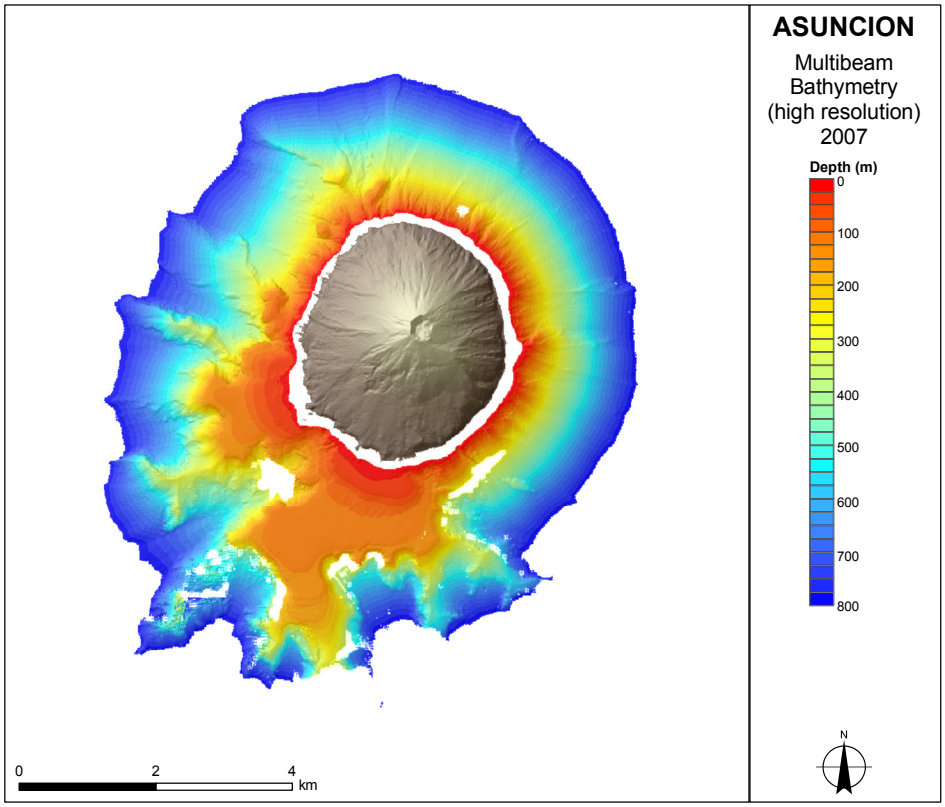
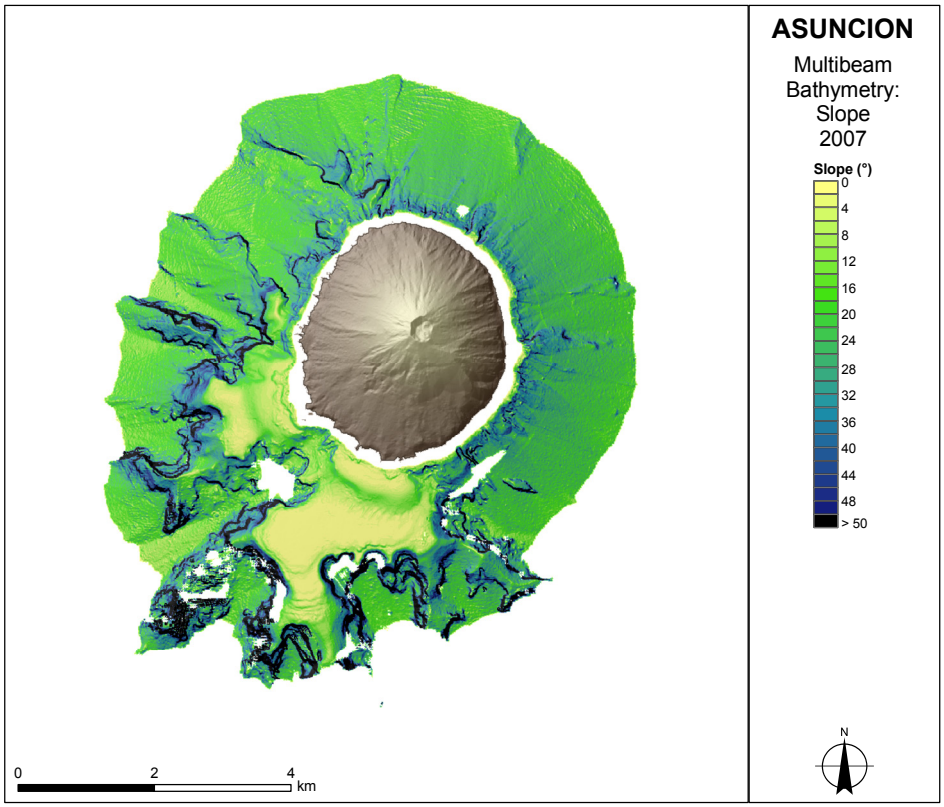


Figure 15.3.1c. Slope (°) of 10-m bathymetric grid around Asuncion. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells.



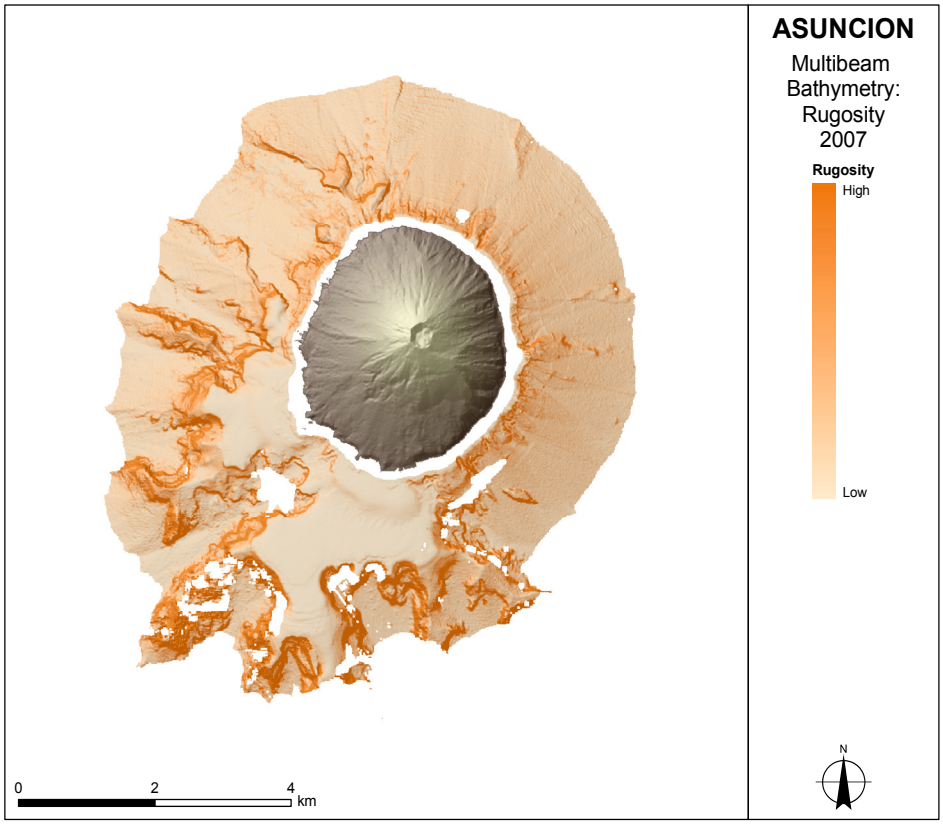


Figure 15.3.1d. Rugosity of 10-m bathymetric grid around Asuncion. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

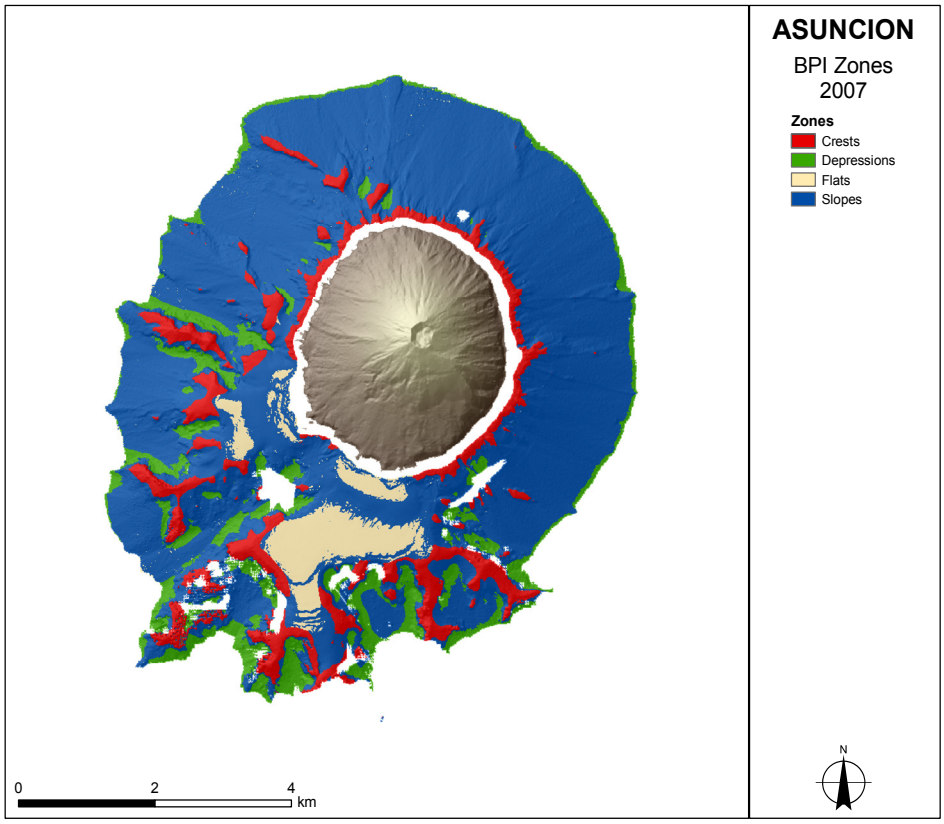


Figure 15.3.1e. BPI zones of 10-m bathymetric grid around Asuncion derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

High-resolution Multibeam Backscatter and Derivatives

High-resolution backscatter data were acquired around Asuncion using a 240-kHz Reson SeaBat 8101 ER sonar. These data were affected by several quality issues. Data gaps were observed around much of this island between the deepest swath and the relatively shallow swaths. Furthermore, backscatter values within the shallow part of the outer swath were higher than within the deep part. This artifact can be caused by steep slopes affecting the intensity of the backscatter return. These backscatter data also may have been affected by sonar settings and sea conditions during data acquisition or other factors discussed in more detail in Chapter 2: "Methods and Operational Background," Section 2.2.2: "Acoustic Mapping: Data Processing," These artifacts were exacerbated in the hard–soft analysis, resulting in false classification of areas because of data quality issues and did not truly reflect the nature of the substrate. Therefore, no hard–soft maps are presented for Asuncion.

Despite these data quality issues, the high-resolution backscatter data acquired around Asuncion do reveal some information about the nature of seabed substrates. The highest backscatter values were recorded on the shallowest of the shelves south and southwest of this island (Fig. 15.3.1f). In contrast, lower backscatter values were recorded on the deeper shelves. These backscatter data and low-rugosity values suggest that these shelves are characterized by soft sediments. Between these 2 shelf areas and east of the southern shelf, backscatter values of very low intensity were recorded, suggesting that soft sediments may accumulate within these wide channels separating the 2 shelves. Elsewhere around Asuncion, high-backscatter values were recorded on shallow seabed areas and lower backscatter values were recorded on the steeply sloping flanks.

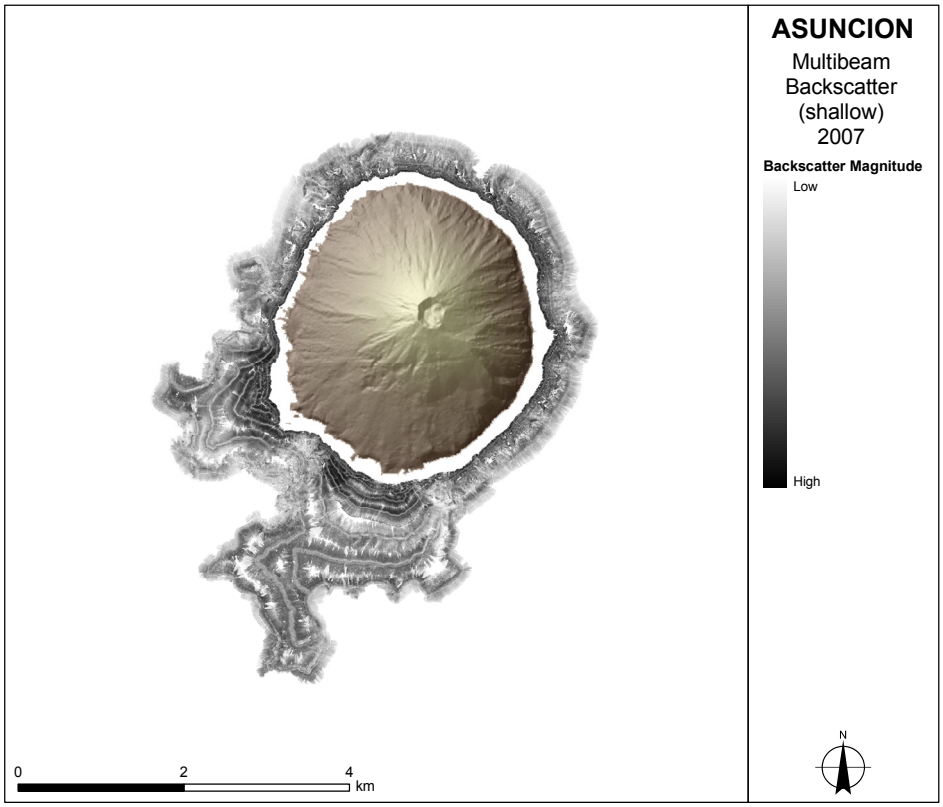


Figure 15.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) collected around Asuncion during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

15.3.2 Optical Validation

During MARAMP 2003, 5 TOAD optical-validation surveys were conducted around Asuncion at depths of 30–120 m. Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live coral cover (Fig. 15.3.3a).

Covering a distance of 31 km at depths of 6–20 m, 16 towed-diver optical-validation surveys of forereef habitats, were conducted around Asuncion during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover, live-hard-coral cover, and habitat complexity using a 6-level categorical scale from low to very high (Fig. 15.3.3a).

15.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Asuncion are discussed in this section. These descriptions are discussed with reference to the 4 geographic regions around Asuncion.

In the northeast region, based on towed-diver surveys conducted during MARAMP 2003, 2005, and 2007, sand cover was predominantly < 20% (Fig. 15.3.3a, top panel), although a small patch of higher sand cover (20.1%–30%) was observed

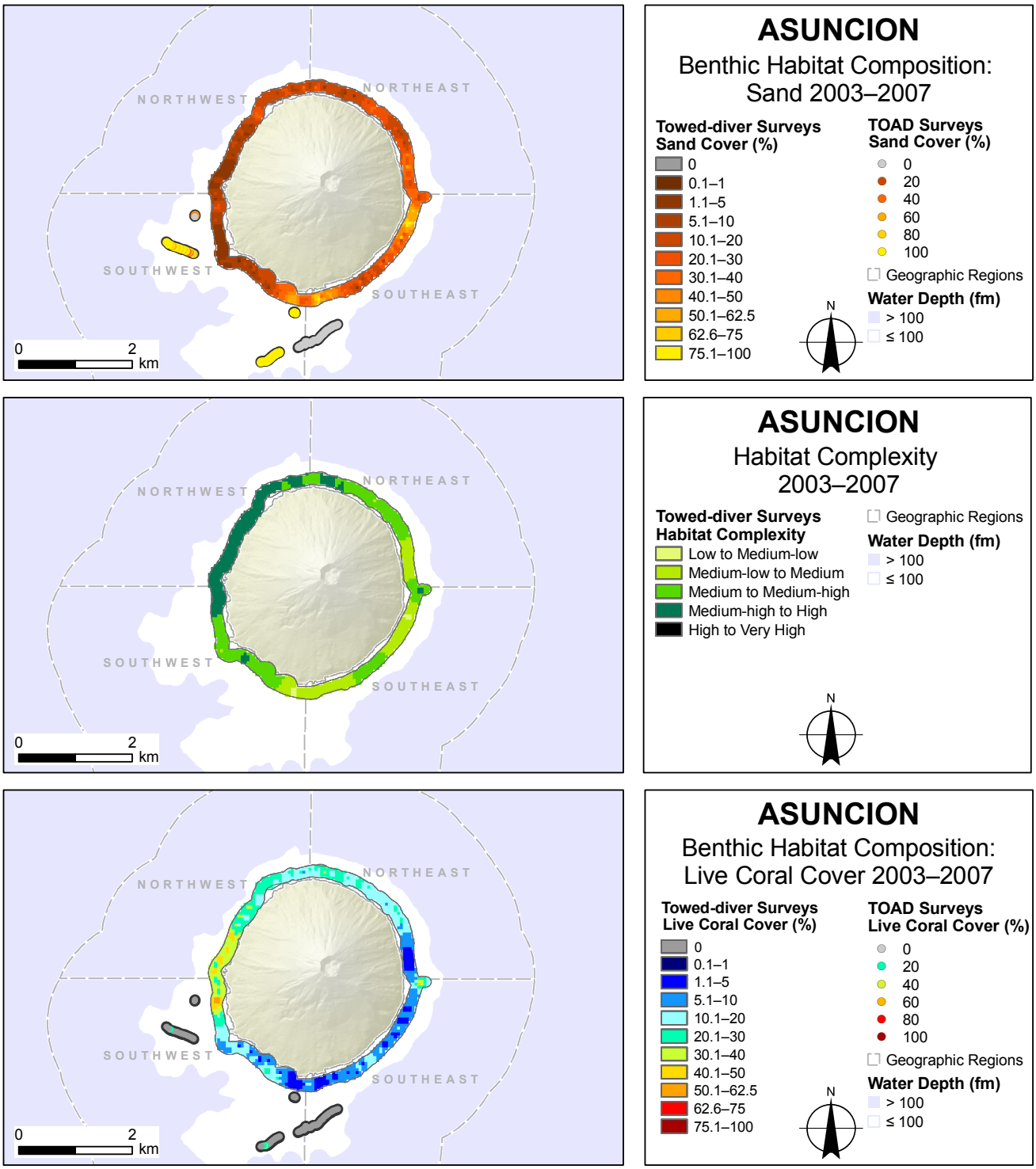


Figure 15.3.3a. Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) live-hard-coral cover (%) from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Asuncion during MARAMP 2003, 2005, and 2007.

where 2 deep channels cut into the flanks of this volcano. Habitats of medium to medium-high complexity were observed in much of this region (Fig. 15.3.3a, middle panel). In this area, live coral cover from towed-diver surveys was < 20% (Fig. 15.3.3a, bottom panel). Collectively, these observations suggest that habitats in this region predominantly are hard substrates that supported low levels of live coral cover. Towed divers described habitats in this area as steeply sloping, irregular, rocky reef and boulders. In the southern part of this region, moderately high (20.1%–50%) sand cover and low (< 10%) live coral cover were observed on a patch of medium-low to medium complexity.

Southeast and south of Asuncion, habitat complexity from towed-diver surveys ranged from low to medium-high. Two areas of medium-low to medium habitat complexity had sandy habitats with sand cover of 30.1%–100% and live coral cover < 10%. The northernmost of these 2 sandy areas had boulders on sand. The southern sand patch, located on an extensive shelf area, had habitats described as spur-and-groove formations, sand flat, and boulders on sand. Located between these 2 sandy areas, hard substrates with < 30% sand cover and < 20% live coral cover were found for a patch of medium to medium-high complexity.

Two TOAD surveys conducted south of Asuncion, a short survey on the shallow shelf area (30-m depth) and a longer survey on the deep shelf (depths of 105–115 m), suggested a seabed characterized by 100% sand cover. On this deep shelf, analysis of several frames of video taken at a depth of 113 m suggested that live coral cover was 20.1%–40%, although no additional cover of live corals was observed in TOAD video footage acquired in this area. An additional TOAD survey conducted on this deep shelf at the same depth found no sand cover (Fig. 15.3.3a, top panel); however, analyses of this video classified the observed substrate as "unconsolidated," a term used to describe substrates where it is difficult to distinguish between sand and mud in video footage. Thus, the seabed in this area also was composed of some kind of soft sediments. In this same TOAD survey, an additional feature of interest was the discovery of a dense aggregation of sea pens (order: Pennatulacea), extending over a linear distance of at least 1.4 km and occurring at depths of 70–120 m (Fig. 15.3.3b). Aggregations were recorded standing as high as ~ 30 cm, and they occurred on a soft substrate, possibly composed of basaltic sand. Sea pens are most commonly observed at night (Allen and Steele 2002), and some species are known to form dense aggregations (Gotshall 1994). However, despite extensive nighttime surveying with the TOAD at similar depths around other islands of the CNMI, high numbers of sea pens were not observed elsewhere. Similarly, extensive nighttime surveying in the Hawaiian Archipelago and American Samoa has not revealed such aggregations of sea pens, making their occurrence at Asuncion an uncommon, if not unique, occurrence.

Near the seaward end of the southernmost TOAD survey, where many sea pens were observed, a decline in density of sea pens at a depth of 120 m was associated with the occurrence of a 100-m-long patch of hard corals. Both corals and sea pens were observed near the eastern side of a steep-sided ledge that extends southward from Asuncion and rises abruptly from



Figure 15.3.3b. Sea pens observed in TOAD video footage acquired south of Asuncion at depths of 70–120 m.

the surrounding seafloor at a depth of ~ 600 m (Fig. 15.3.1b). Strong currents were encountered during TOAD surveys, and persistent strong currents sweeping over the ledge may possibly enhance the atypically high density of benthic life in this area.

Southwest of Asuncion, an area characterized by live coral cover of 5.1%–20% and low sand cover of 1.1%–20%, based on towed-diver surveys. In this area, habitat of medium to medium-high complexity was described as ridges, boulders, continuous reef, and walls.

In the north part of the southwest region and over much of the northwest region, medium-high to high levels of habitat complexity were recorded during towed-diver surveys in an area where sand cover was generally < 20%. This area of spur-and-groove habitat supported the highest level of live coral cover seen around Asuncion, with interpolated coral cover of ~ 30.1%–60%. On the shelf below, analyses of TOAD video footage collected at depths of 55–110 m suggested a seabed characterized by high sand cover and very low live coral cover—with only one analyzed video frame showing live coral cover of 20%. A second TOAD survey was conducted at a depth of 50 m. This short survey revealed patches of high sand cover but no live coral cover.

15.4 Oceanography and Water Quality

15.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 8 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the island of Asuncion on September 5. Temperature, salinity, density, and beam transmission values varied both spatially and vertically around this island (Figs. 15.4.1a and b). Spatial comparisons of water properties at a depth of 10 m suggest small differences in temperature (0.2°C), salinity (0.2 psu), density (0.2 kg m^{-3}), and beam transmission (< 0.2%) values; however, recorded salinity levels were higher around the western half of this island (casts 1–2 and 7–8) than around the eastern half (casts 3–6; Fig. 15.4.1a). Vertical comparisons of CTD profiles reveal intraisland differences in stratification. Well-mixed waters (casts 3–6) were recorded in the northeast and southeast regions, while highly stratified waters were observed in the northwest and southwest regions (casts 1–2 and 7–8). Moderate ranges in temperature (0.8°C) salinity (0.3 psu), and density (0.5 kg m^{-3}) were observed in the stratified regions and were greater than the values recorded in the areas with well-mixed waters (Fig. 15.4.1b). The observed stratification differences around Asuncion are likely a result of enhanced mixing on the windward (east) side and surface heating of the upper water column on the leeward side.

2007 Spatial Surveys

During MARAMP 2007, 12 shallow-water CTD casts were conducted in nearshore waters around Asuncion on June 4. Temperature, salinity, density, and beam transmission values varied both spatially and vertically around this island (Figs. 15.4.1c and d). Spatial comparisons of water properties at a depth of 10 m suggest variability in temperature around Asuncion with cold waters observed in the northeast region and recorded intraisland differences as large as 1.4°C (Fig. 15.4.1c). Vertical comparisons of CTD profiles reveal highly stratified waters with a substantial range in water temperature (3.9°C) and broad ranges in salinity (0.5 psu), density (1.2 kg m^{-3}) and beam transmission (5.7%) values (Fig. 15.4.1d). Cold water intrusions of ~ 26°C originated from depths > 30 m at all CTD cast locations. The large ranges in physical oceanographic conditions at Asuncion can be attributed to localized upwelling of subsurface water, although the physical mechanism driving that upwelling cannot be determined without additional data.

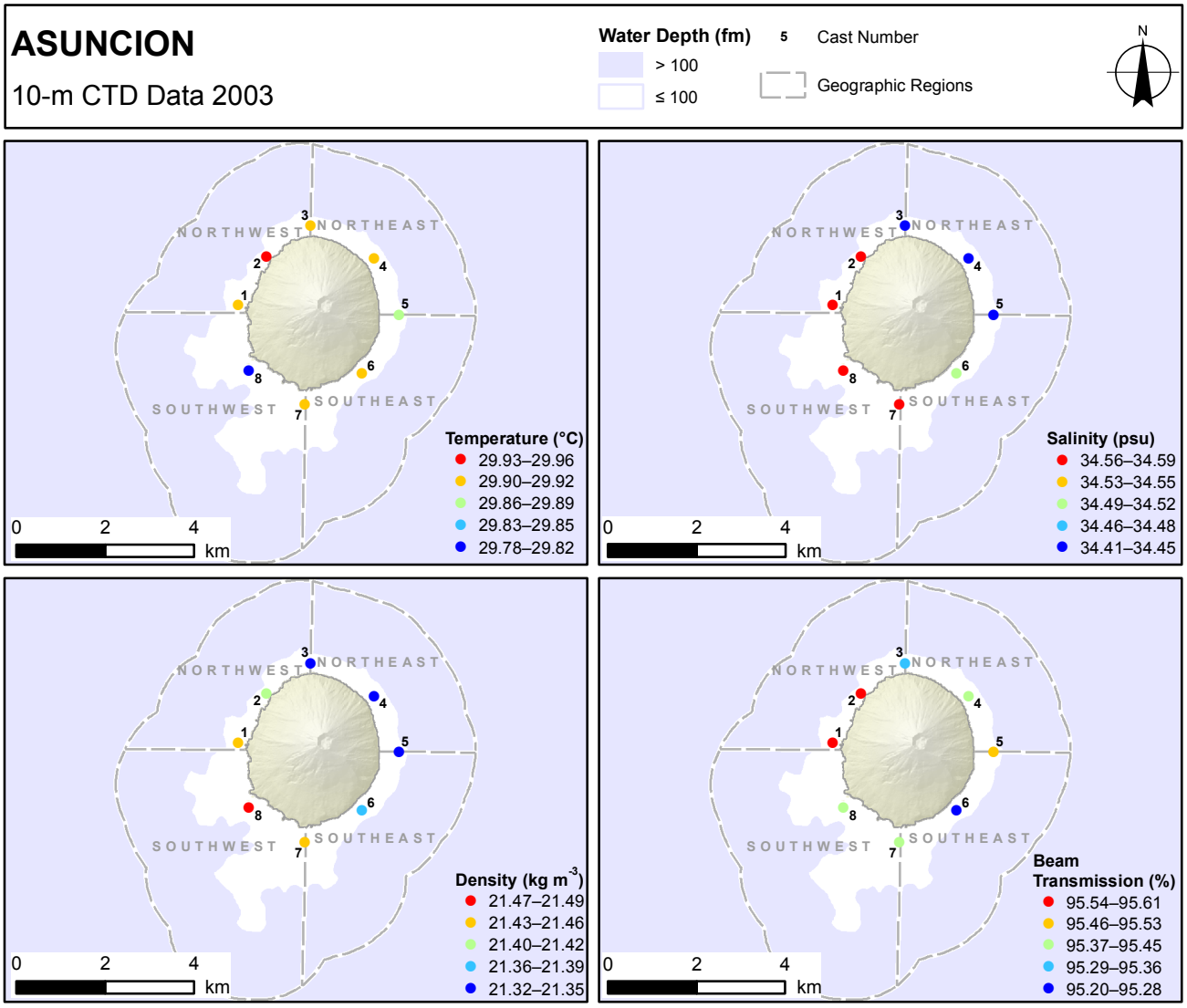
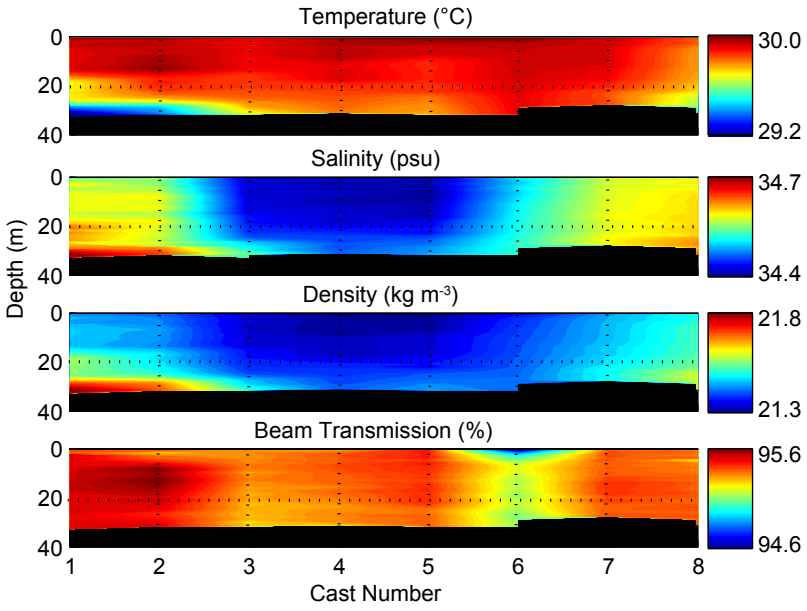


Figure 15.4.1a. Values of *(top left)* water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right)* beam transmission at a 10-m depth from shallow-water CTD casts around Asuncion on September 5 during MARAMP 2003.

Figure 15.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Asuncion on September 5 during MARAMP 2003, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–8, in a clockwise direction around Asuncion. For cast locations and numbers around Asuncion in 2003, see Figure 15.4.1a.



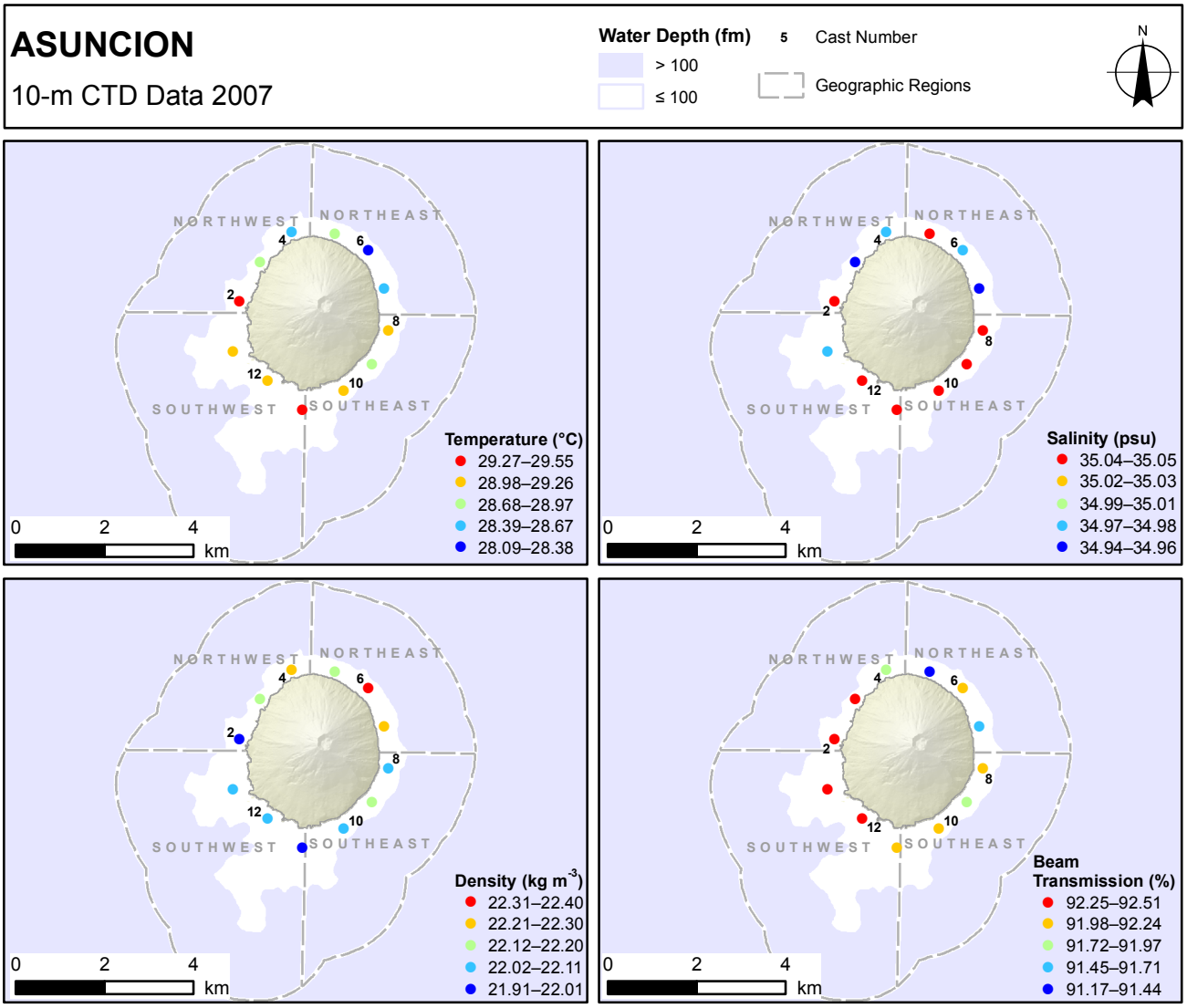


Figure 15.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Asuncion on June 4 during MARAMP 2007.

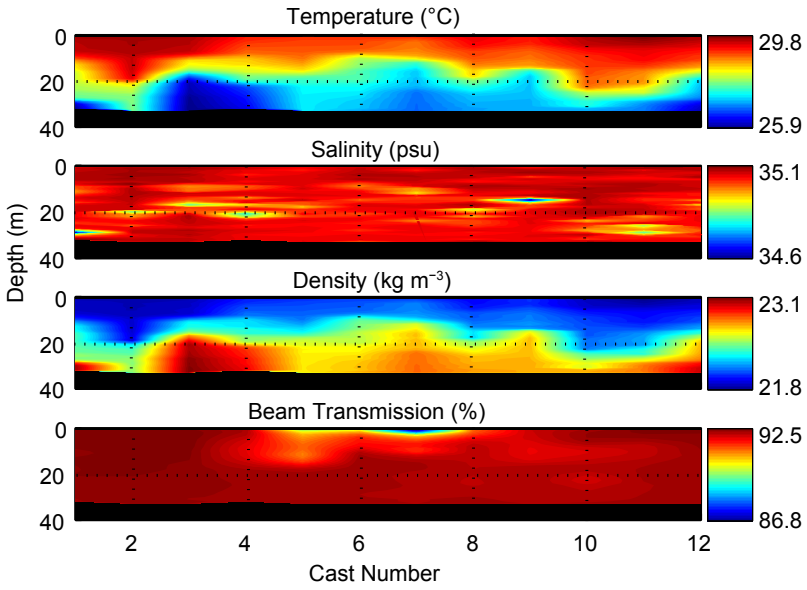


Figure 15.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Asuncion on June 4 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–12, in a clockwise direction around Asuncion. For cast locations and numbers around this island in 2007, see Figure 15.4.1c.

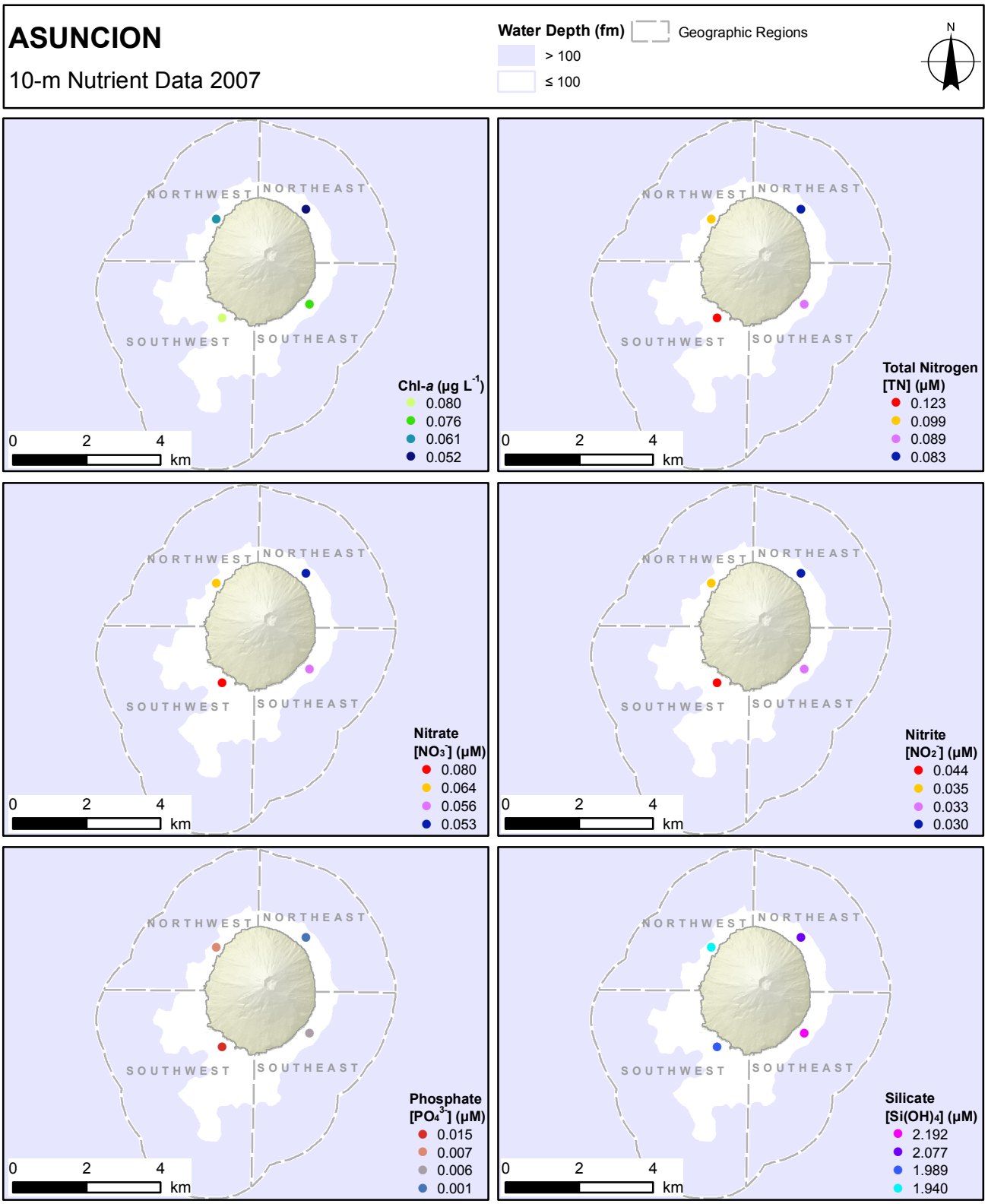


Figure 15.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Asuncion on June 4 during MARAMP 2007.

Water samples were collected in concert with shallow-water CTD casts at 4 select locations at Asuncion in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.05–0.08 μg L^{-1}; total nitrogen (TN), 0.08–0.12 μM; nitrate (NO_3^-), 0.05–0.08 μM; nitrite (NO_2^-), 0.03–0.04 μM; phosphate (PO_4^{3-}), 0–0.02 μM; and silicate [$Si(OH)_4$], 1.94–2.2 μM. Water-quality parameters generally were observed at the relatively low levels typical of the Western Pacific Warm Pool's oligotrophic, oceanic surface layers. The greatest values for most parameters measured were recorded in the southwest region, except for silicate, which was highest in the southeast region (Fig. 15.4.1e).

Temporal Comparison

Temporal comparisons of shallow-water CTD data collected around Asuncion during MARAMP 2003 and 2007 suggest a dynamic physical oceanographic environment. During MARAMP 2003, spatial variability was observed around Asuncion, with the waters surrounding the western half of this island highly stratified and waters surrounding the eastern half well mixed. CTD profiles collected during MARAMP 2007 reported highly stratified waters around this entire island, and the distinct intraisland differences seen in 2003 were not recorded. Cold water intrusions of ~ 26°C (or ~ 3.9°C colder than surface waters) originating from depths below 30 m were recorded in vertical profiles at all CTD cast locations in 2007, possibly a result of upwelling or internal tide activity. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in June, and MARAMP 2003 occurred in September. This change was made to avoid the typhoon season and reduce the probability of weather disruptions.

15.4.2 Time-series Observations

Between MARAMP 2003 and 2007, subsurface temperature recorders (STR) were deployed at a single location at Asuncion to collect time-series observations of a key oceanographic parameter (Fig. 15.4.2a). The location, depth, time frame, and other details about these deployments are provided in Figures 15.4.2a and b.

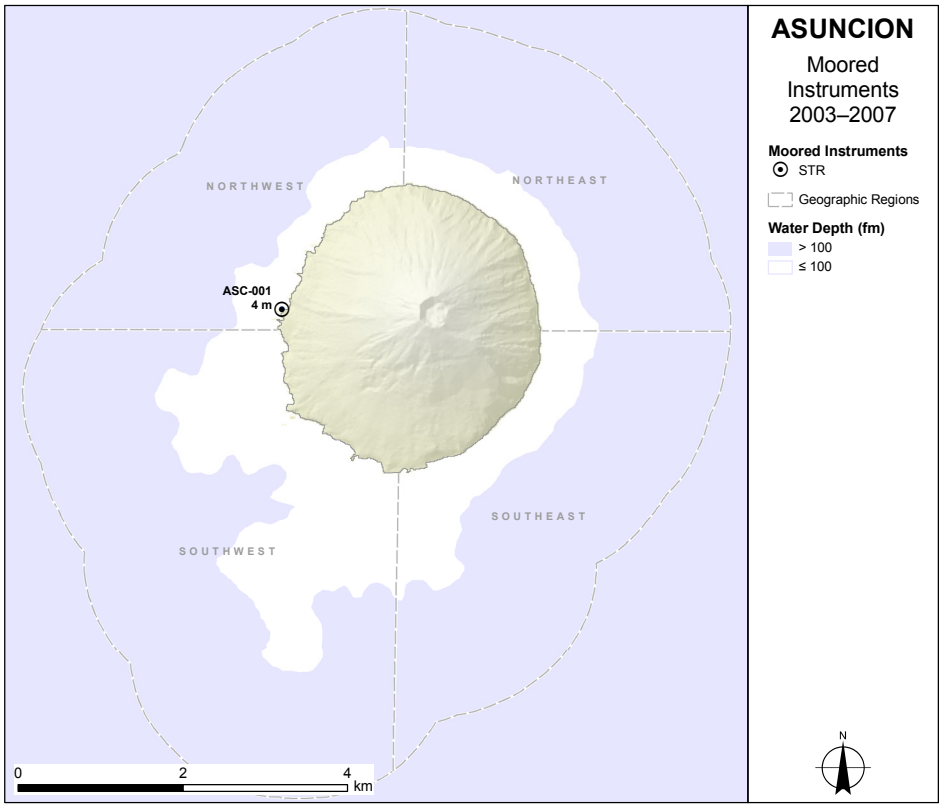


Figure 15.4.2a. Location and depth of the STRs deployed at Asuncion during MARAMP 2003, 2005, and 2007.

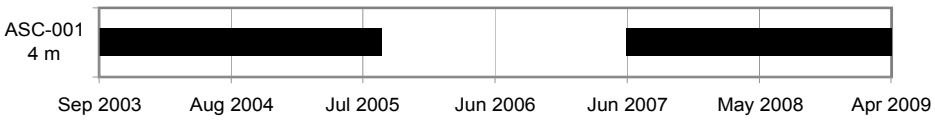


Figure 15.4.2b. Deployment timeline and depth of the STRs moored at Asuncion during the period from September 2003 to April 2009. A solid bar indicates the period for which data were collected by a series of STRs deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 15.2b in Section 15.2: "Survey Effort."

Temperature data from STRs deployed at a single location at a depth of 4 m in the northwest region show seasonal temperature variability of ~ 4°C between summer and winter months (Fig. 15.4.2c). Water temperatures reached ~ 30°C during the months of June–October and fell to a low of ~ 25.5°C during the months of January–May. Additionally, high-frequency (~ 12-h return periods) temperature fluctuations of 1°C–3°C were recorded in spring and summer 2004. During a period in May 2004, an event resulted in water temperatures falling to 24°C. Internal tides are generated when tidal currents interact with steep subsurface topography, resulting in high-frequency variability in temperature, salinity, dissolved nutrients, and suspended particle concentrations that differ significantly from shallow reefs to deep slopes. Although more research and additional data are needed to properly ascertain the nature of these signals, the observed rapid temperature changes likely were the result of internal tides causing vertical displacements of the background stratification at mooring site ASC-001.

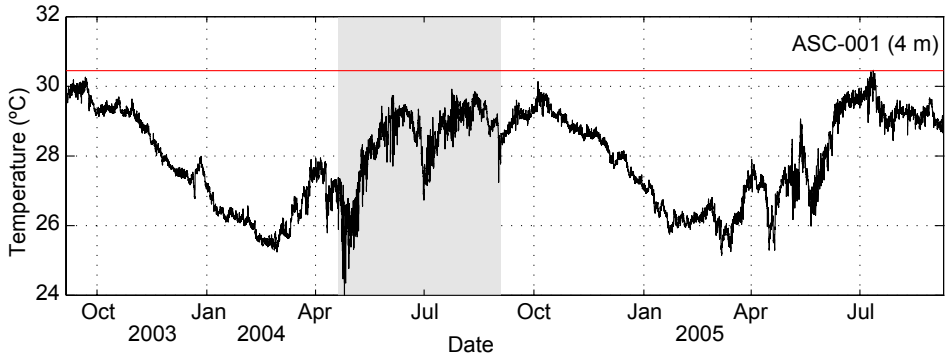


Figure 15.4.2c. Time-series observations of temperature over the period between September 2003 and September 2005 collected from 1 STR mooring site at a depth of 4 m (see Figure 15.4.2a for mooring location). The red line indicates the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean. A grey background indicates a period of high-frequency variability that likely resulted from internal tide activity.

15.4.3 Wave Watch III Climatology

Seasonal wave climatology for Asuncion was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008, and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (Fig. 15.4.3a). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 20 d per season), relatively low-period (8–10 s), relatively small (2–3 m) wave events originating from the east (90°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the south (180°), although they could originate from a broad directional source (120°–200°). These large, episodic waves primarily were generated via typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from the southwest (210°–250°) and probably were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) also was characterized by frequent (> 30 d per season) and low-period (~ 8 s) trade-wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 10 d per season), long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this period and originated from the northwest (330°).

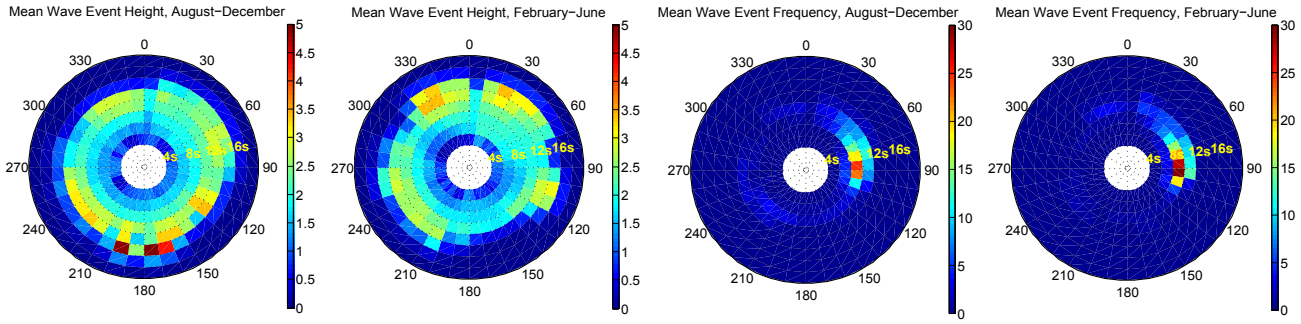


Figure 15.4.3a. NOAA Wave Watch III directional wave climatology for Asuncion from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Asuncion (19° N, 145° E). Mean significant wave height (*far left and left*) for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

15.5 Corals and Coral Disease

15.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Asuncion was 18% (SE 1.9). Coral cover was highest along the west coast with a mean of 40% for 12 survey segments (Fig. 15.5.1a, top panel).

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Asuncion was 16% (SE 2.3). Similar to survey results from 2003, coral cover was highest along the west coast with a mean of 43% for 8 segments (Fig. 15.5.1a, middle panel). Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 0.2% (SE 0.1) of coral cover observed on forereef habitats appeared stressed.

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Asuncion was 16% (SE 1.3). Again, coral cover was highest along the west coast with a mean of 29% over 9 segments (Fig. 15.5.1a, bottom panel). Overall, 2% (SE 0.4) of coral cover observed on forereef habitats appeared stressed; only 1 segment exhibited a high level (5%–10%) of stressed-coral cover (Fig. 15.5.1a, bottom panel). Predation by crown-of-thorns seastars (*Acanthaster planci*) was noted during this 1 segment in the southwest region, and lower levels of predation by crown-of-thorns seastars (COTS) were recorded in other survey areas in the southwest and northwest regions.

During MARAMP 2003, 3 REA benthic surveys using the quadrat method on forereef habitats at Asuncion documented 288 coral colonies within a total survey area of 11.25 m^2. Site-specific colony density ranged from 18.4 to 35.2 colonies m^{-2} with an overall sample mean of 25.6 colonies m^{-2} (SE 5). The highest colony density was recorded at REA site ASC-03 in the northwest region, and the lowest colony density was observed at ASC-02 in the southwest region (Fig. 15.5.1b, top panel).

During MARAMP 2005, 3 REA benthic surveys using the quadrat method on forereef habitats at Asuncion documented 515 coral colonies within a total survey area of 12 m^2. Site-specific colony density ranged from 37.8 to 48 colonies m^{-2} with an overall sample mean of 42.9 colonies m^{-2} (SE 3). The highest colony density was recorded at ASC-03 in the northwest region, and the lowest colony density was observed at ASC-02 in the southwest region (Fig. 15.5.1b, middle panel).

During MARAMP 2007, 3 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Asuncion. Site-specific estimates of live-hard-coral cover from these surveys ranged from 8.8% to 25.5% with an overall sample mean of 15.7% (SE 5). Coral cover was highest at ASC-03 in the northwest region and lowest at ASC-01 in the northeast region (Fig. 15.5.1b, bottom panel).

During MARAMP 2007, 3 REA benthic surveys using the quadrat method on forereef habitats at Asuncion documented 636 coral colonies within a total survey area of 12 m^2. Site-specific colony density ranged from 52 to 53.8 colonies m^{-2} with an overall sample mean of 53 colonies m^{-2} (SE 0.5). Coral-colony density was similar at all 3 sites with values slightly higher than the colony densities observed at these sites in previous MARAMP survey years (Fig. 15.5.1b, bottom panel).

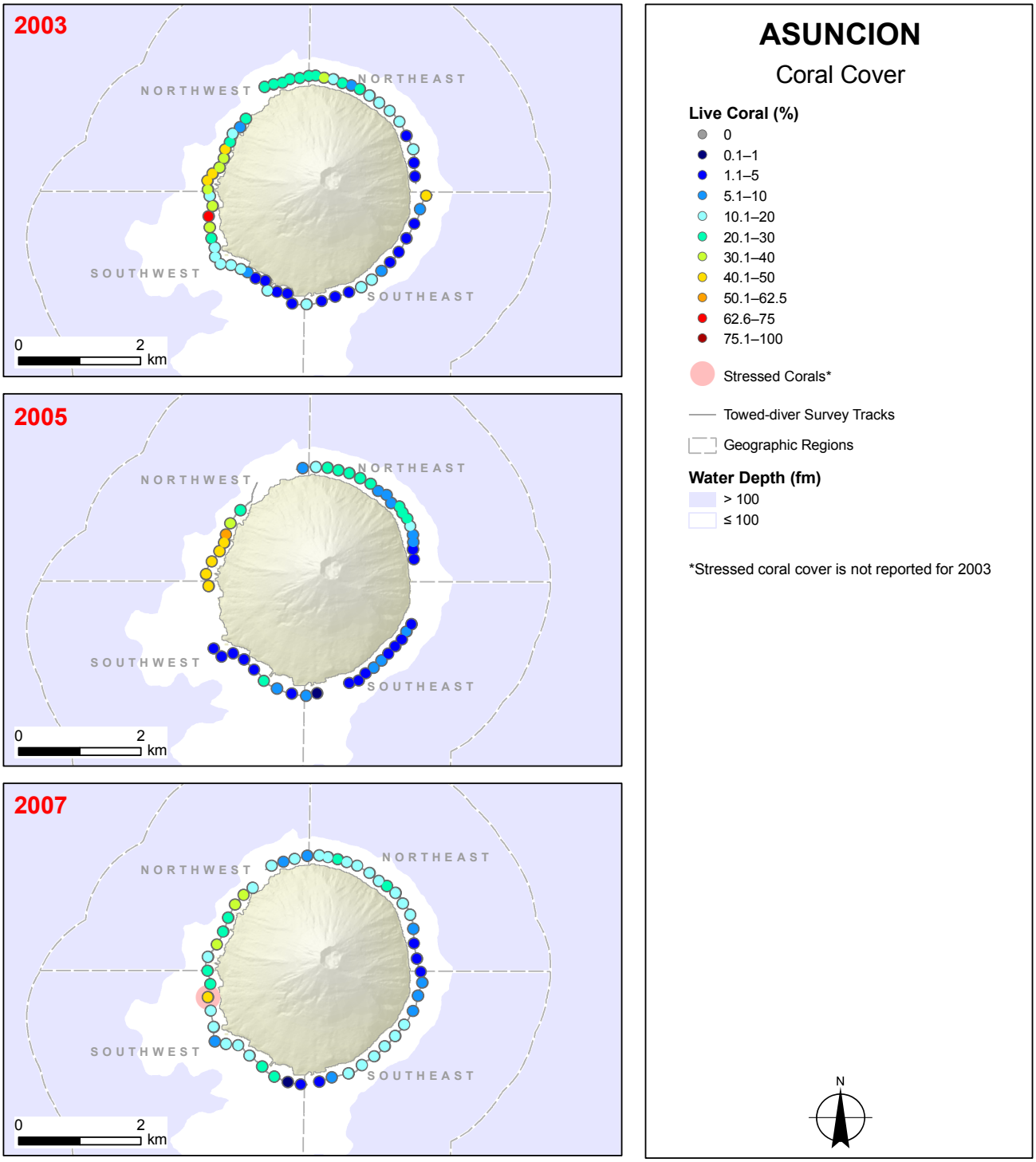


Figure 15.5.1a. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Asuncion during MARAMP 2003, 2005, and 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005 and 2007.

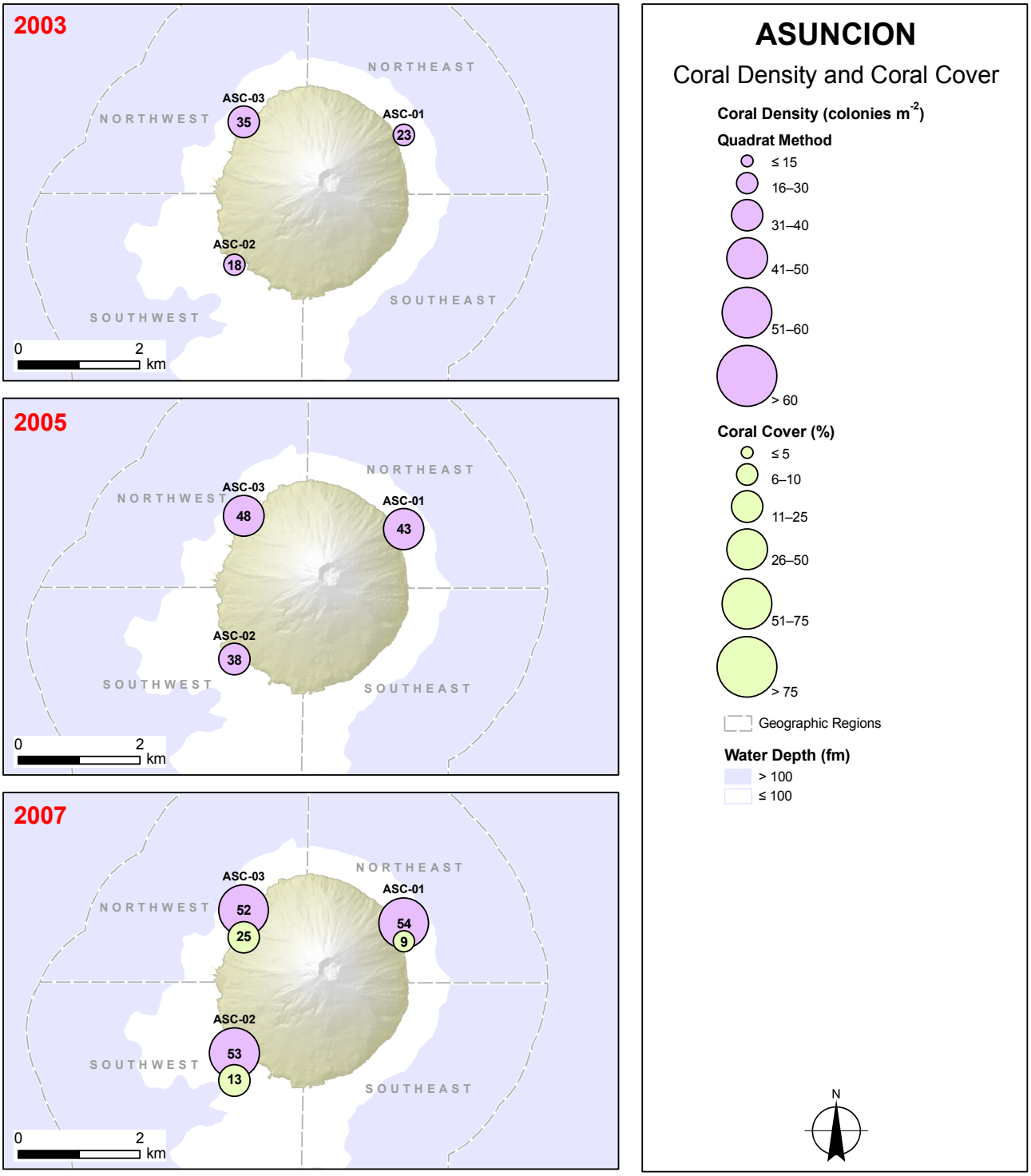


Figure 15.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Asuncion during MARAMP 2003, 2005, and 2007 as well as cover (%) observations of live corals from REA benthic surveys during MARAMP 2007. Values are provided within each symbol. The quadrat method was used to assess coral colony-densities.

Islandwide mean cover of live corals, estimated from towed-diver surveys of forereef habitats, essentially was the same in 2003, 2005, and 2007 (Fig. 15.5.1c): 18% (SE 1.9), 16% (SE 2.3), and 16% (SE 1.3). Congruent with these results from broad-scale towed-diver surveys, the overall sample mean from REA surveys conducted in 2007 was 15.7% (SE 5).

The quadrat method was used during the 3 MARAMP survey years to assess coral-colony density on forereef habitats at Asuncion. The overall sample mean of coral-colony density increased from 25.6 colonies m^{-2} (SE 5) in 2003 to 42.9 colonies m^{-2} (SE 3.0) in 2005 and 53 colonies m^{-2} (SE 0.5) in 2007. This observed increase in colony density between survey years may result from increased recruitment, fragmentation of existing colonies, or quadrat placement (Fig.15.5.1d).

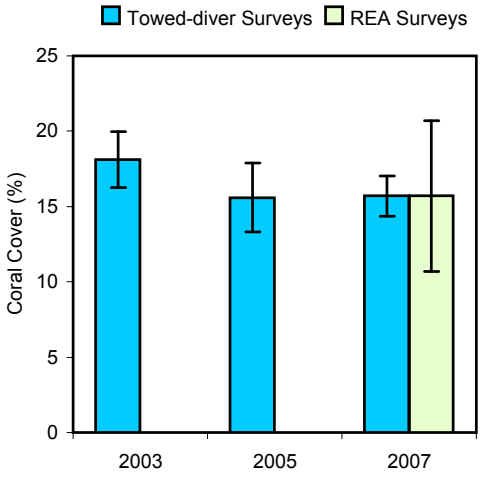


Figure 15.5.1c. Temporal comparison of mean live-coral-cover (%) values from REA and towed-diver benthic surveys conducted on forereef habitats around Asuncion during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted at Asuncion in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Coral Generic Richness and Relative Abundance

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Asuncion during MARAMP 2003. At least 23 coral genera were observed at Asuncion. Generic richness ranged from 10 to 20 with a mean of 15.3 coral genera per site (SE 2.9). The highest generic diversity was recorded at ASC-03 in the northwest region, and the lowest generic diversity was found at ASC-01 in the northeast region (Fig. 15.5.1e, top panel).

Pavona was the most numerically abundant genus, accounting for 19.2% of the total number of colonies enumerated at Asuncion in 2003. All other genera individually accounted for < 10% of the total number of colonies. *Pocillopora* and *Porites* dominated the coral fauna at ASC-01, each accounting for 12.6% of the total number of colonies at that site. *Pavona* dominated the coral fauna at sites ASC-02 and ASC-03, accounting for 17.4% and 40.2% of the total number of colonies recorded at those sites.

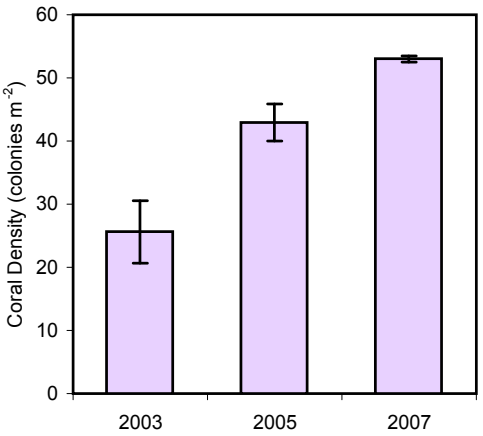


Figure 15.5.1d. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Asuncion during MARAMP 2003, 2005, and 2007. The quadrat method was used in the 3 survey years to measure coral-colony density. Error bars indicate standard error (± 1 SE) of the mean.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Asuncion during MARAMP 2005. At least 24 coral genera were observed at Asuncion. Generic richness ranged from 14 to 18 with a mean of 16.3 coral genera per site (SE 1.2). The highest generic diversity was recorded at ASC-03 in the northwest region, and the lowest generic diversity was found at ASC-01 in the northeast region (Fig. 15.5.1e, middle panel).

Pavona and *Pocillopora* were the most numerically abundant genera, accounting for 17.3% and 16.6% of the total number of colonies enumerated at Asuncion in 2005. All other genera individually accounted for < 10% of the total number of colonies. *Pavona*, *Pocillopora*, and *Porites* dominated at ASC-01, accounting for 22.7%, 21.5%, and 14% of the total number of colonies at that site. *Pocillopora* and *Pavona* dominated the coral fauna at ASC-02, accounting for 19.9% and 11.9% of the total number of colonies observed at that site. *Pavona* and *Favia* dominated at ASC-03, accounting for 17.2% and 10.4% of the total number of colonies found at that site.

Three REA benthic surveys of forereef habitats were conducted using the quadrat method at Asuncion during MARAMP 2007. At least 23 coral genera were observed at Asuncion. Generic richness ranged from 16 to 22 with a mean of 18.3 genera per site (SE 1.9). The highest generic diversity was recorded at ASC-03 in the northwest region, and the lowest generic diversity was found at ASC-01 in the northeast region (Fig. 15.5.1e, bottom panel).

Pocillopora and *Pavona* were the most numerically abundant genera, accounting for 18.5% and 13.1% of the total number of colonies enumerated at Asuncion in 2007. All other genera individually accounted for < 10% of the total number of colonies. *Pocillopora* and *Porites* dominated the coral fauna at ASC-01, accounting for 21.9% and 12.6% of the total number

of colonies observed at that site. *Pocillopora* dominated at ASC-02, accounting for 26.8% of the total number of colonies recorded at that site. *Favia* and *Pavona* dominated at ASC-03, accounting for 17.8% and 21.2% of the total number of colonies found at that site.

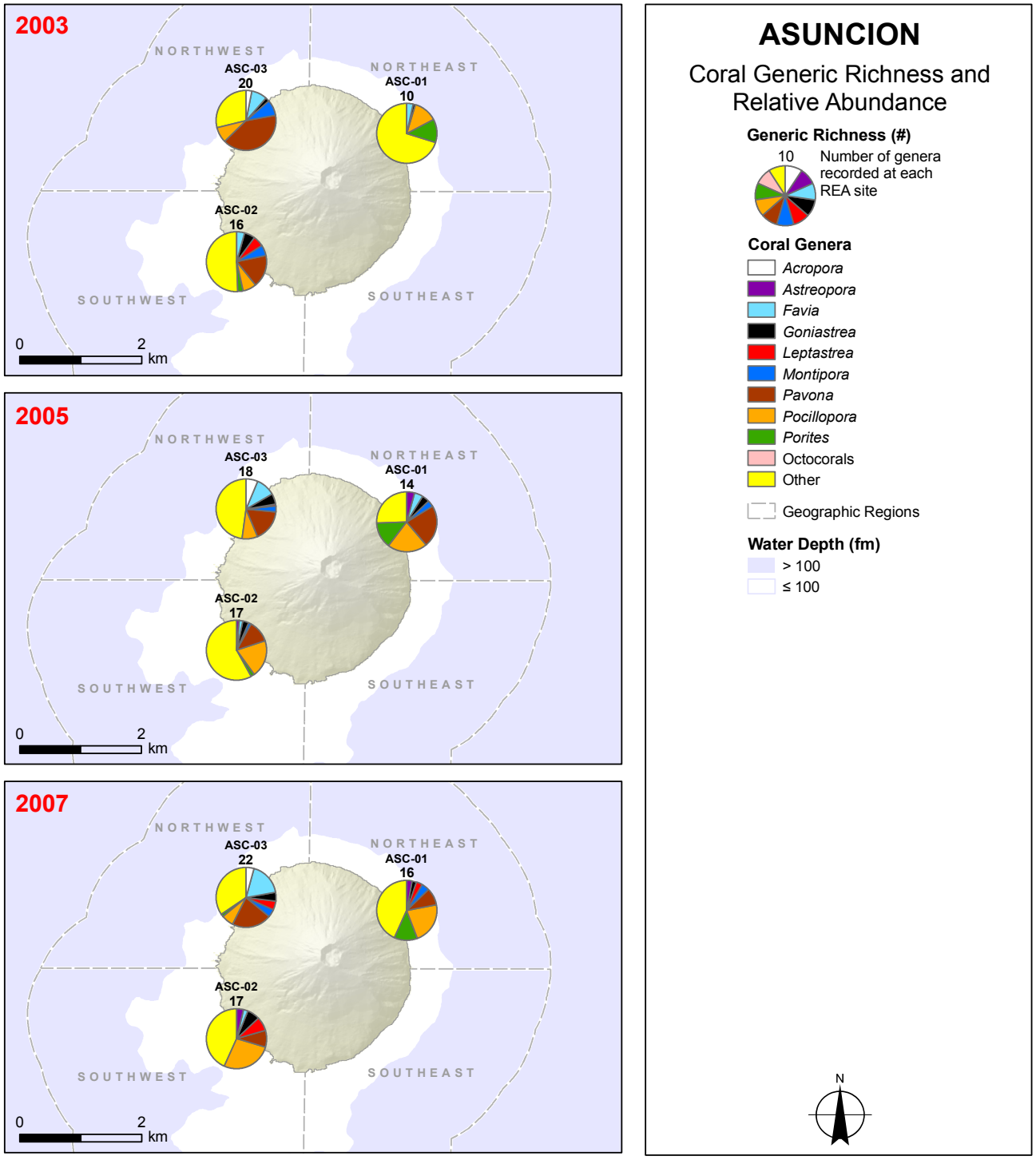


Figure 15.5.1e. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Asuncion during MARAMP 2003, 2005, and 2007. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used to survey coral genera.

The quadrat method was used in each of the 3 MARAMP survey years to assess generic richness on forereef habitats at Asuncion. The overall sample means were essentially the same in 2003, 2005, and 2007: 15.3 genera per site (SE 2.9) in 2003, 16.3 (SE 1.2) in 2005, and 18.3 (SE 1.9) in 2007 (Fig. 15.5.1f). The small variation between survey years likely results from variability in quadrat placement at individual sites.

Across the 3 MARAMP survey years, 29 coral genera were observed on forereef habitats at Asuncion. *Pavona* was an important component of the coral fauna, accounting for > 10% of the total number of colonies enumerated in the 3 survey years. *Pavona* was the most abundant genus in 2003 and 2005 and was the second-most abundant genus in 2007 surveys, accounting for 28.8%, 17.3%, and 13.1% of the total number of colonies enumerated. *Pocillopora* was the most abundant genus in 2007 surveys and the second-most abundant genus in 2005 surveys, accounting for 18.5% and 16.6% of the total number of colonies enumerated. All other genera accounted for < 10% of the total number of colonies recorded in the 3 survey years.

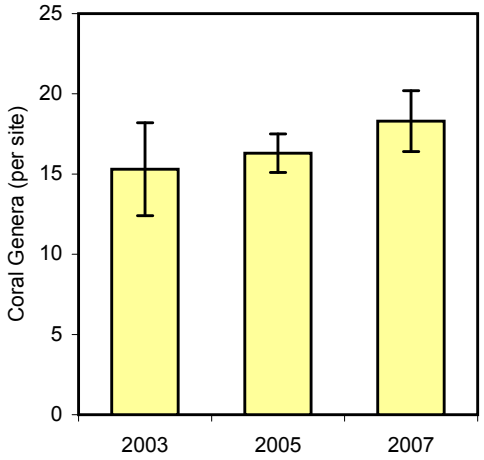


Figure 15.5.1f. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Asuncion during MARAMP 2003, 2005, and 2007. The quadrat method was used to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

Coral Size-class Distribution

During MARAMP 2003, 3 REA benthic surveys of forereef habitats were conducted at Asuncion using the quadrat method. The coral size-class distribution from these surveys shows that the majority (64.3%) of corals had maximum diameters ≤ 5 cm (Fig. 15.5.1g, top panel). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 26.1%, 5.9%, 3.2%, and 0.5% of colonies recorded. No colonies with maximum diameters > 80 cm were observed. At all REA sites, a majority (> 53%) of corals were in the smallest size class (≤ 5 cm).

During MARAMP 2005, 3 REA benthic surveys of forereef habitats were conducted at Asuncion using the quadrat method. The coral size-class distribution from these surveys shows that the majority (70.2%) of corals had maximum diameters ≤ 5 cm (Fig. 15.5.1g, middle panel). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 19%, 8%, 2.6%, and 0.2% of colonies recorded. No colonies with maximum diameters > 80 cm were observed. At all REA sites, a majority (> 54%) of corals were in the smallest size class (≤ 5 cm).

During MARAMP 2007, 3 REA benthic surveys of forereef habitats were conducted at Asuncion using the quadrat method. The coral size-class distribution from these surveys shows that the majority (77.6%) of corals had maximum diameters ≤ 5 cm (Fig. 15.5.1g, bottom panel). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 16.7%, 3.5%, 1.6%, and 0.64% of colonies recorded. No colonies with maximum diameters > 80 cm were observed. At all REA sites, a majority (> 71%) of corals were in the smallest size class (≤ 5 cm).

The quadrat method was used to establish size-class distributions on forereef habitats at Asuncion during the 3 MARAMP survey years. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. For more on these survey methods see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease."

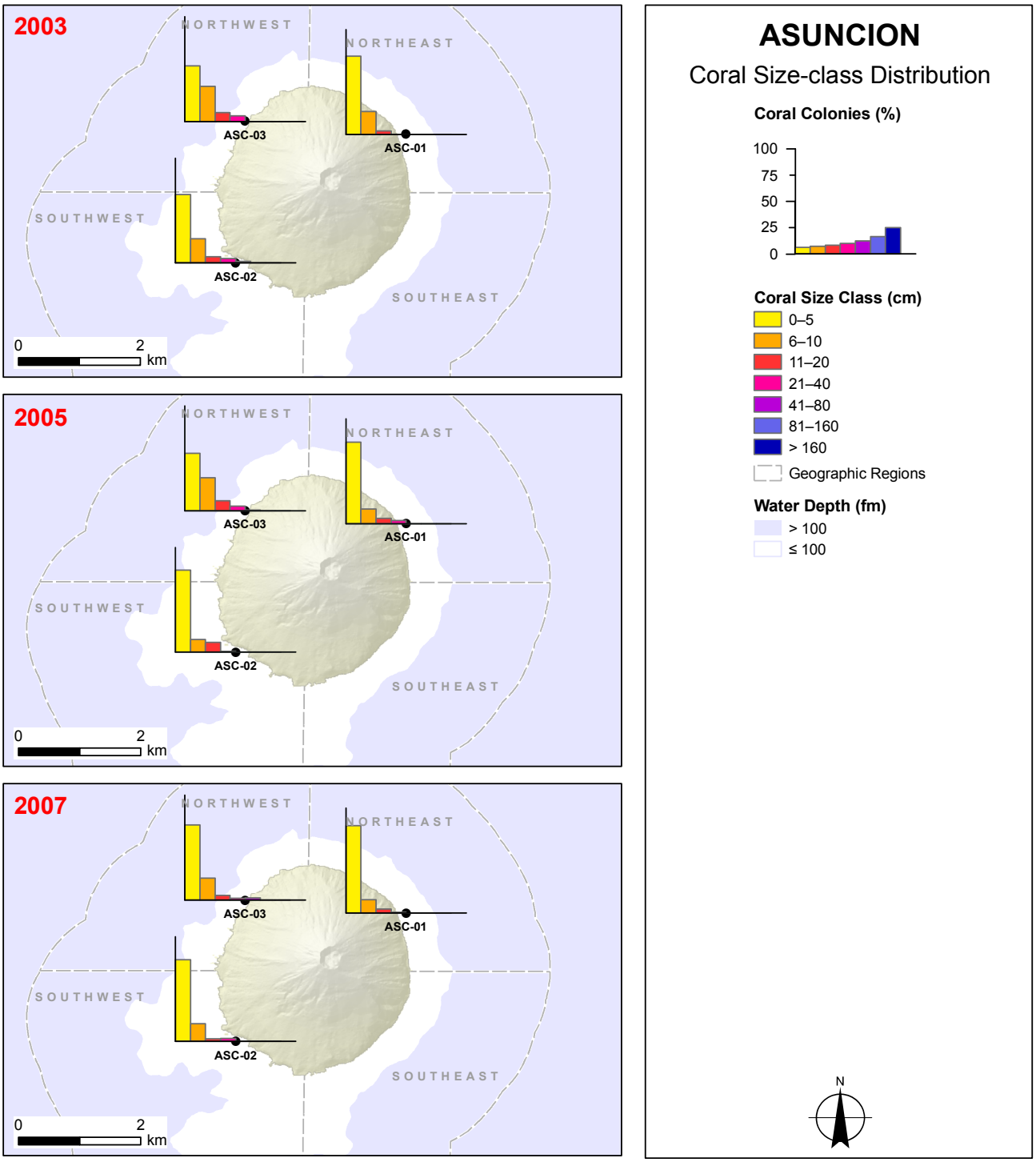


Figure 15.5.1g. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Asuncion during MARAMP 2003, 2005, and 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used to size corals.

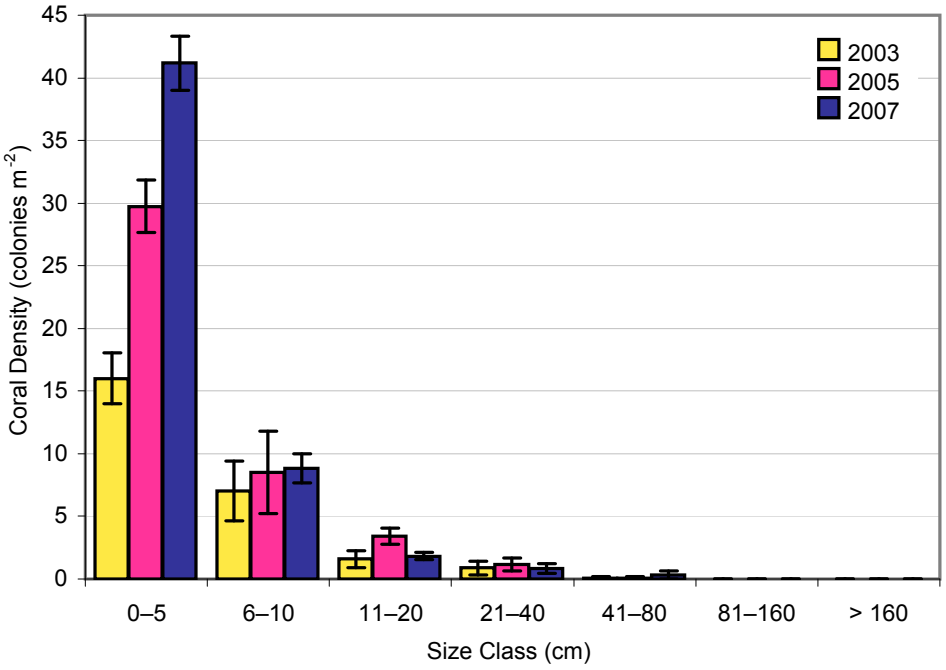


Figure 15.5.1h. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Asuncion during MARAMP 2003, 2005, and 2007. The quadrat method was used in the 3 survey years to size corals. Error bars indicate standard error (± 1 SE) of the mean.

In each of the 3 MARAMP survey years, the number of coral colonies in the smallest size class (0–5 cm) was > 15 colonies m^{-2} (Fig. 15.5.1h). The overall mean proportion of colonies in the smallest size class increased from 64.3% in 2003 to 70.2% in 2005 to 77.6% in 2007. Increase in frequency of the smallest size class may result from recruitment, fragmentation of existing colonies, or both. The relative proportion of corals in the other size classes showed some variability among survey years as well.

15.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted at 3 sites on forereef habitats at Asuncion, covering a total area of 900 m^2. Surveys detected 10 cases of disease, translating to an overall mean prevalence of 0.02% (SE 0.01), excluding predation. Coral-colony counts at all REA sites at Asuncion were conducted using the quadrat method, resulting in high coral-colony densities and, therefore, low disease prevalence values, relative to the levels found at sites at other islands surveyed using the belt-transect method.

Two major disease conditions were detected on forereefs at Asuncion: fungal infection and skeletal growth anomalies. Of the 3 sites surveyed, 2 contained disease: ASC-01 and ASC-03 (Fig. 15.5.2a; the values of overall prevalence shown in Figure 15.5.2a include predation). ASC-01 in the northeast region contained 80% of recorded cases, all of which corresponded to fungal infection (Fig. 15.5.2b). This condition affected a variety of coral genera, including *Cyphastrea*, *Favia*, *Psammocora*, *Hydnophora*, and *Pavona*. The other 20% of recorded lesions were detected at ASC-03 in the northwest region and involved skeletal growth anomalies, all on corals of the genus *Porites*.

Cases of coral predation attributable to COTS or corallivorous snails, such as snails from the genus *Drupella*, were also observed at Asuncion but only at ASC-03.

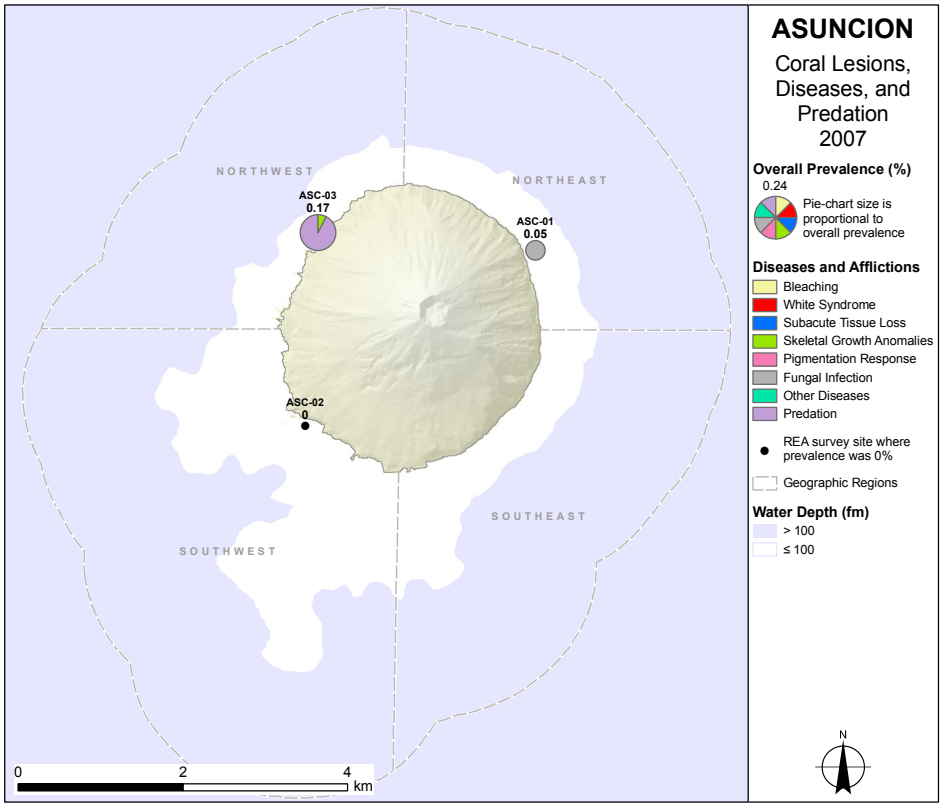


Figure 15.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Asuncion during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie charts indicate disease-specific prevalence.

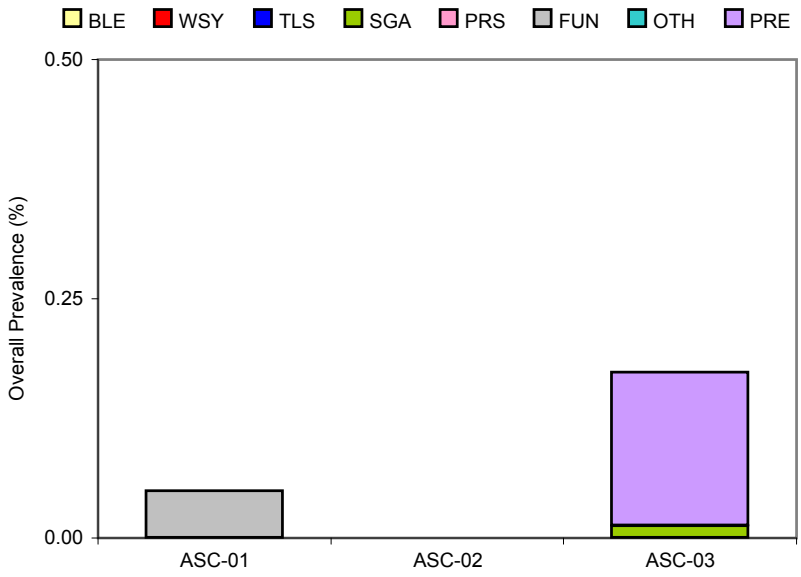


Figure 15.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Asuncion during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesion of unknown etiology; PRE: predation by COTS or corallivorous snails.

15.6 Algae and Algal Disease

15.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Asuncion was 51% (SE 2). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 63%, within a range of 10.1%–75%, occurred in the southwest region (Fig. 15.6.1a, top left panel). The habitat in this area was characterized as pavement reef of medium-high complexity. The majority of the remaining surveys reported rock boulder habitat where macroalgae also appeared to thrive. The surveys in the southwest and northeast regions each reported greater than average macroalgal cover for Asuncion with means of 55% and 53%. Estimates of macroalgal cover never were < 40% in 2003 at Asuncion.

Five TOAD surveys completed at Asuncion during MARAMP 2003 were conducted at depths of 20–120 m. Analyses of TOAD video footage obtained from 3 surveys suggested very low macroalgal cover, with only the occasional video frame (8% of analyzed frames) from the southernmost survey, at depths of 111–119 m, showing cover of 20%.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Asuncion was 5% (SE 1.3). The survey with the highest mean macroalgal cover of 14%, within a range of 5.1%–50%, occurred primarily in the southwest region (Fig. 15.6.1a, middle left panel), where habitat complexity was medium-low to medium. All other surveys reported less than average macroalgal cover for Asuncion, never exceeding 4%.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae around Asuncion was 19% (SE 2.1). The survey with the highest mean macroalgal cover of 43%, within a range of 30.1%–62.5%, occurred along the border between the northeast and northwest regions (Fig. 15.6.1a. bottom left panel). Steep rock reef of medium-high complexity, largely dominated by species of the brown alga *Padina*, was the main structural habitat observed during this survey. Remaining surveys reported cover values lower than the overall mean for Asuncion. The lowest macroalgal cover was observed during a 10-segment survey in the southeast region with a mean of 4%. Species of the green algal genera *Caulerpa* and *Halimeda* accounted for the majority of macroalgal-cover observations around Asuncion (except for the survey along the border of the northeast and northwest regions).

During MARAMP 2007, 3 REA benthic surveys of forereef habitats around Asuncion were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 0% to 2% with an overall sample mean of 1% (SE 0.6). No macroalgae were observed in the northeast region at REA site ASC-01 (Fig. 15.6.1b). At both ASC-02 in the southwest region and at ASC-03 in the northwest region, macroalgal cover was 2%.

Turf-algal cover from these REA benthic surveys in 2007 ranged from 25.5% to 85.3% with an overall sample mean of 59% (SE 17.6). The highest turf-algal cover was observed in the northeast region at ASC-01 (Fig. 15.6.1b). Turf-algal cover was also high (65.7%) in the northwest region at ASC-03.

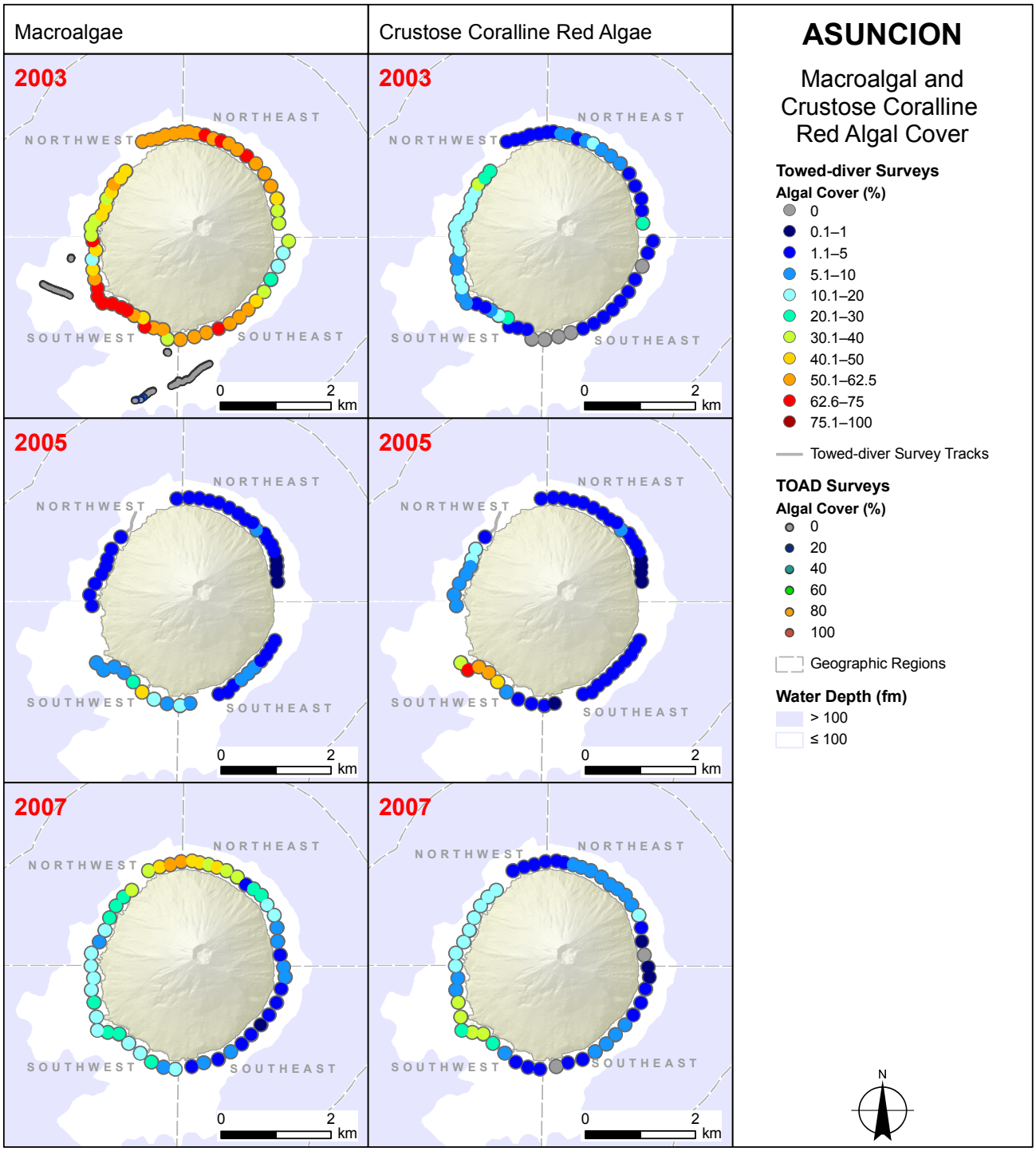


Figure 15.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Asuncion during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Asuncion was 8% (SE 1). Two surveys with the highest crustose-coralline-red-algal cover, each recording a mean of 19%, within a range of 10.1%–40%, occurred in the northwest region and in the southwest region (Fig. 15.6.1a, top right panel). Rock boulders and continuous reef of medium-high to high complexity were the dominant structural features in both surveys.

An additional survey in the southwest region was the only other survey to report greater than average crustose-coralline-red-algal cover for Asuncion, with a mean of 9%. In comparison to these 3 surveys, all other surveys reported low values of crustose-coralline-red-algal cover for Asuncion with means ranging from 2.5% to 7.1%.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Asuncion was 9% (SE 2.8). The survey with the highest mean crustose-coralline-red-algal cover of 23%, within a range of 1.1%–75%, occurred in the southwest region (Fig. 15.6.1a, middle right panel). The low segment values from this survey corresponded to flat, sandy terrain, and the remainder of this surveyed area hosted crustose-coralline-red-algal cover of 30.1%–75%. In contrast, all other surveys around Asuncion reported less than average crustose-coralline-red-algal cover for this island, with means ranging from 1.8% to 7.1% in the southeast and northwest regions.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Asuncion was 10% (SE 1.4). The survey with the highest crustose-coralline-red-algal cover of 18%, within a range of 1.1%–40%, occurred in the southwest region (Fig. 15.6.1a, bottom right panel). The adjacent survey in the northwest region reported mean cover of 13.5%. All other surveys reported less than average values of cover for Asuncion, with means ranging from 3.5% to 4.8%.

During MARAMP 2007, 3 REA benthic surveys were conducted using the line-point-intercept method at Asuncion. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 39.2% with an overall sample mean of 13% (SE 1.5). Crustose-coralline-red-algal cover was observed only at ASC-02 in the southwest region (Fig. 15.6.1b).

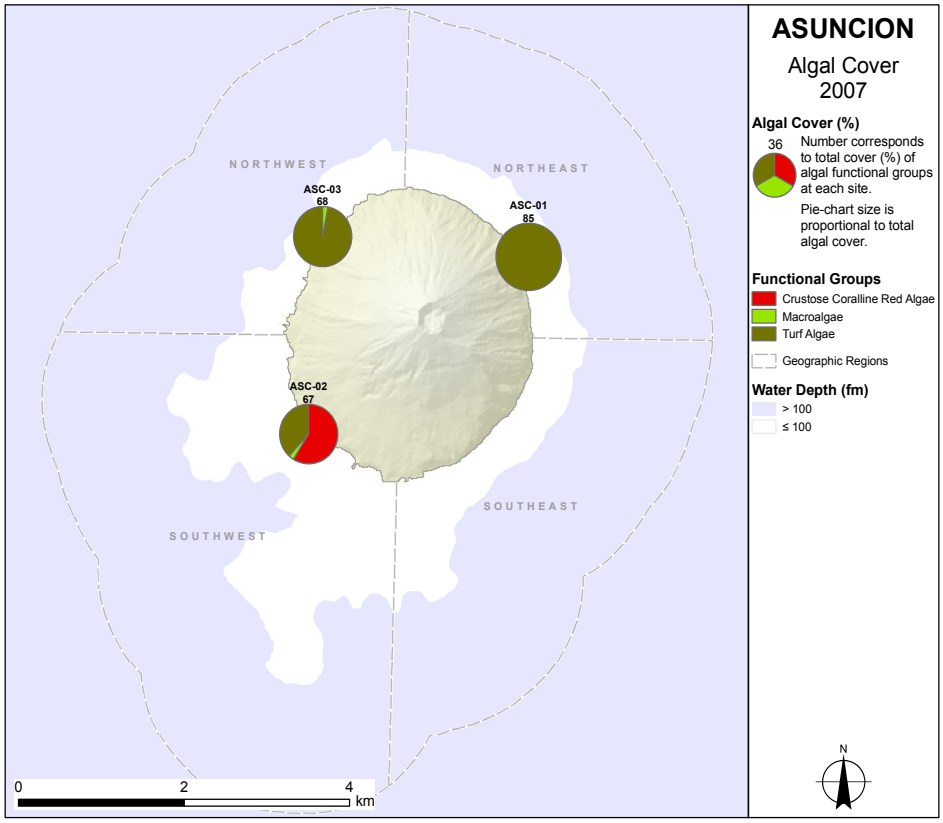


Figure 15.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method at Asuncion during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Algal Cover: Temporal Comparison

Between MARAMP survey years, islandwide mean cover of macroalgal populations around Asuncion, based on towed-diver surveys on forereef habitats, varied as much as 46% (Fig. 15.6.1c). Reefs in the northeast and southwest regions generally hosted higher benthic cover of macroalgae than did the other 2 regions. When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Crustose-coralline-red-algal populations around Asuncion, based on towed-diver surveys on forereef habitats, were similar in islandwide average cover of the benthos between MARAMP survey years (Fig. 15.6.1c). Cover of crustose coralline red algae increased by 4% in the southwest region between MARAMP 2003 and 2005 and by 6% in the northwest region between MARAMP 2005 and 2007. Cover in the southwest region decreased by ~ 5% between 2005 and 2007, but this region still hosted the highest cover of crustose coralline red algae recorded in 2007.

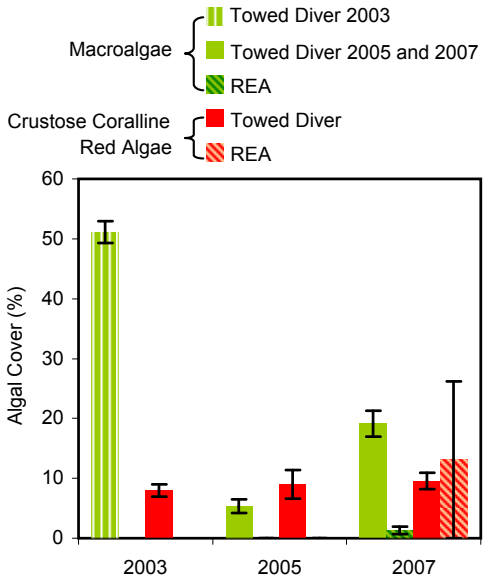


Figure 15.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Asuncion during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 3 sites on forereef habitats at Asuncion. In the field, 10 macroalgal genera (1 red, 3 brown, and 6 green), containing at least 11 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. ASC-03 in the northwest region had the highest macroalgal generic diversity with 7 genera, containing 8 species, documented in the field. The lowest macroalgal generic diversity was found in the southwest region at ASC-02 with 4 species representing 4 genera recorded.

The brown algal species *Lobophora variegata* was ubiquitous at every site surveyed at Asuncion in 2003, occurring in 75% of all sampled photoquadrats (Fig. 15.6.1d, top panel). The green algal genus *Neomeris* also was common, although its occurrence was higher at ASC-02 in the southwest region with 33.3% than at the sites on the northern coast, ASC-01 and ASC-03, where occurrence was 8.3% at each site. Of the remaining 8 taxa tentatively identified, most were observed only at 1 or 2 sites, making distinctive spatial patterns of distribution difficult to determine.

Turf algae were exceptionally common in 2003, occurring in 97% of photoquadrats sampled at Asuncion. Turf-algal communities were common at all sites. Crustose coralline red algae also were observed at all sites, occurring in 22% of sampled photoquadrats. Cyanobacteria, found in 0–50% of sampled photoquadrats, were common only at ASC-02 in the southwest region (Fig. 15.6.1d, top panel).

During MARAMP 2005, REA benthic surveys were conducted at 3 sites on forereef habitats at Asuncion. In the field, 10 macroalgal genera (1 red, 3 brown, and 6 green), containing at least 10 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, nongeniculate calcified red algae, and cyanophytes—were observed. ASC-02 in the southwest region had the highest macroalgal generic diversity with 8 genera, containing 8 species, documented in the field. The lowest macroalgal genera diversity was found at ASC-01 in the northeast region with 5 species representing 5 genera recorded.

Lobophora variegata was exceptionally common at sites surveyed at Asuncion in 2005 (Fig. 15.6.1d, middle panel). Besides *Lopophora*, *Halimeda* and the calcified, red algal genus *Jania* were the only other algal genera recorded at all 3 sites surveyd at Asuncion, occurring in 27.7% and 19.4% of sampled photoquadrats. Although not present at every site, species of the green macroalgal genera *Chlorodesmis*, *Caulerpa*, and *Rhipidosiphon* were common at Asuncion, occurring in 30.5%, 22.2%, and 16.7% of sampled photoquadrats. Of the 10 taxa identified at Asuncion, 8 were found in the southwest region at ASC-02, and only 5 and 6 taxa were found at the 2 sites on the northern coast. Species of the green algal genera

Dictyosphaeria and *Rhipidosiphon* and the brown algal genus *Dictyota* were found exclusively at ASC-02; conversely, species of *Neomeris* were found, in low abundance, at only ASC-01 and ASC-03 on the northern coast.

Turf algae and crustose coralline red algae were exceptionally common, occurring in 97% and 78% of photoquadrats sampled at Asuncion in 2005 (Fig. 15.6.1d, middle panel). Cyanobacteria were recorded only at ASC-03 in the northwest region, occurring in 8.3% of the photoquadrats sampled at this site.

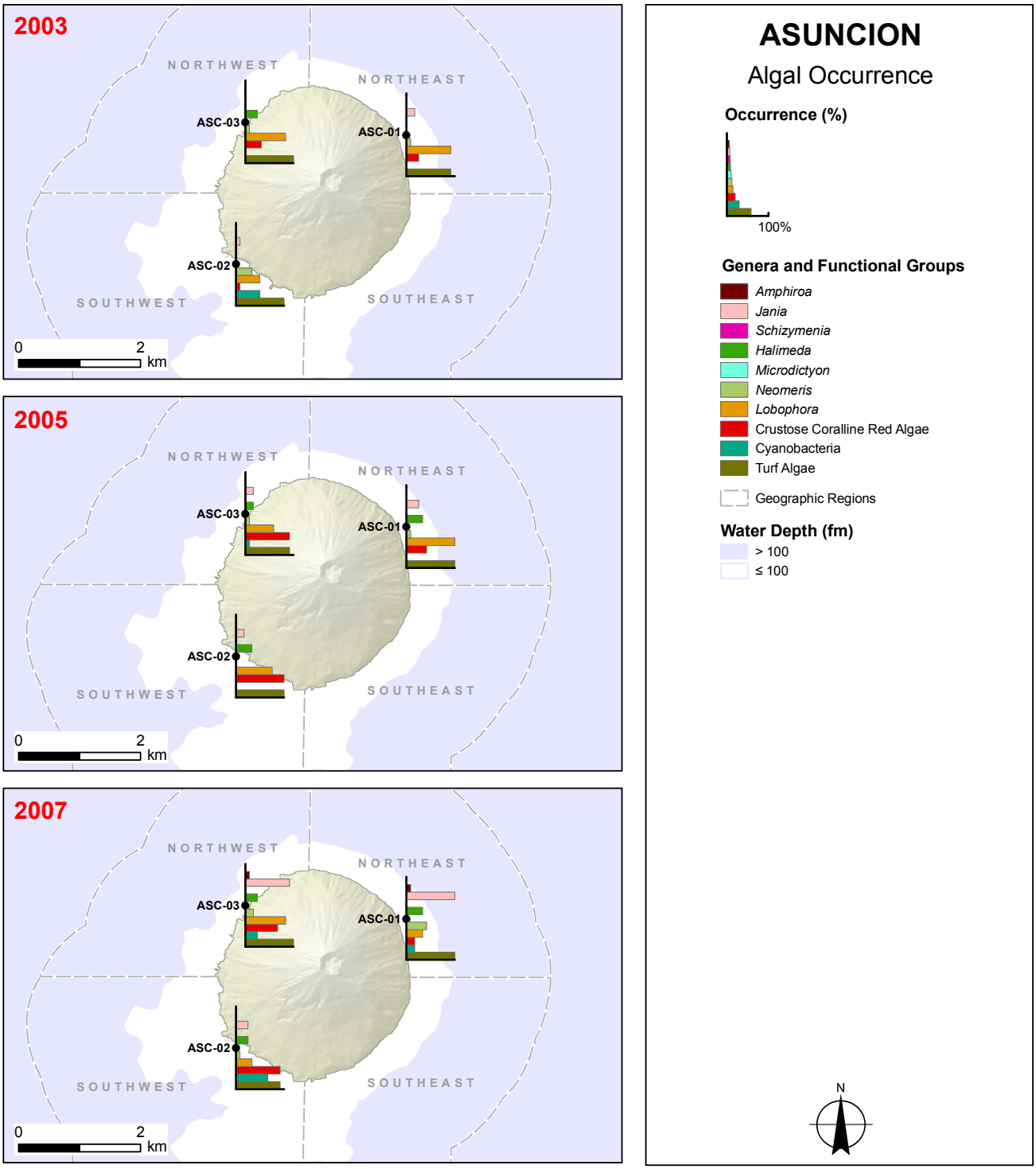


Figure 15.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Asuncion during MARAMP 2003, 2005, and 2007. Occurrence is equivalent to the percentage of photo-quadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2007, REA benthic surveys were conducted at 3 sites on forereef habitats at Asuncion. In the field, 14 macroalgal genera (4 red, 7 green, and 3 brown), containing at least 14 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. ASC-02 in the southwest region had the highest macroalgal generic diversity with 12 genera, containing 12 species, documented in the field. At both ASC-01 and ASC-03, 8 species representing 8 genera were recorded.

Species of the genera *Jania*, *Lobophora*, *Caulerpa*, and *Halimeda* were all ubiquitous at the 3 sites surveyed at Asuncion in 2007, occurring in 72%, 50%, 50%, and 27.8% of sampled photoquadrats (Fig. 15.6.1d, bottom panel). The occurrence of each taxon was quite variable between sites. Species of *Jania* occurred in only 25% of photoquadrats sampled at ASC-02; however, it was extremely abundant at the 2 sites on the northern coast, occurring in 91.7% and 100% of photoquadrats sampled at ASC-03 and ASC-01. *Lobophora variegata* was found in 33.3% of sampled photoquadrats at both ASC-01 and ASC-02 and in 83% of sampled photoquadrats at ASC-03. Species of *Halimeda* were present in 27.8% of photoquadrats sampled at Asuncion.

Turf algae, crustose coralline red algae, and cyanobacteria were all exceptionally common in 2007, occurring in 97%, 58%, and 36% of photoquadrats sampled at Asuncion. Turf algae was found in 91.7%–100% of sampled photoquadrats, and crustose coralline red algae and cyanobacteria, both with more variable occurrence values, were recorded in 16.7%–66.7% of sampled photoquadrats (Fig. 15.6.1d, bottom panel).

A marginal increase in macroalgal biodiversity from 10 to 14 genera between 2005 and 2007 was recorded at Asuncion. The genera discovered in 2007 that were not previously recorded in 2003 or 2005 were the green algal genus *Tydemania* and the red algal genera *Peyssonnelia*, *Amphiroa*, and *Hypnea*. In 2005, algae whose identifications were unknown to field observers were recorded in as many as 16.7% of photoquatrats sampled at ASC-01 in the northeast region and 41.6% at ASC-03 in the northwest region. Because the 4 new genera found in 2007 were known to phycologists working in the field, it is unlikely that they correspond to the unknown taxa recorded in 2005. Substantial increases were observed in abundance of species of *Jania*, which occurred in only 8% of photoquadrats sampled at Asuncion in 2003 but in 19% and 72% of sampled photoquadrats in 2005 and 2007 (Fig. 15.6.1e). The occurrence of species of *Halimeda* also increased. Species of *Halimeda* were recorded in only 8% of photoquadrats sampled at Asuncion in 2003 but were found in 27% of sampled photoquadrats in 2005 and 2007. *Lobophora variegata* was recorded in 75% and 77% of sampled photoquadrats in 2003 and 2005 and then only 50% in 2007. The genera *Neomeris* and *Caulerpa* also were common in the 3 MARAMP survey years. The green algal genera *Rhipidosiphon* and *Chlorodesmis* were common in 2005 but uncommon in 2007, whereas species of *Padina* and *Peysonnelia* were common in 2007 but not in 2005.

Occurrence of turf algae on forereef habitats at Asuncion remained consistent between the 3 MARAMP survey years, and this functional group was recorded in 97.2% of sampled photoquadrats during MARAMP 2003, 2005, and 2007 (Fig. 15.6.1e). The abundance of cyanobacteria appeared variable between survey years, decreasing in occurrence from 16.6% in 2003 to 2.7% in 2005 and then increasing to 36% in 2007. No other temporal trends of increasing or decreasing abundance of functional groups were obvious.

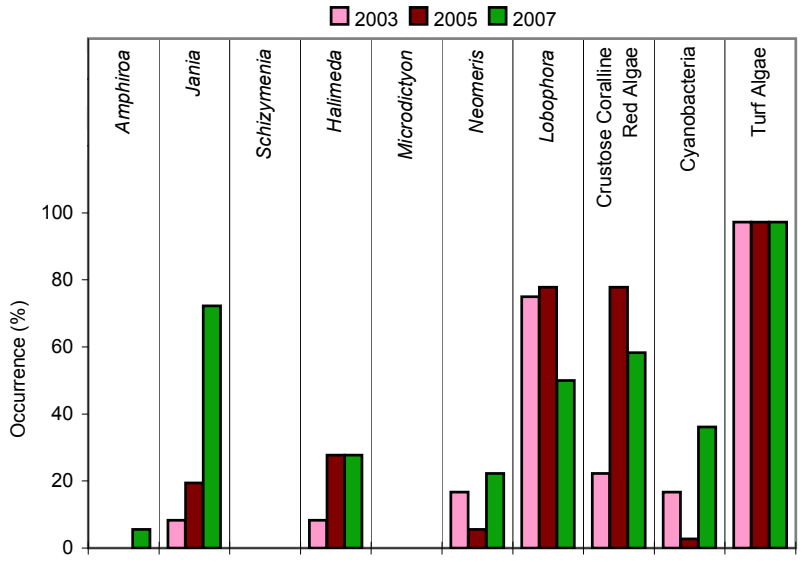


Figure 15.6.1e. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Asuncion during MARAMP 2003, 2005, and 2007.

15.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 3 sites on forereef habitats at Asuncion. These surveys covered a total reef area of 900 m^2 and detected only 1 case of coralline lethal orange disease at site ASC-02 (Fig. 15.6.2a).

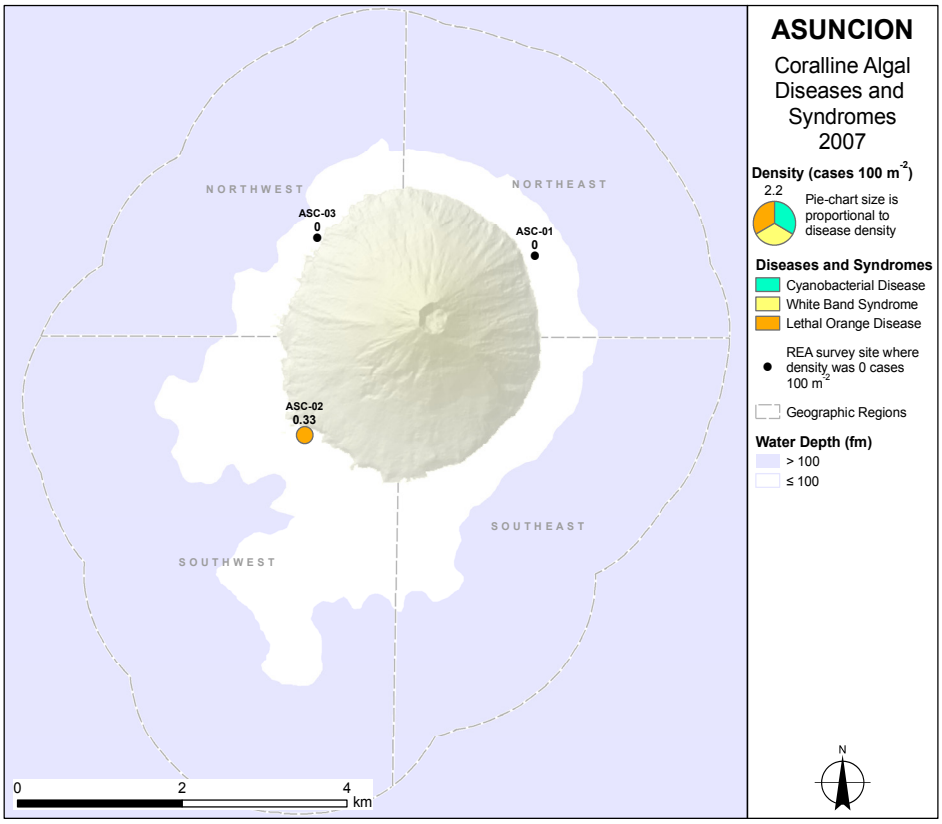


Figure 15.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats at Asuncion during MARAMP 2007.

15.7 Benthic Macroinvertebrates

15.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the island of Asuncion through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during the REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 3 REA benthic surveys and 6 towed-diver surveys were conducted around Asuncion. In 2005, 3 REA surveys and 5 towed-diver surveys were performed, and in 2007, 2 REA surveys and 5 towed-diver surveys were conducted. When considering results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, both REA and towed-diver surveys suggested low daytime macroinvertebrate abundance on forereef habitats around Asuncion compared to the rest of the Mariana Archipelago. Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. Temporal patterns of islandwide mean macroinvertebrate density around Asuncion—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 15.7.1b, d, f and h).

Giant Clams

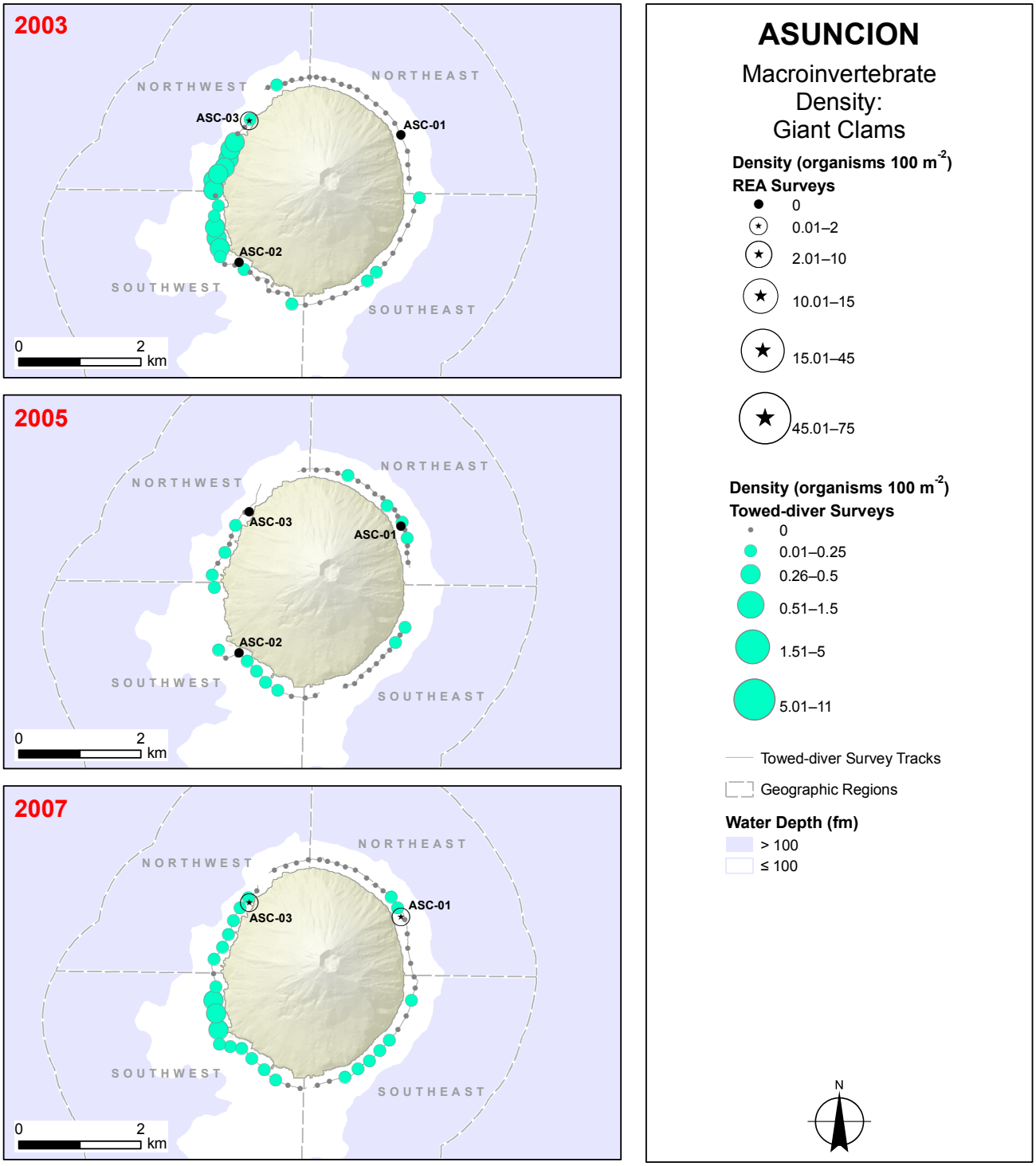


Figure 15.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Asuncion during MARAMP 2003, 2005, and 2007.

During MARAMP 2003, species of *Tridacna* giant clams were observed at 1 of the 3 REA sites surveyed and in 5 of the 6 towed-diver surveys conducted around Asuncion. REA site ASC-03 in the northwest region had a density of 1 organism 100 m^{-2}. The islandwide mean density from towed-diver surveys was 0.073 organisms 100 m^{-2} (SE 0.017). Among all towed-diver surveys around this island, the survey completed in the northwest region had the highest mean density of giant clams with 0.252 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.431 organisms 100 m^{-2} (Fig. 15.7.1a, top panel). The second-greatest mean density of giant clams from a towed-diver survey was 0.149 organisms 100 m^{-2}, recorded in the southwest region; segment densities ranged from 0 to 0.412 organisms 100 m^{-2}.

During MARAMP 2005, no giant clams were observed at the 3 REA sites surveyed at Asuncion, but all 5 towed-diver surveys had recordings of giant clams with an islandwide mean density of 0.034 organisms 100 m^{-2} (SE 0.009). Among all towed-diver surveys around this island, the survey completed in the southwest region had the highest mean density with 0.045 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.108 organisms 100 m^{-2} (Fig. 15.7.1a, middle panel).

During MARAMP 2007, giant clams were observed at both of the REA sites surveyed and in 4 of the 5 towed-diver surveys conducted around Asuncion. The overall mean density of giant clams from REA surveys was 0.5 organisms 100 m^{-2} (SE 0.17), and the islandwide mean density from towed-diver surveys was 0.055 organisms 100 m^{-2} (SE 0.012). Survey results suggest that giant clams were most abundant at ASC-03 in the northwest region with 0.67 organisms 100 m^{-2} (Fig. 15.7.1a, bottom panel). Among all towed-diver surveys around Asuncion, the survey completed in the southwest region had the highest mean density of giant clams with 0.123 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.358 organisms 100 m^{-2}.

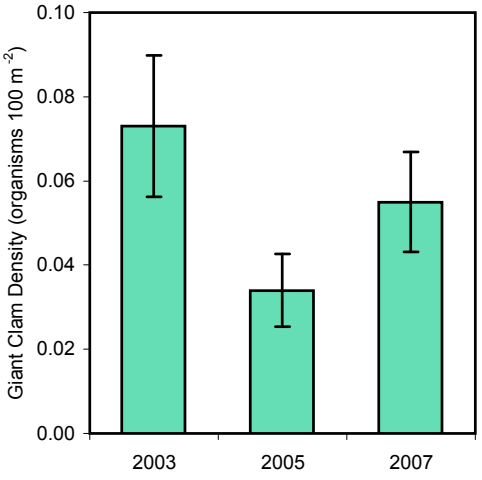


Figure 15.7.1b. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Asuncion during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested low abundance of giant clams around Asuncion during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago (Fig. 15.7.1b). Although densities were low, the highest concentrations of giant clams resided along the west coast in each of the 3 MARAMP survey years. Minor fluctuations in density were observed, but this variation is not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Crown-of-thorns Seastars

During MARAMP 2003, no crown-of-thorns seastars (*Acanthaster planci*) were observed at the 3 REA sites surveyed or in the 6 towed-diver surveys conducted around Asuncion (Fig. 15.7.1c, top panel).

During MARAMP 2005, no COTS were observed at the 3 REA sites surveyed, but 2 of the 5 towed-diver surveys conducted around Asuncion had recordings of COTS with an overall mean density of 0.027 organisms 100 m^{-2} (SE 0.011). Among all towed-diver surveys around Asuncion, the survey completed in the northwest region had the highest mean density of COTS with 0.006 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.056 organisms 100 m^{-2} (Fig. 15.7.1c, middle panel).

During MARAMP 2007, COTS were observed at 1 of the 2 REA sites surveyed and in 2 of the 5 towed-diver surveys conducted around Asuncion. ASC-03 in the northwest region had a density of 1.667 organisms 100 m^{-2}. The islandwide mean density from towed-diver surveys was 0.029 organisms 100 m^{-2} (SE 0.011). The survey completed in the northwest region had the highest density of COTS with 0.117 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.445 organisms 100 m^{-2} (Fig. 15.7.1c, bottom panel). The second-greatest mean COTS density from a towed-diver survey was 0.035 organisms 100 m^{-2}, recorded in the southwest region; segment densities ranged from 0 to 0.164 organisms 100 m^{-2}.

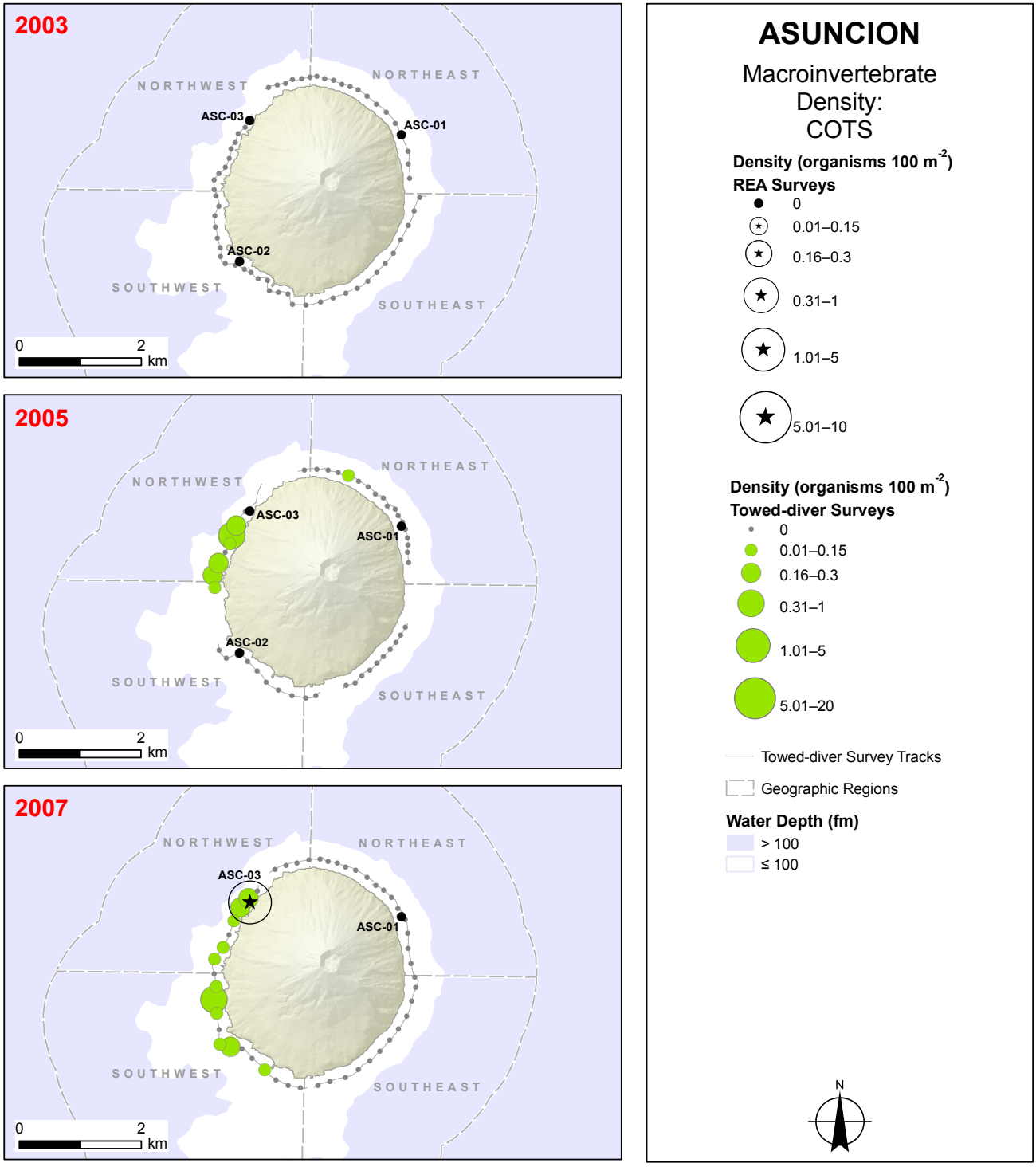


Figure 15.7.1c. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Asuncion during MARAMP 2003, 2005, and 2007.

No observations of COTS were made in towed-diver surveys conducted around Asuncion during MARAMP 2003. However, COTS were recorded during the other survey periods, particularly in the northwest region in 2005 and in the northwest and southwest regions in 2007 (Fig. 15.7.1d). The higher density observed in 2005, versus results from 2003, may have been a reflection of a recruitment pulse of COTS to Asuncion as an increased level of COTS density persisted in 2007. This change will have to be monitored more closely during additional MARAMP cruises. Density of this corallivorous seastar naturally fluctuates with food availability and variation in recruitment success (Birkeland and Lucas 1990; Fabricius et al. 2010; Yamaguchi 1987).

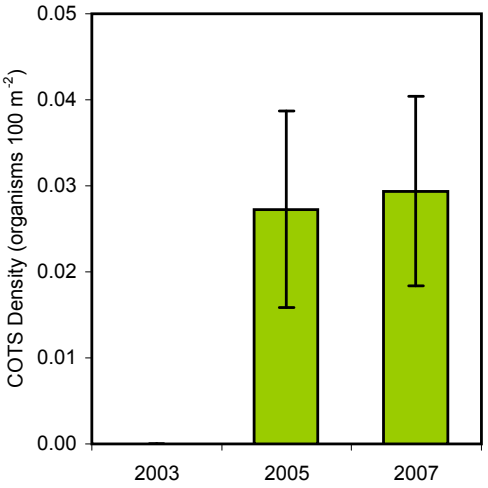


Figure 15.7.1d. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Asuncion during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at 1 of the 3 REA sites surveyed and in 2 of the 6 towed-diver surveys conducted around Asuncion (Fig. 15.7.1e, top panel). ASC-02 had a density of 1 organism 100 m^{-2}; the observed sea cucumber was from the genus *Holothuria*. The islandwide mean density from towed-diver surveys was 0.002 organisms 100 m^{-2} (SE 0.001). The towed-diver survey completed in the northwest region had the highest mean density of sea cucumbers with 0.007 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.069 organisms 100 m^{-2} (Fig. 15.7.1e, top panel).

During MARAMP 2005, no sea cucumbers were observed at the 3 REA sites surveyed at Asuncion, and only 1 of the 5 towed-diver surveys conducted had recordings of sea cucumbers, with a mean density of 0.005 organisms 100 m^{-2} (SE 0.071); segment densities from this survey ranged from 0 to 0.075 organisms 100 m^{-2} (Fig. 15.7.1e, middle panel).

During MARAMP 2007, no sea cucumbers were observed at the 2 REA sites surveyed at Asuncion, and only 2 of the 5 towed-diver surveys conducted had recordings of sea cucumbers, with an islandwide mean density of 0.012 organisms 100 m^{-2} (SE 0.006). The towed-diver survey completed in the northwest region had the highest mean density of sea cucumbers with 0.055 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.312 organisms 100 m^{-2} (Fig. 15.7.1e, bottom panel).

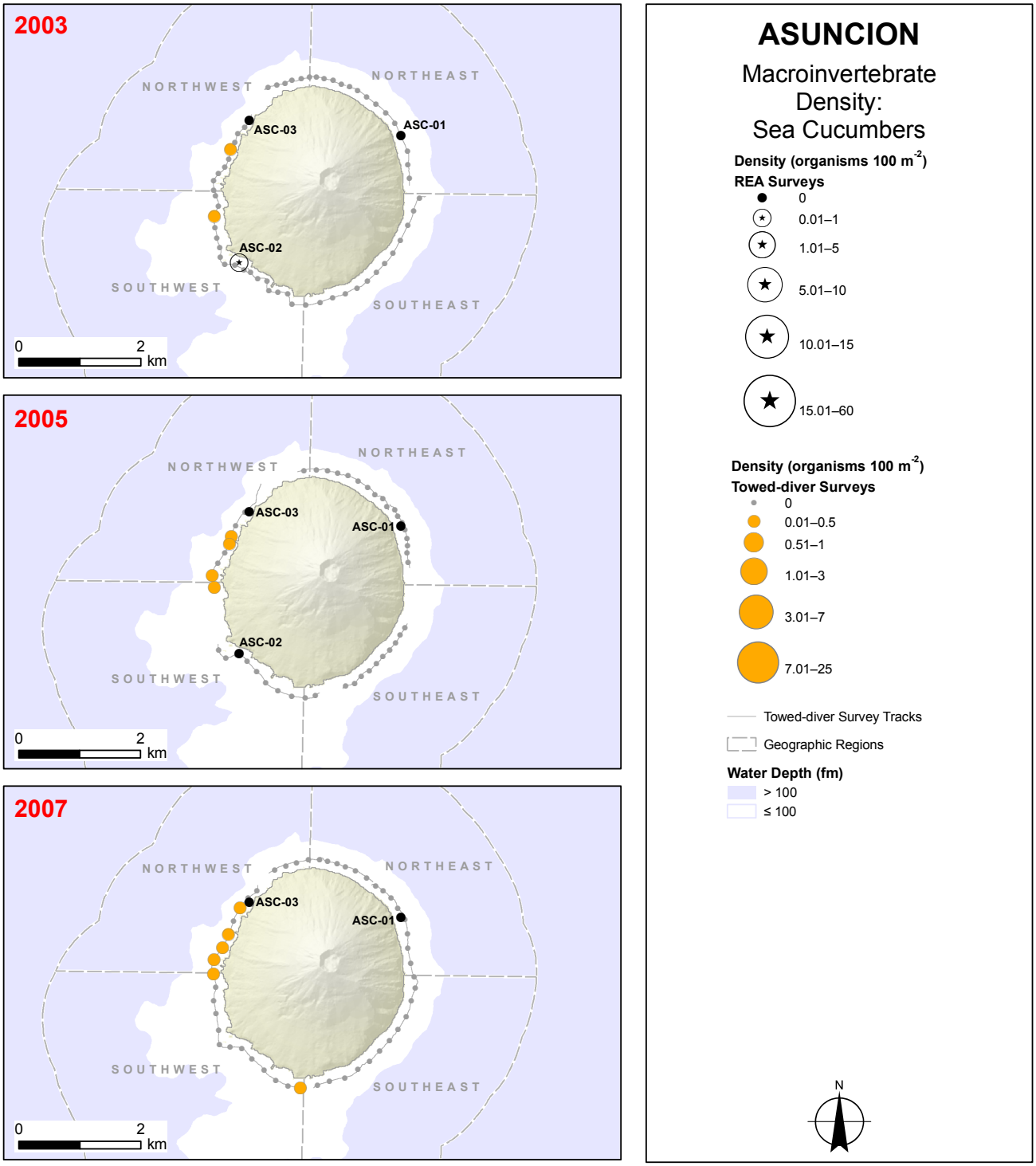


Figure 15.7.1e. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Asuncion during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggested low daytime abundance of sea cucumbers around Asuncion during MARAMP 2003, 2005, and 2007, relative to the rest of the Mariana Archipelago (Fig. 15.7.1f). Sea cucumbers were observed only in the northwest and southwest regions. Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

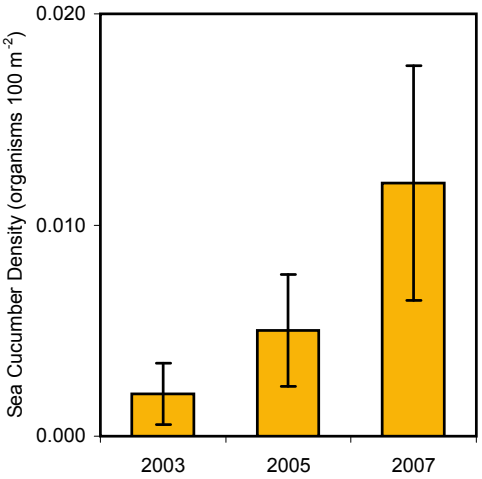


Figure 15.7.1f. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted on forereef habitats around Asuncion during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Urchins

During MARAMP 2003, sea urchins were observed at the 3 REA sites surveyed and in 4 of the 6 towed-diver surveys conducted around Asuncion. The overall mean density from REA surveys was 4.67 organisms 100 m^{-2} (SE 2.03), and the islandwide mean density from towed-diver surveys was 0.144 organisms 100 m^{-2} (SE 0.07). Survey results suggest that sea urchins were most abundant at ASC-02 in the southwest region with 8 organisms 100 m^{-2} (Fig. 15.7.1g, top panel). All observations at this site were species of the genus *Echinothrix*. Other genera observed at Asuncion during REA surveys, in low numbers, included *Echinostrephus*, a genus of rock-boring urchins. Among all towed-diver surveys around Asuncion, the survey completed in the northwest region had the highest mean density of sea urchins with 0.48 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.37 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed at 1 of the 3 REA sites surveyed and in 3 of the 5 towed-diver surveys conducted around Asuncion. ASC-02 had a density of 1 organism 100 m^{-2}; the observed sea urchin was from the genus *Echinostrephus*. The islandwide mean density from towed-diver surveys was 0.11 organisms 100 m^{-2} (SE 0.07). Among all towed-diver surveys around Asuncion, the survey completed in the northeast region had the highest mean density of sea urchins with 0.26 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.39 organisms 100 m^{-2} (Fig. 15.7.1g, middle panel).

During MARAMP 2007, sea urchins were observed at both REA sites surveyed and in 3 of the 5 towed-diver surveys conducted around Asuncion. Both ASC-01 and ASC-02 had a mean density of sea urchins of 0.33 organisms 100 m^{-2}, and, at both sites, only rock-boring urchins from the genus *Echinostrephus* were observed. The islandwide mean density from towed-diver surveys was 0.62 organisms 100 m^{-2} (SE 0.25). Among all towed-diver surveys around Asuncion, the survey completed in the southeast region had the highest mean density of sea urchins with 2.02 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 7.35 organisms 100 m^{-2} (Fig. 15.7.1g, bottom panel). The second-greatest mean density of sea urchins from a towed-diver survey was 1.02 organisms 100 m^{-2}, recorded in the southwest region; segment densities ranged from 0 to 6.97 organisms 100 m^{-2}.

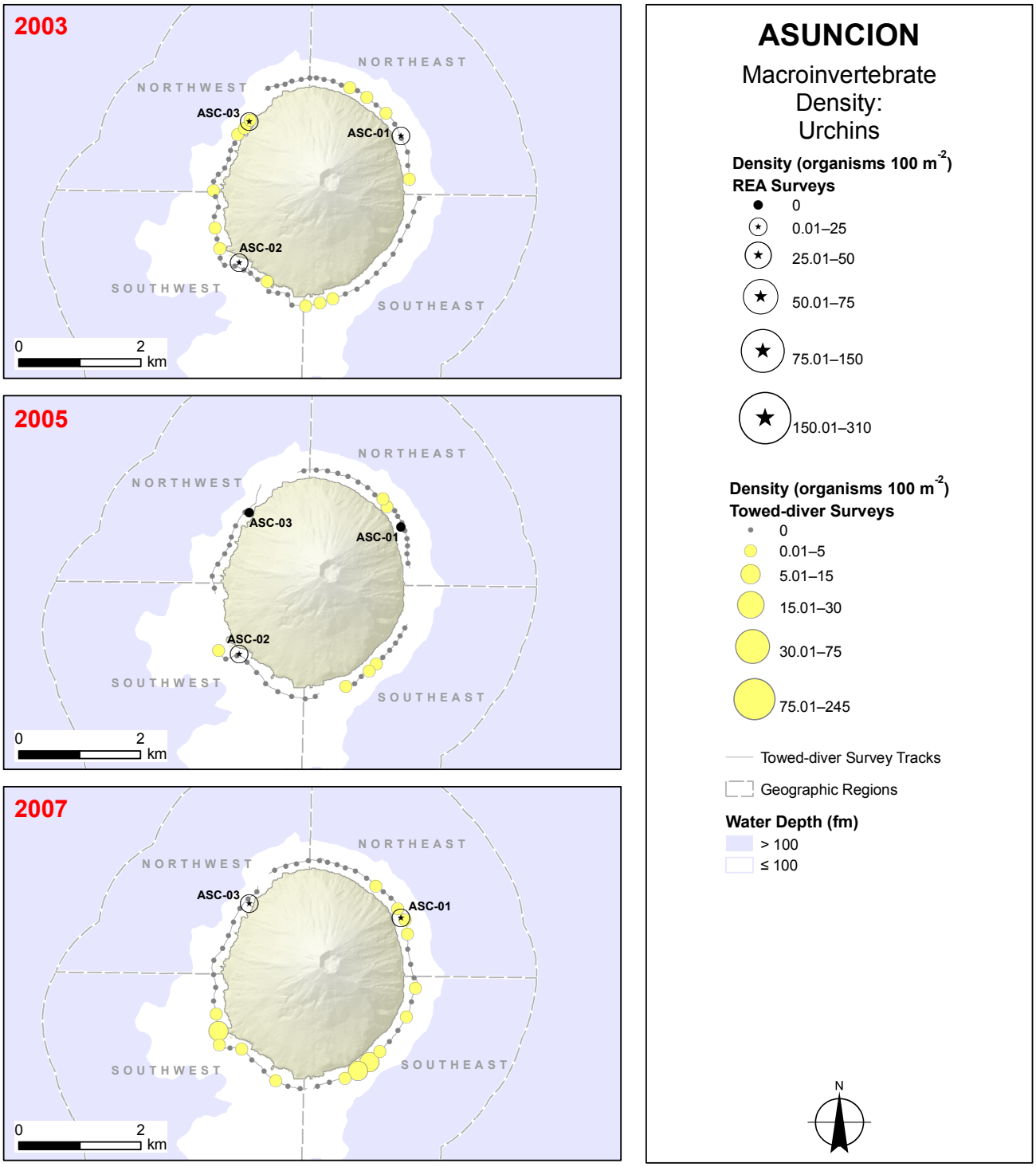


Figure 15.7.1g. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Asuncion during MARAMP 2003, 2005, and 2007.

Towed-diver surveys suggested extremely low abundance of sea urchins around Asuncion during MARAMP 2003, 2005, and 2007, compared to the rest of the Mariana Archipelago (Fig. 15.7.1h). The temporal fluctuations in densities are not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

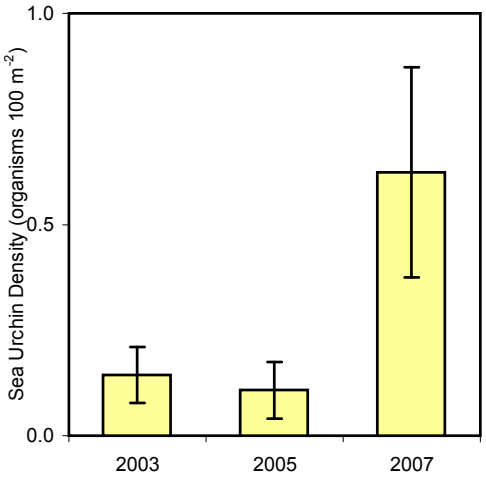


Figure 15.7.1h. Temporal comparison of mean densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Asuncion during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

15.8 Reef Fishes

15.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 6 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Asuncion. The overall estimated mean biomass of large fishes around this island, calculated as weight per unit area, was 2.12 kg 100 m^{-2} (SE 0.26). Observed large-fish biomass was highest in the southeast and southwest regions, where sharks were common (Fig. 15.8.1a, top panel). Snappers (Lutjanidae), reef sharks (Carcharhinidae), and nurse sharks (Ginglymostomatidae) constituted the largest proportion (80%) of the islandwide mean biomass of large fishes. Snappers alone contributed 35% of overall large-fish biomass. The twinspot snapper (*Lutjanus bohar*) was the dominant snapper species by biomass, contributing 0.51 kg 100 m^{-2} to islandwide large-fish biomass. Reef sharks accounted for 34% or 0.71 kg 100 m^{-2} of the overall large-fish biomass. The grey reef shark (*Carcharhinus amblyrhynchos*) was the largest contributor to biomass of reef sharks with 0.62 kg 100 m^{-2}. Nurse sharks also were common, with the tawny nurse shark (*Nebrius ferrugineus*) contributing 0.24 kg 100 m^{-2} of islandwide mean large-fish biomass.

During MARAMP 2005, 5 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Asuncion. The overall estimated mean biomass of large fishes around this island was 1.81 kg 100 m^{-2} (SE 0.45), similar to biomass observed in 2003. As in 2003, observed large-fish biomass in 2005 was highest in the southeast and southwest regions, where sharks were common (Fig. 15.8.1a, middle panel). Reef sharks and nurse sharks dominated observations of large fishes and accounted for the greatest proportion (76%) or 1.38 kg 100 m^{-2} of islandwide mean large-fish biomass. The grey reef shark was the dominant shark species by biomass with 0.95 kg 100 m^{-2}. During this survey period, 60 sharks were observed, with 30 individuals recorded during a single survey. Although sharks were abundant, many of the grey reef sharks observed were smaller than 100 cm in TL, which is below the size of sexual maturity (120–150 cm in TL) for this species.

During MARAMP 2007, 5 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Asuncion. The overall observed mean biomass of large fishes around this island was at 0.78 kg 100 m^{-2} (SE 0.21), lower than estimates made in 2003 and 2005. The highest observed large-fish biomass was found in the northeast region, where sharks and snappers were common (Fig. 15.8.1a, bottom panel). Snappers accounted for the greatest proportion (40%) or 0.31 kg 100 m^{-2} of islandwide mean large-fish biomass. The black and white snapper (*Macolor niger*) and twinspot snapper were the 2 main snapper species by biomass with 0.17 and 0.12 kg 100 m^{-2}. During this survey period, 13 sharks were observed: 8 grey reef sharks; 3 whitetip reef sharks (*Triaenodon obsesus*), and 2 tawny nurse sharks.

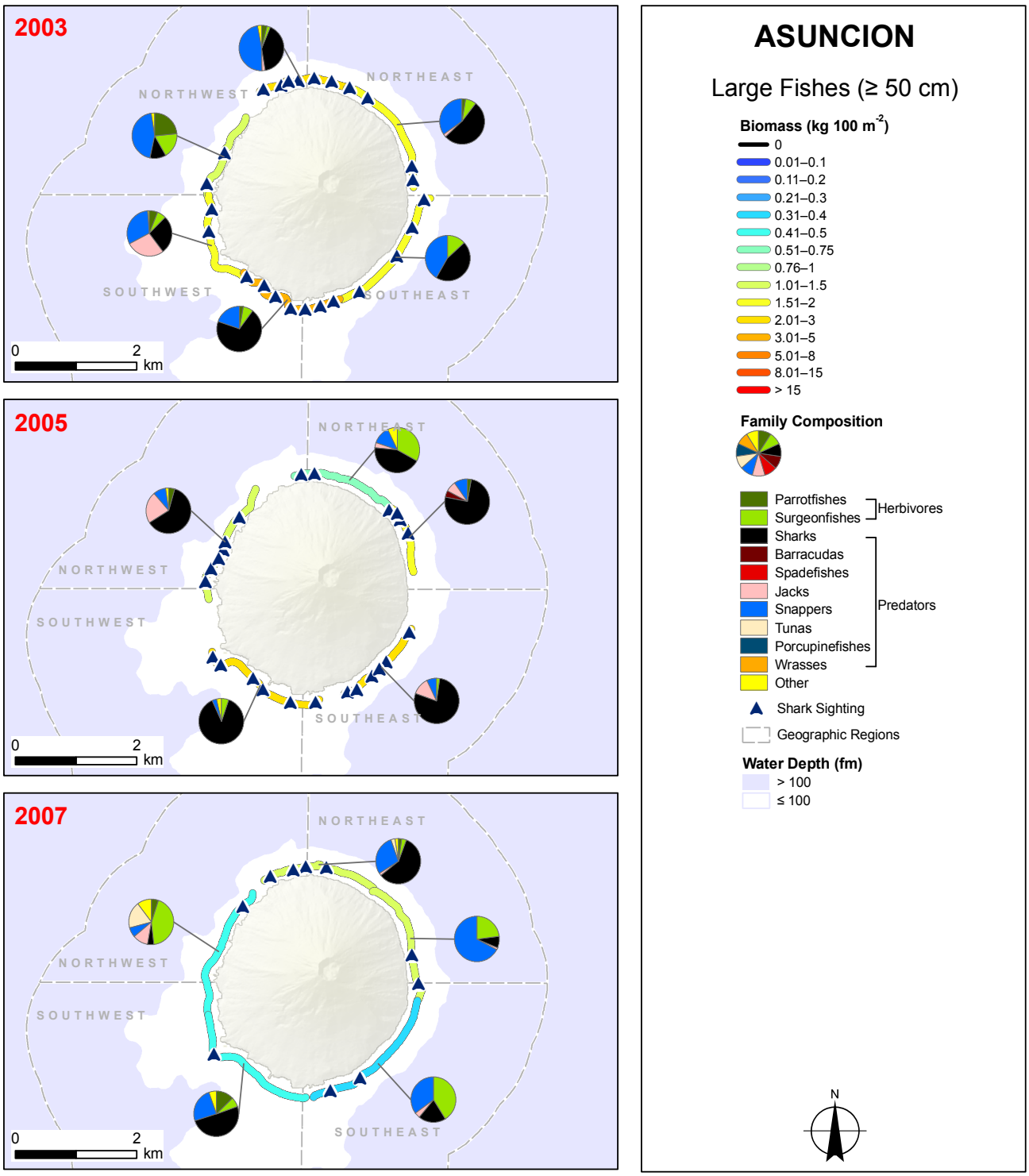


Figure 15.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Asuncion during MARAMP 2003, 2005, and 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

Large-fish biomass from towed-diver surveys of forereef habitats was lower during MARAMP 2007, with an islandwide mean of 0.78 kg 100 m^{-2} (SE 0.21), than during MARAMP 2003 and 2005, when islandwide means were 2.12 kg 100 m^{-2} (SE 0.26) in 2003 and 1.81 kg 100 m^{-2} (SE 0.45) in 2005 (Fig. 15.8.1b). However, large-fish biomass at Asuncion, with an overall mean of 1.57 kg 100 m^{-2} (SE 0.40) across the 3 survey periods, was the second-highest level recorded among the northern islands (estimated biomass was higher only at Farallon de Pajaros). Reef sharks and nurse sharks contributed the greatest percentages of large-fish biomass over the 3 survey periods, with the grey reef shark as the most abundant shark

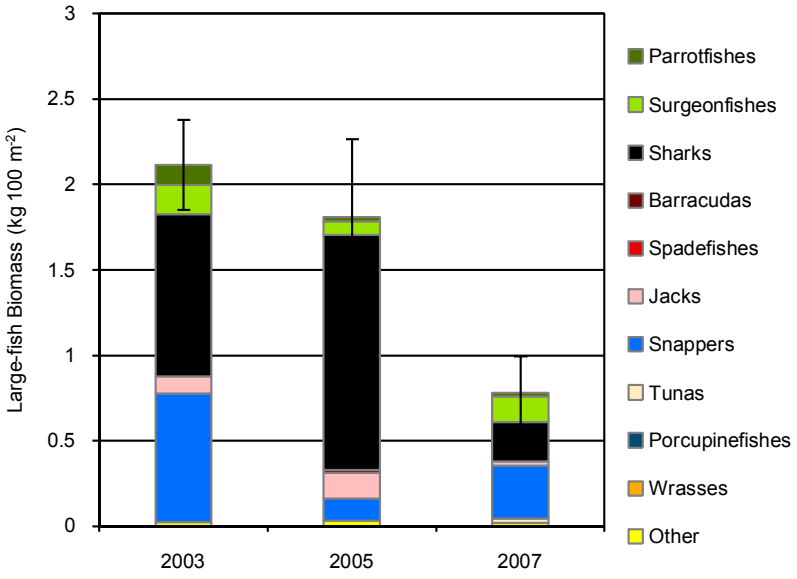


Figure 15.8.1b. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Asuncion during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

species recorded. The size of grey reef sharks observed was unusual, with many estimated to be smaller than 100 cm in TL. Snappers also were common during the 3 MARAMP survey periods, and the twinspot snapper, the black and white snapper, and the midnight snapper (*Macolor macularis*) were the most abundant snapper species. Other notable observations included sightings of the spotted knifejaw (*Oplignathus punctatus*), which was generally rare in the Mariana Archipelago.

Total Fish Biomass

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Asuncion during MARAMP 2003 was somewhat below the average of the northern islands, with an overall sample mean of 7.39 kg 100 m^{-2} (SE 0.65). The highest biomass of 8.28 kg 100 m^{-2} was observed at REA site ASC-01 in the northeast region (Fig. 15.8.1c, top panel). Surgeonfishes (Acanthuridae), snappers, and fusiliers (Caesionidae) accounted for the greatest proportions of total fish biomass: 20%, 13%, and 13%. The orangespine unicornfish (*Naso lituratus*) was the dominant surgeonfish species by biomass, and the twinspot snapper was the main snapper species by biomass. Fusiliers were abundant at ASC-03, located in the northwest region, where schools of the yellow and blueback fusilier (*Caesio terres*) and Marr's fusilier (*Pterocaesio marri*) were observed.

Based on REA surveys conducted during MARAMP 2003, species richness was variable among the 3 sites surveyed with a range of 25–38 species 100 m^{-2}. The highest diversity was found at ASC-03 in the northwest region (Fig. 15.8.1c, top panel). Wrasses (Labridae) and surgeonfishes composed the 2 most represented families with 24 and 18 species observed. The ornate wrasse (*Halichoeres ornatissimus*) was the most numerically abundant wrasse species, and the orangespine unicornfish was the most numerically abundant surgeonfish species. Damselfishes (Pomacentridae) were the most numerically abundant fish taxa overall, with Vanderbilt's chromis (*Chromis vanderbilti*) dominating counts with over 100 individuals 100 m^{-2} observed.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Asuncion during MARAMP 2005 was the highest level recorded in the Mariana Archipelago in this survey period, with an overall sample mean of 26.36 kg 100 m^{-2} (SE 1.42). Biomass was nearly uniformly high across the 3 sites, with site-specific biomass ranging from 24.87 to 29.20 kg 100 m^{-2} (Fig. 15.8.1c, middle panel). Reef sharks accounted for the largest proportion (28%) of total fish biomass. During this survey period, 12 sharks were observed: 10 gray reef sharks and 2 whitetip reef sharks. At least 1 shark was observed at all 3 of the sites in 2005. Surgeonfishes, chubs (Kyphosidae), and snappers also were large contributors to total fish biomass. The orangespine unicornfish accounted for the largest proportion (22%) of surgeonfish biomass. The humpback red snapper (*Lutjanus gibbus*) and twinspot snapper together constituted 98% of snapper biomass.

Based on REA surveys conducted during MARAMP 2005, species richness was high at Asuncion with a range of 40–45 species 100 m^{-2}. The highest diversity was seen at ASC-03 in the northwest region (Fig. 15.8.1c, middle panel). Consistent with observations made in 2003, wrasses and surgeonfishes composed the 2 most represented families with 21 and 15 species observed. The ornate wrasse was again the most numerically abundant wrasse species, while the brown surgeonfish (*Acanthurus nigrofuscus*) was the most abundant surgeonfish species. Damselfishes were the most abundant fish taxa overall, and the midget chromis (*Chromis acares*) dominated counts with more than 200 individuals 100 m^{-2} observed.

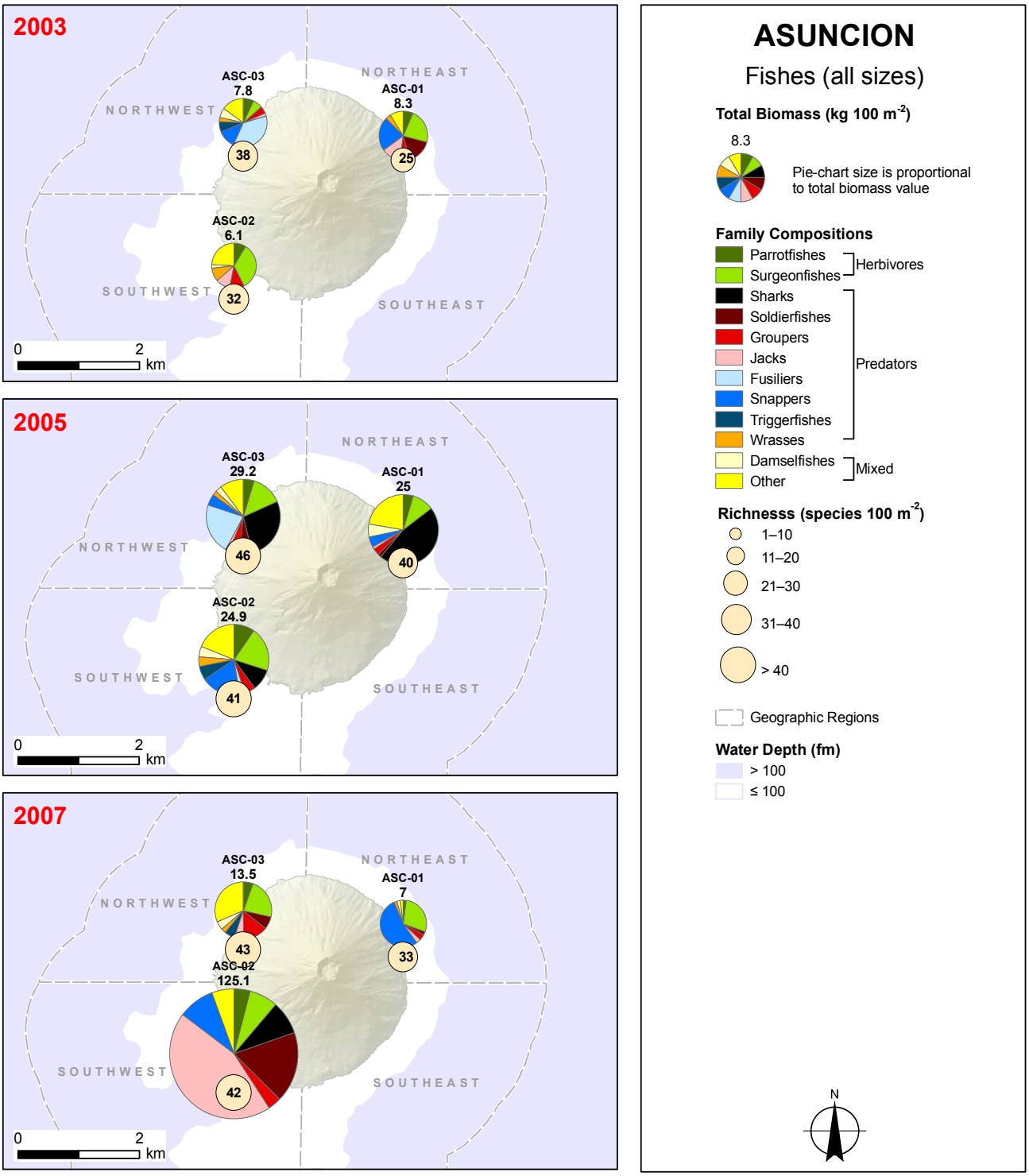


Figure 15.8.1c. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Asuncion during MARAMP 2003, 2005, and 2007.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Asuncion during MARAMP 2007 was the highest level observed in the Mariana Archipelago in the any of the 3 survey periods, with an overall sample mean of 48.54 kg 100 m^{-2} (SE 38.31). This very high value was partly a consequence of the observation at ASC-02 of 6 large giant trevally (*Caranx ignobilis*), each with estimated TL > 100 cm (Fig. 15.8.1c, bottom panel). Jacks (Carangidae) alone contributed 38% of total fish biomass. Soldierfishes (Holocentridae) accounted for the second-greatest proportion (16%) of total fish biomass, and surgeonfishes and snappers each made up another ~ 10% of total fish biomass

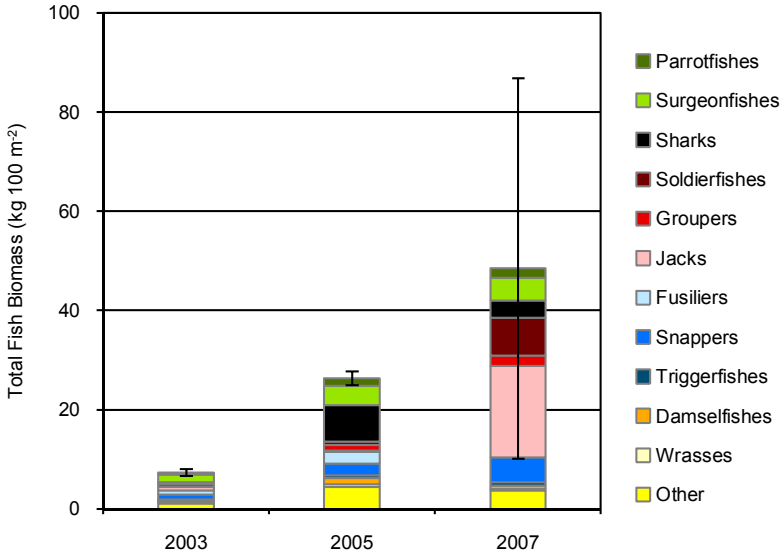


Figure 15.8.1d. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Asuncion during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

(4.63 and 5.01 kg 100 m^{-2}). The blotcheye soldierfish (*Myripristis berndti*) was the major soldierfish species and made up more than 90% of soldierfish biomass. Snappers and surgeonfishes also were common at Asuncion, contributing 5.01 kg 100 m^{-2} and 4.63 kg 100 m^{-2} to total fish biomass.

Based on REA surveys conducted during MARAMP 2007, species richness was moderate with a range of 33–43 species 100 m^{-2}. The highest diversity was found at ASC-03 in the northwest region (Fig. 15.8.1c, bottom panel). Wrasses and surgeonfishes composed the 2 most represented families with 19 and 18 species observed. Planktivorous fishes dominated counts with damselfishes again observed as the most abundant fish taxa overall. The midget chromis was by far the most abundant damselfish species with more than 300 individuals 100 m^{-2} recorded. The amethyst anthias (*Pseudanthias pascalus*) was the second-most numerically abundant species with more than 100 individuals 100 m^{-2} observed.

No clear spatial patterns were evident for total fish biomass in forereef habitats at Asuncion during the 3 MARAMP survey years. When compared with the rest of the Mariana Archipelago, estimated reef fish biomass was very high. The overall mean biomass across the 3 survey periods of 27.43 kg 100 m^{-2} (SE 11.89) was the highest observed at any island, reef, or bank in the Mariana Archipelago. Snappers and surgeonfishes made up substantial portions of total fish biomass in each of the 3 MARAMP survey periods, collectively accounting for 20%–33% of total fish biomass per survey year (Fig. 15.8.1d).

Mean species richness ranged from 32–42 species 100 m^{-2} for the 3 MARAMP survey periods. The highest diversity was found at ASC-03 in the northwest region, and the lowest species richness was seen at ASC-01 in the northeast region. Wrasses and surgeonfishes composed the 2 most represented families with an average of 21 and 16 species observed. Damselfishes were the most numerically abundant taxa of fishes overall, with the midget chromis and Vanderbilt's chromis dominating counts.

15.9 Marine Debris

15.9.1 Marine Debris Surveys

During MARAMP 2003, 2 sightings of derelict fishing gear were recorded in the 6 towed-diver surveys conducted on forereef habitats around the island of Asuncion (Fig. 15.9.1a). One sighting was documented in the northwest region, and another was noted in the southeast region. No additional descriptive information was recorded during towed-diver surveys. No munitions, wrecks, or other man-made objects were identified.

During MARAMP 2005, no marine debris sightings were recorded in the 5 towed-diver surveys conducted on forereef habitats around Asuncion.

During MARAMP 2007, 1 sighting of derelict fishing gear was recorded in the 5 towed-diver surveys conducted on forereef habitats around Asuncion: an old net located in the northeast region. No munitions, wrecks, or other man-made objects were identified.

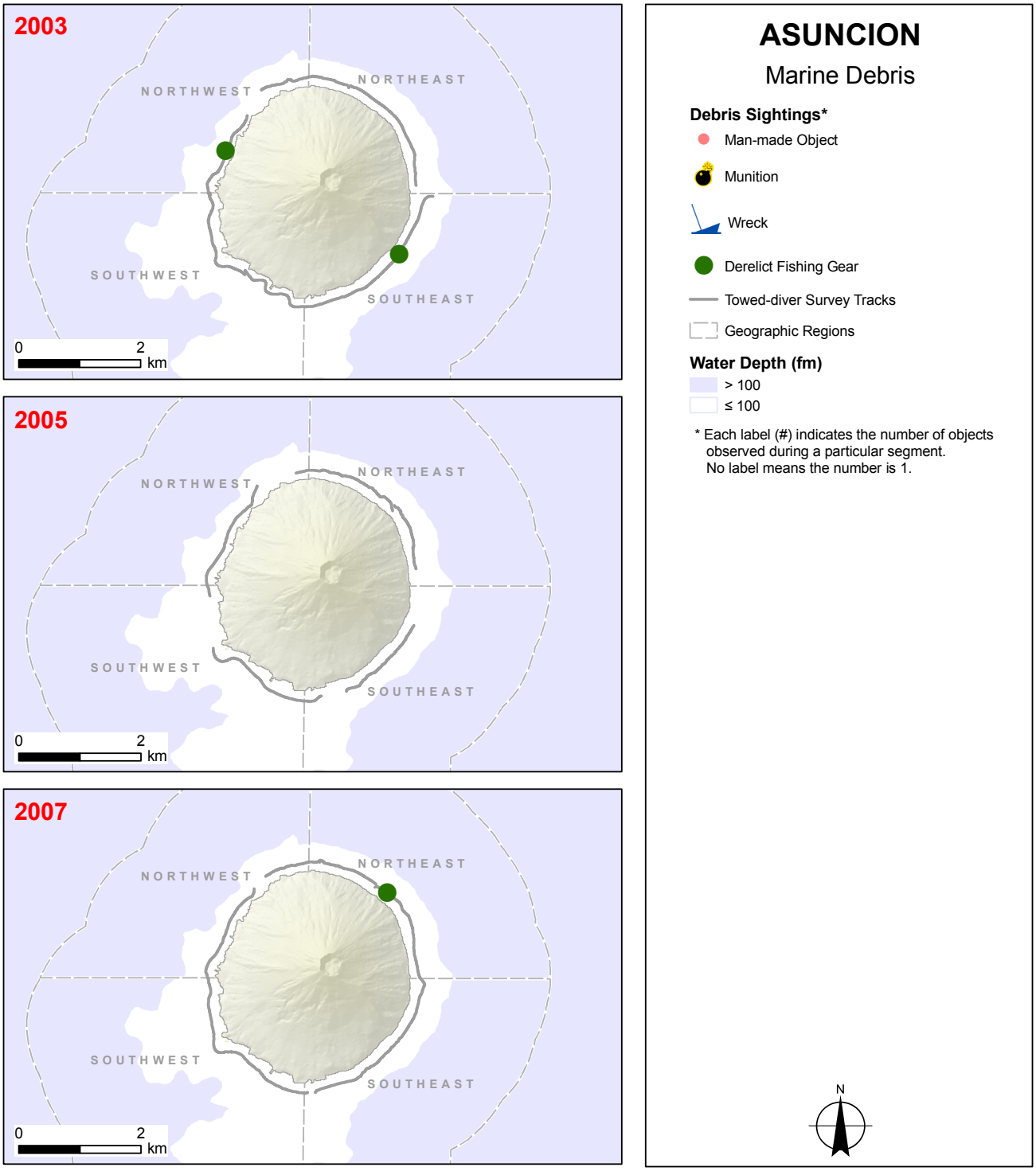


Figure 15.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Asuncion during MARAMP 2003 and 2007. No debris was identified in 2005. Symbols indicate the presence of specific debris types.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments.

15.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Asuncion are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations on an archipelagic scale of different ecosystem elements and their potential relationships across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Asuncion as well as the other 13 islands covered in this report.

Asuncion is the steepest of the northern volcanic islands of the Mariana Archipelago, a fact that is reflected in the onshore and submarine topography surrounding this island (Figs. 15.3.1b and c in Section 15:3.1: "Acoustic Mapping"). This steep terrain, in combination with predominant weather and oceanographic patterns (Fig. 15.10a), creates a dynamic environment and ultimately produces a unique ecosystem of varying habitat types.

The steepest slopes and highest sea cliffs, as well as the steepest submarine topography, occur on the northern and eastern sides of this island. Asuncion's steep benthic habitat is characterized by rocky reef strewn with boulders that support little cover of macroalgae or live hard corals (Fig. 15.10a). The east coast of Asuncion experiences the predominant weather influences, including trade winds and high ambient and moderate-to-high episodic wave energy relative to the west coast (Fig. 15.10a), and these conditions likely cause currents on the eastern side. All of these factors contribute to the dynamic, frequently changing environment of this side of the island, and they may present difficulties for recruitment of benthic organisms.

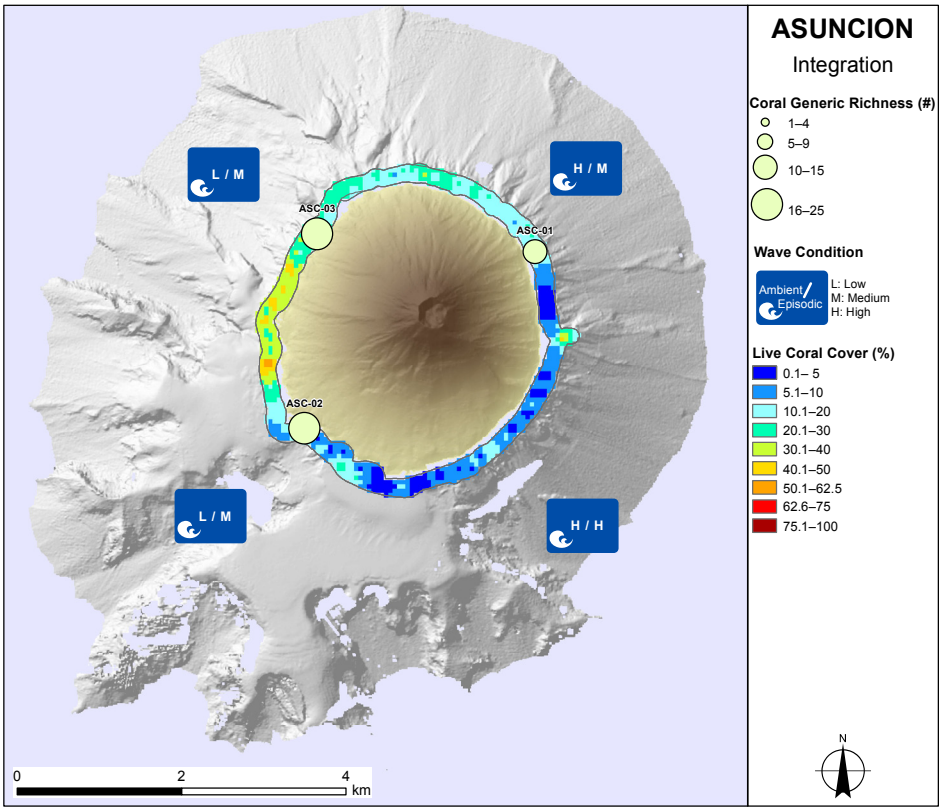


Figure 15.10a. Cover (%) observations of live hard corals from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Asuncion during MARAMP 2003, 2005, and 2007. Values of coral cover represent interpolated values from the 3 MARAMP survey years, and generic-richness values represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region. Underlying these data in grey scale is the hillshade bathymetry.

The southern and southwestern sides of Asuncion are characterized by less dramatic topside and benthic topography, resulting in a biological seascape that is very different from the rest of Asuncion. In these areas, submarine terraces extend up to 2 km from the shoreline (Fig. 15.3.1b in Section 15:3.1: "Acoustic Mapping"). The southern side of this volcano also is subject to frequent landslides. These landslides presumably carry substantial amounts of sediment and rock into nearshore waters. The shelves on the southern side of Asuncion are composed largely of sand and boulders, resulting in an environment of medium-low to medium complexity that supports little coral growth with estimated coral cover predominantly < 10% (Fig. 15.10a).

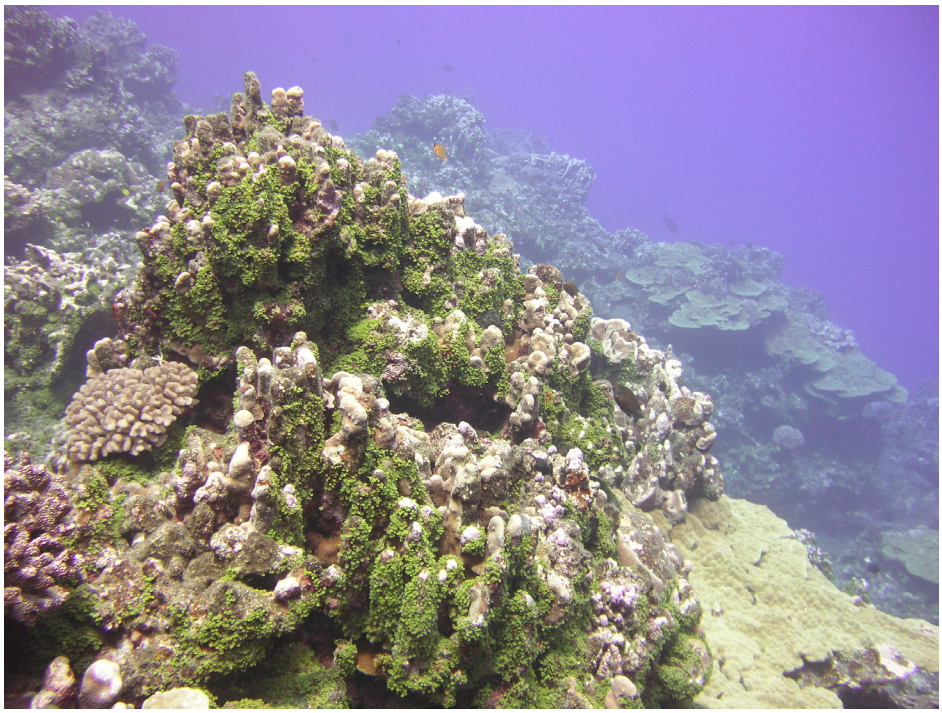


Figure 15.10b. Reef habitat on the west side of Asuncion. *NOAA photo by Robert Schroeder*

The west side of this island, including sections of the northwest and southwest regions, is marked by several ash deposits along the moderately steep slope of this volcano and by a shallow terrace that extends out from shore to below the surface (Fig. 15.3.1a). Sheltered from the prevailing weather patterns, this nearshore habitat provides prime reef-building conditions—as demonstrated by the high levels of live coral cover recorded in both REA and towed-diver surveys conducted in this area (Figs. 15.5.1a and b in Section 15:5.1: "Coral Surveys") and the high diversity recorded at REA site ASC-03 (Fig. 15.5.1b), relative to other surveyed areas at Asuncion. The reefs along the west coast also supported the highest coral-colony densities observed in 2003 and 2005, the highest crustose-coralline-red-algal cover, and the greatest macroalgal diversity observed at Asuncion during each of the 3 MARAMP survey years (Fig. 15.10b). The west side was notable for consistently supporting the greatest abundance of sea cucumbers, COTS, and giant clams observed around Asuncion.



Figure 15.10c. A diver observing a grey reef shark (*Carcharhinus amblyrhynchos*) during an REA fish survey at Asuncion. *NOAA photo by Robert Schroeder*

In the absence of any known fishing pressure, the waters surrounding Asuncion support abundant stocks of reef fishes compared to other islands of the Mariana Archipelago. Large-fish biomass, from towed-diver surveys, averaged over the 3 MARAMP survey periods was the second-highest level observed among the islands of the Mariana Archipelago (excluding the offshore banks) after Farallon de Pajaros (Fig. 15.8.1a in Section 15.8.1: "Reef Fish Surveys"). Results from REA surveys for fishes of all sizes and species also were high overall, with the average over the 3 survey periods being the highest total fish biomass estimated for this archipelago, and fish assemblages included a broad range of herbivorous and piscivorous species (Fig. 15.8.1c). High numbers of sharks were seen at Asuncion during the 3 survey years, compared to observations at other islands of the Mariana Archipelago (Fig. 15.10c).

15.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Asuncion. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Asuncion chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Asuncion, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Asuncion as well as some of the key natural processes and anthropogenic activities influencing these ecosystems:

- Asuncion has a land area of 7.86 km^2 and is the third-most northerly island of the Mariana Archipelago.
- Asuncion is part of a protected reserve, established for the protection of habitat for birds, wildlife, and plants through the CNMI Constitution. The waters and submerged lands of Asuncion also are part of the Islands Unit of the Marianas Trench Marine National Monument, which was established by presidential proclamation in January 2009.
- Asuncion is the steepest of the northern volcanic islands, a fact reflected in its onshore and submarine topography. The east side of Asuncion is consistently much steeper than the western side.
- The reefs on the west side of Asuncion supported the highest levels of live coral cover seen at Asuncion, greatest coral-colony densities observed in 2003 and 2005, highest crustose-coralline-red-algal cover and macroalgal diversity observed in each of the 3 MARAMP survey years, and highest densities of giant clams, COTS, and sea cucumbers recorded around Asuncion.
- In the northern part of the northeast region, towed-diver surveys suggested habitats of medium to medium-high complexity and hard substrates supporting low levels of live-hard-coral cover. South of Asuncion, the seabed topography is dominated by a large, low-rugosity shelf composed of a number of terraces.
- Wave model output shows ambient trade wind swells impacting the northeast and southeast regions. Episodic wave energy from storm tracks impacts the southeast region and to a lesser extent the other 3 regions.
- In 2007, mean cover of live corals was 15.7% from the 3 REA sites surveyed using the line-point-intercept method at Asuncion. Overall mean live coral cover around Asuncion from towed-diver surveys ranged from 10% to 18% during the 3 MARAMP survey years.
- Coral-disease surveys in 2007 were conducted at 3 REA sites at Asuncion and detected 10 cases of disease. The overall mean prevalence from these sites was 0.02%. Two major disease conditions, fungal infection and skeletal growth anomalies, accounted for 80% and 20% of cases found on reefs at Asuncion.
- A TOAD survey conducted south of Asuncion at depths of 70–120 m over a distance of more than 1.4 km, revealed a dense aggregation of sea pens (order: Pennatulacea). Aggregations were recorded standing as high as ~ 30 cm and occurred on a soft substrate, possibly composed of basaltic sand.

- In this same area south of Asuncion, a decline in density of sea pens at a 120-m depth was associated with the occurrence of a patch of live hard corals that was 100 m long. Both corals and sea pens were observed near the east side of the steep-sided ledge that extends south from Asuncion and rises abruptly from the surrounding seafloor at a depth of ~ 600 m.

- Overall mean cover of macroalgae around Asuncion was higher in 2007 than in 2005. Dramatic increases in abundance of species of *Jania* were observed from 2003 to 2007. Only one coralline-algal disease, coralline lethal orange disease, was detected around Asuncion, at site ASC-02 in the southwest region.

- Overall large-fish biomass from towed-diver surveys for the 3 MARAMP survey periods combined was high relative to results from other islands of the Mariana Archipelago, second only to Farallon de Pajaros. Survey data indicated decreased large-fish biomass in 2007, when overall mean large fish biomass was 0.78 kg 100 m^{-2} versus the overall means of 2.12 and 1.81 kg 100 m^{-2} recorded in 2003 and 2005.

- During towed-diver surveys for large fishes, 54 sharks were observed in 2003, and 60 sharks were seen in 2005 with half of those recorded during a single towed-diver survey. Although sharks were abundant at Asuncion in 2005, many of the grey reef sharks (*Carcharhinus amblyrhynchos*) encountered were smaller than 100 cm in TL, which is below the size of sexual maturity (120–150 cm TL) for this species. In 2007, only 13 sharks were observed.

- When compared to the rest of the Mariana Archipelago, total fish biomass from REA surveys for fishes of all sizes and species was very high at Asuncion. The overall mean over the 3 MARAMP survey periods, 27.43 kg 100 m^{-2}, was the highest value for this archipelago.

- Densities of COTS were extremely low in 2003 and 2005, compared to survey results from other islands in the Mariana Archipelago; however, in the northwest region, the observed COTS density increased sharply in 2007.

- Sea cucumbers and sea urchins were observed at low densities at Asuncion during each of the 3 survey years and only reported from the west coast. Giant clams were fairly common along the west coast of Asuncion.

16 MAUG

16.1 Introduction

Maug consists of 3 separate islands, which are actually the rim of a submerged caldera of a large volcano (Fig. 16.1a). Known as East (Higashi-shima), West (Nishi-shima), and North (Kita-shima) Islands, they are located at 20°02′ N, 145°13′ E and 67 km southeast of Farallon de Pajaros and 41 km northwest of Asuncion. The outer diameter of this circle of islands is ~ 3.3 km, and the inner diameter of the submerged caldera is ~ 2.2 km. With a combined land area of 2.14 km^2, these islands are the smallest islands of the Commonwealth of the Northern Mariana Islands (CNMI). The highest elevation is 227 m on the ridge of the crater rim on North Island. The highest elevations of East and West Islands are 215 m and 178 m. These 3 islands are each characterized by a narrow central ridge with slopes on either side ending in steep cliffs along their coasts (Fig. 16.1b).

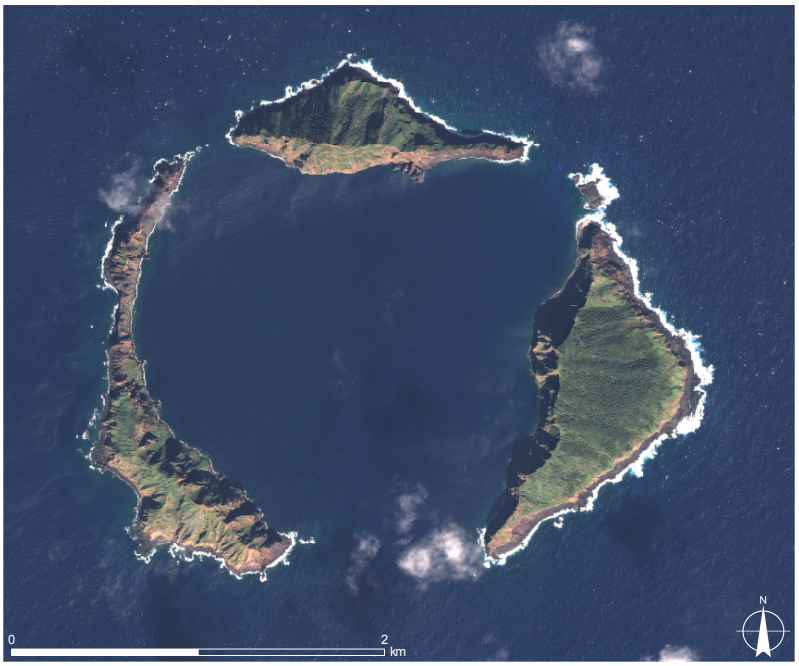


Figure 16.1a. Satellite image of Maug (© 2003 DigitalGlobe Inc. All rights reserved).



Figure 16.1b. A view of Maug from the south, as seen from the NOAA Ship *Hi`ialakai* in 2007. *NOAA photo*

16.1.1 History and Demographics

There has been no permanent inhabitation of Maug since 1695, when Spain forced all inhabitants of the northern islands of the Mariana Archipelago to relocate to Guam (Rogers 1995). In 1909, while under German administration, Maug was leased to the Pagan Gesellschaft for exploitation of bird plumage for a period of 3 years, along with Agrihan, Asuncion, Guguan, Farallon de Pajaros, Farallon de Medinilla, and Sarigan. During this time, Japanese bird catchers employed on these islands may have been resident there temporarily, and other fishing or hunting parties may have also periodically resided on Maug. Prior to and during World War II (1939–1945), a Japanese weather station and fish processing plant were established on Maug. Since 1978, inhabitation of Maug has been prohibited by the CNMI Constitution under Article XIV.

Maug falls within the Northern Islands Municipality of the CNMI, and the political history of Maug follows that of the CNMI as a whole, which is described in more detail in Chapter 1: "Introduction" and Chapter 8: "Saipan," Section 8.1.1: "History and Demographics."

16.1.2 Geography

Located at the northern end of the Mariana Archipelago, the 3 islands of Maug are formed by the exposed sections of the rim of a caldera that is largely submerged and 2.5 km wide. Each island is characterized by a central ridge, forming the rim of a caldera, with steep slopes on the inner flanks and more gentle slopes on the outer flanks (Fig. 16.1.2a).

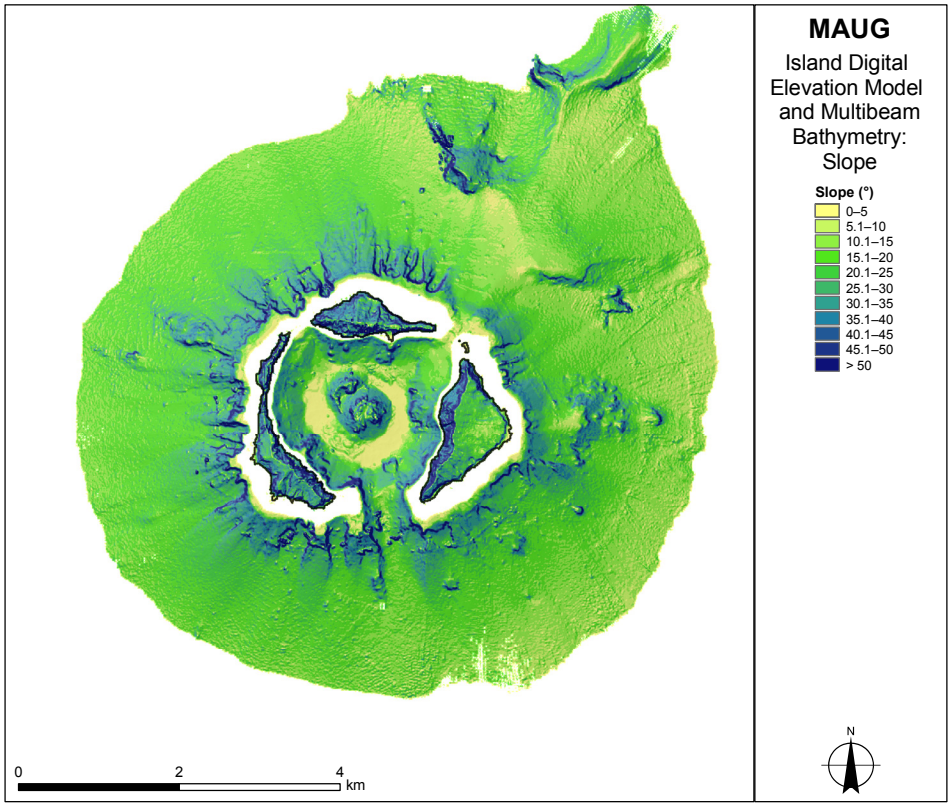


Figure 16.1.2a. Combined slope map using the digital elevation model (grid cell size: 10 m) and multibeam bathymetry (grid cell size: 10 m) for Maug.

Maug forms a twin volcanic massif with Supply Reef, which lies 18 km to the northwest of Maug (Siebert and Simkin 2002–; see Figure 18.2.3a in Chapter 18: "Reefs and Banks of the CNMI"). Lava flows and pyroclastic deposits cut by radial dikes are exposed on the inner walls of the Maug caldera (Fig. 16.1.2b), while the outer flanks of this caldera are overlain with bedded ash deposits (Siebert and Simkin 2002–). North and West Islands are dominated by basaltic columns (Scripps 2009).

The island slopes of Maug are vegetated, covered mainly with coarse grass and patches of low-lying shrubs (Fig. 16.1.2c). The largest island, East Island, has coconut groves on its west coast and trees covering its high slopes. Areas of forest are also present along the shoreline of Maug and continue up ravines, while the steepest slopes of these islands are rocky with less vegetation (Mueller-Dombois and Fosberg 1998).

No volcanic eruptions have been recorded at Maug since the Spanish ship *Trinidad*, captained by Gómez de Espinosa, landed in 1522. However, exploration of the Mariana Archipelago in 2003 revealed active hydrothermal discharge within the Maug caldera (Embley et al. 2004).

West of East Island, a hydrothermal vent system appears to affect the temperature and quality of the water surrounding it. During MARAMP 2007, water samples were taken at a single location near this vent system to gain insight into the marine geochemistry of hydrothermal vents in the CNMI and the possible influences this specific vent system had on the surrounding benthic ecosystem (see Section 16.4: "Oceanography and Water Quality").



Figure 16.1.2b. A radial dike, the vertical column in the center of this photo, on Maug bisecting layers of lava flows (dark horizontal bands) and ash-rich lava units (rust-colored bands). *Photo courtesy of the NOAA Vents Program*

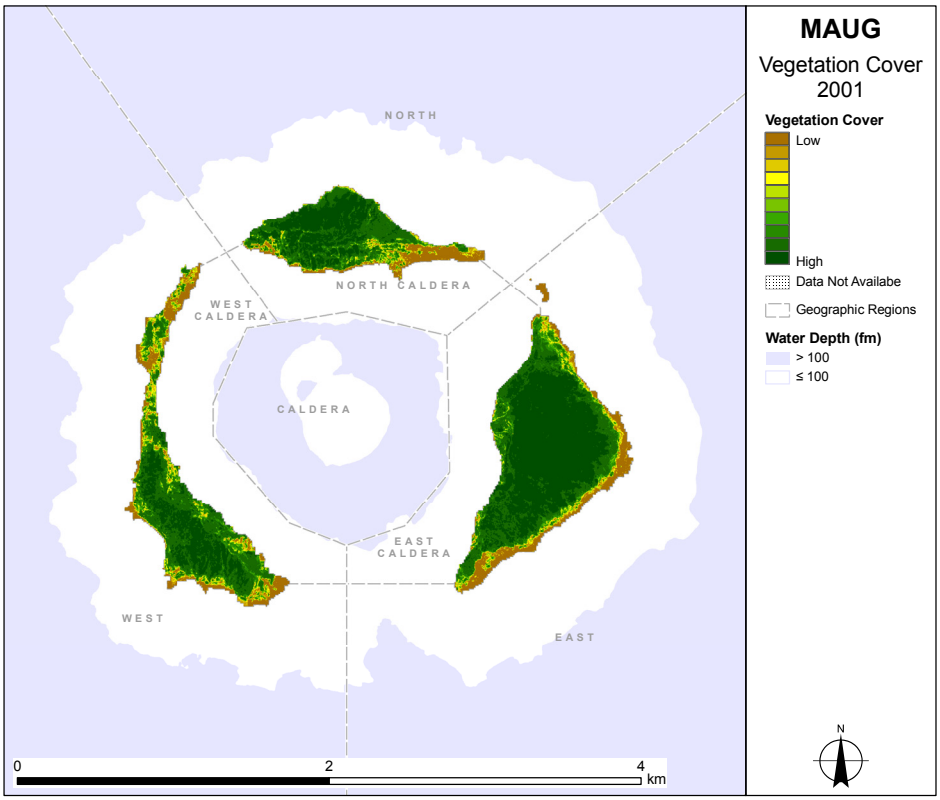


Figure 16.1.2c. Vegetation cover on Maug, derived using the Normalized Difference Vegetation Index from a satellite image (grid cell size: 4 m; IKONOS Carterra Geo Data 2001).

16.1.3 Environmental Issues on Maug

Maug is part of a protected reserve area established under Article XIV of the CNMI Constitution and managed by the CNMI Division of Fish and Wildlife. This legislation states that the islands of Maug are to be retained as uninhabited places, and no permanent structures can be built on these islands, except for the preservation and protection of natural resources (CNMI Constitution). Maug is preserved as a habitat for birds, wildlife, and plants. On these islands, 25 species of birds are protected, including two birds that breed on Maug, the Micronesian megapode (*Megapodius laperouse*), which is listed Federally as endangered (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), and the near-threatened (BirdLife International 2008) white-throated ground-dove (*Gallicolumba xanthonura*). Terrestrial plants present include several species endemic to the Mariana Archipelago, but none are endemic specifically to Maug (Pacific Protected Areas Database).

Because of Maug's isolation and lack of inhabitants, local anthropogenic impacts around these islands are thought to be few. However, non-native species, including several species of plants, rats, and goats are thought to have been introduced to these islands (Pacific Protected Areas Database). Fishing activity within the CNMI tends to be focused around the southern islands of the Mariana Archipelago, with multi-day fishing trips focusing on the islands and banks south of Guguan (Western Pacific Fishery Management Council 2009). While fishing at Maug is considered uncommon, fishing and diving have been observed at Maug during MARAMP cruises.

Maug became part of the Marianas Trench Marine National Monument, which was established in January 2009 by presidential proclamation. This Marine National Monument includes a Trench Unit, an Islands Unit, and a Vents Unit. The Islands Unit includes the waters and submerged lands of the islands of Maug, Asuncion, and Farallon de Pajaros.

16.2 Survey Effort

Extensive biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing coral reef ecosystems around the islands of Maug since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 7 geographic regions around

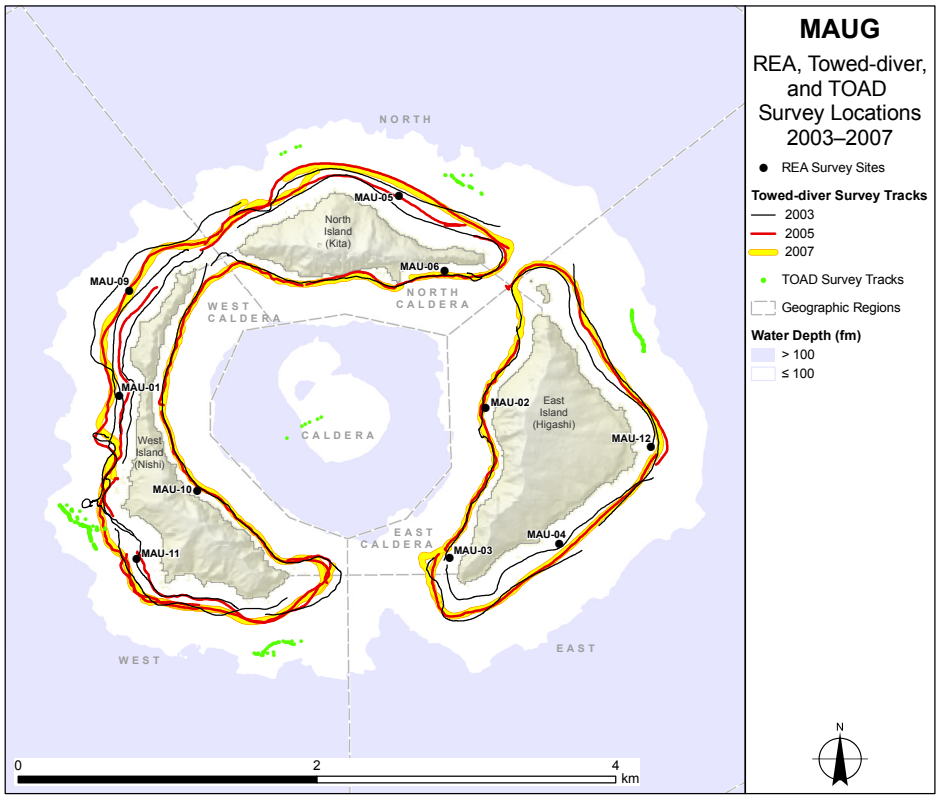


Figure 16.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Maug during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 7 geographic regions: north, east, west, caldera, north caldera, east caldera, and west caldera.

Maug are delineated in Figure 16.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Maug. Potential reef habitat around this island is represented by a 100-fm contour shown in white on this map.

Benthic habitat mapping data were collected around Maug using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around Maug, Asuncion, Farallon de Pajaros, and Supply Reef with multibeam sonar covered a combined total area of 3856 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 16.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Maug was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 16.5–16.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 16.2a, along with their mean depths and total survey areas or length. For one of the 11 towed-diver surveys conducted in 2007, GPS and depth data were not available, and, thus, depth and biological data collected during that survey cannot be shown on maps in this report.

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Maug were collected using (1) two types of moored instruments designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007. Results for some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 16.2b, and results are discussed in Section: 16.4: "Oceanography and Water Quality."

Table 16.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Maug during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	8	8	9
	Mean Depth (m)	13.1 (SD 1.5)	15.1 (SD 5.1)	13.4 (SD 1.6)
Benthic	Number of Surveys	9	8	9
	Mean Depth (m)	14.7 (SD 5.2)	15.1 (SD 5.1)	13.4 (SD 1.6)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	16	13	11
	Total Survey Area (ha)	29.0	24.2	25.1
	Mean Depth (m)	12.3 (SD 3.5)	13.9 (SD 2.9)	14.9 (SD 1.7)
TOAD		**2003**		
	Number of Surveys	6		
	Total Length (km)	1.85		

Table 16.2b. Numbers of oceanographic instruments deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Maug during MARAMP 2003, 2005, and 2007. Two types of instruments were moored around Maug: sea-surface temperature (SST) buoy and subsurface temperature recorder (STR). Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Additional deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
SST	1	1	1	1	1	–	1
STR	1	1	4	4	5	5	–
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	33	34		20			87
Deepwater Casts	–	10		4			14
Water Samples		**2005**		**2007**			**Total**
		14		9			23

Towed-diver Surveys: Depths

Figures 16.2b–e illustrate the locations and depths of towed-diver-survey tracks around Maug and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

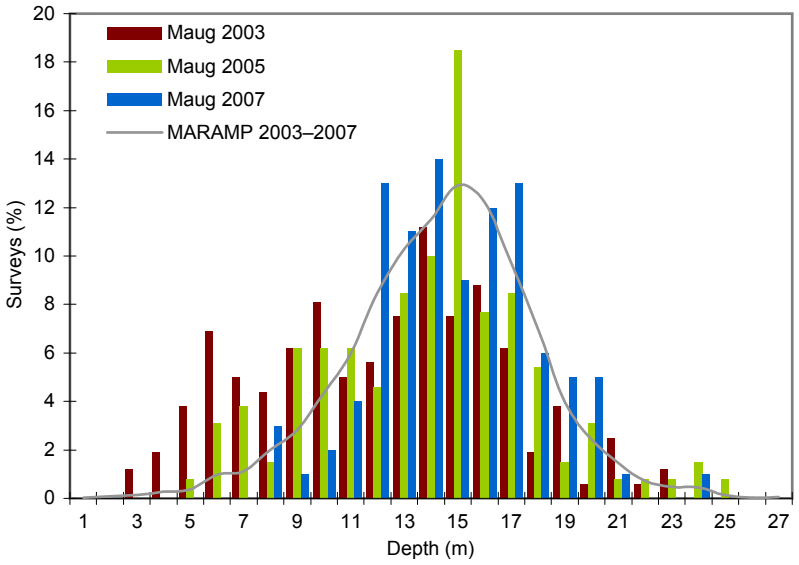


Figure 16.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

During MARAMP 2003, 16 towed-diver surveys were conducted along the forereef slopes around Maug (Figs. 16.2b and c). The mean depth of all survey segments was 12.3 m (SD 3.5), and the mean depths of individual surveys ranged from 5 m (SD 1.6) to 17 m (SD 6.7).

During MARAMP 2005, 13 towed-diver surveys were conducted along the forereef slopes around most of Maug (Figs. 16.2b and d). Mean depth of all survey segments was 13.9 m (SD 2.9), and the mean depths of individual surveys ranged from 7.6 m (SD 2.4) to 17.3 m (SD 4.5).

During MARAMP 2007, 11 towed-diver surveys were conducted along the forereef slopes of Maug (Figs. 16.2b and e). Mean depth of all survey segments was 14.9 m (SD 1.7), and the mean depths of individual surveys ranged from 12.4 m (SD 3) to 17.6 m (SD 4.6).

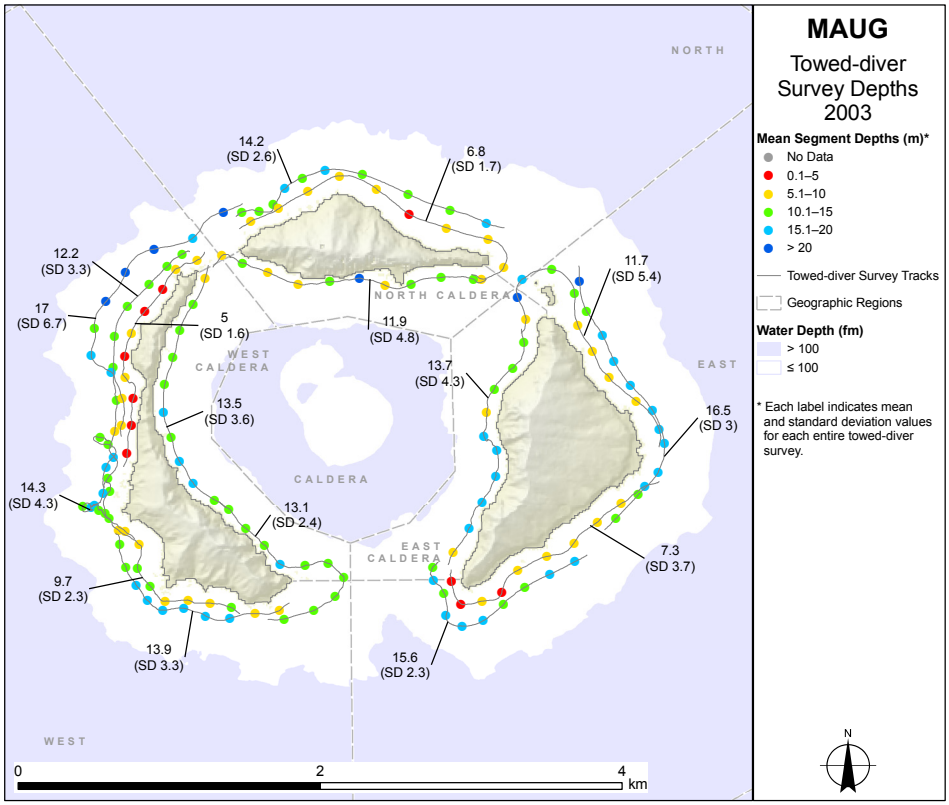


Figure 16.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

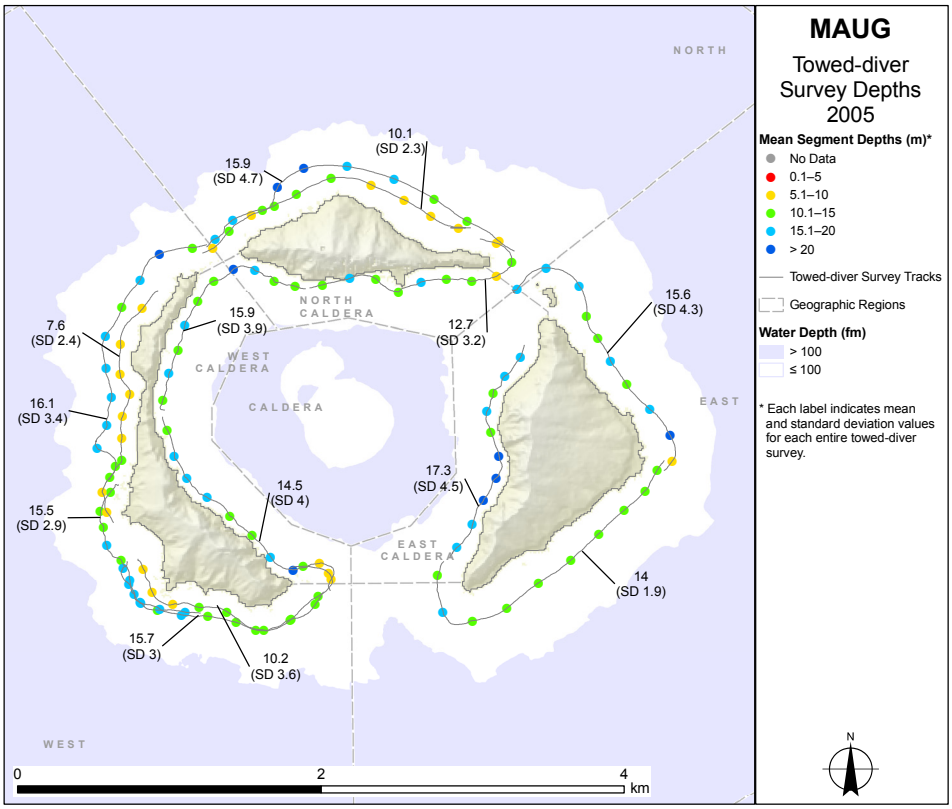


Figure 16.2d. Depths and tracks of towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

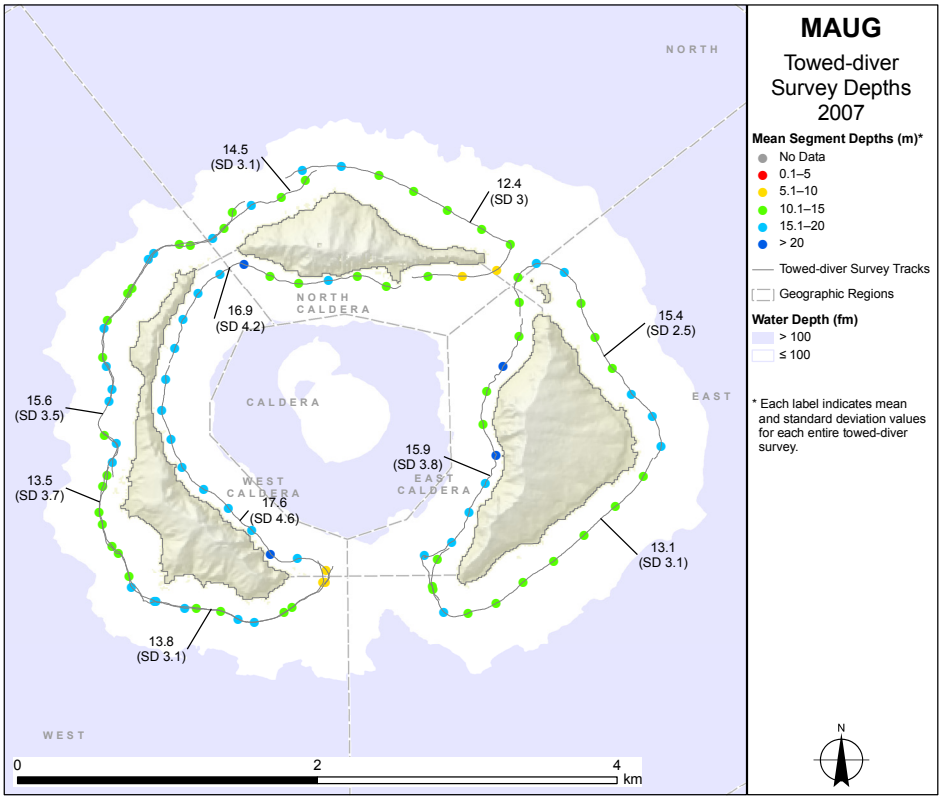


Figure 16.2e. Depths and tracks of towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

16.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the islands of Maug were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 10–2300 m. Multibeam coverage was almost complete around the 3 islands of Maug, including the seafloor within the submerged caldera. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of ~ 1–150 m.

16.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 16.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around Maug, Farallon de Pajaros, Asuncion and Supply Reef during MARAMP 2007 encompassed an area of 3856 km^2.

The 3 islands of Maug are formed by the caldera walls of a volcano, separated by narrow channels where the walls have collapsed. The multibeam bathymetry acquired around Maug reveals the submerged caldera at a depth of 200–240 m, from which a twin-peaked submarine dome rises to a depth of 20 m (Fig 16.3.1a, top panel). This submarine dome is likely the youngest feature of the volcano. The bathymetry data show the volcano's steep outer flanks, which descend rapidly to the depth of 1000 m within ~ 3 km of the shoreline. North and east of Maug, the seabed continues to descend until reaching a plateau at a depth of ~ 2100 m. Northwest of Maug at a depth of ~ 1700 m, the seabed descends to a channel, which separates Maug from a submarine volcanic cone 18 km northwest called Supply Reef (for more about this reef, see Chapter 18: "Reefs and Banks in the CNMI"). The bathymetry shows shallow ridges and channels on the flanks, and a steep-sided ridge is present northeast of North Island (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). North and west of Maug, the multibeam bathymetry reveals large blocks of material on the deep flanks. At 4–8 km southeast of East Island, the bathymetry data reveal an anomalous feature that rises from the main flanks at a depth of ~ 1600 m to a depth of 850 m. The 2 mechanisms that might have caused this feature are mass wasting (the movement of soil and surface materials by gravity) and volcanic activity.

Intensity of low-resolution backscatter around Maug was uniform throughout much of the area covered. Higher intensity backscatter values were observed around the edge of the small bank southeast of East Island and on the ridge northeast of North Island (Fig. 16.3.1a, bottom panel). Blocky materials on the flanks north and west of Maug had high-intensity backscatter, suggesting that these areas are characterized by hard substrates at or near the seabed surface.

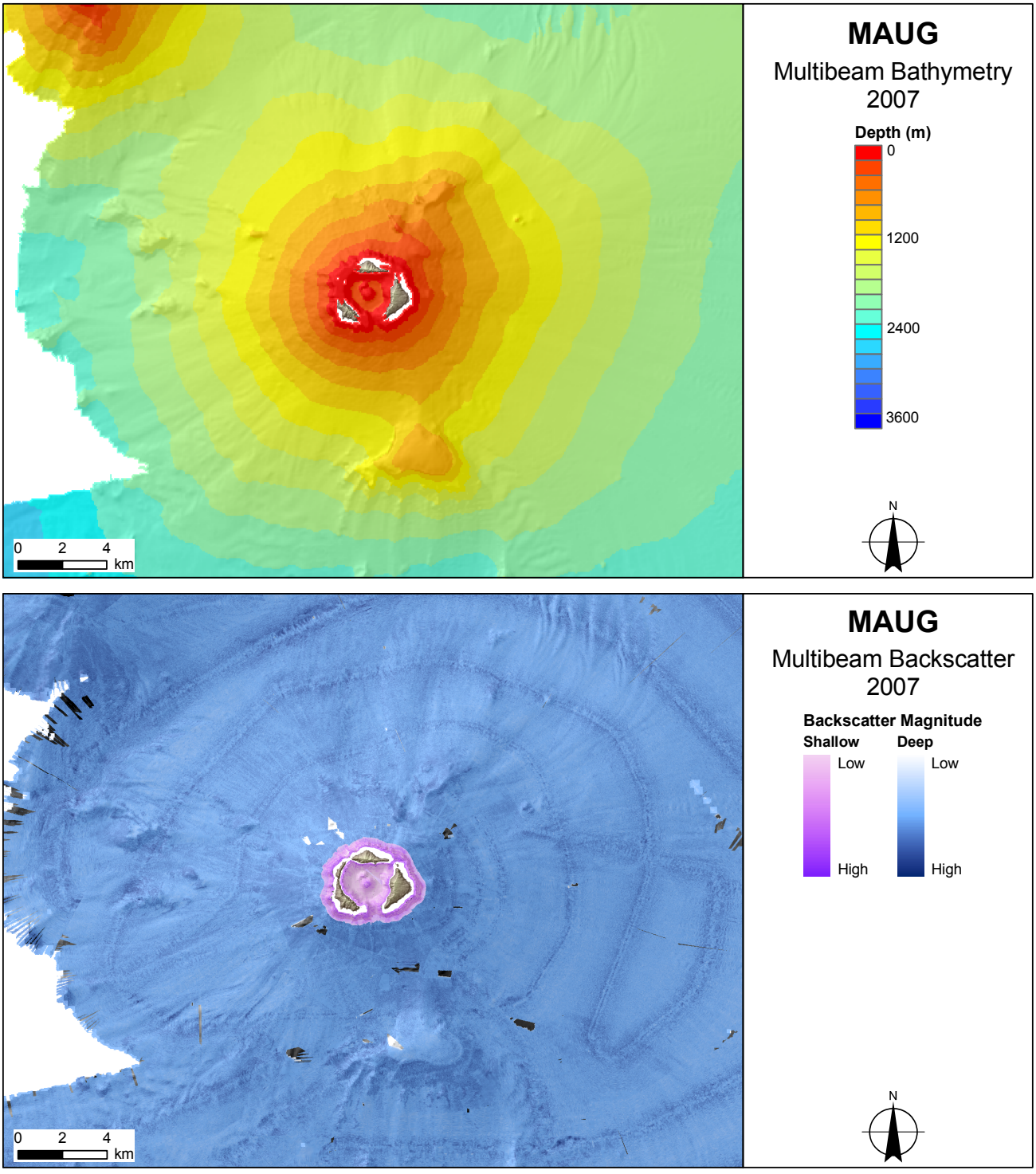


Figure 16.3.1a Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Maug during MARAMP 2003 and 2007 at depths of ~ 10–2300 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. For both sonars, light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

High-resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in the nearshore (depths of 0–800 m) waters around Maug (Fig. 16.3.1b) were combined into a grid at 10-m resolution to allow for the identification of fine-scale features. These data were used to derive benthic maps showing slope (Fig. 16.3.1c), rugosity (Fig. 16.3.1d) and bathymetric position index (BPI) zones (Fig. 16.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Maug.

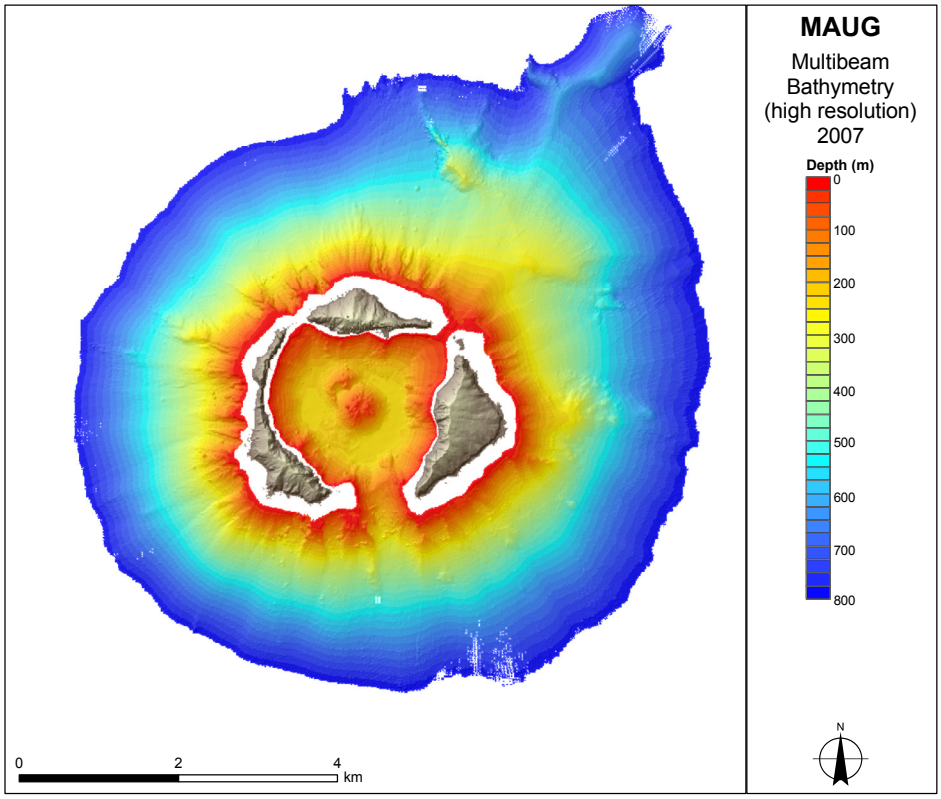


Figure 16.3.1b. High-resolution multibeam bathymetry (grid cell size: 10 m) collected around Maug during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives.

The high-resolution bathymetry reveals additional detail on the flanks of Maug, including numerous ridges and ravines that incise the flanks and radiate out from the crater edge. These ridges have very steep slopes on either side (frequently > 50°) but are generally fairly short, extending for only up to 500 m away from the shore (Fig. 16.3.1c). High levels of rugosity are associated with these steep slopes (Fig. 16.3.1d). Below the ridges, the flanks are more uniform, with slopes of 10°–20° and low rugosity levels. Blocky material is shown along the upper flanks, particularly south of East and West Islands on either side of the southern channel that separates these islands. This material may have resulted from the failure of the caldera rim that created this channel. A smaller amount of material was shown within the caldera itself. The high-resolution data suggest that the southern channel is much deeper (~ 150 m) and wider than the 2 channels on either side of North Island (Fig. 16.3.1b).

On the flanks east of Maug, slope and rugosity maps show a complex area with steep slopes and high rugosity on the downslope side, likely a result of slumping from the crater wall. Similar but smaller features are shown southeast and west of Maug.

High-resolution bathymetry, slope, and rugosity reveal intricate topography of the twin-peaked dome that emerges from the submerged caldera.

BPI analysis highlights the dominance of slope zones around Maug, with crests and depressions created by the central dome and shallow ridges creating additional topographic complexity. A very small flat zone is identified on the caldera floor surrounding the central dome (Fig. 16.3.1e).

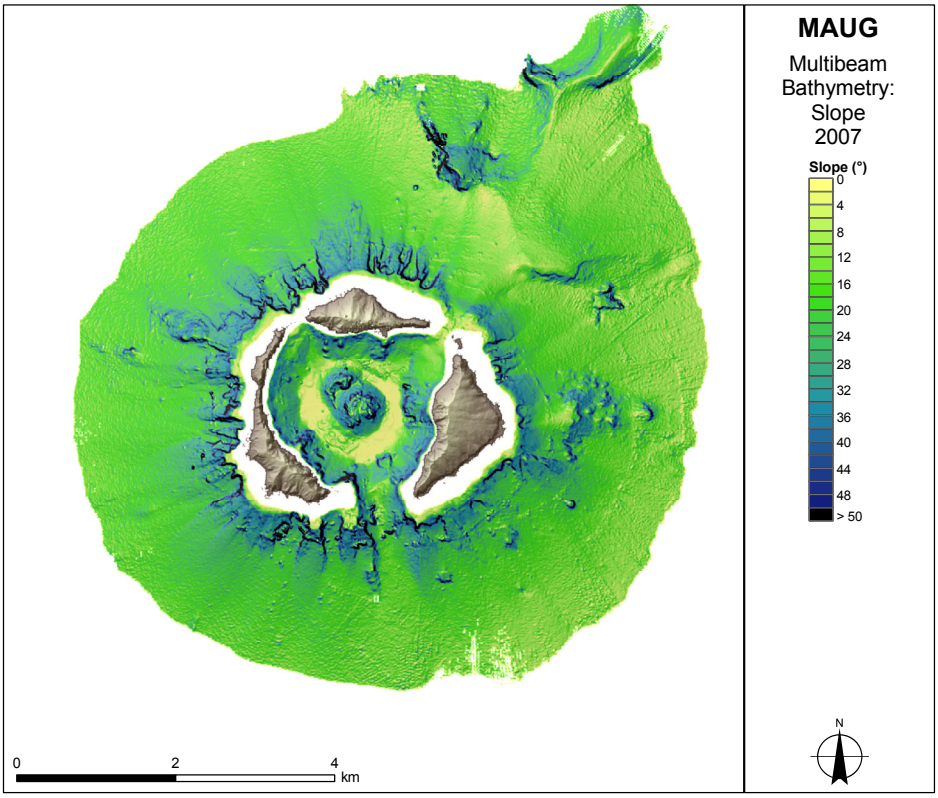


Figure 16.3.1c. Slope (°) of 10-m bathymetric grid around Maug. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest blue shades and the flattest areas in yellow shades.

In the shallowest waters surveyed, the BPI analysis identifies reef crests (Fig, 16.3.1e). However, this classification is likely an artifact of the methodology, since no data are available for immediately inshore areas and no comparison can be made to the innermost cells of the grid. Instead, these areas probably should be characterized as slopes.

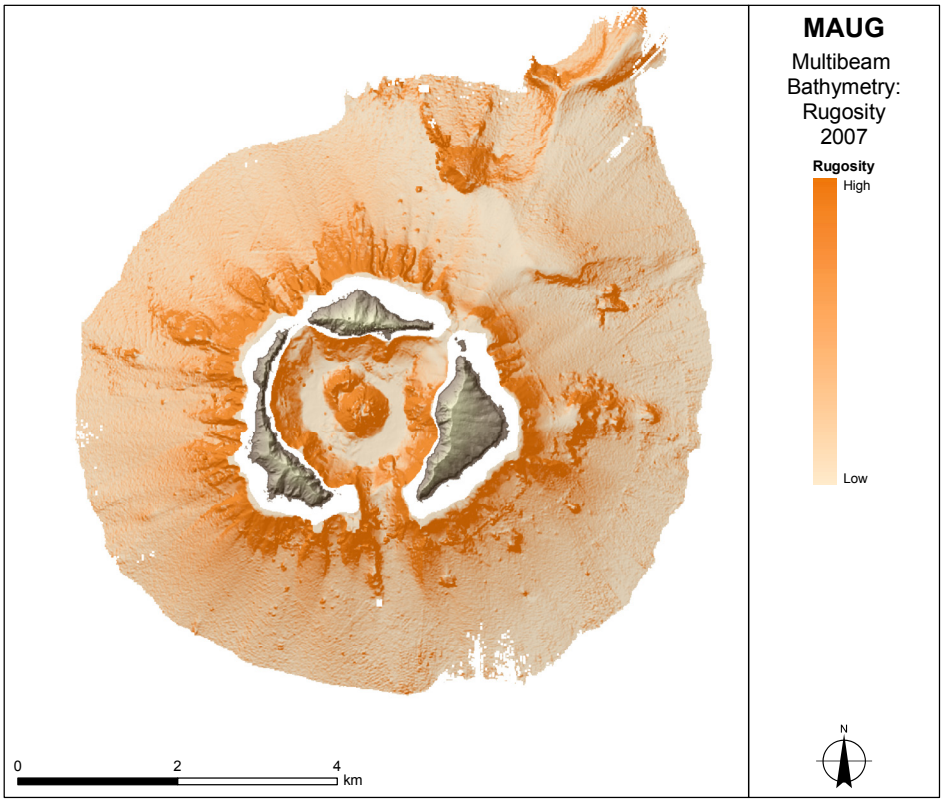


Figure 16.3.1d. Rugosity of 10-m bathymetric grid around Maug. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

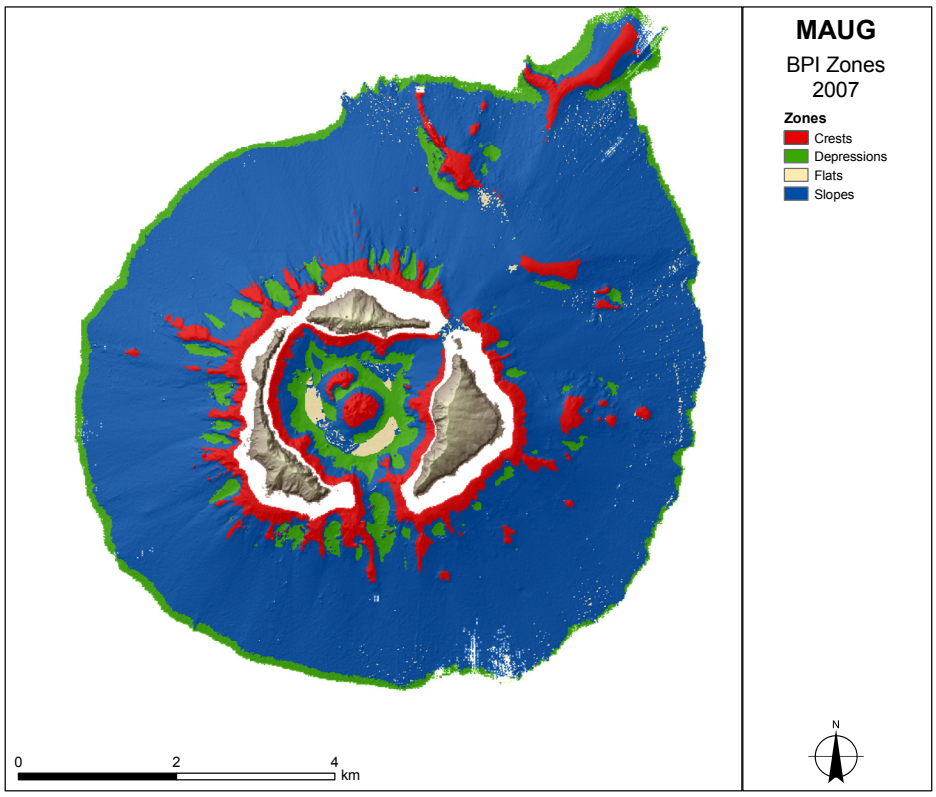


Figure 16.3.1e. BPI zones of 10-m bathymetric grid around Maug derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

High-resolution Multibeam Backscatter and Derivatives

Backscatter data acquired around Maug were generally of good quality, with coverage to a depth of 250 m, and reveal patterns in the seabed character around Maug (Fig. 16.3.1f) that relate to features in the topography.

Some artifacts were present in the data, such as higher backscatter values recorded within the shallower part of the outer swath versus the deeper part. This can be caused by steep slopes affecting the intensity of the backscatter return. These backscatter data may have been affected by sonar settings and sea state during data acquisition or by other factors discussed in more detail in Chapter 2: "Methods and Operational Background," Section 2.2.2: "Acoustic Mapping: Data Processing.". To exclude these artifacts, the backscatter data were clipped to a depth of 200 m prior to deriving the hard–soft substrate map.

The caldera floor is characterized by very low-intensity backscatter, indicative of soft sediments, and much of this area is classified as soft substrates in the hard–soft map. Similarly, backscatter values are low within the channel between East and West Islands, suggesting that the soft sediments characteristic of the caldera floor continue through this channel. In contrast, the twin peaks of the central dome have much higher backscatter values and are characterized as hard substrates (Fig. 16.3.1g).

Areas along the inner crater wall, with predominantly high backscatter values, are classified as hard substrates. The shallow outer flanks and ridges are classified as hard substrates, but, in the channels between these ridges, some low backscatter values suggest soft substrates.

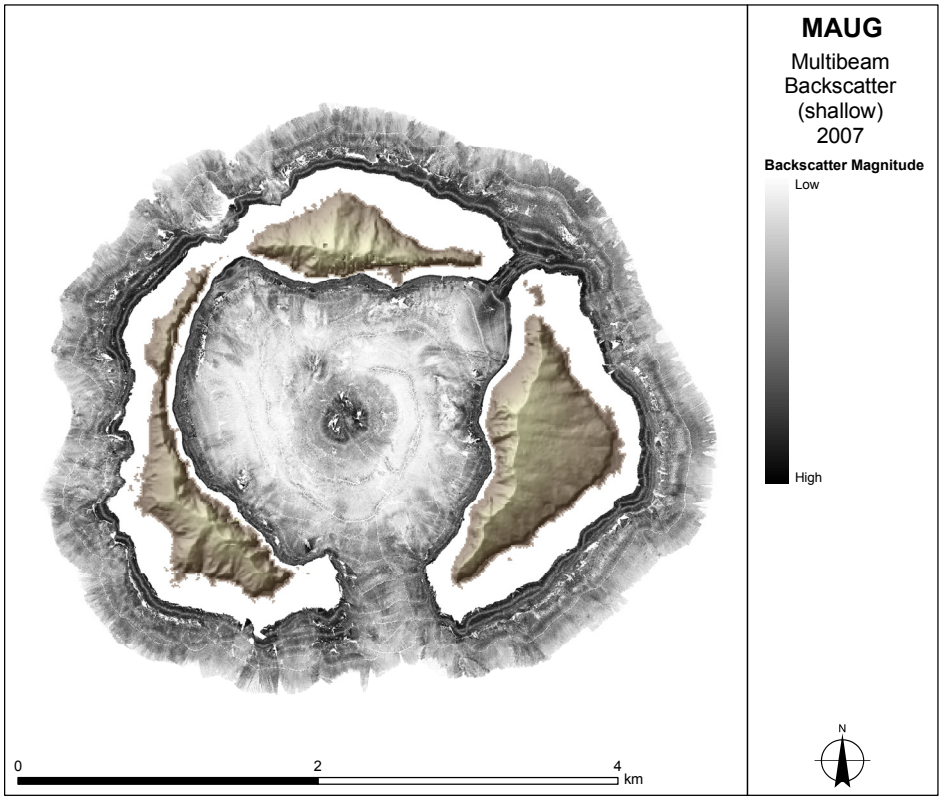


Figure 16.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) collected around Maug during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

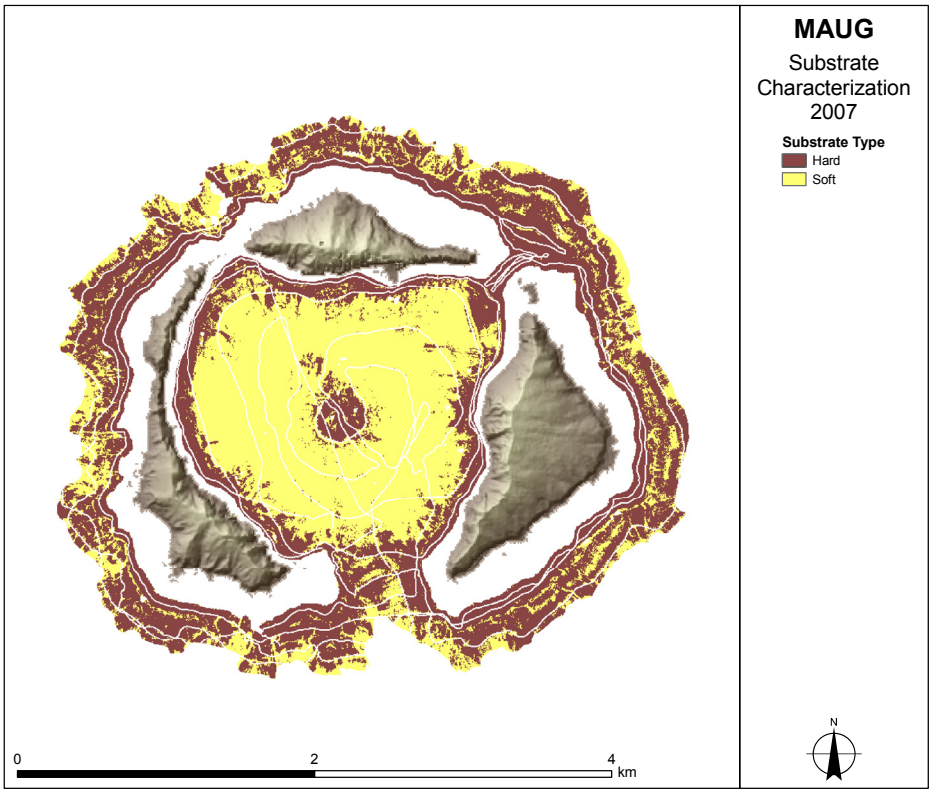


Figure 16.3.1g. Hard and soft substrates (grid cell size: 5 m) at depths < 200 m based upon an unsupervised classification of multibeam bathymetry and backscatter data around Maug in 2007. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

16.3.2 Optical Validation

During MARAMP 2003, 6 TOAD optical-validation surveys were conducted around Maug at depths of ~ 20–225 m (Fig. 16.3.2a). Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live-hard-coral cover.

Covering a distance of 76 km at depths of ~ 3–25 m, 40 towed-diver optical-validation surveys of forereef habitats were conducted around Maug during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover as well as habitat complexity using a 6-level categorical scale from low to very high.

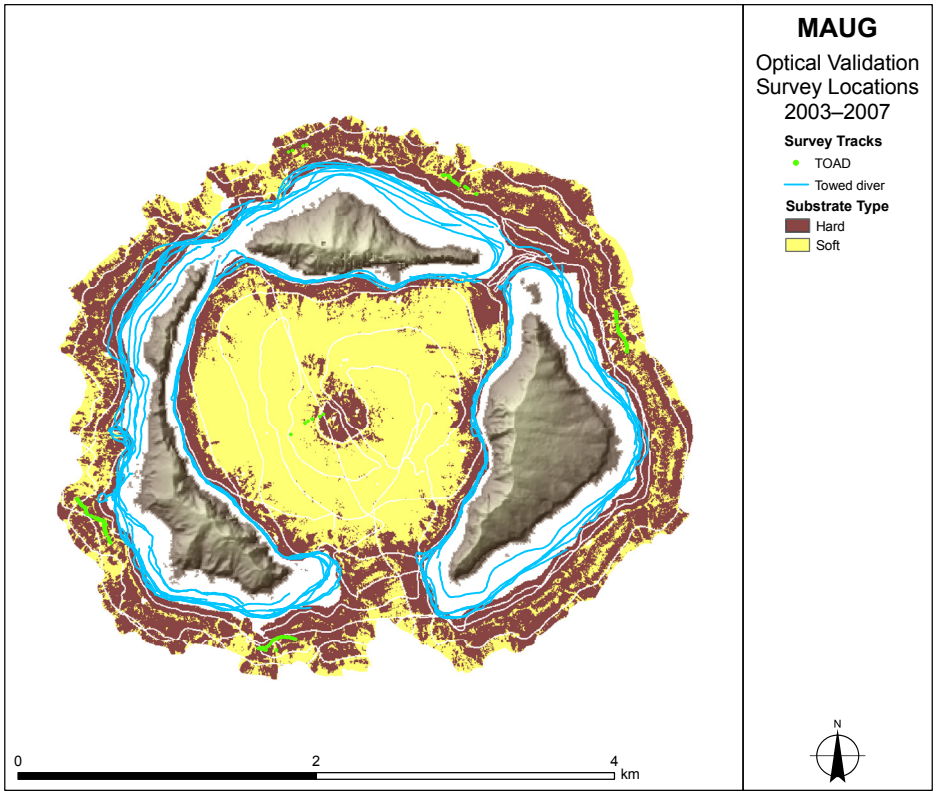


Figure 16.3.2a. Towed-diver tracks from surveys of forereef habitats conducted around Maug during MARAMP 2003, 2005, and 2007, and TOAD camera-sled tracks for MARAMP 2003. Survey tracks are displayed over the multibeam hard–soft substrate map. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

16.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Maug are discussed in this section. These descriptions are discussed with reference to the 7 geographic regions around Maug.

Towed-diver observations during MARAMP 2003, 2005, and 2007 recorded medium to high habitat complexity through most of the area surveyed, with only 2 moderately sized patches where habitat complexity was lower (Fig. 16.3.3a). These low-complexity areas were on the inner crater edge between North and West Islands near the northwest channel into the caldera and on the inner crater south of the pass between North and East Islands. In both areas, the habitat had predominantly sand and other soft sediment (classified as sand using the towed-diver benthic classification), with sand cover > 75% in places (Fig. 16.3.3b) and live coral cover < 20% (Fig. 16.3.3c).

Based on qualitative observations and photographic data from towed-diver surveys, sand was primarily basalt-derived around Maug; however, sand composition shifted noticeably as divers progressed south of the pass between North and East Islands, changing from basalt-based sand to fine, unconsolidated sediments that were brown, orange, and yellow-tinted, with an increase in particulate suspension of similar color within the water column. These areas of "fluffy" silt appeared to be associated with a hydrothermal vent system, which was documented in the east caldera region near REA site MAU-02 (for the location of REA sites, see Figure 16.2a in Section 16.2: "Survey Effort"). In 2007, water samples, gas bubbles, and temperatures were collected at this vent system near CTD cast 17 (for the location of this nearshore cast, see Figure 16.4.1f

in Section 16.4: Oceanography and Water Quality"). A second hydrothermal site was noted near the middle of the northern caldera slope west of MAU-06, with divers noting decreased water visibility, yellow sediment intermixed with basaltic sand, increased benthic substrate temperature (hot sand), and increased water temperature.

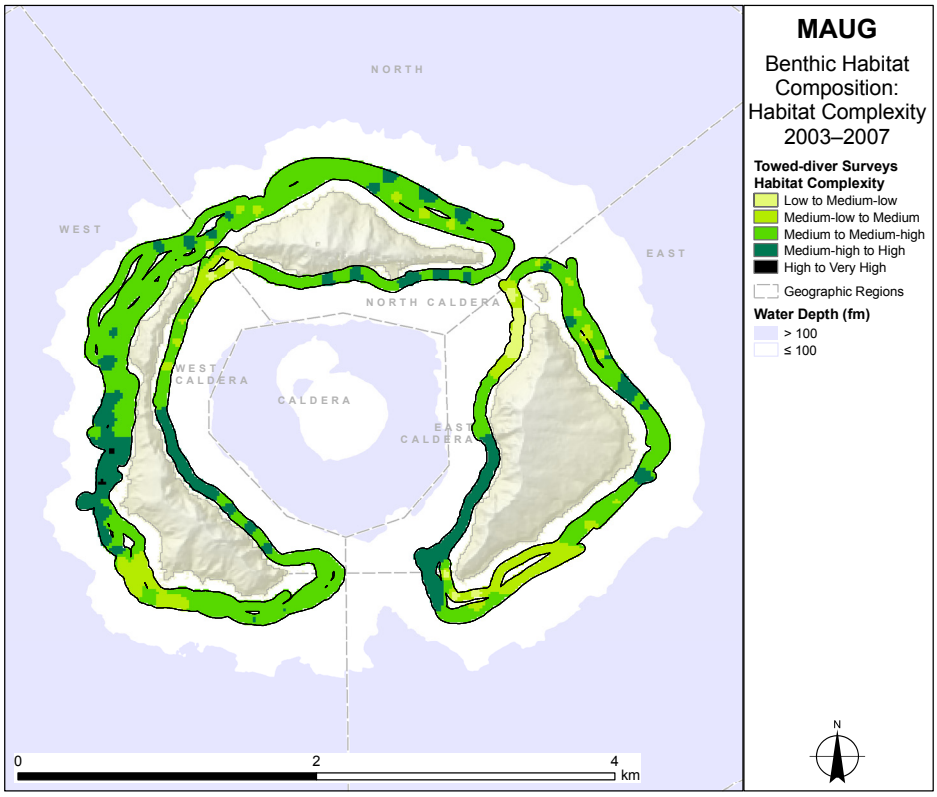


Figure 16.3.3a. Observations of benthic habitat complexity from towed-diver survey of forereef habitats conducted around Maug during MARAMP 2003, 2005, and 2007.

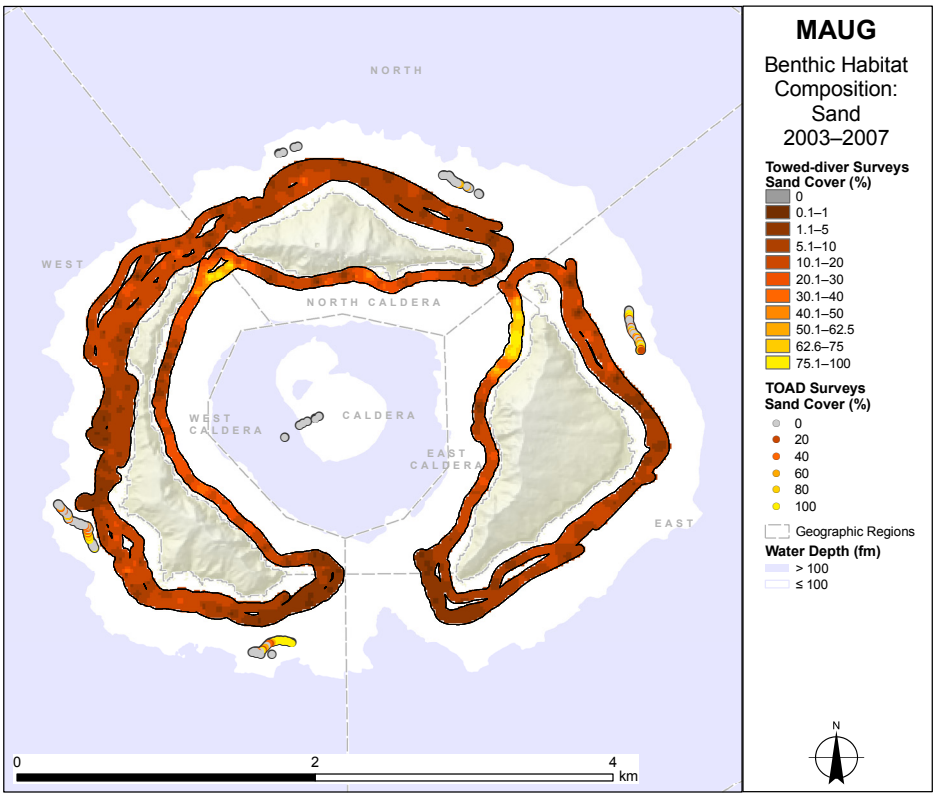


Figure 16.3.3b. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Maug during MARAMP 2003, 2005, and 2007.

Throughout the MARAMP survey years, sand cover around Maug was low, with the exception of the 2 previously described areas of low complexity where sand cover was high. Sand cover was 20% on the outer flanks and < 30% within the caldera. Analyses of TOAD video acquired in deep waters around Maug suggest that sand cover was patchy. The distribution of sand in these areas appears related to the ridge and channel topography with sand accumulating in channels between the ridges; however, the resolution of the data is insufficient to be highly confident in this hypothesis.

Live coral cover recorded during towed-diver surveys was predominantly > 20%. Areas of lower coral cover included the 2 sandy areas previously described and 2 areas with habitat of medium-low to medium complexity observed south of West Island in the west region and south of East Island in the east region close to the southern entrance into the lagoon. In these 4 locations, live coral cover was < 20%. The highest levels of live coral cover were recorded by towed divers in the west region, where live coral cover > 40% was observed, and in the west caldera region, where interpolated live coral cover for a smaller patch was > 50%. Around the 3 islands, towed divers observed habitats of continuous reef, spur-and-groove reef, and boulder fields.

Although towed-diver surveys in shallow waters found abundant coral habitats, very few live corals were recorded in the deeper waters surveyed using the TOAD. Live coral cover was observed in video footage from only 1 of the 5 TOAD surveys conducted on the outer flanks. Completed off West Island, this survey recorded live coral cover in 2 video frames at a depth of 30 m and 2 video frames at a depth of 80 m. Another survey was conducted over the central dome, but the steep slopes made surveying difficult and only 2 video frames could be fully classified. Live corals were observed in 1 of these video frames at a depth of ~ 160 m.

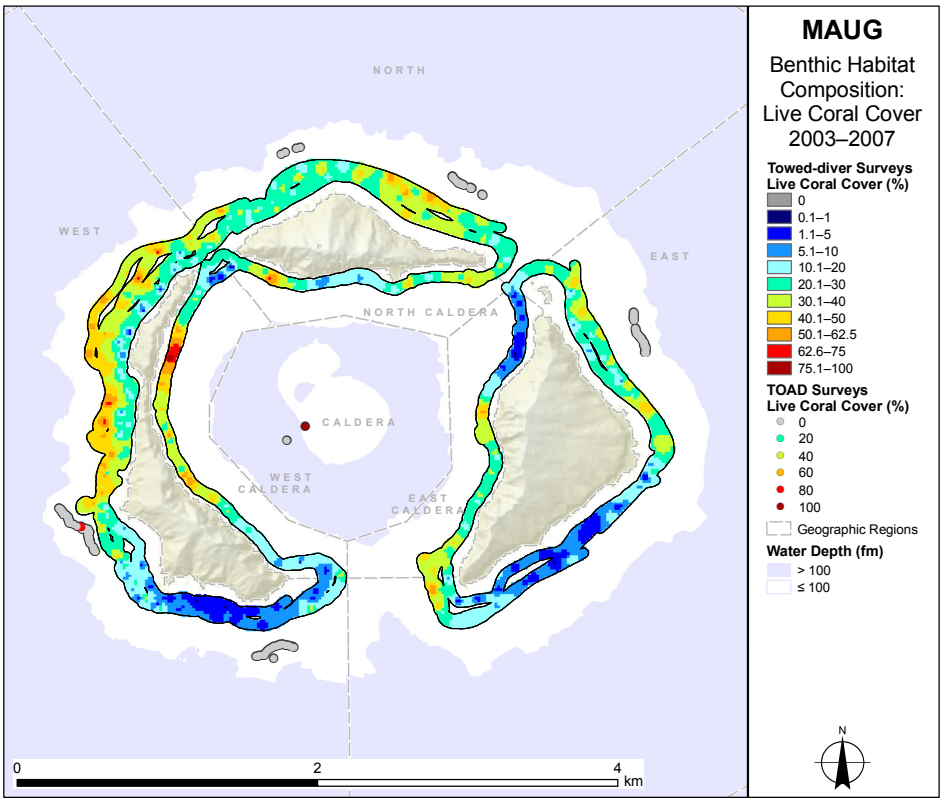


Figure 16.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Maug during MARAMP 2003, 2005, and 2007.

16.4 Oceanography and Water Quality

16.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the islands of Maug over the period of September 2–4. Data from 32 of these casts show that temperature, salinity, density, and beam transmission values varied both spatially and vertically around these islands. Spatial comparisons of water properties at a depth of 10 m suggest moderate variability (Fig. 16.4.1a). Salinity ranges were small (0.11 psu); however, a clear pattern of higher salinity inside the caldera, compared to the outer regions, was present. The highest temperature (30.19°C) and lowest beam transmission (93.07%) values at Maug were also recorded inside the caldera (cast 24), principally owing to the warm and turbid water located at a hydrothermal vent system west of East Island (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). More information on this vent system is provided later in the "2007 Spatial Surveys" discussion. Vertical comparisons of CTD profiles (Fig. 16.4.1b) reveal a broad range in temperature (1.7°C) that was likely a result of the cooler water (28.5°C) intrusions observed below the depth of 23 m in the north and east regions (casts 10–12). In general, data show mostly well-mixed, homogenous waters around Maug; however, salinity values were distinctly higher inside the caldera regions (casts 17–32) than in the outer regions (casts 1–16). Beam transmission values were lower and density values were higher on the inside of Maug than on the outside.

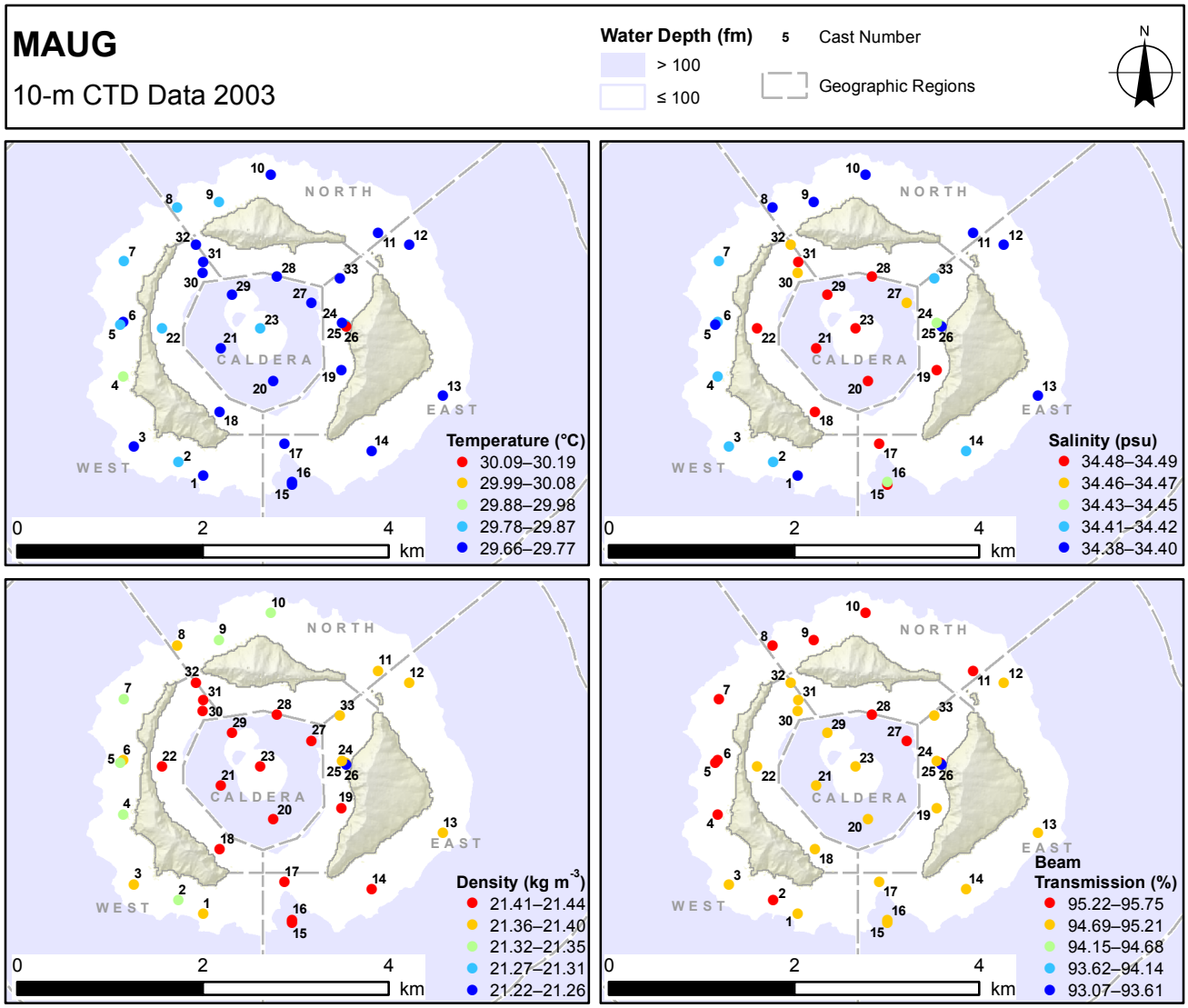


Figure 16.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Maug on September 2–4 during MARAMP 2003.

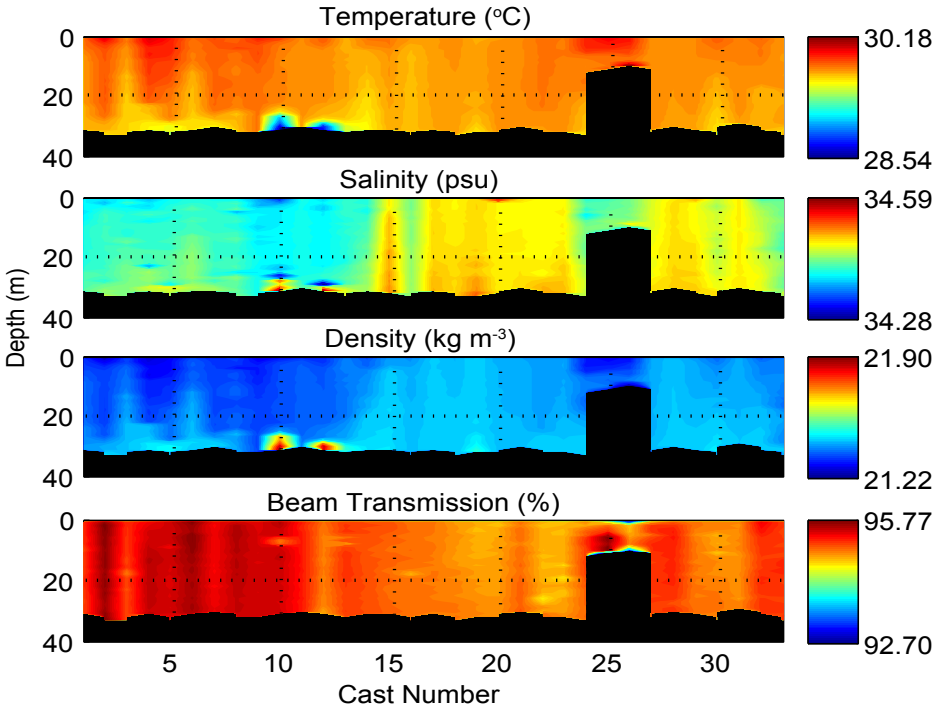


Figure 16.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Maug on September 2–4 during MARAMP 2003, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–32, in a clockwise direction around Maug. For cast locations and numbers around these islands in 2003, see Figure 16.4.1a.

2005 Spatial Surveys

During MARAMP 2005, shallow-water CTD casts were conducted in nearshore waters around Maug over the period of September 11–13. Data from 31 of these casts show that waters varied both spatially and vertically around these islands. Spatial comparisons of water properties at a depth of 10 m suggest low variability in temperature (0.15°C), salinity (0.07 psu), density (0.09 kg m^{-3}), and beam transmission (0.99%); however, waters were slightly cooler and more saline in the regions outside of Maug than in the caldera regions (Fig. 16.4.1c). Vertical comparisons of CTD profiles reveal a highly stratified water column with a large range in temperature (1.2°C) values accompanied by moderate ranges in salinity (0.3 psu), density (0.5 kg m^{-3}), and beam transmission (2.8%) values (Fig. 16.4.1d). In general, surface temperatures in the outer regions were similar to values found in the caldera regions, but cooler (~ 0.5°C) temperatures were observed below the depth of 5 m in the outer regions. Differences in salinity and density values show a marked correspondence with differences in temperature values.

Water samples were collected in concert with shallow-water CTD casts at select locations around Maug in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.09–1.20 µg L^{-1}; total nitrogen (TN), 0.04–0.25 µM; nitrate (NO_3^-), 0.02–0.23 µM; nitrite (NO_2^-), 0.010–0.032 µM; phosphate (PO_4^{3-}), 0.006–0.034 µM; and silicate [$Si(OH)_4$], 0.70–1.31 µM. Based on data from 13 sample locations, total nitrogen and nitrate concentrations were all higher in the outer regions versus the caldera regions, whereas nitrite, phosphate, and silicate values showed the opposite spatial pattern (Fig. 16.4.1e). Chl-*a* levels at Maug were consistently lower inside of the caldera than outside, where Chl-*a* concentrations were higher in the east and west regions than just outside the north region. Total nitrogen and nitrate followed a similar pattern except that values were low in the west region compared to the other outer regions.

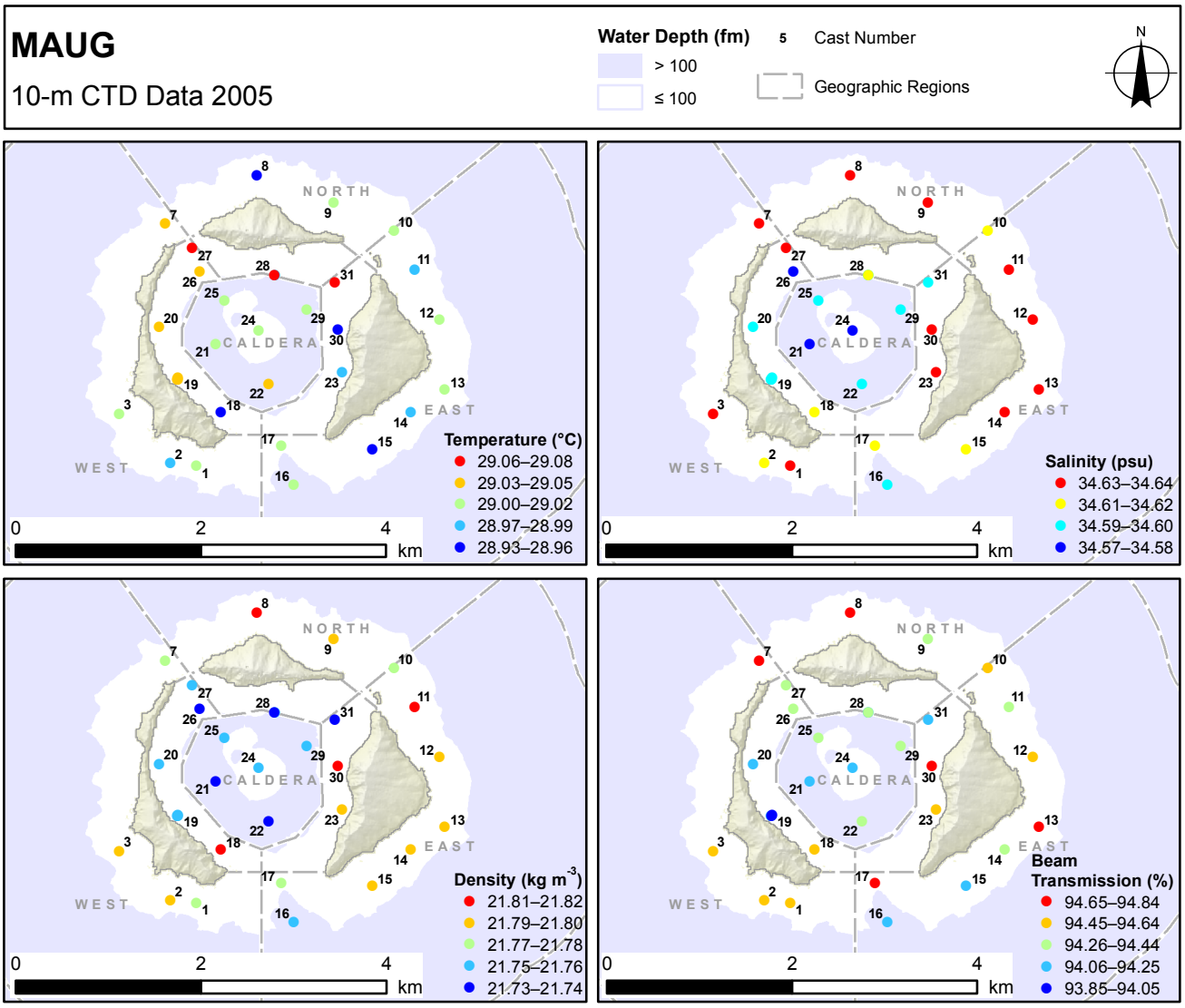


Figure 16.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Maug on September 11–13 during MARAMP 2005. Data for casts 4–6 are not presented in this map because those casts did not go down to a depth of 10 m.

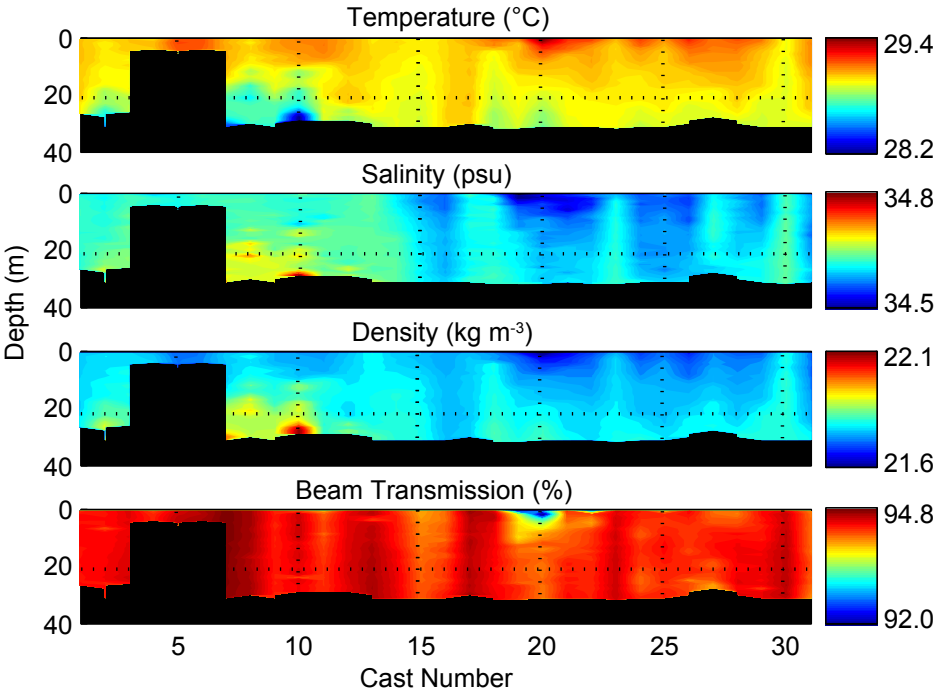


Figure 16.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Maug on September 11–13 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%).Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–31, in a clockwise direction around Maug. For cast locations and numbers around these islands in 2005, see Figure 16.4.1c.

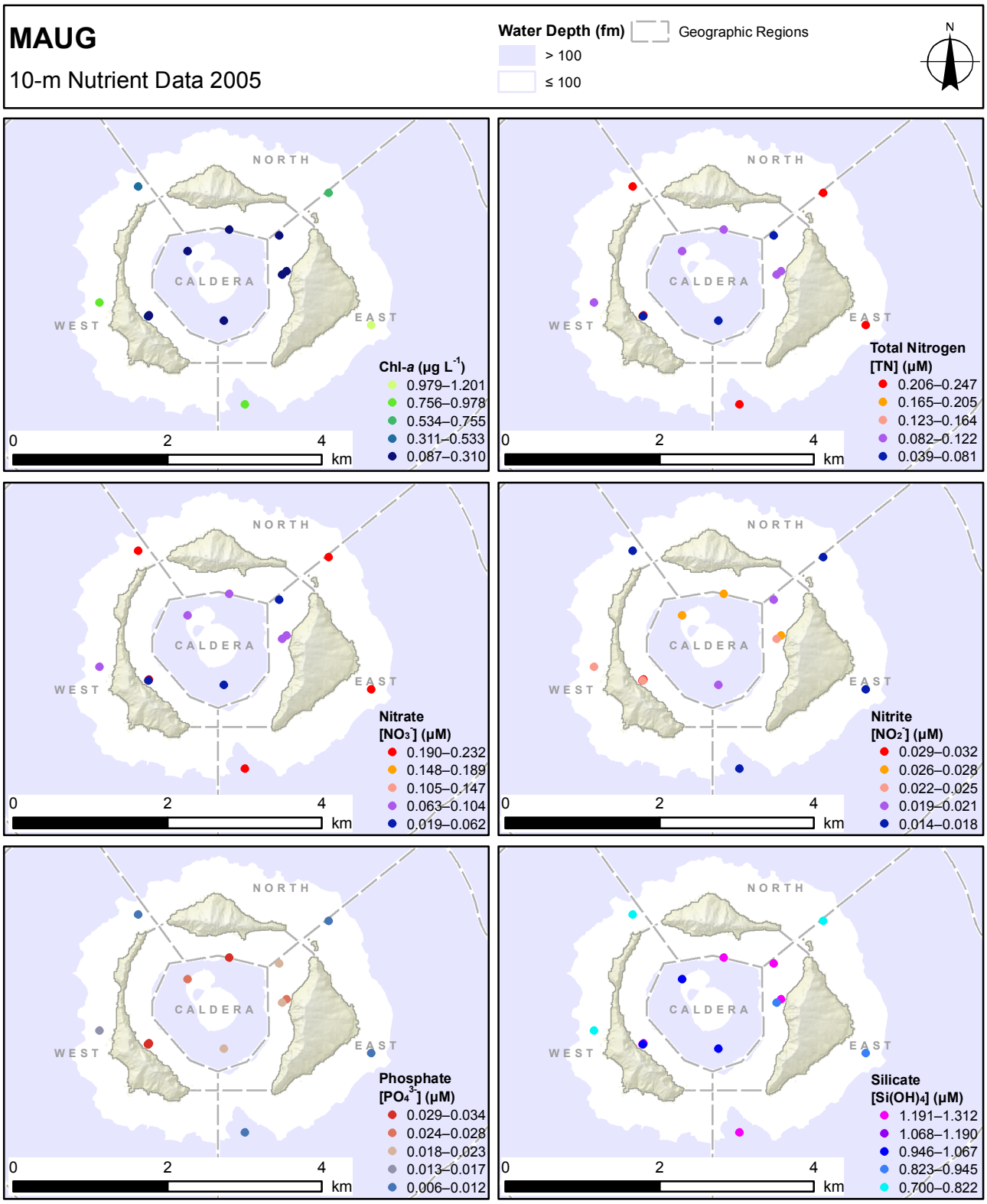


Figure 16.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected in concert with shallow-water CTD casts around Maug on September 11–13 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, 20 shallow-water CTD casts were conducted in nearshore waters around Maug over the period of May 30–June 1. Temperature, salinity, density, and beam transmission values from these casts varied both spatially and vertically around these islands. Spatial comparisons of water properties at a depth of 10 m suggest moderate variability in temperature (0.68ºC) values, with low variability in salinity (0.04 psu), density (0.23 kg m^{-3}), and beam transmission (0.94%) values (Fig. 16.4.1f). Vertical comparisons of CTD profiles from Maug reveal water properties with considerable ranges in temperature (3.7°C) and density (1.2 kg m^{-3}) values and moderate ranges in salinity (0.4 psu) and beam transmission (3.7%) values (Fig. 16.4.1g). This range in temperature can be attributed to local upwelling of subsurface waters below the depth of 15 m on the outside of these islands. The physical mechanism driving this upwelling is unknown; however, the subsurface temperature data obtained from a depth of 10 m at Maug, and presented later in Section 16.4.2: "Time-series Observations" (Fig 16.4.2d, mooring site MAU-003), show high-frequency temperature fluctuations of 1°C–3°C, suggesting internal tide activity.

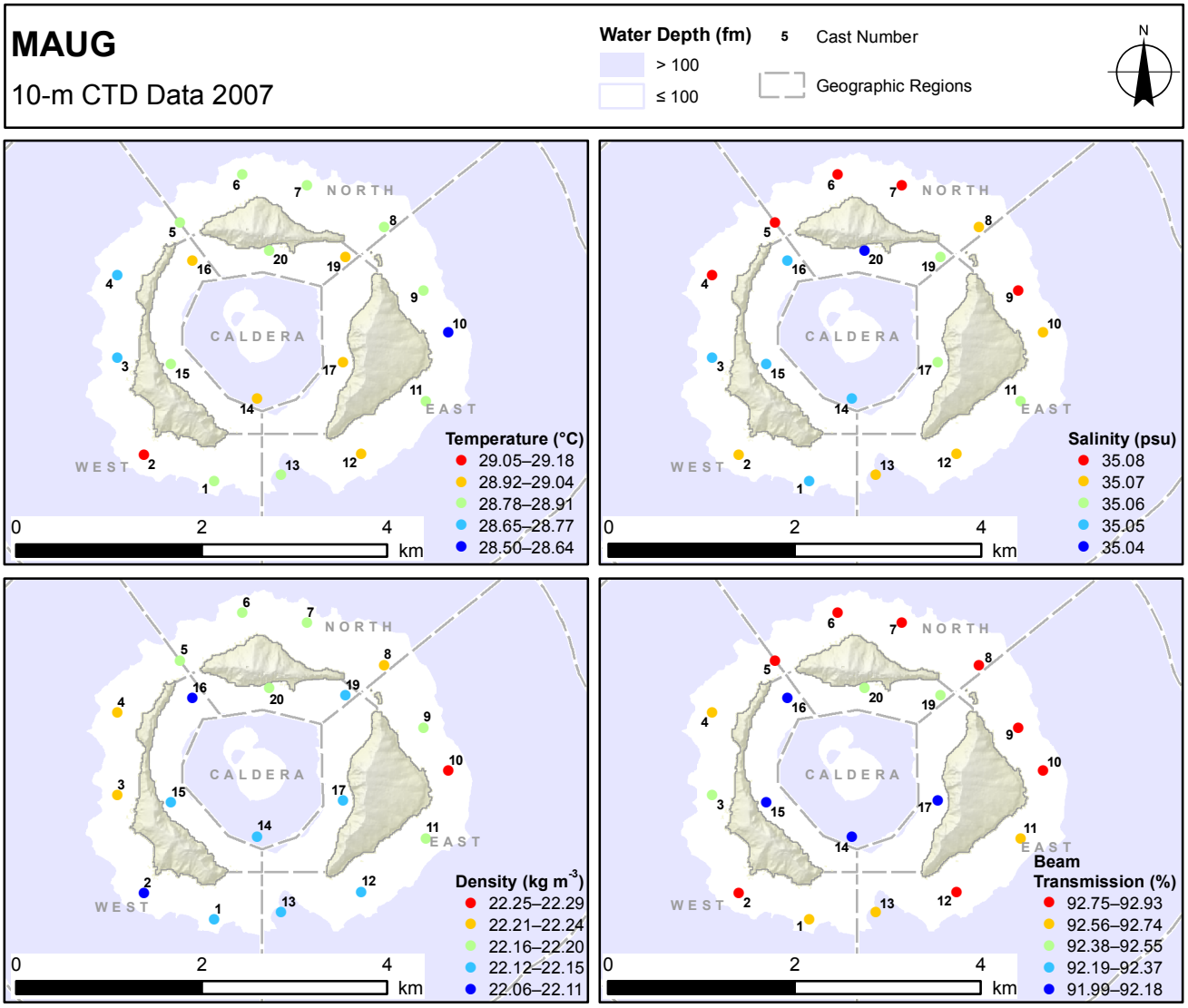


Figure 16.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, (*bottom right*) and beam transmission at a 10-m depth from shallow-water CTD casts around Maug on May 30–June 1 during MARAMP 2007. Data for cast 18 are not presented in this map because that cast did not go down to a depth of 10 m.

Water samples were collected in concert with shallow-water CTD casts at 9 select locations around Maug in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: Chl-*a*, 0.04–0.18 µg/L; total nitrogen (TN), 0.001–0.092 µM; nitrate (NO_3^-), 0.001–0.084 µM; nitrite (NO_2^-), 0–0.010 µM; phosphate (PO_4^{3-}), 0.001–0.010 µM; and silicate [$Si(OH)_4$], 1.15–1.96 µM. All measured parameters, except silicate, were generally observed at the relatively low levels typical of the Western Pacific Warm Pool's oligotrophic, oceanic surface layers. The highest values of silicate were recorded inside the caldera at Maug, while values in the outer regions were relatively homogenous (Fig. 16.4.1h). Also, Chl-*a* values were higher inside than outside the caldera.

A survey was performed during MARAMP 2007 at a single site (cast 17) at the hydrothermal vent system located in the caldera west of East Island. The purpose of this survey was to collect and analyze area-wide and near-vent water samples to gain insight into the marine geochemistry of hydrothermal vents in the CNMI and the possible influences of this specific vent system on the surrounding benthic ecosystem. Divers collected gas bubbles for analyses of carbon dioxide (CO_2) and hydrogen sulfide (H_2S) concentrations, water samples for dissolved inorganic carbon (DIC), total alkalinity (TA), pH, iron, manganese, trace metal, and nutrient concentrations, and temperatures from multiple locations within this vent site. Temperatures near this vent system, measured with a hand-held thermometer, ranged from 45°C to 63°C, levels that were 16°C–34°C above ambient water temperatures. Preliminary analyses of water samples collected at this vent site found pH as low as 6.07, TA of 3.56, and aragonite saturation state of 0.25 (D Butterfield, pers. comm.), suggesting a highly corrosive environment at this vent system.

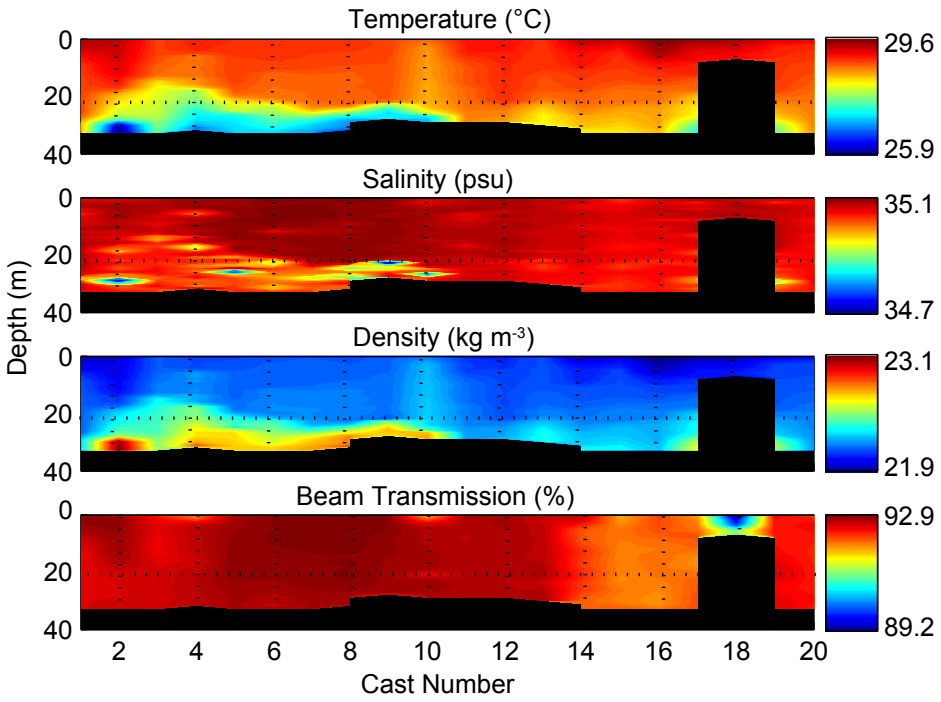


Figure 16.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Maug on May 30–June 1 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–20, in a clockwise direction around Maug. For cast locations and numbers around these islands in 2007, see Figure 16.4.1f.

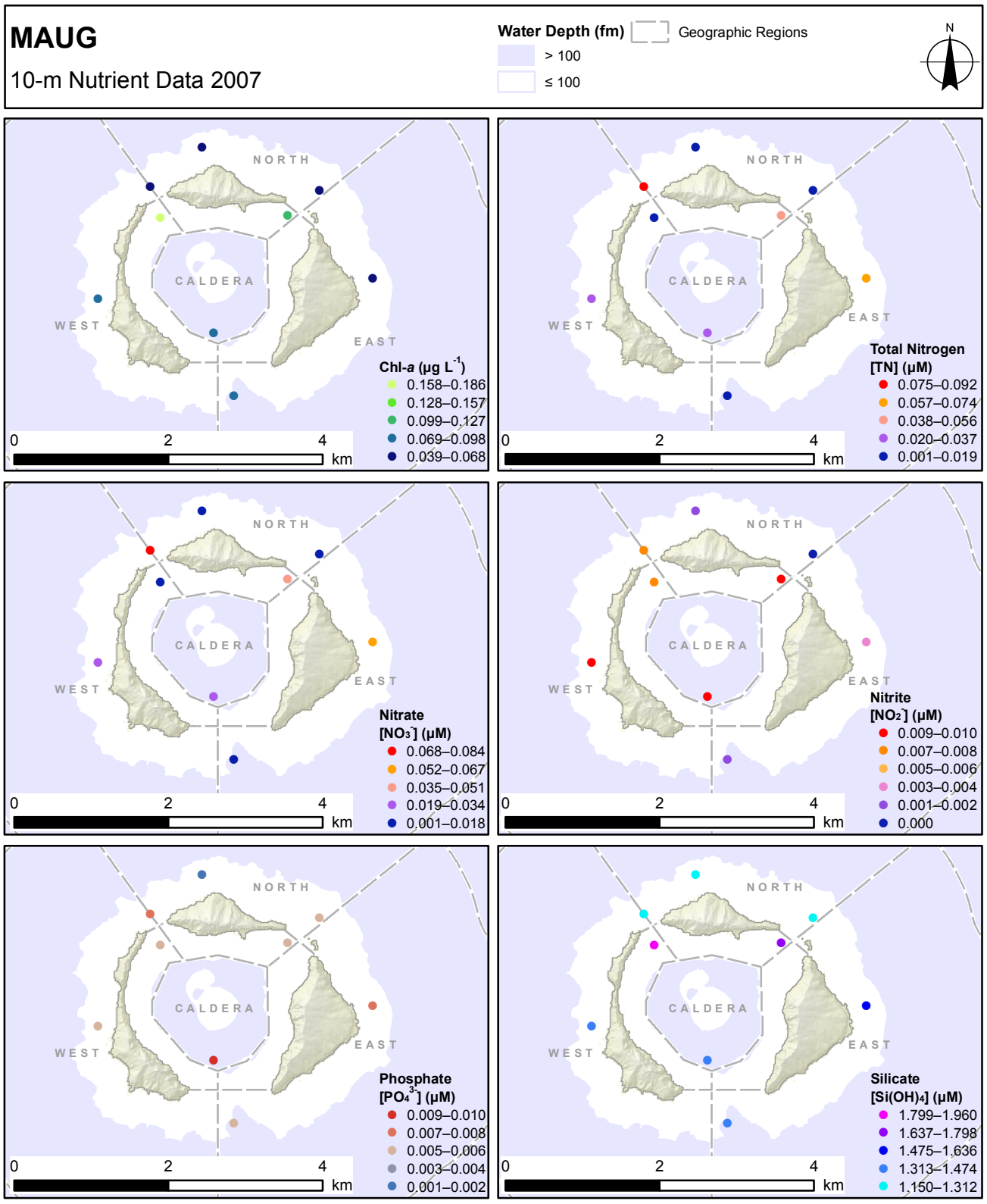


Figure 16.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected in concert with shallow-water CTD casts around Maug on May 30–June 1 during MARAMP 2007.

Temporal Comparison

Comparisons between survey periods of shallow-water CTD data collected around Maug during MARAMP 2003, 2005, and 2007 suggest a dynamic physical environment. During the first 2 MARAMP survey periods, low spatial variability and moderate vertical structure were observed, yet substantial spatial heterogeneity in physical water properties was found during the third survey period in 2007. Intrusions of cooler (25.9°C) waters in the outer regions were prominent in 2007, likely a result of upwelling or internal tide activity. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May, and MARAMP 2003 and 2005 occurred in September. This change was made to avoid the typhoon season and reduce the probability of weather disruptions. Additionally, differences in salinity values between the caldera regions and the outer regions were prominent in 2003 and 2005; however, data from 2003 show that salinity values were higher inside than outside the caldera at Maug, whereas data from 2005 present the opposite pattern.

Water-quality data obtained during MARAMP 2005 and 2007 suggest that nutrient concentrations were variable spatially between survey years. Values for nearly all of the parameters measured were lower in 2007 than in 2005, particularly Chl-*a* values, which were an order of magnitude lower. Total nitrogen, nitrate, and nitrite values were also notably lower in 2007 than 2005. Whether these differences resulted from a seasonal effect or some other process is unknown at this time. This pattern is seemingly paradoxical given the observed variability in temperature and water movement between 2005 and 2007; however, the water-quality data presented in this report were collected at a depth of 10 m, whereas the cooler water was recorded below the depth of 20 m, and, therefore, no nutrient signal is expected in this depth bin.

16.4.2 Time-series Observations

Between 2003 and 2007, 2 types of moored instruments were deployed at Maug to collect time-series observations of temperature, a key oceanographic parameter. The locations, depths, timeframes, and other details about these deployments are provided in Figures 16.4.2a and b.

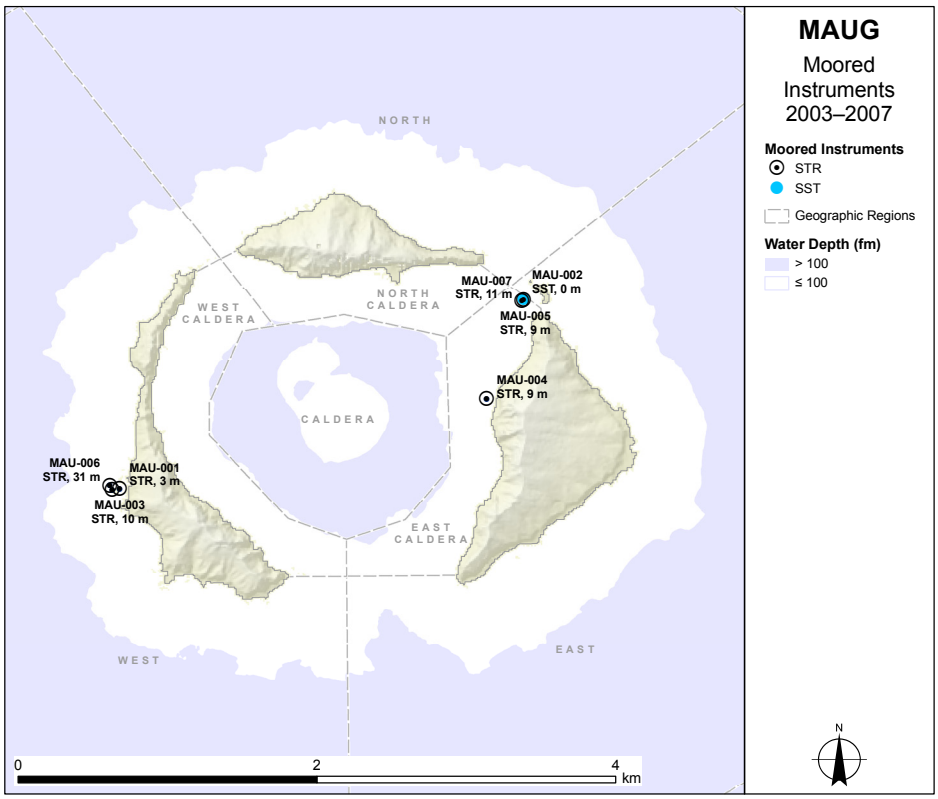


Figure 16.4.2a. Locations, depths, and types of oceanographic instrument moorings deployed at Maug during MARAMP 2003, 2005, and 2007. Two types of instruments were moored at Maug: subsurface temperature recorder (STR) and sea-surface temperature (SST) buoy.

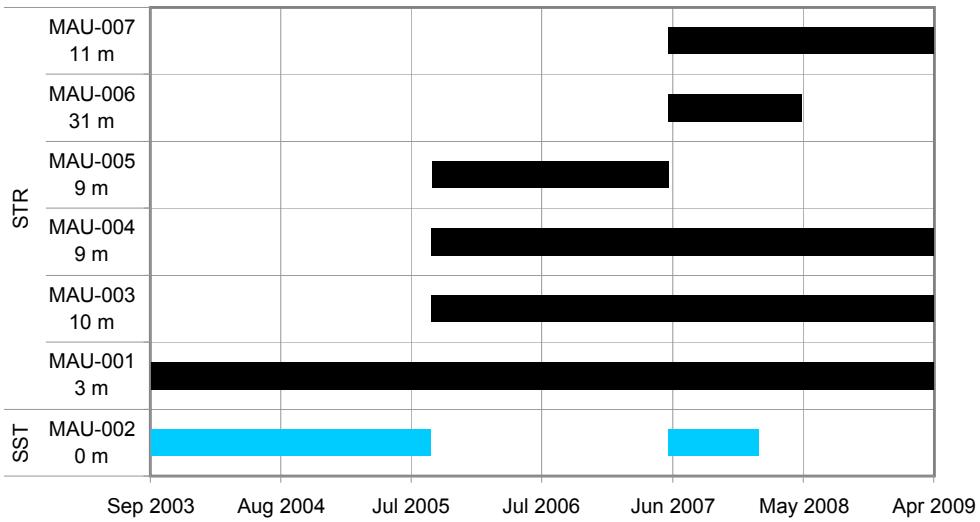


Figure 16.4.2b. Deployment timelines and depths of oceanographic instruments moored at Maug during the period from September 2003 to April 2009. A solid bar indicates the period for which temperature data were collected by a single instrument or a series of them that were deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 16.2a in Section 16.2: "Survey Effort." The time periods shown in this figure for data stored on and collected from buoys may differ from the period for which telemetered SST data, shown in Figure 16.4.2c, were available.

Satellite-derived (Pathfinder) sea-surface temperature (SST) and in situ temperature observations around Maug reveal that the seasonal maxima for water temperatures around Maug were typically reached in late August or September. The monthly maximum climatological mean from Pathfinder SST was 29.5°C (Fig. 16.4.2c[a]). Winter minima occurred in February with a monthly minimum climatological mean of 25.9°C. In the winters of 2004 and 2007, Pathfinder SST observations were 1°C cooler than the climatological mean. In general, Pathfinder SST matched SST in situ observations; however, on a number of occasions, including in April 2006, in situ temperatures dropped 0.5°C–1°C below temperatures from Pathfinder data, suggesting a local cooling event not observed in the satellite record. It's important to note that Pathfinder SST represents the upper few millimeters of oceanographic temperatures within the region of an island, as opposed to site- or reef-specific temperatures.

Periods of elevated mean wave heights of 3–4 m were usually more frequent during winter (Fig. 16.4.2c[b]). The largest episodic events of wave heights > 4 m, however, tended to happen during periods of warm temperatures. Warm temperatures typically occur during the period of August–December, when wave heights of > 4 m are generally associated with typhoons. This pattern was especially noticeable during the summer of 2004 with the passages of Typhoons Tingting and Chaba.

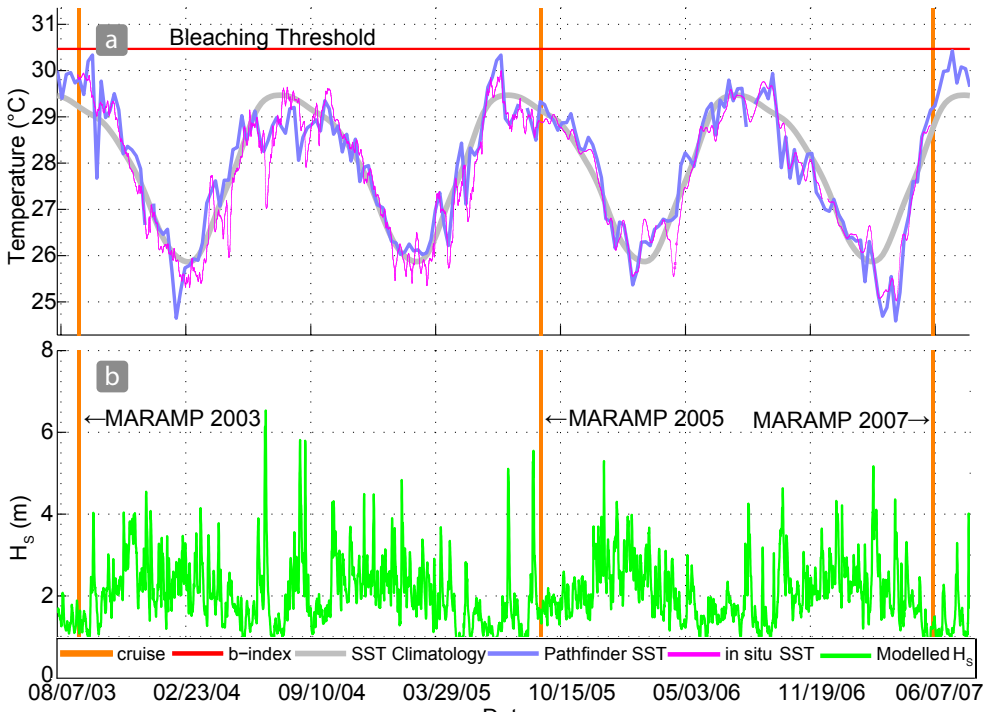


Figure 16.4.2c. Time-series observations of (a) SST and (b) wave height around Maug for the period between August 2003 and June 2007. Remotely sensed data (SST climatology and weekly Pathfinder-derived SST) and modeled significant wave height (HS) derived from Wave Watch III are shown with CRED in situ temperature data from SST buoys (see Figure 16.4.2a for buoy locations). The 2 high points in the modeled wave height in the summer of 2004 show the occurrences of Typhoons Tingting and Chaba. The horizontal red and vertical orange bars represent the bleaching threshold and the MARAMP research cruise dates, respectively.

Subsurface temperature recorders (STRs) were deployed at 6 locations at depths of 3–31 m around Maug beginning in September 2003. Data from STRs at 4 of these locations show seasonal temperature variability of 4°C–6°C (Fig. 16.4.2d). Water temperatures reached ~ 31°C during the months of June–October and fell to a low of ~ 25°C during the months of January–May. Temperature at all 4 locations in September 2006 reached the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean for the region. Temperatures at the shallowest sensor, MAU-001 deployed at a depth of 3 m, exceeded the threshold of 31°C by almost 0.3°C. Diurnal temperature fluctuation was ~ 0.5°C for the shallowest sensor and ~ 0.25°C for the other 3 sensors, which were deployed at depths of 9–10 m. Solar heating and cooling likely caused the fluctuation in diurnal temperature to be greater at MAU-001 than at the other deployments. Additionally, rapid (return periods of 12–24 h) drops of 1°C–3°C in temperature were observed in the spring of 2006 at MAU-003, located on the western side of West Island (outside of the caldera) at a depth of 10 m. Internal tides are generated when tidal currents interact with steep subsurface topography, resulting in high-frequency variability in temperature, salinity, dissolved nutrients, and suspended particle concentrations that differ significantly from shallow reefs to deep slopes. Although more research and additional data are needed to properly ascertain the nature of this signal, the observed rapid temperature changes likely were the result of internal tides causing vertical displacements of the background stratification at MAU-003.

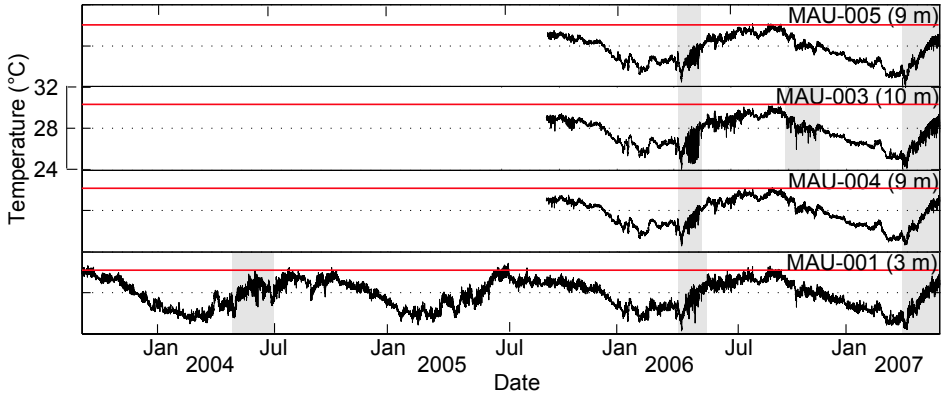


Figure 16.4.2d. Time-series observations of temperature over the period between September 2003 and May 2007 collected from 4 STR mooring sites at different locations and depths at Maug (see Figure 16.4.2a for mooring locations). A grey background indicates a period of high-frequency variability that likely resulted from internal tide activity. The red lines indicate the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

16.4.3 Wave Watch III Climatology

Seasonal wave climatology for Maug was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008 (Fig. 16.4.3a), and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), relatively short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (90°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the south (180°), although they could originate from a broad directional source (120°–200°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from the west and southwest (210°–250°) and likely were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) was also characterized by frequent (> 30 d per season) and short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 10 d per season) and long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this period and originate from the northwest (330°).

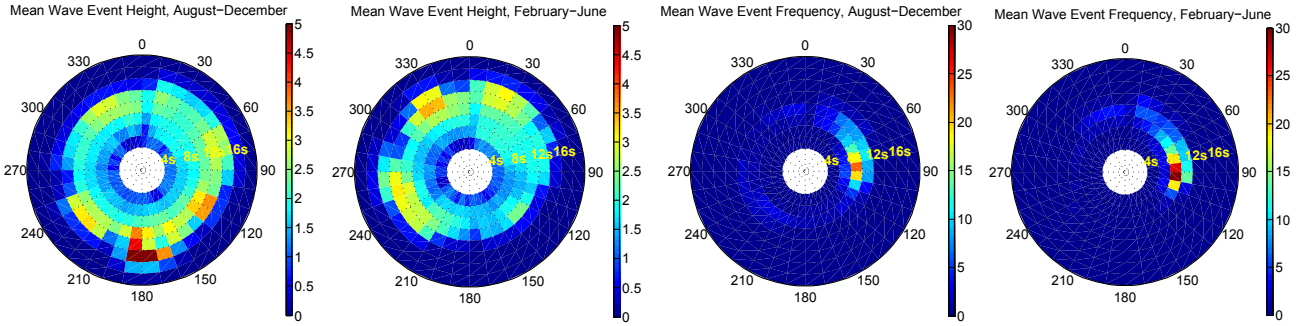


Figure 16.4.3a. NOAA Wave Watch III directional wave climatology for Maug from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Maug (20° N, 144°48′ E). Mean significant wave height (*top*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*bottom*) that conditions in each directional and frequency bin occur in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

16.5 Corals and Coral Disease

16.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the islands of Maug was 27% (SE 1.4). Coral cover was lowest in the east and west regions, adjacent to the southern channel entrance into the caldera (Fig. 16.5.1a). Coral cover was highest in the north and west regions. Localized areas of high coral cover were observed in the west caldera region with means in a range of 75.1%–100%.

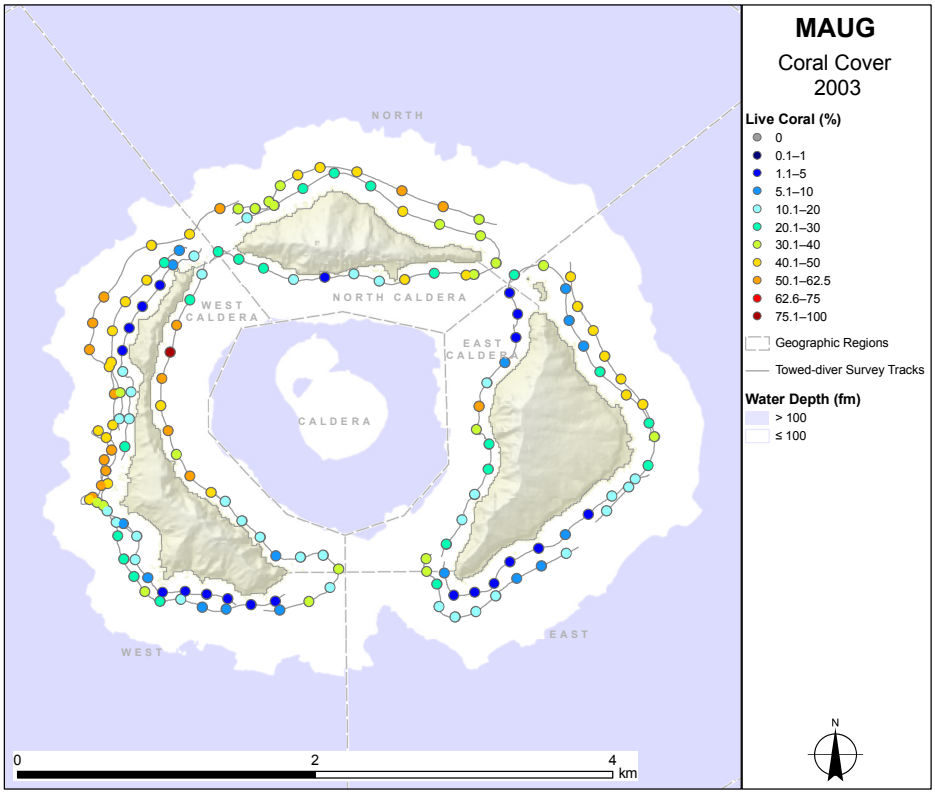


Figure 16.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2).

During MARAMP 2003, 8 REA benthic surveys using the quadrat method on forereef habitats at Maug documented 892 coral colonies within a total survey area of 30 m^2. Site-specific colony density ranged from 8.8 to 59.5 colonies m^{-2} with an overall sample mean of 29.7 colonies m^{-2} (SE 5.9). The highest colony density was recorded at MAU-03 in the east caldera region, and the lowest colony density was observed in the east region at MAU-04 (Fig. 16.5.1b).

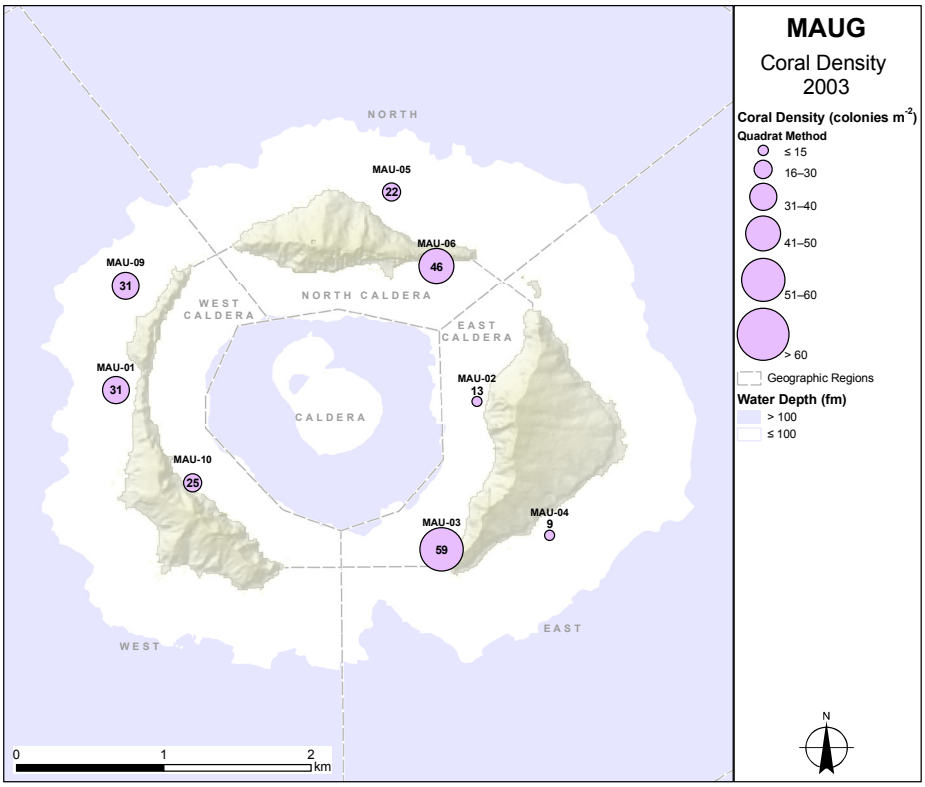


Figure 16.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2003. Values are provided within or above each symbol. The quadrat method was used in 2003 to assess coral-colony density.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Maug was 21% (SE 1.7). As seen in surveys in 2003, coral cover was lowest in the east and west regions, adjacent to the southern channel entrance into the caldera (Fig. 16.5.1c). Coral cover was variable in all other regions with localized areas of relatively high mean coral cover along the outer flank in the west region and in the west caldera and east caldera regions.

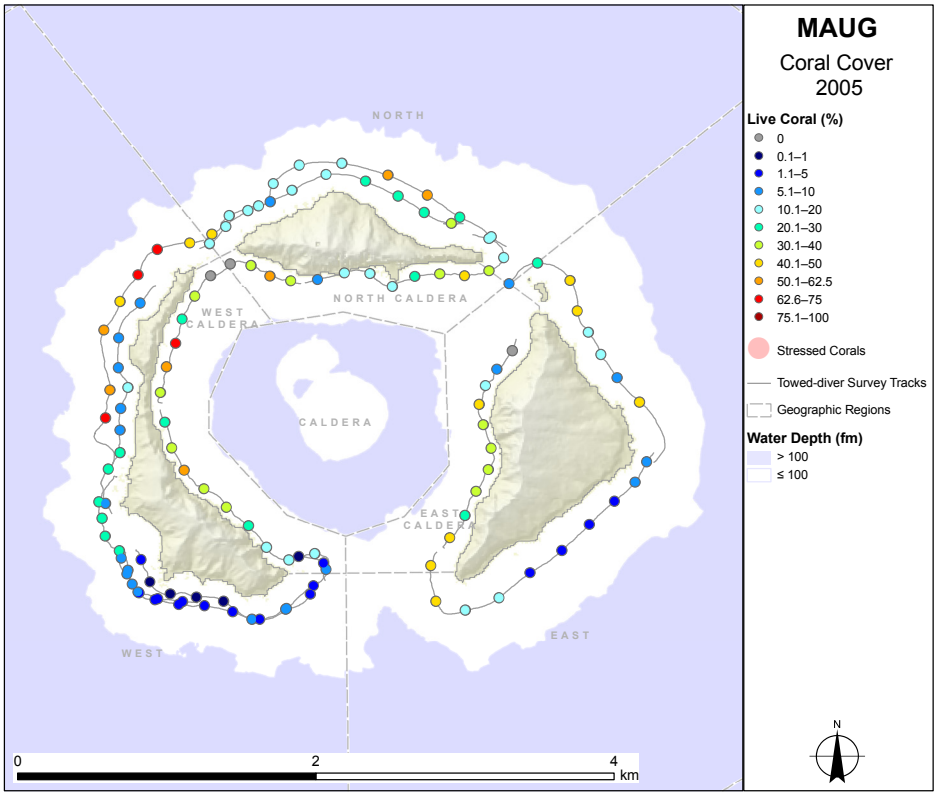


Figure 16.5.1c. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols are shown only for segments with stressed-coral cover > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005.

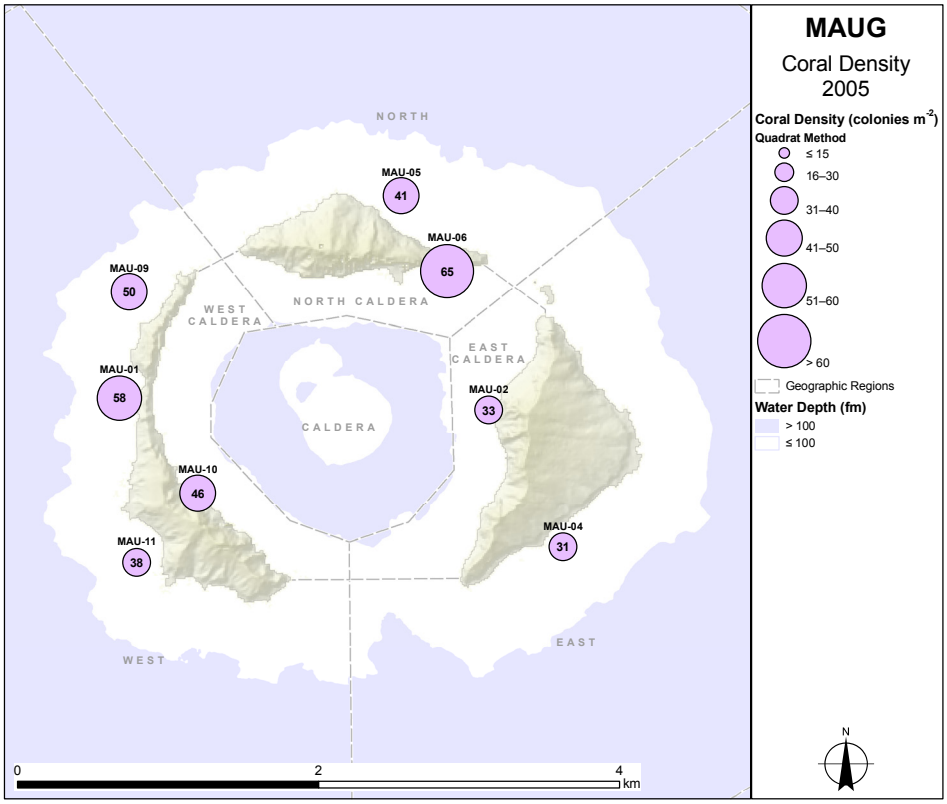


Figure 16.5.1d. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2005. Values are provided within or above each symbol. The quadrat method was used in 2005 to assess coral-colony density.

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 0.5% (SE 0.1) of coral cover observed on forereef habitats around Maug appeared stressed in 2005. The occurrence of stressed-coral cover was low for the majority of forereefs surveyed around Maug in 2005.

During MARAMP 2005, 8 REA benthic surveys using the quadrat method on forereef habitats at Maug documented 1443 coral colonies within a total survey area of 32 m^2. Site-specific colony density ranged from 31 to 64.8 colonies m^{-2} with an overall sample mean of 45.1 colonies m^{-2} (SE 4.2). The highest colony density was recorded at MAU-06 in the north caldera region, and the lowest colony density was observed in the east region at MAU-04 (Fig. 16.5.1d).

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Maug was 26% (SE 1.6). As seen in the previous MARAMP survey years, coral cover was lowest in the east and west regions, adjacent to the southern channel entrance into the caldera. (Fig. 16.5.1e). Coral cover was variable in all other regions with relatively high mean coral cover observed along the outer flanks in the west region. Localized areas of high coral cover were recorded at numerous locations within the caldera, including the southern corner of East Island and isolated locations in the west caldera and north caldera regions (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort").

Overall, 1.4% (SE 1.3) of coral cover observed on forereef habitats around Maug appeared stressed in 2007 (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). The occurrence of stressed-coral cover was low for the majority of forereefs surveyed at Maug. Stressed-coral cover > 10% was observed over 2 segments in the west caldera region and 1 segment in the north caldera region (Fig. 16.5.1e).

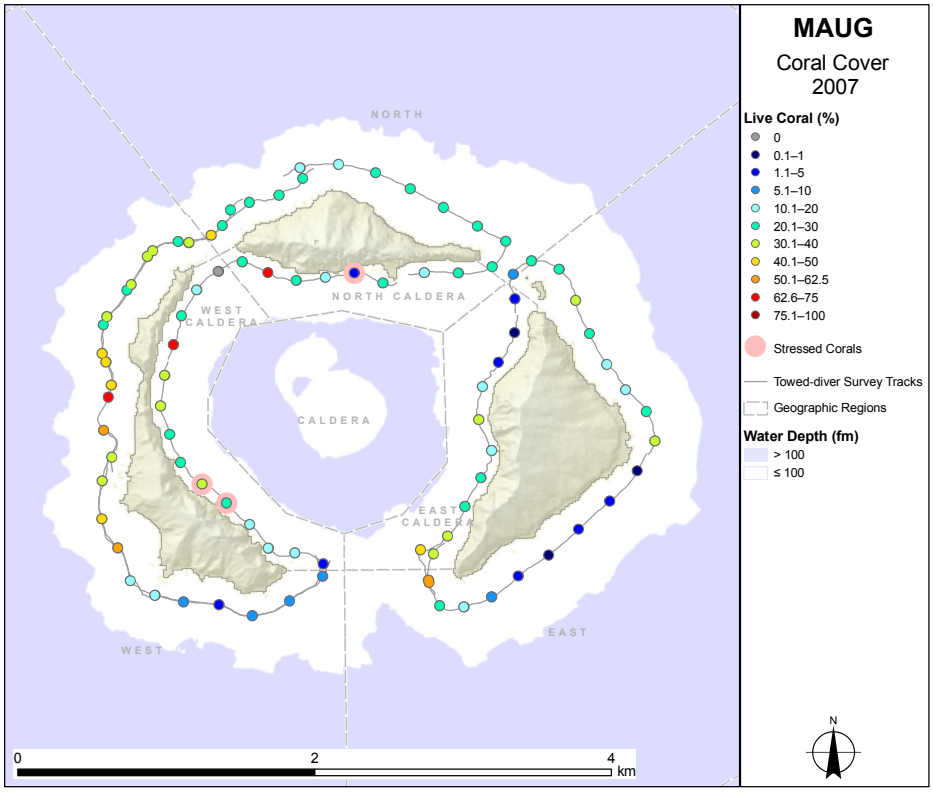


Figure 16.5.1e. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2007.

During MARAMP 2007, 9 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Maug. Site-specific estimates of live-hard-coral cover from these surveys ranged from 8.8% to 66.7% with an overall sample mean of 34.1% (SE 5.7). Live coral cover was highest at MAU-02 located near a volcanic vent in the east caldera region and lowest at MAU-04 in the east region (Fig. 16.5.1f).

During MARAMP 2007, 9 REA benthic surveys using the quadrat method on forereef habitats at Maug documented 1699 coral colonies within a total survey area of 36 m^2. Site-specific colony density ranged from 39.5 to 67.3 colonies m^{-2} with an overall sample mean of 47.2 colonies m^{-2} (SE 3). The highest colony density was recorded at MAU-06 in the north caldera region, and the lowest colony density was observed in the east region at MAU-04.

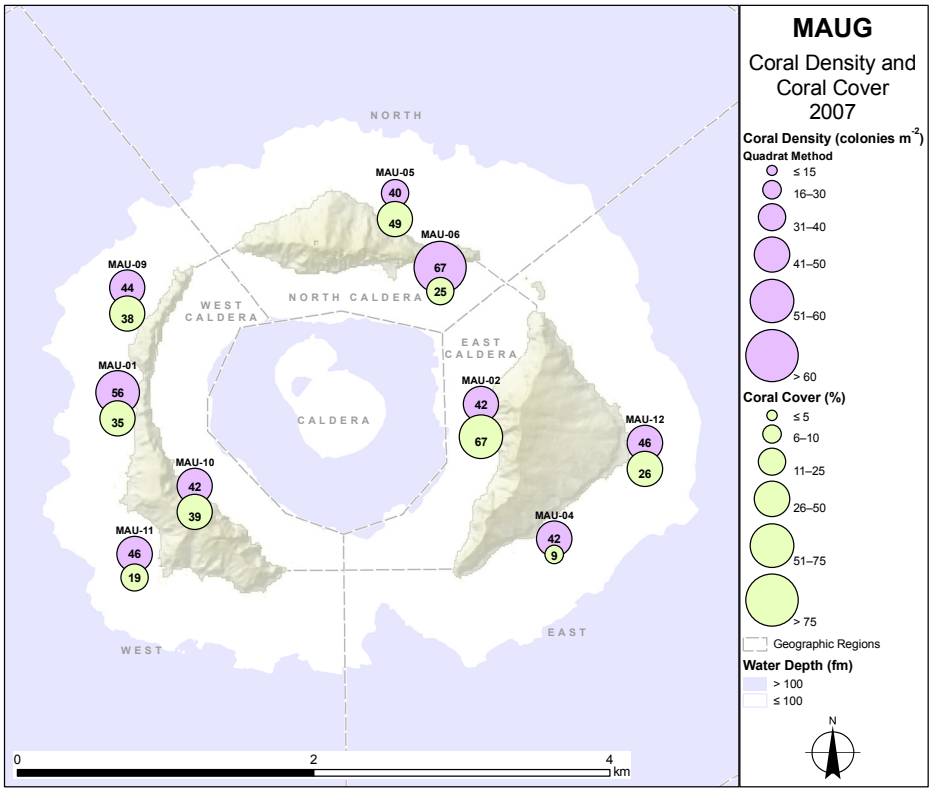


Figure 16.5.1f. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. Values are provided within or above each symbol. The quadrat method was used in 2007 to assess coral-colony density.

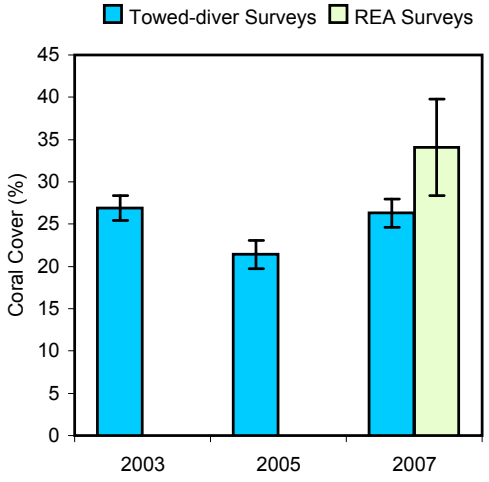


Figure 16.5.1g. Temporal comparison of mean live coral cover (%) values from REA and towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted around Maug in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Overall mean cover of live corals, estimated from towed-diver surveys of forereef habitats, was 27% (SE 1.4) in 2003, 21% (SE 1.7) in 2005, and 26% (SE 1.6) in 2007 (Fig. 16.5.1g). This relatively small variation in overall mean values of live coral cover between MARAMP survey years does not necessarily reflect actual changes in overall coral cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Estimates of live coral cover from REA surveys generally exceeded levels recorded in towed-diver surveys; REA surveys target hard-bottom communities, whereas towed-diver surveys include a wider array of substrate types. Site-specific estimates of coral cover ranged from 8.8% to 66.7% with an overall mean of 34.1% (SE 5.7) for the 9 REA sites surveyed in 2007 (Maug was not surveyed for coral cover using the line-point-intercept method in 2003 or 2005).

The quadrat method was used during the 3 MARAMP survey years to assess coral-colony density. Overall mean coral-colony density from REA benthic surveys of forereef habitats at Maug increased from 29.7 colonies m^{-2} (SE 5.9) in 2003 to 45.1 colonies m^{-2} (SE 4.2) in 2005 and 47.2 colonies m^{-2} (SE 3) in 2007 (Fig. 16.5.1h). The same temporal pattern exists when only the 7 sites that were surveyed in all 3 survey years are examined. For example, observed mean coral-colony density increased from 26.3 colonies m^{-2} (SE 4.8) in 2003 to 46.1 colonies m^{-2} (SE 4.7) in 2005 and 47.5 colonies m^{-2} (SE 3.9) in 2007. This observed increase in coral-colony density may result from differences in the placement of individual quadrats, increased recruitment, or fragmentation of existing colonies.

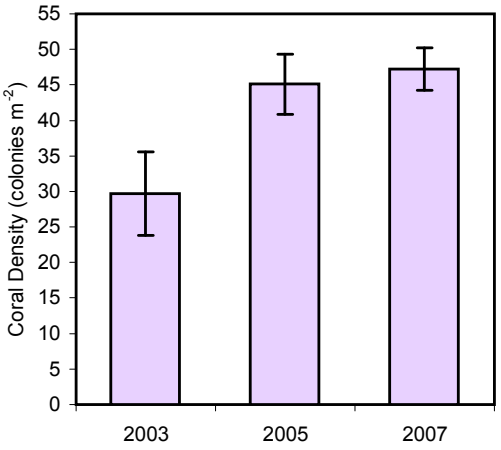


Figure 16.5.1h. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Maug during MARAMP 2003, 2005, and 2007. The quadrat method was used in all 3 years to measure coral-colony density. Error bars indicate standard error (± 1 SE) of the mean.

Coral Generic Richness and Relative Abundance

Eight REA benthic surveys of forereef habitats were conducted using the quadrat method at Maug during MARAMP 2003. At least 22 coral genera were observed at Maug. Generic richness ranged from 6 to 16 with a mean of 12.3 (SE 1.3) coral genera per site (Fig. 16.5.1i). The highest generic diversity was seen at both MAU-01 and MAU-03 in the west region and east caldera region, and the lowest generic diversity was recorded at MAU-04 in the east region.

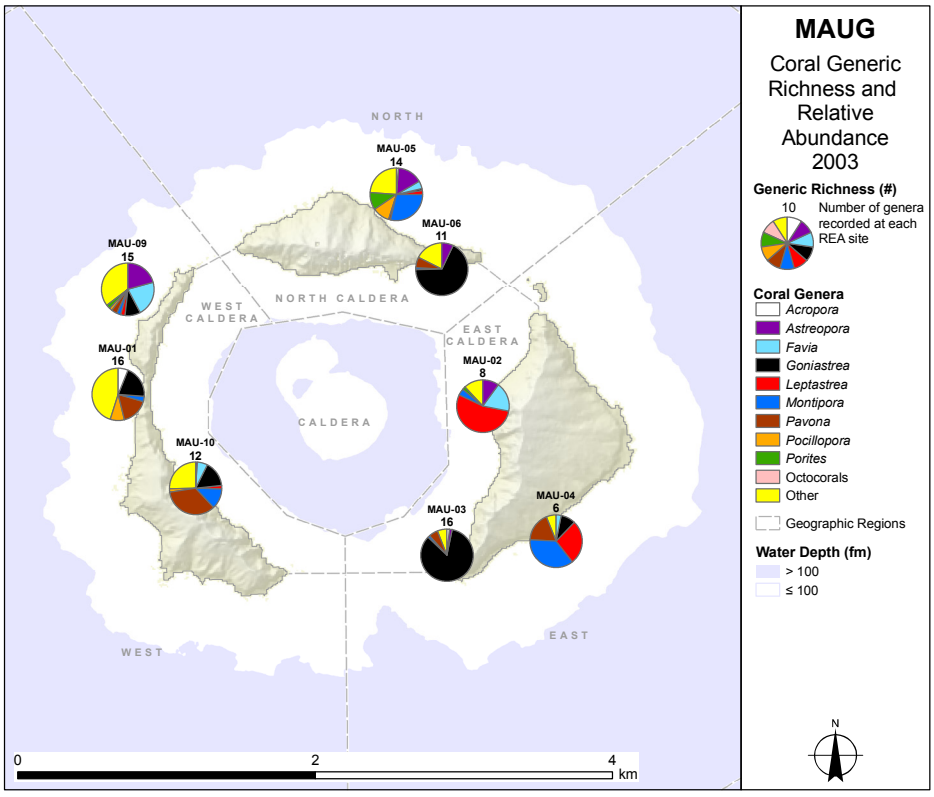


Figure 16.5.1i. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2003. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to survey coral genera.

Goniastrea was the most numerically abundant genus, contributing 25.3% of the total number of colonies enumerated at Maug during MARAMP 2003. *Leptastrea*, *Montipora*, and *Pavona* were the next most numerically abundant genera, accounting for 11.2%, 11.3%, and 10.7 of the total number of colonies enumerated at Maug. All other genera individually contributed < 10% of the total number of colonies. *Goniastrea* dominated the coral fauna at MAU-03 and MAU-06 in the east caldera and north caldera regions, accounting for 81.2% and 66.5% of the total number of colonies at those sites (Fig. 165.1i). *Leptastrea* dominated the coral fauna at MAU-02 in the east caldera region, contributing 54% of the total number of colonies. *Pavona* was the most common genus at MAU-10, accounting for 34.7% of the total number of colonies. *Montipora* dominated MAU-04 and MAU-05 in the east and north regions, contributing 36.4% and 28.6% of the total number of colonies.

Eight REA benthic surveys of forereef habitats were conducted using the quadrat method at Maug during MARAMP 2005. At least 26 coral genera were observed at Maug. Generic richness ranged from 14 to 18 with a mean of 16 (SE 0.5) coral genera per site (Fig. 16.5.1j). The highest generic diversity was seen at both MAU-09 and MAU-05 in the west and north regions, and the lowest generic diversity was recorded at MAU-02 in the east caldera region.

Goniastrea, *Porites*, and *Pavona* were the most numerically abundant genera, contributing 18%, 9%, and 11.6% of the total number of colonies enumerated at Maug during MARAMP 2005. All other genera individually contributed < 10% of the total number of colonies. *Porites* dominated at MAU-02 in the east caldera region, accounting for 40.5% of the total number of colonies (Fig. 16.5.1j). *Goniastrea* dominated at MAU-06 in the north caldera region, MAU-10 in the west caldera region, and MAU-11 in the west region, contributing 34.4%, 20.9%, and 19.1% of the total number of colonies.

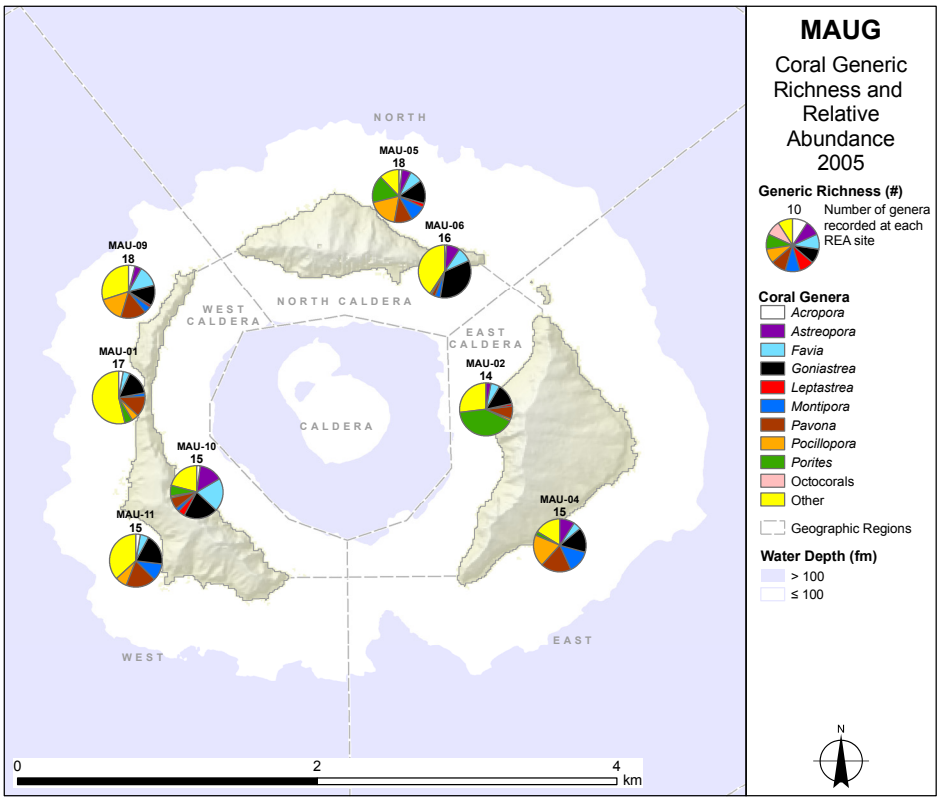


Figure 16.5.1j. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2005. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2005 to survey coral genera.

Nine REA benthic surveys of forereef habitats were conducted using the quadrat method at Maug during MARAMP 2007. At least 27 coral genera were observed at Maug. Generic richness ranged from 11 to 20 with a mean of 15.4 (SE 1.0) genera per site (Fig. 16.5.1k). The highest generic diversity was seen at MAU-09 in the west region, and the lowest generic diversity was recorded at MAU-02 in the east caldera region.

Pocillopora, *Goniastrea*, *Pavona*, and *Porites* were the most numerically abundant genera, contributing 16%, 16.5%, 11.9%, and 7.8% of the total number of colonies enumerated at Maug during MARAMP 2007. All other genera individually accounted for < 10% of the total number of colonies. As seen in 2005 surveys, *Goniastrea* dominated at MAU-06 in

the north caldera region and MAU-11 in the west region, contributing 42.8% and 20.1% of the total number of colonies, and *Porites* dominated the coral fauna at MAU-02 in the east caldera region, contributing 42.2% of the total number of colonies (Fig. 16.5.1k).

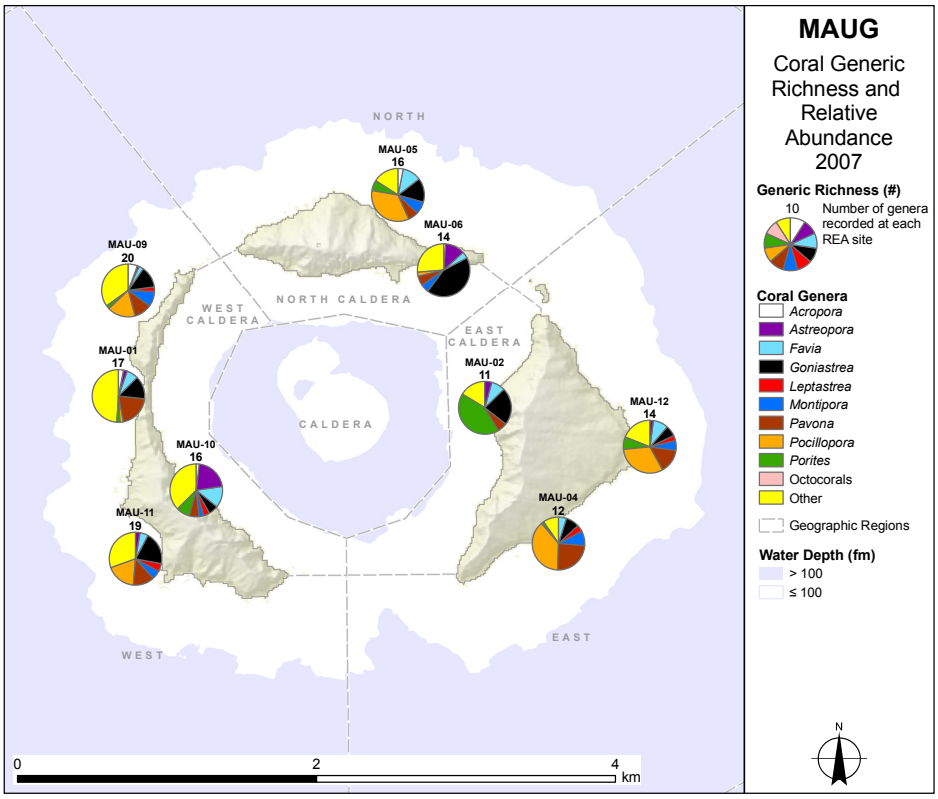


Figure 16.5.1k. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2007 to survey coral genera.

The overall sample mean of generic richness on forereef habitats at Maug changed from 12.3 (SE 1.3) coral genera per site in 2003 to 16 (SE 0.5) and 15.4 (SE 1) coral genera per site in 2005 and 2007 (Fig. 16.5.1l). The same temporal pattern exists when only the 7 sites surveyed in all 3 MARAMP survey periods are examined. For example, mean generic richness increased from 11.7 (SE 1.2) coral genera per site in 2003 to 16.1 (SE 0.5) and 15.1 (SE 0.9) coral genera per site in 2005 and 2007.

During the 3 survey years, 29 coral genera were observed on forereef habitats at Maug. *Goniastrea* and *Pavona* were important components of the coral fauna, accounting for > 10% of the total number of colonies enumerated at Maug in the 3 MARAMP survey years. *Leptastrea* and *Montipora* were important components of the coral fauna in 2003, but their contribution decreased to < 10% of the total number of colonies enumerated in 2005 and 2007. Conversely, *Porites* was not a major part of the coral fauna overall in 2003 but in both 2005 and 2007 accounted for > 10% of the total number of colonies enumerated. Similarly, *Pocillopora* was not a major contributor to the coral fauna at Maug in 2003 or 2005, but its contribution exceeded 10% in 2007. All other taxa contributed < 10% of the total number of colonies enumerated in the 3 survey years.

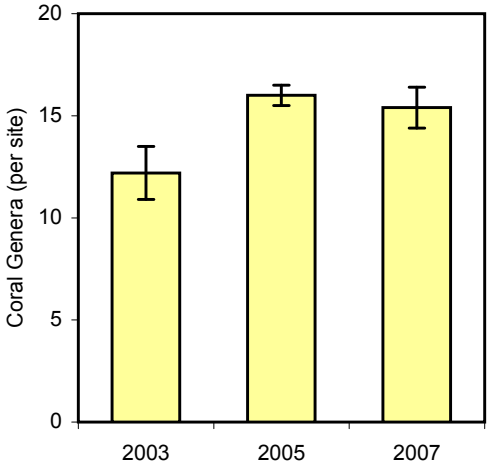


Figure 16.5.1l. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Maug during MARAMP 2003, 2005, and 2007. The quadrat method was used in all 3 years to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

Coral Size-class Distribution

During MARAMP 2003, 8 REA benthic surveys of forereef habitats were conducted at Maug using the quadrat method. The coral size-class distribution from these surveys shows that the majority (50.5%) of corals had maximum diameters ≤ 5 cm (Fig. 16.5.1m). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 31%, 13%, 5.2%, and 0.67% of colonies recorded. A majority (> 62%) of colonies at MAU-02, MAU-03, and MAU-04 in the east caldera and east regions were in the smallest size class (0–5 cm), but distributions were less strongly skewed at the other sites surveyed at Maug.

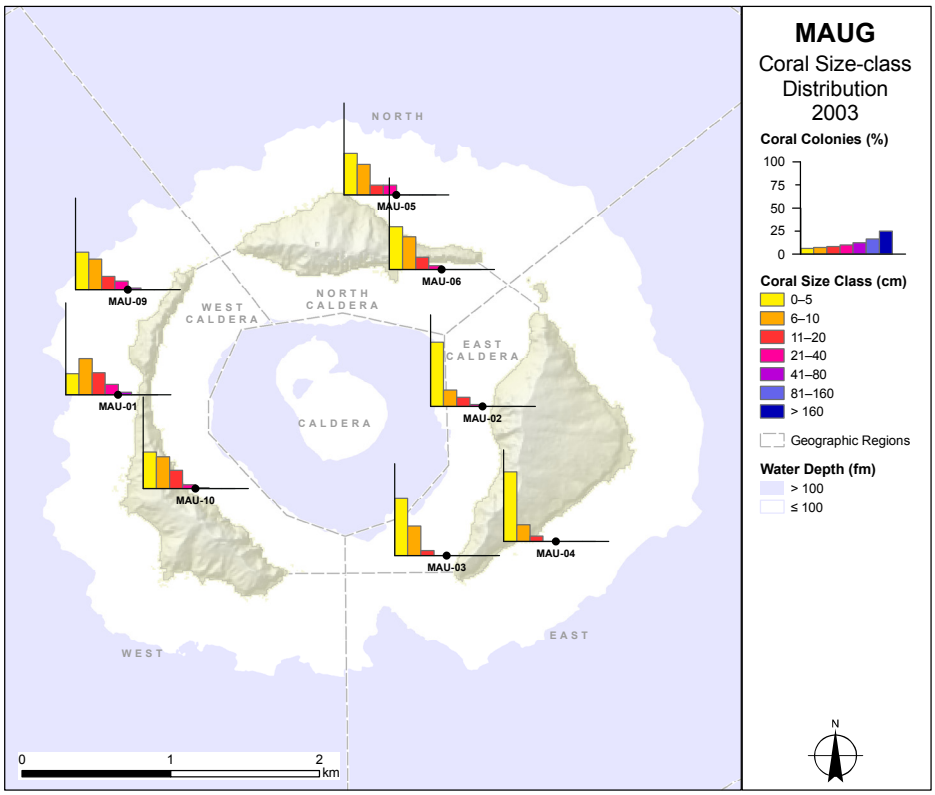


Figure 16.5.1m. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.

During MARAMP 2005, 8 REA benthic surveys of forereef habitats were conducted at Maug using the quadrat method. The coral size-class distribution from these surveys conducted shows that the majority (60%) of corals had maximum diameters ≤ 5 cm (Fig. 16.5.1n). The next 4 size classes (6–10, 11–20, 21–40, and 41–80) accounted for 23.5%, 10.4%, 4.7%, and 1.1% of colonies recorded, and corals with maximum diameters > 80 cm contributed 0.19% of colonies observed. At all REA sites surveyed in 2005, a near majority (> 48%) of corals were in the smallest size class (0–5 cm).

During MARAMP 2007, 8 REA benthic surveys of forereef habitats were conducted at Maug using the quadrat method. The coral size-class distribution from these surveys shows that the majority (62.7%) of corals had maximum diameters ≤ 5 cm (Fig. 16.5.1o). The next 4 size classes (6–10, 11–20, 21–40, and 41–80) accounted for 24.7%, 7.5%, 3.9%, and 1.1% of colonies recorded, and corals with maximum diameters > 80 cm contributed 0.2% to colonies observed. At all REA sites surveyed in 2007, a majority (> 52%) of corals were in the smallest size class (0–5 cm).

The quadrat method was used to establish size-class distributions on forereef habitats at Maug during the 3 MARAMP survey periods. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. For more on these survey methods, see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease."

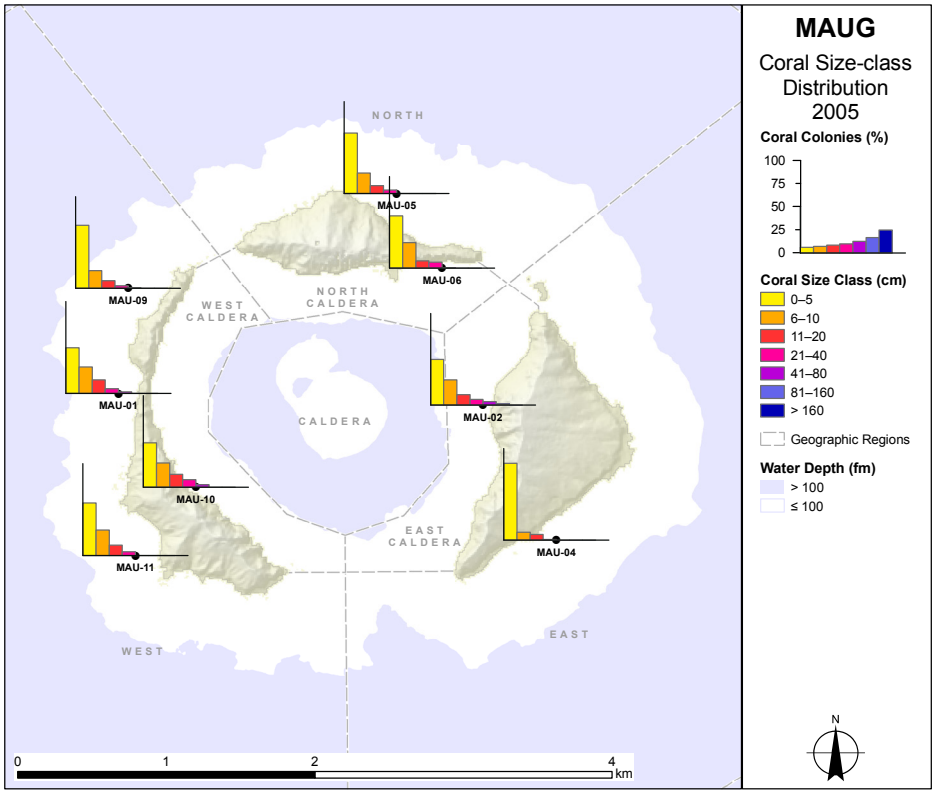


Figure 16.5.1n. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2005. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2005 to size corals.

During the 3 MARAMP survey years, corals in the smallest (0–5 cm) size class had the highest colony density recorded (Fig. 16.5.1p). The overall observed mean proportion of colonies at Maug that had a maximum diameter ≤ 5 cm increased from 50.5% in 2003 to 60% in 2005 and 62.7% in 2007. The increase between 2003 and 2005 may have resulted from recruitment, fragmentation of existing colonies, or both. Minor changes in overall and site-specific size-class distributions between 2005 and 2007 likely resulted from chance variation in the placement of individual quadrats.

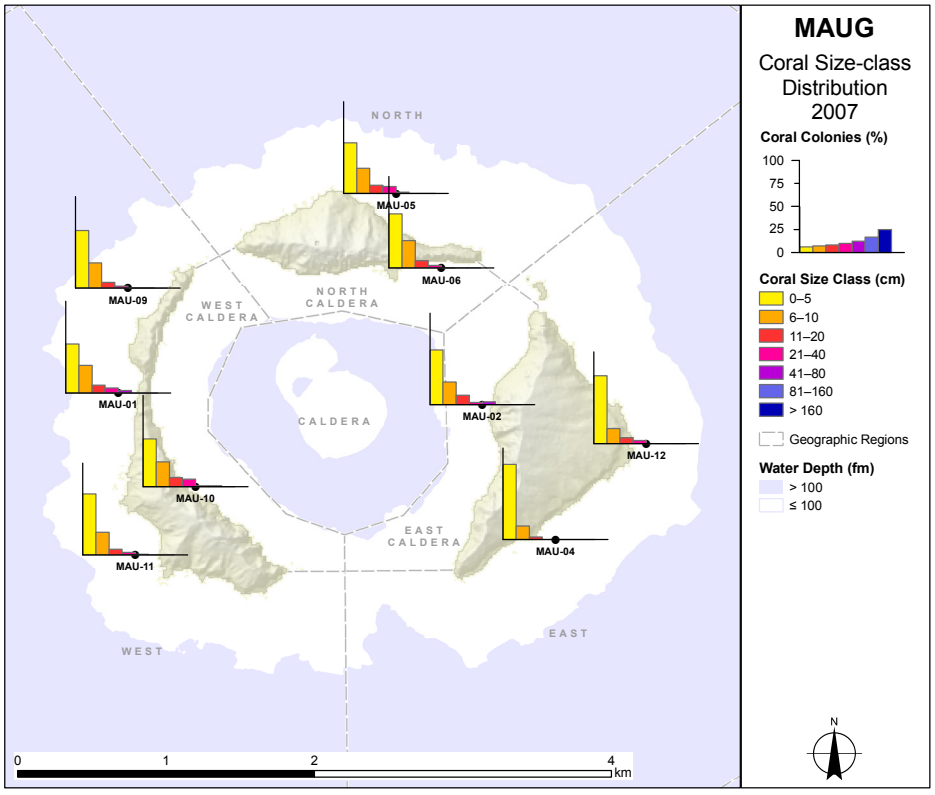


Figure 16.5.1o. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2007 to size corals.

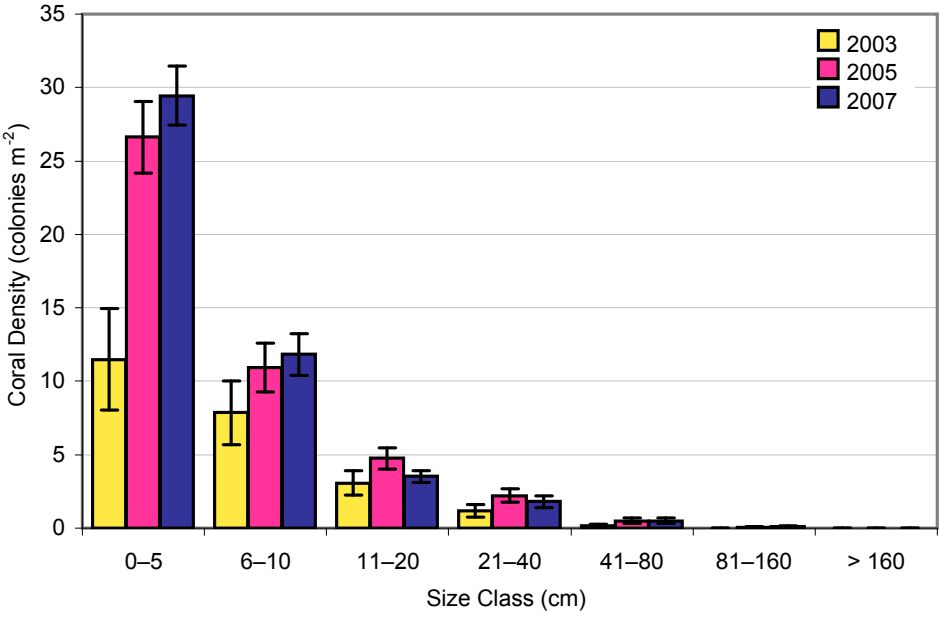


Figure 16.5.1p. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2003, 2005, and 2007. The quadrat method was used in all 3 years to size corals. Error bars indicate standard error (± 1 SE) of the mean.

16.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted using the quadrat method at 9 sites on forereef habitats at Maug, covering a total area of 2700 m^2. Surveys detected 17 cases of disease, translating to an overall mean prevalence of 0.02% (SE 0.01), excluding predation. The use of the quadrat method for coral-colony counts at all REA sites at Maug resulted in higher-than-expected coral-colony densities, and, therefore, lower-than-expected disease-prevalence values. Four major disease conditions were observed at Maug. In order of numerical abundance, these conditions were subacute tissue loss, skeletal growth anomalies, bleaching, and fungal infection. Of the 9 sites surveyed, 4 contained disease: MAU-02 in the east caldera region, MAU-05 in the north region, MAU-10 in the west caldera region, and MAU-11 in the west region (Figs. 16.5.2a and b; the values of overall disease prevalence shown in Figure 16.5.2a include predation). All 4 disease states and nearly 65% of cases were recorded at MAU-05.

More than 60% of the afflictions recorded at Maug were observed on corals of the genus *Porites*. Other disease-hosting coral genera included *Acropora*, *Astreopora*, *Montipora*, *Goniastrea*, *Goniopora*, and *Platygyra*. Afflictions involving subacute tissue loss were present at MAU-05 in the north region on *Porites* and *Montipora* with overall prevalence of 0.04% and at MAU-02 in the east caldera region on *Goniopora* with prevalence of 0.01%. Cases of bleaching were detected on *Porites* at MAU-05 and MAU-11 in the north and west regions and on *Platygyra* at MAU-10 in the west caldera region. Disease conditions involving skeletal growth anomalies were observed at MAU-05, MAU-02, and MAU-10 on a diverse assortment of coral genera, including *Porites*, *Acropora*, and *Astreopora*.

Cases of coral predation attributable to crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails, such as snails from the genus *Drupella*, were the highest at MAU-10 and MAU-06 in the west caldera and north caldera regions with prevalence values of nearly 0.10% and 0.07%. These relatively high levels of coral predation appeared to correspond with survey areas where observed stressed-coral cover exceeded 10% during towed-diver surveys in the west caldera region near MAU-10 and in the north caldera region adjacent to MAU-06 (Figs. 16.5.1e and 16.5.2a). For more information about crown-of-thorns seastars (COTS) observed at Maug, see Section 16.7: "Benthic Macroinvertebrates."

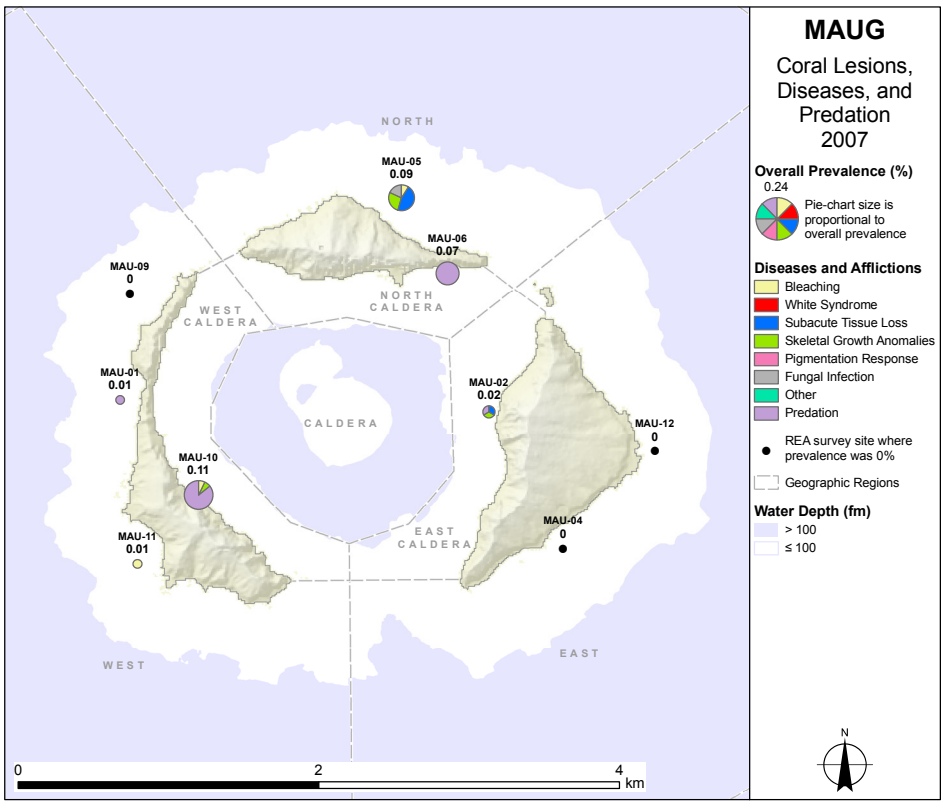


Figure 16.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie charts indicate disease-specific prevalence.

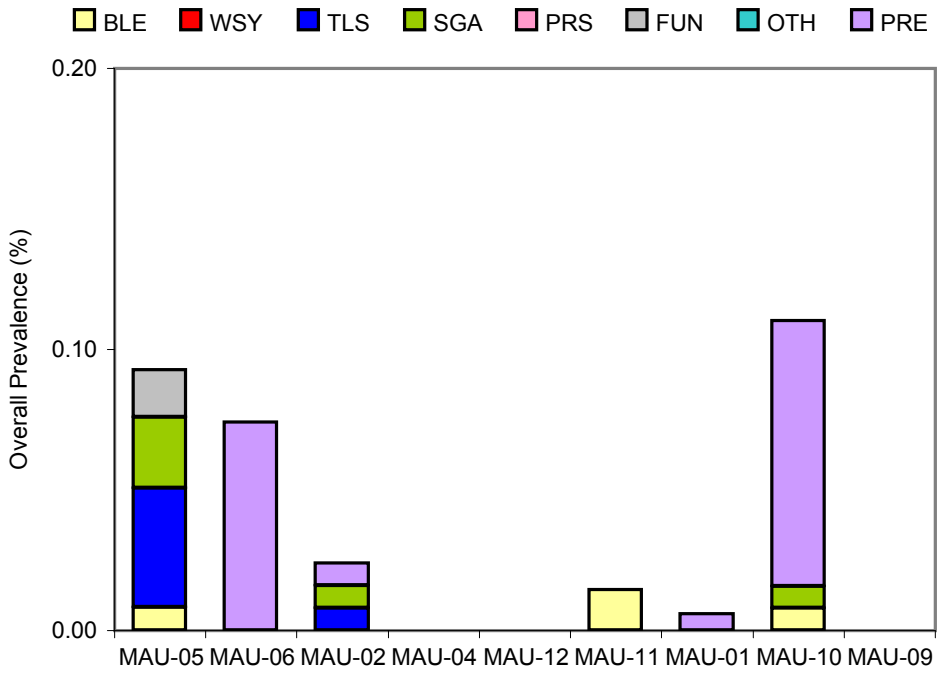


Figure 16.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesions of unknown etiology; PRE: predation by COTS or corallivorous snails.

16.6 Algae and Algal Disease

16.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the islands of Maug was 46% (SE 1.3). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 65%, within a range of 40.1%–75%, occurred on the shallow forereef in the west region off the northwestern coast of West Island (Fig. 16.6.1a, top left panel; for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). The habitat in this area consisted of continuous reef with areas of rock boulders and bedrock of medium-high complexity. Medium-low complexity and the second-greatest mean macroalgal cover of 59% was recorded for the igneous bedrock and rock boulder habitat in the east region off the southeastern coast of East Island. A survey off the southwestern coast of West Island also reported high macroalgal cover with a mean of 56% over spur-and-groove pavement. In general, values of mean macroalgal cover were slightly higher on exposed reefs on the outer flanks than on the sheltered reefs within the caldera. The greatest exception to this pattern occurred on the reefs in the north caldera region where macroalgal cover of 54% was recorded for rock boulder and bedrock habitat.

TOAD surveys completed at Maug during MARAMP 2003 were conducted at depths of 20–225 m. Analyses of TOAD video footage obtained from 5 surveys suggests that there were little or no macroalgae, at least as seen in images; however, a sixth survey conducted at depths of 60–120 m off the southwestern coast of West Island, did record infrequent patches of macroalgal cover of up to 100%.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Maug was 27% (SE 1.8). The survey with the highest mean macroalgal cover of 52%, within a range of 30.1%–75%, occurred off the southwestern coast of West Island over habitat of medium complexity (Fig. 16.6.1a, middle left panel). Around Maug, macroalgal cover generally was greater outside the caldera than within it. This difference was exemplified in the north region, off the northeastern coast of East Island, and off the northwestern coast of West Island, where greater-than-average values (49.5%, 36%, and 29.4%) of macroalgal cover were recorded. In the caldera, macroalgal-cover values were greatest for the survey conducted in the east caldera region with a mean of 26%. Each of the 3 other surveys conducted in the caldera reported low values of macroalgal cover that never exceeded 9.8%.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats around Maug was 8% (SE 0.7). Two surveys reported the highest mean macroalgal cover of 10%, within a range of 1.1%–30%: 1 around the western end of North Island and 1 off the southwestern coast of West Island (Fig 16.6.1a, bottom left panel). The habitats observed during these surveys had predominantly light spur-and-groove continuous reef of medium to medium-high complexity and were dominated by species of the calcified green algal genus *Halimeda*. Off the northeastern coast of East Island, mean macroalgal cover of 8.3% was recorded and species of *Halimeda* and the red algal genus *Liagora* were frequently observed. All remaining surveys reported less-than-average levels of macroalgal cover.

During MARAMP 2007, 9 REA benthic surveys of forereef habitats at Maug were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 0% to 24.5% with an overall mean of 5% (SE 2.7). The REA survey with the highest macroalgal cover occurred in the east region at MAU-04 (Fig. 16.6.1b). Macroalgal cover from all other surveys was ≤ 9.8%. No macroalgae were recorded at 3 sites: MAU-01 and MAU-09 in the west region and MAU-10 in the west caldera region.

Turf-algal cover from these REA benthic surveys ranged from 22.5% to 57.8% with an overall mean of 41% (SE 3.7). The highest turf-algal cover occurred in the east region at MAU-04. Relatively high turf-algal-cover values of 55.9%, 46.1%, and 40.2% were found in the east region at MAU-12, north caldera region at MAU-06, and west region at MAU-01. The lowest turf-algal cover was recorded in the east caldera region at MAU-02.

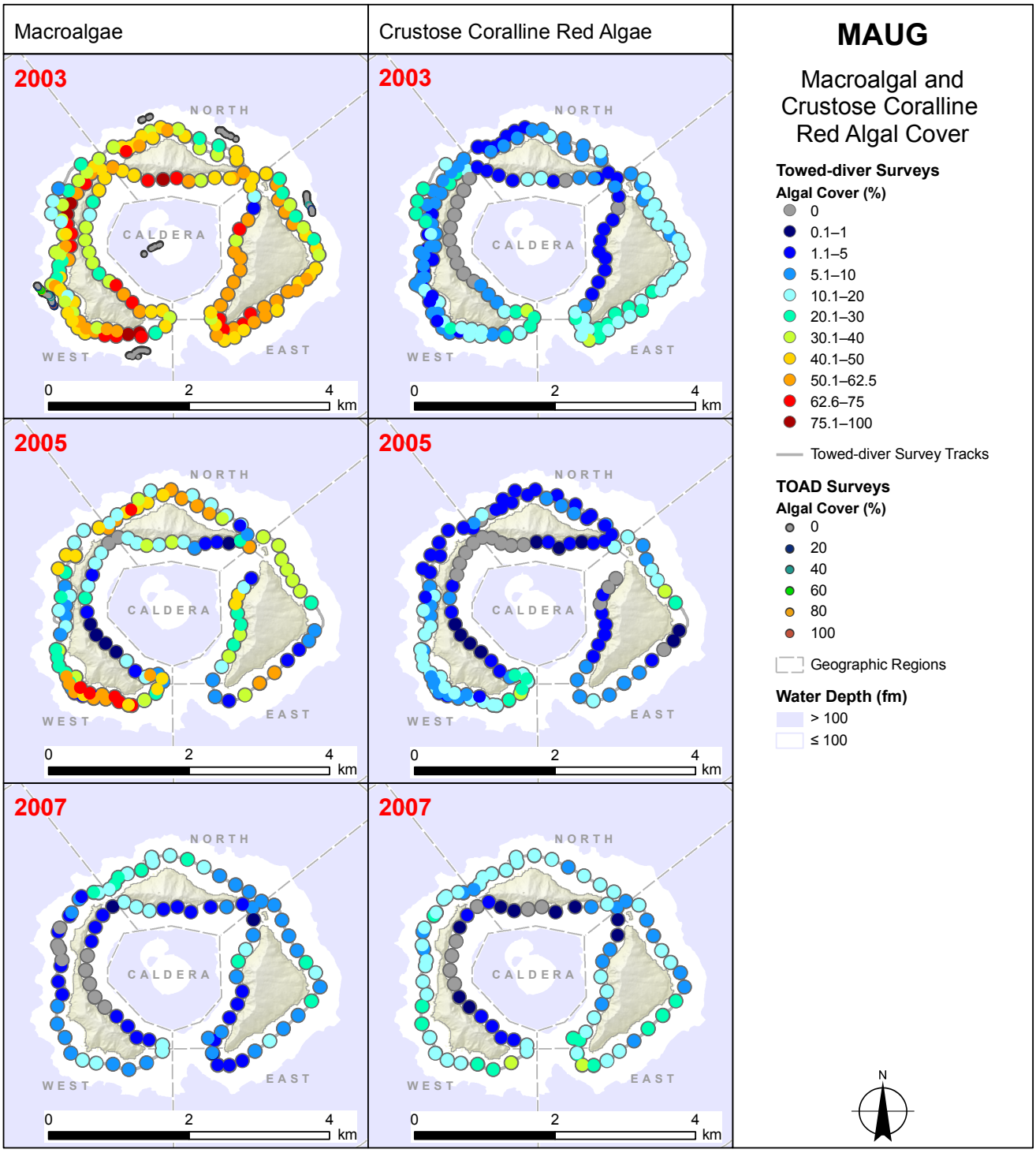


Figure 16.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Maug was 10% (SE 0.6). The survey with the highest mean crustose-coralline-red-algal cover of 20%, within a range of 10.1%–40%, occurred along the southeastern coast of East Island (Fig. 16.6.1a, top right panel). A survey around the southern coast of West Island that wrapped into the west caldera region reported the second-greatest cover value for crustose coralline red algae with a mean of 18%. Other survey areas of relatively high cover with means of 15% included the northeastern coast of East Island and the northwestern coast of West Island.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Maug was 8% (SE 0.8). The survey with the highest mean crustose-coralline-red-algal cover of 17%, within a range of 5.1%–75%, occurred around the southern end of West Island (Fig. 16.6.1a, middle right panel). The majority of this survey reported mean cover of ~ 12%; however, a single 5-min segment along a stretch of continuous reef reported cover of 62.6%–75%. The survey conducted along the northeastern coast of East Island also reported greater than average cover with a mean of 16%. Cover values for crustose coralline red algae were low in all caldera regions.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Maug was 12% (SE 0.8) %. The survey with the highest mean crustose-coralline-red-algal cover of 22%, within a range of 5.1%–40%, occurred on the southeastern coast of East Island where continuous reef of medium-high complexity was the dominant structural feature (Fig. 16.6.1a, bottom right panel). A survey conducted along the southwestern coast of West Island also reported high cover values for crustose coralline red algae with a mean of 21%. Habitat complexity for spur-and-groove reef along the southwestern coast of West Island ranged from medium-high to very high. The forereef habitat along the northwestern coasts off both North and West Islands exhibited above-average cover of ~ 13.9%. All other towed-diver surveys conducted in 2007 reported below-average values for cover of crustose coralline red algae.

During MARAMP 2007, 9 REA benthic surveys of forereef habitats at Maug were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 10.8% with an overall mean of 4% (SE 1.2). The REA survey with the highest crustose-coralline-red-algal cover occurred in the west region at MAU-01 (Fig. 16.6.1b). No crustose coralline red algae were recorded at both MAU-06 in the north caldera region and MAU-10 in the west caldera region.

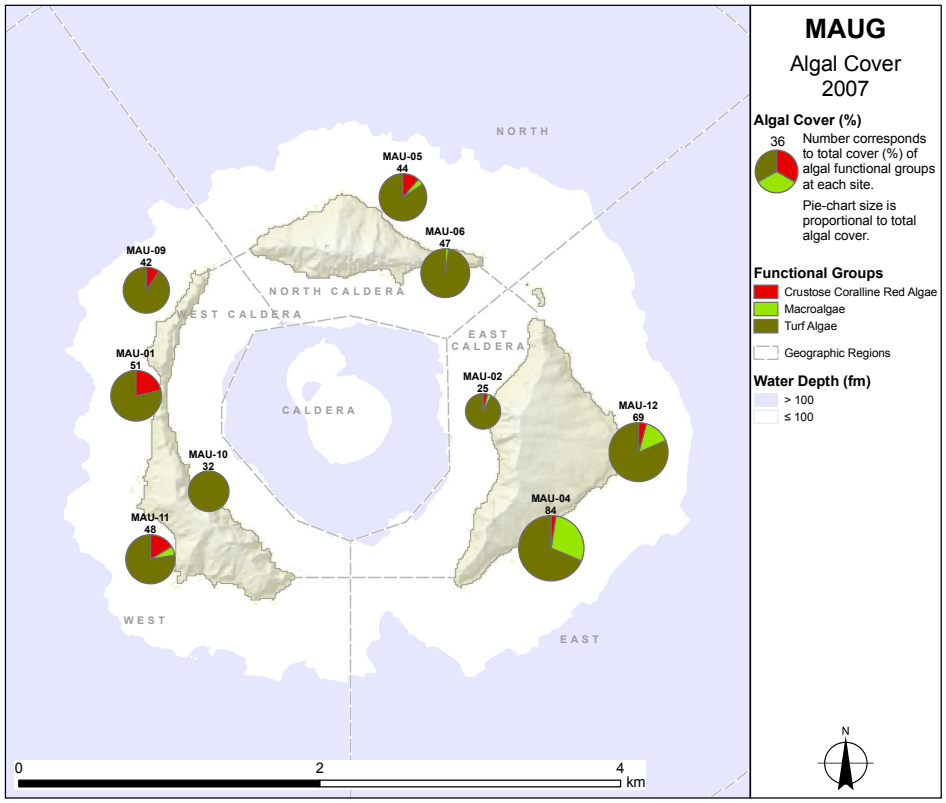


Figure 16.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method at Maug during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, overall mean cover of macroalgal populations around Maug, based on towed-diver surveys of forereef habitats, varied by 19% (Fig. 16.6.1c). When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Estimates of macroalgal cover collected around Maug show no recognizable patterns. In general, macroalgal populations were greater in surveys off the southwestern coast of West Island than in other areas surveyed around the islands of Maug. The southwestern reef experienced less change, when surveys in other areas reported substantial changes for the same time period.

Populations of crustose coralline red algae around Maug, based on towed-diver surveys on forereef habitats, varied as much as 5% in average cover of the benthos between MARAMP survey years. Estimates of cover values for crustose coralline red algae decreased 3% overall around Maug from 2003 to 2005. This observed decline was most apparent on the southeastern reefs off East Island with a decrease of 16% from 2003 to 2005. Conversely, crustose-coralline-red-algal cover around Maug increased 5% from 2005 to 2007. This increase was seen most on the southeastern reefs off East Island, where estimates made in 2003 and 2007 were similar. Across the 3 MARAMP survey years, populations of crustose coralline red algae were less abundant in the caldera than on the outer flanks of Maug.

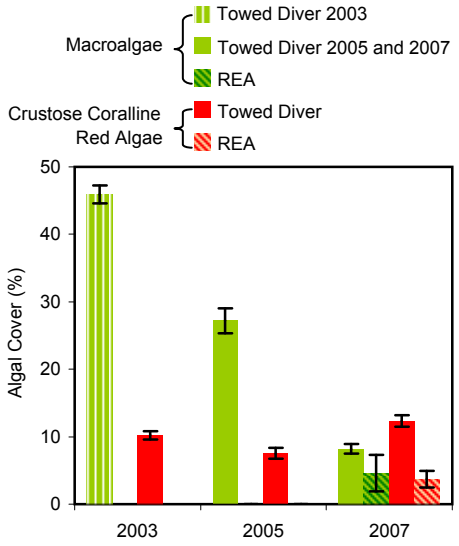


Figure 16.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted at Maug in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 8 sites on forereef habitats at Maug. In the field, 19 macroalgal genera (5 red, 10 green, and 4 brown), containing at least 22 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. MAU-05 in the north region had the highest macroalgal generic diversity with 9 genera, containing 9 species, documented in the field. The lowest macroalgal generic diversity was found at MAU-03 in the east caldera region with 3 species representing 3 genera recorded.

Species of the red algal genus *Amphiroa* were common at Maug in 2003, occurring in 24% of sampled photoquadrats, although they only occurred in 83.3%, 58.3% and 50% of photoquadrats sampled at sites in the caldera, MAU-03, MAU-06, and MAU-10 (Fig. 16.6.1d). Species of *Halimeda* were also common around these islands, occurring in 18.8% of sampled photoquadrats overall and at 6 of the 8 sites surveyed. At MAU-05 in the north region, species of *Halimeda* occurred in 66.7% of sampled photoquadrats. Species of the green algal genera *Neomeris* and *Ventricaria* were common members of

the algal community at Maug, occurring in 10.4% and 11.5% of photoquadrats sampled and at 5 and 6 of the sites surveyed. Species of the brown algal genus *Lobophora* occurred at 5 of the sites surveyed and in 25% of sampled photoquadrats. For the remaining 17 taxa tentatively identified in the field, no distinctive spatial patterns of distribution were observed at Maug.

Turf algae and crustose coralline red algae were both common in 2003, occurring in 83% and 43% of photoquadrats sampled at Maug. However, the occurrence of both functional groups varied widely with a range of 8.3%–91.7% for crustose coralline red algae and a range of 16.7%–100% for turf algae (Fig. 16.6.1d). Cyanobacteria were less common, occurring in 8.3%–41.7% of sampled photoquadrats at 6 of the 8 sites surveyed.

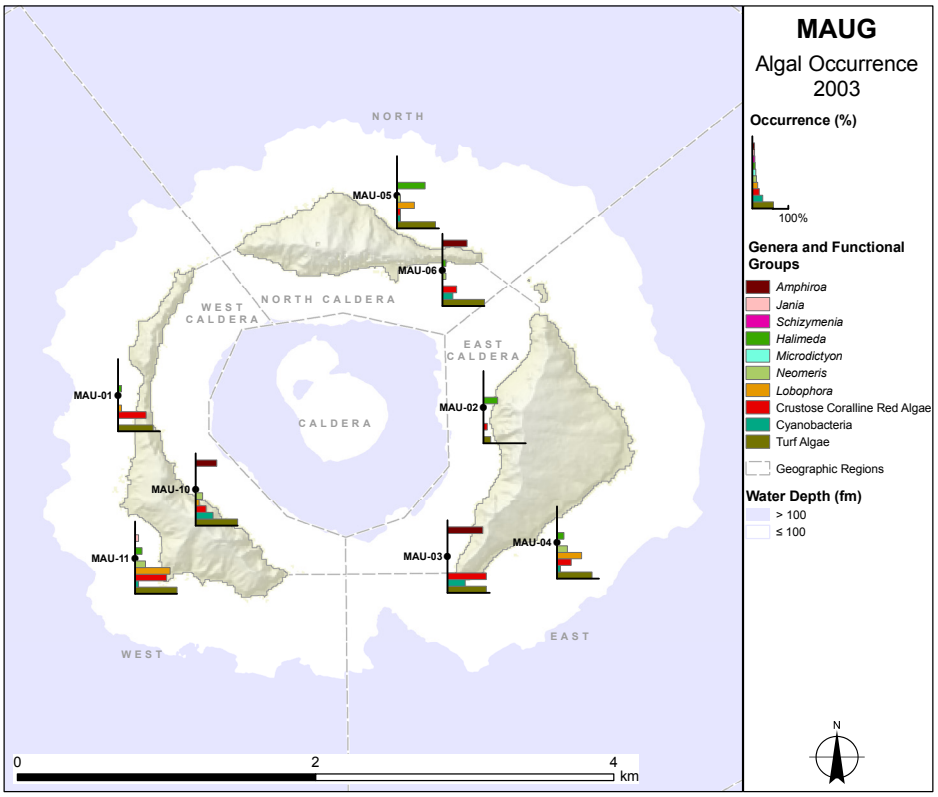


Figure 16.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA algal surveys of forereef habitats conducted at Maug during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2005, REA benthic surveys were conducted at 8 sites on forereef habitats at Maug. In the field, 16 macroalgal genera (5 red, 8 green, and 3 brown), containing at least 17 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, nongeniculate calcified red algae, and cyanophytes—were observed. MAU-11, located in the west region southwest of West Island, had the highest macroalgal generic diversity with 9 genera, containing 10 species, documented in the field. The lowest macroalgal generic diversity was found at MAU-10 off the southeast coast of West Island with 4 species representing 4 genera recorded.

Species of the genera *Halimeda, Dictyosphaeria, Jania, Lobophora*, and *Ventricaria* were common at most sites surveyed at Maug in 2005, occurring in 32.4%, 11.1%, 12%, 38.9%, and 10.2% of sampled photoquadrats. Species of *Halimeda*, found at 7 of the 8 sites surveyed and 8.3%–100% of photoquadrats sampled at Maug, were the dominant macroalgae at most sites (Fig. 16.6.1e). Species of *Lobophora,* occurring at 6 of the 8 sites surveyed and in 8.3%–75% of sampled photoquadrats, were also a prominent part of the macroalgal community at Maug. Of the 16 macroalgal species tentatively identified in the field, only a select few showed any spatial pattern of distribution. Species of *Halimeda* were most prevalent at outer flank sites in the north and west regions of Maug, with the highest occurrence documented at MAU-05 off the northern coast of North Island. *Lobophora variegata* was commonly observed at forereef sites on the outer flanks at Maug, occurring in 50%–75% of sampled photoquadrats, but, in the caldera, was recorded only at a single site, occurring in 8.3% of photoquadrats sampled at MAU-02. Species of *Amphiroa* were found only at the caldera sites, MAU-02, MAU-06, and MAU-10, occurring in 25%–83.3% of photoquadrats sampled at these sites.

Turf algae and crustose coralline red algae were both common in 2005, occurring in 81% and 49% of photoquadrats sampled at Maug. Prevalent at all sites surveyed in 2005, turf-algal communities were recorded in 66.7%–100% of sampled photoquadrats (Fig. 16.6.1e). Communities of crustose coralline red algae were also found at all sites but with larger variability, occurring in 16.7%–100% of sampled photoquadrats. A minor component of the algal community at Maug were cyanobacteria, which were documented at 5 of the 8 sites surveyed and in 8.3%–25% of photoquadrats sampled at outer flank sites MAU-01 and MAU-05 and caldera sites MAU-02, MAU-06, and MAU-10. Nongeniculate, calcified, branched red algae were a minor component of the algal community at 2 sites, occurring in 25% and 8.3% of photoquadrats sampled at MAU-01 and MAU-09 in the west region.

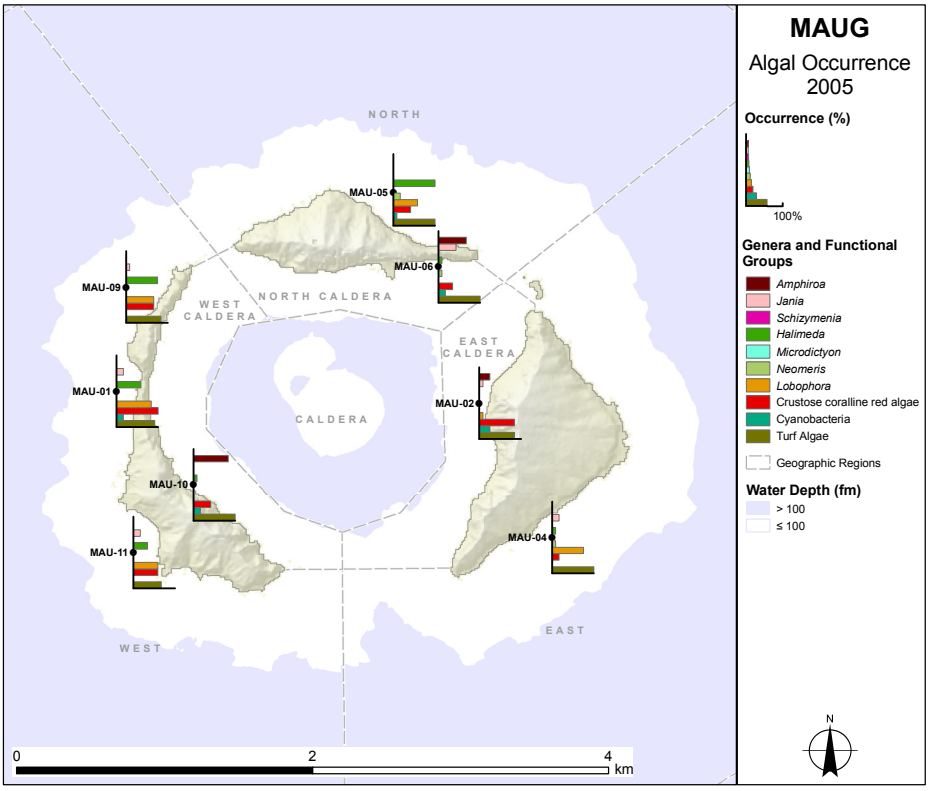


Figure 16.6.1e. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2007, REA benthic surveys were conducted at 9 sites on forereef habitats at Maug. In the field, 21 macroalgal genera (7 red, 8 green, and 6 brown), containing at least 21 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. MAU-04, MAU-05, and MAU-10 in the east, north, and west caldera regions had the highest macroalgal generic diversity with 11 genera, containing 11 species, documented in the field at each site. The lowest macroalgal generic diversity was found at MAU-09 off the northwest coast of West Island with 6 species representing 6 genera recorded.

Species of the genera *Jania* and *Schizymenia* were common at every site surveyed at Maug in 2007, occurring in 33.3% and 47.2% of sampled photoquadrats. Species of the macroalgal genera *Halimeda, Dictyosphaeria, Neomeris, Lobophora, Peyssonnelia, Turbinaria*, and *Ventricaria* were found at most sites surveyed around these islands, occurring in 32.4%, 7.4%, 17.6%, 10.2%, 6.5%, 8.3%, and 6.5% of sampled photoquadrats (Fig. 16.6.1f). For all but a few of the 21 macroalgal species tentatively identified in the field, no distinctive spatial patterns of distribution were observed at Maug. Species of *Schizymenia* were generally more prevalent at the forereef sites on the outer flanks, occurring in 33.3%–83.3% of photoquadrates sampled at MAU-01, MAU-04, MAU-05, MAU-09, MAU-11, and MAU-12, than at sites in the caldera, occurring in 8.3%–25% of photoquadrats sampled at MAU-02, MAU-06, and MAU-10. Only found at the outer flank sites, species of *Halimeda* occurred in 8.3%–83.3% of phtotoquadrats sampled at MAU-01, MAU-04, MAU-05, MAU-09, MAU-11, and MAU-12. Species of *Amphiroa* were found in 16.7%–58.3% of photoquadrats sampled at caldera sites and in 8.3% of photoquadrats sampled at MAU-01, an outer flank site in the west region.

Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2007, occurring in 80%, 66%, and 44% of photoquadrats sampled at Maug. Cyanobacteria were more prevalent at the outer flank sites with 33.3%–91.7% occurrence than at caldera sites with 8.3%–16.7% occurrence (Fig. 16.6.1f). No other spatial patterns of distribution were apparent for these functional groups.

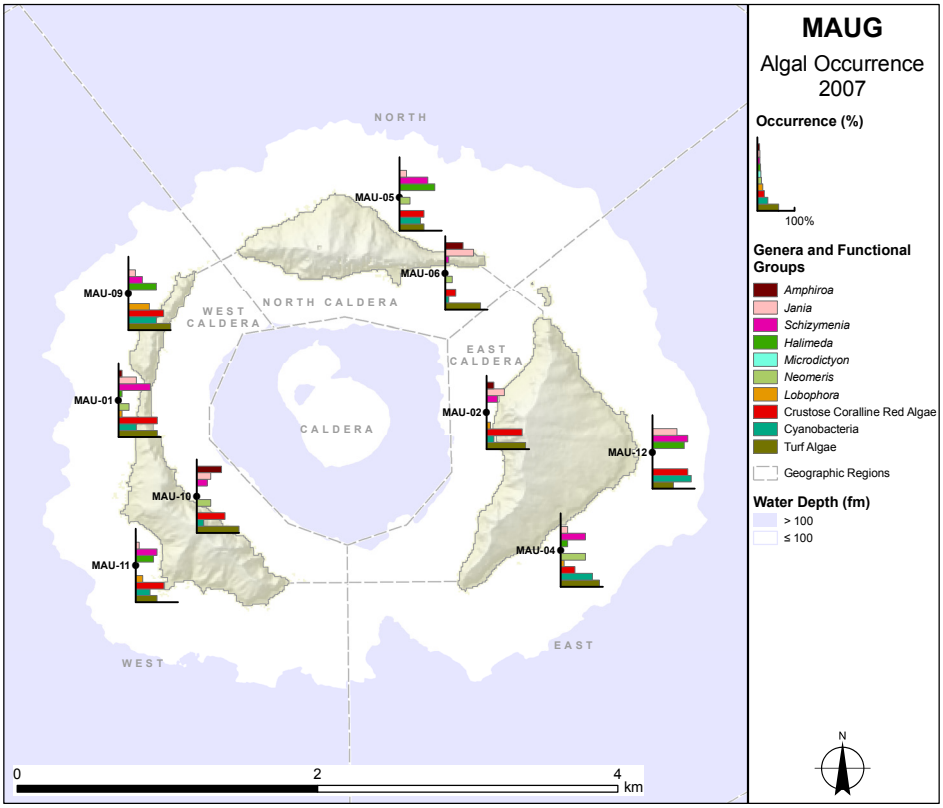


Figure 16.6.1f. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

The number of macroalgal genera recorded at Maug decreased from 19 to 16 genera between MARAMP 2003 and 2005 but increased to 21 genera during MARAMP 2007. Differences in survey effort and other factors likely can account for these small changes in estimated macroalgal diversity (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Species of *Halimeda* were consistently the most prominent members of the macroalgal community across the 3 MARAMP survey years, with average occurrence of 18.8%–32.4% (Fig. 16.6.1g). A steady increase in abundance was observed for *Amphiroa*, also among the most prevalent genera with an aver-

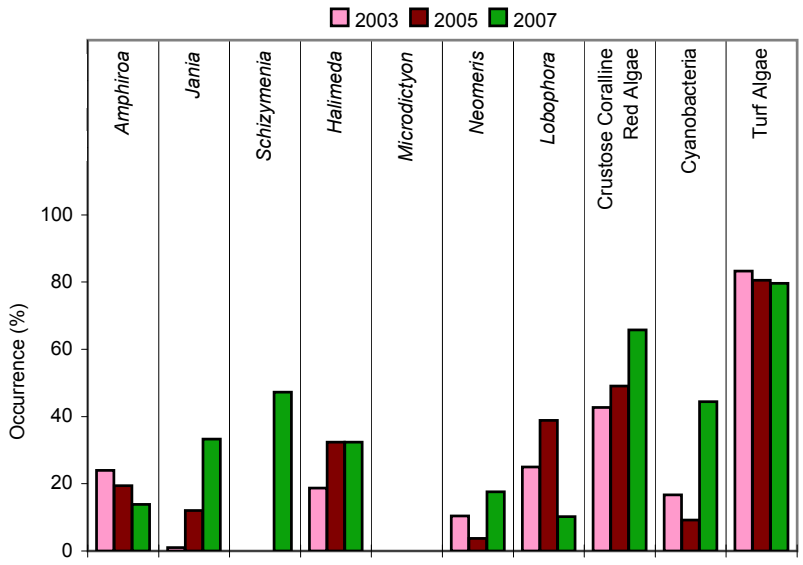


Figure 16.6.1g. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Maug during MARAMP 2003, 2005, and 2007.

age occurrence of 13.9%–24% in the MARAMP survey periods. Increases in occurrence were also recorded for species of *Jania* and *Turbinaria*, which were found in 1%–33.3% and 3.1%–8.3% of photoquadrats sampled over the 3 MARAMP survey years. Species of the green algal genera *Rhipidosiphon* and *Ventricaria* were found in 2.1% and 11.5% of sampled photoquadrats in 2003 but in only 0% and 6.5% of sampled photoquadrats in 2007. Species of the green algal genus *Caulerpa*, also prominent components of the algal community during the 3 MARAMP survey years, were found in 7.4%–10.2% of sampled photoquadrats, but no distinct patterns in abundance were observed for this genus.

Turf algae occurred in 79.6%–83.3% of photoquadrats sampled at Maug during MARAMP 2003, 2005, and 2007 with slight decreases in abundance (Fig. 16.6.1g). Crustose coralline red algae were found in 42.7%–65.7% of photoquadrats sampled in the 3 MARAMP survey years with an increase in abundance each year. No patterns in abundance were observed at Maug for cyanobacteria, which occurred in 9.3%–44.4% of sampled photoquadrats.

16.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 9 sites on forereef habitats at Maug. These surveys covered a total reef area of 2700 m^2 and detected 12 cases. These numbers translate to a low overall mean density of 0.4 cases 100 m^{-2} (SE 0.3), compared to survey results for other areas in the Mariana Archipelago. Only 1 major type of coralline-algal disease was observed at Maug: coralline lethal orange disease, present at 3 of the 9 sites surveyed. The greatest density of 2.3 cases 100 m^{-2} was found at MAU-01 in the west region, and much lower disease densities were recorded at the other 2 sites (Fig. 16.6.2a).

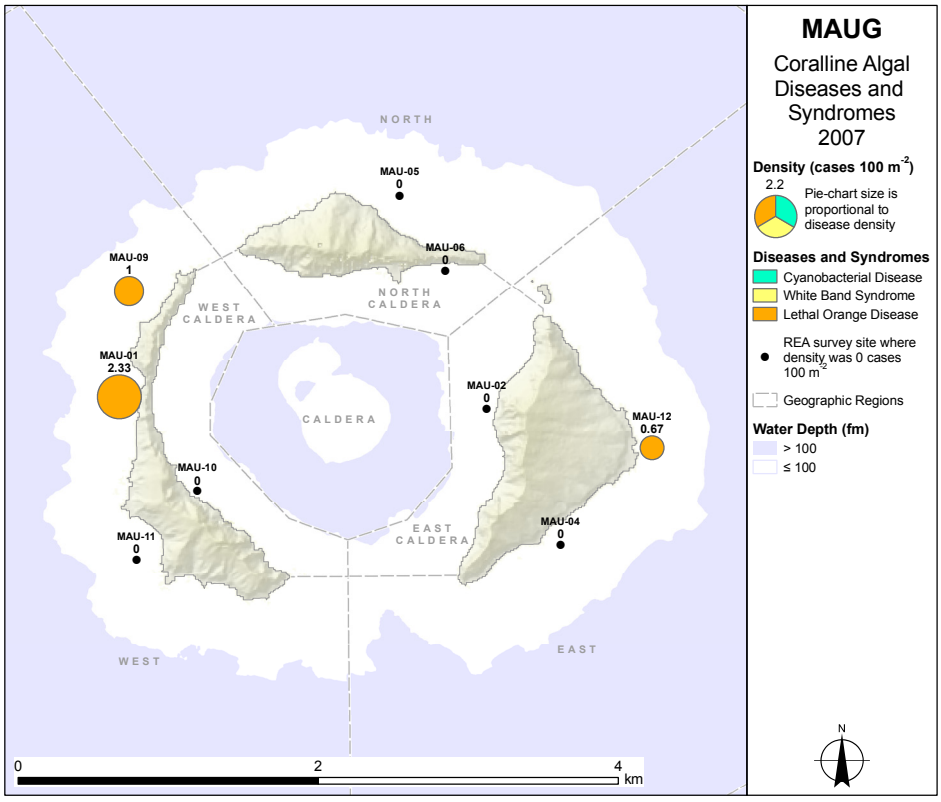


Figure 16.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats at Maug during MARAMP 2007. The color-coded portions of the pie charts indicate disease-specific density.

16.7 Benthic Macroinvertebrates

16.7.1 Benthic Macroinvertebrate Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the islands of Maug through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 8 REA surveys and 16 towed-diver benthic surveys were conducted around Maug, and, in 2005, 8 REA surveys and 13 towed-diver benthic surveys were performed. Data are reported for 9 REA surveys and 10 towed-diver benthic surveys conducted in 2007. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. For each target organism, temporal patterns of overall mean macroinvertebrate density on forereef habitats around Maug—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 16.7.1d, h, l, and p).

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at 7 of the 8 REA sites surveyed and in 14 of the 16 towed-diver surveys conducted around Maug (Fig. 16.7.1a). The overall mean density of giant clams from REA surveys was 19.75 organisms 100 m^{-2} (SE 9.42), and the overall mean density from towed-diver surveys was 0.52 organisms 100 m^{-2} (SE 0.13). Survey results suggest that giant clams were most abundant at REA site MAU-06 in the north caldera region with 74 organisms 100 m^{-2}, followed by MAU-01 with 44 organisms 100 m^{-2}.

Among all towed-diver surveys conducted around Maug in 2003, the survey completed along the southern shore of North Island had the highest mean density of giant clams with 3.27 organisms 100 m^{-2}; segment densities from this survey ranged from 0.07 to 8.92 organisms 100 m^{-2} (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). The second-greatest mean density of giant clams from a towed-diver survey was 1.59 organisms 100 m^{-2}, recorded in the west caldera region; segment densities ranged from 0.05 to 4.09 organisms 100 m^{-2}. The third-greatest mean density of giant clams from a towed-diver survey was 1.43 organisms 100 m^{-2}, recorded in the west region; segment densities ranged from 0 to 10.99 organisms 100 m^{-2}.

During MARAMP 2005, giant clams were observed at 5 of the 8 REA sites surveyed and in 12 of the 13 towed-diver surveys conducted around Maug (Fig. 16.7.1b). The overall mean density of giant clams from REA surveys was 5.25 organisms 100 m^{-2} (SE 3.13), and the overall mean density from towed-diver surveys was 0.38 organisms 100 m^{-2} (SE 0.08). Survey results suggest giant clams were most prevalent at MAU-06 in the north caldera region with 26 organisms 100 m^{-2}, followed by MAU-10 off the eastern coast of West Island with 8 organisms 100 m^{-2}.

Among all towed-diver surveys conducted around Maug in 2005, the survey completed in the north caldera region had the highest mean density of giant clams with 1.33 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 4.92 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 1.01 organisms 100 m^{-2}, recorded on a survey that started in the west caldera region along the northeast-facing coast of West Island and ended in the north caldera region along the southwest-facing coast of North Island; segment densities ranged from 0 to 2.64 organisms 100 m^{-2}.

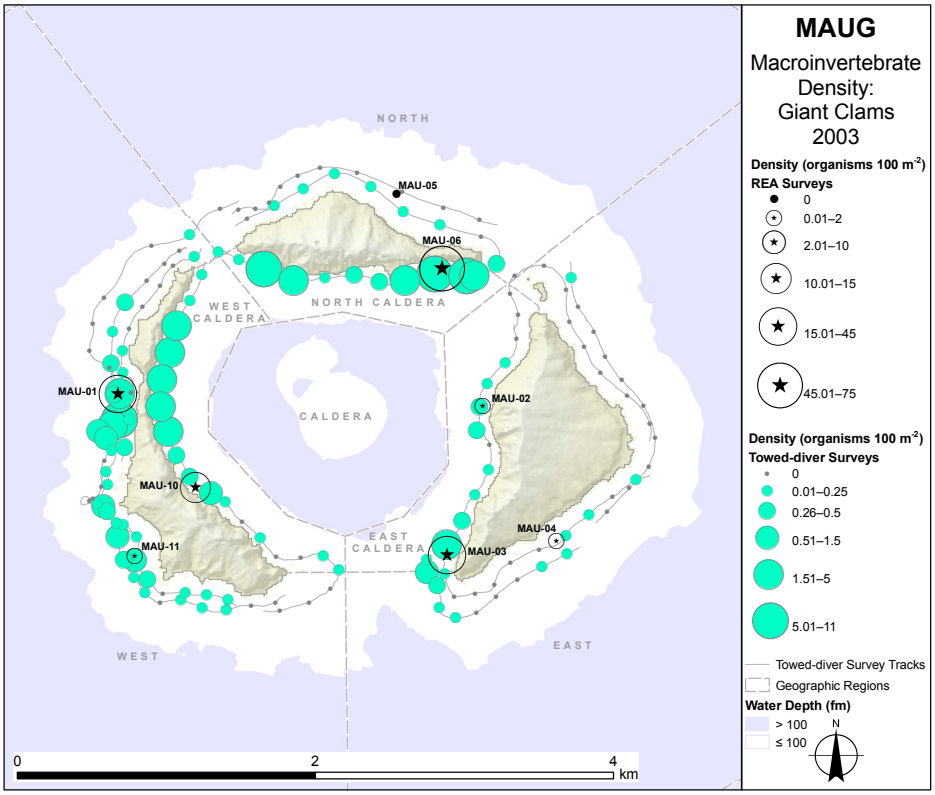


Figure 16.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003.

During MARAMP 2007, giant clams were observed at all 9 REA sites surveyed and in 10 towed-diver surveys conducted around Maug (Fig. 16.7.1c). The overall mean density of giant clams from REA surveys was 5.41 organisms 100 m^{-2} (SE 2.3), and the overall mean density from towed-diver surveys was 0.27 organisms 100 m^{-2} (SE 0.05). Survey results suggest giant clams were most abundant at MAU-01 in the west region with 17.67 organisms 100 m^{-2}, followed by MAU-06 in the north caldera region with 17.33 organisms 100 m^{-2}.

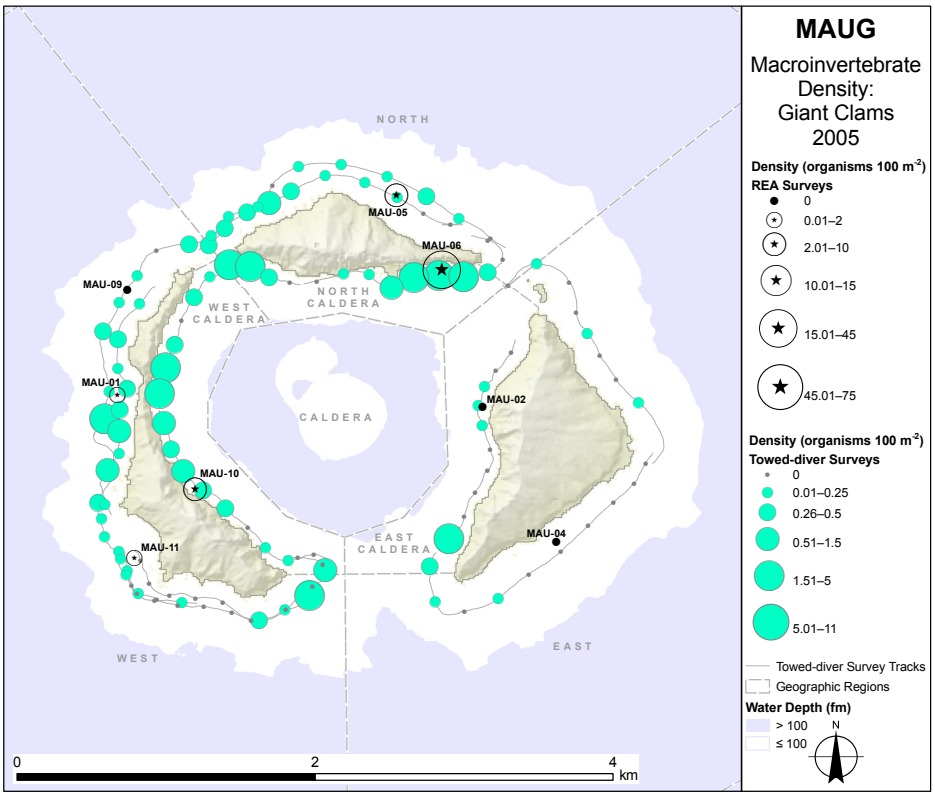


Figure 16.7.1b. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005.

Among all towed-diver surveys conducted around Maug in 2007, the survey completed along the southern coast of North Island in the north caldera region had the highest mean density of giant clams with 0.81 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 3.52 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.51 organisms 100 m^{-2}, recorded along the western shore of West Island; segment densities ranged from 0.05 and 1.33 organisms 100 m^{-2}.

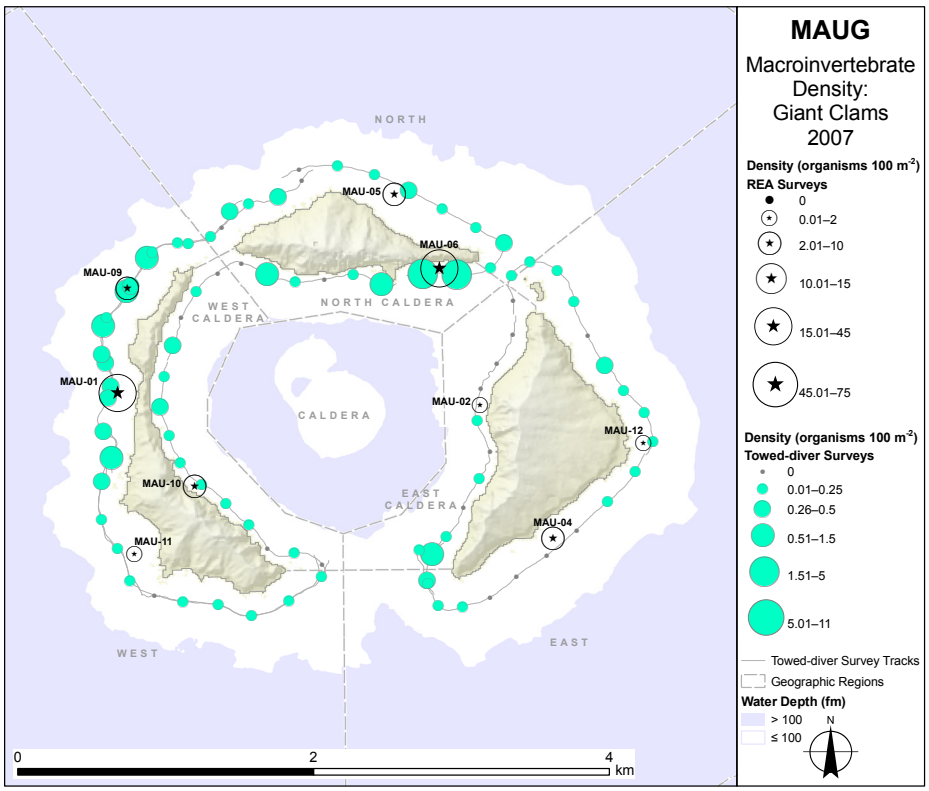


Figure 16.7.1c. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007.

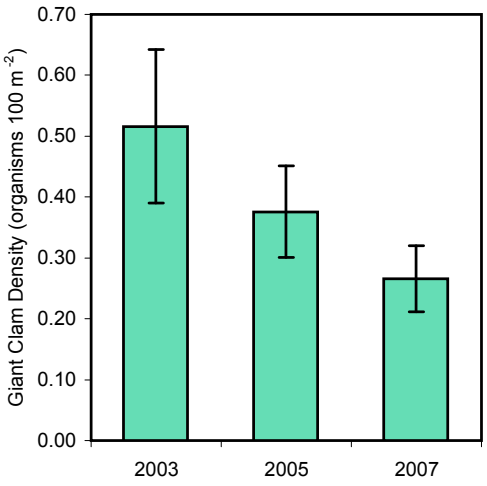


Figure 16.7.1d. Temporal comparison of mean densities (organisms m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested high abundance of giant clams around Maug during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago. In the 3 survey years, the greatest densities of giant clams were recorded in the north caldera region along the southern coast of North Island. The overall observed mean density of giant clams at Maug was lower in 2007 than in 2003 (Fig. 16.7.1d). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Crown-of-thorns Seastars (COTS)

During MARAMP 2003, no crown-of-thorns seastars (*Acanthaster planci*) were observed at the 8 REA sites surveyed at Maug, but 5 of the 16 towed-diver surveys had recordings of COTS (Fig. 16.7.1e), with an overall mean density of 0.045 organisms 100 m^{-2} (SE 0.017). Among all towed-diver surveys conducted around Maug, the survey completed in the west caldera region had the highest mean density of COTS with 0.685 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.569 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.011 organisms 100 m^{-2}, recorded along the southern shore of East Island; segment densities ranged from 0 to 0.111 organisms 100 m^{-2}.

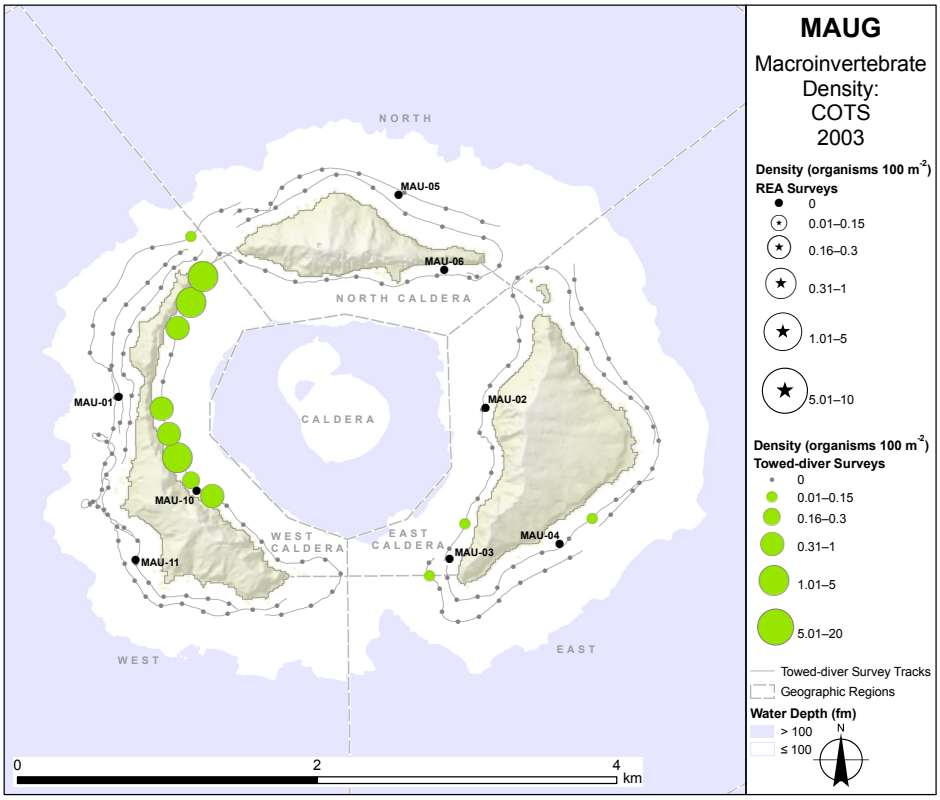


Figure 16.7.1e. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003.

During MARAMP 2005, no COTS were observed at the 8 REA sites surveyed at Maug, but 6 of the 13 towed-diver surveys had recordings of COTS (Fig. 16.7.1f), with an overall mean density of 0.015 organisms 100 m^{-2} (SE 0.005). Among all towed-diver surveys conducted around Maug, the survey completed in the west caldera region had the highest mean density with 0.097 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.41 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.048 organisms 100 m^{-2}, recorded in the north caldera region; segment densities ranged from 0 to 0.173 organisms 100 m^{-2}.

During MARAMP 2007, no COTS were observed at the 9 REA sites surveyed at Maug, but 5 of 10 towed-diver surveys had recordings of COTS (Fig. 16.7.1g), with an overall mean density of 0.013 organisms 100 m^{-2} (SE 0.004). Among all towed-diver surveys conducted around Maug, the survey completed in the west caldera region had the highest mean density with 0.048 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.294 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.026 organisms 100 m^{-2}, recorded during a survey that stretched from the north caldera region along the southern coast of North Island to the west caldera region along the northeastern coast of West Island; segment densities ranged from 0 to 0.156 organisms 100 m^{-2}.

Figure 16.7.1f. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005.

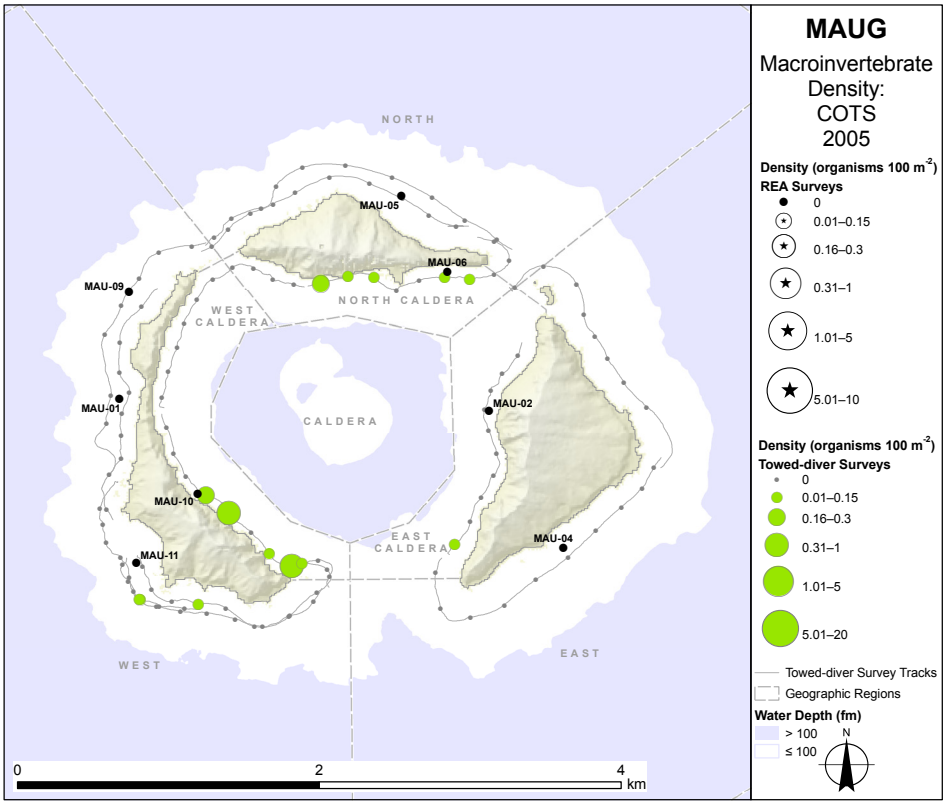
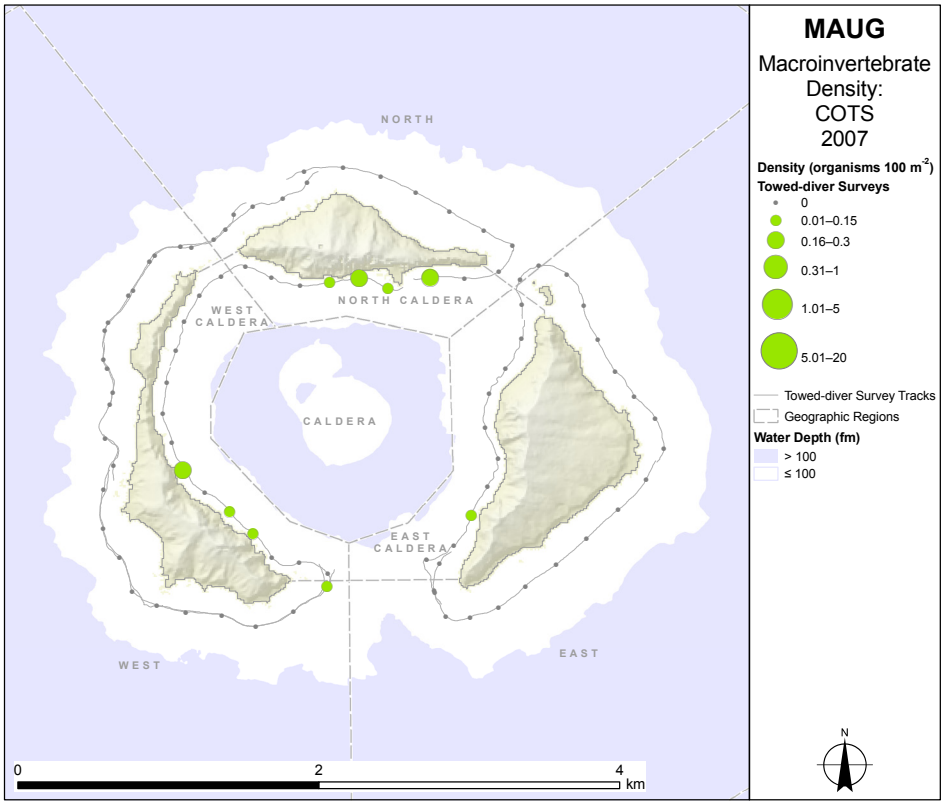


Figure 16.7.1g. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007.



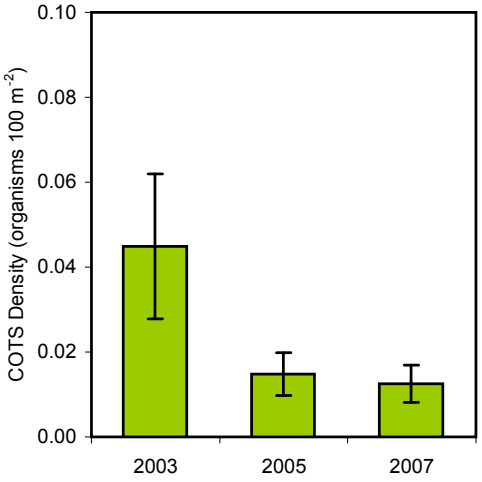


Figure 16.7.1h. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested relatively low daytime densities of COTS around Maug during MARAMP 2003, 2005, and 2007, compared to other sites surveyed in the Mariana Archipelago, with the exception of one localized area in 2003. The overall observed mean density of COTS was higher in 2003 than in 2005 and 2007 (Fig. 16.7.1h). Given that these corallivorous seastars can decimate a reef, understanding whether their observed densities signify an outbreak is important. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure established for using scuba divers to conduct MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms per km^2 (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of density and considering each towed-diver survey as an individual reef area, only one localized area was found during MARAMP 2003 with relatively high densities of COTS that suggest that they were undergoing an outbreak. This area was in the west caldera region, where densities of COTS from towed-diver surveys were estimated at 0.685 organisms 100 m^{-2}. However, the highest density of COTS was observed in this coral-rich area along the eastern coast of West Island during each of the 3 MARAMP survey years. Therefore, a relatively large COTS population likely resides naturally in this west caldera region, and the observed high densities are not indicative of an outbreak population.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at only 3 of the 8 REA sites surveyed and in 10 of the 16 towed-diver surveys conducted around Maug (Fig. 16.7.1i). The overall mean density of sea cucumbers from REA surveys was 0.5 organisms 100 m^{-2} (SE 0.267), and the overall mean density from towed-diver surveys was 0.028 organisms 100 m^{-2} (SE 0.013). Survey results suggest that sea cucumbers were most abundant at MAU-10 in the west caldera region with 2

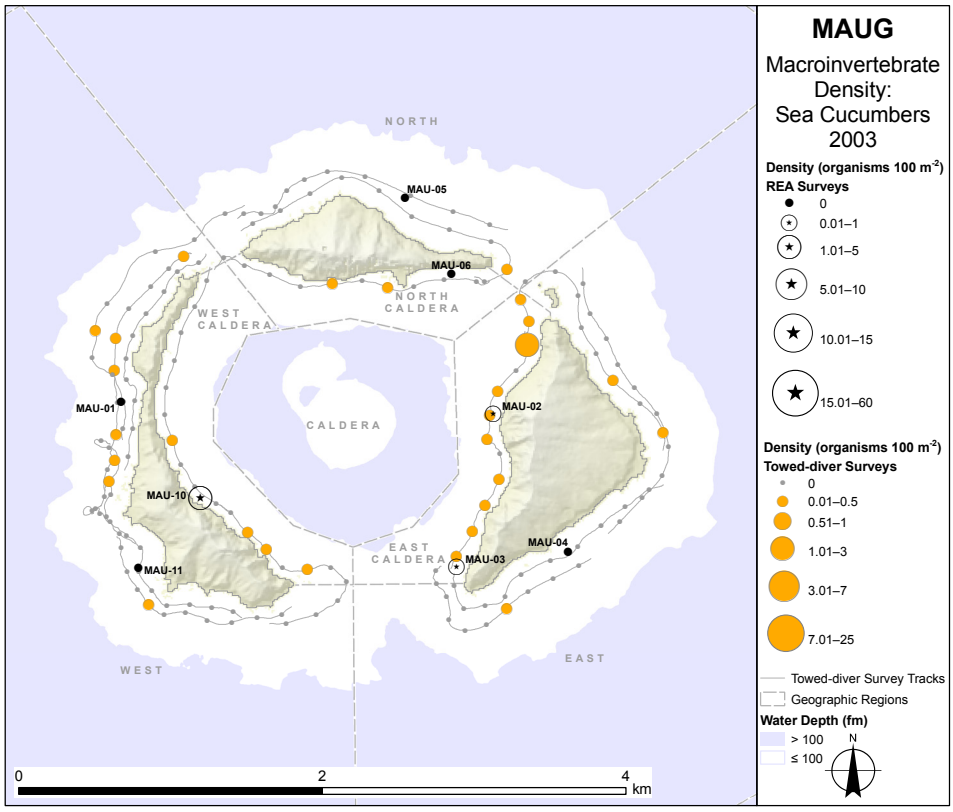


Figure 16.7.1i. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003.

organisms 100 m^{-2}; both of these sea cucumbers were from the genus *Holothuria*. Among all towed-diver surveys conducted around Maug, the survey completed in the east caldera region had the highest mean density of sea cucumbers with 0.253 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.959 organisms 100 m^{-2}.

During MARAMP 2005, sea cucumbers were observed at only 1 of the 8 REA sites surveyed and in 11 of the 13 towed-diver surveys conducted around Maug (Fig.16.7.1j). MAU-02 in the east caldera region had a density of sea cucumbers with 1 organism 100 m^{-2}; this sea cucumber was from the genus *Pearsonothuria.* The overall mean density of sea cucumbers from towed-diver surveys was 0.055 organisms 100 m^{-2} (SE 0.022). Among all towed-diver surveys conducted around Maug, the survey completed in the north caldera region had the highest mean density of sea cucumbers with 0.267 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.462 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.150 organisms 100 m^{-2}, recorded around the southern end of West Island; segment densities ranged from 0 to 0.419 organisms 100 m^{-2}.

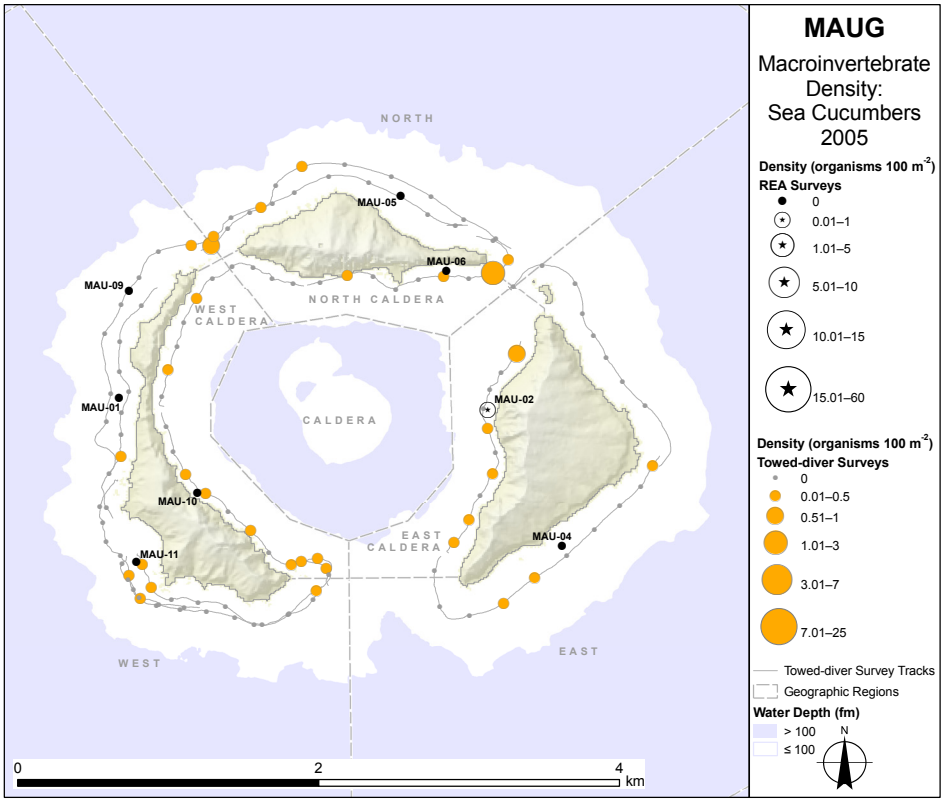


Figure 16.7.1j. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005.

During MARAMP 2007, sea cucumbers were observed at only 1 of the 9 REA sites surveyed but recorded in 10 of the towed-diver surveys conducted around Maug (Fig.16.7.1k). MAU-10 in the west caldera region had a density of 4 organisms 100 m^{-2}, and 83% of these sea cucumbers were from the genus *Holothuria.* Two other genera were represented at Maug: *Actinopyga* and *Pearsonothuria.* The overall mean density of sea cucumbers from towed-diver surveys was 0.043 organisms 100 m^{-2} (SE 0.008). Among all towed-diver surveys conducted around Maug, the survey completed in the east caldera region had the highest density of sea cucumbers with 0.124 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.403 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.079 organisms 100 m^{-2}, recorded in the west caldera region; segment densities ranged from 0 to 0.343 organisms 100 m^{-2}.

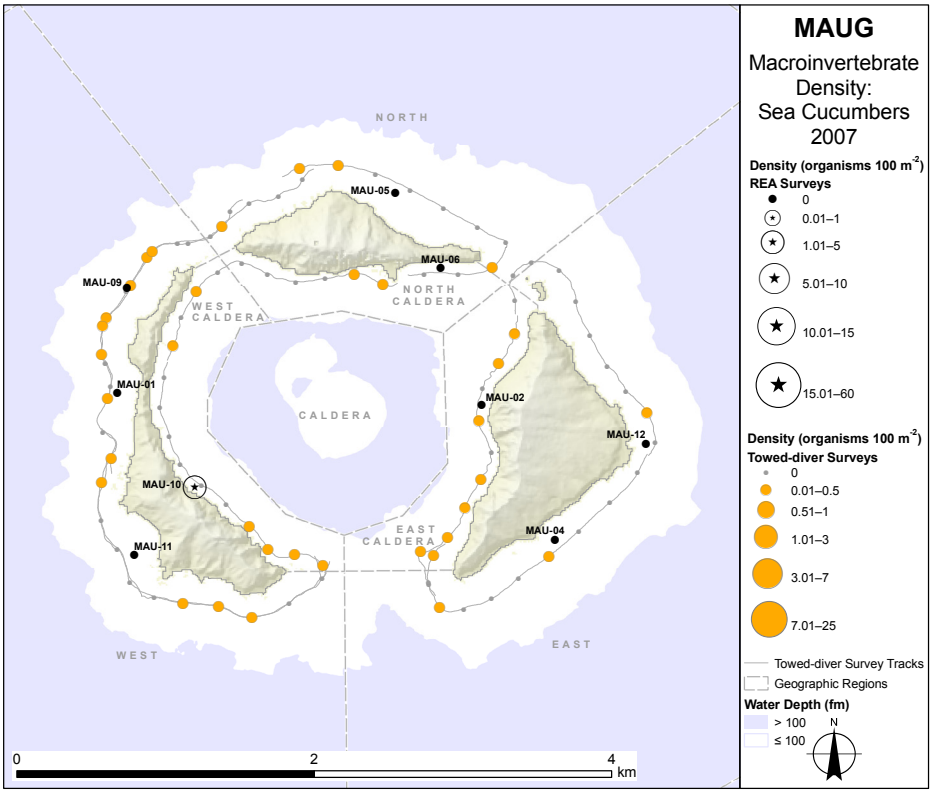


Figure 16.7.1k. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007.

Towed-diver surveys suggested relatively low daytime abundance of sea cucumbers around Maug during MARAMP 2003, 2005, and 2007 (Fig. 16.7.1l), relative to the rest of the Mariana Archipelago. Although densities were low in the 3 MARAMP survey years, the highest concentrations of sea cucumbers around Maug were observed in the caldera regions. Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

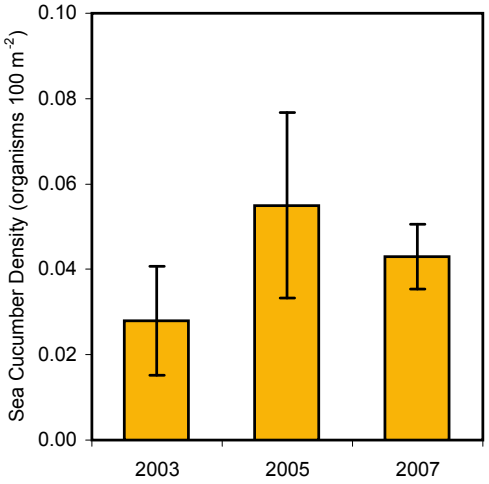


Figure 16.7.1l. Temporal comparison of sea cucumber mean densities (organisms m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Urchins

During MARAMP 2003, sea urchins were observed at 6 of the 8 REA sites surveyed and in all 16 of the towed-diver surveys conducted around Maug (Fig. 16.7.1m). The overall mean density of sea urchins from REA surveys was 18.37 organisms 100 m^{-2} (SE 10.68), and the overall mean density from towed-diver surveys was 4.70 organisms 100 m^{-2} (SE 0.89). Survey results suggest that sea urchins were most abundant at MAU-05 in the north region with 76 organisms 100 m^{-2}. Rock-boring urchin species from the genus *Echinostrephus* were the dominant macroinvertebrates at this site, accounting for 79% of urchins recorded. Other genera represented at this site included *Echinothrix* and *Echinometra.* MAU-04 in the east region had the second-greatest density with 57 organisms 100 m^{-2}. Also at this site, rock-boring urchin species from the genus *Echinostrephus* were the dominant macroinvertebrates, accounting for 87.7% of sea urchins recorded. Species of *Echinothrix* were also observed at MAU-04.

Among all towed-diver surveys conducted around Maug in 2003, the survey completed in the east region had the highest mean density of 27.85 organisms 100 m^{-2}; segment densities from this survey ranged from 10.38 to 49.41 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 23.03 organisms 100 m^{-2}, recorded along the southwestern shore of West Island; segment densities ranged from 0 to 55.13 organisms 100 m^{-2}.

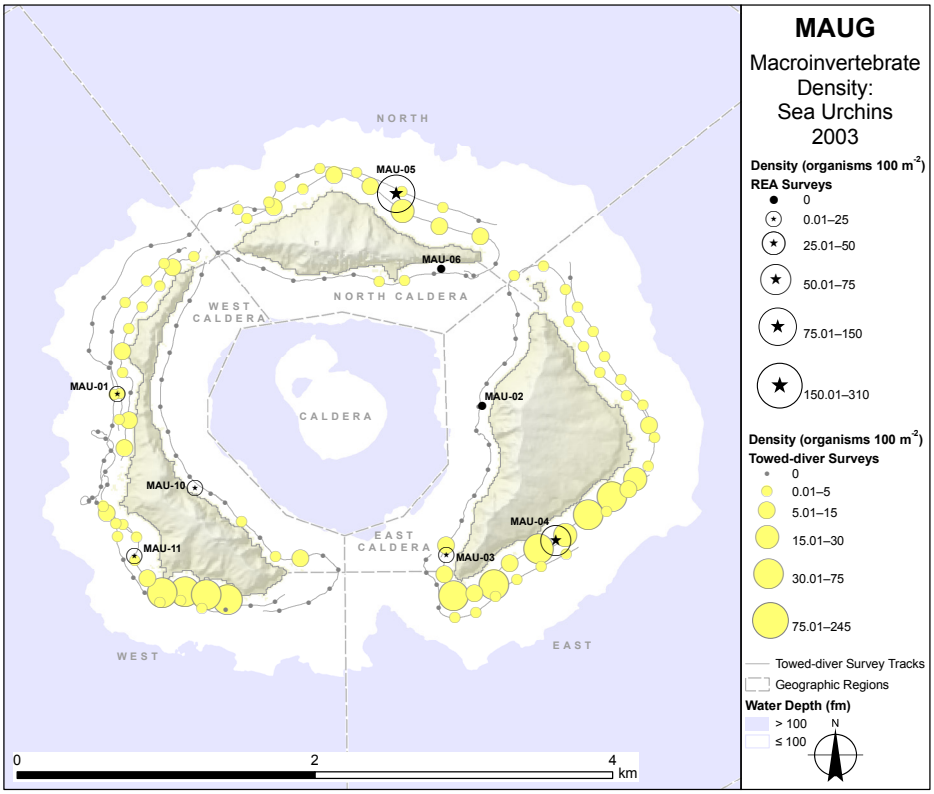


Figure 16.7.1m. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003.

During MARAMP 2005, sea urchins were observed at 5 of the 8 REA sites surveyed and in 10 of the 13 towed-diver surveys conducted around Maug (Fig. 16.7.1n). The overall mean density from REA surveys was 2.5 organisms 100 m^{-2} (SE 1.24), and the overall mean density from towed-diver surveys was 3.97 organisms 100 m^{-2} (SE 0.97). Survey results suggest that sea urchins were most abundant at MAU-04 in the east region with a mean density of 9 organisms 100 m^{-2}, with 79% of these sea urchins belonging to the rock-boring genus *Echinostrephus*. Species of *Echinothrix* were also observed at MAU-04.

Among all towed-diver surveys conducted around Maug in 2005, the survey completed along the southwestern coast of West Island had the highest mean density of sea urchins with 19.45 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 64.57 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 18.49 organisms 100 m^{-2}, recorded in the north region; segment densities ranged from 0 to 42.64 organisms 100 m^{-2}.

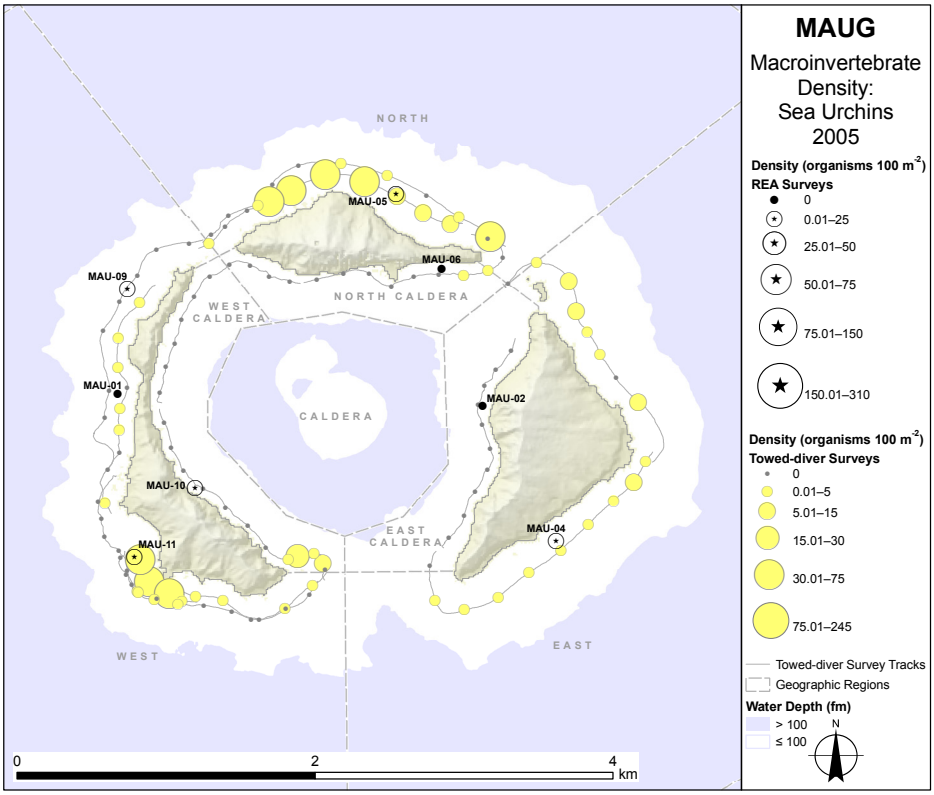


Figure 16.7.1n. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005.

During MARAMP 2007, sea urchins were observed at 6 of the 9 REA sites surveyed and in 8 of 10 towed-diver surveys conducted around Maug (Fig. 16.7.1o). The overall mean density for REA surveys was 16.96 organisms 100 m^{-2} (SE 10.78), and the overall mean density from towed-diver surveys was 1.83 organisms 100 m^{-2} (SE 0.31). Survey results suggest that sea urchins were most abundant at MAU-04 in the east region with 100.33 organisms 100 m^{-2}, with 99% of these

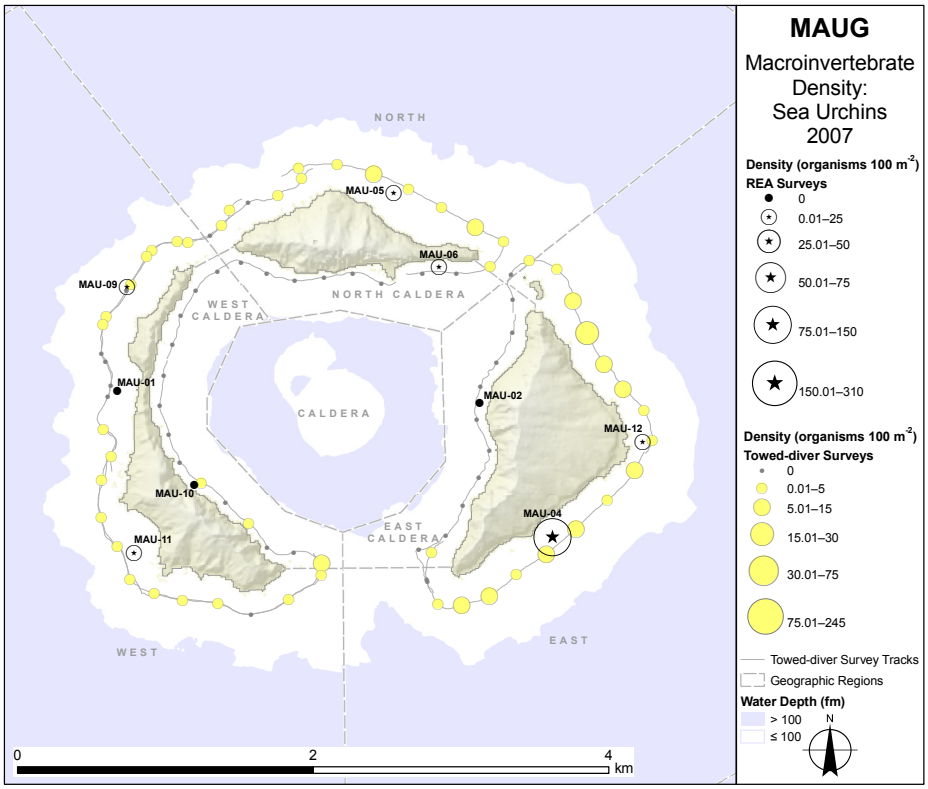


Figure 16.7.1o. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007.

sea urchins belonging to the rock-boring genus *Echinostrephus*. MAU-05 had the second-greatest density of sea urchins with 22.33 organisms 100 m^{-2}, with 98% of these sea urchins also belonging to the rock-boring genus *Echinostrephus*. The only other genus represented from REA surveys was *Echinothrix*.

Among all towed-diver surveys conducted around Maug in 2007, the survey completed along the southeastern coast of East Island had the highest mean density of sea urchins with 5.28 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 14.05 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 5.25 organisms 100 m^{-2}, recorded along the northeastern coast of East Island; segment densities ranged from 0 to 15.56 organisms 100 m^{-2}.

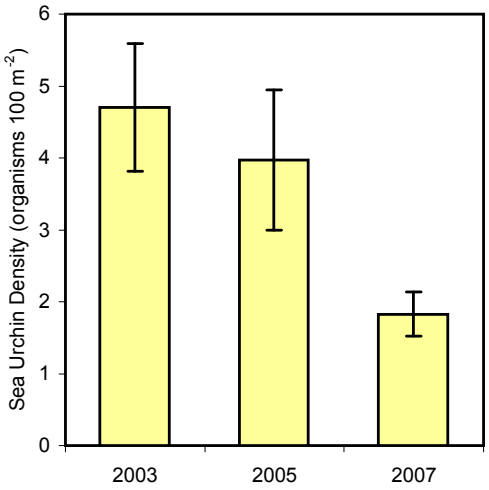


Figure 16.7.1p. Temporal comparison of mean densities (organisms m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested low daytime abundance of sea urchins around Maug, compared to the rest of the Mariana Archipelago, with the exception of the survey areas along the southern coasts of both East and West Islands and in the north region. The overall observed mean density of sea urchins was lower in 2007 than in 2003 and 2005 (Fig. 16.7.1p). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). The highest sea urchin densities around Maug were observed during the MARAMP 2003 and 2005 towed-diver surveys conducted the closest to shore. These shallower surveys were not repeated during MARAMP 2007, and this change in survey effort is a likely cause of the observed decline in overall sea urchin density in 2007.

16.8 Reef Fishes

16.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 16 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the islands of Maug. Surveys circumnavigated all 3 of the islands that compose Maug, and multiple surveys were conducted on the forereef slopes at Maug (Fig. 16.8.1a). The overall estimated mean biomass of large fishes around Maug, calculated as weight per unit area, was 1.61 kg 100 m^{-2} (SE 0.31), a moderately high value compared to other survey areas in the Mariana Archipelago. Snappers (Lutjanidae) and sharks (Carcharhinidae and Ginglymostomatidae) contributed 39% and 30% (0.62 and 0.49 kg 100 m^{-2}) of overall large-fish biomass. The twinspot snapper (*Lutjanus bohar*) was the major snapper species by biomass, while the grey reef shark (*Carcharhinus amblyrhynchos*) was the major shark species. Of the 90 sharks observed in 2003, 61 were grey reef sharks. Other shark species recorded were the whitetip reef shark (*Triaenodon obesus*) and tawny nurse shark (*Nebrius ferrugineus*). Observed large-fish biomass was highest in the east region, where sharks and snappers were common. Additionally, a large school of bigeye trevally (*Caranx sexfaciatus*) was observed in the north region with numerous individuals exhibiting spawning behavior.

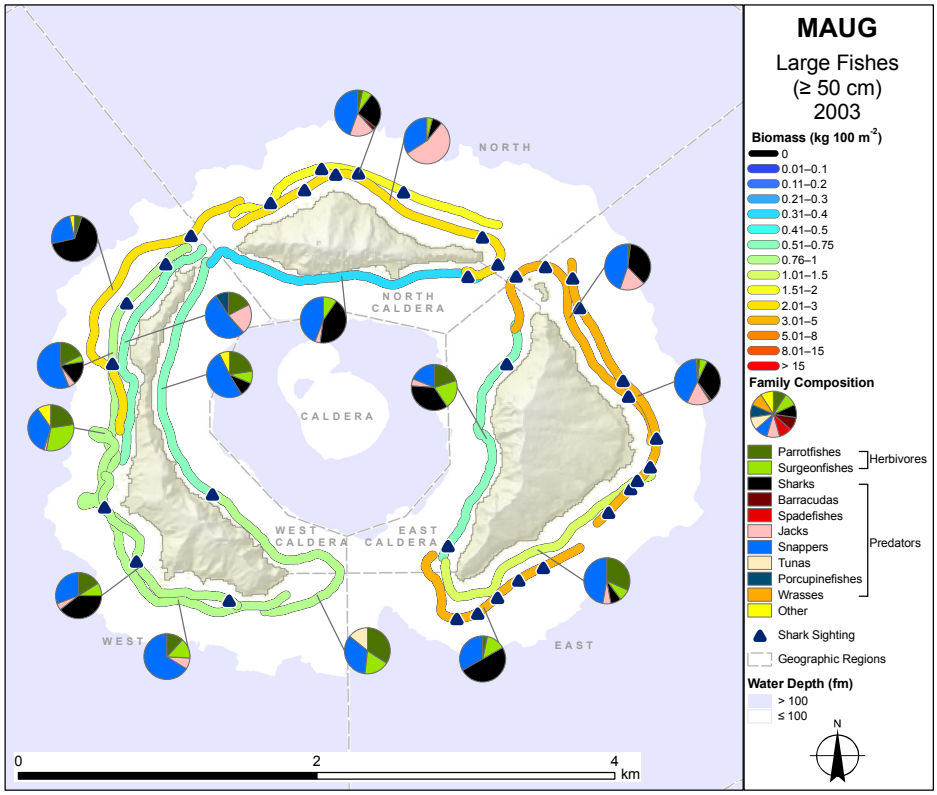


Figure 16.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Maug during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which they are shown.

During MARAMP 2005, 12 towed-diver surveys for large fishes (≥ 50 cm TL) were conducted in forereef habitats around Maug. The overall estimated mean biomass of large fishes around these islands was 0.85 kg 100 m^{-2} (SE 0.16). Reef sharks and jacks (Carangidae) contributed 53% and 19% (0.45 and 0.16 kg 100 m^{-2}) of overall mean large-fish biomass. In 2005, 86 sharks were observed, primarily on the outer flanks of these islands, and the most abundant shark species were the

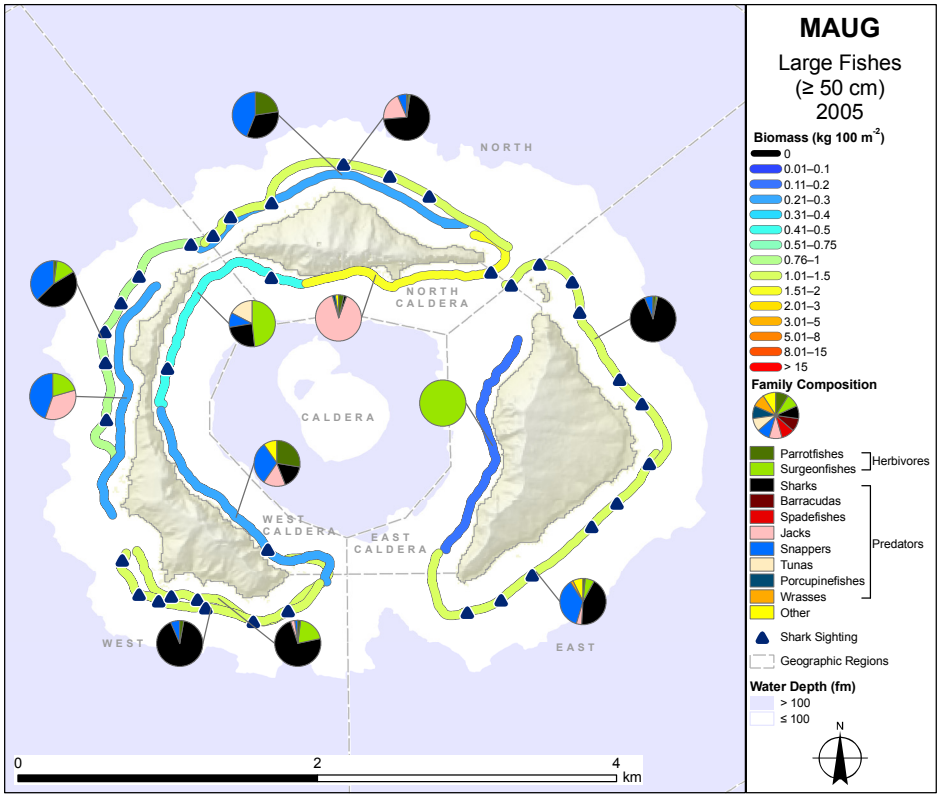


Figure 16.8.1b. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Maug during MARAMP 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which they are shown.

whitetip reef shark and grey reef shark (Fig. 16.8.1b). The bigeye trevally was the major jack species by biomass, a result of the sighting of a large school in the channel between North and East Islands (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). The twinspot snapper and black-and-white snapper (*Macolor niger*) were also common in 2005.

During MARAMP 2007, 9 towed-diver surveys for large fishes (≥ 50 cm TL) were conducted in forereef habitats around Maug (Fig. 16.8.1c). The overall estimated mean biomass of large fishes around these islands was 0.72 kg 100 m^{-2} (SE 0.11). Reef sharks and snappers together contributed 67% or 0.48 kg 100 m^{-2} of overall large-fish biomass. Snappers alone accounted for 38% of overall large-fish biomass, and the twinspot snapper had the highest biomass among the species in that family observed at Maug. Reef sharks accounted for 20% of overall mean large-fish biomass, dominated by the whitetip reef shark with 20 individuals observed. Ten grey reef sharks also were observed in 2007. Other notable observations included sightings of dogtooth tuna (*Gymnosarda unicolor*) and large, planktivorous surgeonfishes (Acanthuridae), such as the sleek unicornfish (*Naso hexacanthus*) seen along steep slopes of the outer flanks of Maug.

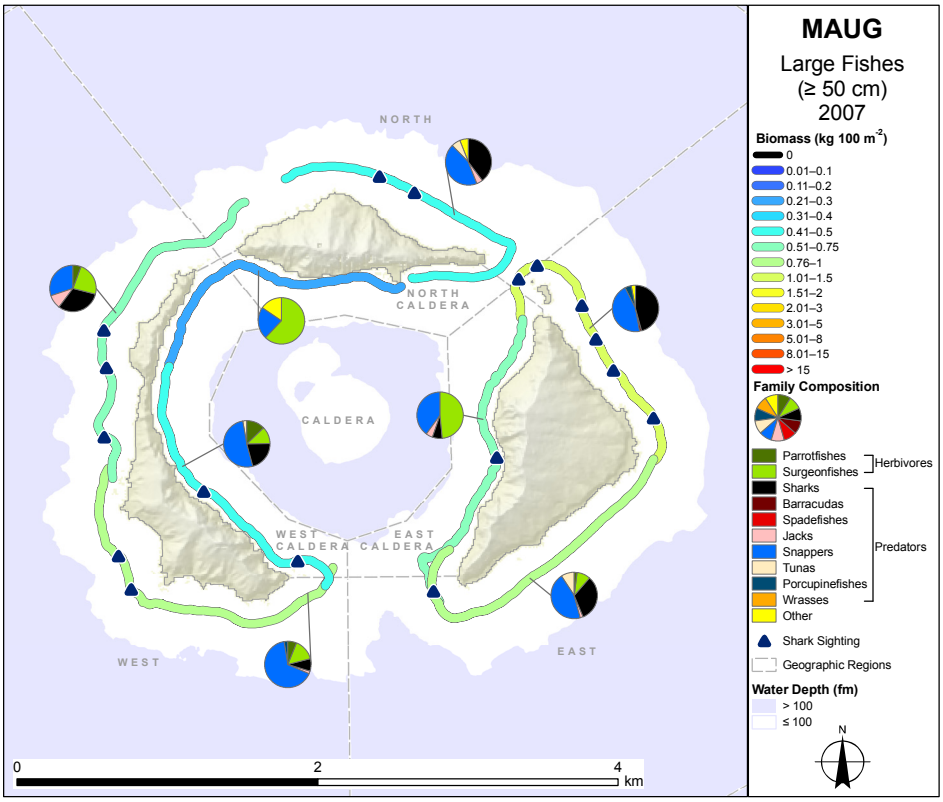


Figure 16.8.1c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Maug during MARAMP 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which they are shown.

Overall large-fish biomass around Maug was about average for the unpopulated islands in the Mariana Archipelago, based on values recorded during towed-diver surveys of forereef habitats. Observed biomass declined from 1.61 kg 100 m^{-2} (SE 0.31) in 2003 to 0.72 kg 100 m^{-2} (SE 0.11) in 2007 (Fig. 16.8.1d). Reef sharks contributed the largest percentage of overall mean biomass of large fishes, and the whitetip reef shark was the most common shark species observed in the 3 MARAMP survey years. A large school of bigeye trevally was observed in 2003 and 2005. Notable observations included sightings of the rare giant grouper (*Epinephelus lanceolatus*) and scalloped hammerhead shark (*Sphyrna lewini*), both observed in 2003; however, both species were observed off transect and were not recorded during the quantitative surveys. No humphead wrasse (*Cheilinus undulatus*) or bumphead parrotfish (*Bolbometopon muricatum*) were observed during the 3 MARAMP survey periods.

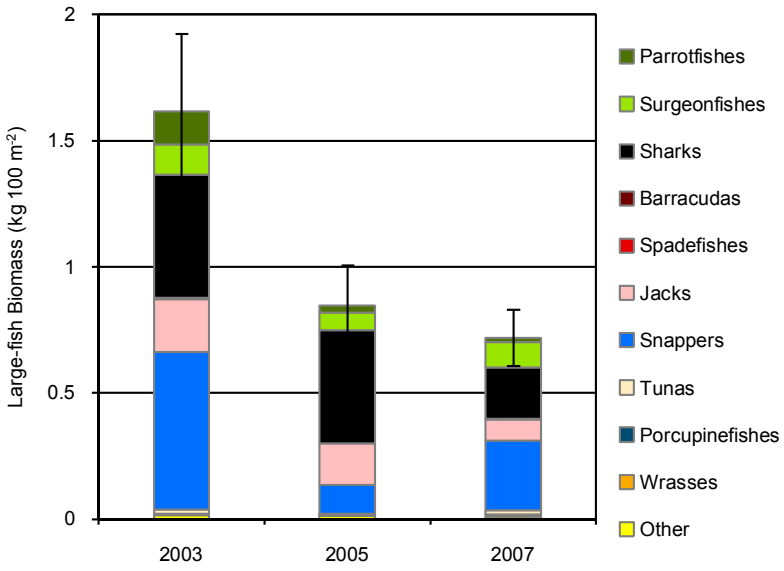


Figure 16.8.1d. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Total fish biomass for the 8 REA sites surveyed in forereef habitats at Maug during MARAMP 2003 was moderately high compared to other sites in the Mariana Archipelago with an overall sample mean of 7.80 kg 100 m^{-2} (SE 3.13). The highest biomass of 28.78 kg 100 m^{-2} was seen at MAU-03 in the east region (Fig. 16.8.1e). Fusiliers (Caesionidae) accounted for 33% or 2.56 kg 100 m^{-2} of total fish biomass at Maug. The yellow and blueback fusilier (*Caesio teres*) was the most abundant fusilier species with large schools of this planktivore observed at MAU-02 and MAU-03 in the east region. The only shark species observed in 2003 was the whitetip reef shark, with 3 individuals recorded.

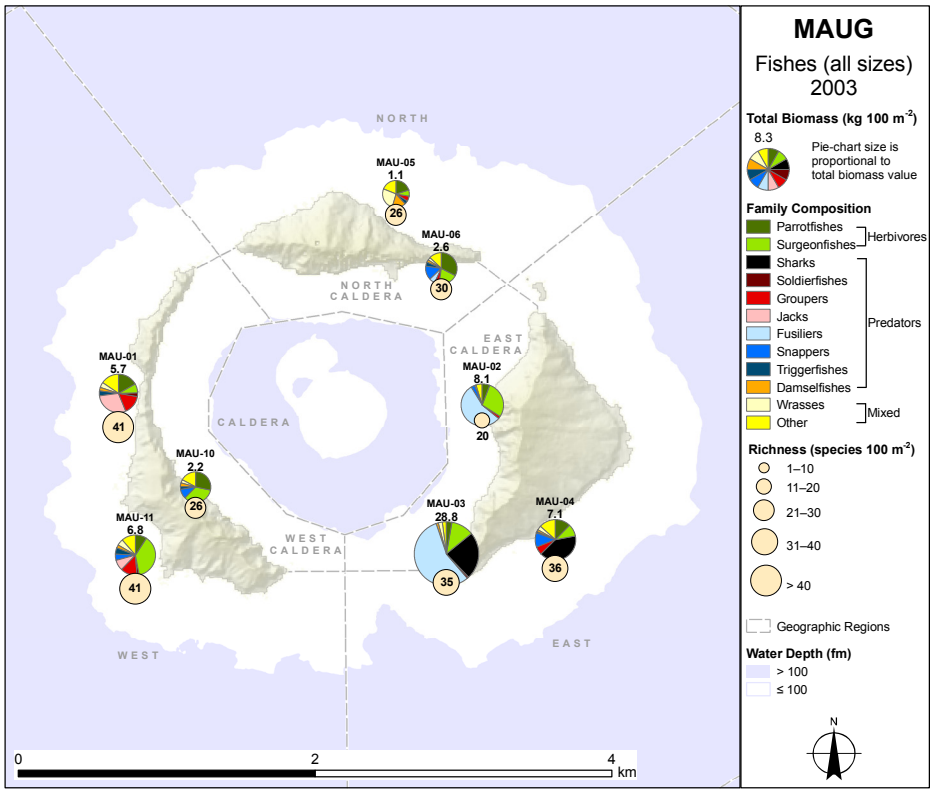


Figure 16.8.1e. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Maug during MARAMP 2003.

Based on REA surveys conducted during MARAMP 2003, species richness at Maug ranged from 20 to 41 species 100 m^{-2}. The lowest diversity was seen at MAU-02 in the east caldera region, while the highest diversity was found at MAU-01 and MAU-11 in the west region. Damselfishes (Pomacentridae) composed the most abundant fish family with Vanderbilt's chromis (*Chromis vanderbilti*), midget chromis (*Chromis acares*), and agile chromis (*Chromis agilis*) dominating count estimates. Additionally, the orangespine unicornfish (*Naso lituratus*) was the fourth-most abundant fish species seen at Maug, a result likely due in part to a recent recruitment.

Total fish biomass for the 8 REA sites surveyed in forereef habitats at Maug during MARAMP 2005 was similar to estimates in 2003 with an overall sample mean of 7.16 kg 100 m^{-2} (SE 1.19). The highest biomass of 13.57 kg 100 m^{-2} was seen at MAU-01 in the west region (Fig. 16.8.1f). Surgeonfishes contributed 35% or 2.54 kg 100 m^{-2} of total fish biomass at Maug. The orangespine unicornfish accounted for 32% of surgeonfish biomass. The whitecheek surgeonfish (*Acanthurus nigricans*) was the most abundant surgeonfish species observed with a mean of 8 individuals 100 m^{-2}. Reef sharks were rare, with only 1 whitetip reef shark observed at MAU-10 in 2005.

Based on REA surveys conducted during MARAMP 2005, species richness at Maug ranged from 27 to 40 species 100 m^{-2}. The lowest diversity was seen at MAU-10 in the west caldera region, and the highest diversity levels were found at MAU-11 and MAU-01 in the west region. Wrasses (Labridae), damselfishes, and surgeonfishes composed the most represented families with 28, 17, and 17 species recorded. The midget chromis was the most abundant species with an overall mean density of 39 individuals 100 m^{-2}.

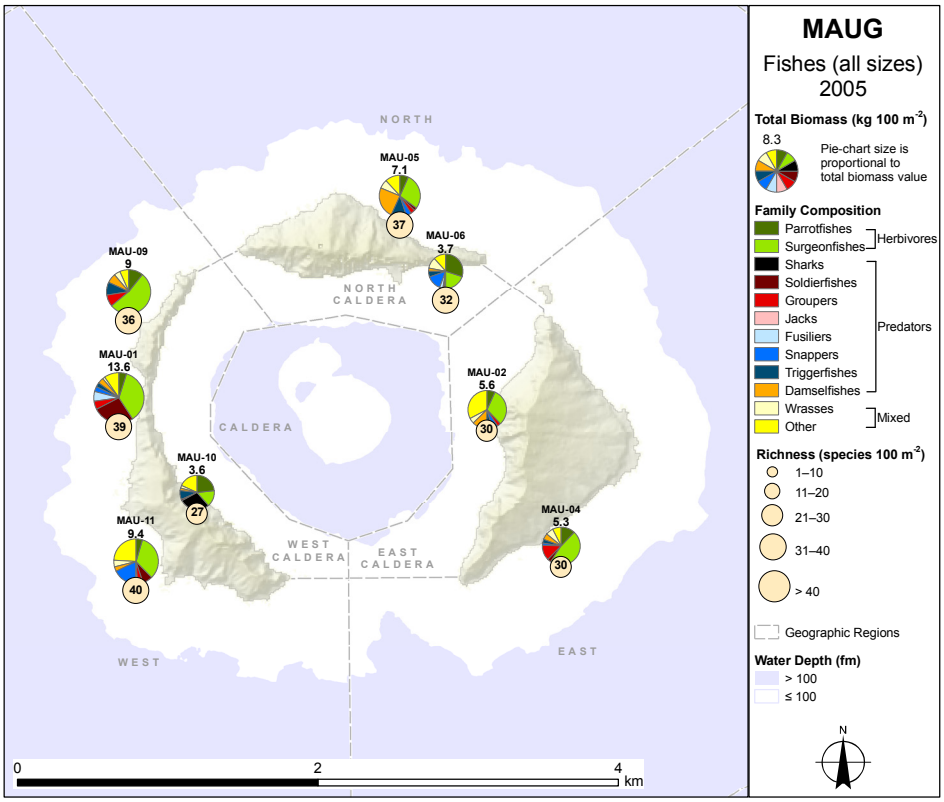


Figure 16.8.1f. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Maug during MARAMP 2005.

Total fish biomass for the 9 REA sites surveyed in forereef habitats at Maug during MARAMP 2007 was moderate compared to other sites in the Mariana Archipelago with an overall sample mean of 6.60 kg 100 m^{-2} (SE 1.51). Similar to observations made in 2005, surgeonfishes accounted for the largest proportion (38%) or 2.52 kg 100 m^{-2} of total fish biomass at Maug (Fig. 16.8.1g). The orangespine unicornfish accounted for 29% of surgeonfish biomass. Snappers were also common, contributing 10% of total fish biomass at Maug. The twinspot snapper accounted for 89% of observed snapper biomass. Large predators were rare except at MAU-12 on the outer flank in the east region, where 2 whitetip reef sharks and 1 giant trevally (*Caranx ignobilis*) were observed.

Based on REA surveys conducted during MARAMP 2007, species richness at Maug ranged from 27 to 38 species 100 m^{-2}. The highest diversity was seen at MAU-09 in the west region, and the lowest diversity was found at the 3 sites in the caldera regions: MAU-02, MAU-06, and MAU-10. Damselfishes were by far the most abundant fishes, and the midget chromis and Vanderbilt's chromis dominated counts with overall mean densities of 77 and 59 individuals 100 m^{-2}.

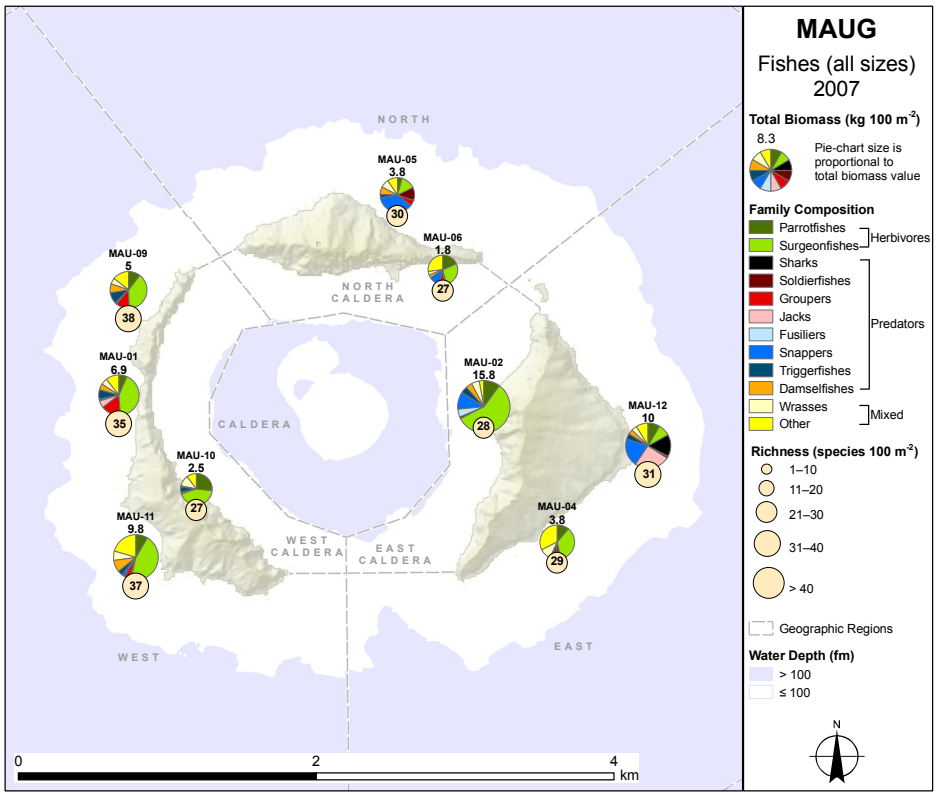


Figure 16.8.1g. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Maug during MARAMP 2007.

No clear spatial patterns in total fish biomass were observed at Maug between the 3 MARAMP survey years. In general, overall mean total fish biomass was moderately low compared to estimates from other remote, uninhabited islands in the northern part of the Mariana Archipelago. Mean values of total fish biomass were similar over the 3 survey periods, ranging from 7.80 kg 100 m^{-2} (3.13 SE) in 2003 to 6.60 kg 100 m^{-2} (1.51 SE) in 2007 (Fig. 16.8.3h). Large predatory species, such as reef sharks, were rare during REA surveys with only 6 whitetip reef sharks observed over the 3 survey years. A likely recruitment pulse of the orangespine unicornfish was observed in 2003. The initial recruitment carried over into the following survey years with the orangespine unicornfish accounting for ~ 11% of the overall mean fish biomass in 2005 and 2007.

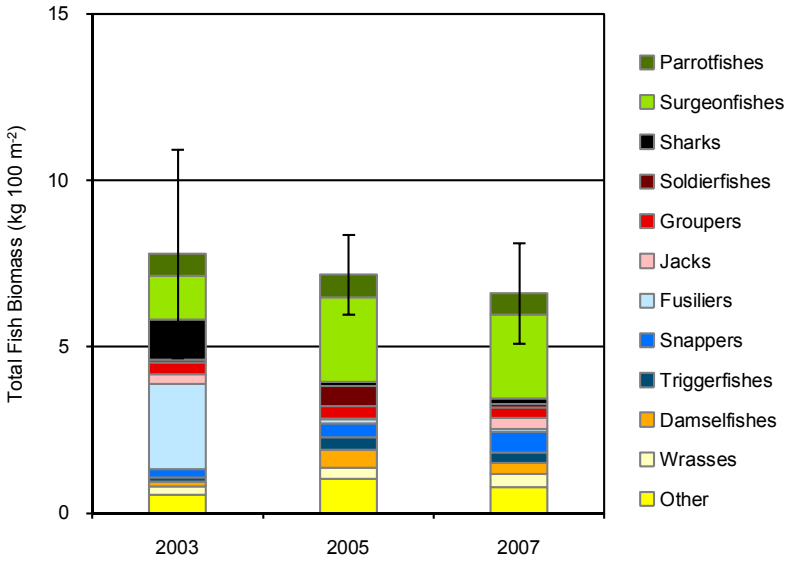


Figure 16.8.1h. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Species richness for the 3 MARAMP survey periods was highest at the forereef sites located on the outer flanks in the west region. These seaward-facing sites in the west region had the highest mean species richness of 37 species 100 m^{-2}. Wrasses, damselfishes, and surgeonfishes were well represented with high species diversity among REA sites. Damselfishes were the most abundant fish taxa, and the midget chromis and Vanderbilt's chromis dominated counts.

16.9 Marine Debris

16.9.1 Marine Debris Surveys

During MARAMP 2003, 7 sightings of derelict fishing gear and 5 sightings of other man-made objects were recorded in the 16 towed-diver surveys conducted on forereef habitats around the islands of Maug (Fig. 16.9.1a). Of the 7 sightings involving fishing nets or lines, 4 were recorded in the west region and 3 in the west caldera region. The 5 man-made objects were observed during a single survey segment in the west region. No munitions or wrecks were identified.

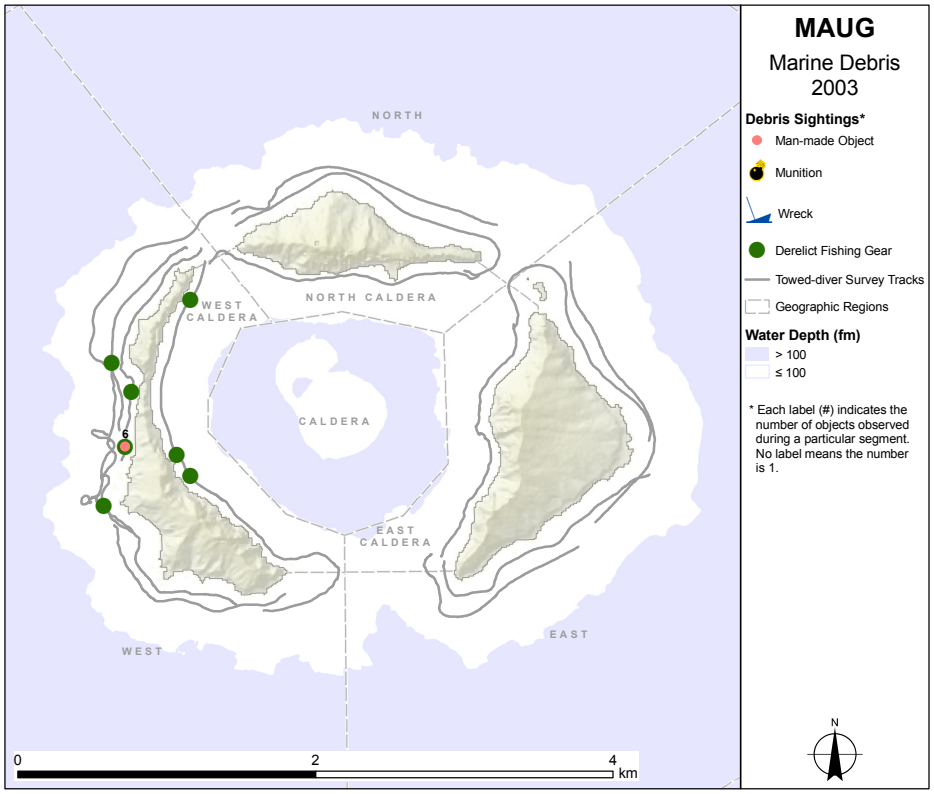


Figure 16.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003. Symbols indicate the presence of specific debris types.

During MARAMP 2005, 2 sightings of derelict fishing gear were recorded in the 13 towed-diver surveys conducted on forereef habitats around Maug (Fig. 16.9.1b). Fishing lines were observed in the east caldera and west caldera regions. No munitions, wrecks, or other man-made objects were identified.

During MARAMP 2007, 2 sightings of derelict fishing gear were recorded in the 11 towed-diver surveys conducted on forereef habitats around Maug (Fig. 16.9.1c). One fishing line was observed in the east caldera region, and a net was seen inside of the channel entrance between the east caldera and east regions. No munitions, wrecks, or other man-made objects were identified.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments. No locations of marine debris sightings at Maug overlapped between 2005 and 2007.

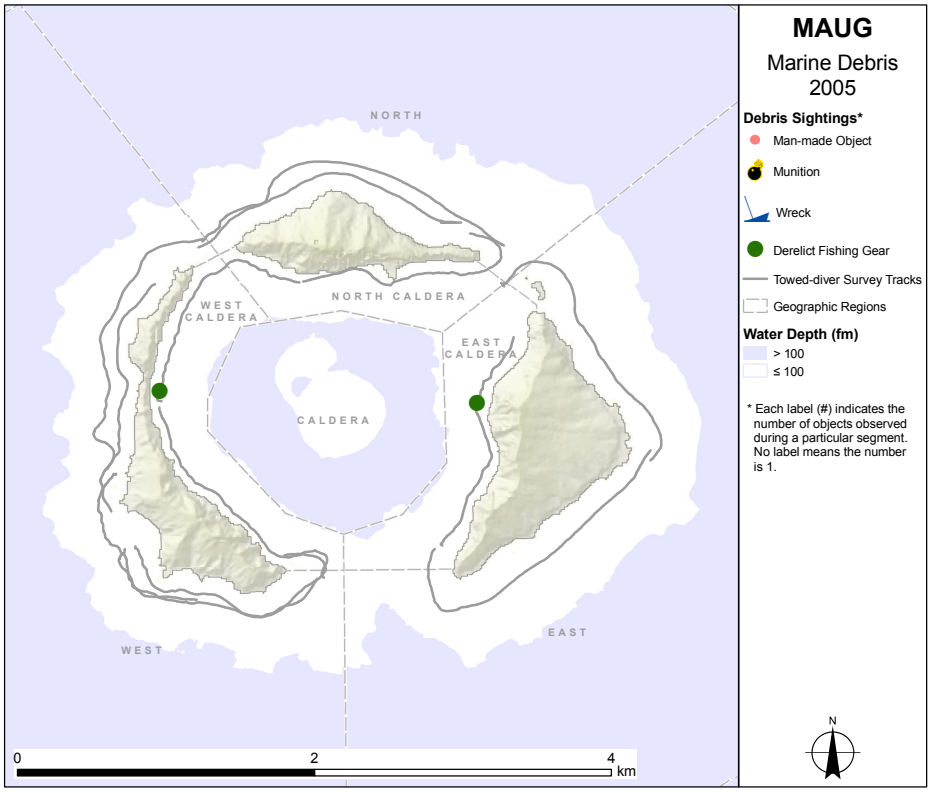


Figure 16.9.1b. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005. Symbols indicate the presence of specific debris types.

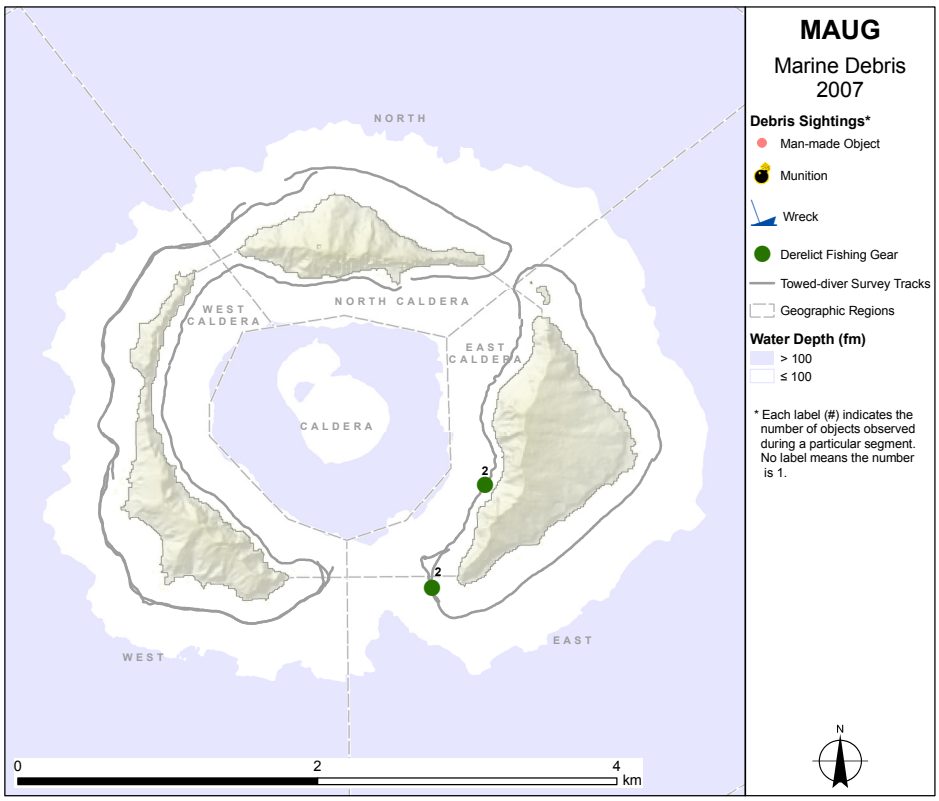


Figure 16.9.1c. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007. Symbols indicate the presence of specific debris types.

16.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the islands of Maug are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components both inside the caldera of Maug and on the outer flanks of these islands. In addition to this island-level analysis, evaluations across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Maug as well as the other 13 islands covered in this report.

Maug is unique among the islands of the Mariana Archipelago in its geomorphology. All northern islands and banks have been created by volcanic activity, but Maug's crater rim has been breached by the sea, producing a submerged, flooded caldera that is 2 km in diameter and connected to the open ocean by 3 narrow channels. This distinctive feature creates unusual conditions that, as observed during MARAMP surveys, supported a diversity of habitats that was greater around Maug than around the other northern islands in the Mariana Archipelago. Ongoing subsurface hydrothermal venting activity within the caldera of Maug has augmented this habitat diversity.

Inside the Caldera

The inner slopes of the 3 islands of Maug, formed by caldera walls, are all very steep. Underwater, these steep slopes plunge to depths > 200 m and then rise again in the center of this small caldera to depths < 20 m. The nearshore slopes of Maug are less steep in the 3 areas where the crater rim has slumped and created channels that separate these islands. The steep slopes within this volcanic crater provide a protected environment that, based on MARAMP results from towed-diver and REA surveys, generally supported live-hard-coral cover > 10%, with a few exceptions that included the 2 areas of silt adjacent to the channels that separate North Island from West and East Islands (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). Many areas of this protected environment were dominated by the coral genus *Goniastrea*, species of which grow on steep walls, providing a framework for other corals and invertebrates. Also numerically abundant were the genera *Porites* and *Astreopora*.



Figure 16.10a. Hydrothermal vents release gas bubbles, warm water at a site west of East Island. "Fluffy" silt that is brown, orange, and yellow-tinted covers the seafloor. *NOAA photo*

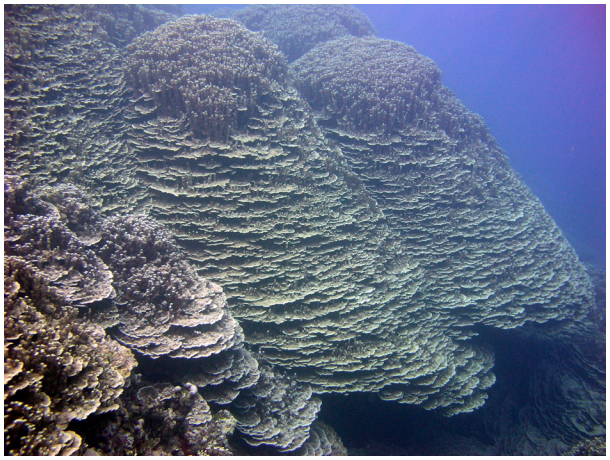


Figure 16.10b. *Porites rus* seen on the west coast of East Island at REA site MAU-02, where the genus *Porites* was a dominant part of the coral reef assemblage in 2005 and 2007. *NOAA photo*

Another uncommon feature of Maug was the presence of hydrothermal vents in its caldera. For all of the other shallow-water coral reefs surveyed in the Mariana Archipelago, observed hydrothermal activity was restricted to land. West of East Island in the northern part of the east caldera region, divers observed vents releasing warm water and gas bubbles. Divers surveying at this hydrothermal vent system found water temperatures of 48°C–63°C, pH of 6.09, TA of 3.56, and an undersaturated aragonite saturation state of 0.25. The seafloor surrounding these vents was littered with boulders and rubble, presumably from a previous landslide, with every surface covered with a layer of "fluffy" silt that was brown, orange, and yellow-tinted (Fig. 16.10a). No benthic surveys were conducted at this vent system, so precise values for this site are not presented in this report. However, a REA survey conducted at MAU-02 only 15 m south of this vent site revealed levels of live coral cover that were on average very high: 67% in 2007. The genus *Porites* was a dominant component of the coral reef assemblage at MAU-02 (Fig. 16.10b) in both MARAMP 2005 and 2007, having a much higher relative abundance at MAU-02 than at any other REA site surveyed at Maug (see Figures 16.5.1j, k, and l in Section 16.5.1: "Coral Surveys").

Outer Flanks

The outer flanks of Maug are characterized by the steep slopes typical of the northern islands in the Mariana Archipelago. The presence of a number of volcanic dikes that protrude many meters seaward from these island slopes increase habitat complexity by providing vertical relief. During towed-divers surveys, high concentrations of sea fans, other gorgonians, and corals were recorded.

In 2 areas where multiple towed-diver surveys were conducted, northeast of East Island and west of West Island, observed coral cover was higher in the outer surveys conducted at depths of 10–28 m than in the adjacent, inner surveys conducted at depths < 10 m. The inner surveys primarily documented rock and boulder habitat that presumably originated from landslides. Live coral cover was lower and a macroalgal cover was higher on these shallower habitats than on the deeper survey areas on the outer flanks, where habitats of spur-and-groove, continuous reef were recorded (Fig. 16.10c; also see Figures 16.5.1a, c, and e in Section 16.5.1: "Coral Surveys" and Figure 16.6.1a in Section 3.6.1: "Algal Surveys"). These outer survey areas also supported a higher biomass of large fishes (≥ 50 cm in TL) than did the adjacent surveys in shallower waters (Figs. 16.8.1a, b, and c in Section 16.8.1: "Reef Fish Surveys").

Towed-diver surveys conducted west of West Island at depths of 12–23 m consistently recorded some of the highest levels of live coral cover observed anywhere around Maug, with a range of 30%–75% in most survey segments (Figs. 16.10c and 16.5.1a, c, and e). This same area—characterized as high relief spur-and-groove habitat, interspersed with canyons and walls—also supported consistently low cover of macroalgae in MARAMP 2003, 2005, and 2007, compared to other areas surveyed in the Mariana Archipelago. COTS and stressed-coral cover were not observed in this area. Data from an STR deployed at a depth of 10 m just south of this survey area show rapid (return periods of 12–24 h) drops (1°C–3°C) in temperature, likely a result of local internal tides. Internal tides were likely formed when tidal currents interacted with steep subsurface topography, causing high-frequency variability in temperature and concentrations of dissolved nutrients and suspended particles. This vertical uplift of subsurface waters off the west coast of West Island, as observed in STR data, was likely affecting the benthic coral reef community in this area.

In contrast to the western flanks of Maug, the exposures south of West and East Islands had consistently low cover of live hard corals recorded during towed-diver surveys in the 3 MARAMP survey years, compared to other areas surveyed around Maug. Live coral cover of < 30% was observed in all but 5 segments of surveys conducted at depths of 5–20 m on these southern flanks. REA survey results also suggest low abundance with live coral cover of 19% at MAU-11 on the southwestern coast of West Island and 9% at MAU-04 on the southeastern coast of East Island in 2007. These habitats were dominated by boulders and supported high macroalgal cover, reaching 75%–100% in some locations, relative to other areas surveyed around Maug (Fig. 16.6.1a in Section 16.6.1: "Algal Cover"). The complexity of these habitats generally was slightly lower than the complexity observed at other survey areas around Maug (Fig. 16.3.3b in Section 16.3.3: "Habitat Characterization"). The south-facing shores of the islands of Maug are also subject to large episodic waves, primarily generated by typhoons that occur on annual to interannual time scales. Along with underlying geology, these large wave events can influence the types of habitats supported along the southern coasts.

Fish Community

In addition to the benthic features described previously, Maug also supported a fish community with medium to high levels of fish biomass and species richness, as observed in both towed-diver surveys of large fishes and REA surveys of fishes of all sizes, compared to the rest of the Mariana Archipelago (see Chapter 3: "Archipelagic Comparisons," Section 3.7: "Reef Fishes" for more details). Reef sharks were observed in towed-diver surveys during each of the 3 MARAMP survey years. In addition, a number of rare species—including the giant grouper (*Epinephelus lanceolatus*) and scalloped hammerhead shark (*Sphyrna lewini*)—were recorded at Maug that were otherwise seen only at a small number of survey locations in the Mariana Archipelago. However, despite the remote location of Maug and the protection offered by the Commonwealth Constitution (Article XIV, Section 2) since 1978, derelict fishing gear was observed during the 3 survey years, suggesting that reef-fish communities may not have been fully protected from fishing activities in the past.

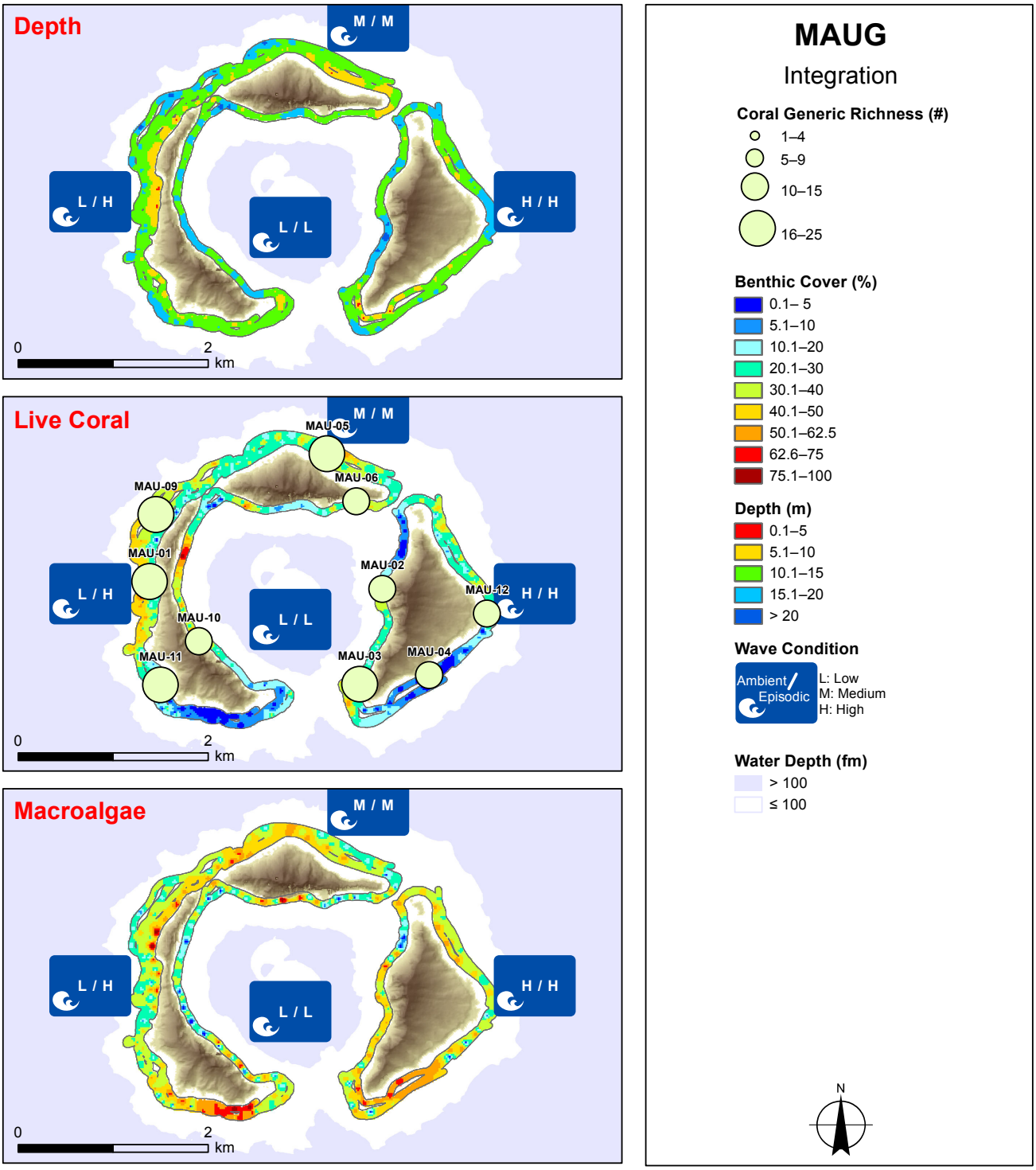


Figure 16.10c. Observations of depth (m), live coral cover (%), and macroalgal cover (%) from towed-diver surveys and coral generic richness from REA surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Values of depth, coral cover, and macroalgal cover represent interpolated values from the 3 MARAMP survey years, and generic-richness values represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.

16.11 Summary

MARAMP integrated ecosystem observations of the islands of Maug provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats of the islands of Maug. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods," and specific limitations of the data or analyses presented in this Maug chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of Maug's fish and benthic communities and the overall ecosystem relative to all the other islands in the Mariana Archipelago are discussed in Chapter 3: "Archipelagic Comparisons".

This section presents an overview of the status of coral reef ecosystems around the islands of Maug as well as some of the key natural processes and anthropogenic activities influencing coral reefs around these islands (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"):

- Maug includes 3 separate islands formed by the rim of a submerged caldera. Each island is characterized by a central ridge that is very narrow with steep slopes that end in sea cliffs at the coast. Their combined area of 2.14 km^2 makes these islands the smallest in the CNMI.

- No volcanic eruptions have been recorded at Maug in nearly 500 years. Active subsurface hydrothermal discharge was recorded within the Maug caldera in 2003 and a hydrothermal vent has been observed during the 3 MARAMP cruises.

- Maug is a protected reserve under the CNMI Constitution and inhabitation or building of permanent structures has been prohibited since 1978. The reserve was established for the protection of habitat for birds, wildlife, and plants. The islands of Maug and its waters and submerged lands are also included in the Islands Unit of the Marianas Trench Marine National Monument, which was established by presidential proclamation in January 2009.

- The outer flanks of the Maug volcano are steep, descending to a depth of ~ 2100 m north and east of Maug and to a depth of ~1700 m in the channel northwest of Maug. This channel separates Maug from Supply Reef. The submerged caldera of the Maug volcano lies at depths of 200–240 m, from which a twin-peaked submarine dome rises to a depth of 20 m.

- East of Maug, a complex area with steep slopes and high rugosity is present on the flanks, possibly a result of slumping from the crater wall. Bathymetry data show similar but smaller features southeast and west of Maug.

- Habitat complexity was medium to high through most of the areas surveyed by towed divers, except when surveys passed over a few sandy or silty patches.

- Generally, towed-diver surveys characterized habitats as hard substrates and recorded low levels of sand cover, relative to other areas surveyed in the Mariana Archipelago. Sand observed in deeper waters, during analyses of TOAD video footage, was related to topographic features with sand accumulating between ridges.

- Rapid (return periods of 12–24 h) drops in temperature (1°C–3°C) were observed in spring 2006 by STR moored off the west coast of West Island at a depth of 10 m. This signal was likely caused by an internal tide, generated when tidal currents interact with steep subsurface topography and result in high-frequency fluctuations in temperature and concentrations of dissolved nutrients and suspended particles that increase significantly from shallow reef crests to deep slopes.

- STR data show that temperatures in the west region and in the east caldera region reached the coral bleaching threshold in September 2006 but signs of significant thermal stress were not observed in these regions.

- Overall mean live coral cover was 21%–27% in the shallow waters surveyed by towed divers during the 3 survey years. Very little live coral cover was found in analyses of TOAD video footage recorded in deeper waters. Live coral cover was observed in TOAD video footage from a deployment on the central dome at a depth of ~ 160 m.

- The overall mean coral cover at Maug, estimated from 9 REA surveys, was 10.6% in 2007.

- Overall mean prevalence of coral disease was 0.02% at Maug in 2007. Four major disease states were found, including subacute tissue loss, skeletal growth anomalies, bleaching, and fungal infection. Out of the 9 sites surveyed, 4 contained disease. MAU-05 in the north region contained all 4 disease states and nearly 65% of cases. More than 60% of coral disease cases were observed on colonies of the genus Porites.

- Predation attributable to crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails was also observed at Maug, with an overall prevalence of 0.1%, a high level relative to results from other islands in the Mariana Archipelago.

- Overall mean macroalgal cover, observed during towed-diver surveys, decreased by 19% from 2005 to 2007. The forereef off the southwestern shore of West Island hosted greater macroalgal populations than elsewhere around Maug. This reef experienced less change, especially between MARAMP 2003 and 2005, when surveys conducted in other areas reported substantial changes over the same time period.

- Across the 3 MARAMP survey years, crustose coralline red algae were less abundant inside the caldera than on the outer flanks of Maug.

- Of the 9 REA sites surveyed at Maug in 2007, 3 contained algal disease. Only coralline lethal orange disease was recorded.

- Biomass of large fishes (≥ 50 cm in TL), estimated from towed-diver surveys, was moderate over the 3 survey periods, close to the average found at other unpopulated islands surveyed in the Mariana Archipelago. Observed biomass declined from 1.61 kg 100 m^{-2} in 2003 to 0.72 kg 100 m^{-2} in 2007.

- Biomass of fishes of all sizes at Maug, assessed by REA surveys, was among the lowest levels found at the unpopulated islands surveyed in the Mariana Archipelago, but still more than twice the average recorded at the populated, southern islands. In 2003, the observed overall mean of total fish biomass at Maug was 7.8 kg 100 m^{-2}, with the highest mean of 28.78 kg 100 m^{-2} recorded in the east region at MAU-03. In 2005, the overall mean of total fish biomass was 7.16 kg 100 m^{-2}, and MAU-01 in the west region had the greatest biomass of 13.57 kg 100 m^{-2}. In 2007, mean total fish biomass was 6.6 kg 100 m^{-2}, and the highest biomass of 15.78 kg 100 m^{-2} was found in the east caldera region at MAU-02.

- Mean species richness of fishes at Maug for the 3 MARAMP survey years was highest at REA sites located on the forereefs of the outer flanks.

- Giant clams were most abundant along the southern shore of North Island in the north caldera region and the western shore of West Island in the west region. Daytime abundance levels of sea cucumbers and sea urchins were low around Maug during the 3 MARAMP survey years, relative to results from other islands surveyed in the Mariana Archipelago.

- Crown-of-thorns seastars (COTS) were observed predominantly in the west caldera region during the 3 MARAMP survey years. In 2003, high densities of crown-of-thorns seastars (COTS), compared to other areas surveyed in the Mariana Archipelago, were recorded in a localized area in the west caldera region, suggesting a possible outbreak. The overall observed mean density of COTS was higher in 2003 than in 2005 and 2007.

17 FARALLON DE PAJAROS

17.1 Introduction

Farallon de Pajaros is the most northerly of the 14 islands of the Commonwealth of the Northern Mariana Islands (CNMI) and is located 67 km northwest of Maug at 20°33′ N and 144°54′ E. Farallon de Pajaros, which translates from Spanish to Isle of the Birds, is also known as Uracas from the Spanish word *urraca* meaning magpie. This island is ~ 1.6 km wide and 1.8 km long with a land area of 2.25 km^2, making it the second smallest island in the CNMI (Fig. 17.1a). The part of Farallon de Pajaros that is visible above the ocean is the small, aerial portion of a large volcano, the base of which lies in depths > 2000 m and is some 15–20 km in diameter. The rim of this volcano's crater is the highest point on this island with an elevation of 360 m, and it is surrounded by steeply sloping sides that lead to precipitous cliffs around much of this island's coast (Fig. 1717.1b).

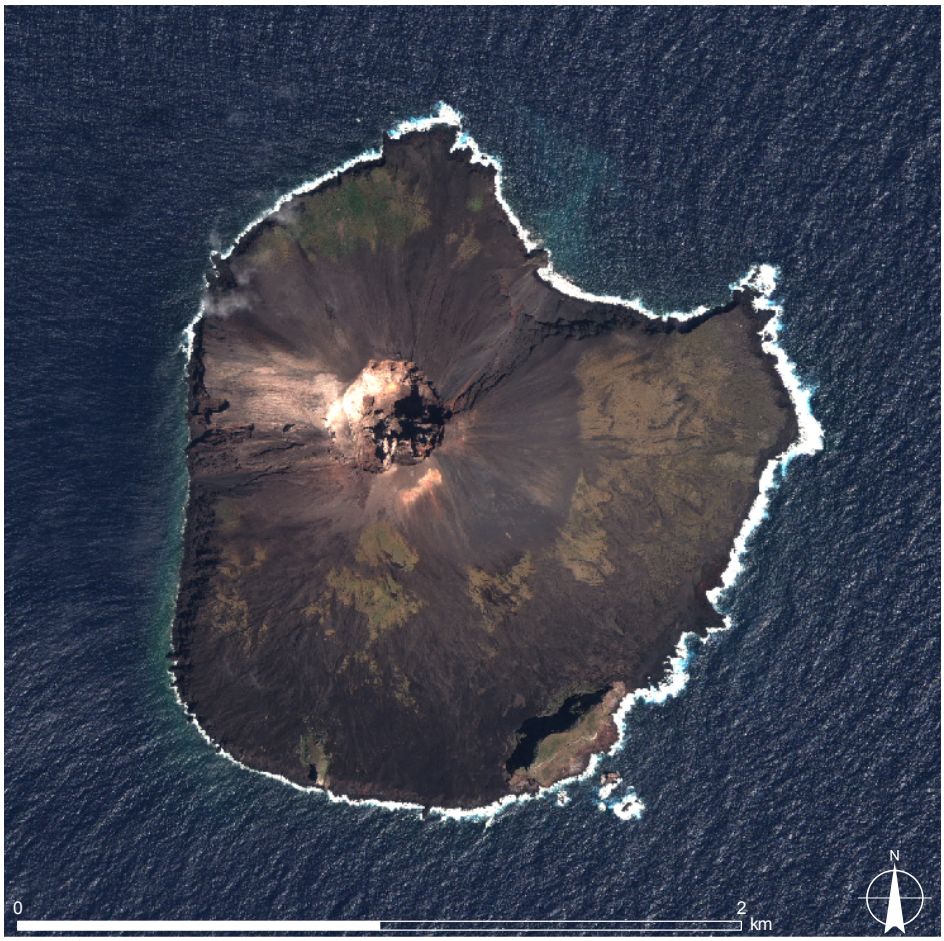


Figure 17.1a. Satellite image of Farallon de Pajaros (© 2004 DigitalGlobe Inc. All rights reserved).



Figure 17.1b. The west side of Farallon de Pajaros as seen from the NOAA Ship *Hi`ialakai* in June 2007. *NOAA photo by Emily Hirsch*

17.1.1 History and Demographics

Farallon de Pajaros is, and has probably always been, permanently uninhabited because of its inhospitable terrain, frequent volcanic activity, small size, and, now, protected status. The political history of Farallon de Pajaros is that of the CNMI as a whole, which has been described in more detail in Chapter 1: "Introduction" and Chapter 8: "Saipan," Section 8.1: "Introduction." In 1909, while under administration by Germany, Farallon de Pajaros (along with Agrihan, Asuncion, Guguan, Maug, Farallon de Medinilla, and Sarigan) was leased to the Pagan Gesellschaft for exploitation of bird plumage for a period of 3 years (Spennemann 1999b). During this time Japanese bird catchers were employed on these islands and may have been temporarily resident on Farallon de Pajaros.

17.1.2 Geography

Farallon de Pajaros, like other islands in the northern Mariana Arc, is a high volcanic island. It is a steeply sloping, recently active volcano with most of its surface covered with lava, cinders, and ash (Figs. 17.1.2a and b). At some point during the volcano's history, flank fissures have fed lava flows, creating platforms along the coast of Farallon de Pajaros (Siebert and Simkin 2002–). This island's summit is a central cone within a small caldera that cuts into an older edifice (Siebert and Simkin 2002–).

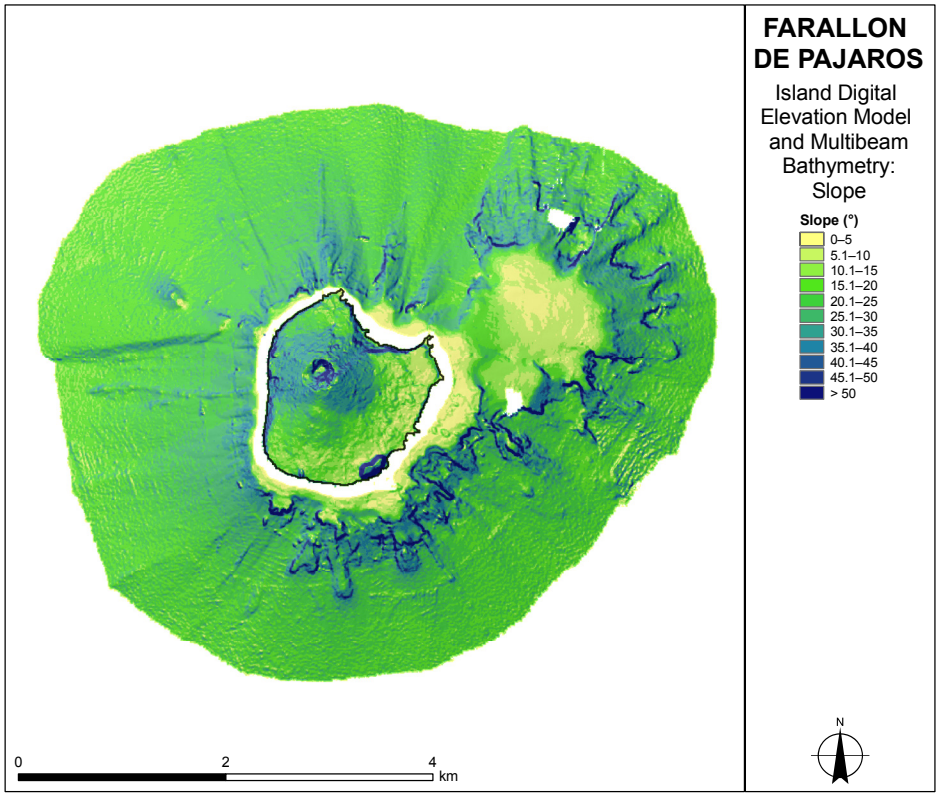


Figure 17.1.2a. Combined slope map using the digital elevation model and multibeam bathymetric data for Farallon de Pajaros (grid cell size: 10 m).

Farallon de Pajaros is considered one of the most volcanically active islands of the CNMI with at least 15 eruptions since 1864. Frequent eruptions during the 19th century led it to be known as the "Lighthouse of the Pacific." Eruptive activity was recorded throughout the 1940s, 1950s, and 1960s. The last known eruption was recorded in 1967, and a team of volcanologists, during a recent visit to this island, reported fumaroles continuing to emit gas and sulfur visible within the crater (University of California San Diego 2009). The Makhanas Seamount, which is located at 10 km southwest of Farallon de Pajaros, and Ahyi Seamount, which lies 18 km southeast of this island, are also still active (Siebert and Simkin 2002–).



Figure 17.1.2b. A view of the northwest side of Farallon de Pajaros, showing sulfurous rocks and ash slopes. *NOAA photo by Russell Moffitt*

The volcanic material that is widespread across Farallon de Pajaros supports little in the way of vascular plants. This island is largely unvegetated, although older rocks support thin, grassy vegetation (Fig. 17.1.2c). Two large outcropping rocks on the south coast of this island are vegetated (Fig. 17.1a). Small areas of vegetation include sedge communities and succulent communities on coastal rock (Mueller-Dombois and Fosberg 1998). Coconut and other trees planted by Georg Fritz, the first German administrator, during his visit to this island in 1901, apparently could not subsist, as photographs taken some 50 years later show no evidence of any trees on this island (Mueller-Dombois and Fosberg 1998). Landslides on this island's steep slopes have been observed during biennial Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) surveys.

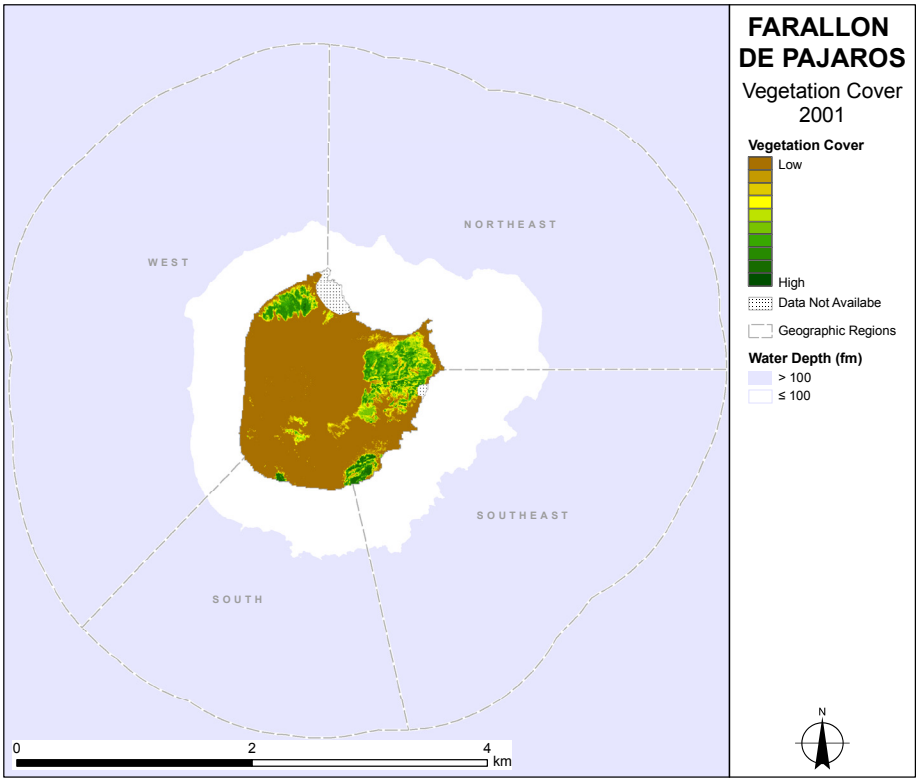


Figure 17.1.2c. Vegetation cover on Farallon de Pajaros, derived using the Normalized Difference Vegetation Index from a satellite image (grid cell size: 4 m; IKONOS Carterra Geo Data, 2001). Hatched lines display areas where data are not available because cloud cover obscures the satellite image.

17.1.3 Environmental Issues on Farallon de Pajaros

Because of its isolated location and lack of inhabitants, Farallon de Pajaros likely has few anthropogenic pressures. Fishing activity within the CNMI tends to be focused around the southern islands of the Mariana Archipelago, with multi-day fishing trips focusing on the islands and banks south of Guguan (Western Pacific Fishery Management Council 2009).

This island is part of a protected wildlife reserve, the Uracas Island Preserve, established in 1985 under an amendment of Article XIV of the CNMI Constitution and managed by the CNMI Division of Fish and Wildlife. This legislation states that Farallon de Pajaros and other islands "shall be maintained as uninhabited places and used only for the preservation and protection of natural resources" (CNMI Constitution). This island is preserved as a habitat for birds, wildlife, and plants. The Uracas Island Preserve protects 20 species of birds, including the red-tailed and white-tailed tropicbirds (*Phaethon rubricauda* and *P. lepturus*), 3 species of booby (masked, *Sula dactylatra*; red-footed, *S. sula*; and brown, *S. leucogaster*), and the endangered Micronesian megapode (*Megapodius laperouse*), which is locally common, breeds on this island, and is listed both Federally as an endangered species (U.S. Fish and Wildlife Service) and locally as a threatened or endangered species (Berger et al. 2005). Unlike on many other islands of the CNMI, no feral goats have been reported on Farallon de Pajaros (Pacific Protected Areas Database).

Farallon de Pajaros was included within the Marianas Trench Marine National Monument, formed by presidential proclamation in January 2009. This Marine National Monument includes a Trench Unit, an Islands Unit, and a Vents Unit. The Islands Unit includes the waters and submerged lands of the islands of Asuncion, Maug, and Farallon de Pajaros.

17.2 Survey Effort

Biological, physical, and chemical observations collected under MARAMP have documented the conditions and processes influencing coral reef ecosystems around the island of Farallon de Pajaros since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around Farallon de Pajaros are delineated in Figure 17.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) and towed-diver surveys conducted around this island. Potential reef habitat is represented by a 100-fm contour shown in white on this map.

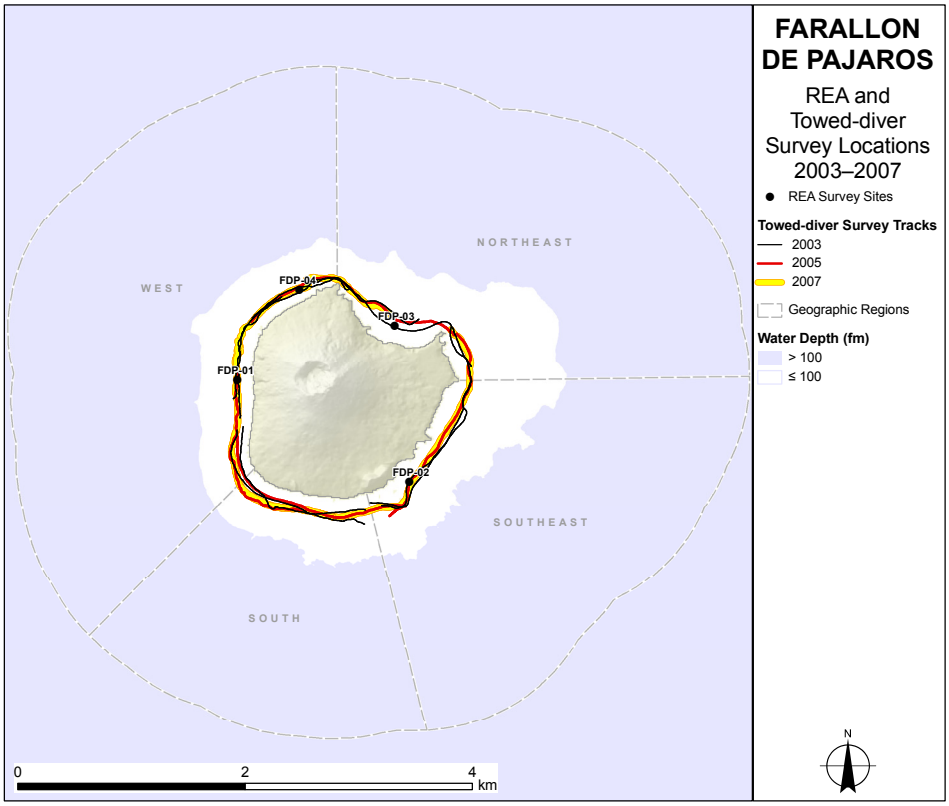


Figure 17.2a. Locations of REA and towed-diver benthic surveys conducted around Farallon De Pajaros during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 4 geographic regions: northeast, southeast, south and west.

Benthic habitat mapping data were collected around Farallon de Pajaros using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around Farallon de Pajaros, Asuncion, Maug, and Supply Reef with multibeam sonar covered a total area of 3856 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver surveys that documented live-hard-coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 17.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Farallon de Pajaros was collected using REA and towed-diver surveys. The results of these surveys are reported in Sections 17.5–17.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 17.2a, along with their mean depths and total areas or length.

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Farallon de Pajaros were collected using (1) subsurface temperature recorders (STRs) designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-a analyses. CTD casts

Table 17.2a. Numbers, mean depths (m), and total areas (ha) of REA and towed-diver surveys conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	4	3	3
	Mean Depth (m)	13.4 (SD 2.3)	14.5 (SD 0.5)	14.5 (SD 0.5)
Benthic	Number of Surveys	4	3	3
	Mean Depth (m)	13.4 (SD 2.3)	14.5 (SD 0.5)	14.5 (SD 0.5)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	8	4	4
	Total Survey Area (ha)	13.4	7.5	8.6
	Mean Depth (m)	13.7 (SD 1.6)	14.9 (SD 3.1)	15.2 (SD 1.7)

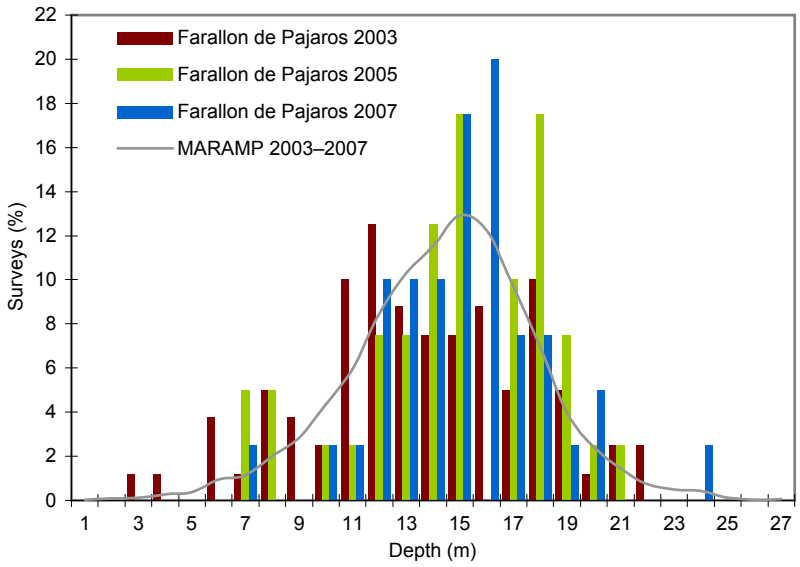
were performed during MARAMP 2003, 2005, and 2007, and water sampling was conducted during MARAMP 2005 and 2007 (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 17.2b. Results are discussed in Section: 17.4: "Oceanography and Water Quality."

Table 17.2b. Numbers of STRs deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Farallon De Pajaros during MARAMP 2003, 2005, and 2007. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: Archipelagic Comparisons.

Observation Type	Year						
Instruments	**2003**	**2005**		**2007**		**2009**	**Lost**
	Deployed	**Retrieved**	**Deployed**	**Retrieved**	**Deployed**	**Retrieved**	
STR	1	–	1	1	6	6	1
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	8	12		7			27
Deepwater Casts	–	8		1			9
Water Samples		**2005**		**2007**			**Total**
		4		3			7

Towed-diver Surveys: Depths

Figure 17.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.



Figures 17.2b and c illustrate the locations and depths of towed-diver-survey tracks around Farallon de Pajaros and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

During MARAMP 2003, 8 towed-diver surveys were conducted along the forereef slopes around Farallon de Pajaros (Figs. 17.2b and 17.2c, top panel). The mean depth of all survey segments was 13.7 m (SD 1.6), and the mean depth of individual surveys ranged from 12.1 m (SD 6.4) to 16.3 m (SD 4.5).

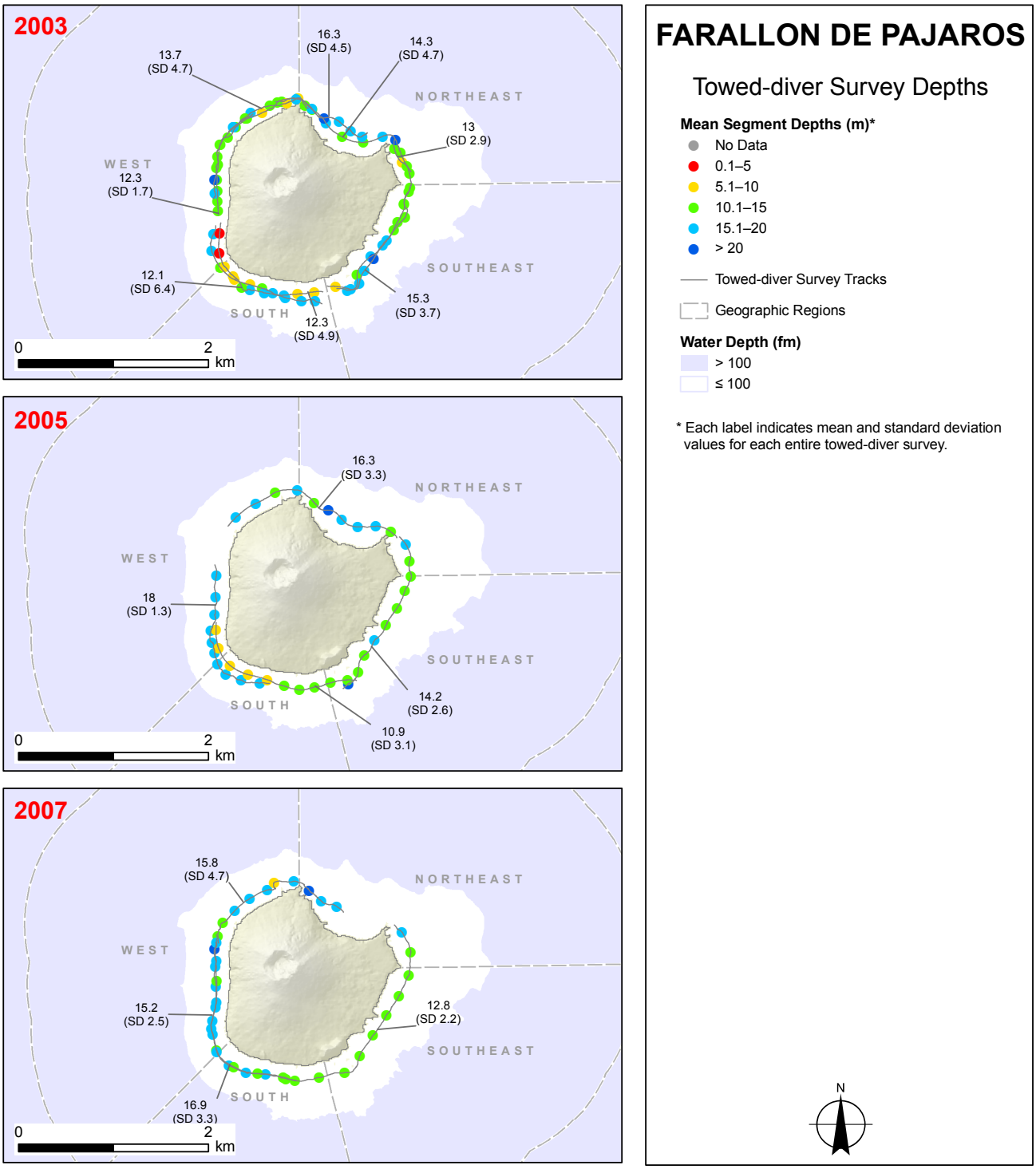


Figure 17.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Farallon De Pajaros during MARAMP 2003, 2005, 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

During MARAMP 2005, 4 towed-diver surveys were conducted along the forereef slopes around most of Farallon de Pajaros (Figs. 17.2b and 17.2c, middle panel). The mean depth of all survey segments was 14.9 m (SD 3.1), and the mean depth of individual surveys ranged from 10.9 m (SD 3.1) to 18 m (SD 1.3).

During MARAMP 2007, 4 towed-diver surveys were conducted along the forereef slopes around most of Farallon de Pajaros (Figs. 17.2b and 17.2c, bottom panel). The mean depth of all survey segments was 15.2 m (SD 1.7), and the mean depth of individual surveys ranged from 12.8 m (SD 2.2) to 16.9 m (SD 3.3).

17.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Farallon de Pajaros were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 15–1500 m. Optical validation and benthic characterization were performed using towed-diver surveys conducted at depths < 5–26 m.

17.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 17.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around Farallon de Pajaros, Asuncion, Maug, and Supply Reef in 2007 encompassed an area of 3856 km^2.

Low-resolution multibeam bathymetry acquired during MARAMP 2007 suggests uniformly steep slopes with ridges that radiate out perpendicularly from this active volcanic island.

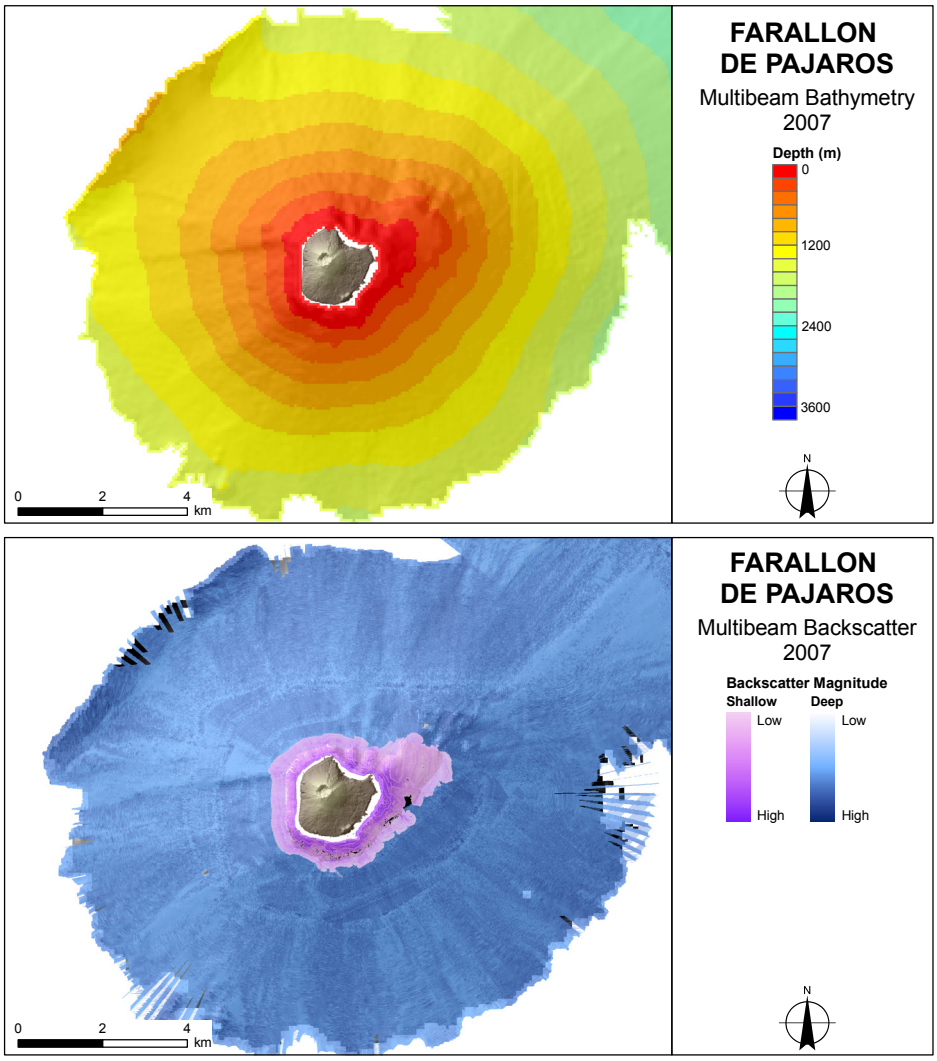


Figure 17.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Farallon de Pajaros during MARAMP 2007 at depths of ~ 15–1500 m. Shallow-backscatter data (shown in purple) were collected using a 240 kHz Reson SeaBat 8101 ER sonar, and deep-backscatter data (shown in blue) were collected using a 30 kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

Low-resolution backscatter data acquired around Farallon de Pajaros show relatively uniform backscatter intensity, with some bands of lower intensity backscatter on the northwest and southwest flanks. Topographic features revealed by the high-resolution multibeam data and derivatives are described in more detail in the following section.

High-resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in nearshore (depths of 0–800 m) waters around Farallon de Pajaros were combined into a grid at 10-m resolution to allow for the identification of fine-scaled features (Fig. 17.3.1b). These high-resolution data have also been used to derive maps showing slope (Fig. 17.3.1c), rugosity (Fig. 17.3.1d), and bathymetric position index (BPI) zones (Fig. 17.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Farallon de Pajaros.

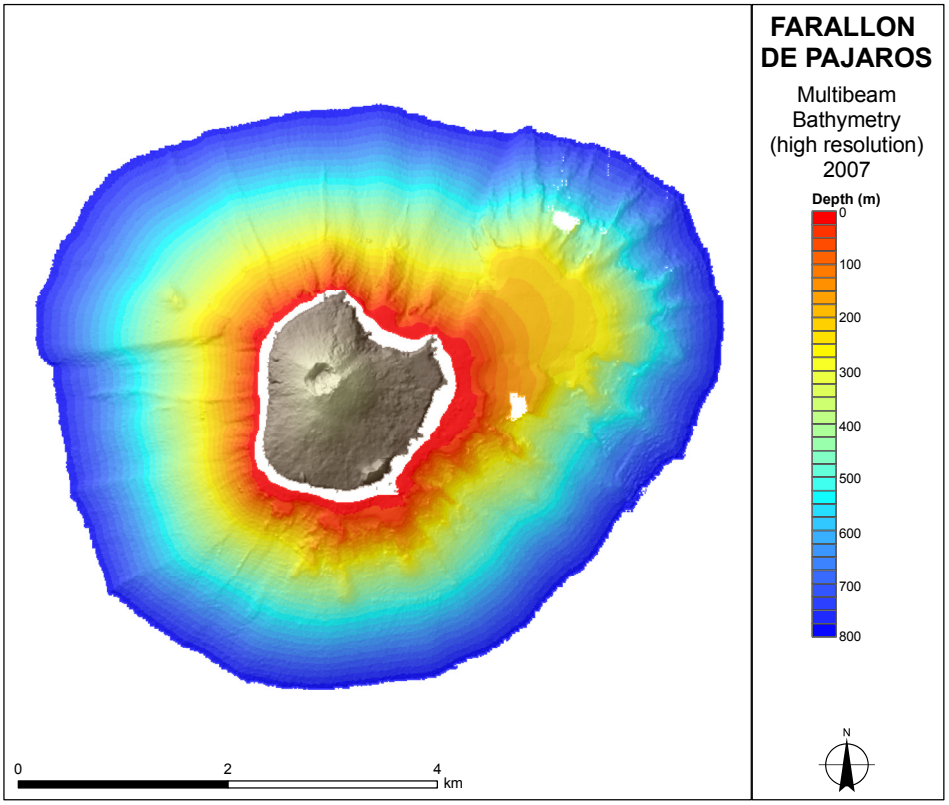


Figure 17.3.1b. High-resolution multibeam bathymetry collected around Farallon de Pajaros during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives.

Steeply sloping flanks characterize much of the seabed around Farallon de Pajaros with very few flat BPI zones identified (Figs. 17.3.1c and e). High-resolution multibeam bathymetry reveals ridges on the flanks that extend from depths < 30 m to depths of 400–600 m. The slope along the sides of these ridges is commonly 20°–30° although along some ridges very steep slopes > 50° occur (Figs. 17.3.1b and c).

South and east of Farallon de Pajaros, high-resolution multibeam bathymetry reveals a narrow shelf area at depths of 10–40 m and a second, larger shelf, which fans out from the northeastern point of Farallon de Pajaros and gently deepens from a depth of ~ 150 m to 250–300 m. The slope and rugosity analyses both suggest that the shelf, which may be related to an older portion of the volcano, has a smooth surface. Both shelves are surrounded by steep slopes and numerous small ridges and channels that descend from the shelf edges. Blocky material revealed on these and other flanks around Farallon de Pajaros suggests mass-wasting (movement of soil and surface materials by gravity).

West of Farallon de Pajaros, the seabed is characterized by uniformly steep slopes of 20°–50°, with the steepest slopes occurring at depths < 100 m (Fig. 17.3.1c).

In the shallowest waters surveyed, the BPI analysis identifies reef crests (Fig. 17.3.1e). However, this classification is likely an artifact of the methodology, since no data are available for immediately inshore areas and no comparison can be made to the innermost cells of the grid. Instead, these areas probably should be characterized as slopes

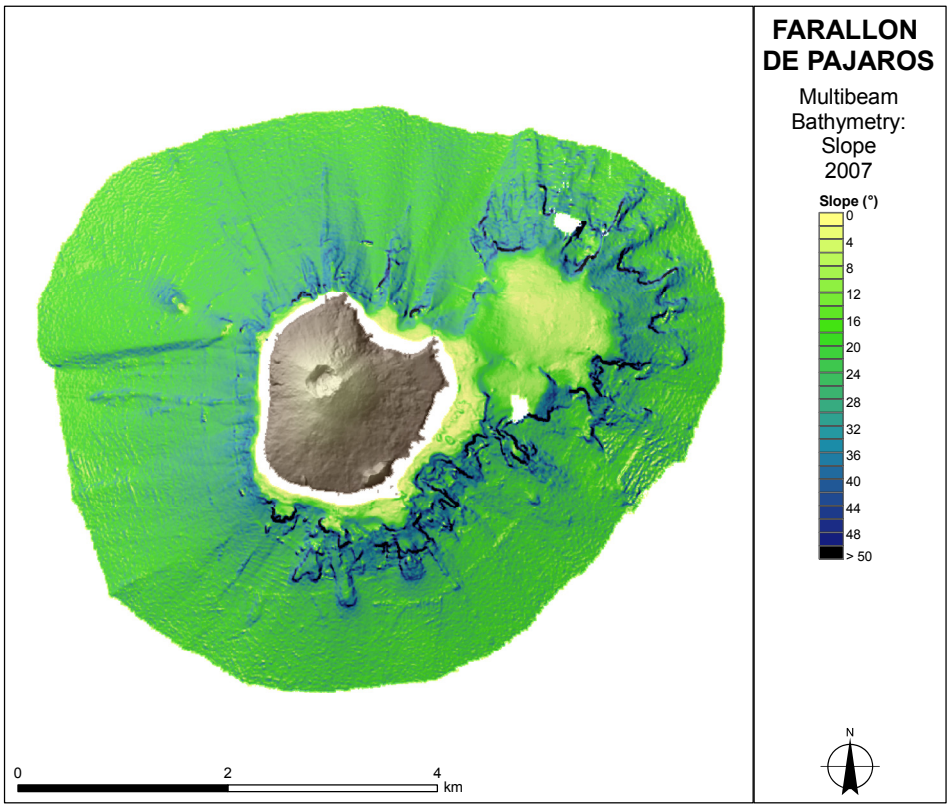


Figure 17.3.1c. Slope (°) of 10-m bathymetric grid around Farallon de Pajaros. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades.

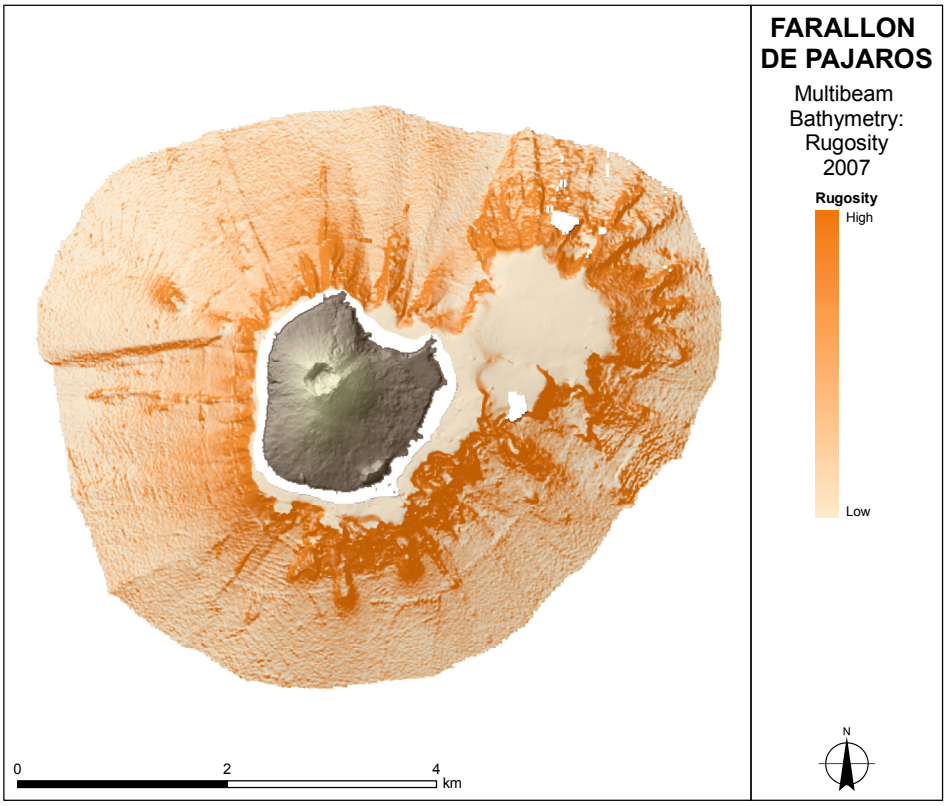


Figure 17.3.1d. Rugosity of 10-m bathymetric grid around Farallon de Pajaros. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

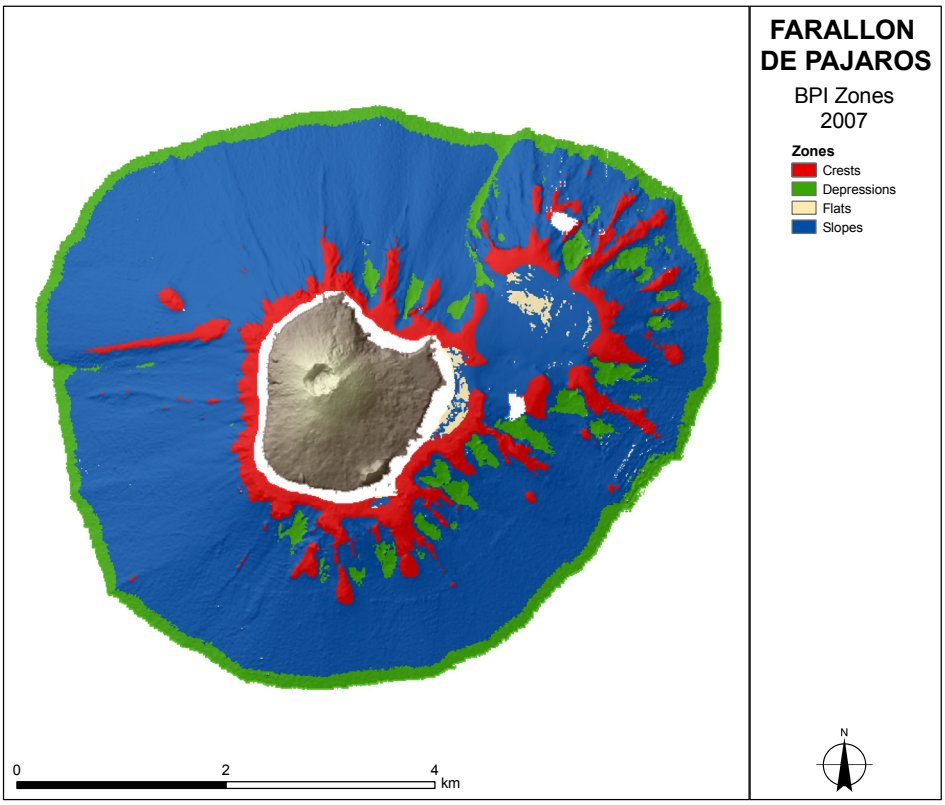


Figure 17.3.1e. BPI Zones of 10-m bathymetric grid around Farallon de Pajaros derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

High-resolution Multibeam Backscatter and Derivatives

High-resolution backscatter data were acquired around Farallon de Pajaros using a 240-kHz Reson SeaBat 8101 ER multibeam echosounder and a 30-kHz Kongsberg EM 300 sonar. This data set had some noticeable artifacts that impaired data

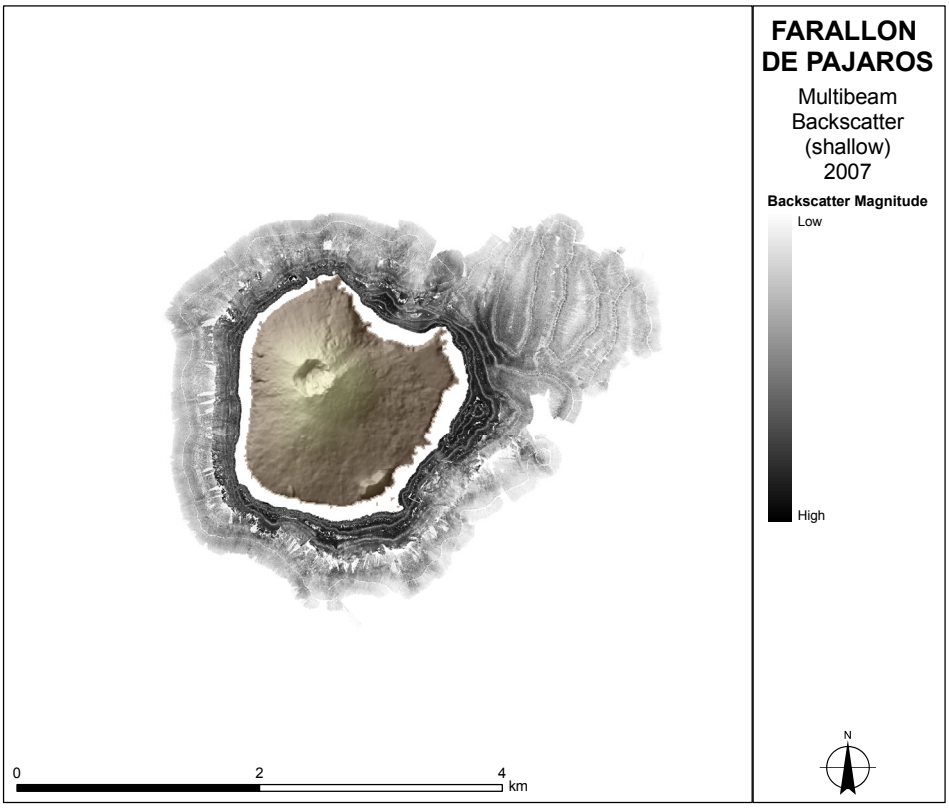


Figure 17.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) collected around Farallon de Pajaros during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

quality, including a distinct difference in backscatter intensity between the shallow and deeper swaths around much of this island and large gaps in data between inner and outer swaths. Such artifacts may have resulted from any number of factors, such as the steep slopes occurring within the survey area, sea state, or changes in sonar settings during acquisition (discussed in more detail in Chapter 2: "Methods and Operational Background", Section 2.2.2: "Acoustic Mapping"). Effects of artifacts were exacerbated in the hard–soft analysis, resulting in some substrate areas being falsely classified. Because of data quality issues, no hard–soft maps are presented for Farallon de Pajaros. However, some patterns in the backscatter intensity are discernable and probably reflect the nature of the seabed (Fig. 17.3.1f). High-intensity-backscatter values were observed on the shallow shelf areas east and south of this island. The steep flanks elsewhere were found in general to have low backscatter intensity. This observation suggests that substrates here may be predominantly soft, although, in these areas, the backscatter values may be strongly influenced by the steepness of the slopes in addition to the acoustic characteristics of the substrate.

High backscatter values were recorded on some of the ridges north and east of Farallon de Pajaros, suggesting that these may be characterized by hard substrate at or near the seabed surface. Between the ridges, low backscatter values were observed, which may be a result of soft sediments accumulating in the channels.

Low-intensity backscatter values were also recorded on the shelf northeast of Farallon de Pajaros. As slope would not be an influencing factor here, it is likely that these results suggest soft sediments on the shelf.

17.3.2 Optical Validation

Covering a distance of 29 km at depths of 4–24 m, 16 towed-diver optical-validation surveys of forereef habitats were conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007 (for survey locations, see Figure 17.2a in Section 17.2: "Survey Effort"). At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

17.3.3 Habitat Characterization

Results from towed-diver optical-validation surveys, weighted by data from the shallow shelf areas unique to the east side of this island, suggest different seabed characteristics in the northeast and southeast regions in comparison to the south and west regions. The highest levels of sand cover were recorded on the shallow shelf extending from the large embayments in the northeast and southeast regions (Fig. 17.3.3a, top panel). This area also supported the lowest levels of habitat complexity around this island (Fig. 17.3.3a, middle panel). The main habitat type in this area was boulders on sand. In some locations, hard pavements were seen extending into sandy slopes.

In the west and south regions, low levels of sand cover were observed, generally ranging from 10% to 30% (Fig. 17.3.3a, top panel). The predominant habitat characterizing these regions was boulders on sand with some patches of rocky reef. Recorded levels of habitat complexity were higher in these regions than elsewhere around this island, falling mainly within the complexity category of medium to medium-high.

Observations from towed-diver surveys suggested very low levels of live coral cover, rarely exceeding 20%, in all of the areas surveyed (Fig. 17.3.2a, bottom panel). Live-coral cover was observed to be particularly uncommon (< 10%) in the northeast and south regions. The highest levels of live-coral cover were observed on the shallow shelf in the southeast region, where interpolated coral cover reached 30%. These low levels of coral cover may be a result of the recent volcanic activity, which may not have abated long enough for coral reef development; however, the steeply sloping boulder and sand habitats provide little substrate suitable for coral settlement.

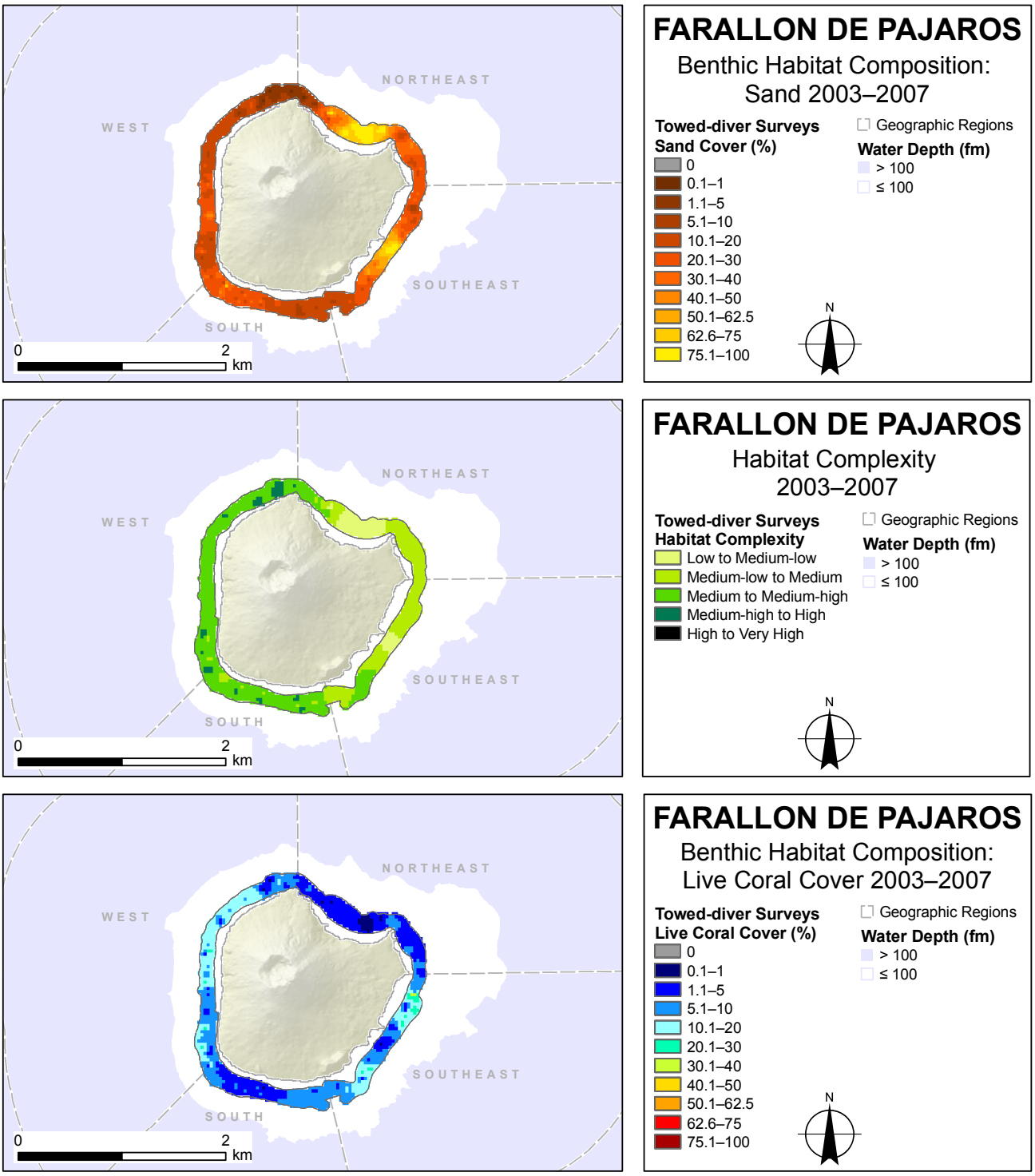


Figure 17.3.3a. Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) cover (%) of live hard-corals from towed-diver surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007.

17.4 Oceanography and Water Quality

17.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 8 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the island of Farallon de Pajaros on August 30. Spatial comparisons of water properties at a depth of 10 m suggest small differences in temperature (0.26°C), salinity (0.03 psu), density (0.1 kg m^{-3}), and beam transmission (< 0.75%) values (Fig. 17.4.1a). Vertical comparisons of CTD profiles reveal differences in stratification around Farallon de Pajaros: well-mixed waters were recorded in the west and northeast regions (casts 1–4), and highly stratified waters were recorded in the south and southeast regions and part of the northeast region (casts 5–8), where the moderate differences in temperature (0.49°C), density (0.4 kg m^{-3}), and beam transmission (1.53%) values and small difference in salinity (0.08 psu) values were greater than the differences found in the well-mixed area (Fig. 17.4.1b). These observed differences in stratification around this island are likely a result of enhanced mixing on the wind-exposed east side and surface heating of the upper water column on the leeward side.

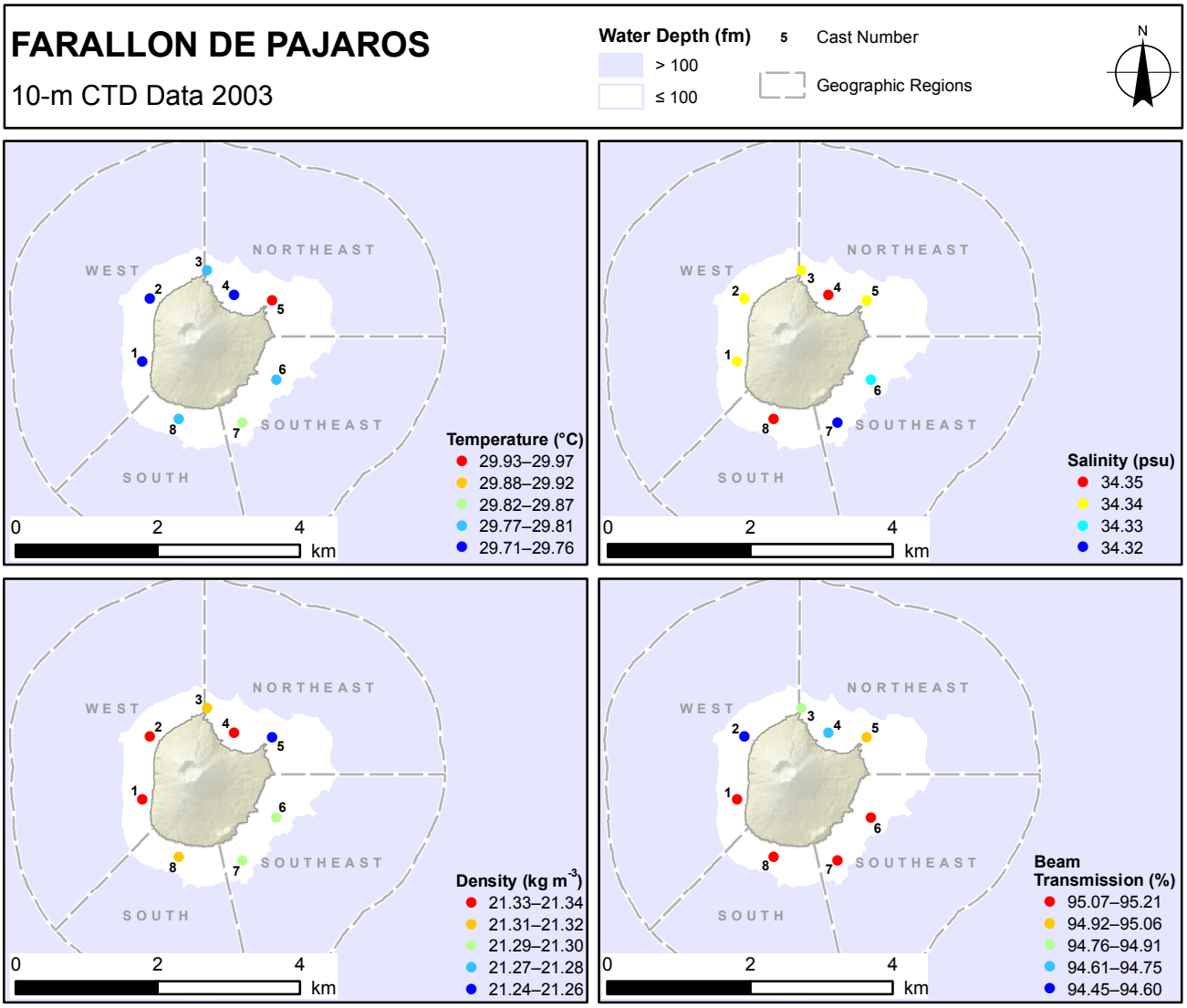


Figure 17.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Farallon de Pajaros on August 30 during MARAMP 2003.

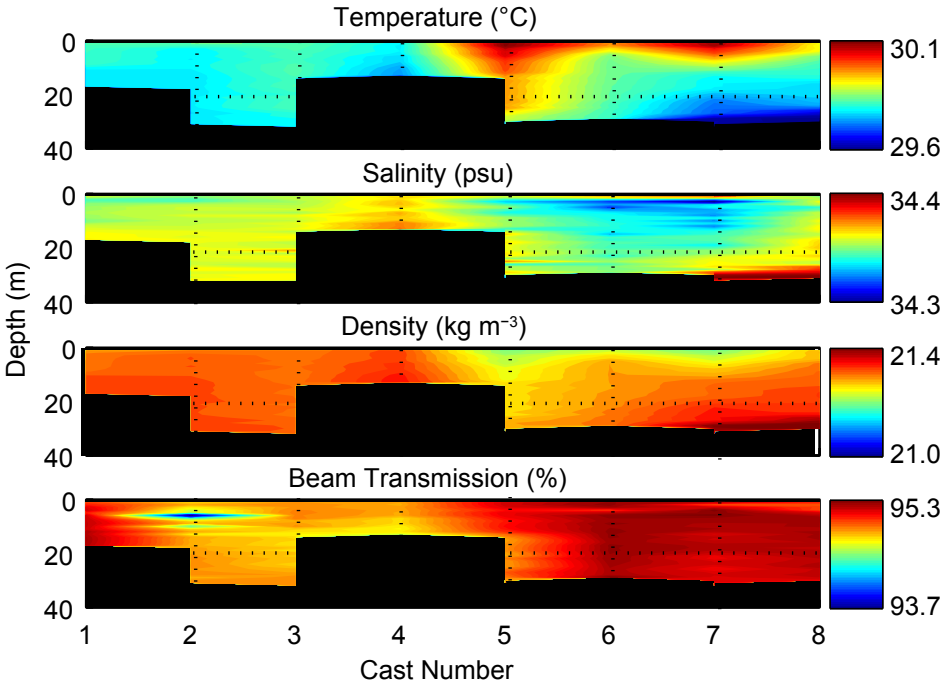


Figure 17.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Farallon de Pajaros on August 30 during MARAMP 2003, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–8 in a clockwise direction around Farallon de Pajaros. For cast locations and numbers around this island in 2003, see Figure 17.4.1a.

2005 Spatial Surveys

During MARAMP 2005, 12 shallow-water CTD casts were conducted in nearshore waters around Farallon de Pajaros on September 10. Spatial comparisons of water properties at a depth of 10 m suggest small ranges in temperature (0.12°C), salinity (0.04 psu), density (0.03 kg m^{-3}), and beam transmission (< 0.31%) values (Fig. 17.4.1c). Vertical comparisons of CTD profiles reveal a generally well-mixed water column with small differences in temperature (0.22°C), salinity (0.06 psu), density (0.09 kg m^{-3}), and beam transmission (1.48%) values (Fig. 17.4.1d).

Water samples were collected in concert with shallow-water CTD casts at 4 select locations around Farallon de Pajaros in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.29–1.15 µg L^{-1}; total nitrogen (TN), 0.039–0.44 µM; nitrate (NO_3^-), 0.017–0.022 µM; nitrite (NO_2^-), 0.021–0.023 µM; phosphate (PO_4^{3-}), 0.004–0.008 µM; and silicate [$Si(OH)_4$], 0.65–1.41 µM. Chl-*a* values were highest in the south and southeast regions; total nitrogen, nitrate, nitrite, and phosphate values were similar in all regions; and silicate values were higher in the west and northeast regions than in the south and southeast regions (Fig. 17.4.1e).

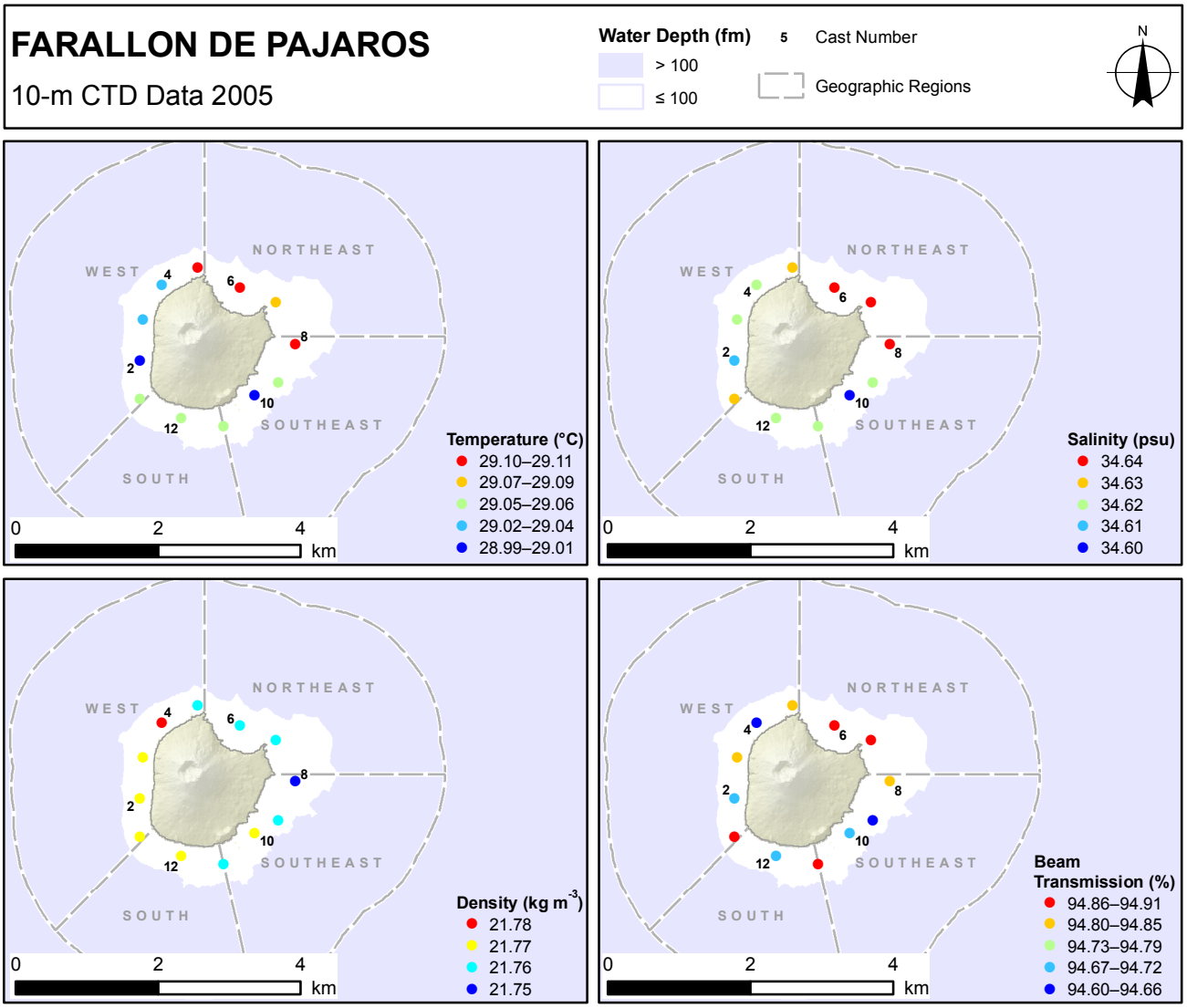
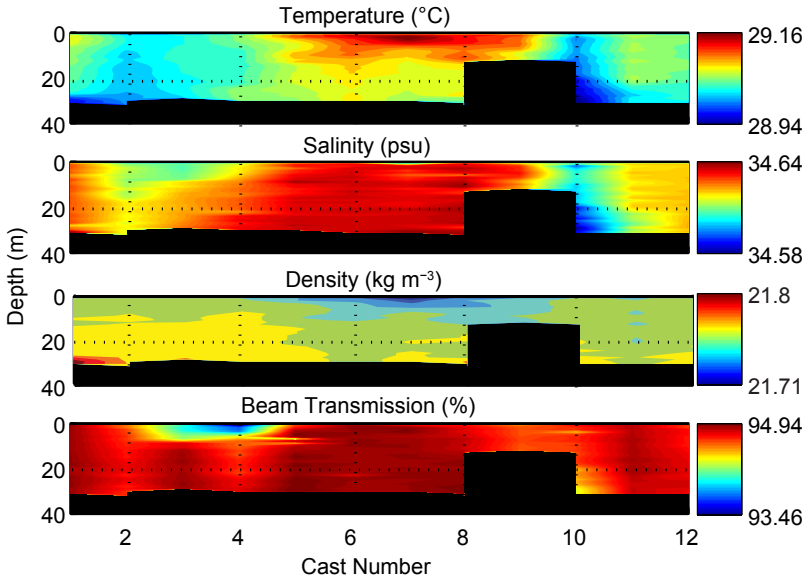


Figure 17.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom right*) density, and (*bottom left*) beam transmission at a 10-m depth from shallow-water CTD casts around Farallon de Pajaros on September 10 during MARAMP 2005.

Figure 17.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Farallon de Pajaros on September 10 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–12 in a clockwise direction around Farallon de Pajaros. For cast locations and numbers around this island in 2005, see Figure 17.4.1c.



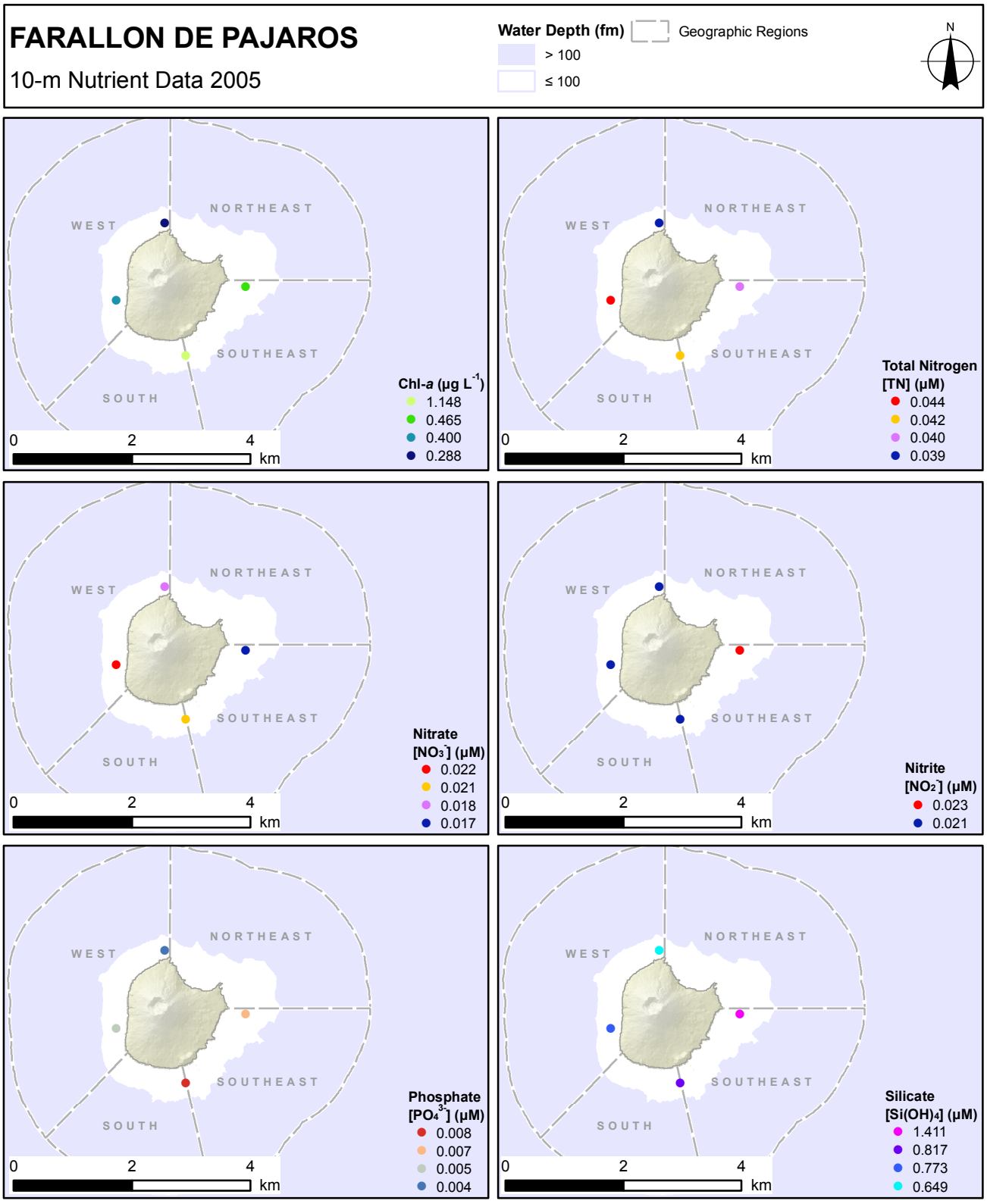


Figure 17.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Farallon de Pajaros on September 10 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, 7 shallow-water CTD casts were conducted in nearshore waters around Farallon de Pajaros on June 3. Spatial comparisons of water properties at a depth of 10 m suggest generally moderate differences around this island with a large range in temperature measured up to 0.98°C (Fig. 17.4.1f). Vertical comparisons of CTD profiles reveal considerable temperature (3.44°C) and density (1.99 kg m^{-3}) stratification, a moderate difference in salinity (0.34 psu) levels, and a small difference in beam transmission (0.43%) values (Fig. 17.4.1g). The large variation in temperatures could have been a result of localized upwelling of subsurface waters. The definitive mechanism driving this process is unclear; however, subsurface temperature data obtained from Farallon de Pajaros, and presented later in this section (see Section 17.4.2: "Time-series Observations"), exhibit high-frequency fluctuations that are often associated with internal tide activity.

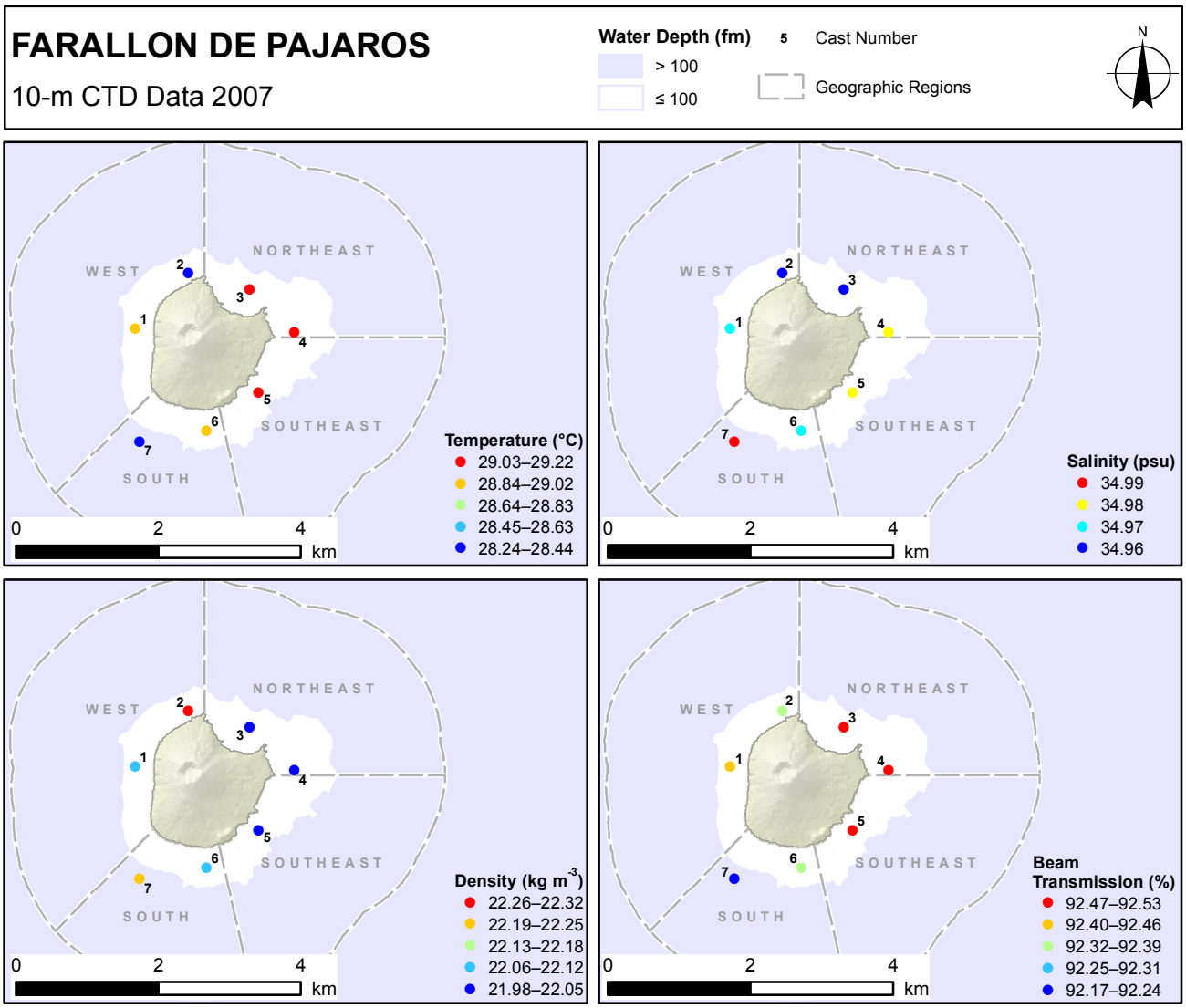


Figure 17.4.1f. Values of (top left) water temperature, (top right) salinity, (bottom left) density, and (bottom right) beam transmission at a 10-m depth from shallow-water CTD casts around Farallon de Pajaros on June 3 during MARAMP 2007.

Water samples were collected in concert with shallow-water CTD casts at 3 select locations around Farallon de Pajaros in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: Chl-*a*, 0.01–0.07 µg L^{-1}; total nitrogen (TN), 0.014–0.024 µM; nitrate (NO_3^-), 0.006–0.013 µM; nitrite (NO_2^-), 0.008–0.011 µM; phosphate (PO_4^{3-}), 0.002–0.003 µM; and silicate [Si(OH)4], 1.27–1.77 µM. Water-quality parameters were generally observed at the relatively low levels typical of the Western Pacific Warm Pool's oligotrophic, oceanic surface layers. The lowest Chl-*a* value corresponded with the highest total nitrogen value in the west region (Fig. 17.4.1h). The lowest concentration of total nitrogen was found in the northeast region. Values for nitrate, nitrite, and phosphate were similar around this island. Silicate concentrations were highest in the south and lowest in the northeast region.

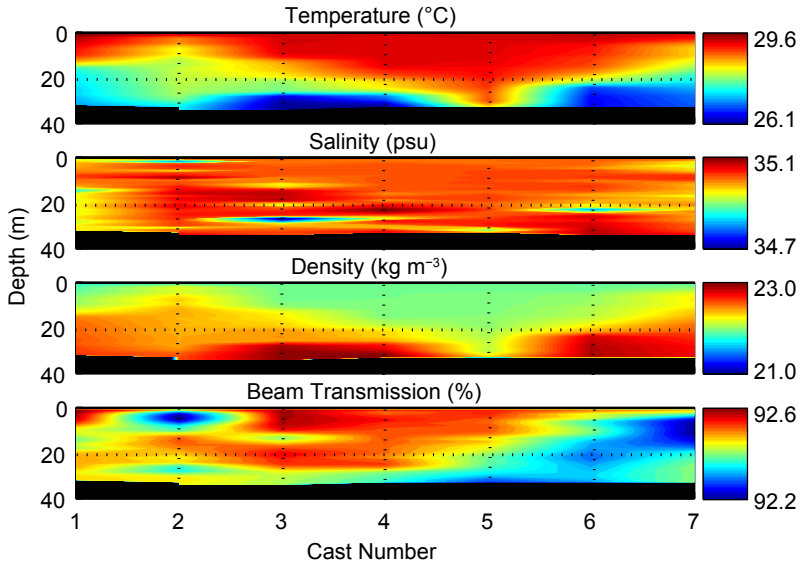


Figure 17.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Farallon de Pajaros on June 3 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%).Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–7 in a clockwise direction around Farallon de Pajaros. For cast locations and numbers around this island in 2007, see Figure 17.4.1f.

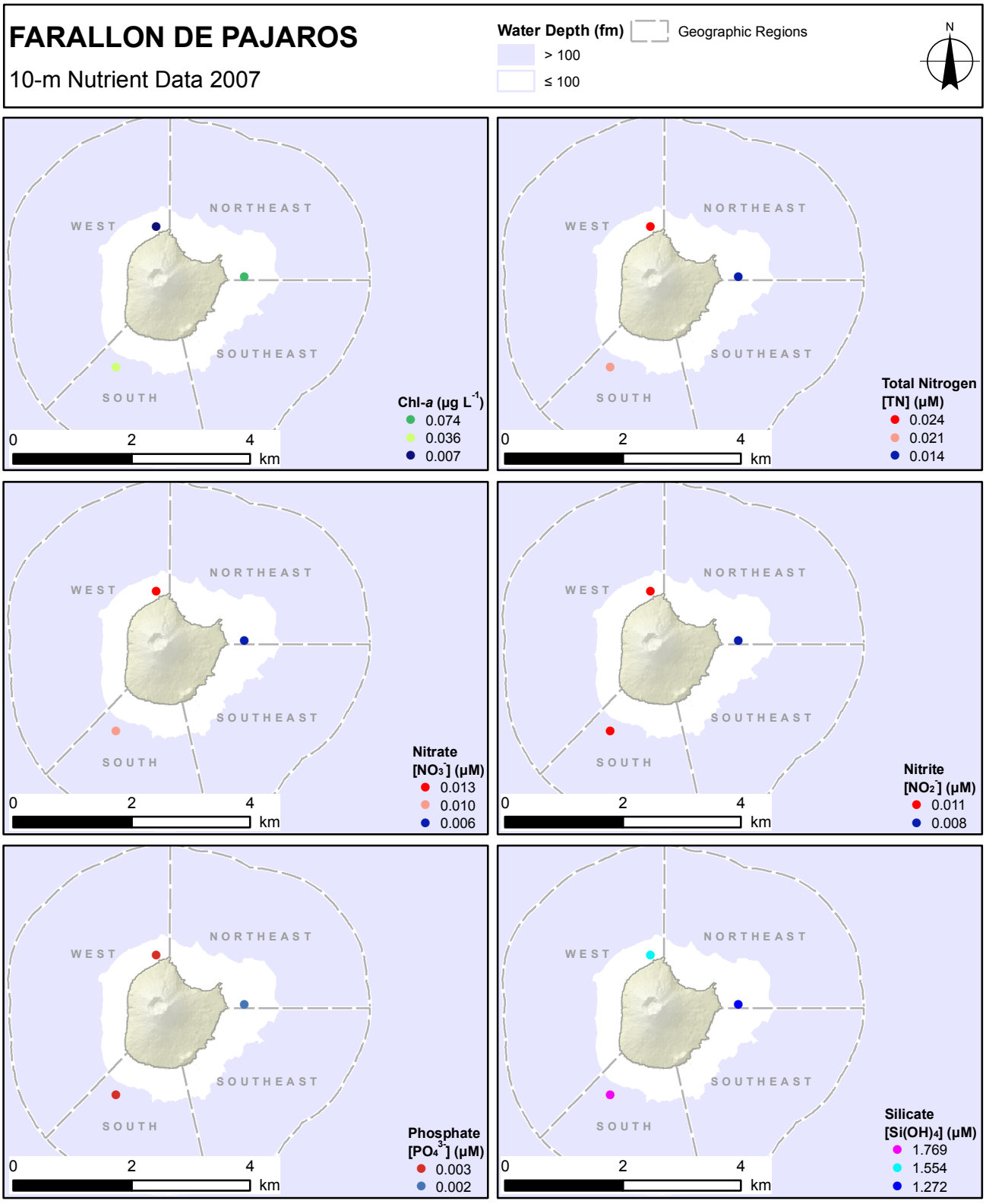


Figure 17.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Farallon de Pajaros on June 3 during MARAMP 2007.

Temporal Comparison

Comparisons of shallow-water CTD data between MARAMP surveys in 2003, 2005, and 2007 suggest a dynamic physical oceanographic environment around Farallon de Pajaros. Data from MARAMP 2003 and 2005 exhibit low spatial variability and moderate vertical variability, while the data from MARAMP 2007 exhibit substantial spatial variability in water properties. Cold-water intrusions (26.1°C, or 3.5°C colder than surface waters) originating from below a depth of 30 m were prominent in 2007, likely a result of upwelling or internal tide activity. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in June, and MARAMP 2003 and 2005 occurred in August and September. This change was made to avoid the typhoon season and reduce the probability of weather disruptions.

Water-quality data obtained during MARAMP 2005 and 2007 suggest that nutrient concentrations are highly variable spatially and temporally and patterns within years are generally incongruous with one another. All of the parameters measured were lower in 2007 than in 2005, except for silicate. Chl-*a* concentrations were notably lower in 2007 than 2005. Differences between these survey years are likely a result of seasonal effects. Precipitation data show that MARAMP 2005 occurred during a period of seasonally high precipitation, while MARAMP 2007 occurred during a period of seasonally low precipitation (For precipitation information, see Chapter 3: "Archipelagic Comparisons," Section 3.1: "Oceanography and Water Quality: Seasonal Climatologies").

17.4.2 Time-series Observations

Between 2003 and 2007, subsurface temperature recorders (STRs) were deployed along 2 vertical transects at Farallon de Pajaros to collect time-series observations of a key oceanographic parameter. These data were collected in part to investigate the temperature and depth ranges of the possible internal tidal signal mentioned previously in the "2007 Spatial Surveys" part of this section. The locations, depths, time frames, and other details about these deployments are provided in Figures 17.4.2a and b.

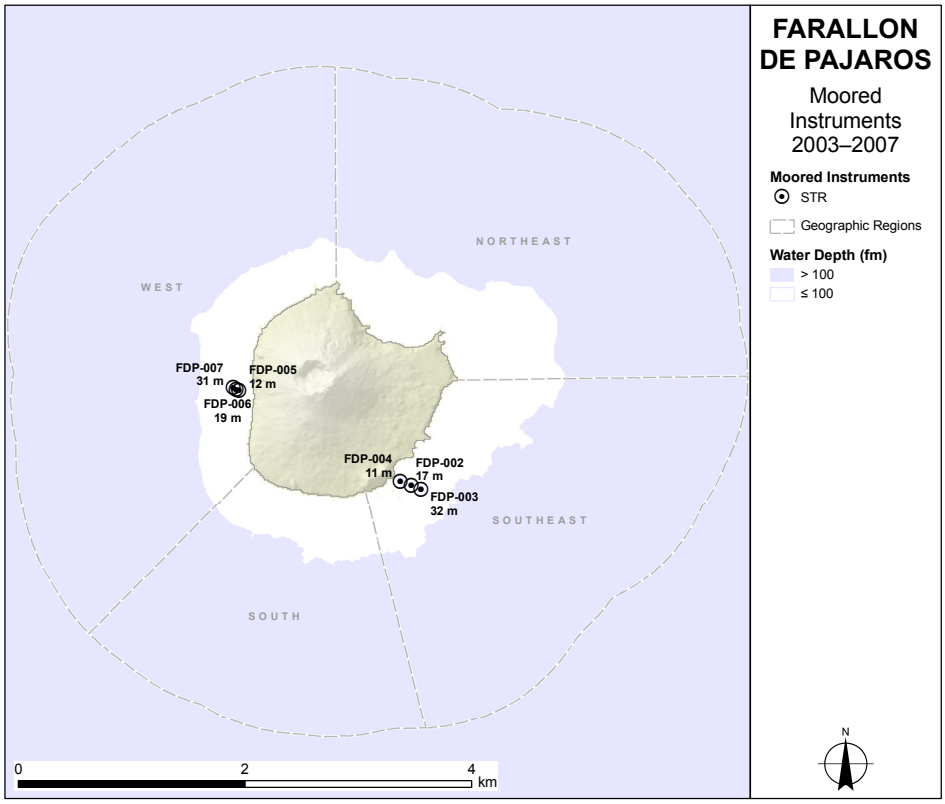


Figure 17.4.2a. Locations and depths of the STRs deployed at Farallon de Pajaros during MARAMP 2003, 2005, and 2007.

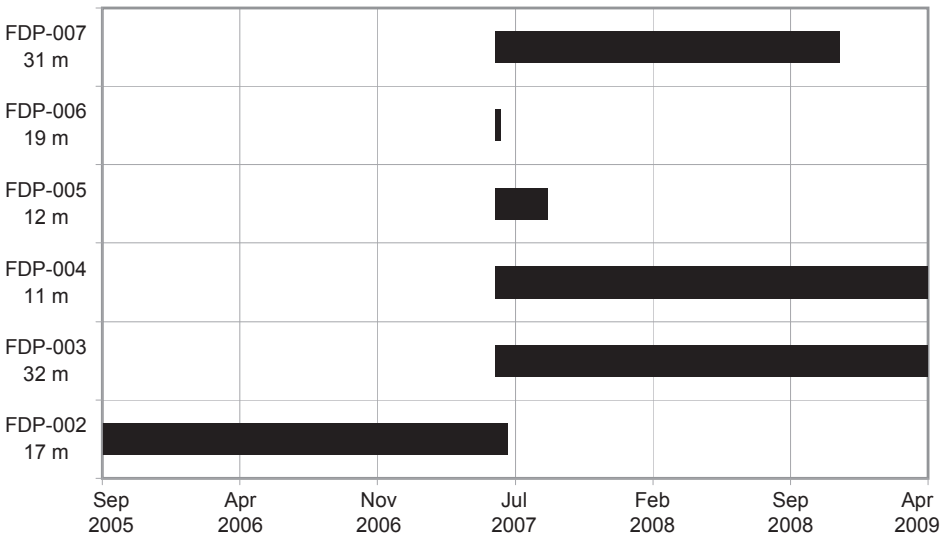


Figure 17.4.2b. Deployment timelines and depths of the STRs installed at Farallon de Pajaros during the period from September 2005 to April 2009. A solid bar indicates the period for which temperature data were collected by a single or a series of STRs deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 17.2b in Section 17.2: "Survey Effort."

Temperature data from 1 STR located at a depth of 17 m in the southeast region of Farallon de Pajaros show typical seasonal temperature variability of ~ 5°C (Fig. 17.4.2c). Water temperatures reached ~ 29.5°C during the months of July–October and fell to a low of ~ 25°C during the months of January–May. Rapid (~ 12-h return periods) temperature fluctuations of 1°C–3°C were recorded in the springs of 2006 and 2007. Internal tides are generated when tidal currents interact with steep subsurface topography, resulting in high-frequency variability in temperature, salinity, dissolved nutrients, and suspended particle concentrations that differ significantly from shallow reefs to deep slopes. Although more research and additional data are needed to properly ascertain the nature of these signals, these high-frequency temperature plunges likely were the result of internal tides carrying colder, more nutrient-rich water from greater depths into the shallow-water coral reefs.

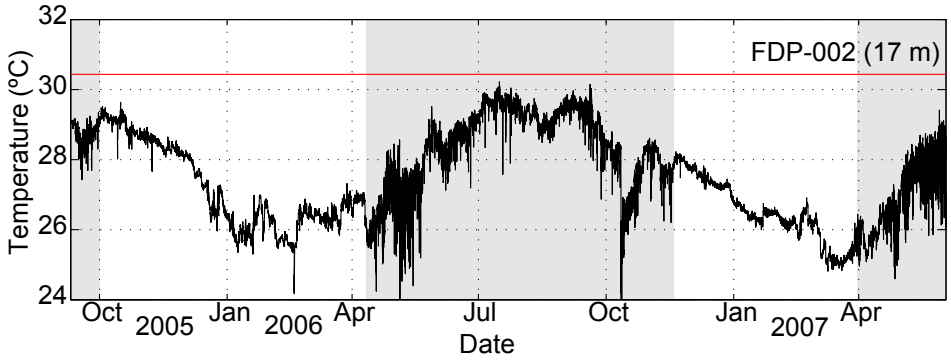


Figure 17.4.2c. Time-series observations of temperature from September 2005 to July 2007 collected from 1 STR mooring site at a depth of 17 m at Farallon de Pajaros (see Figure 17.4.2a for the location). A grey background indicates a period of high-frequency variability that likely resulted from internal tide activity. The red line shows the satellite-derived coral bleaching threshold.

17.4.3 Wave Watch III Climatology

Seasonal wave climatology for Farallon de Pajaros was derived using the NOAA Wave Watch III model for the period of January 1997–May 2008 (Fig. 17.4.3a), and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–3 m) wave events originating almost exclusively from the east (90°). Superimposed with these short-period trade wind swells were large (> 4 m), long-period (12–16 s) wave events principally from the south (180°), although they could originate from a broad directional source (120°–200°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from the southwest (210°–250°) and likely were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) was also characterized by frequent (> 30 d per season) and short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 10 d per season) and long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this period and originate from the northwest (~ 330°).

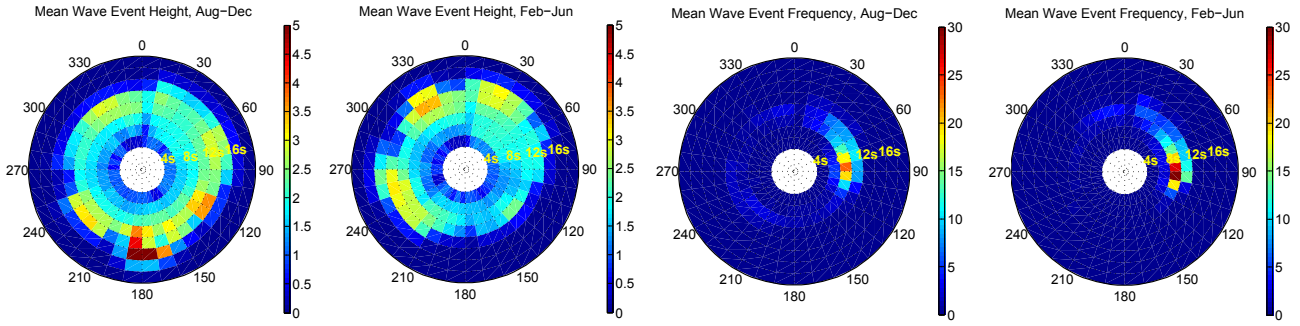


Figure 17.4.3a. NOAA Wave Watch III directional wave climatology for Farallon de Pajaros from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Farallon de Pajaros (20°30' N, 144°54' E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occur in each season, indicated by color scale ; for example, if the color indicates 30, then, on average, the condition occurred during 30 out of 150 days of that season.

17.5 Corals and Coral Disease

17.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the island of Farallon de Pajaros was 10% (SE 0.9). Coral cover was low in all regions, compared with results from surveys conducted around other islands in the Mariana Archipelago, with the majority (81%) of survey segments exhibiting < 10% live coral cover (Fig. 17.5.1a, top panel). In one segment of a survey conducted in the southeast region, estimates of coral cover were 30%–40%, the highest level observed around this island.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Farallon de Pajaros was 5% (SE 0.8). Coral cover was low in all regions (Fig. 17.5.1a, middle panel). Towed divers recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5: "Corals and Coral Disease"). Overall, 2% (SE 1.1) of coral cover observed on forereef habitats around Farallon de Pajaros appeared stressed. This observation of stressed corals was made in the west region during a survey for which estimates of coral cover were 1%–5%.

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Farallon de Pajaros was 5% (SE 0.6). Similar to findings in 2005, coral cover was low in all regions (Fig. 17.5.1a, bottom panel). Overall, 2% (SE 0.8) of coral cover observed on forereef habitats appeared stressed. Two segments with stressed-coral cover > 10% were noted along the exposure of the west and northeast regions; estimates of coral cover for these segments were 1%–10%.

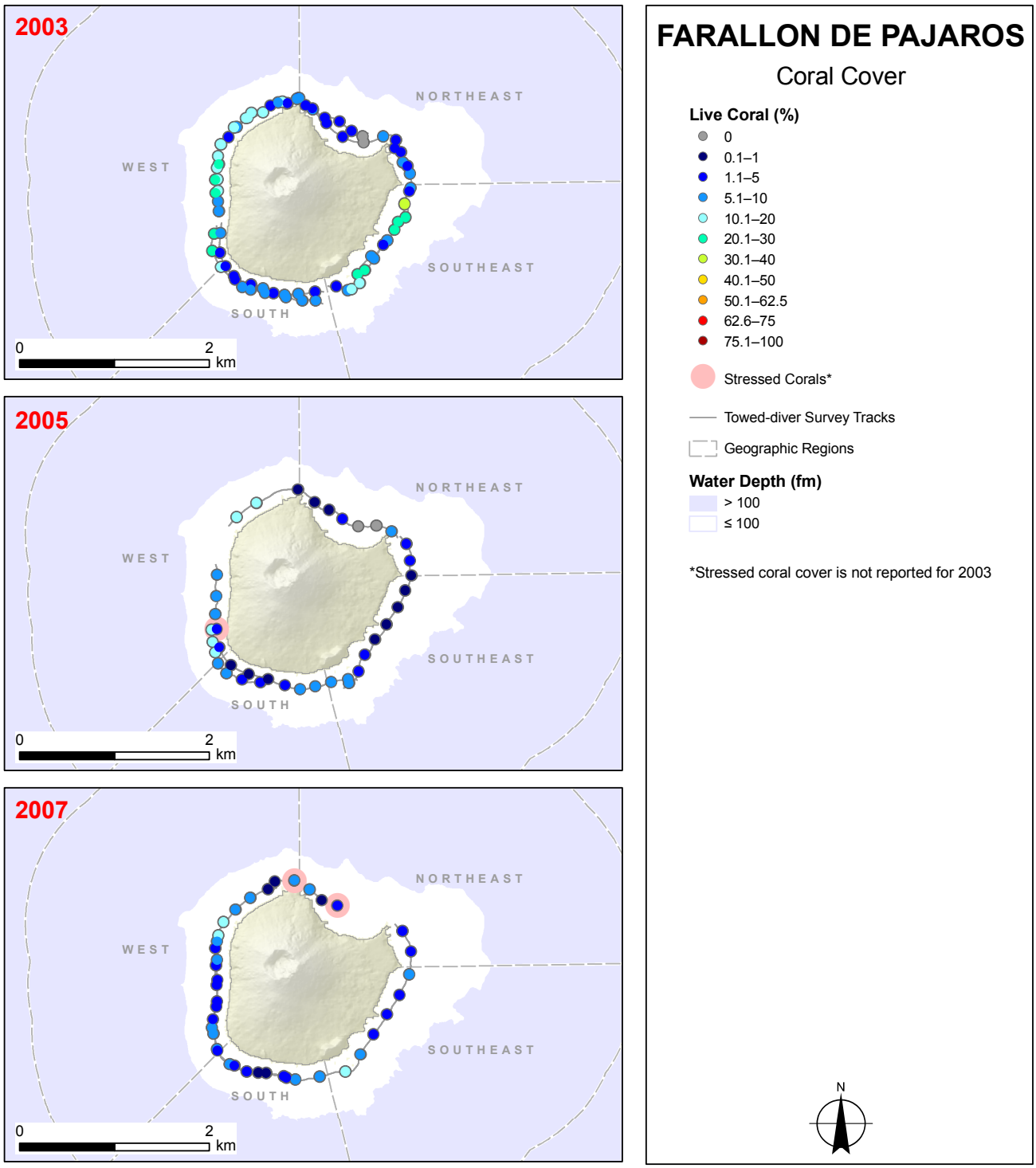


Figure 17.5.1a. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005 and 2007.

During MARAMP 2003, 2 REA benthic surveys using the quadrat method on forereef habitats at Farallon de Pajaros documented 83 coral colonies within a total survey area of 7.5 m^2. Site-specific colony densities were 10.1 colonies m^{-2} at REA site FDP-02 in the west region and 12.2 colonies m^{-2} at FDP-01 in the southeast region (Fig. 17.5.1b, top panel) with a mean of 11.1 colonies m^{-2} (SE 0.9).

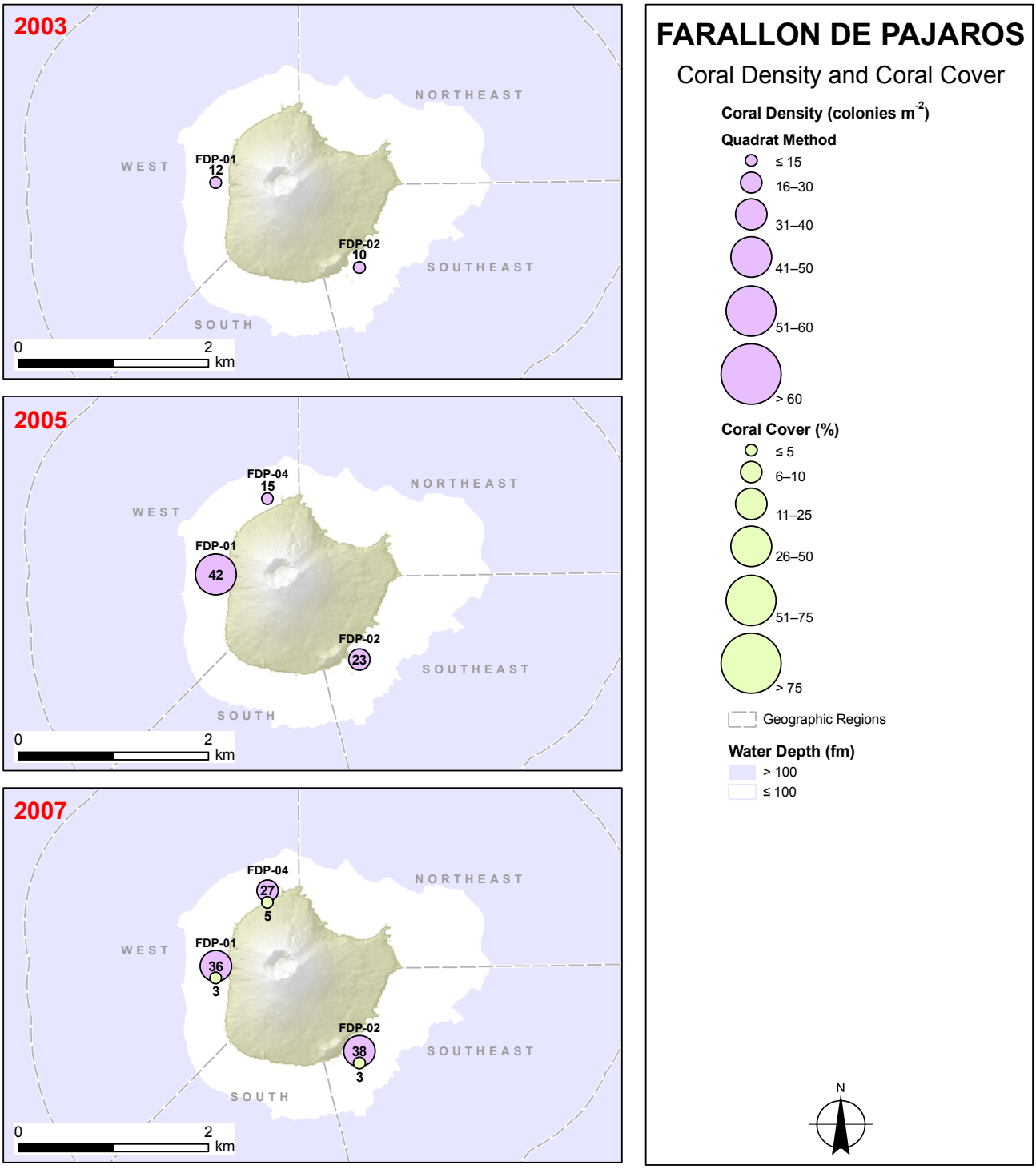


Figure 17.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Farallon de Pajaros during MARAMP 2003, 2005, and 2007 and cover (%) observations of live corals from REA benthic surveys during MARAMP 2007. Values are provided within, above, or below each symbol. The quadrat method was used to assess coral-colony density.

During MARAMP 2005, 3 REA benthic surveys using the quadrat method on forereef habitats at Farallon de Pajaros documented 318 coral colonies within a total survey area of 12 m^2. Site-specific colony density ranged from 14.8 to 41.5 colonies m^{-2} with an overall sample mean of 26.5 colonies m^{-2} (SE 7.9). The highest colony density was recorded at FDP-01 (Fig. 17.5.1b, middle panel).

During MARAMP 2007, 3 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Farallon de Pajaros. Site-specific estimates of live-hard-coral cover from these surveys ranged from 2.9% to 4.9% (Fig. 17.5.1b, bottom panel) with an overall sample mean of 3.6% (SE 0.7). Live coral cover was slightly higher at FDP-04 compared to FDP-01 and FDP-02.

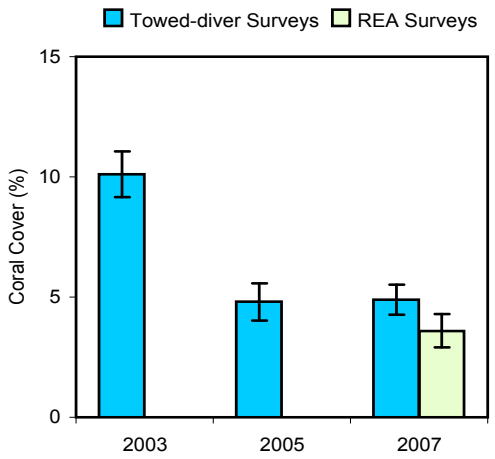


Figure 17.5.1c. Temporal comparison of the mean live coral cover (%) values from REA and towed-diver benthic surveys conducted on forereef habitats around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted around Farallon de Pajaros in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

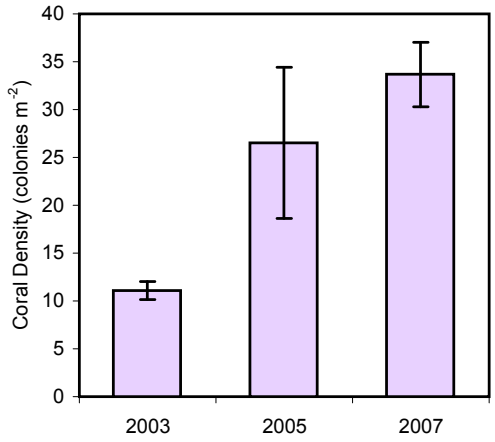


Figure 17.5.1d. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Farallon de Pajaros during MARAMP 2003, 2005, and 2007. The quadrat method was used in all 3 years to measure coral-colony density. Error bars indicate standard error (± 1 SE) of the mean.

During MARAMP 2007, 3 REA benthic surveys using the quadrat method on forereef habitats at Farallon de Pajaros documented 404 coral colonies within a total survey area of 12 m^2. Site-specific colony density ranged from 27 to 37.8 colonies m^{-2} with an overall sample mean of 33.7 colonies m^{-2} (SE 3.4). The highest colony density was recorded at FDP-02 (Fig. 17.5.1b, bottom panel).

Islandwide mean cover of live corals, estimated from towed-diver surveys of forereef habitats, varied between MARAMP survey years, ranging from 10% (SE 0.9) in 2003 to 5% (SE 0.8) in 2005 (Fig. 17.5.1c); the estimate in 2007 was also 5% (SE 0.6). The decrease by half in coral cover between 2003 and 2005 does not appear to be a reflection of spatial variation in survey effort between the 2 MARAMP survey years, since the areas with highest coral cover in 2003 were resurveyed in 2005 and 2007. The decline in coral cover between 2003 and 2005 is particularly evident in the southeast and west regions. In each survey year, looking at results by region, the highest level of coral cover was recorded in the west region. Similar to estimates of coral cover from towed-diver surveys conducted at this island in 2007, site-specific estimates of coral cover averaged 3.6% (SE 0.7) for the 3 REA sites surveyed in 2007 (Farallon de Pajaros was not surveyed for coral cover using the line-point-intercept method in 2003 or 2005).

The overall sample mean of coral-colony density from REA benthic surveys of forereef habitats around Farallon de Pajaros increased from 11.1 colonies m^{-2} (SE 0.9) in 2003 to 26.5 colonies m^{-2} (SE 7.9) in 2005 and 33.7 colonies m^{-2} (SE 3.4) in 2007 (Fig. 17.5.1d). The same temporal pattern exists when only the 2 sites surveyed in all 3 years (FDP-01 and FDP-02) are examined: mean density increased from 11.1 colonies m^{-2} (SE 0.9) in 2003 to 32.4 colonies m^{-2} (SE 9.1) in 2005 and 37 colonies m^{-2} (SE 0.8) in 2007. The change in colony density between 2003 and 2007 could reflect increased recruitment, fragmentation of existing colonies, or both.

Coral Generic Richness and Relative Abundance

Two REA benthic surveys of forereef habitats were conducted using the quadrat method at Farallon de Pajaros during MARAMP 2003, and at least 7 coral genera were observed at each site (Fig. 17.5.1e, top panel). Three REA benthic surveys of forereef habitats were conducted using the quadrat method during MARAMP 2005. Generic richness in 2005 ranged from 2 genera at FDP-04 to 13 genera at FDP-01, with an overall mean of 6 (SE 3.5) coral genera per site (Fig. 17.5.1e, middle panel). The same 3 sites were surveyed using the quadrat method during MARAMP 2007. The fewest gen-

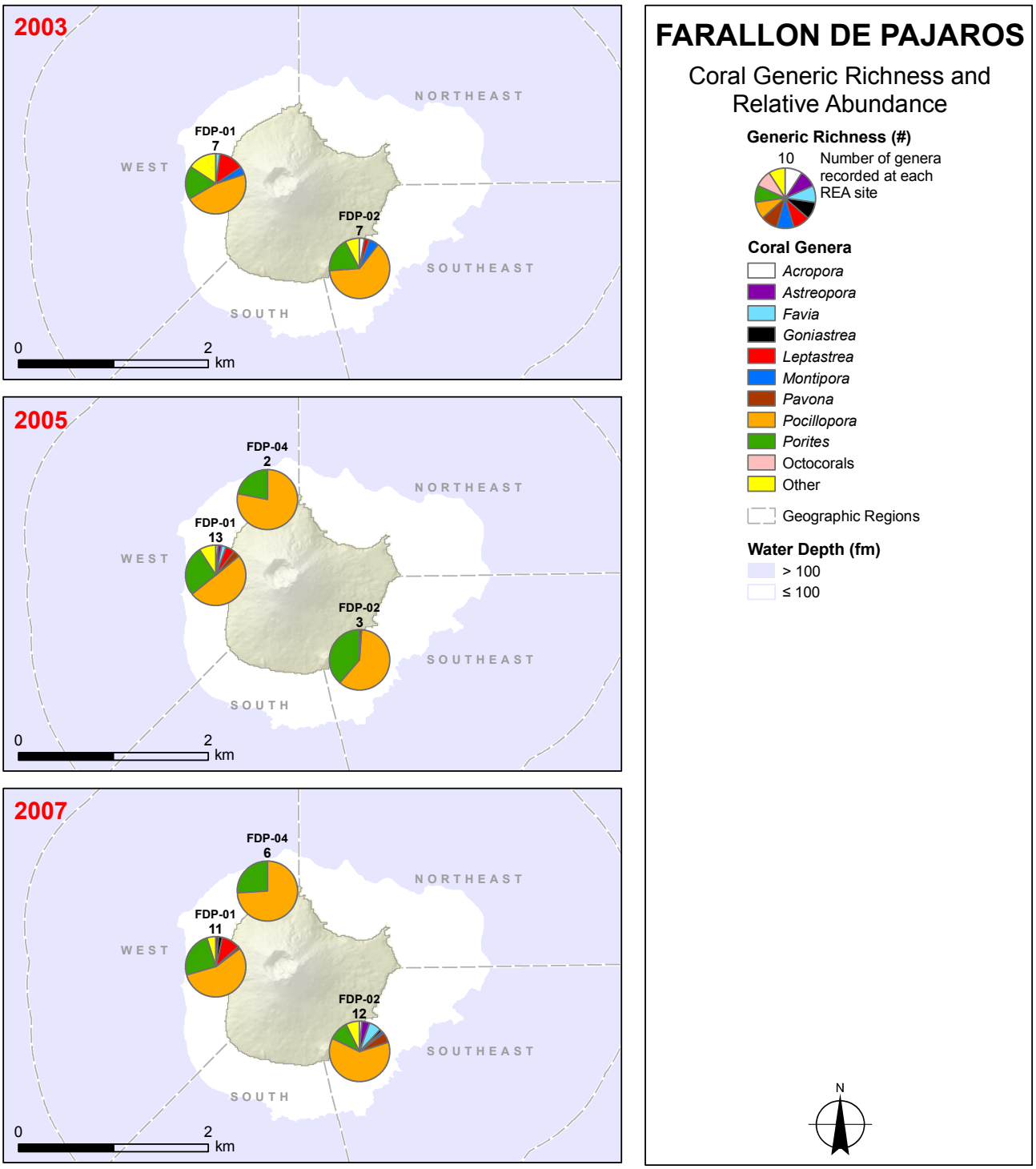


Figure 17.5.1e. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Farallon de Pajaros during MARAMP 2003, 2005, and 2007. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in all 3 years to survey coral genera.

era (6) were again found at FDP-04 in 2007, but the most genera (12) were now observed at FDP-02 (Fig. 17.5.1e, bottom panel). This higher number of genera detected at FDP-02 in 2007 (12, compared to 3 in 2005) contributed to an increase in the overall mean to 9.7 (SE 1.9) coral genera per site.

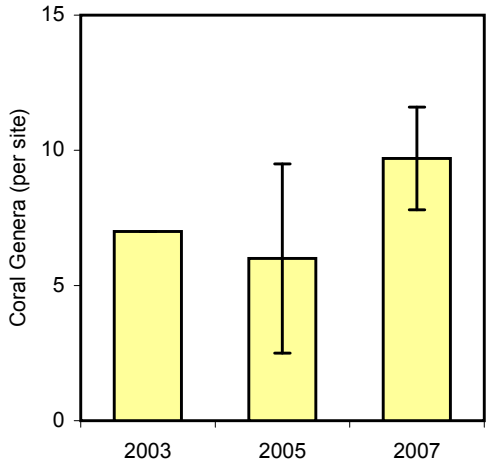


Figure 17.5.1f. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. The quadrat method was used in the 3 years to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

The overall sample mean of generic richness on forereef habitats at Farallon de Pajaros was higher in 2007 with 9.7 (SE 1.9) coral genera per site than in 2003 and 2005 with 7 (SE 0) and 6 (SE 3.5) coral genera per site (Fig. 17.5.1f). This change is also seen when only the 2 sites surveyed in all 3 years (FDP-01 and FDP-02) are examined. Mean generic richness for these 2 sites increased from 7 (SE 0) coral genera per site in 2003 to 11.5 (SE 0.5) coral genera per site in 2007. This increase in observed generic richness between 2003 and 2007 resulted from both a greater number of genera being recorded at individual sites and from additional genera being recorded in 2007.

During the 3 MARAMP survey years, 17 coral genera were observed on forereef habitats at this island. *Pocillopora* and *Porites* were the most dominant genera, contributing more than 10% of the total number of colonies enumerated at Farallon de Pajaros in the 3 survey years. *Pocillopora* was the most numerically abundant genus of the coral fauna in all 3 survey years, accounting for 54.9%, 62.7%, and 62.7% of the total number of colonies enumerated in 2003, 2005 and 2007. *Porites* was the second-most numerically abundant taxon in all 3 survey periods, contributing 18.1%, 29.1%, and 19.9% of the total number of colonies in 2003, 2005, and 2007. All other taxa contributed < 10% to the total number of colonies in all 3 MARAMP survey years.

Coral Size-class Distribution

During MARAMP 2003, 2 REA benthic surveys of forereef habitats were conducted at Farallon de Pajaros using the quadrat method. The coral size-class distribution from these surveys shows that the majority (78.6%) of corals had maximum diameters ≤ 5 cm (Fig. 17.5.1g, top panel). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 13%, 7.3%, and 1.1% of colonies recorded. No colonies with maximum diameters > 40 cm were recorded. High proportions of small (≤ 10 cm) colonies were found at the 2 sites surveyed with 91.1% and 92.1% at FDP-01 and FDP-02. The proportions of midsize (11–40 cm) colonies at the same sites were 8.9% and 7.9%.

During MARAMP 2005, 3 REA benthic surveys of forereef habitats were conducted at Farallon de Pajaros using the quadrat method. The coral size-class distribution from these surveys shows that the majority (95%) of corals had maximum diameters ≤ 5 cm (Fig. 17.5.1g, middle panel). The next 2 size classes (6–10 and 11–20 cm) accounted for 3.5% oand 1.5% of colonies recorded. No colonies with maximum diameter > 20 cm were recorded. High proportions of small (≤ 10 cm) colonies were found at all 3 sites surveyed with 100%, 98.9%, and 96.6% at FDP-01, FDP-02, and FDP-04. Correspondingly, low proportions of midsize (11–40 cm) colonies were observed at the same sites: 0%, 1.1%, and 3.4%.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats were conducted at Farallon de Pajaros using the quadrat method. The coral size-class distribution from these surveys shows that the majority (93.3%) of corals had maximum diameters ≤ 5 cm (Fig. 17.5.1g, bottom panel). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 4.8%, 1.7%, and 0.2% of colonies recorded. No colonies with maximum diameter > 40 cm were recorded. High proportions of small (≤ 10 cm) colonies were found at all 3 sites surveyed with 97.9%, 97.4%, and 99.1% at FDP-01, FDP-02, and FDP-04. Correspondingly, low proportions of midsize (11–40 cm) colonies were observed at the same sites: 2.1%, 2.7%, and 0.9%.

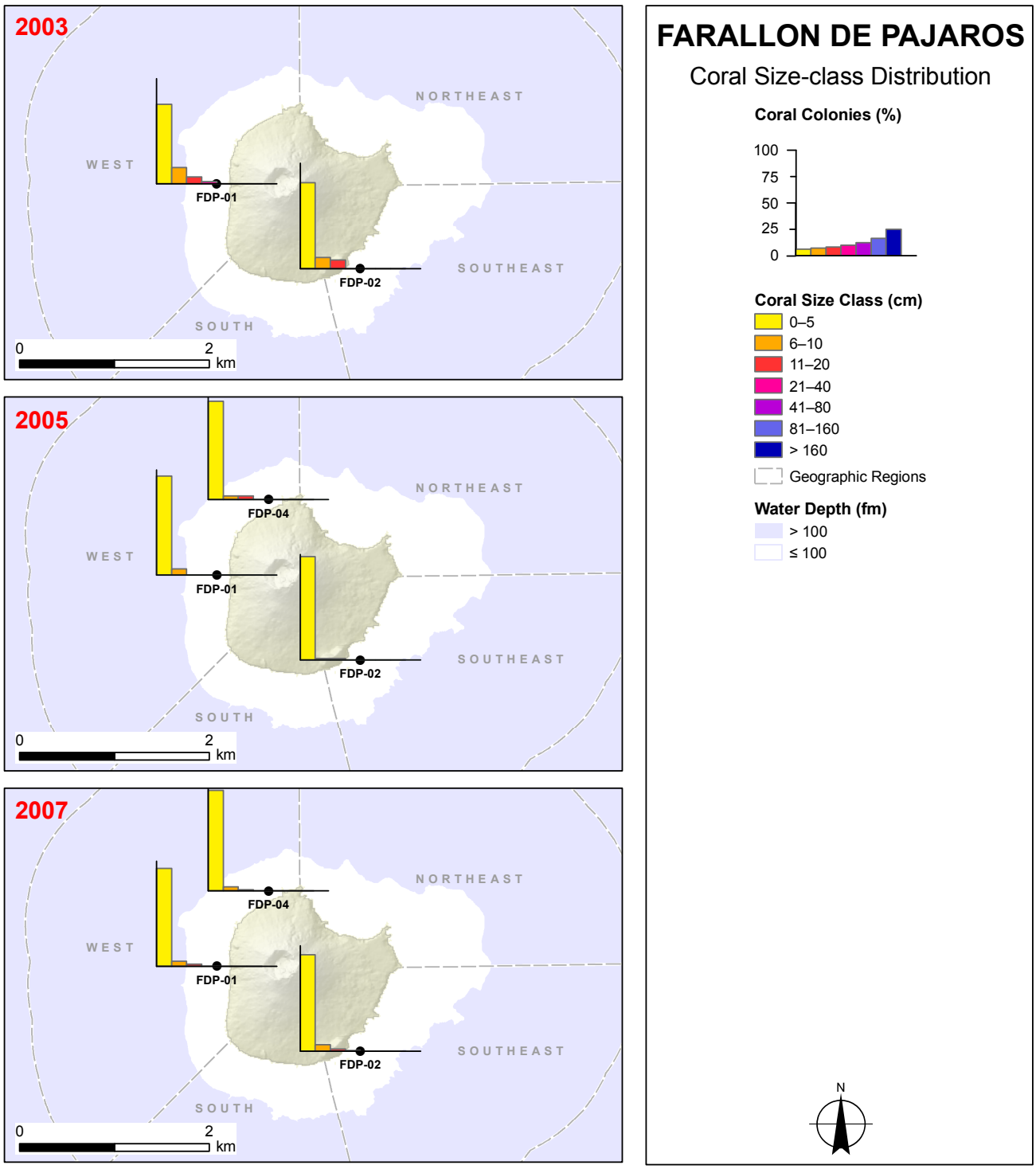


Figure 17.5.1g. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Farallon de Pajaros during MARAMP 2003, 2005 and 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used to size corals.

The quadrat method was used to establish size-class distributions on forereef habitats around Farallon de Pajaros during the 3 MARAMP survey periods. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. For more on this survey method, see Chapter 2, "Methods and Operational Background, Section 2.4.5: "Corals and Coral Disease."

In each of the 3 MARAMP survey years, the number of coral colonies in the smallest size class (< 5 cm) was much higher than the number in any of the other size classes (Fig. 17.5.1h). The overall sample mean proportion of colonies censused on forereef habitats at Farallon de Pajaros in the smallest size class increased from 78.6% in 2003 to 95% in 2005, as did the site-specific values for the 2 sites surveyed in both years (FDP-01 and FDP-02). Concordantly, the overall sample mean proportion of colonies in most other size classes decreased between 2003 and 2005, as did many site-specific proportions. This shift towards the smallest size class may reflect recruitment, fragmentation of existing colonies, or both. Minor changes in overall and site-specific size-class distributions between 2005 and 2007 likely reflect chance variation in the placement of individual quadrats.

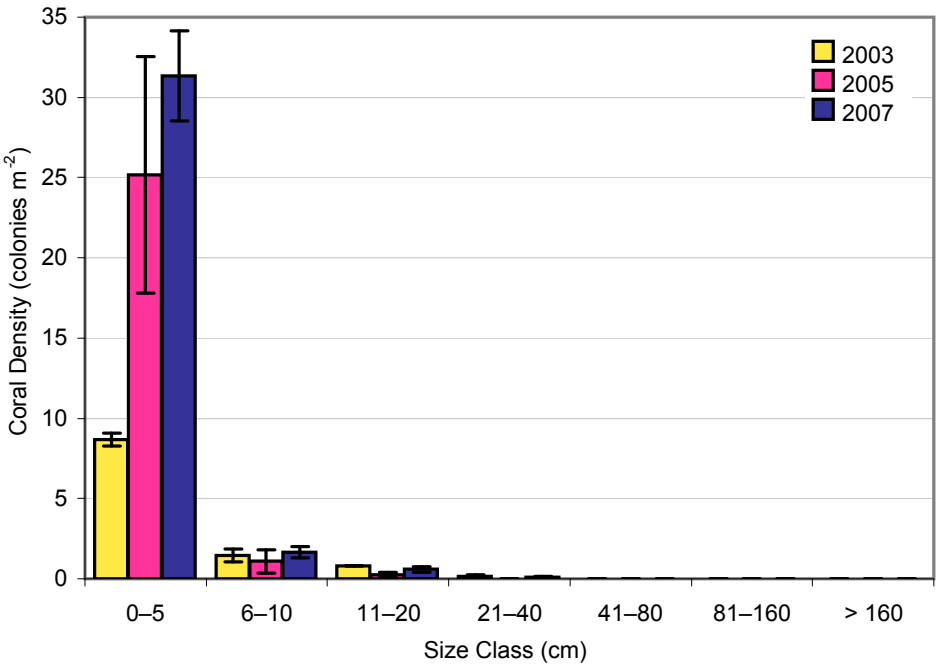


Figure 17.5.1h. Mean coral-colony density (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. The quadrat method was used in the 3 survey years to size corals. Error bars indicate standard error (± 1 SE) of the mean.

17.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted using the belt-transect method at 3 sites on forereef habitats around Farallon de Parajos, covering a total area of 900 m^2. No cases of coral disease or predation were detected. Farallon de Pajaros was the only island in the Mariana Archipelago to exhibit no coral disease.

17.6 Algae and Algal Disease

17.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the island of Farallon de Pajaros was 60% (SE 2.6). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 71%, within a range of 40.1%–100%, occurred in the west region (Fig. 17.6.1a, top left panel). Habitat in this area primarily comprised rock boulders and was classified as medium to medium-high complexity. Similar habitats were found at all survey sites, yet mean values of macroalgal cover were slightly greater on leeward reefs than on windward reefs. The lowest level of macroalgal cover was recorded in the southeast region, where mean macroalgal cover did not fall below 51%.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Farallon de Pajaros was only 4% (SE 1.3). Mean macroalgal cover was low during all surveys, never exceeding 5%, a level that was recorded in the southeast region (Fig. 17.6.1a, middle left panel). Surveys reported habitat as rock boulders and sand, and habitat complexity was classified predominantly as medium-low to medium.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats around Farallon de Pajaros was 3% (SE 0.4). As in 2005, mean macroalgal cover was low during all surveys. The surveys with the highest macroalgae cover of 5%, within a range of 1.1%–10%, occurred in the south and west region (Fig. 17.6.1a, bottom left panel). Surveys reported habitat as rock boulders and sand, and habitat complexity was classified predominantly as medium-high.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats around Farallon de Pajaros were conducted using the line-point-intercept method. No macroalgae were observed during these surveys. At all 3 REA sites surveyed in 2007, total algal cover was made up entirely of turf algae. Turf-algal cover ranged from 85.3% to 95.1% with an overall sample mean of 90% (SE 2.9). The survey with the highest turf-algal cover occurred in the west region at FDP-04 (Fig. 17.6.1b). Relatively high values of turf-algal cover also were recorded in the southeast region with 85.3% at FDP-02 and in the west region with 88.2% at FDP-01.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Farallon de Pajaros was 3% (SE 0.8). The survey with the highest mean crustose-coralline-red-algal cover of 10%, within a range of 0%–40%, occurred in the west region (Fig. 17.6.1a, top right panel). All other surveys reported relatively low values of 0%–4% for cover of crustose coralline red algae.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Farallon de Pajaros was 8% (SE 1.5). Similar to survey results in 2003, the survey with the highest mean crustose-coralline-red-algal cover of 10%, within a range of 0%–40%, occurred in the west region (Fig. 17.6.1a, middle right panel). Mean cover values of 14% and 15% were observed in areas the along eastern and western coasts. No crustose coralline red algae were observed on northern and southern coasts.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Farallon de Pajaros was 5% (SE 0.8). The surveys with the highest mean crustose-coralline-red-algal cover of 10%, within a range of 5.1%–20%, occurred in the west and south regions (Fig. 17.6.1a, bottom right panel). All other surveys reported relatively low values of 0%–4% for cover of crustose coralline red algae. Mean cover in both the northeast and southeast region was < 2%.

During MARAMP 2007, 3 REA benthic surveys of forereef habitats around Farallon de Pajaros were conducted using the line-point-intercept method. No crustose coralline red algae were observed during these surveys (Fig. 17.6.1b).

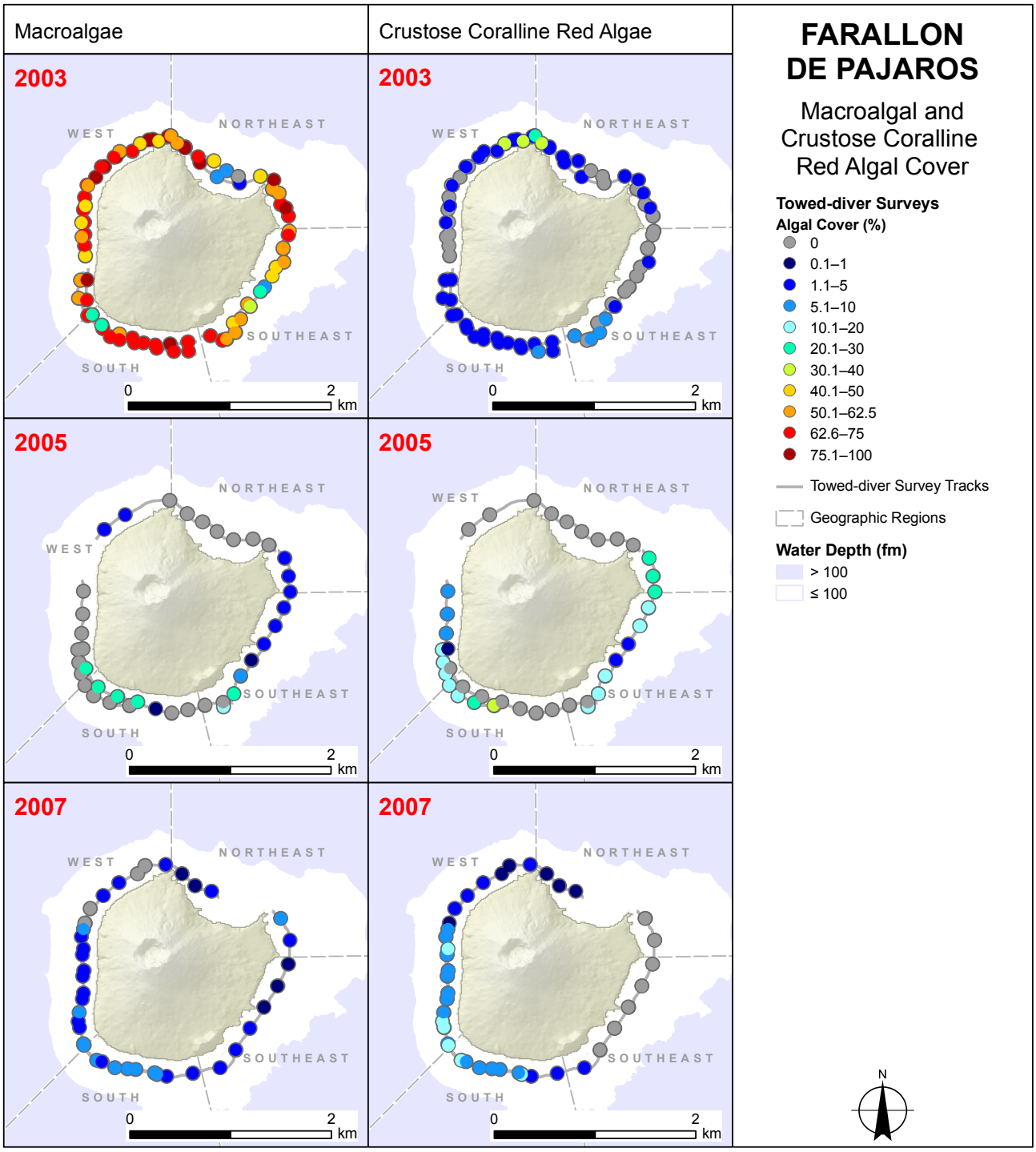


Figure 17.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003).

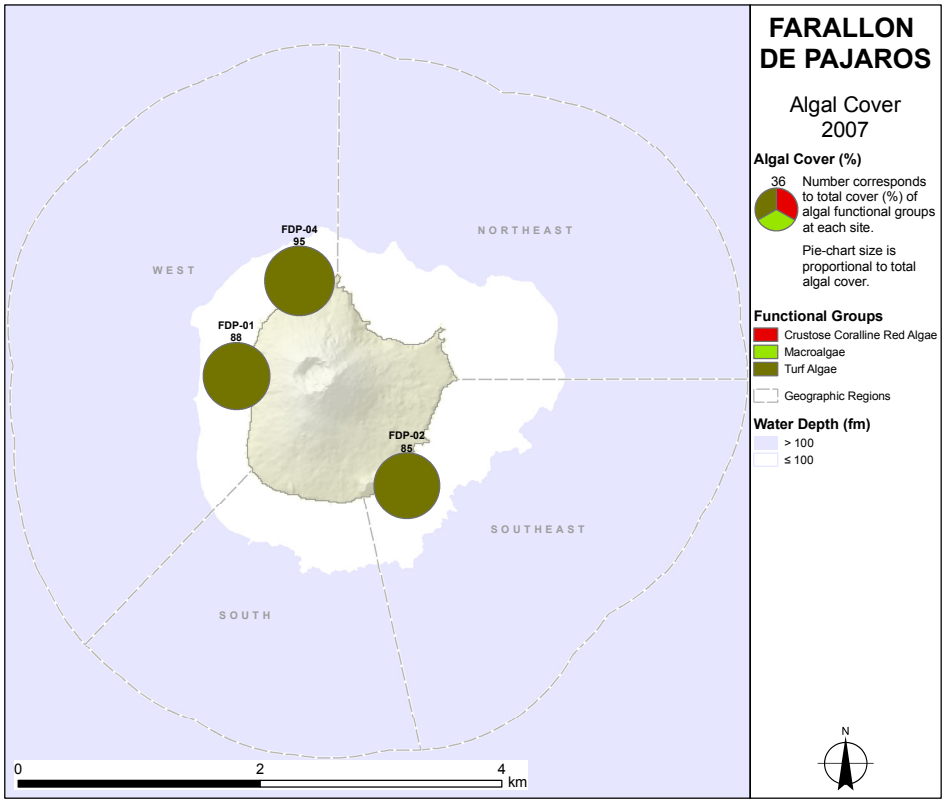


Figure 17.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method around Farallon de Pajaros during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, islandwide mean cover of macroalgal populations around Farallon de Pajaros, based on towed-diver surveys of forereef habitats, essentially remained the same (Fig. 17.6.1c). When considering results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Macroalgal cover decreased slightly from MARAMP 2005 to 2007 for some survey areas, particularly for east-facing reefs, but increased slightly between survey periods in the northeast region and along the west and south coasts.

Crustose-coralline-red-algal populations around Farallon de Pajaros, based on towed-diver surveys of forereef habitats, varied as much as 5% in average cover of the benthos between MARAMP survey years. The primary reason for the 5% increase in overall mean cover of crustose coralline red algae between MARAMP 2003 and 2005 was the observation of higher cover values along the east- and west-facing reefs in 2005 than in 2003. Crustose-coralline-red-algal cover values for the north- and south-facing reefs were all < 1% in 2005. Overall cover values decreased between MARAMP 2005 and 2007, particularly in surveys conducted in the northeast and southeast regions. Cover values in the west region decreased by 6%.

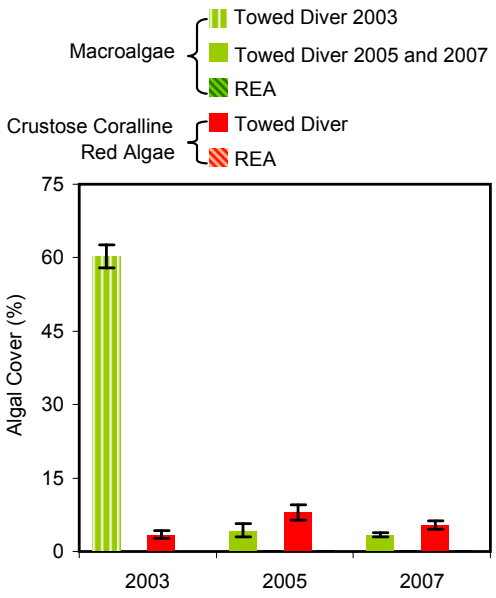


Figure 17.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats at Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted around Farallon de Pajaros in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 4 sites on forereef habitats around Farallon de Pajaros. In the field, 7 macroalgal genera (4 green and 3 brown), containing at least 7 species, as well as 2 additional algal functional groups—turf algae and crustose coralline red algae—were observed in the field. FDP-02 in the southeast region had the highest macroalgal generic diversity with 6 genera, containing 6 species, documented in the field. The lowest macroalgal generic diversity was found at FDP-01 with only turf algae and no macroalgae recorded.

The brown algal genus *Lobophora* was the most common component of the algal communities found around Farallon de Pajaros in 2003, observed in 35.4% of total sampled photoquadrats with 50% occurrence at FDP-02 and 91.7% occurrence at FDP-04 (Fig. 17.6.1d, top panel). *Lobophora* was the only genus to have > 17% occurrence at any site surveyed during MARAMP 2003. Of the remaining 6 taxa tentatively identified, none were observed at more than 1 of the 4 sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae around Farallon de Pajaros.

Turf algae were common in 2003, occurring in 75% of photoquadrats sampled around Farallon de Pajaros (Fig. 17.6.1d, top panel). The only site where turf algae were missing was FDP-03; however, no other algal functional group was recorded at that site. Crustose coralline red algae were common only at site FDP-04 in the north region, occurring in 41.7% of sampled photoquadrats, and sparse at site FDP-02, occurring in 8.3% of sampled photoquadrats. No cyanobacteria were observed in 2003.

During MARAMP 2005, REA benthic surveys were conducted at 3 sites on forereef habitats around Farallon de Pajaros. In the field, 5 macroalgal genera (1 red, 2 green, and 2 brown), containing at least 5 species, as well as 1 additional algal functional group—turf algae—were observed in the field. FDP-01 and FDP-04, located in the west and northwest regions, had the highest macroalgal generic diversity with 4 genera, each containing 4 species, documented in the field. The lowest macroalgal generic diversity was found in the southeast region at FDP-02 with 3 species representing 3 genera recorded.

Species of *Lobophora* and the red algal genus *Jania* were common at every site surveyed around Farallon de Pajaros in 2005, occurring in 77.8%, and 44.4% of sampled photoquadrats (Fig. 17.6.1d, middle panel). *Lobophora*, found in 75%–83% of photoquadrats sampled, was the dominant macroalgal genus at all sites; however, no distinct spatial pattern was observed. Species of *Jania* occurred in 33% of sampled photoquadrats at FDP-01 and FDP-04, both located in the west region, and in 67% of sampled photoquadrats at FDP-02 in the southeast region. Species of the green algal genera *Dictyosphaeria* and *Rhipidosiphon* were documented in low occurrence (< 17%) at 2 sites each; however, no distinct spatial pattern was observed.

Turf algae were abundant in 2005, occurring in 89% of photoquadrats sampled around Farallon de Pajaros (Fig. 17.6.1d, middle panel). Turf algae were ubiquitous around this island, but no distinct spatial pattern of distribution was observed for turf-algal assemblages at Farallon de Pajaros. No crustose coralline red algae and cyanobacteria were recorded in 2005.

During MARAMP 2007, REA benthic surveys were conducted at 3 sites on forereef habitats around Farallon de Pajaros. In the field, 8 macroalgal genera (2 red, 4 green, and 2 brown), containing at least 8 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed in the field. FDP-02 in the southeast region had the highest macroalgal generic diversity with 8 genera, containing 8 species, documented in the field. The lowest macroalgal generic diversity was found at FDP-01 with 4 species representing 4 genera recorded.

Lobophora was the dominant macroalgal genus around Farallon de Pajaros in 2007, occurring in 94.4% of sampled photoquadrats within a range of 83%–100% (Fig. 17.6.1d, bottom panel). Species of the genus *Jania* also abundant at all sites, were found in 91.7%, within a range of 75%–100% ,of photoquadrats sampled at this island. No distinct spatial pattern of distribution was documented for either genus. Species of *Dictyosphaeria* and the brown algal genus *Padina* were documented at all 3 sites surveyed in 2007, occurring in 25% and 13.9% of all sampled photoquadrats. At the genus level, 4 of

the 8 taxa tentatively identified occurred only at 1 or 2 sites, making distinctive spatial patterns of distribution difficult to determine for most macroalgae around Farallon de Pajaros. For species occurring across all sites, no distinct spatial patterns were documented, possibly in part because of the low number of sites surveyed at this island and the relatively small geographical area encompassed by this island.

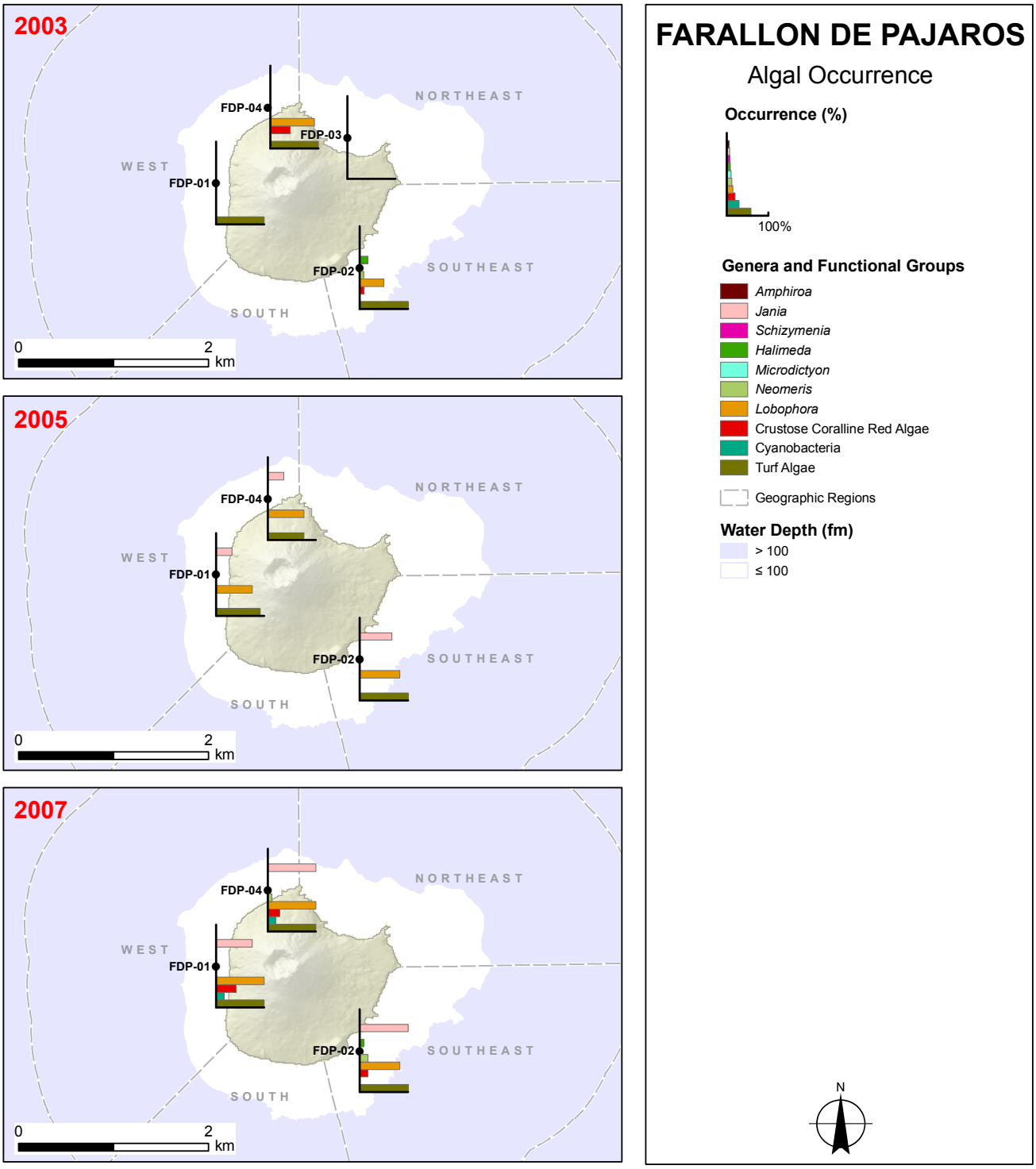


Figure 17.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

Turf algae occurred in 100% of photoquadrats sampled around Farallon de Pajaros in 2007 (Fig. 17.6.1d, bottom panel). Communities of crustose coralline red algae were common at all sites, occurring in 41.7%, 16.7%, and 25% of photoquadrats at FDP-01, FDP-02, and FDP-04. Cyanobacteria, observed only at 2 of the 3 REA sites surveyed, were found in 16.7% of photoquadrats sampled at those sites.

No distinct pattern of changes in the number of macroalgal genera was recorded. The overall occurrence of macroalgal genera did not fluctuate greatly, varying by 5%–8%, between 2003, 2005, and 2007 (Fig. 17.6.1e). The percentages of sampled photoquadrats in which species of *Dictyosphaeria, Jania,* and *Lobophora* were found increased between survey years. The genus *Lobophora* consistently had the highest occurrence levels during each of the 3 survey years with average values ranging from 35.4% to 94.4%. *Jania,* found in 0%–91.7% of sampled photoquadrats, was the second-most prevalent genus, followed by *Dictyosphaeria*, occurring in 0%–25% of sampled photoquadrats.

Crustose coralline red algae occurred in 0%–27.8%, and cyanobacteria in 0%–11%, of photoquadrats sampled at Farallon de Pajaros during MARAMP 2003, 2005, and 2007. No patterns of changes in the abundance of these functional groups were obvious. Turf algae occurred in 75% of sampled photoquadrats in 2003 and in 88.9% in 2005 and 100% in 2007.

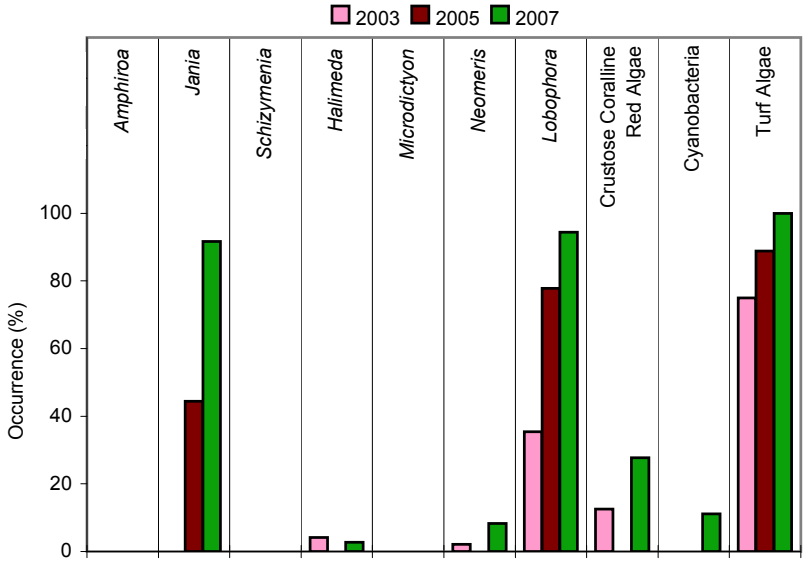


Figure 17.6.1e. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats around Farallon de Pajaros during MARAMP 2003, 2005, and 2007.

17.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal-disease were conducted in concert with coral-disease assessments at 3 sites at Farallon de Pajaros. No cases of coralline-algal disease were detected.

17.7 Benthic Macroinvertebrates

17.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorn seastars (COTS)—were monitored on forereef habitats around the island of Farallon de Pajaros through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 8 towed-diver surveys were conducted around Farallon de Pajaros, and, in both 2005 and 2007, 4 towed-diver surveys were performed. In each of these survey years, 3 REA surveys were done. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Overall, both the REA and towed-diver surveys suggested extremely low daytime macroinvertebrate abundance on forereef habitats around Farallon de Pajaros compared to other areas surveyed in the Mariana Archipelago. Minor fluctuations in observed densities between MARAMP survey periods occurred with half of the target groups. Temporal patterns of islandwide mean benthic macroinvertebrate density around Farallon de Pajaros—from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are also shown in this section (Figs. 17.1b and f).

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at 1 of the 3 REA sites surveyed and in 2 of the 8 towed-diver surveys conducted around Farallon de Pajaros (Fig. 17.7.1a, top panel). REA site FDP-02 had a giant-clam density of 4 organisms 100 m^{-2}. Islandwide mean density from towed-diver surveys was 0.004 organisms 100 m^{-2} (SE 0.002). Giant clams were observed only during 2 towed-diver surveys and only in survey segments in the south region Between these 2 towed-diver surveys completed around the southwestern shore, one had the higher mean density of giant clams with 0.022 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.089 organisms 100 m^{-2}.

During MARAMP 2005, no giant clams were observed at the 3 REA sites surveyed around Farallon de Pajaros, but 1 of the 4 towed-diver surveys had recordings of giant clams (Fig. 17.7.1a, middle panel), with an islandwide mean of 0.001 organisms 100 m^{-2} (SE 0.001). The single towed-diver survey with observations of giant clams was completed in the southeast region. The mean density of giant clams from this survey was 0.005 organisms 100 m^{-2}; segment densities ranged from 0 to 0.053 organisms 100 m^{-2}.

During MARAMP 2007, giant clams were observed at 2 of the 3 REA sites surveyed and in 3 of the 4 towed-diver surveys conducted around Farallon de Pajaros (Fig. 17.7.1a, bottom panel). The overall sample mean density of giant clams from REA surveys was 0.555 organisms 100 m^{-2} (SE 0.4), and the islandwide mean density from towed-diver surveys was 0.013 organisms 100 m^{-2} (SE 0.004). Survey results suggest giant clams were most abundant at FDP-02 in the southeast region with a density of 1.33 organisms 100 m^{-2}. Among all towed-diver surveys around this island, the survey completed in the south region had the highest mean density of giant clams with 0.036 organisms 100 m^{-2}; segment densities for this survey ranged from 0 to 0.107 organisms 100 m^{-2}.

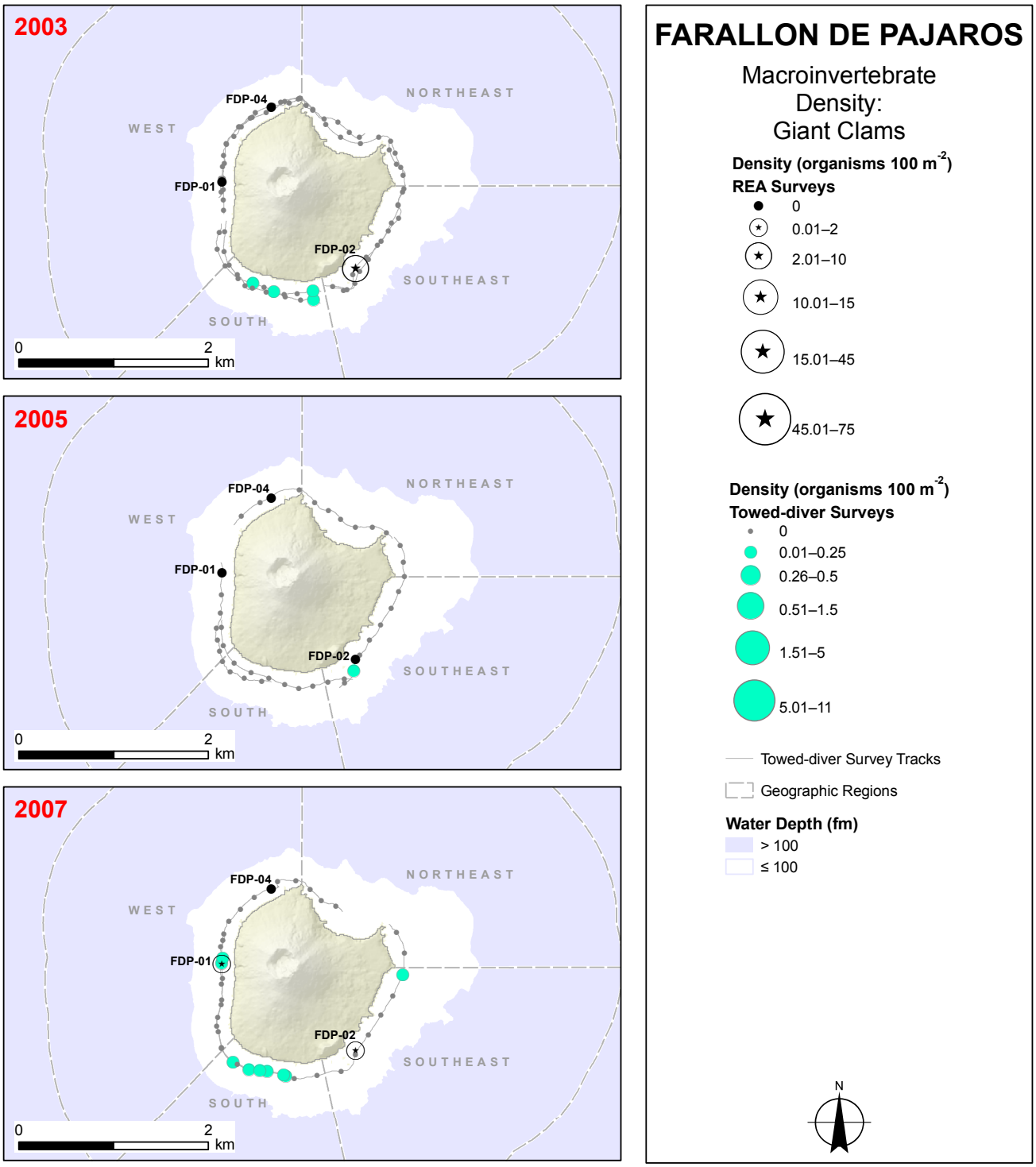


Figure 17.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007.

Towed-diver benthic surveys suggested low abundance of giant clams around Farallon de Pajaros during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago. The south region had the most giant clams during each of the 3 survey years. The overall observed mean density of giant clams around Farallon de Pajaros was higher in 2007 than in 2003 and 2005 (Fig. 17.7.1b). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

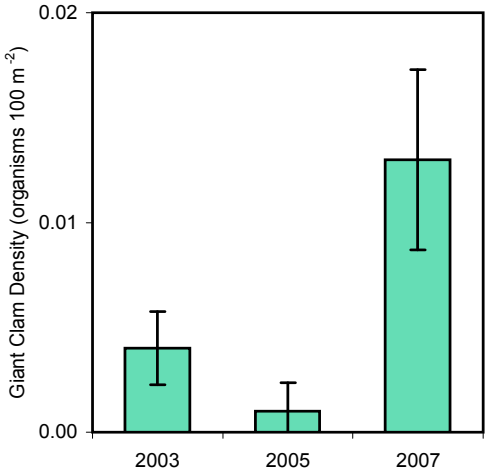


Figure 17.7.1b. Temporal comparison of mean densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Crown-of-thorns Seastars

No crown-of-thorns seastars were observed at the REA sites surveyed or during towed-diver surveys conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007.

Sea Cucumbers

No sea cucumbers were observed at the REA sites surveyed or during towed-diver surveys conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007.

Sea Urchins

During MARAMP 2003, sea urchins were observed at all 3 REA sites surveyed and in 5 of the 8 towed-diver surveys conducted around Farallon de Pajaros (Fig. 17.7.1c, top panel). The overall sample mean density of sea urchins from REA surveys was 55 organisms 100 m^{-2} (SE 51.5), and the islandwide mean density from towed-diver surveys was 1.06 organisms 100 m^{-2} (SE 0.48). Survey results suggest that sea urchins were most abundant at FDP-02 in the southeast region with 158 organisms 100 m^{-2}; rock-boring urchins accounted for 99% of all urchin observations at this site. Rock-boring urchins from the genus *Echinostrephus* were the dominant macroinvertebrates at all sites, accounting for 96.3% of all recorded urchins. The other genera observed in low numbers at REA sites included *Echinometra* and *Echinothrix*. Among all towed-diver surveys around Farallon de Pajaros, one of the surveys completed in the southeast region had the greatest mean density of 6.52 organisms 100 m^{-2}; segment densities ranged from 0 to 28.63 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed at 1 of the 3 REA sites surveyed and in 3 of the 4 towed-diver surveys conducted around Farallon de Pajaros (Fig. 17.7.1c, middle panel). REA site FDP-01 had a sea-urchin density of 4 organisms 100 m^{-2}. Observed species were from the rock-boring genus *Echinostrephus* and from the genus *Diadema*. The islandwide mean density of sea urchins from towed-diver surveys was 3.71 organisms 100 m^{-2} (SE 1.36). Among all towed-diver surveys around Farallon de Pajaros, the survey completed in the southeast region had the highest mean density of 12.21 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 39.69 organisms 100 m^{-2}. The second-highest mean density of sea urchins from a towed-diver survey was 2.26 organisms 100 m^{-2} survey, recorded along the southern shoreline; segment densities ranged from 0 to 10.57 organisms 100 m^{-2}.

During MARAMP 2007, sea urchins were observed at 1 of the 3 REA sites surveyed and in 3 of the 4 towed-diver surveys conducted around Farallon de Pajaros (Fig. 17.7.1c, bottom panel). REA site FDP-02 had a sea-urchin density of 54 organisms 100 m^{-2}. All but one of the observed urchins were recorded as species from the rock-boring urchin genus *Echinostrephus*. The islandwide mean density of sea urchins from towed-diver surveys was 1.98 organisms 100 m^{-2} (SE 0.9). Among all towed-diver surveys around Farallon de Pajaros, the survey completed along the southeastern shore had the highest mean density of 7.86 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 29.20 organisms 100 m^{-2}.

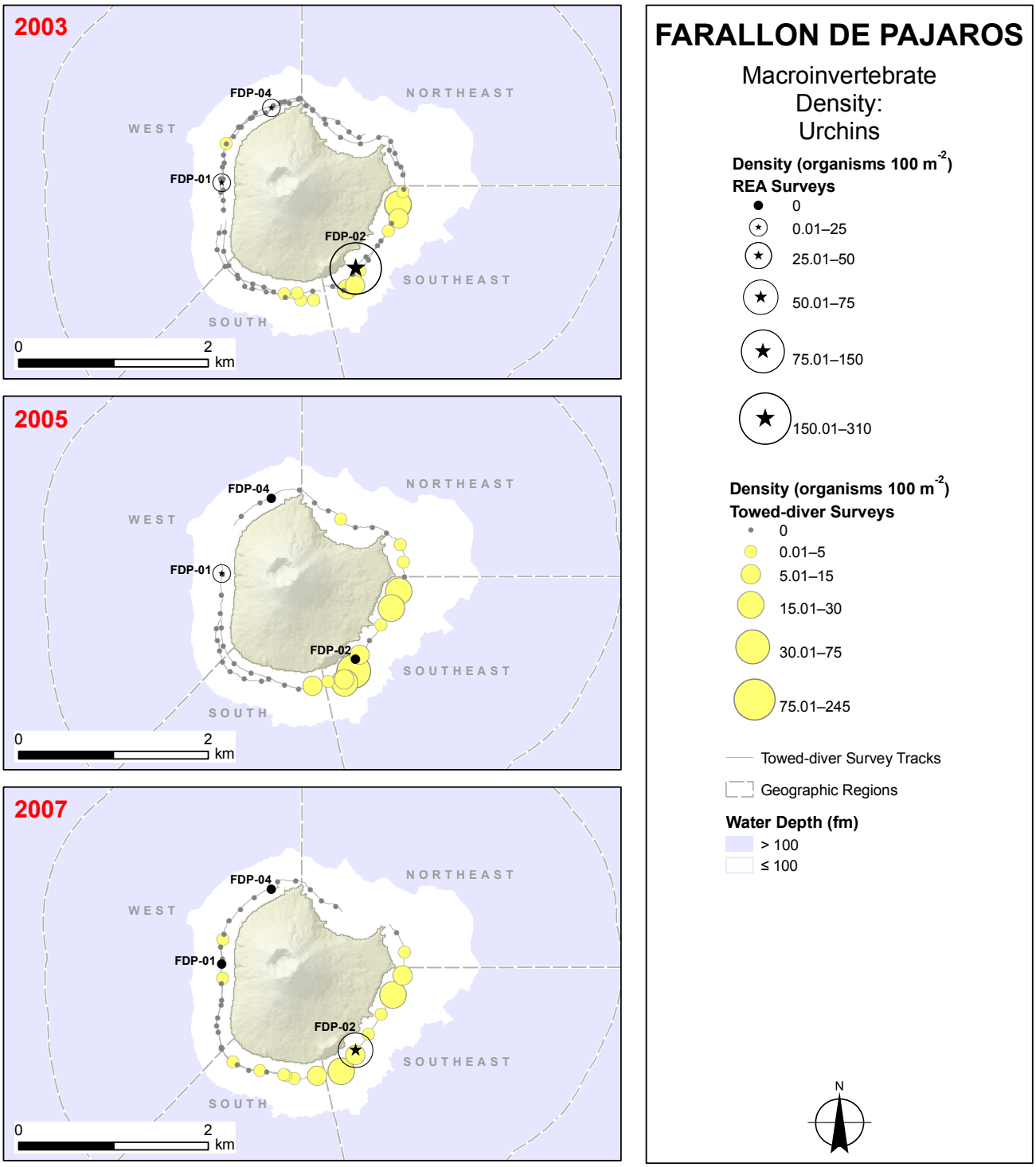


Figure 17.7.1c. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007.

With the exception of the southeastern shoreline, towed-diver surveys suggested low daytime abundance of sea urchins around Farallon de Pajaros during MARAMP 2003, 2005, and 2007, compared to the rest of the Mariana Archipelago. The overall observed mean density of sea urchins was lower in 2003 than in 2005 and 2007 (Fig. 17.7.1d). Fluctuations in densities are not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Although sea urchins were not recorded down to the genus level during towed-diver surveys, REA surveys suggested that more than 96% of the sea urchin species observed around Farallon de Pajaros were rock-boring urchins from the genus *Echinostrephus*.

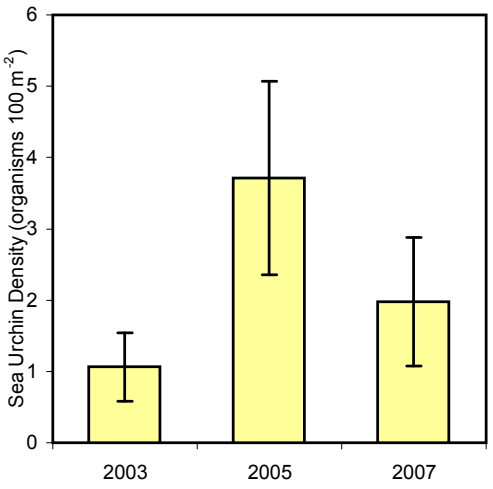


Figure 17.7.1d. Temporal comparison of mean densities (organisms m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

17.8 Reef Fishes

17.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 8 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the island of Farallon de Pajaros. The islandwide estimated mean biomass of large fishes, calculated as weight per unit area, was 3.24 kg 100 m^{-2} (SE 0.52), a moderate level compared to other survey areas in the Mariana Archipelago. Observed mean biomass was heterogeneous around this island with the highest values in the west region and along the north shore, where sharks and jacks were common (Fig. 17.8.1a, top panel). Jacks (Carangidae), snappers (Lutjanidae), reef sharks (Carcharhinidae), and nurse sharks (Ginglymostomatidae) together accounted for 82% or 2.67 kg 100 m^{-2} of islandwide mean large-fish biomass. Sharks accounted for the greatest proportion (34%) of the overall biomass of large fishes. Around this island, 82 sharks were observed, and the most common species was the grey reef shark (*Carcharhinus amblyrhynchos*) and whitetip reef shark (*Triaenodon obesus*).

During MARAMP 2005, 4 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Farallon de Pajaros. The islandwide estimated mean biomass of large fishes was 0.20 kg 100 m^{-2} (SE 0.08), a low value compared to results from surveys completed in 2003. Low biomass and numerical densities were observed in all regions around this island (Fig. 17.8.1a, middle panel). Although large-fish biomass estimates were low in 2005, jacks, snappers, and reef sharks contributed 89% or 0.18 kg 100 m^{-2} of the islandwide biomass of large fishes. Only 3 sharks were observed, all of them whitetip reef sharks.

During MARAMP 2007, 4 towed-diver surveys for large fishes (≥ 50 cm in TL) were conducted in forereef habitats around Farallon de Pajaros. The islandwide estimated mean biomass of large fishes was 2.21 kg 100 m^{-2} (SE 0.61), higher than the level recorded in 2005 and similar to the value observed in 2003. Observed values of large-fish biomass were similar in all areas around this island (Fig. 17.8.1a, bottom panel). Consistent with previous years, sharks, snappers, and jacks accounted for 84% or 1.87 kg 100 m^{-2} of large-fish mean biomass for this island. Around this island, 20 sharks were observed, accounting for the largest proportion (47%) of overall large-fish biomass.

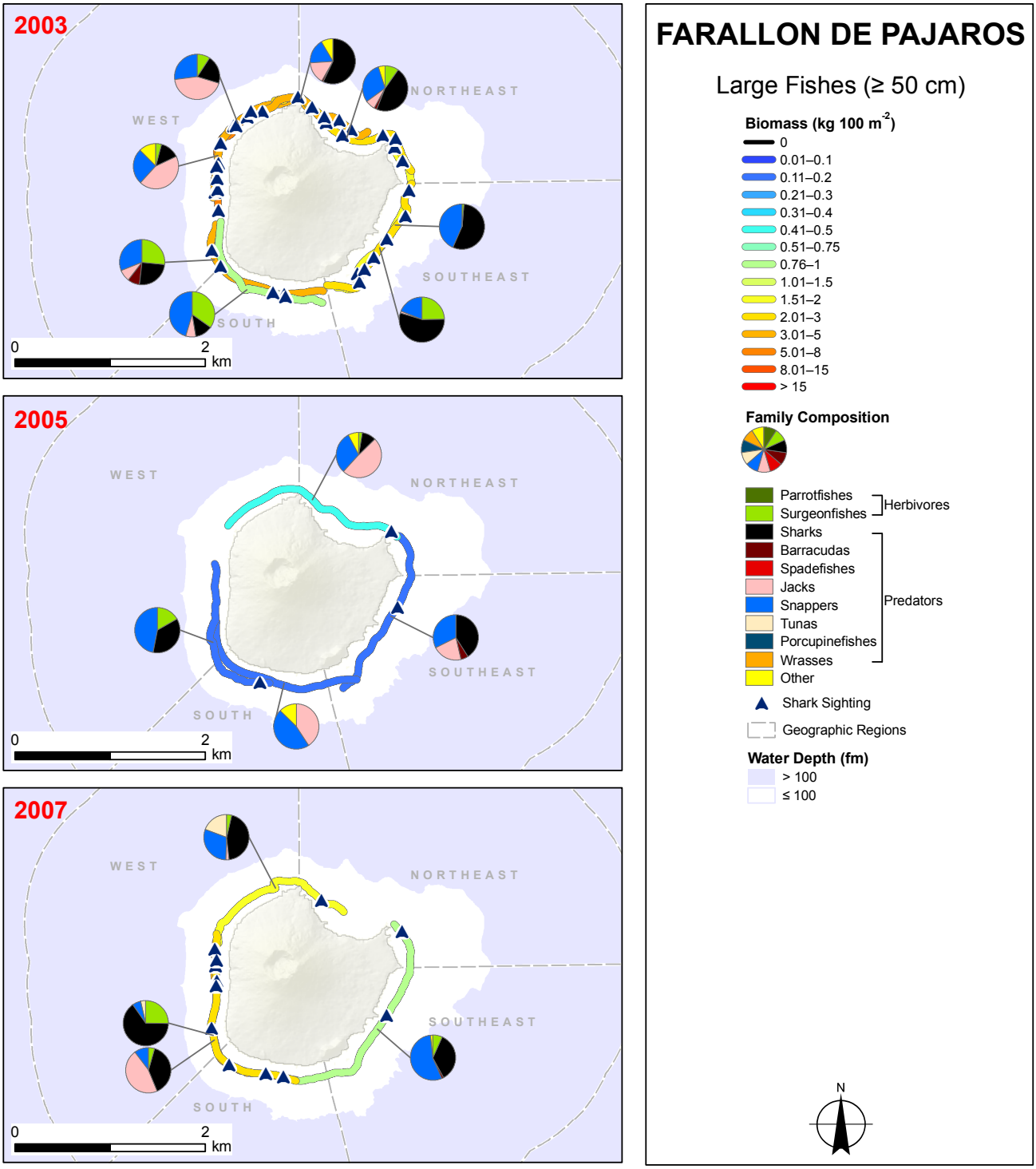


Figure 17.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown.

In general, for the 3 MARAMP survey periods, the highest values of large-fish biomass from towed-diver surveys of forereef habitats were recorded in the west region. Observed large-fish biomass was surprisingly low in 2005, compared to results from surveys conducted in 2003 and 2007 (Fig. 17.8.1b). For each of the 3 survey periods, sharks, jacks, and snappers composed the largest proportions of islandwide mean large-fish biomass. Most remarkable were observations made in 2007, when reef sharks alone contributed 47% of overall biomass of large fishes. Also notable were sightings of the rare giant grouper (*Epinephelus lanceolatus*) in 2003 and sightings of numerous large twinspot snappers (*Lutjanus bohar*), black and white snappers (*Macolor niger*), and midnight snappers (*Macolor macularis*) during each of the 3 survey periods.

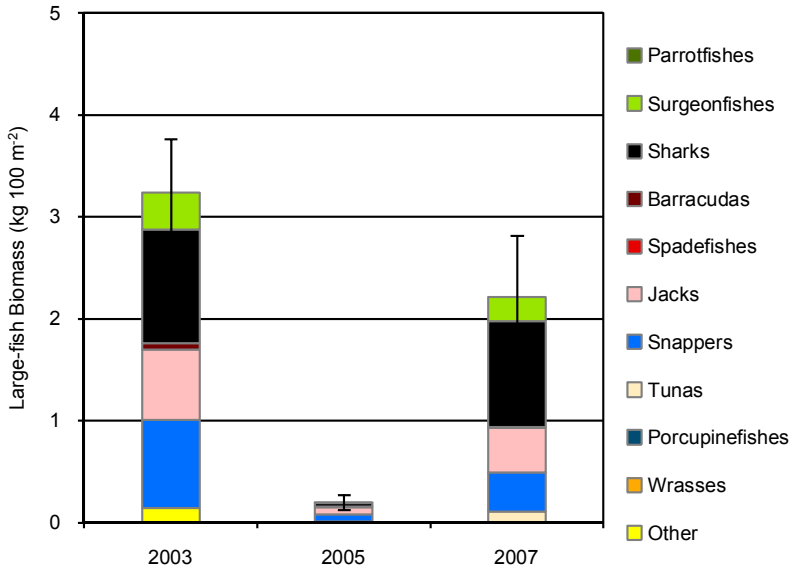


Figure 17.8.1b. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Total fish biomass for the 4 REA sites surveyed in forereef habitats at Farallon de Pajaros during MARAMP 2003 was high, compared to other sites in the Mariana Archipelago, with an overall sample mean of 16.17 kg 100 m^{-2} (SE 9.89). The highest biomass of 45.10 kg 100 m^{-2} was observed at REA site FDP-01 in the west region, and the lowest biomass of 0.48 kg 100 m^{-2} was found at FDP-03 (Fig. 17.8.1c, top panel). Reef sharks accounted for the largest proportion (39%) or 6.36 kg 100 m^{-2} of total fish biomass for this island. Snappers were also common, contributing 24% of overall total fish biomass. Over half of the total fish biomass at FDP-01 was comprised of sharks, primarily the grey reef shark.

Based on REA surveys conducted during MARAMP 2003, species richness at Farallon de Pajaros was extremely variable with a range of 5–51 species 100 m^{-2}. The highest diversity was seen at FDP-01 in the west region (Fig. 17.8.1c, top panel). Surgeonfishes (Acanthuridae) composed the most abundant family. Recent recruitment of orangespine unicornfishes (*Naso lituratus*) contributed to the rank of this species as the most abundant species observed.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Farallon de Pajaros during MARAMP 2005 was precipitously lower than estimates from 2003 with an overall sample mean of 6.77 kg 100 m^{-2} (SE 2.18). The highest biomass was observed at FDP-04 in the west region (Fig. 17.8.1c, middle panel). Surgeonfishes accounted for the largest proportion (40%) or 2.69 kg 100 m^{-2} of total fish biomass for this island. The orangeband surgeonfish (*Acanthurus olivaceus*) and orangespine unicornfish were the most dominant surgeonfishes by weight. Medium to large-bodied fishes, such as sharks, jacks (Carangidae), and groupers (Serranidae), were infrequently encountered during this survey period.

Based on REA surveys conducted in MARAMP 2005, species richness at Farallon de Pajaros was moderate with a range of 24–30 species 100 m^{-2} and lower than both observations made at this island in 2003 and estimates made for the Mariana Archipelago. The highest diversity was observed at FDP-01 in the west region (Fig. 17.8.1c, middle panel). Damselfishes (Pomacentridae) and wrasses (Labridae) composed the most abundant families. The midget chromis (*Chromis acares*) was the most abundant damselfish species, and the ornate wrasse (*Halichoeres ornatissimus*) was the most abundant wrasse species.

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Farallon de Pajaros during MARAMP 2007 was high, compared to estimates from 2003 and 2005, with an overall sample mean of 15.77 kg 100 m^{-2} (SE 6.54). Consistent with results from MARAMP 2003 and 2005, the highest biomass for this island was observed in the west region (Fig. 17.8.1c, bottom panel). Surgeonfishes accounted for the largest proportion (37%) or 5.84 kg 100 m^{-2} of total fish biomass for this island. Fusiliers (Caesionidae) and snappers (Lutjanidae) were also common, contributing 16% and 12% of overall total fish biomass. No sharks were observed during REA surveys in 2007.

Based on REA surveys conducted in 2007, species richness at Farallon de Pajaros was moderate with a range of 29–34 species 100 m^{-2}. The highest diversity was observed at FDP-02 in the southeast region (Fig. 17.8.1c, bottom panel). Damselfishes composed the most abundant family with Vanderbilt's chromis (*Chromis vanderbilti*) and midget chromis being the 2 most abundant species.

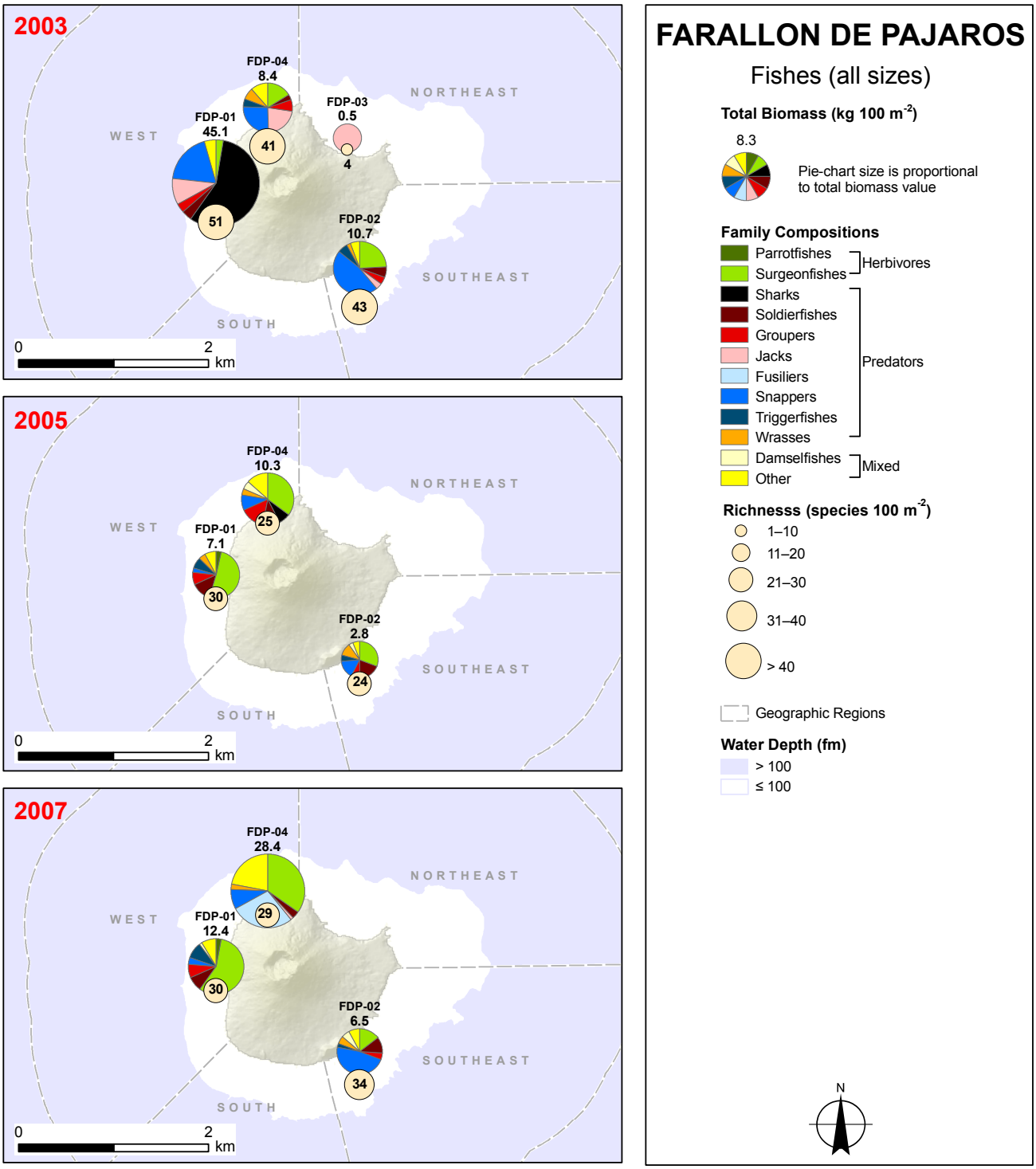


Figure 17.8.1c. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Farallon de Pajaros during MARAMP 2003, 2005, and 2007.

REA surveys conducted during all 3 MARAMP survey periods showed the west region to have the highest mean value of total fish biomass. Survey results for overall total fish biomass were similar in 2003 and 2007 (Fig. 17.8.1d). In 2003, reef sharks composed 39% or 6.36 kg 100 m^{-2} of the overall total fish biomass observed at Farallon de Pajaros. Surgeonfishes, specifically the orangeband surgeonfish and the orangespine unicornfish, were also abundant and contributed substantially to overall biomass during each survey period.

The highest species richness was observed in 2003 with 51 species 100 m^{-2} at FDP-01 in the west region. Species richness for other sites and during subsequent years averaged 30 species 100 m^{-2}.

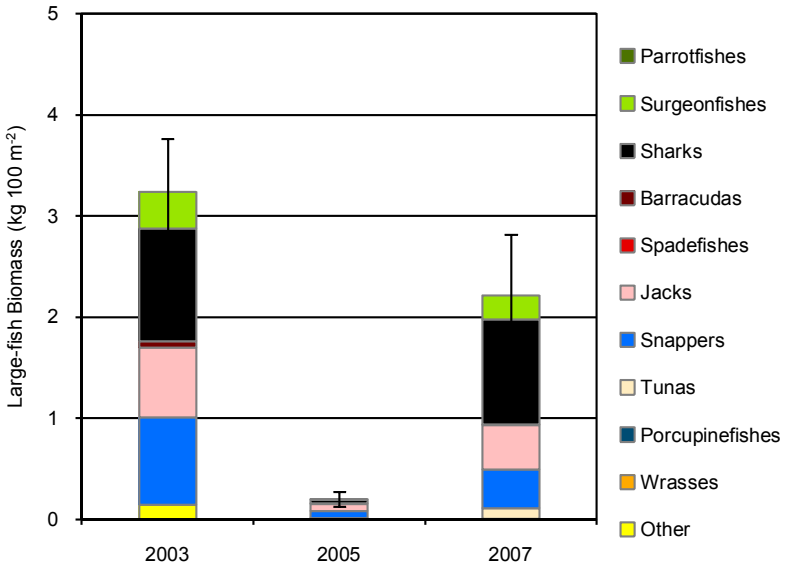


Figure 17.8.1d. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

17.9 Marine Debris

17.9.1 Marine Debris Surveys

During MARAMP 2003, no sightings of marine debris were recorded in the 8 towed-diver surveys conducted on forereef habitats around Farallon de Pajaros (Fig. 17.9.1a, top panel). In the 4 towed-diver surveys conducted during MARAMP 2005 on forereef habitats around this island, 4 sightings of derelict fishing gear were documented (Fig. 17.9.1a, middle panel). All 4 of these observations were of old fishing lines near the border between the south and west regions. During MARAMP 2007, 2 sightings of derelict fishing gear were recorded in the 4 towed-diver surveys conducted on forereef habitats around Farallon de Pajaros (Fig. 17.9.1a, bottom panel). Both of these observations were of old fishing lines and, similar to results seen in 2005, were made at the border between the south and west regions. No munitions, wrecks, or other man-made objects were identified during any of the 3 MARAMP survey years.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments.

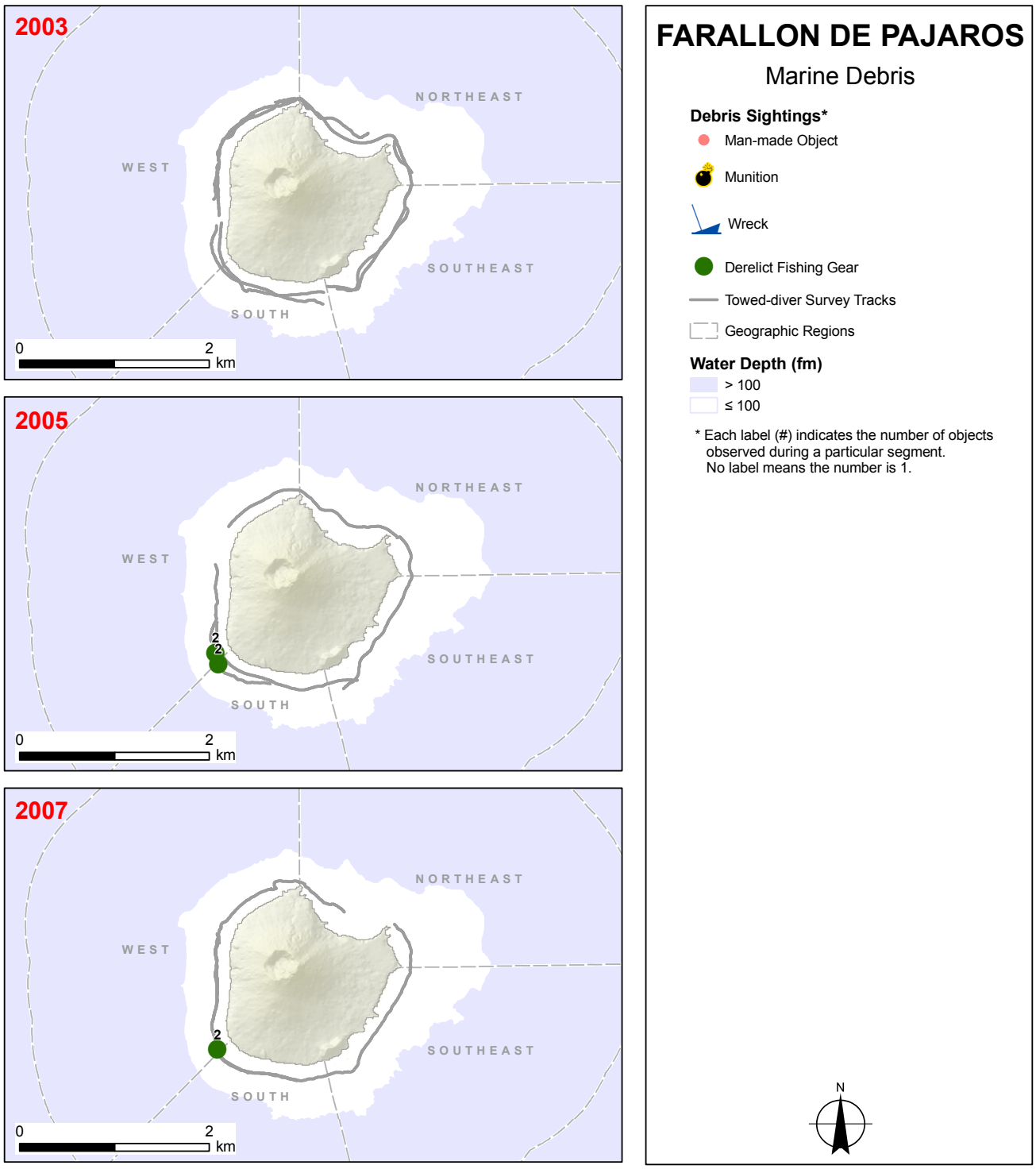


Figure 17.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. No debris sightings were recorded in 2003. Symbols indicate the presence of specific debris types.

17.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Farallon de Pajaros are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Farallon de Pajaros as well as the other 13 islands covered in this report.

Farallon de Pajaros is an active volcano, and frequent eruptions during the 19th century affected both its landscape and seascape. The steep onshore slopes of Farallon de Pajaros continue underwater, forming steep submarine flanks. These flanks are incised by ridges that radiate out from depths < 30 m to depths of 400–600 m. High backscatter values were recorded on some of these ridges, suggesting that they may be characterized by hard substrate at or near the seabed surface. Between these ridges, low backscatter values indicate soft sediments accumulating in channels. Cold-water intrusions (26.1°C, which was 3.5°C colder than surface waters) originating from depths > 30 m were prominent around Farallon de Pajaros in 2007, likely because of upwelling or internal tide activity.

The variable topography and oceanographic conditions around Farallon de Pajaros provide a highly variable coral reef habitat. Overall, live-hard-coral cover on forereef habitats was low during the 3 MARAMP survey years, compared to observations at other islands in the Mariana Archipelago (Fig. 17.10a). Coral-colony density was highest for the smallest size class (0–5 cm) in each of the 3 survey years (Fig 17.10b), and densities increased from 2003 to 2005. Forereef habitats, as observed by towed divers, were generally loose boulders and rubble and are likely inhospitable environments for prolonged coral growth. Conditions are most extreme in the northeast, southeast, and south regions, where high wave energy causes regular overturning of the loose substrate (Fig 17.10c).

In the west region, forereef habitats of medium to medium-high complexity included boulders on sand and patches of rocky reef. This region is characterized by low ambient wave activity and medium episodic activity, suggesting that this area is relatively sheltered compared to the rest of this island. Estimates of coral cover from towed-diver surveys were consistently highest in this region, compared to the other 3 regions (Fig. 17.10a). In each of the 3 MARAMP survey years, mean large-fish biomass was highest in the west region, where sharks (Carcharhinidae and Ginglymostomatidae) and jacks (Carangidae) were common (Fig. 17.8a in Section 17.8: "Reef Fishes"). Similarly, REA benthic surveys conducted during the 3 MARAMP survey periods showed the highest total fish biomass in the west region.

The southeast and northeast regions of Farallon de Pajaros are characterized by high ambient wave energy. An STR deployed at a depth of 17 m in the southeast region recorded high-frequency (~ 12-h return periods) temperature fluctuations of 1°C–3°C during the springs of 2006 and 2007. Internal tides are generated when tidal currents interact with steep subsurface topography. High-frequency variability in temperature, dissolved nutrients, and suspended particle concentrations could be a result of internal tides carrying deeper water onto the shallow reef shelf in this area. In both the southeast and northeast regions, a narrow shelf is present at depths of 10–40 m. Towed divers observed sandy habitats of low complexity on this shelf. A second, larger shelf, which may be related to an older portion of this volcano, fans out from the northeastern point of this island and gently deepens from a depth of ~ 150 m to depths of 250–300 m.

In 2007, 3 REA sites on forereef habitats were surveyed for coral disease around Farallon de Pajaros, and no cases were detected. Farallon de Pajaros was the only island in the Mariana Archipelago to exhibit no coral disease. The lack of coral disease observed at Farallon de Pajaros could be a result of the generally low level of coral cover recorded.

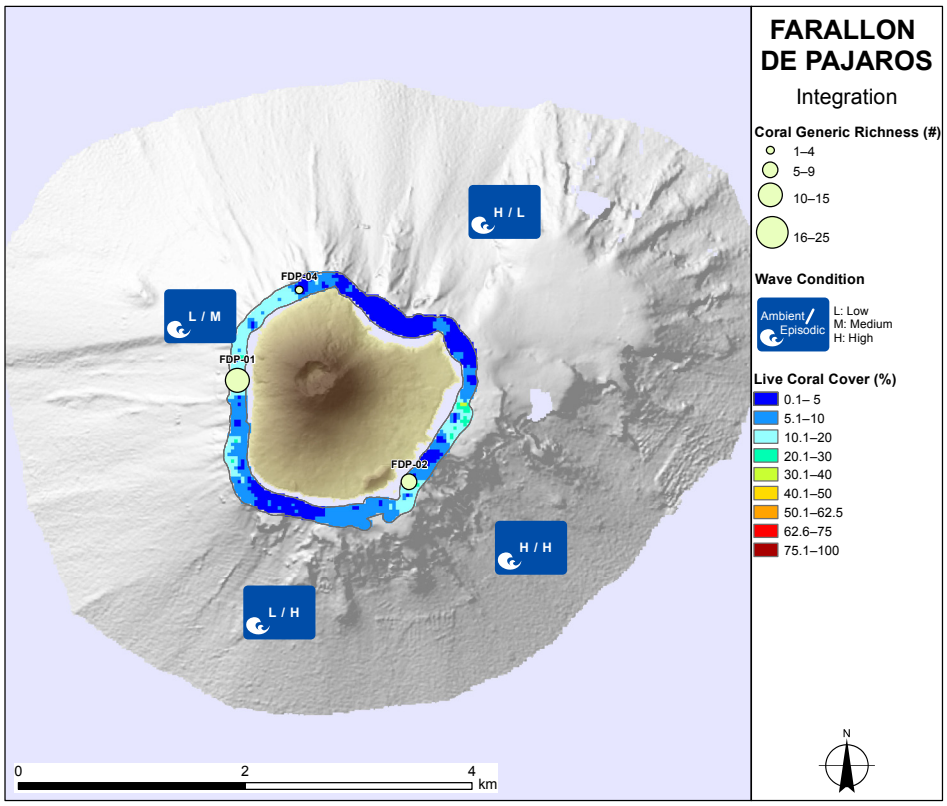


Figure 17.10a. Observations of cover (%) of live hard corals from towed-diver surveys and generic richness from REA surveys conducted on forereef habitats around Farallon de Pajaros during MARAMP 2003, 2005, and 2007. Values of coral cover represent interpolated values from the 3 MARAMP survey years, and values of coral generic richness represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.

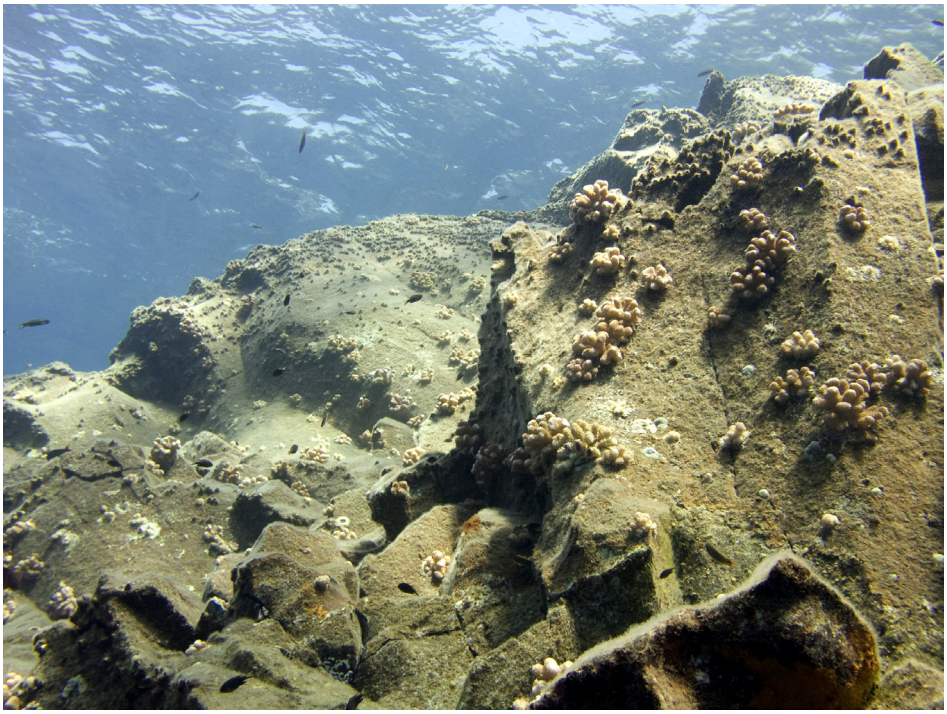


Figure 17.10b. Young coral recruits on the steep flanks of Farallon de Pajaros. *NOAA photo by Robert Schroeder*

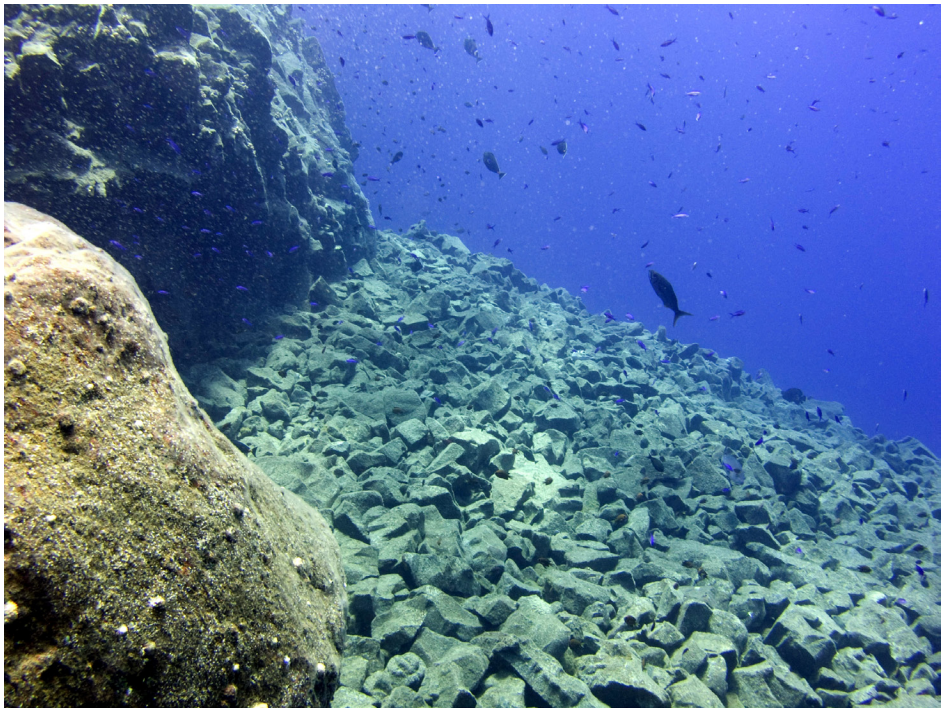


Figure 17.10c. Rocky terrain on most flanks of Farallon de Pajaros makes them inhospitable for coral growth. *NOAA photo by Robert Schroeder*

17.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Farallon de Pajaros. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Farallon de Pajaros chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Farallon de Pajaros, relative to all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Farallon de Pajaros as well as some of the key natural processes and anthropogenic activities influencing these ecosystems:

- Farallon de Pajaros, which translates from Spanish to Isle of the Birds, is also known as Uracas. With a land area of 2.2 km^2, it is the second-smallest and most northerly island in the CNMI. This island is an active volcano, with only the top visible above sea level and a base that is 15–20 km in diameter. The rim of this volcano's still active crater is the highest point of this island with an elevation of 360 m.

- Farallon de Pajaros is a protected reserve under the CNMI Constitution, a status that prohibits inhabitation or building of permanent structures. This island, including its waters and submerged lands, is also included within the Islands Unit of the Marianas Trench Marine National Monument, which was established by presidential proclamation in January 2009.

- Farallon de Pajaros is surrounded by uniformly steep slopes that are incised by ridges that radiate out from this island from depths < 30 m to depths of 400–600 m. In the west and south regions, towed divers reported habitats of medium to medium-high complexity that included boulders on sand and patches of rocky reef. In the southeast and northeast regions, a narrow shelf is present at depths of 10–40 m. Towed divers observed sandy habitats of low complexity on this shelf.

- Wave model output shows high, ambient trade wind energy impacting the northeast and southeast exposures of this island. Episodic, long-period, high wave energy from storm-driven swells impact the south and southeast exposures and to a lesser extent the west.

- High-frequency (return periods of ~ 12 h) temperature fluctuations of 1°C–3°C were recorded in the springs 2006 and 2007. These temperature fluctuations could be an internal tide signal generated when tidal currents interact with steep subsurface topography and deep water is drawn upward onto the shallow reef.

- Mean cover of live hard corals was 3.6%, based on surveys at 3 REA sites in 2007. Islandwide mean coral cover from towed-diver surveys declined from 10% in 2003 to 5% in 2005 and 2007. These values are low compared to other survey areas in the Mariana Archipelago.

- In 2007, 3 REA sites at Farallon de Pajaros were surveyed for the occurrence of coral disease and predation, and no cases were detected. Farallon de Pajaros was the only island in the Mariana Archipelago to exhibit no coral disease, likely because of the low abundance of corals observed.

- Macroalgal cover from towed-diver surveys was slightly lower in 2007 than in 2005 for some areas surveyed, particularly for east-facing reefs. The overall occurrence of macroalgal genera recorded at REA sites did not fluctuate greatly between MARAMP 2003, 2005, and 2007.

- Cover of crustose coralline red algae increased by 5% from 2003 to 2005. The primary reason for this change was the observation of higher cover values along the east- and west-facing reefs in 2005 than in 2003. Overall mean cover fell from 8% in 2005 to 5% in 2007, and declines were observed particularly in surveys conducted in the east region. No cases of coralline-algal disease were registered.

- Large-fish biomass was relatively high at Farallon de Pajaros, compared to other survey areas in the Mariana Archipelago. In general, large-fish biomass was highest in the west region, where sharks (Carcharhinidae and Ginglymostomatidae) and jacks (Carangidae) were common. Sharks were especially common in 2003, when towed divers observed 82 individuals, versus the only 3 and 20 sharks seen in 2005 and 2007. Similarly, results from REA surveys of fishes of all sizes conducted during the 3 MARAMP survey periods show that the highest levels of fish biomass were recorded in the west region.

- Notable observations from towed-diver fish surveys included sightings of the rare giant grouper (*Epinephelus lanceolatus*) in 2003.

- No COTS or sea cucumbers were observed at Farallon de Pajaros, and densities of giant clams were extremely low during each of the 3 MARAMP survey years, compared to levels observed at other islands surveyed. Sea urchins were common in the southeast region.

18 REEFS & BANKS of the CNMI

18.1 Introduction

Biological, oceanographic, and habitat data of various amounts were collected on Ahyi Seamount, Supply Reef, Zealandia Bank, Marpi Bank, and Esmeralda Bank on the Mariana Arc and on Stingray Shoal, Pathfinder Reef, and Arakane Reef on the West Mariana Ridge during MARAMP 2003, 2005, and 2007. Each of these offshore banks and remote reefs is discussed independently in this chapter along with the corresponding data available for that location. Figure 18.1a shows the locations of these 8 reefs and banks in relation to the islands of the Mariana Archipelago.

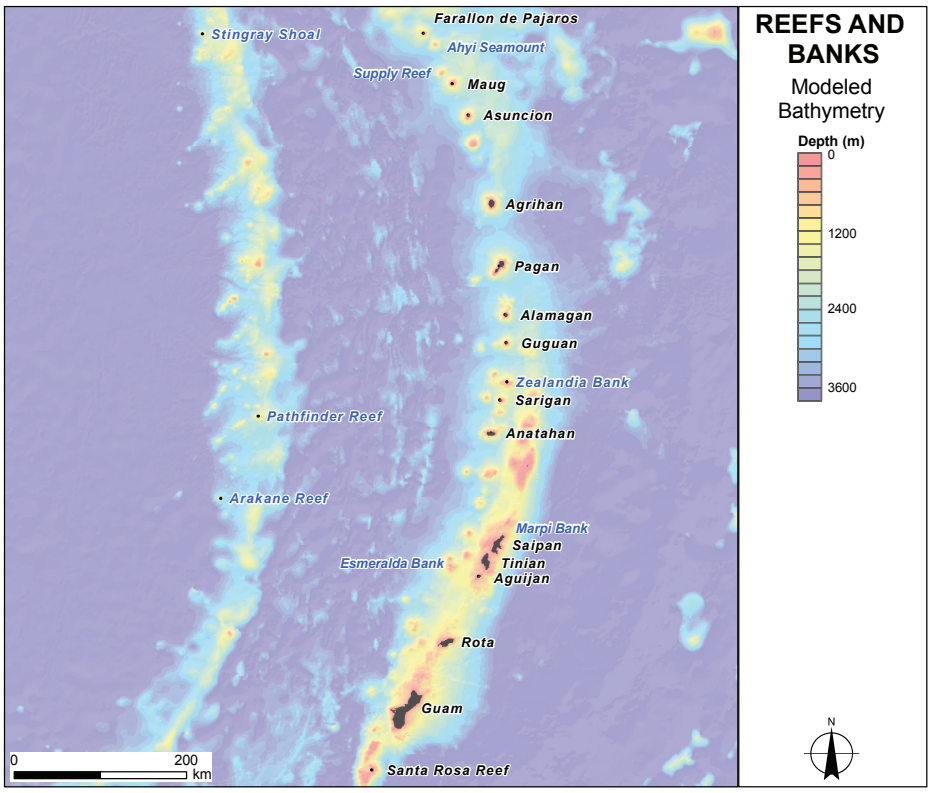


Figure 18.1a. Locations of the offshore banks—Ahyi Seamount, Supply Reef, Zealandia Bank, Marpi Bank, and Esmeralda Bank—and remote reefs—Stingray Shoal, Pathfinder Reef, and Arakane Reef—surveyed in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

18.1.1 Geologic Setting

The reefs and banks of the Commonwealth of the Northern Mariana Islands (CNMI) can be split into 3 groups based on their geologic history: Mariana active arc, frontal arc of the Mariana arc-trench system, and West Mariana Ridge (for more information on the geologic setting of the Mariana Archipelago, see Chapter 1: "Introduction," Section 1.1.2: "Geologic and Geographic Setting").

Four of the seamounts located on the Mariana Arc are active or dormant volcanoes formed within the past 4 million years as a result of the subduction of the Pacific Plate under the Philippine Plate at the Mariana Trench, which is located ~ 200 km to the east of the Mariana Arc. During MARAMP 2003, 2005, or 2007, 3 of these 4 seamounts were surveyed by the Coral Reef Ecosystem Division (CRED): Ahyi Seamount, Supply Reef, and Zealandia Bank. A fourth active seamount, Esmeralda Bank, located ~ 57 km southwest of Saipan, has been mapped as part of an ongoing series of NOAA Ocean Explorer expeditions.

Esmeralda Bank is one of the southernmost active stratovolcanoes in the Mariana Arc (Stern and Bibee 1984) and has a clear caldera that is breached on the west. Zealandia Bank, located northeast of Sarigan, has a more elongated shape and

is formed by 2 adjacent volcanic pinnacles ~ 1 km apart. Supply Reef and Ahyi Seamount, located between Farallon de Pajaros and Maug, are steeply sloping conical features, the typical morphology for stratovolcanoes. One of Zealandia's pinnacles reaches ~ 1 m above sea level during low tide (Siebert and Simkin 2002–), and it is possible that the shallow summits of Esmeralda Bank (43 m), Supply Reef (~ 10 m), and Ahyi Seamount (~ 80 m) have also emerged during previous sea level stands.

Supply Reef is joined to Maug by a low saddle at a depth of ~ 1800 m, and together these two features form a twin volcanic massif (Siebert and Simkin 2002–). Ahyi Seamount, in contrast, is an isolated conical feature and is thought to be volcanically active. Fishermen in a boat near the seamount in 1979 experienced shocks and observed upwelling of sulfur-bearing water, and, in April 2001, a seismic station detected an explosive eruption somewhere in the vicinity of this summit (Siebert and Simkin 2002–). Fumarolic activity also was detected at Zealandia Bank in 2004 (Siebert and Simkin 2002–). No volcanic activity has been recorded at Supply Reef, while Esmeralda Bank is currently active and frequent surface discoloration and sulfur boils have been seen in the area of this bank (Embley et al. 2004).

Two of the offshore, submerged banks surveyed for MARAMP, Marpi Bank and Tatsumi Reef, are part of the remnant Mariana frontal arc formed during the late Eocene and early Miocene epochs (15–20 million years ago), along with the islands of Farallon de Medinilla, Saipan, Tinian, Aguijan, Rota, and Guam. Data from Marpi Bank, located ~ 11 km north of Saipan, are presented in this chapter. Located only 3 km south of Tinian, Tatsumi Reef is discussed in Chapter 7: "Tinian and Tatsumi Reef." Like the islands on this part of the Mariana Arc, both banks are characterized by a flat top and probably made up of uplifted limestone overlying an older volcanic core.

Three reefs located on the West Mariana Ridge—Stingray Shoal, Pathfinder Reef, and Arakane Reef—were surveyed during MARAMP 2003. This ridge is separated from the Mariana Arc by the Mariana Trough, which continues to spread over time, expanding the distance between the 2 arcs. A remnant volcanic island arc, West Mariana Ridge is of an intermediate age between the modern, active arc and the frontal arc that make up the Mariana Arc. This ridge is now composed of a series of seamounts, none of which break the surface. Shallow summits suggest that some of these seamounts probably formed islands at some time in their history. The 3 reefs visited in 2003 all have minimum depths of 10–13 m.

18.1.2 Environmental Issues

Esmeralda Bank, Zealandia Bank, Ahyi Seamount, and Stingray Shoal are 4 of the 21 seamounts that are part of the Marianas Trench Marine National Monument, which was established by presidential proclamation in January 2009. The Volcanic Unit of the Marianas Trench Marine National Monument includes the submerged lands within 1 nautical mile (or 1.85 km) of 21 designated volcanic sites, and these volcanoes are part of the National Wildlife Refuge System. No waters are included as part of the Volcanic Unit, indicating that fishing is still allowed.

It has been noted that large vessels (9–21 m) in the CNMI that are able to fish on multiday trips focus their efforts from Esmeralda Bank to Zealandia Bank (Western Pacific Fishery Management Council 2011). Aside from this fishing pressure, little is known about the existing or potential effects of human activities on any of the surveyed reefs and banks. Their remoteness from land means that they are less subject to many of the anthropogenic pressures that affect the populated islands of the Mariana Archipelago; however, the extent to which fishing occurs in these remote areas is unknown.

18.2 Ahyi Seamount

18.2.1 Introduction

Ahyi Seamount is a stratovolcano located ~ 17 km south of Farallon de Pajaros on the Mariana Arc (Fig. 18.2.3a). Fishermen in a boat near the seamount in 1979 experienced shocks and observed upwelling of sulfur-bearing water, and, in April 2001, a seismic station detected an explosive eruption somewhere in the vicinity of this summit (Siebert and Simkin 2002–). Ahyi Seamount is designated as part of the Volcanic Unit of the Marianas Trench Marine National Monument.

18.2.2 Survey Effort

During MARAMP 2007, CRED partially mapped Ahyi Seamount with multibeam sonar east and south of this stratovolcano, adding to multibeam data that had been collected by the NOAA VENTS Program during a series of "Submarine Ring of Fire" cruises (Weiss et al. 2008; Embley et al. 2007). To provide a more complete picture of the topography of this reef, among others, these limited multibeam bathymetry data are presented overlying a bathymetry grid with a 30-arcsecond (~ 900-m) resolution and based on a satellite-gravity model calibrated with depth soundings (Becker et al. 2009).

Two towed optical assessment device (TOAD) surveys were conducted on Ahyi Seamount during MARAMP 2003 at depths of ~ 315–375 m, covering a distance of 0.66 km. Subsequent analyses of the video footage obtained from these surveys showed that the camera was too high above the seabed and the quality of the video was insufficient for detailed analyses.

18.2.3 Benthic Habitat Mapping and Characterization

The bathymetry data suggest that Ahyi Seamount is a steep-sided, conical seamount, with a minimum depth of < 80 m. A linear ridge extends southwest of this summit from a depth of ~ 200–300 m. A small number of ridges are shown radiating down the flanks of this seamount, but these flanks otherwise appear relatively smooth (Fig. 18.2.3a). Because of the limited coverage of MARAMP multibeam data, no backscatter analysis was done.

TOAD optical-validation surveys were conducted on the southern flanks of Ahyi Seamount. Analyses of the video footage from both surveys suggest a hard substrate, but further classification of the benthic cover was not possible because of the low quality of much of the video footage obtained. The benthos could be classified in ~ 30% of the video frames from these surveys: no live scleractinian (hard) corals were seen, although some other types of benthic fauna were observed.

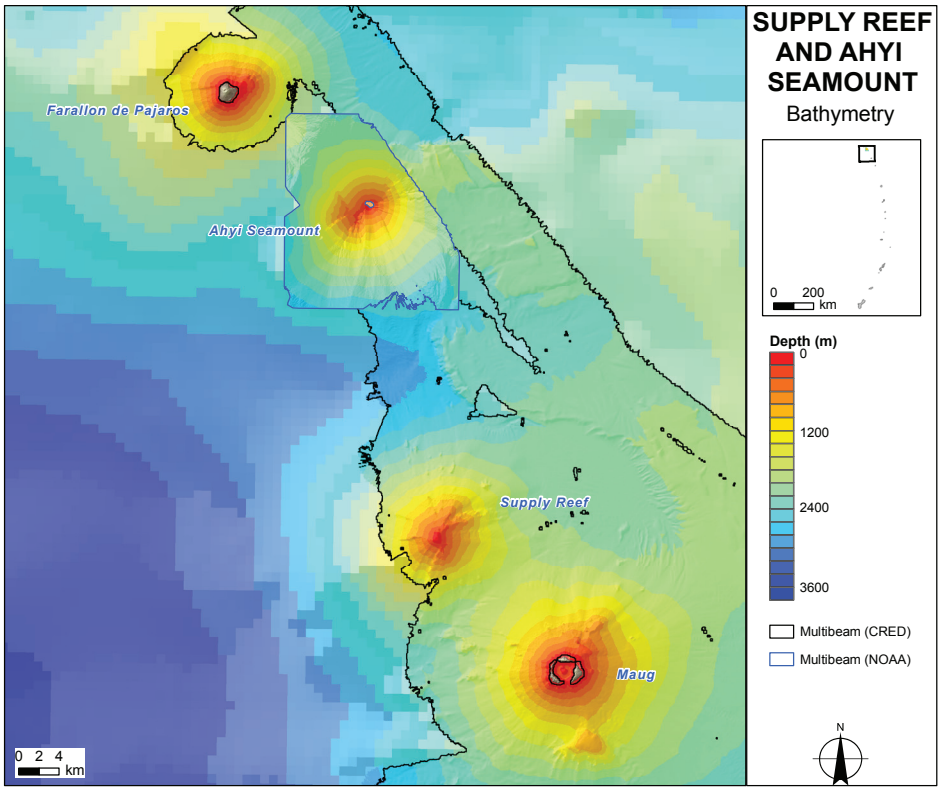


Figure 18.2.3a. Gridded multibeam bathymetry (grid cell size: 60 m, shown outlined in black) collected by CRED during MARAMP 2007 at depths of 10–3000 m using a 30-kHz Kongsberg EM 300 sonar with gridded multibeam bathymetry (grid cell size: 35 m, shown outlined in blue) collected by NOAA in 2003 using a Kongsberg EM 300 sonar (Merle et al. 2003). Shown elsewhere are modeled bathymetry data (grid cell size: 30 arcsecond or ~ 900 m; Becker et al. 2009).

18.3 Supply Reef

18.3.1 Introduction

Supply Reef is a stratovolcano located ~ 25 km north of Maug on the active Mariana Arc (see Figure 18.2.3a in Section 18.2: "Ahyi Seamount"). Supply Reef is joined to Maug by a low saddle at a depth of ~ 1800 m, and these 2 features together form a twin volcanic massif, meaning a single undersea mountain with 2 peaks (Siebert and Simkin 2002–). No volcanic activity has been recorded at Supply Reef.

18.3.2 Survey Effort

Benthic habitat mapping data were collected on Supply Reef using a combination of acoustic and optical survey methods. During MARAMP 2007, Supply Reef was mapped using multibeam sonar, adding to multibeam data that had been collected by the NOAA VENTS Program during a series of "Submarine Ring of Fire" cruises (Weiss et al. 2008; Embley et al. 2007). Multibeam sonar data collected by CRED around Supply Reef, Asuncion, Maug, and Farallon de Pajaros in 2007 covered a total area of 3856 km^2. Optical validation and habitat characterization were completed in 2003 using towed-diver and TOAD surveys that documented live-hard-coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in the next section.

Information on habitat and the composition and distribution of biological communities on Supply Reef was collected using towed-diver and TOAD surveys during MARAMP 2003. Because of the small size of this reef, only a single towed-diver survey was conducted there, covering a distance of 0.98 km at depths of 4–25 m (Table 18.3.2a and Fig. 18.3.2a). Two TOAD surveys were conducted on Supply Reef at depths of 76–171 m, covering a distance of 0.63 km (Fig. 18.3.2a). Results from these surveys are reported in Sections 18.3.3: "Benthic Mapping and Characterization" and 18.3.5: "Biological Characterization." The numbers of surveys conducted are presented in Table 18.3.2a, along with their depth and total area or length.

Table 18.3.2a. Numbers, depth (m), total area (ha), and total length (km) of towed-diver and TOAD surveys conducted on Supply Reef during MARAMP 2003.

Survey Type	Survey Detail	Year
Towed Diver		**2003**
	Number of Surveys	1
	Total Survey Area (ha)	1.0
	Depth (m)	17.4
TOAD		**2003**
	Number of Surveys	2
	Total Length (km)	0.63

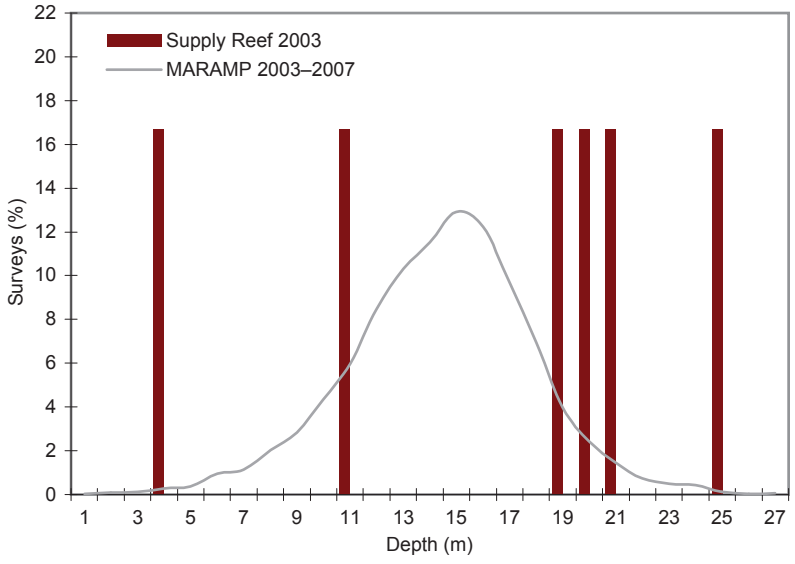


Figure 18.3.2a. Depth histogram plotted from mean depths of 5-min segments of the towed-diver survey conducted on Supply Reef during MARAMP 2003. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Temporal observations of key oceanographic parameters influencing reef conditions were collected on Supply Reef using (1) two types of moored instruments designed for long-term observations of high-frequency variability of temperature and wave height and (2) conductivity, temperature, and depth (CTD) profiles of the vertical structure of deepwater properties. A summary of deployed instruments and CTD cast activities is provided in Table 18.3.2b. Data from the wave-and-tide recorder (WTR) are discussed in Section 18.3.4: "Oceanography." Results from deepwater CTD casts performed on Supply Reef are discussed in Chapter 3: "Archipelagic Comparisons." Interpretation of the data from the STR deployed on this reef is beyond the time frame (2003–2007) of this report.

Table 18.3.2b. Numbers of oceanographic instruments deployed and deepwater CTD casts performed on Supply Reef during MARAMP 2003, 2005, and 2007. Deepwater CTD casts were conducted to a 500-m depth. Information on deepwater CTD casts is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
STR	–	–	–	–	1	1	–
WTR	1	1	1	1	1	1	–
CTD Casts		2005		2007			Total
Deepwater Casts		3		2			5

18.3.3 Benthic Habitat Mapping and Characterization

Supply Reef is steep-sided and conical, with ridges on all flanks and a minimum depth of ~ 10 m (see Figure 18.2.3a in Section 18.2: "Ahyi Seamount"). The bathymetry data also show some blocks of material in deep waters north of Supply Reef, including a small cone-shaped block northeast of this reef.

Sufficient multibeam coverage was obtained over Supply Reef, and these data were used to generate maps of slope, rugosity, and bathymetric position index (BPI) zones. High-resolution multibeam bathymetry data collected on Supply Reef show a steeply sloping, conical bank that arises to a narrow summit at a depth of ~ 10 m (Fig. 18.3.3a). The bathymetry and slope maps of Supply Reef suggest that the topography on the summit of this reef is slightly lumpy in texture and is ~ 300 m in diameter (Figs. 18.3.3a and b). Ridges extend northeast and southeast of this summit, and from them a network of smaller ridges radiate, eventually descending to 800 m, which is the limit of the mapping data. Aside from these ridges, the flanks of this reef are characterized by uniformly steep slopes. The steepest slopes (> 50°) were recorded on the sides of the ridges, while the flattest areas were recorded on the ridge tops and the summit. The rugosity map shows a similar pattern with the lowest rugosity recorded on the summit and ridge tops and elsewhere having moderate to high rugosity (Fig. 18.3.3c). These observations are supported by the BPI terrain analysis, which revealed a landscape dominated by slopes and ridges (Fig. 18.3.3d). The only depression zones identified were on the edge of the data, and the continuous ring of depressions shown on the BPI zone map appears to be an artifact of the data; the low-resolution bathymetry map clearly shows that the flanks continue to descend in a fairly uniform way. No flat zones were identified in the BPI terrain analysis. Backscatter data collected over Supply Reef were affected by steep slopes, which can influence backscatter intensity and, hence, prevent accurate interpretation of data; therefore, no backscatter data analysis for Supply Reef is presented in this report.

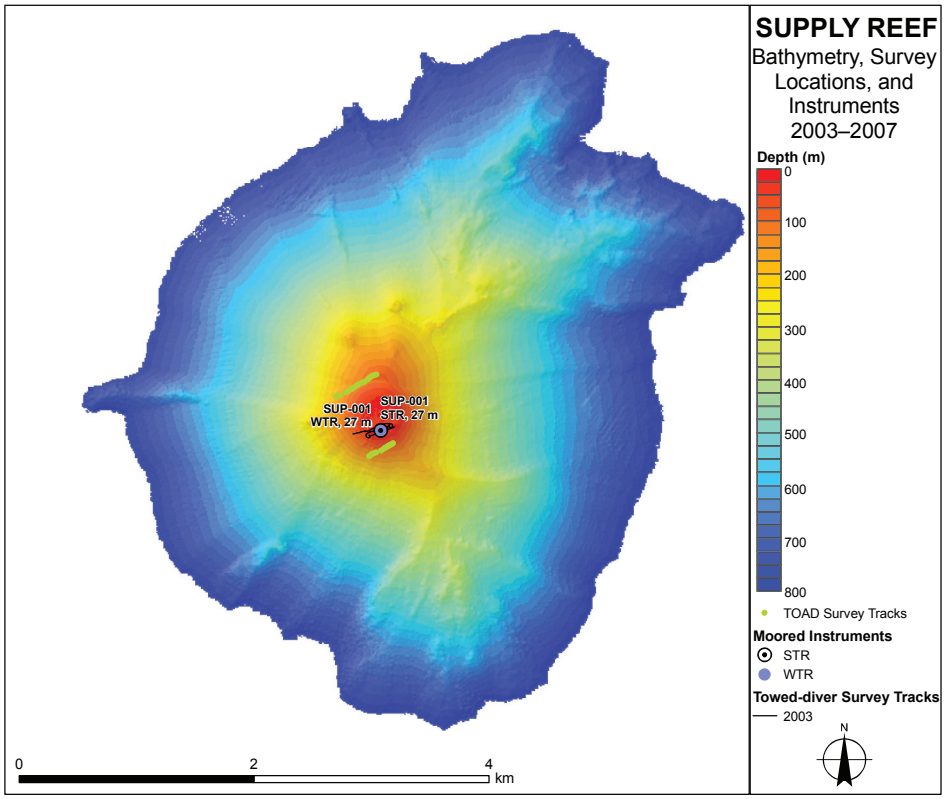


Figure 18.3.3a. High-resolution multibeam bathymetry collected by CRED on Supply Reef using Reson SeaBat 8101 ER and Kongsberg EM 300 sonars during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives. Also shown are the location and depth of the mooring site for the WTRs and STR deployed and the tracks of the towed-diver and TOAD surveys conducted on Supply Reef during MARAMP 2003, 2005, and 2007.

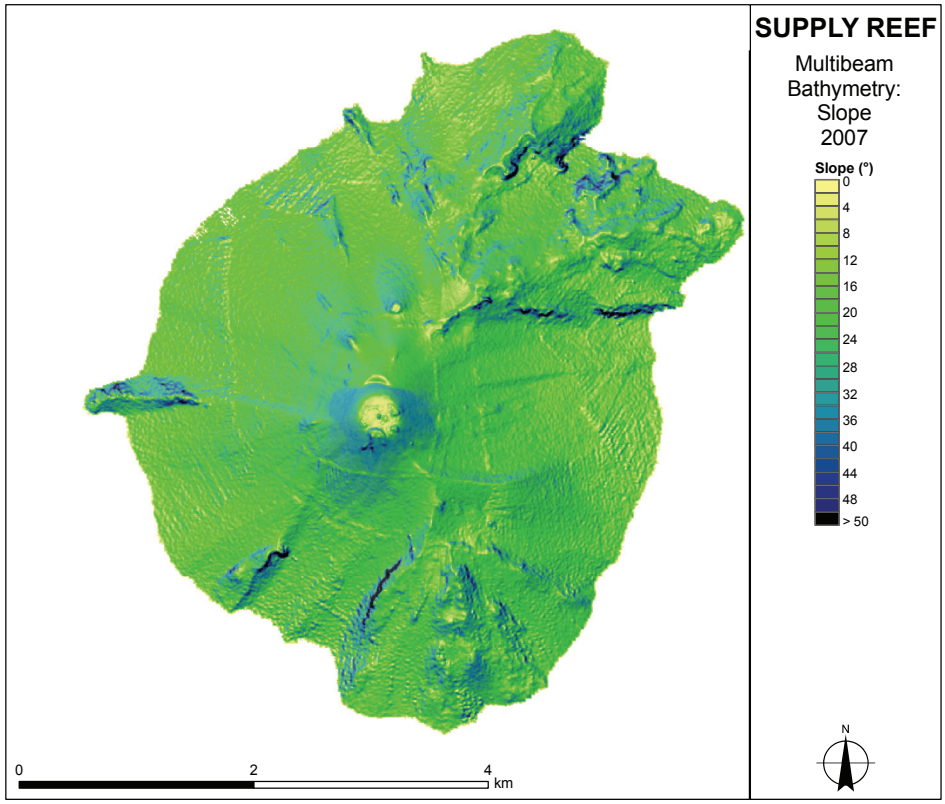


Figure 18.3.3b. Slope (°) of 10-m bathymetric grid on Supply Reef. Derived from data collected during MARMP 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest shades of blue and the flattest areas in yellow shades.

During MARAMP 2003, 1 towed-diver survey and 2 TOAD surveys were conducted on Supply Reef. At 5-min intervals within each towed-diver survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high. Results from this survey suggest habitat of medium-high to high complexity, characterized by very low sand cover (< 5%) and high (30%–50%) live coral cover (Fig. 18.3.3e), compared to

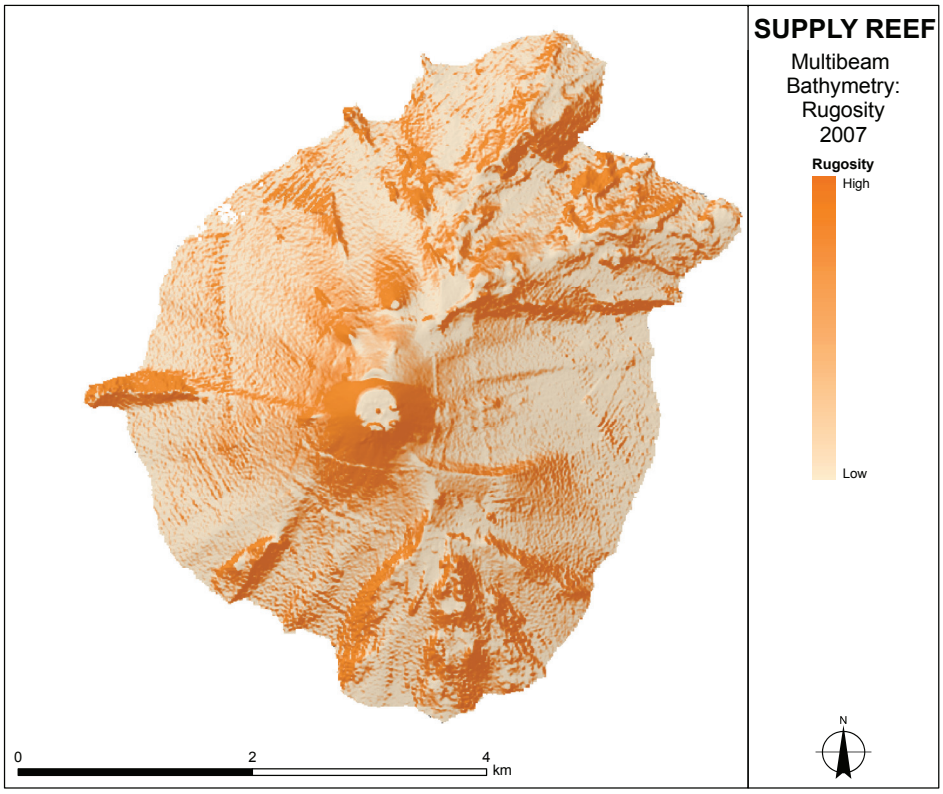


Figure 18.3.3c. Rugosity of 10-m bathymetric grid on Supply Reef. Derived from data collected during MARAMP 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

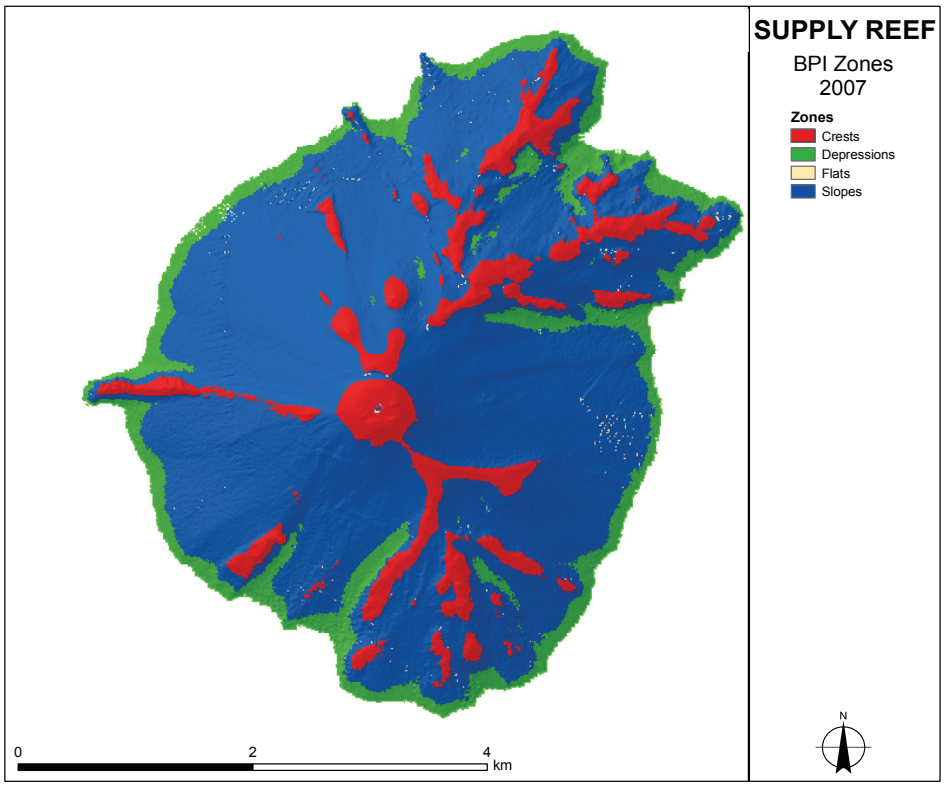
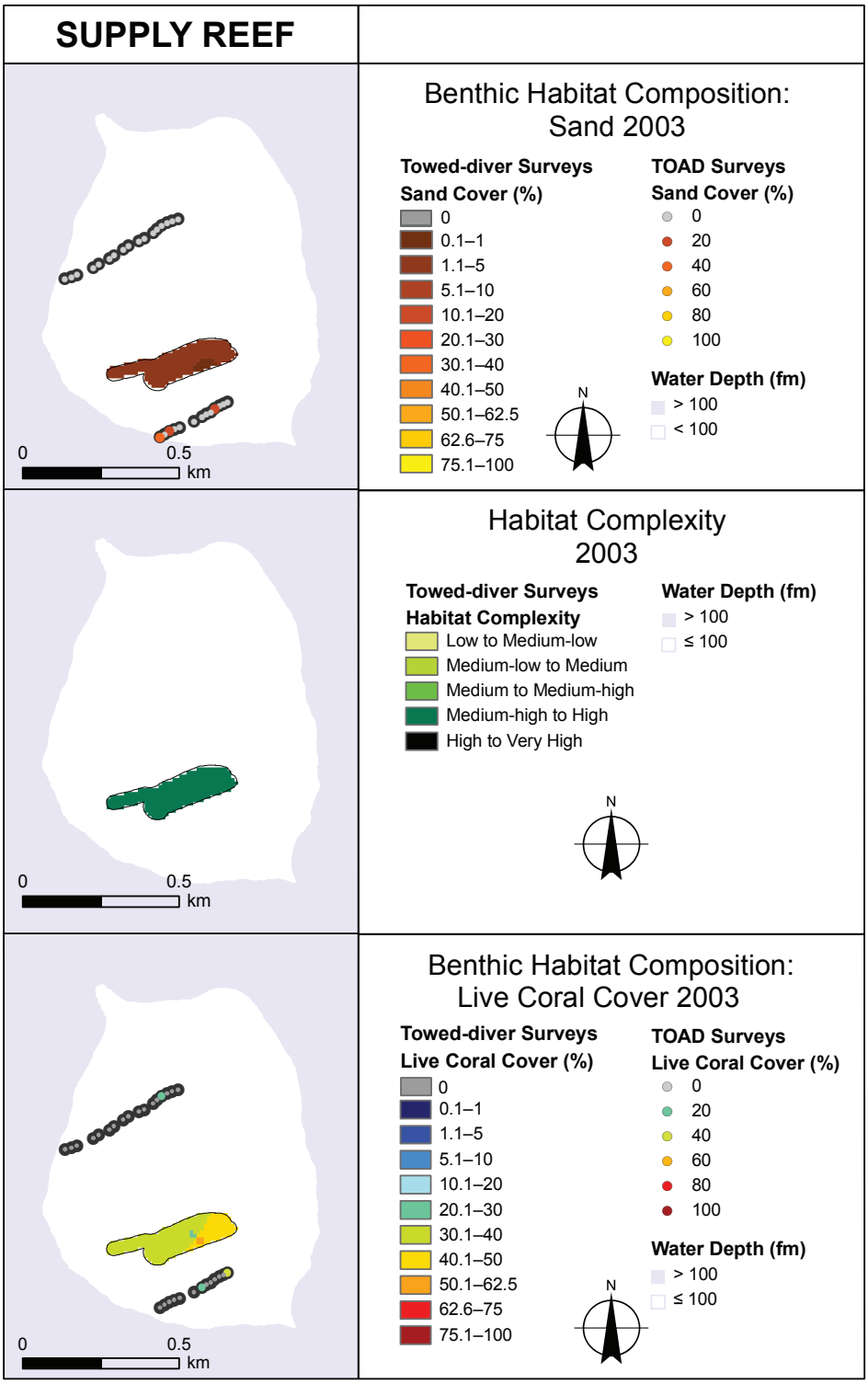


Figure 18.3.3d. BPI zones of 10-m bathymetric grid at Supply Reef derived from data collected during MARAMP 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—have been used in this analysis.

other reef areas surveyed in the Mariana Archipelago. Results from the 2 TOAD surveys conducted on the flanks north and south of the summit of Supply Reef suggest that the substrate there was predominantly hard with only a few small patches having any sand (20%–40% cover). Live corals were rare, and, when observed, coral cover was 20%, based on analyses of the about one-third of the TOAD video footage that could be used to assess benthic cover (Fig. 18.3.3e).

Figure 18.3.3e Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) cover (%) of live hard corals from the towed-diver survey conducted and analysis of TOAD video collected on Supply Reef during MARAMP 2003. The 100-fm contour shown in white represents potential reef habitat.



18.3.4 Oceanography

Between MARAMP 2003 and 2007, two types of moored instruments were deployed on Supply Reef to collect time-series observations of key oceanographic parameters influencing reef conditions. The time frame and depth of these deployments are provided in Figure 18.3.4a.

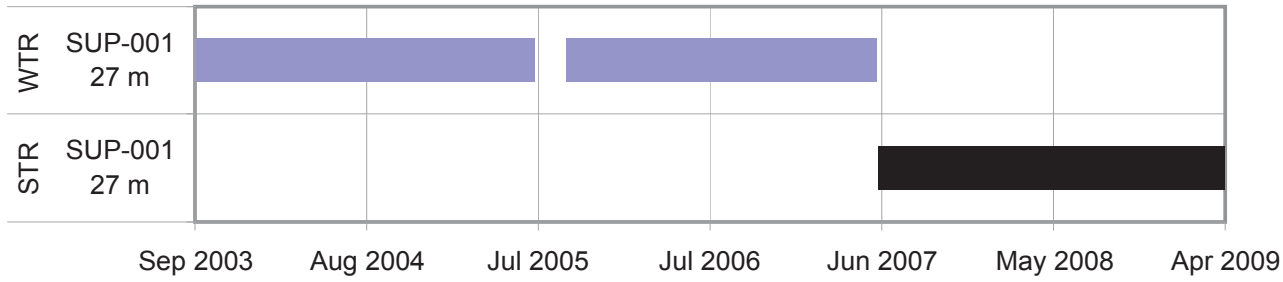


Figure 18.3.4a. Deployment timelines and depths of the WTRs and STR installed at Supply Reef during the period from September 2003 to April 2009. A solid bar indicates the period for which data were collected by a single or a series of instruments that were deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 18.3.2b.

Wave heights at Supply Reef, for the period from August 2003 to June 2007, were generally dominated by a seasonal pattern, with the highest ambient wave heights occurring through winter and the lowest heights occurring through summer (Fig. 18.3.4b). Superimposed on these seasonal fluctuations were episodic wave events characterized by brief periods of high (> 4 m) wave heights, which were typically associated with the typhoon season of August–December but also were observed during other time periods. Wave conditions were highly variable from year to year. Wave conditions on Supply Reef in 2004 were characterized by a few large wave events (> 6 m), while only 2 events in the next 3 years (2005–2007) exceeded 6 m. Wave events recorded in 2004 were 1 m smaller on Supply Reef than on Zealandia Bank, which is located farther south on the Mariana Arc and, therefore, more proximate to latitudes of typhoon generation.

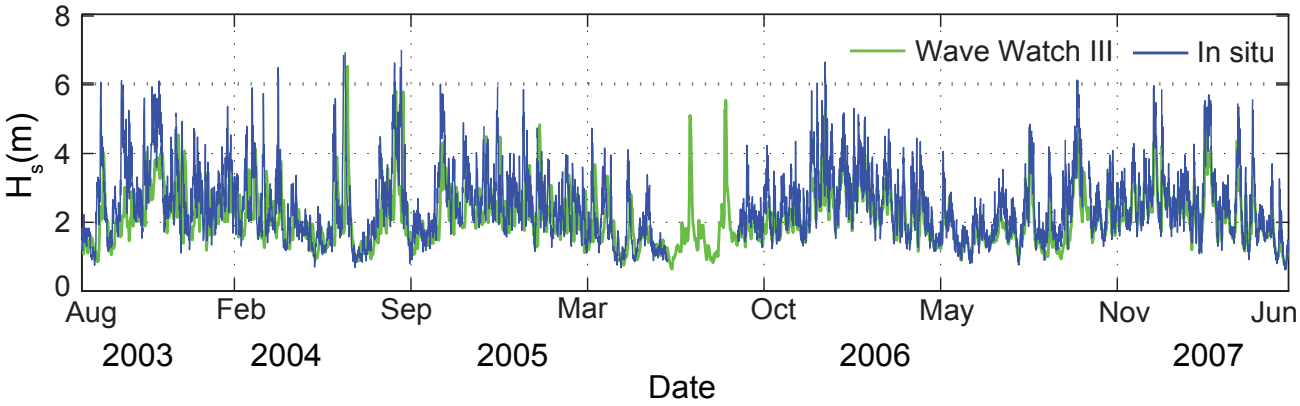


Figure 18.3.4b. Time-series observations of wave height (H_s) for the period from August 2003 to June 2007 using data from WTRs deployed on Supply Reef at a depth of 27 m and from the NOAA Wave Watch III model (see Figure 18.3.3a for mooring location; for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling").

18.3.5 Biological Characterization

18.3.5.1 Coral Surveys

From the MARAMP 2003 towed-diver survey, mean cover of live hard corals was 39% (SE 9.2) on Supply Reef (Fig. 18.3.5.1a).

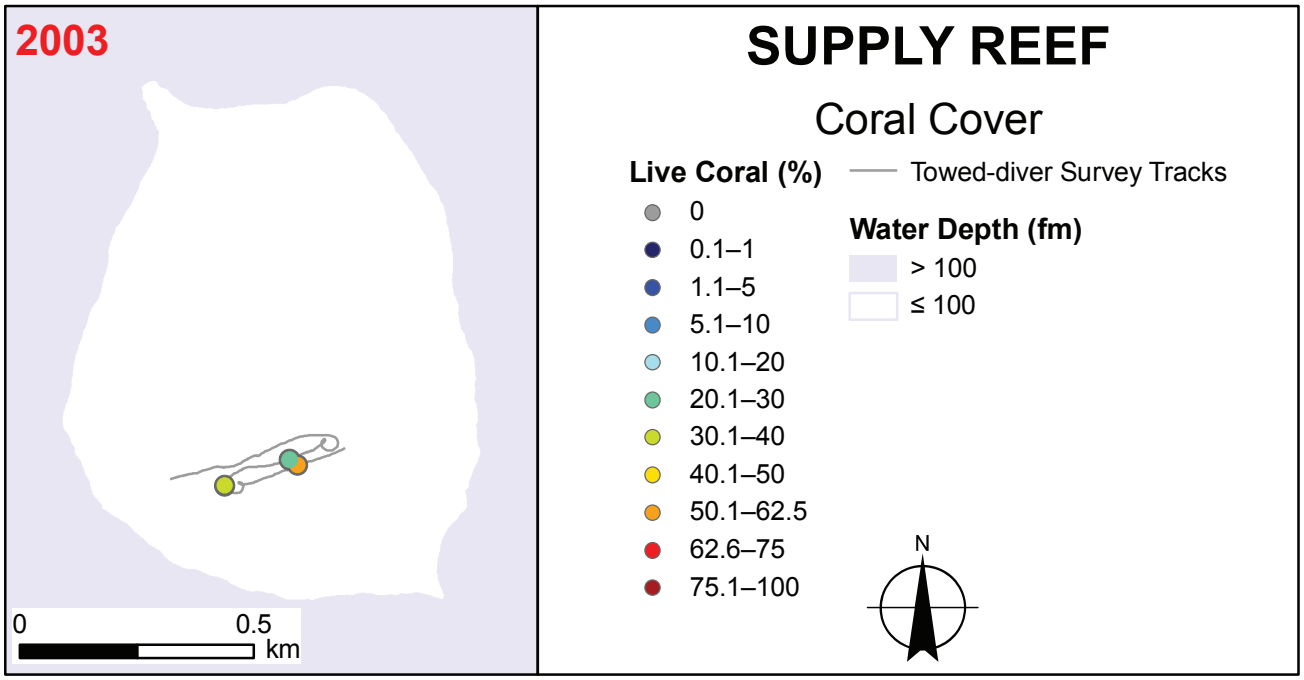


Figure 18.3.5.1a. Cover (%) observations of live hard corals from the single towed-diver benthic survey conducted on Supply Reef during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m²). The 100-fm contour shown in white represents potential reef habitat.

18.3.5.2 Algal Surveys

From the MARAMP 2003 towed-diver survey, mean macroalgal cover was 19% (SE 5.8), and mean cover of crustose-coralline red algae was 35% (SE 5.8) on Supply Reef (Fig. 18.3.5.2a). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. Habitat complexity was recorded only for the first 3 segments of this survey. Bedrock habitat of high complexity was recorded for each segment.

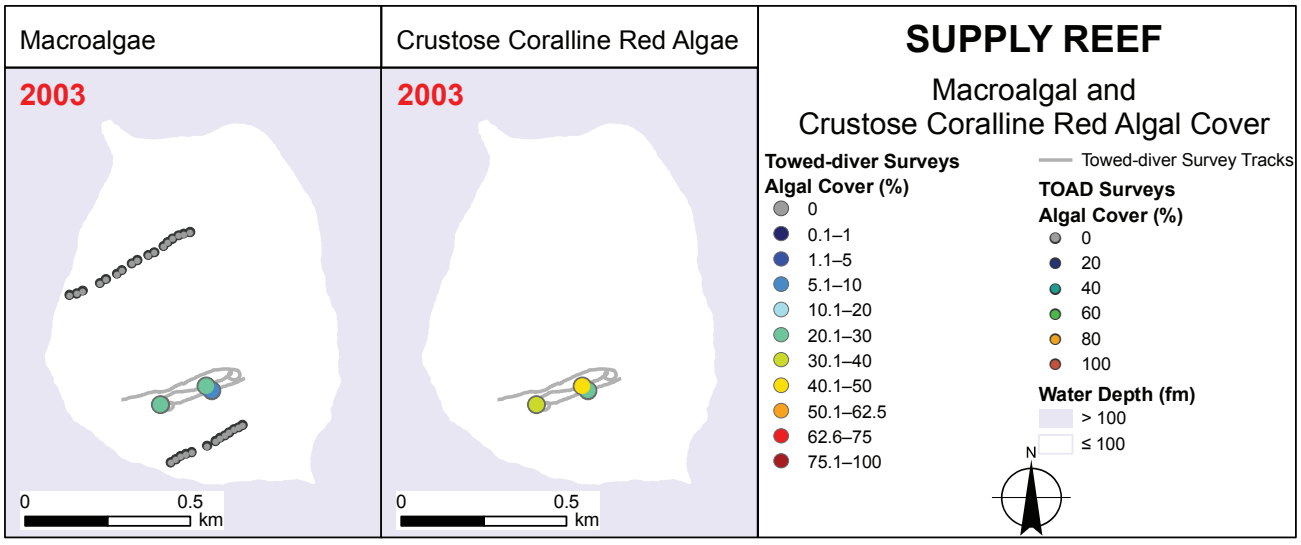


Figure 18.3.5.2a. Cover (%) observations for (*left*) macroalgae and (*right*) crustose coralline red algae from the single towed-diver benthic survey conducted on Supply Reef during MARAMP 2003. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m²). The macroalgal panel shows observations of both macroalgae and turf algae. In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys. The 100-fm contour shown in white represents potential reef habitat.

18.3.5.3 Fish Surveys

During MARAMP 2003, a single towed-diver survey for large fishes (≥ 50 cm in total length [TL]) was conducted on Supply Reef with a mean biomass, calculated as weight per unit area, of 2.99 kg 100 m^{-2}. Jacks accounted for the greatest proportion (49%) or 1.46 kg 100 m^{-2} of estimated large-fish biomass (Fig. 18.3.5.3a). The bluefin trevally (*Caranx melampygus*) accounted for 79% of jack biomass. Reef sharks (Carcharhinidae) accounted for the second-greatest proportion (28%) of observed mean biomass of large fishes. During this survey period, 5 sharks were observed: 3 grey reef shark (*Carcharhinus amblyrhynchos*) and 2 whitetip reef shark (*Triaenodon obesus*), accounting for 57% and 43% of shark biomass. Snappers (Lutjanidae) accounted for 12% of large-fish biomass. The twinspot snapper (*Lutjanus bohar*) contributed 84% of snapper biomass.

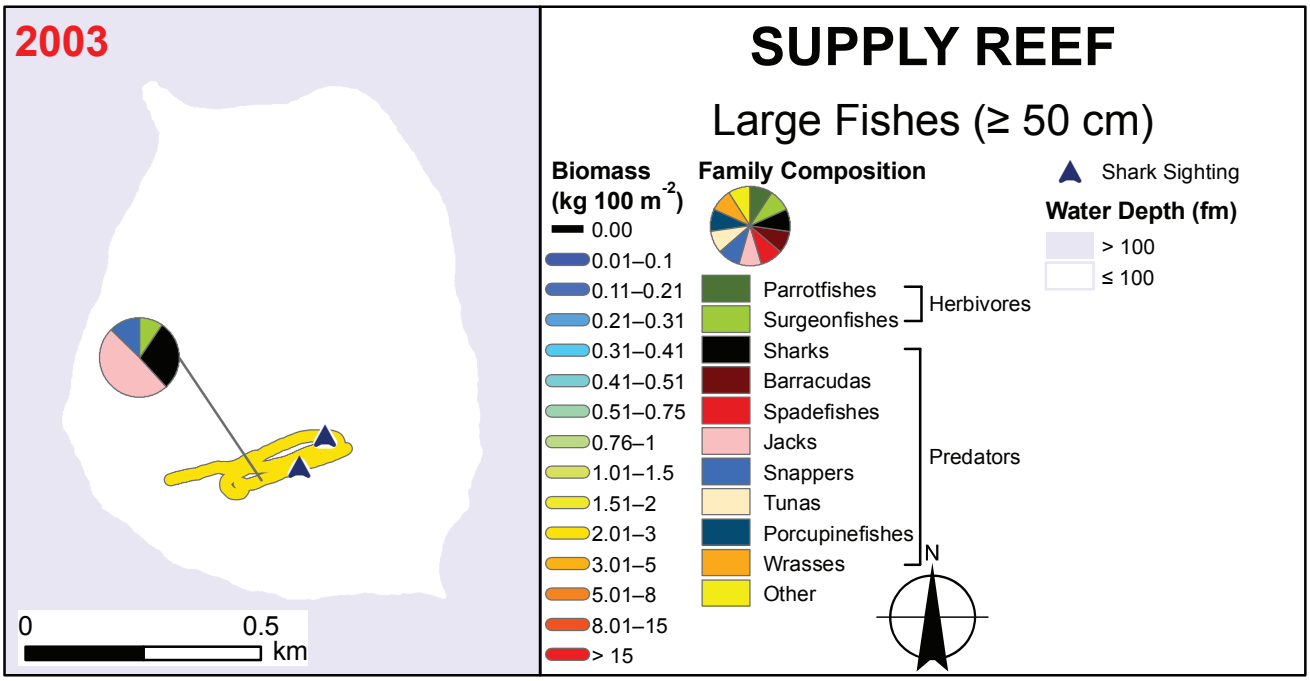


Figure 18.3.5.3a Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from the single towed-diver fish survey conducted on Supply Reef during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which it is shown. The 100-fm contour shown in white represents potential reef habitat.

18.4 Zealandia Bank

18.4.1 Introduction

Zealandia Bank is a stratovolcano located ~ 25 km northeast of Sarigan on the active Mariana Arc (Fig. 18.4.3a). Zealandia Bank has an elongated shape and is formed by 2 adjacent volcanic pinnacles ~ 1 km apart. During low tide, 1 of these 2 pinnacles is ~ 1 m above sea level. Fumarolic activity was detected at Zealandia Bank in 2004 (Siebert and Simkin 2002–). Zealandia Bank is part of the Volcanic Unit of the Marianas Trench Marine National Monument.

18.4.2 Survey Effort

Benthic habitat mapping data were collected on Zealandia Bank using a combination of acoustic and optical survey methods. During MARAMP 2007, Zealandia Bank was partially mapped using multibeam sonar, adding to multibeam data that had been collected by the NOAA VENTS Program during a series of "Submarine Ring of Fire" cruises (Weiss et al. 2008; Embley et al. 2007). To provide a more complete picture of the topography of this reef, the combined multibeam bathymetry data are presented overlying a bathymetry grid with a 30-arcsecond (~ 900-m) resolution and based on a satellite-gravity model calibrated with depth soundings (Becker et al. 2009). Multibeam sonar data collected by CRED around Zealandia, Sarigan, Anatahan, Alamagan, and Guguan in 2007 covered a total area of 2228 km^2.

To collect information on the composition of the biological communities on Zealandia Bank, a single TOAD survey was conducted on Zealandia Bank during MARAMP 2003 (Fig. 18.4.3b), covering a distance of 1.17 km at depths of 72–121 m. Results from this survey are reported in the next section. Rapid Ecological Assessment (REA) surveys were attempted, but no data were obtained.

Temporal observations of key oceanographic parameters influencing reef conditions were collected on Zealandia Bank using (1) two types of moored instruments designed for long-term observations of high-frequency variability of temperature and wave height and (2) CTD profiles of the vertical structure of deepwater properties. A summary of deployed instruments and CTD cast activities is provided in Table 18.4.2b. Data from the WTRs are discussed in Section: 18.4.4: "Oceanography." Results from deepwater CTD casts on Zealandia Bank are not presented in this report, since data were collected for only one year. Interpretation of the data from the STR deployed on this bank is beyond the time frame (2003–2007) of this report.

Table 18.4.2b. Numbers of oceanographic instruments deployed and deepwater CTD casts performed on Zealandia Bank during MARAMP 2003, 2005, and 2007. Deepwater CTD casts were conducted to a 500-m depth.

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
STR	–	–	–	–	1	1	–
WTR	1	1	1	1	1	1	–
CTD Casts		**2005**		**2007**			**Total**
Deepwater Casts		2		–			2

18.4.3 Benthic Habitat Mapping and Characterization

Multibeam data collected around Zealandia Bank provide incomplete coverage of the summit of this seamount (Fig. 18.4.3a). These available data reveal an elongated bank, with ridges radiating from what may be a shallow shelf area on the east. The bathymetry data suggest a longer ridge extending northwards and a conical feature east of this bank. In deeper waters around Zealandia Bank, the bathymetry data identify blocks of material that could be either erosional or volcanic features.

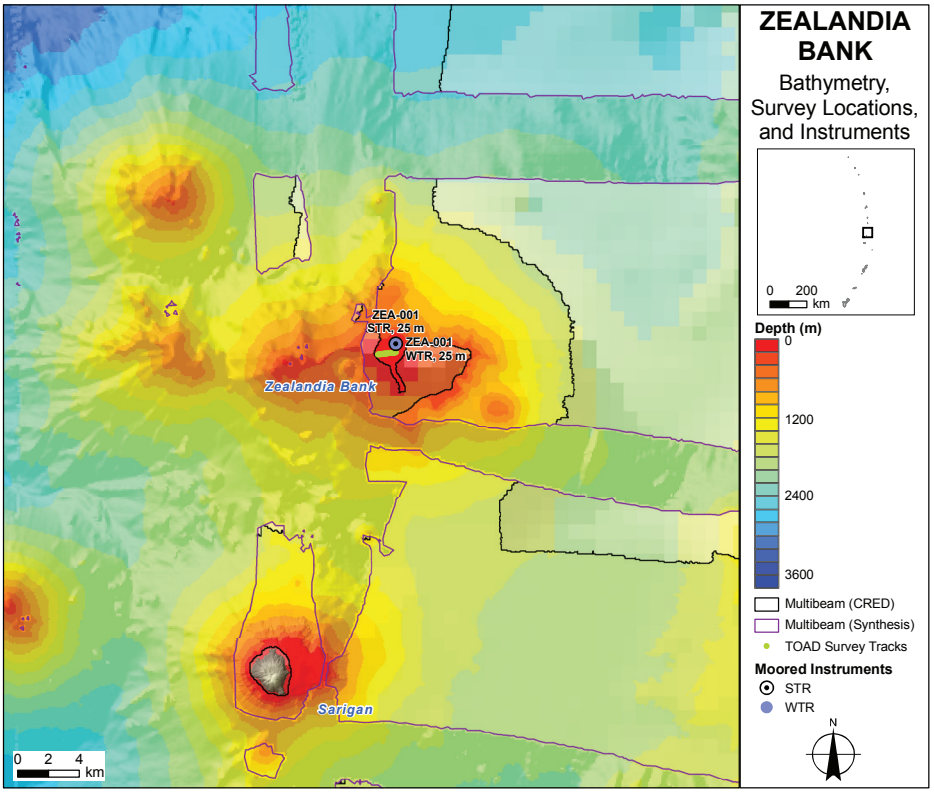


Figure 18.4.3a. Gridded multibeam bathymetry (grid cell size: 60 m, shown outlined in black) collected by CRED on Zealandia Bank during MARAMP 2007 at depths of 25–2500 m using a 30-kHz Kongsberg EM 300 sonar with gridded synthesis of additional multibeam bathymetry data (grid cell size: 100 m, shown outlined in purple) collected on various cruises using multibeam echosounders and compiled from public data available from NOAA's National Geophysical Data Center. Shown elsewhere are modeled bathymetry data (grid cell size: 30 arcsecond or ~ 900 m; Becker et al. 2009). Also shown are the location and depths of the mooring site for the WTRs and STR deployed on Zealandia Bank during MARAMP 2003, 2005, and 2007. The yellow-green bar just south of the mooring site represents the track of the TOAD survey conducted during MARAMP 2003.

During MARAMP 2003, a single TOAD survey was conducted on Zealandia Bank. Analyses of video footage obtained from this survey suggest a variable substrate, with more than a third of the observed benthos classified as hard substrate and the remainder either as sandy or a mixed substrate (Fig. 18.4.3b). No live hard corals were recorded.

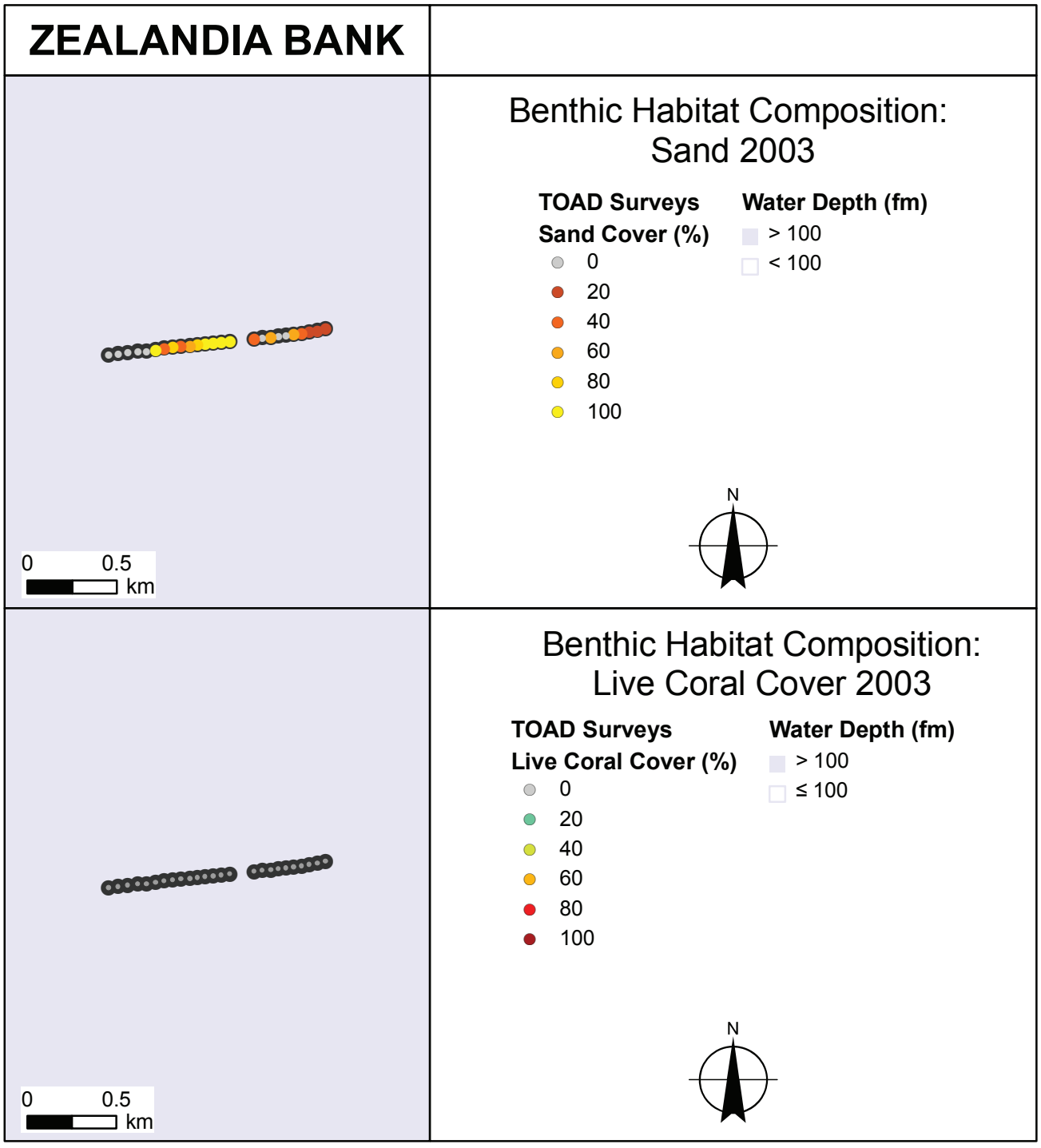


Figure 18.4.3b. Observations of (*top*) sand cover (%) and (*bottom*) cover (%) of live hard corals from analysis of TOAD video collected on Zealandia Bank during MARAMP 2003.

18.4.4 Oceanography

From MARAMP 2003 to 2007, two types of moored instruments were deployed on Zealandia Bank to collect time-series observations of key oceanographic parameters influencing reef conditions. The time frame and depth of these deployments are provided in Figure 18.4.4a.

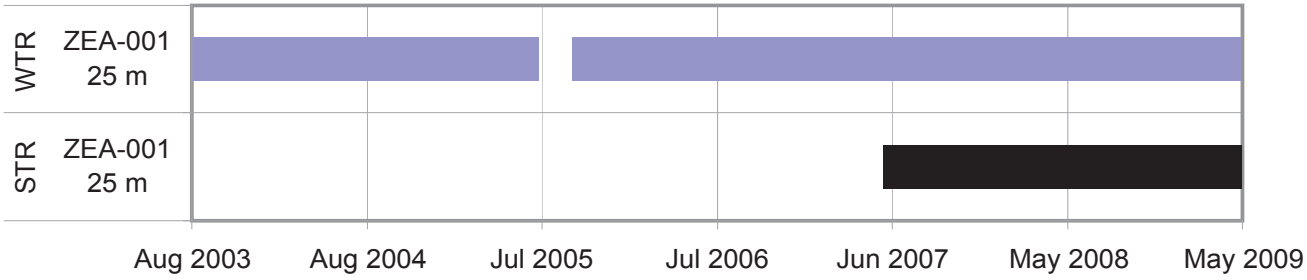


Figure 18.4.4a. Deployment timelines and depth of the WTRs and STR moored at Zealandia Bank during the period from August 2003 to April 2009.

Wave heights at Zealandia Bank, for the period from August 2003 to June 2007, were generally dominated by a seasonal pattern, with the highest ambient wave heights occurring through winter and the lowest heights occurring through summer (Fig. 18.4.4b). Superimposed on these seasonal fluctuations were episodic wave events characterized by brief periods of high (> 4 m) wave heights, which were typically associated with the typhoon season of August–December but also were observed during other time periods. Wave conditions could be highly variable from year to year. Wave conditions on Zealandia Bank in 2004 were characterized by a few large wave events (> 6 m), while no such extreme wave events occurred in the next 3 years (2005–2007). Wave events recorded in 2004 were 1 m larger on Zealandia Bank than on Supply Reef, since Zealandia is located farther south on the Mariana Arc and, therefore, closer to latitudes of typhoon generation.

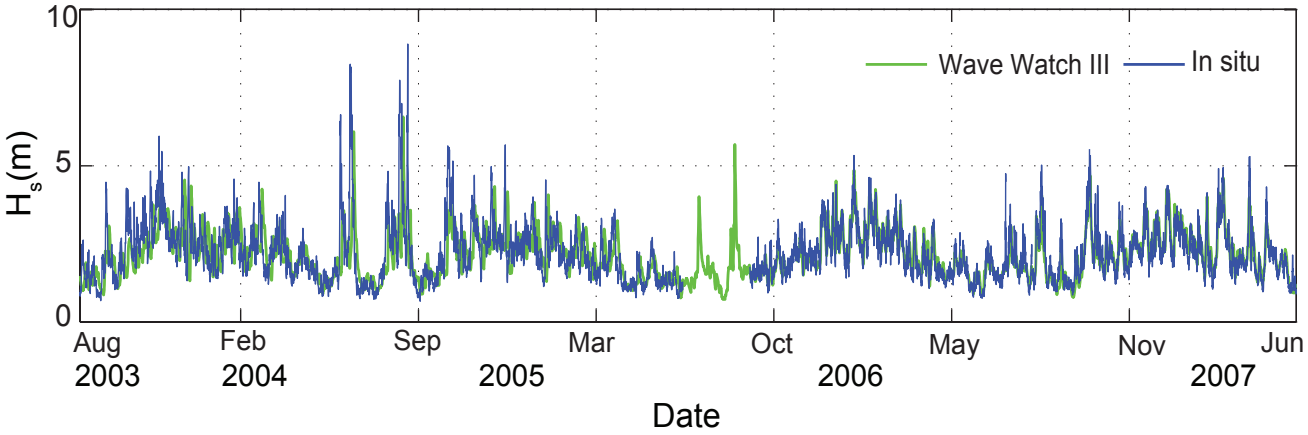


Figure 18.4.4b. Time-series observations of wave height (H_s) for the period from August 2003 to June 2007 using data from WTRs deployed on Zealandia Bank at a depth of 25 m and from the NOAA Wave Watch III model (see Figure 18.4.3a for mooring location; for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling").

18.5 Marpi Bank

18.5.1 Introduction

Marpi Bank, located ~ 18 km north of Saipan, is part of the remnant Mariana frontal arc formed during the late Eocene and early Miocene epochs (15–20 million years ago). Like Saipan, Tinian, Tatsumi Reef, Rota, and Aguijan, Marpi Bank has a flat top and is probably made up of uplifted limestone overlying an older volcanic core.

18.5.2 Survey Effort

Benthic habitat mapping data were collected on Marpi Bank using acoustic survey methods. Multibeam sonar data collected by CRED around Marpi Bank, Saipan, Tinian, and Tatsumi Reef in 2003 using the NOAA R/V *Acoustic Habitat Investigator* covered a total area of 213.4 km^2, and data collected by CRED in 2007 using the NOAA Ship *Hi'ialakai* covered a total area of 1800 km^2. These multibeam sonar data are the only data available for Marpi Bank.

18.5.3 Benthic Habitat Mapping and Characterization

Multibeam bathymetry data collected on Marpi Bank suggest a flat-topped bank with a minimum depth of 53 m and an elongated shape that runs in a northeast–southwest direction and is ~ 7 km long and 3 km wide (Fig. 18.5.3a). Bathymetry data suggest that the surrounding seafloor is similar in character to the seafloor around Saipan and Tinian: relatively low slopes punctuated with ridges and fissures and blocks of material that may have resulted from erosional processes.

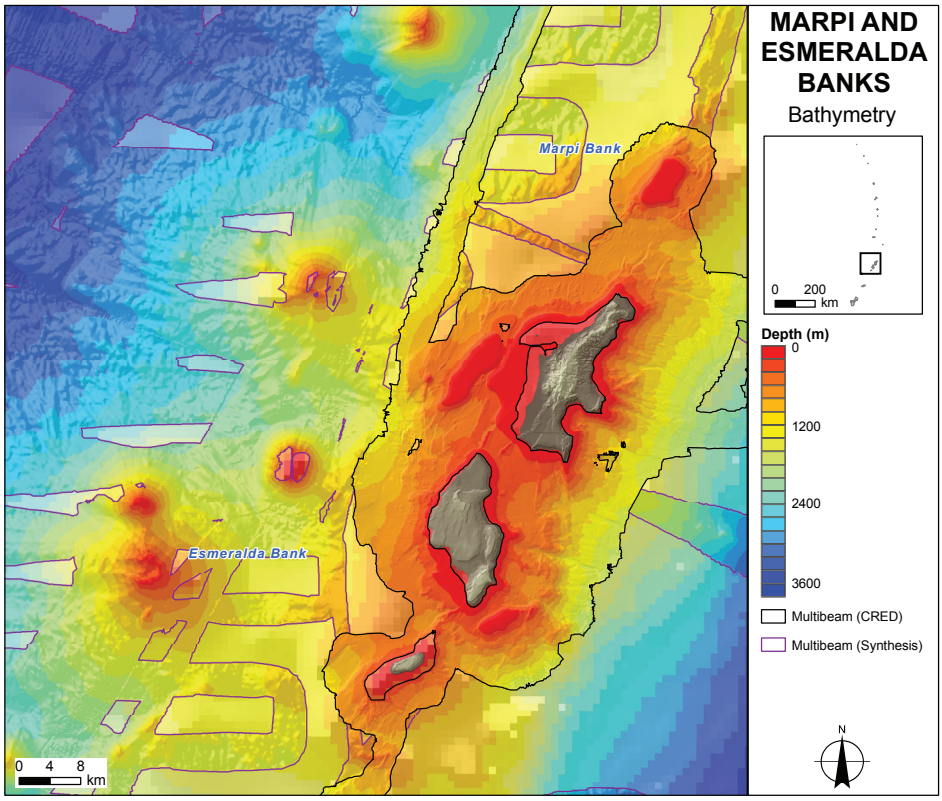


Figure 18.5.3a. Gridded multibeam bathymetry (grid cell size: 60 m, shown outlined in black) collected by CRED during MARAMP 2007 at depths of 60–4000 m using a 30-kHz Kongsberg EM 300 sonar with gridded synthesis of additional multibeam bathymetry data (grid cell size: 100 m, shown outlined in purple) collected on various cruises using multibeam echosounders and compiled from public data available from NOAA's National Geophysical Data Center. Shown elsewhere are modeled bathymetry data (grid cell size: 30 arcsecond or ~ 900 m; Becker et al. 2009).

High-resolution multibeam bathymetry data also were collected on Marpi Bank. These data reveal the texture of this flat-topped bank (Fig 18.5.3b). Various mounds and channels on top of the bank may indicate coral habitat. A depth range of 53–70 m suggests very little depth variation on the bank top, with the shallowest areas shown on the southern part of this bank. The high-resolution data obtained on Marpi Bank were patchy in places because they were collected at survey speeds that were higher than optimal. When bathymetric grids are patchy, artifacts can affect derived products, such as slope and rugosity, and accurate interpretation can be difficult; thus, no derived products are presented for Marpi Bank.

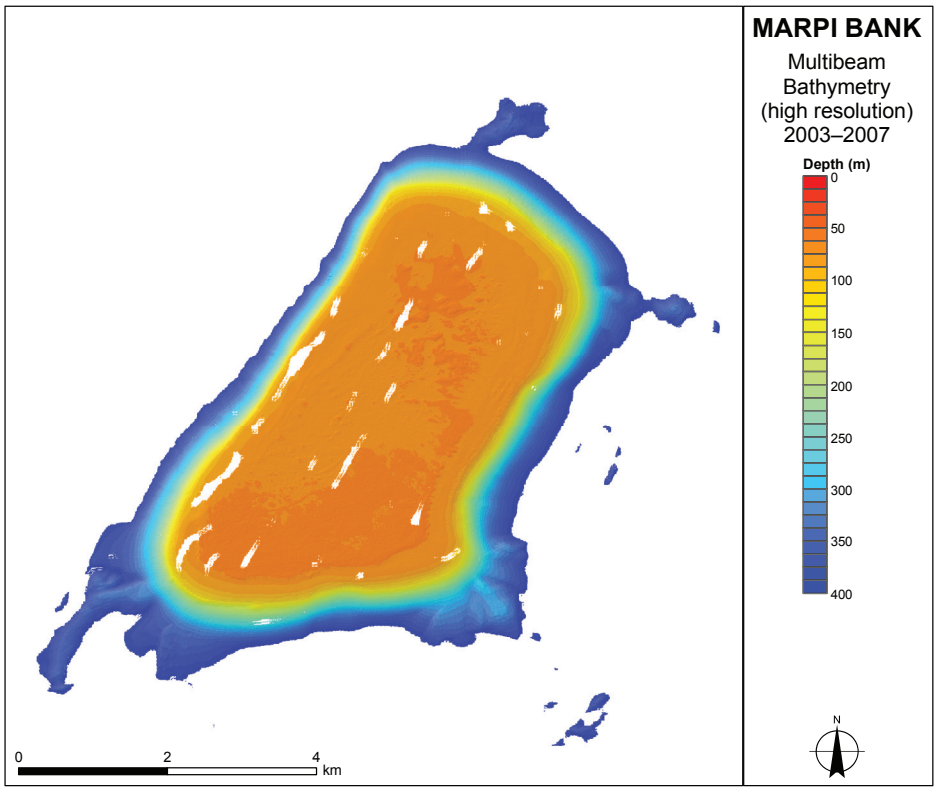


Figure 18.5.3b. High-resolution multibeam bathymetry collected on Marpi Bank using Reson SeaBat 8101 ER and Kongsberg EM 300 sonars during MARAMP 2007. This 5-m bathymetry grid has been clipped at 400 m.

18.6 Esmeralda Bank

18.6.1 Introduction

Esmeralda Bank, a stratovolcano located 57 km southwest of Saipan, is one of the southernmost active volcanoes on the Mariana Arc (Stern and Bibee 1984). Hydrothermal activity and venting have been observed on Esmeralda Bank during several NOAA Ocean Explorer cruises (Embley et al. 2004). Esmeralda Bank is part of the Volcanic Unit of the Marianas Trench Marine National Monument.

18.6.2 Survey Effort

CRED has not collected multibeam data on Esmerelda during MARAMP surveys. Multibeam data have been collected as part of an ongoing series of NOAA Ocean Explorer expeditions that have included NOAA VENTS Program "Submarine Ring of Fire" cruises (Weiss et al. 2008; Embley et al. 2007). To provide a picture of the topography of this reef, these multibeam bathymetry data are presented as part of a bathymetry grid with a 100-m resolution that was synthesized from a compilation of public data available from NOAA's National Geophysical Data Center.

Data for optical validation and habitat characterization were collected during MARAMP 2003 using TOAD surveys, which documented live coral cover, sand cover, and habitat complexity. Three TOAD surveys were conducted on Esmeralda Bank, covering a distance of 1.07 km at depths from ~ 63 to > 100 m (exact depth measurements with the sensor on the TOAD is impossible). The results of these efforts are discussed in the next section.

18.6.3 Benthic Habitat Mapping and Characterization

Multibeam data show that the summit of Esmeralda Bank is actually the rim of a crater, which appears to be breached to the west, and from this breach a wide channel runs into deeper water (Fig. 18.6.3a).

During MARAMP 2003, 3 TOAD surveys were conducted on Esmeralda Bank, all of them located on the north crater rim. Analyses of the TOAD video footage obtained from these surveys suggest that the southernmost survey area had predominantly sandy seabeds, while the rest of the areas surveyed mostly had hard substrates (Fig. 18.6.3b). Analyses of video footage from TOAD surveys also suggest that live corals were rare.

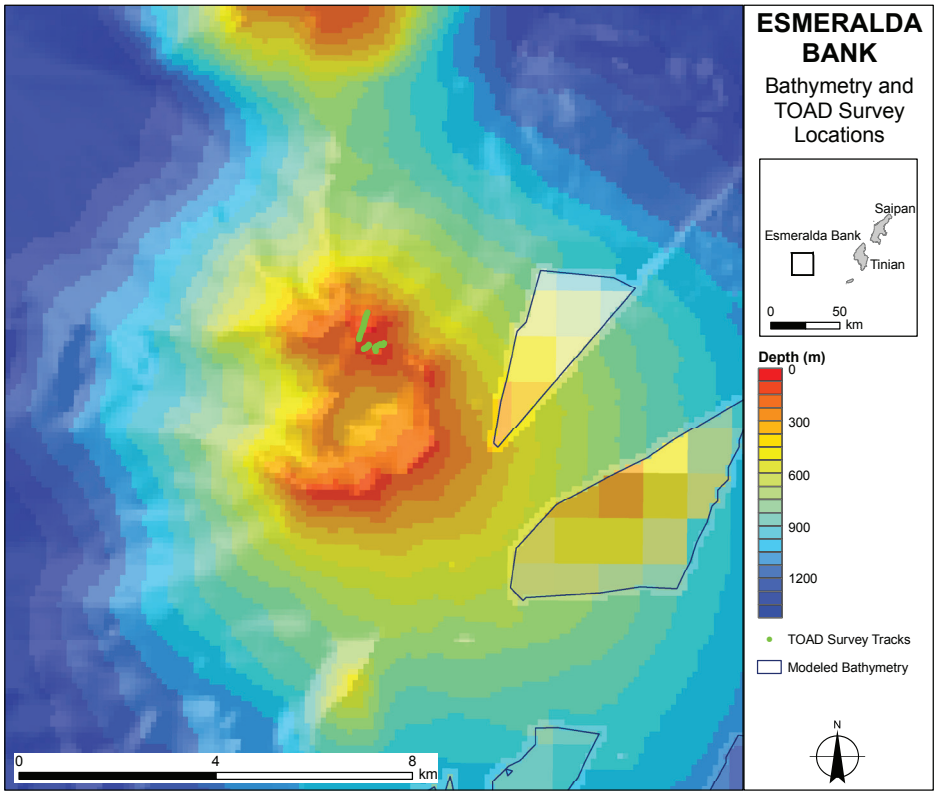


Figure 18.6.3a. Gridded synthesis of multibeam bathymetry data (grid cell size: 100 m) collected on Esmeralda Bank during various cruises using multibeam echosounders and compiled from public data available from NOAA's National Geophysical Data Center. Modeled bathymetry data (grid cell size: 30 arcsecond or ~ 900 m) are shown within the small areas outlined in indigo (Becker et al. 2009). For a different view of these data in a larger context, see Figure 18.5.3a in Section 18.5: "Marpi Bank." Also shown are the tracks of the TOAD surveys conducted on Esmeralda Bank during MARAMP 2003.

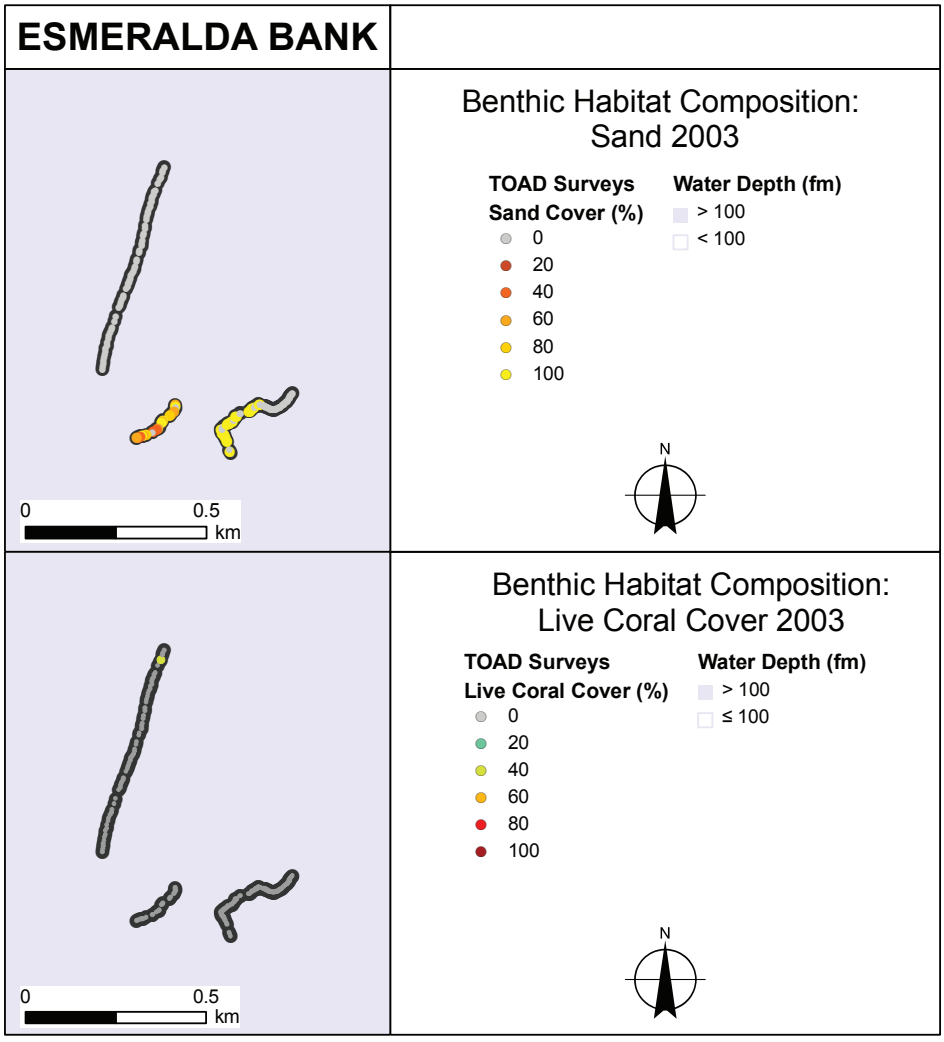


Figure 18.6.3b. Observations of (*top*) sand cover (%) and (*bottom*) cover (%) of live hard corals from analysis of TOAD video collected on Esmeralda Bank during MARAMP 2003.

18.7 Stingray Shoal

18.7.1 Introduction

Stingray Shoal is a remnant volcanic seamount located on the northern end of the West Mariana Ridge. Stingray Shoal is part of the Volcanic Unit of the Marianas Trench Marine National Monument.

18.7.2 Survey Effort

No multibeam acoustic bathymetry data were collected over Stingray Shoal. Single-depth soundings were obtained from a small boat using a handheld depth sounder and handheld GPS over Stingray Shoal during MARAMP 2003.

REA, towed-diver, and TOAD surveys were conducted on Stingray Shoal during MARAMP 2003 to collect information on habitat and the composition and distribution of biological communities. No data were obtained from REA surveys, and the results of towed-diver and TOAD surveys are reported in Section 18.7.3: "Benthic Mapping and Characterization" and Section 18.7.5 "Biological Characterization." The numbers of these surveys are presented in Table 18.7.2a, along with their mean depth and total area or length. Two TOAD surveys were conducted on Stingray Shoal at depths of ~ 20–110 m, covering a distance of 0.94 km. Subsequent analyses of the video acquired from these surveys provided estimates of sand cover and live coral cover. Four towed-diver surveys were conducted along parts of the forereef slope of Stingray Shoal at depths of 6–26 m (mean depth 12.8 m), covering a distance of 4.95 km.

Table 18.7.2a. Numbers, mean depth (m), total area (ha), and total length (km) of towed-diver and TOAD surveys conducted on Stingray Shoal during MARAMP 2003.

Survey Type	Survey Detail	Year
Towed Diver		**2003**
	Number of Surveys	4
	Total Survey Area (ha)	5.0
	Mean Depth (m)	12.8
TOAD		**2003**
	Number of Surveys	2
	Total Length (km)	0.94

18.7.3 Benthic Habitat Mapping and Characterization

Single-depth soundings collected over Stingray Shoal revealed an apparently conical seamount with an estimated minimum depth of 13 m (Fig. 18.7.3a).

During MARAMP 2003, 4 towed-diver surveys and 2 TOAD surveys were conducted. At 5-min intervals within each towed-diver survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high. Both observations from towed-diver surveys conducted and analyses of TOAD video footage collected over Stingray Shoal suggested a predominantly hard substrate with very few areas exhibiting sand cover of > 5%. Towed-diver surveys completed on the summit of Stingray Shoal recorded habitat of medium-high to high complexity supporting consistently high cover of live hard corals, compared to other areas surveyed in the Mariana Archipelago, over continuous, well-developed reef (Fig. 18.7.3b). Live coral cover of 40.1%–100% was observed for all but 2 survey segments. Analyses of video footage obtained from TOAD surveys revealed that these high levels of live coral cover were seen more sporadically in the deeper waters of the northern and southern parts of this reef.

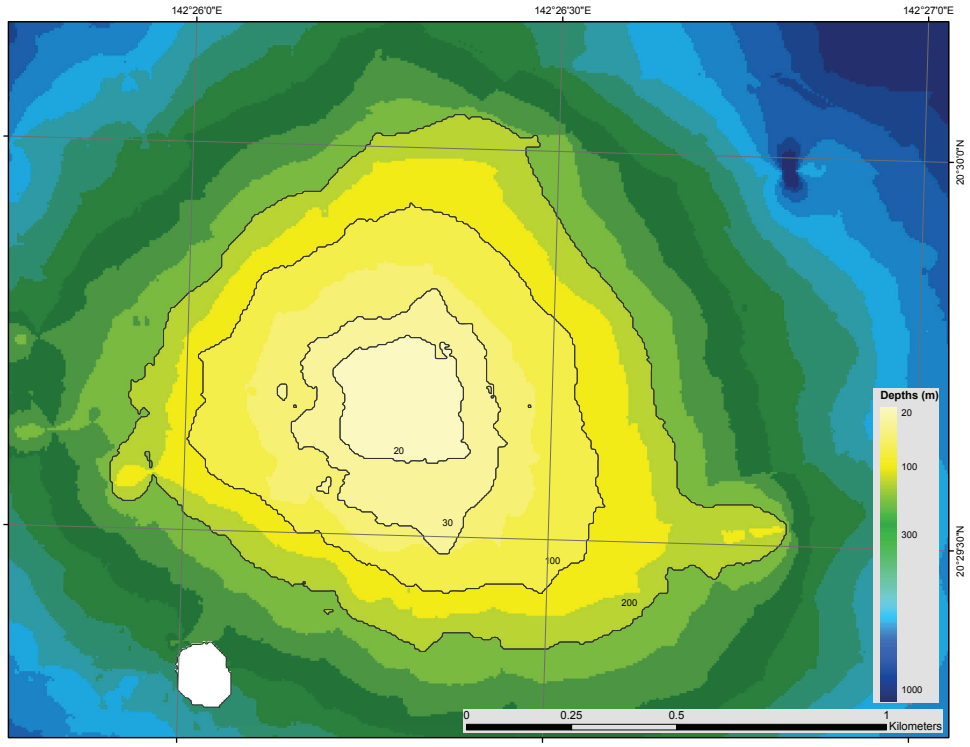
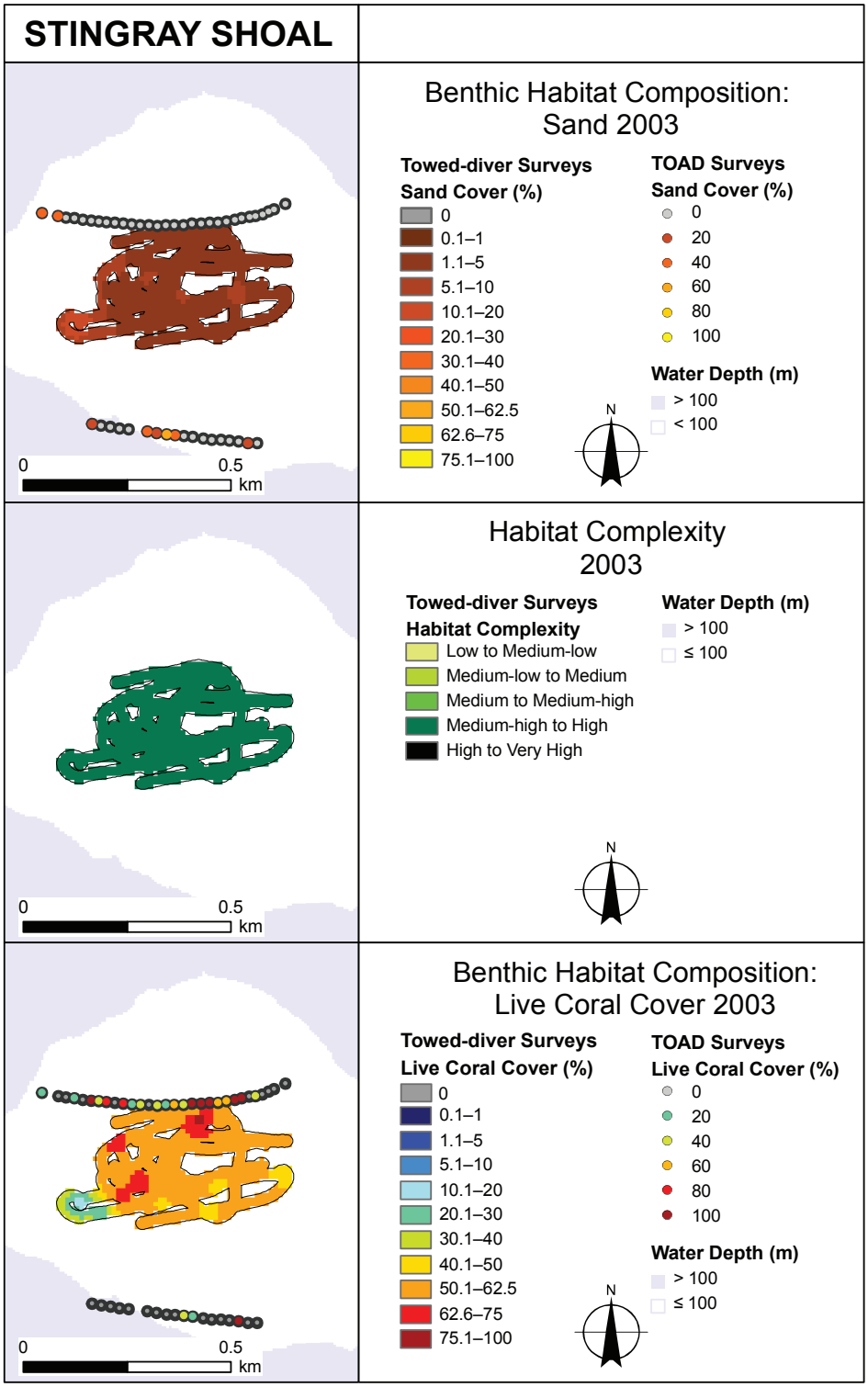


Figure 18.7.3a. Contoured map derived from single-depth soundings collected using a handheld depth sounder on Stingray Shoal during MARAMP 2003.

Figure 18.7.3b. Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) cover (%) of live hard corals from towed-diver surveys conducted and analysis of TOAD video collected on Stingray Shoal during MARAMP 2003.



18.7.4 Biological Characterization

During MARAMP 2003, towed-diver surveys conducted on Stingray Shoal were short in duration (5 or 7 segments instead of the typical 10 segments) because of deep depths.

18.7.4.1 Coral Surveys

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals was 55% (SE 2.7) on Stingray Shoal (Fig. 18.7.4.1a), the highest level recorded for an island or bank in the Mariana Archipelago during any of the 3 MARAMP survey years. For all but 2 survey segments, live coral cover was 40.1%–100%. The highest coral cover was observed in the north and west, with segment means of 75% and 76%.

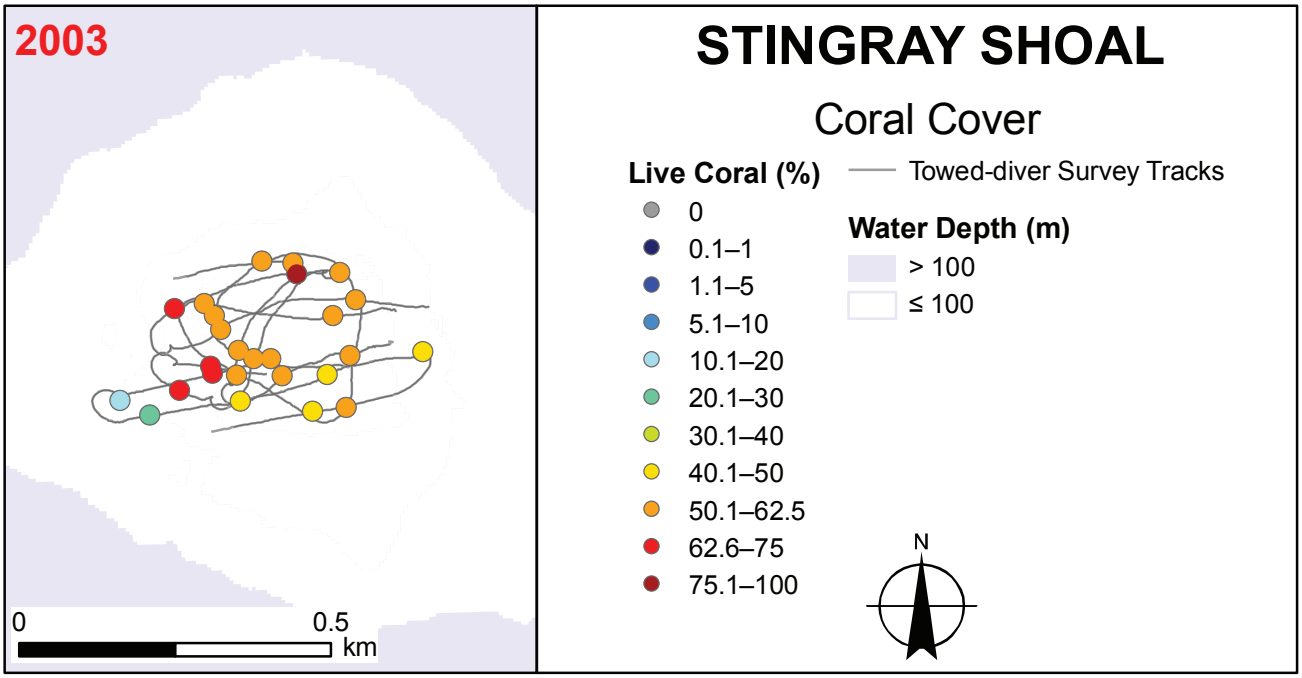


Figure 18.7.4.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys conducted on Stingray Shoal during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 100-fm contour shown in white represents potential reef habitat.

18.7.4.2 Algal Surveys

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on Stingray Shoal was 34% (SE 1.9), with mean values for the 4 surveys of 21%, 32%, 35%, and 44% (Fig 18.7.4.2a). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The overall estimated mean for cover of crustose coralline red algae was 2% (SE 0.4), with survey means of 0%, 0%, 3%, and 5%. Continuous reef was the most commonly reported habitat type and complexity was high and medium high.

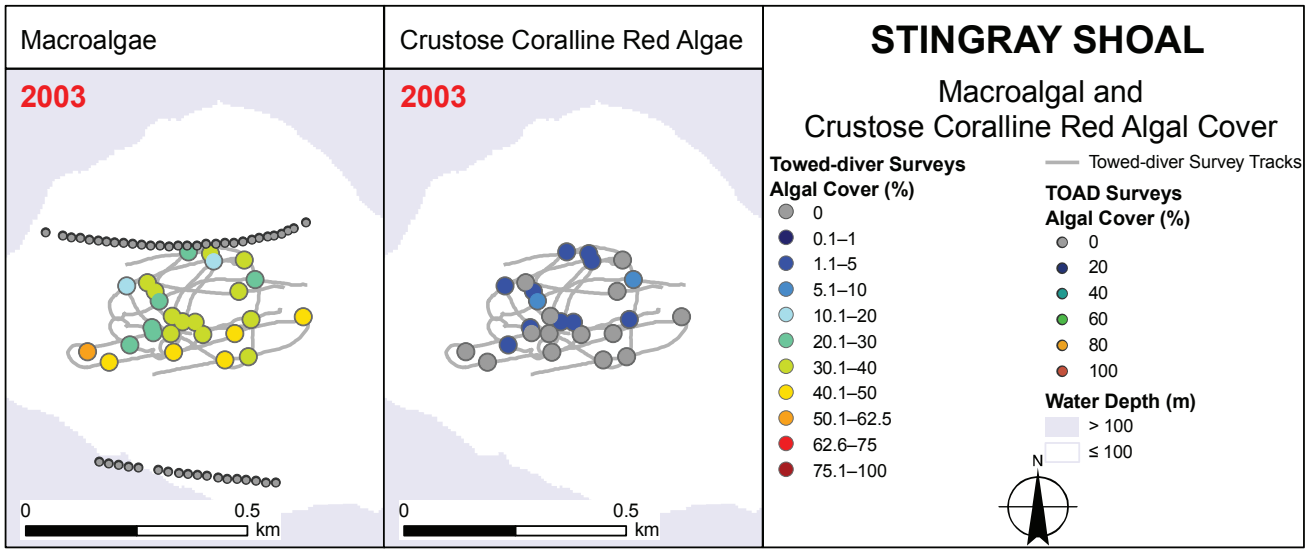


Figure 18.7.4.2a. Cover (%) observations for (*left*) macroalgae and (*right*) crustose coralline red algae from towed-diver benthic surveys conducted on Stingray Shoal during MARAMP 2003. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m²). The macroalgal panel shows observations of both macroalgae and turf algae. In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys. The 100-fm contour shown in white represents potential reef habitat.

18.7.4.3 Benthic Macroinvertebrate Surveys

During MARAMP 2003, species of *Tridacna* giant clams were observed in 1 of the 4 towed-diver surveys conducted on Stingray Shoal, with an overall mean density of 0.002 organisms 100 m^{-2}. Giant clams were seen over only 1 survey segment, which had a density of 0.053 organisms 100 m^{-2} (Fig. 18.7.4.3a).

Crown-of-thorns seastars (*Acanthaster planci*) were not observed on Stingray Shoal in 2003 during towed-diver surveys.

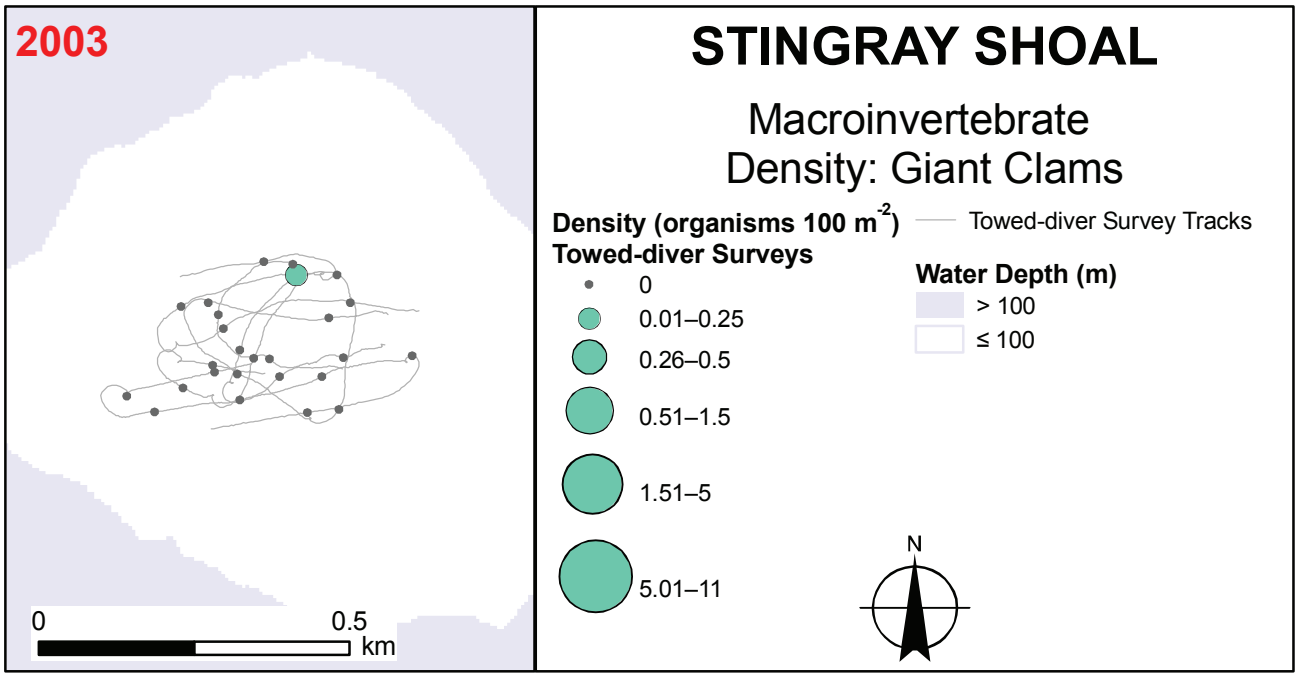


Figure 18.7.4.3a. Densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on Stingray Shoal during MARAMP 2003. The 100-fm contour shown in white represents potential reef habitat.

Sea cucumbers were observed in 2 of the 4 towed-diver surveys conducted on Stingray Shoal in 2003, with an overall mean density of 0.006 organisms 100 m^{-2}. Between the 2 surveys, the higher mean density of sea cucumbers was 0.018 organisms 100 m^{-2}; sea cucumbers were observed during only 1 segment, which had a density of 0.089 organisms 100 m^{-2}.

Sea urchins were observed in all 4 towed-diver surveys conducted on Stingray Shoal in 2003, with an overall mean density of 0.84 organisms 100 m^{-2}. The greatest mean density from a towed-diver survey was 1.55 organisms 100 m^{-2}; segment densities ranged from 0 to 3.64 organisms 100 m^{-2} (Fig. 18.7.4.3b).

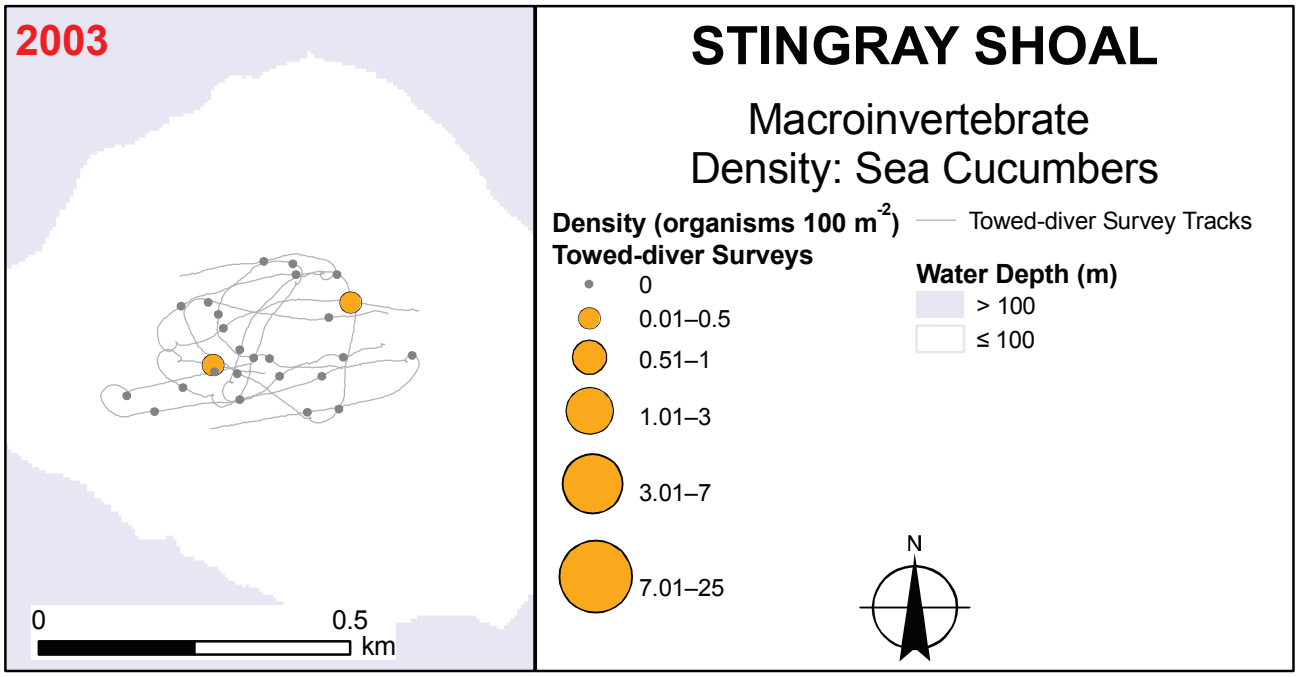


Figure 18.7.4.3b. Densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted on Stingray Shoal during MARAMP 2003. The 100-fm contour shown in white represents potential reef habitat.

18.7.4.4 Fish Surveys

During MARAMP 2003, 4 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted on Stingray Shoal (Fig. 18.7.4.4a.). The overall estimated mean biomass, calculated as weight per unit area, was at 5.15 kg 100 m^{-2} (SE 1.08), a high value compared to other areas surveyed in the Mariana Archipelago. Reef sharks accounted for the highest proportion (52%) or 2.67 kg 100 m^{-2} of large-fish biomass. The grey reef shark accounted for 88% or 2.36 kg 100 m^{-2} of shark biomass. During this survey period, 71 sharks, with a mean length of 103.4 cm TL, were observed: 65 grey reef shark and 6 whitetip reef shark. Surgeonfishes (Acanthuridae) accounted for the second-greatest proportion (31%) of overall biomass of large fishes, with the sleek unicornfish (*Naso hexacanthus*) and the bulbnose unicornfish (*Naso tonganus*) making up the majority of surgeonfish biomass, at 0.92 kg 100 m^{-2} and 0.56 kg 100 m^{-2}. Snappers also were commonly observed and accounted for 13% of the overall large-fish biomass. The twinspot snapper contributed 94% of snapper biomass.

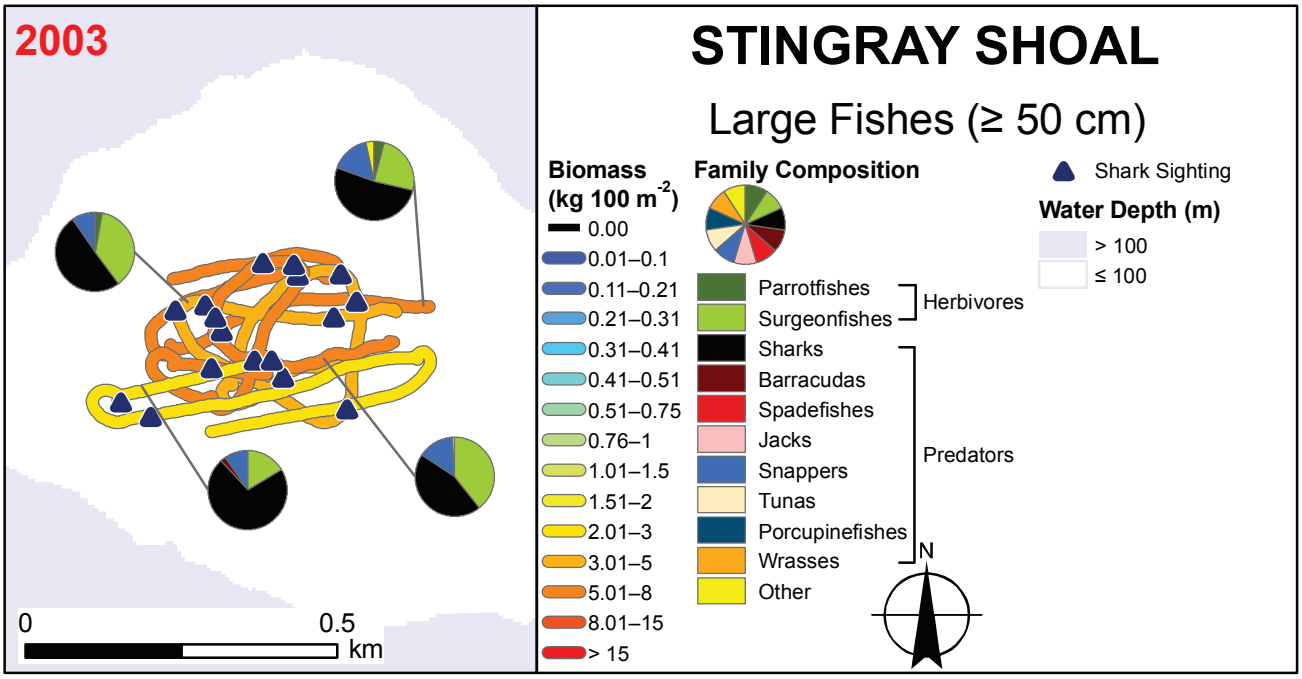


Figure 18.7.4.4a Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver surveys conducted on Stingray Shoal during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside the survey area over which it is shown. The 100-fm contour shown in white represents potential reef habitat.

18.8 Pathfinder Reef

18.8.1 Introduction

Pathfinder Reef is a remnant, volcanic, submerged ridge located ~ 150 km west of Saipan on the southern end of the West Mariana Ridge with a minimum depth of 10 m.

18.8.2 Survey Effort

No multibeam acoustic bathymetry data were collected over Pathfinder Reef. To provide some indication of the minimum depth, single-depth soundings were obtained from a small boat using a handheld depth sounder and handheld GPS over Pathfinder Reef during MARAMP 2003.

REA, towed-diver, and TOAD surveys were conducted on Pathfinder Reef during MARAMP 2003 and 2005 to collect information on habitat and the condition, abundance, diversity, and distribution of biological communities. Results from these surveys are discussed in Section 18.8.3: "Benthic Mapping and Characterization" and Section 18.8.4 "Biological Characterization." The numbers of these surveys are presented in Table 18.8.2a, along with their mean depths and total areas or length. Two TOAD surveys were conducted on Pathfinder Reef during MARAMP 2003 at depths of ~ 12–34 m, covering a distance of 2.21 km. Subsequent analyses of the video acquired from these surveys provided estimates of the percentages of sand cover and live coral cover.

For both MARAMP survey years combined, 7 towed-diver surveys were conducted on Pathfinder Reef at depths of 0–22 m, covering a distance of 13.68 km. The mean depths of individual surveys ranged from 16.4 m (SD 2.9) to 17.4 m (SD 3.2) in 2003 and from 15.7 m (SD 1.9) to 16.7 m (SD 1.9) in 2005. Figures 18.8.2a and b illustrate the locations and depths of towed-diver-survey tracks on Pathfinder Reef and should be referenced when further examining results of the towed-diver surveys from MARAMP 2003 and 2005.

Survey Type	Survey Detail	Year	
REA		**2003**	**2005**
Fish	Number of Surveys	2	2
	Mean Depth (m)	17 (SD 2.8)	17 (SD 2.8)
Benthic	Number of Surveys	2	2
	Mean Depth (m)	17 (SD 2.8)	17 (SD 2.8)
Towed Diver		**2003**	**2005**
	Number of Surveys	4	3
	Total Survey Area (ha)	7.5	6.2
	Mean Depth (m)	17 (SD 0.5)	16.3 (SD 0.5)
TOAD		**2003**	
	Number of Surveys	2	
	Total Length (km)	2.21	

Table 18.8.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted at Pathfinder Reef during MARAMP 2003 and 2005. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys for corals, algae, and macroinvertebrates.

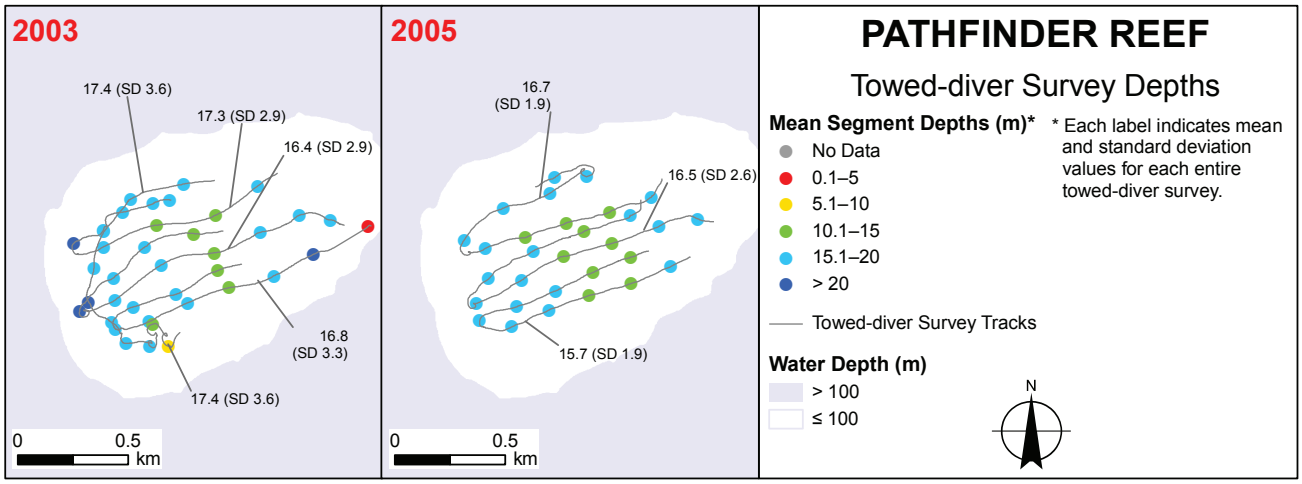


Figure 18.8.2a. Depths and tracks of towed-diver surveys conducted on Pathfinder Reef during MARAMP 2003 and 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate. The 100-fm contour shown in white represents potential reef habitat.

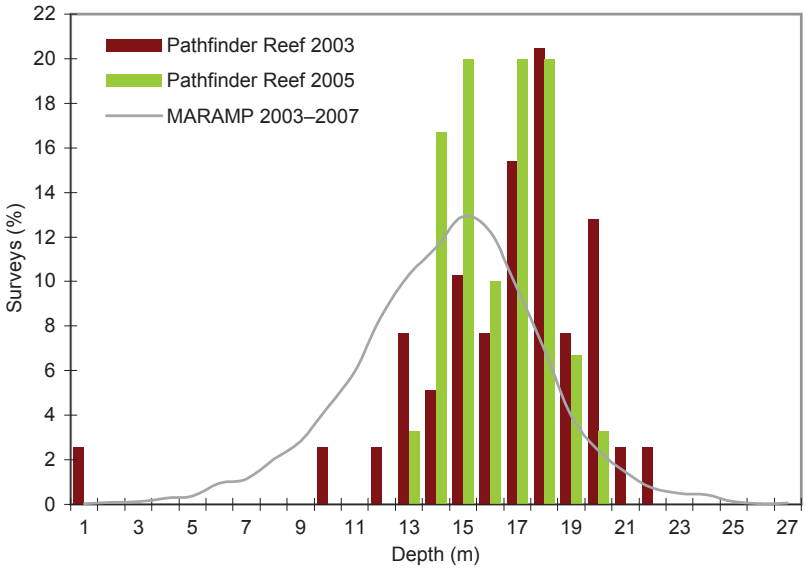


Figure 18.8.2b. Depth histogram plotted from mean depths of 5-min segments of the towed-diver surveys conducted on Pathfinder Reef during MARAMP 2003 and 2005. Mean segment depths are derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

18.8.3 Benthic Habitat Mapping and Characterization

Figure 18.8.3a presents a contoured map of the handheld depth soundings collected on Pathfinder Reef.

During MARAMP 2003, 4 towed-diver surveys and 2 TOAD surveys were conducted, and, during MARAMP 2005, 3 towed-diver surveys were completed. At 5-min intervals within each towed-diver survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high. Both observations from towed-diver surveys conducted and analyses of TOAD video footage collected over Pathfinder Reef revealed a predominantly hard substrate with sand cover of 100% observed in only 3 video frames (Fig. 18.8.3b). Habitat complexity was lower here than at Stingray Shoal and ranged from medium-low to medium high. Habitats on Pathfinder Reef were described as atypical spur-and-groove reef with gently sloping mounds of coral interspersed with hard pavement channels. Estimates of live coral cover from towed-diver surveys were consistent, with means of 10.1%–40% recorded in all but 1 survey segment. Results for live coral cover from analyses of video footage obtained from TOAD surveys were more variable and ranged from 0% to 100%. These results reflect the differences between the 2 survey methods, with TOAD surveys providing snapshots of the seabed in a restricted area and towed-diver surveys covering a larger area, with observations averaged by survey segment.

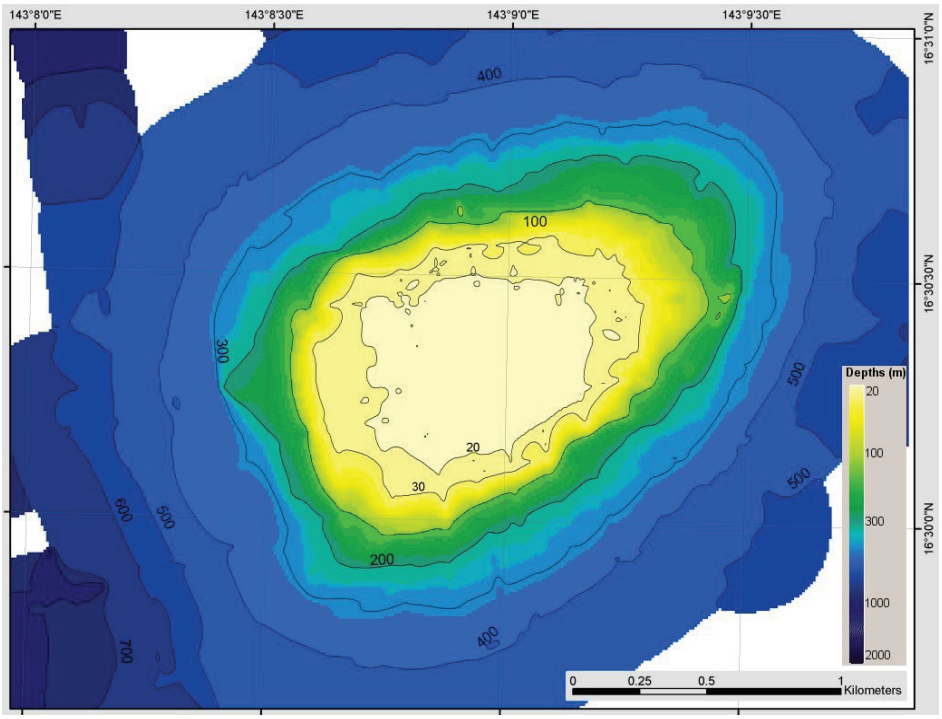


Figure 18.8.3a. Contoured map derived from single-depth soundings collected using a handheld depth sounder on Pathfinder Reef during MARAMP 2003.

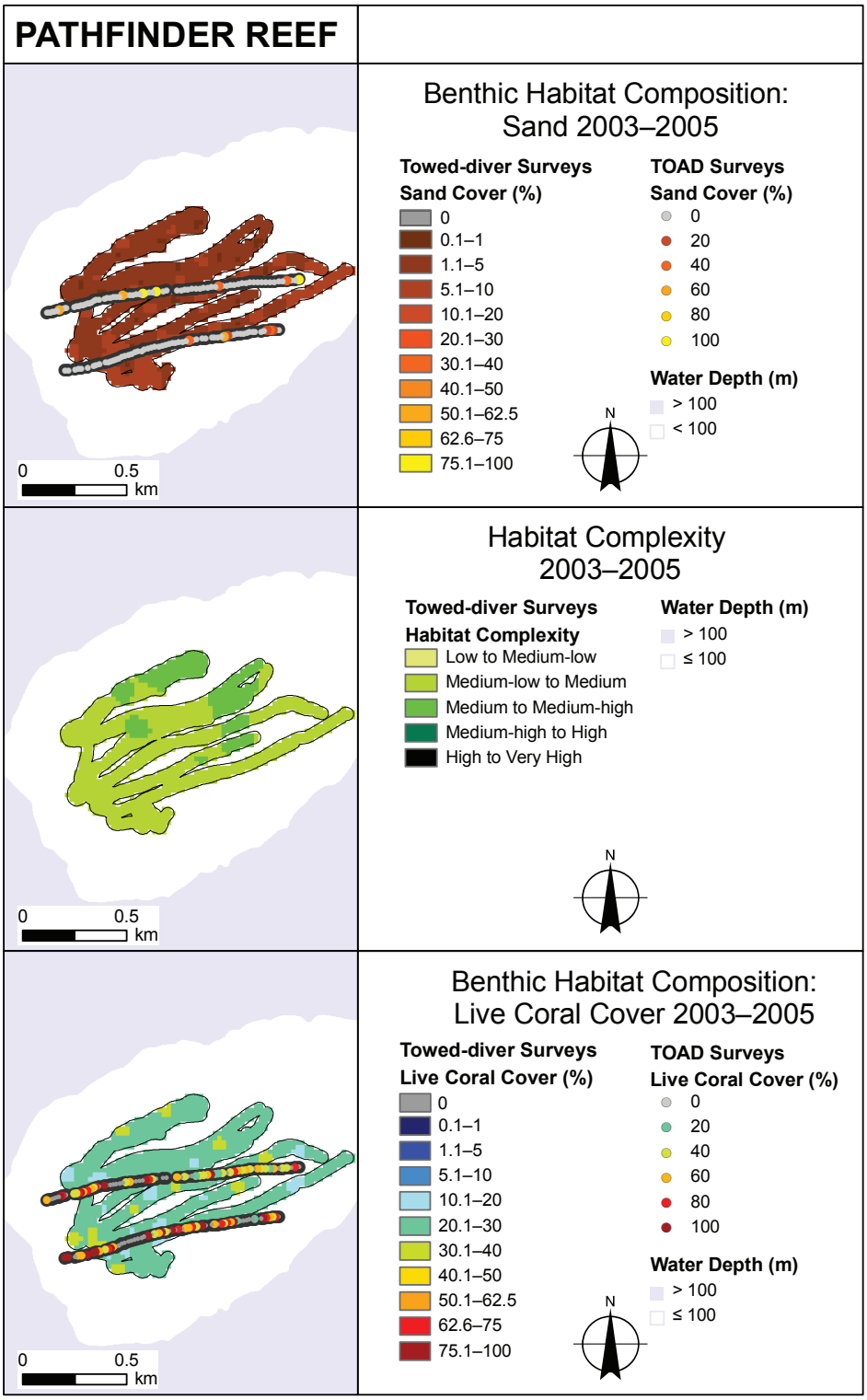


Figure 18.8.3b. Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) cover (%) of live hard corals from towed-diver surveys conducted and analysis of TOAD video collected on Pathfinder Reef during MARAMP 2003 and 2005. The 100-fm contour shown in white represents potential reef habitat.

18.8.4 Biological Characterization

18.8.4.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on Pathfinder Reef was 24% (SE 0.9). Coral cover was relatively uniform, with means of 10.1%–30% recorded for a majority of survey segments. The highest coral cover was observed along the western edge of Pathfinder, with a mean of 35% over 4 segments (Fig. 18.8.4.1a, left panel).

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on Pathfinder Reef was 25% (SE 1.4). Coral cover remained relatively uniform, again with the majority of survey segments having means of 10.1%–30%. The highest coral cover was observed along the interior, western edge, and northern border of Pathfinder, with a mean of 35% for 8 segments (Fig. 18.8.4.1a, right panel).

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including coral that was fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, < 1% of coral cover observed on Pathfinder Reef appeared stressed in 2005.

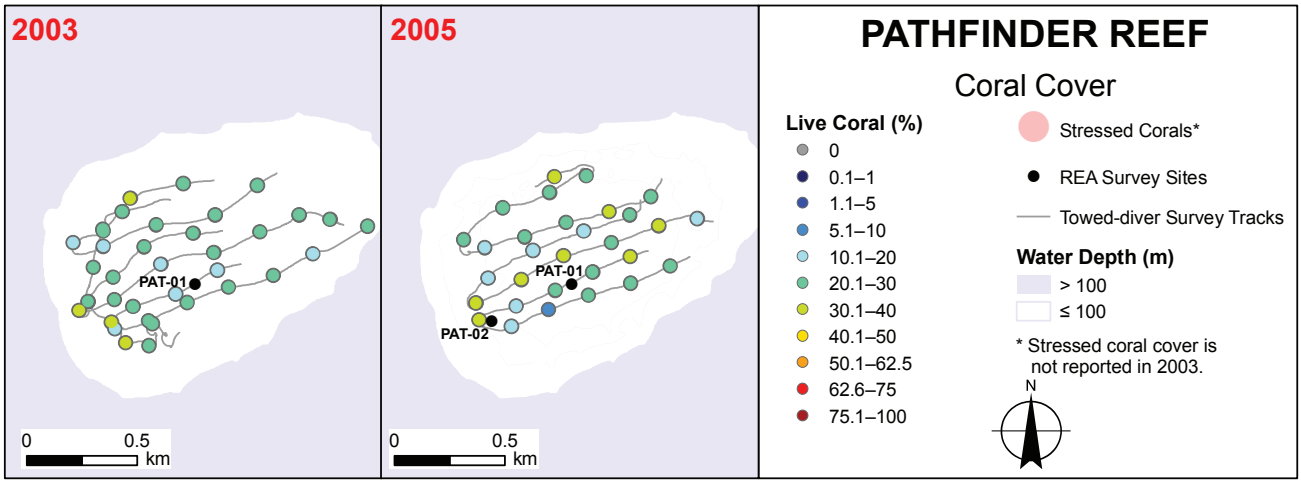


Figure 18.8.4.1a. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys conducted on Pathfinder Reef during MARAMP 2003 and 2005. Each colored point represents an estimate of live coral over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols are not shown here, since they represent only segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005. The 100-fm contour shown in white represents potential reef habitat.

During MARAMP 2003, 1 REA benthic survey using the quadrat method on Pathfinder Reef documented 77 coral colonies within a survey area of 3.75 m^2, yielding a site-specific colony density of 20.5 colonies m^{-2} (Table 18.8.4.1a).

During MARAMP 2005, 2 REA benthic surveys using the quadrat method on Pathfinder Reef documented 280 coral colonies within a survey area of 8 m^2. Site-specific colony density ranged from 28 to 42 colonies m^{-2} with a sample mean of 35 colonies m^{-2} (SE 7). The higher colony density was recorded at REA site PAT-02 on the western edge of this reef (Table 18.8.4.1a).

Between MARAMP survey years, little difference was seen in overall mean coral cover at Pathfinder Reef, as estimated from towed-diver surveys. At the single REA site surveyed in both years, PAT-01 in the center of this reef, observed coral-colony density increased from 20.5 to 28 colonies m^{-2}. The increase in estimates of colony density between 2003 and 2005 could reflect increased recruitment, fragmentation of existing colonies, or both, or could simply reflect sampling variation.

Coral Generic Richness and Relative Abundance

One REA benthic survey was conducted using the quadrat method on Pathfinder Reef during MARAMP 2003, and 11 coral genera were observed (Table 18.8.4.1a). Two REA benthic surveys were conducted using the quadrat method during MARAMP 2005. Generic richness in 2005 ranged from 11 genera at PAT-01 to 15 genera at PAT-02, with a mean of 13 (SE 2) coral genera per site.

Across the 2 MARAMP survey years, 16 coral genera were observed. *Pocillopora*, *Montastrea*, and *Psammocora* were important components of the coral fauna at Pathfinder Reef, contributing > 10% of the total number of colonies enumerated in both survey years. *Pocillopora* was the most numerically abundant taxon at PAT-01 in 2003 (Table 18.8.4.1a), contributing 40.3% of the total number of colonies observed at that site. *Montastrea* and *Psammocora* were the two next-most abundant taxa, contributing 18.2% and 10.4% of the total number of colonies. *Pocillopora* also was the most abundant taxon in 2005, contributing 36% of the total number of colonies enumerated. *Psammocora* and *Montastrea* were the next-most abundant taxa in 2005, contributing 16.5% and 10.1% of the total number of colonies recorded. All other taxa contributed < 10% of the total number of colonies enumerated in both survey years.

Table 18.8.4.1a. Observations of colony densities (colonies m^{-2}), coral generic richness, size-class distribution (%), and relative abundance of coral genera from REA benthic surveys conducted using the quadrat method on Pathfinder Reef during MARAMP 2003 and 2005.

				Size-class Distribution (%)							Abundance (%)										
Year	Site	Density (colonies 100 m^{-2})	Generic Richness (#)	0–5 cm	6–10 cm	11–20 cm	21–40 cm	41–80 cm	81–169 cm	> 160 cm	*Acropora*	*Astreopora*	*Favia*	*Goniastrea*	*Leptastrea*	*Montipora*	*Pavona*	*Pocillopora*	*Porites*	Octocorals	Other
2003	PAT-01	21	11	41.6	33.8	19.5	3.9	1.3	0	0	0	1.3	2.6	0	3.9	0	2.6	40.3	7.79	0	41.6
2005	PAT-01	28	11	54.5	27.7	13.4	3.57	0.89	0	0	0	0	0.89	0	2.68	3.57	3.57	50	5.36	0	33.9
2005	PAT-02	42	15	63.7	17.9	13.7	4.76	0	0	0	0	5.95	5.36	0	1.19	1.19	4.17	22	12.5	0	47.6

Coral Size-class Distribution

During MARAMP 2003, the coral size-class distribution at PAT-01 showed that no single size class contained the majority of corals. The greatest proportion of corals (41.6%) belonged to the smallest size class (≤ 5 cm; Table 18.8.4.1a). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 33.8%, 19.5%, 3.9%, and 1.3% of colonies recorded. No colonies with maximum diameters > 80 cm were recorded.

During MARAMP 2005, the coral size-class distributions on Pathfinder Reef showed that the majority (59.1%) of corals had maximum diameters ≤ 5 cm (Table 18.8.4.1a). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 22.8%, 13.5%, 4.2%, and 0.4% of colonies recorded. No colonies with maximum diameters > 80 cm were recorded.

At the single site surveyed in both MARAMP survey years, PAT-01, the proportion of colonies in the smallest size class (≤ 5 cm) increased from 41.5% to 54.6% between 2003 and 2005, and the proportion of colonies in all other size classes decreased. This shift towards the smallest size class may reflect recruitment, fragmentation of existing colonies, or both.

18.8.4.2 Algal Surveys

Algal Cover

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on Pathfinder Reef was 37% (SE 1.3), with mean values for the 4 surveys of 30%, 38%, 38%, and 45% (Fig. 18.8.4.2a, left top panel). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The overall estimated mean for cover of crustose coralline red algae was 6% (SE 0.8), with survey means of 0%, 4%, 7%, and 10% (Fig. 18.8.4.2a, right top panel). Spur-and-groove reef of medium-low complexity was the most commonly noted habitat type throughout these surveys.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on Pathfinder Reef was 29% (SE 1.1), with mean values for the 3 surveys of 24%, 28%, and 35% (Fig. 18.8.4.2a, bottom left panel). The overall estimated mean for cover of crustose coralline red algae was 10% (SE 1.2), slightly higher than the overall mean for 2003; means for individual surveys were 3%, 13%, and 13% (Fig. 18.8.4.2a, right bottom panel). Habitat complexity was most frequently noted as medium, except one survey had a higher incidence of medium-high complexity.

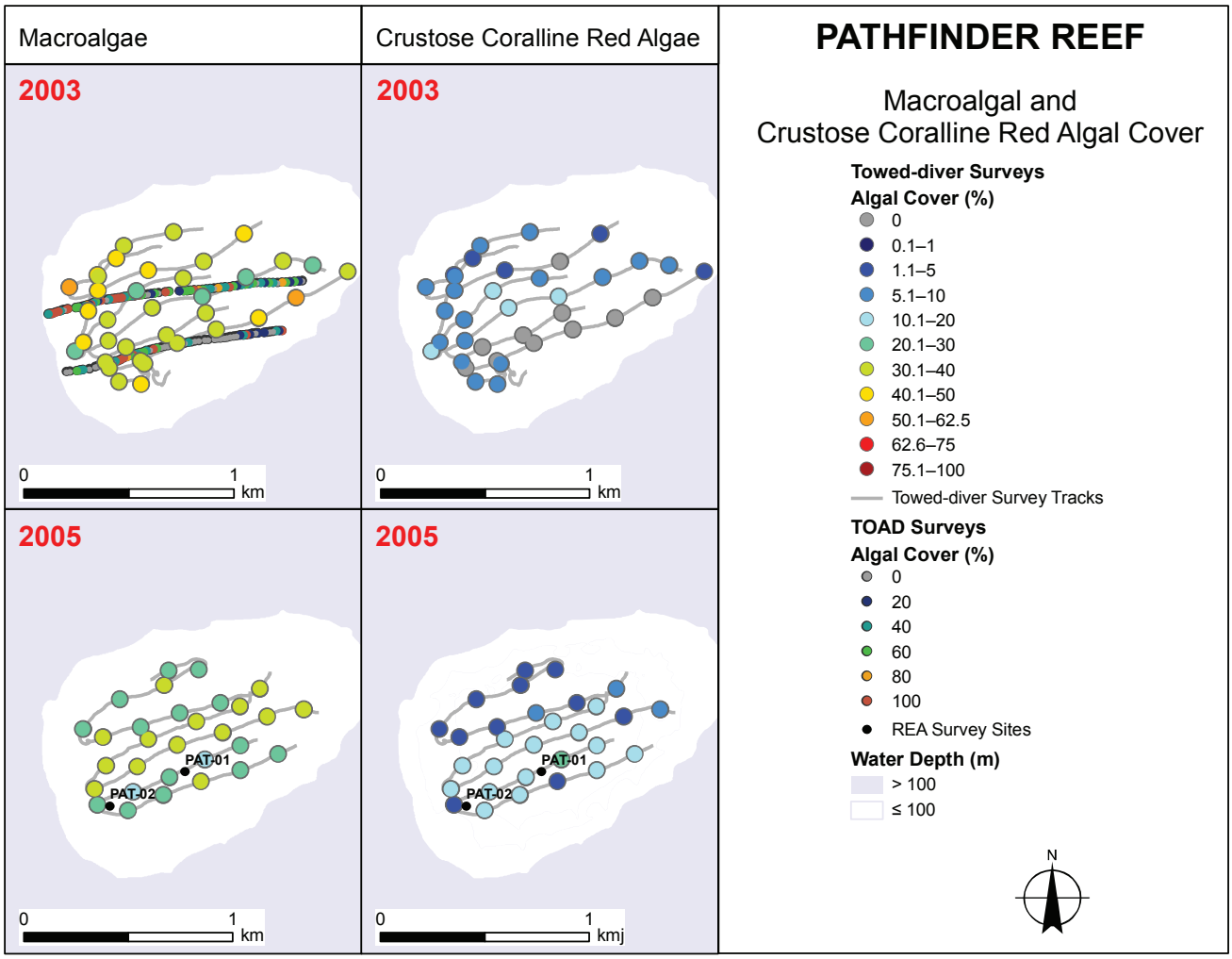


Figure 18.8.4.2a. Cover (%) observations for (*left*) macroalgae and (*right*) crustose coralline red algae from towed-diver benthic surveys conducted on Pathfinder Reef during MARAMP 2003 and 2005. Each large, colored point represents an estimate over a 5-min observation segment with a towed-diver survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (turf algae were included in towed-diver surveys only during MARAMP 2003).In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys. The 100-fm contour shown in white represents potential reef habitat.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites on the West Mariana Ridge has not been undertaken yet. Ultimately, based on microscopic analysis that may occur in the future, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2005, REA benthic surveys were conducted at 2 sites on Pathfinder Reef. In the field, 10 macroalgal genera (2 red, 7 green, and 1 brown), containing at least 10 species, as well as 3 additional algal functional groups—turf

algae, crustose coralline red algae, and cyanophytes—were observed. Macroalgal generic diversity was approximately equal at both sites with 7 genera, each containing 1 species, observed at each site. However, the macroalgal generic composition varied slightly between sites with *Caulerpa, Dictyosphaeria*, and *Neomeris* observed only at PAT-01 and *Actinotrichia*, *Dictyota*, and *Rhipidosiphon* recorded only at PAT-02.

The most widely distributed algal genera on Pathfinder Reef in 2005 were chlorophytes. Species of the genera *Halimeda* and *Chlorodesmis* were the most common component of algal communities (Table 18.8.4.2a), occurring in 87.5% and 70.8% of photoquadrats sampled at both sites. Species of the algal genera *Actinotrichia, Caulerpa, Dictyosphaeria, Dictyota, Jania, Neomeris, Rhipidosiphon* and *Valonia* also were present, occurring in < 12.5% of the sampled photoquadrats.

Turf algae and crustose coralline red algae were both exceptionally common in 2005, occurring in 95.8% and 62.5% of photoquadrats sampled at both sites on Pathfinder Reef. Turf-algal communities, ubiquitous at both sites, were found in 91.7%–100% of sampled photoquadrats (Table 18.8.4.2a). Crustose coralline red algae also were observed at both sites, in 50%–75% of photoquadrats sampled.

	Occurrence (%)									
Site	*Amphiroa*	*Jania*	*Schizymenia*	*Halimeda*	*Microdictyon*	*Neomeris*	*Lobophora*	*Crustose Coralline Red Algae*	*Cyanobacteria*	*Turf Algae*
PAT-01	0	8.33	0	75	0	8.33	0	50	8.33	100
PAT-02	0	16.7	0	100	0	0	0	75	33.3	91.7

Table 18.8.4.2a. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys conducted on Pathfinder Reef during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed.

18.8.4.3 Macroinvertebrate Surveys

During MARAMP 2003, species of *Tridacna* giant clams were observed in all 4 towed-diver surveys conducted on Pathfinder Reef (Fig. 18.8.4.3a, left panel), with an overall mean density of 0.094 organisms 100 m^{-2}. The greatest mean density from a towed-diver survey was 0.12 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.308 organisms 100 m^{-2}.

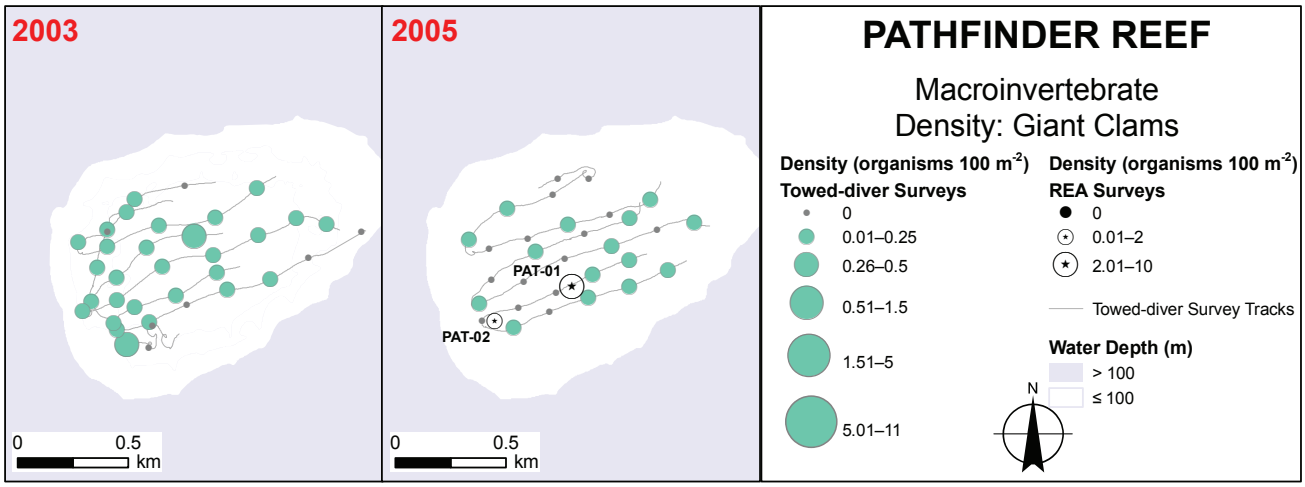


Figure 18.8.4.3a. Densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on Pathfinder Reef during MARAMP 2003 and 2005. The 100-fm contour shown in white represents potential reef habitat.

During MARAMP 2005, giant clams were observed in all 3 towed-diver surveys conducted on Pathfinder Reef (Fig. 18.8.4.3a, right panel), with an overall mean density of 0.052 organisms 100 m^{-2}. The greatest mean density from a towed-diver survey was 0.064 organisms 100 m^{-2}; segment densities ranged from 0 to 0.159 organisms 100 m^{-2}.

Crown-of-thorns seastars were not observed on Pathfinder Reef during MARAMP 2003 and 2005.

During MARAMP 2003, sea cucumbers were observed in 1 of the 4 towed-diver surveys conducted on Pathfinder Reef, with a mean density of 0.005 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.132 organisms 100 m^{-2} (Fig. 18.8.4.3b, left panel). During MARAMP 2005, sea cucumbers were recorded in 1 of the 3 towed-diver surveys conducted on Pathfinder Reef, with a mean density of 0.002 organisms 100 m^{-2}. Sea cucumbers were observed during only 1 segment from that survey, at a density of 0.069 organisms 100 m^{-2} (Fig. 18.8.4.3b, right panel).

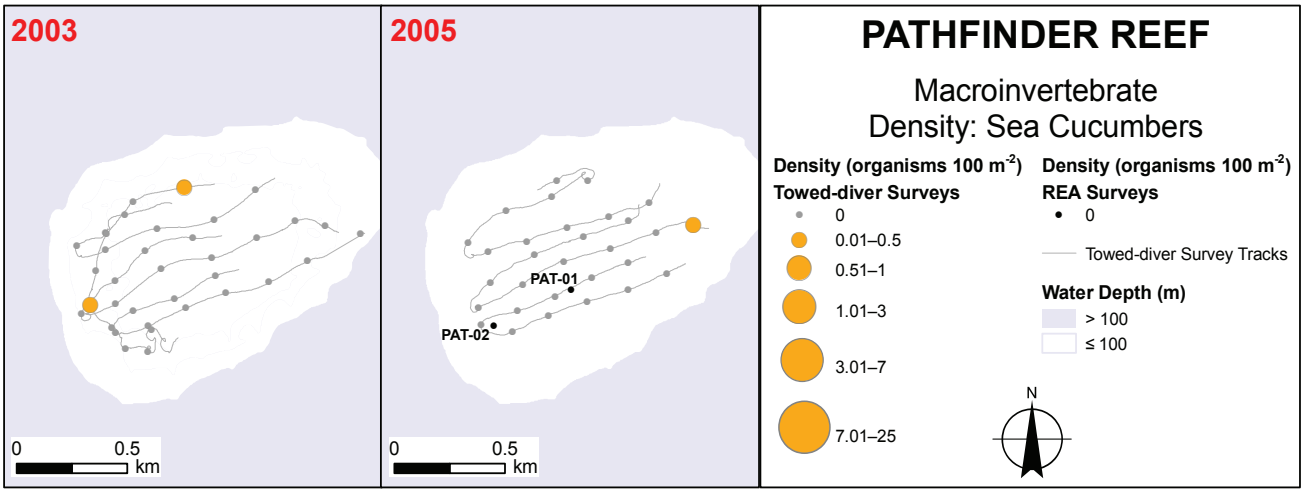


Figure 18.8.4.3b. Densities (organisms 100 m^{-2}) of sea cucumbers from towed-diver benthic surveys conducted at Pathfinder Reef during MARAMP 2003 and 2005. The 100-fm contour shown in white represents potential reef habitat.

During MARAMP 2003, sea urchins were observed in all 4 towed-diver surveys conducted on Pathfinder Reef, with an overall mean density was 9.92 organisms 100 m^{-2} (Fig. 18.8.4.3c, left panel). The greatest mean density from a towed-diver survey was 14.11 organisms 100 m^{-2}; segment densities from this survey ranged from 5.82 to 29.11 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed in all 3 towed-diver surveys conducted on Pathfinder Reef, with an overall mean density of 5.10 organisms 100 m^{-2} (Fig. 18.8.4.3c, right panel). The greatest mean density from a towed-diver survey was 6.83 organisms 100 m^{-2}; segment densities ranged from 2.06 to 19.63 organisms 100 m^{-2}.

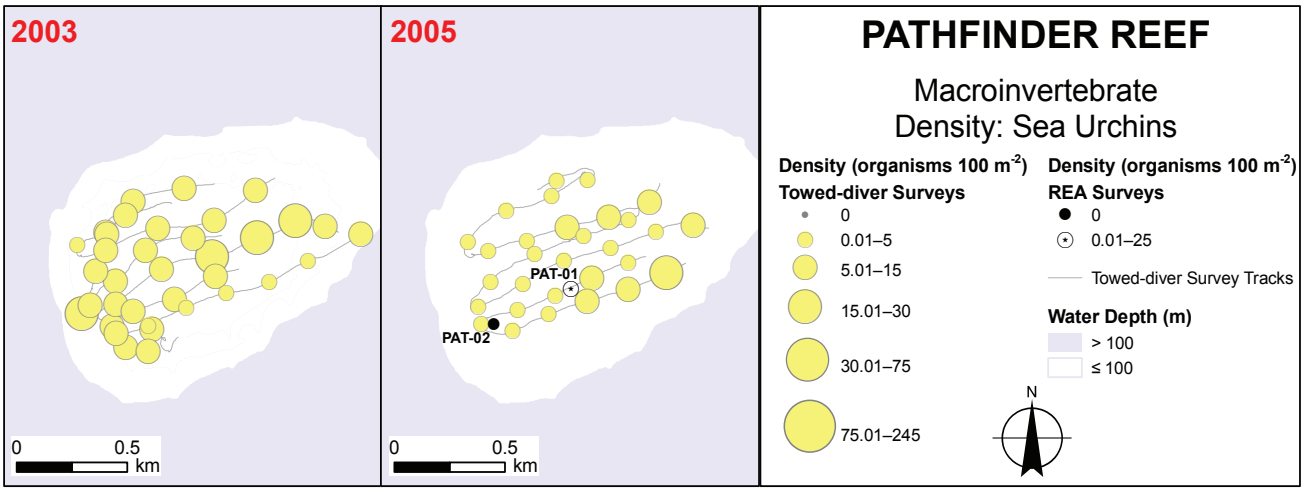


Figure 18.8.4.3c. Densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted at Pathfinder Reef during MARAMP 2003 and 2005. The 100-fm contour shown in white represents potential reef habitat.

18.8.4.4 Reef Fish Surveys

During MARAMP 2003, 4 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted on Pathfinder Reef. The overall estimated mean biomass, calculated as weight per unit area, was 1.44 kg 100 m^{-2} (SE 0.41). Observed large-fish biomass was highest in the northern part of this reef where jacks, snappers, and sharks were common (Fig. 18.8.4.4a, left panel). Reef sharks and jacks each accounted for the highest proportion (21%) or 0.30 kg 100 $m^{-2}$of overall large-fish biomass. The whitetip reef shark accounted for 44% of reef shark biomass. During this survey period, 19 sharks were observed: 11 whitetip reef sharks and 8 grey reef sharks. The bigeye trevally (*Caranx sexfaciatus*) accounted for 94% of jack biomass. Snappers and surgeonfishes also were commonly observed, accounting for 21% and 23% of overall estimates of large-fish biomass. The twinspot snapper made up 99% of snapper biomass. The bulbnose unicornfish and sleek unicornfish were the 2 surgeonfish species encountered, contributing 0.17 and 0.16 kg 100 m^{-2} to overall large-fish biomass.

During MARAMP 2005, 3 towed-diver surveys for large-fishes (≥ 50 cm in TL) were conducted on Pathfinder Reef (Fig. 18.8.4.4a, right panel.). The overall estimated mean biomass was 0.54 kg 100 m^{-2} (SE 0.12), lower than the level observed in 2003 (Fig. 18.8.4.4b). Reef sharks accounted for the highest proportion (46%) or 0.25 kg 100 m^{-2} of reef-wide large-fish

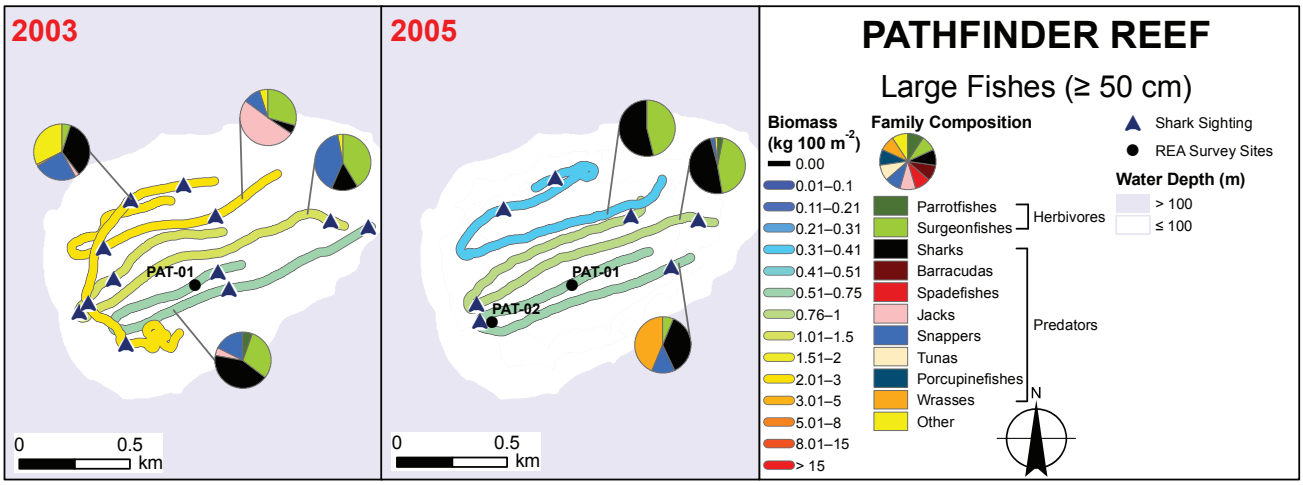


Figure 18.8.4.4a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys conducted on Pathfinder Reef during MARAMP 2003 and 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside the survey area over which it is shown. The 100-fm contour shown in white represents potential reef habitat.

biomass. Consistent with observations made in 2003, whitetip reef sharks were the most abundant shark species. During this survey period, 13 sharks were observed: 8 whitetip reef shark and 5 grey reef shark. Surgeonfishes accounted for 32% of overall large-fish. As seen in 2003, the bulbnose unicornfish and sleek unicornfish were the 2 major surgeonfishes by biomass, contributing 0.11 kg 100 m^{-2} and 0.04 kg 100 m^{-2} to overall mean biomass of large fishes. A notable sighting was a single large (100 cm in TL) humphead wrasse (*Cheilinus undulatus*).

Total fish biomass for the single REA site surveyed for fishes of all sizes and species on Pathfinder Reef during MARAMP 2003 was 4.72 kg 100 m^{-2} (Table 18.8.4.4a). Snapper accounted for the highest proportion (46%) or 2.15 kg 100 m^{-2} of total fish biomass. The twinspot snapper was the only snapper species observed with 10 individuals seen in total. Jacks accounted for the second-greatest proportion (32%) of total fish biomass. The bluefin trevally accounted for 87% or 1.31 kg 100 m^{-2} of jack biomass.

From the single REA survey conducted on Pathfinder Reef during MARAMP 2003, species richness was 23.7 species 100 m^{-2}, and 38 species in total were observed (Table 18.8.4.4a). Wrasses (Labridae) and damsel-

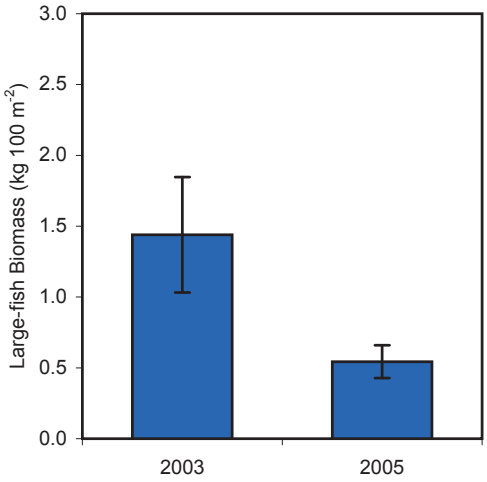


Figure 18.8.4.4b. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver surveys conducted on Pathfinder Reef during MARAMP 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

fishes (Pomacentridae) were the 2 most diverse families, each with 7 species recorded. The bluntheaded wrasse (*Thalassoma amblycephalum*) was the most abundant species overall, with 45 individuals 100 m^{-2}, and the Pacific gregory (*Stegastes fasciolatus*) was the most abundant damselfish species.

Table 18.8.4.4a. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method on Pathfinder Reef during MARAMP 2003 and 2005.

Year	Site	Richness (species 100 m^{-2})	Biomass (kg 100 m^{-2})												
			Total	Parrotfishes	Surgeonfishes	Sharks	Soldierfishes	Groupers	Jacks	Fusiliers	Snappers	Triggerfishes	Wrasses	Damselfishes	Other
2003	PAT-01	23.7	4.72	0.26	0.17	0	0	0.01	1.5	0	2.15	0.08	0.36	0.05	0.13
2005	PAT-01	19.5	9.11	0.06	1.05	0	0	0.05	1.22	0	5.88	0.09	0.42	0.1	0.23
2005	PAT-02	29.5	5.24	0	0.48	0.76	0.05	0.8	0.79	0	1.6	0.23	0.37	0.07	0.1

Total fish biomass for the 2 REA sites surveyed on Pathfinder Reef during MARAMP 2005 was slightly higher than observations made in 2003, with an overall sample mean of 7.18 kg 100 m^{-2} (SE 1.93). Estimated fish biomass was higher at PAT-01, located in the center of this reef, at 9.11 kg 100 m^{-2} (Table 18.8.4.4a). Similar to the results from surveys in 2003, snapper accounted for around half or 3.74 kg 100 m^{-2} of total fish biomass. The twinspot snapper again was the only snapper species seen, with 22 individuals recorded in 2005. Jacks accounted for the second-greatest proportion (14%) of total fish biomass, with the black jack (*Caranx lugubris)* accounting for 78% or 0.78 kg 100 m^{-2} of jack biomass. Surgeonfishes also were commonly observed, accounting for 11% of total fish biomass. The bulbnose unicornfish contributed more than half or 0.41 kg 100 m^{-2} of surgeonfish biomass. During this survey period, 2 reef sharks were observed; both were small (75 cm in TL) grey reef shark.

From the 2 REA surveys conducted during MARAMP 2005, species richness on Pathfinder Reef ranged between 19.5 and 29.5 species 100 m^{-2}, with the higher species richness found at PAT-02 on the western edge of this reef (Table 18.8.4.4a). As in 2003, wrasses and damselfishes were the 2 most diverse families, with 10 and 11 species recorded. The bluntheaded wrasse was the most abundant species overall with 21 individuals 100 m^{-2}, but Katherine's wrasse (*Cirrhilabrus katherinae*) was nearly as abundant with 20 individuals 100 m^{-2}. The midget chromis (*Chromis acares*) was the most abundant damselfish species.

There were insufficient REA surveys at Pathfinder Reef to attempt to discern meaningful spatial or temporal trends. When compared with the rest of the Mariana Archipelago, total fish biomass was moderately high with the mean for the 2 MARAMP survey periods at 5.95 kg 100 m^{-2}. Snappers accounted for the greatest proportion of total fish biomass, with the twinspot snapper alone contributing about half of total fish biomass in both survey years. Jacks also were commonly observed, accounting for the second-greatest proportion of total fish biomass. Two grey reef shark were observed in 2005; no other reef sharks were observed during REA fish surveys conducted on Pathfinder Reef.

For both MARAMP survey periods, wrasses and damselfishes were the 2 most diverse families, averaging 8.5 and 9 species per family. Wrasses were the most abundant fishes tallied for both survey years, and the bluntheaded wrasse was the most abundant species overall with > 20 individuals 100 m^{-2} observed in both survey periods.

18.9 Arakane Reef

18.9.1 Introduction

Part of the West Mariana Ridge, Arakane Reef is a small (~ 1.8 × 1 km), shallow bank located ~ 110 km southwest of Tinian.

18.9.2 Survey Effort

Benthic habitat mapping data were collected on Arakane Reef using a combination of acoustic and optical survey methods. During MARAMP 2003, depth soundings were obtained from a small boat using a handheld depth sounder and handheld GPS to provide guidance for locating subsequent diving operations. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live-hard-coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in the next section.

REA, towed-diver, and TOAD surveys were conducted on Arakane Reef during MARAMP 2003 and 2005 to collect information on habitat and the condition, abundance, diversity, and distribution of biological communities. Results from these surveys are discussed in Section 18.9.3: "Benthic Mapping and Characterization" and Section 18.9.4 "Biological Characterization." The numbers of these surveys are presented in Table 18.9.2a, along with their mean depths and total areas or length. Three TOAD surveys were conducted on Arakane Reef during MARAMP 2003 at depths of 20–280 m, covering a distance of 1.33 km. Subsequent analyses of the video acquired from these surveys provided estimates of the percentages of sand cover and live coral cover.

For both MARAMP survey years combined, 9 towed-diver surveys were conducted on Arakane Reef at depths of 13–23 m, covering a distance of 17.13 km. The mean depths of individual surveys ranged from 14.9 m (SD 2.4) to 20.7 m (SD 2.5) in 2003 and from 15.6 m (SD 1.9) to 18.1 m (SD 1.6) in 2005. Figures 18.9.2a and b illustrate the locations and depths of towed-diver-survey tracks on Arakane Reef and should be referenced when further examining results of the towed-diver surveys from MARAMP 2003 and 2005.

Survey Type	Survey Detail	Year	
REA		**2003**	**2005**
Fish	Number of Surveys	2	2
	Mean Depth (m)	18 (SD 2.8)	18 (SD 2.8)
Benthic	Number of Surveys	2	2
	Mean Depth (m)	18 (SD 2.8)	18 (SD 2.8)
Towed Diver		**2003**	**2005**
	Number of Surveys	6	3
	Total Survey Area (ha)	10.7	6.5
	Mean Depth (m)	16.9 (SD 2.1)	16.8 (SD 1.2)
TOAD		**2003**	
	Number of Surveys	3	
	Total Length (km)	1.33	

Table 18.9.2a. Numbers, mean depths (m), total areas (ha), and total lengths (km) of REA, towed-diver, and TOAD surveys conducted at Arakane Reef during MARAMP 2003 and 2005. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

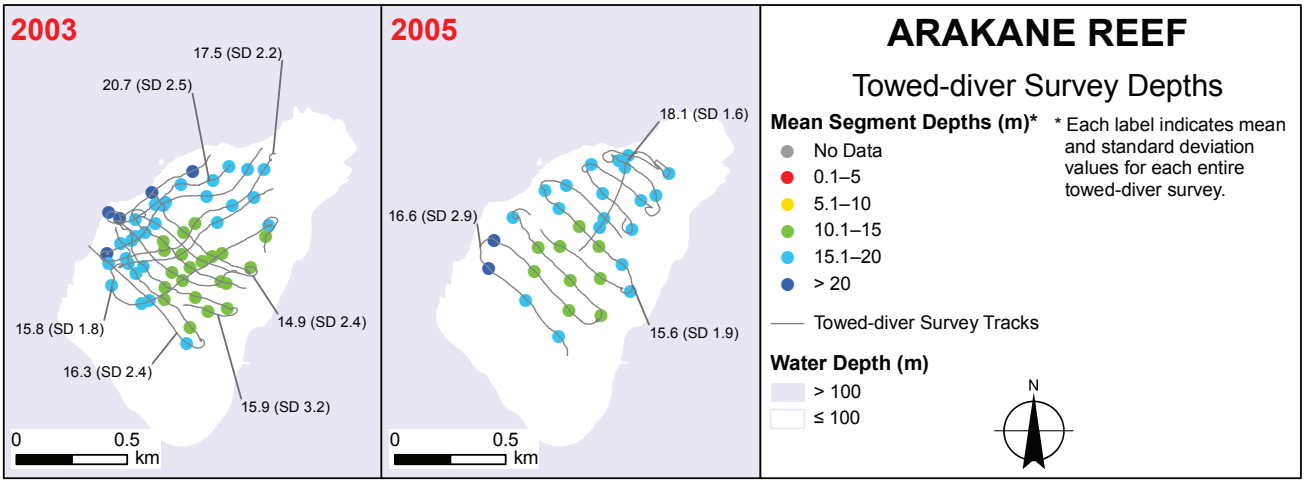


Figure 18.9.2a. Depths and tracks of towed-diver surveys conducted on Arakane Reef during MARAMP 2003 and 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate. The 100-fm contour shown in white represents potential reef habitat.

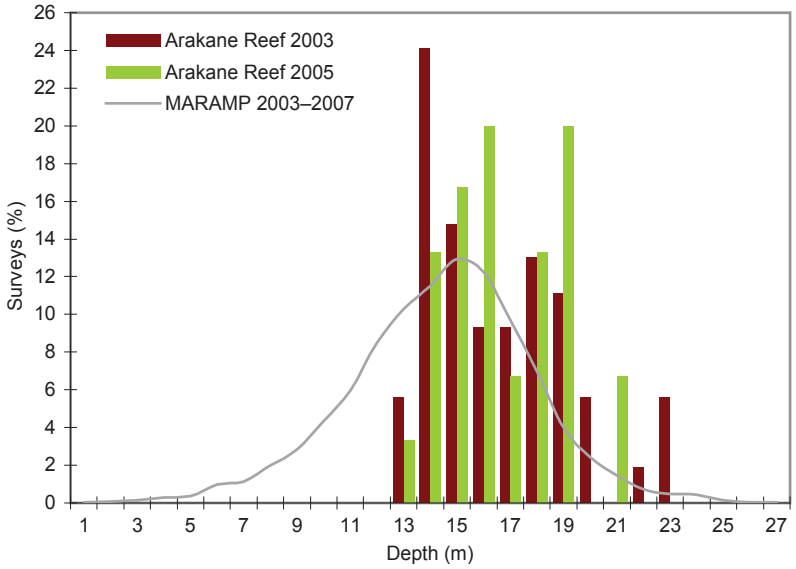


Figure 18.9.2b. Depth histogram plotted from mean depths of 5-min segments of the towed-diver surveys conducted on Arakane Reef during MARAMP 2003 and 2005. Mean segment depths are derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

18.9.3 Benthic Habitat Mapping and Characterization

Figure 18.9.3a presents a contoured map of the handheld depth soundings collected on Arakane Reef.

During MARAMP 2003, 6 towed-diver surveys and 3 TOAD surveys were conducted, and, during MARAMP 2005, 3 towed-diver surveys were completed. At 5-min intervals within each towed-diver survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high. Habitats on Arakane Reef were found to have uniformly medium-low to medium habitat complexity (Fig. 18.9.3b). As with the 2 other reefs surveyed on the West Mariana Ridge, the substrate of the surveyed area was predominantly hard; however, some small patches of sand were observed during both towed-diver surveys and analyses of TOAD video. Cover of live hard corals at Arakane Reef, based on towed-diver surveys was the lowest level observed among the reefs on the West Mariana Ridge, with segment means of 1.1%–50% and a majority of them at 10.1%–30%. Results for live coral cover from analyses of video footage obtained from TOAD surveys ranged from 0% to 100%, with live coral cover higher for the southernmost survey than for the other survey. Divers surveying Arakane Reef described a high abundance of soft and fire corals, which are not represented in the maps showing only cover of hard corals.

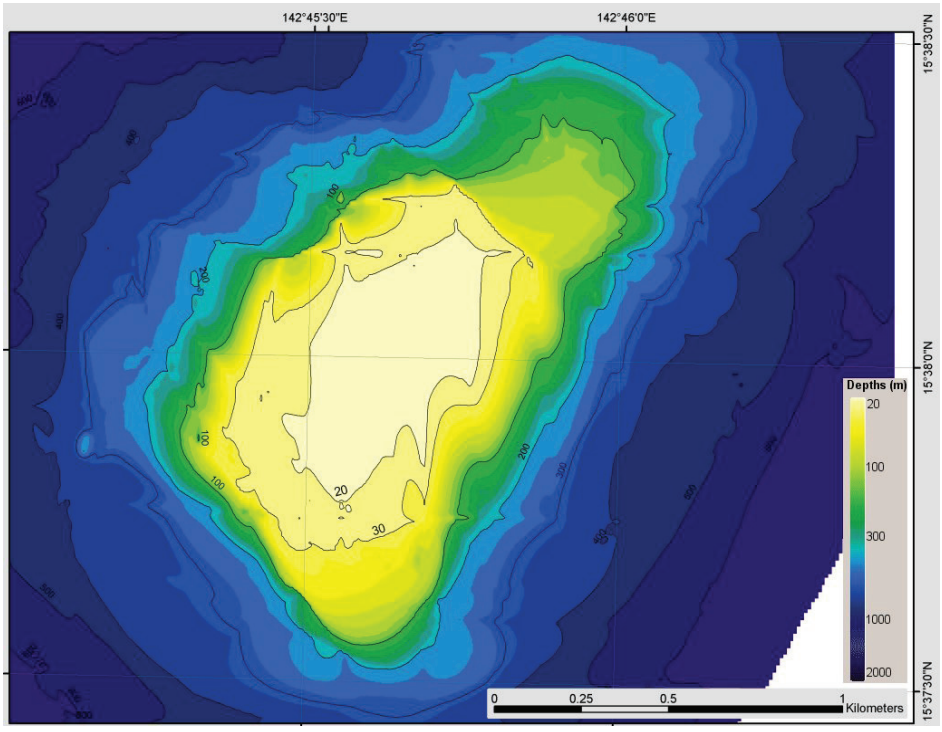


Figure 18.9.3a. Contoured map derived from depth soundings collected using a handheld depth sounder on Arakane Reef during MARAMP 2003.

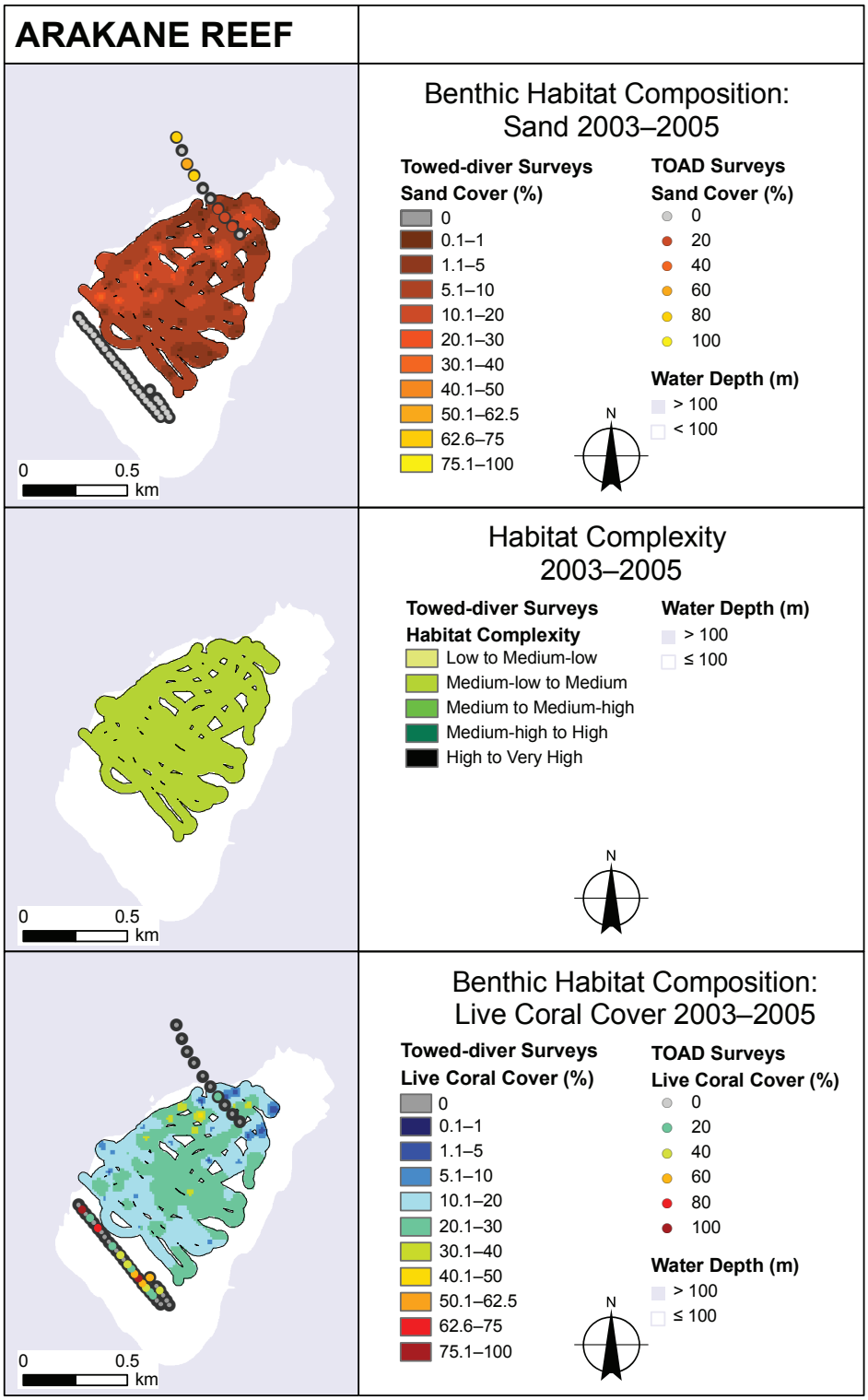


Figure 18.9.3b Observations of (*top*) sand cover (%), (*middle*) benthic habitat complexity, and (*bottom*) cover (%) of live hard corals from towed-diver surveys conducted and analysis of TOAD video collected on Arakane Reef during MARAMP 2003 and 2005. The 100-fm contour shown in white represents potential reef habitat.

18.9.4 Biological Characterization

18.9.4.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on Arakane Reef was 24% (SE 1.1). For a majority of segments (45 of 53 segments) coral cover was 10.1%–30%. The highest coral cover was observed on the northern part of this reef, with a mean of 39% over 6 segments (Fig. 18.9.4.1a, left panel).

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on Arakane Reef was 12% (SE 1.6). Over all survey segments coral cover was 1.1%–30%. The highest coral cover was recorded on the center of this reef, with a mean of 25% over 6 segments (Fig. 18.9.4.1a, right panel).

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, < 1% of coral cover observed on Arakane Reef in 2005 appeared stressed.

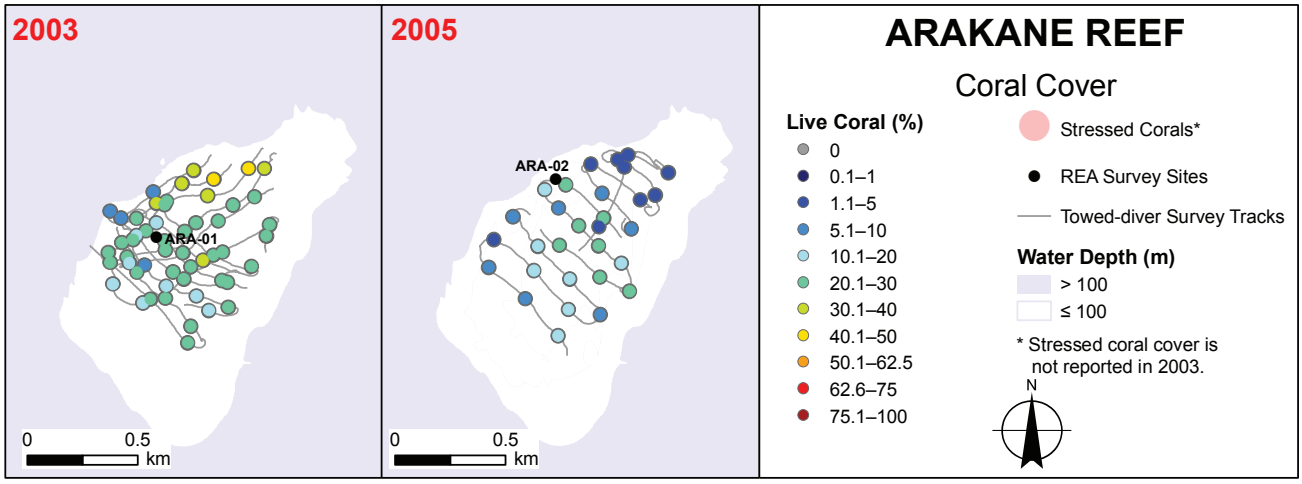


Figure 18.9.4.1a. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys conducted on Arakane Reef during MARAMP 2003 and 2005. Each colored point represents an estimate of live coral over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols are not shown here, since they represent only segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005. The 100-fm contour shown in white represents potential reef habitat.

During MARAMP 2003, 1 REA benthic survey using the quadrat method at Arakane Reef documented 90 coral colonies within a survey area of 3.75 m^2, yielding a site-specific colony density of 24 colonies m^{-2} (Table 18.9.4.1a).

During MARAMP 2005, 1 REA benthic survey using the quadrat method at Arakane Reef documented 121 coral colonies in a survey area of 4 m^2, yielding a site-specific colony density of 30.3 colonies m^{-2} (Table 18.9.4.1a).

Between MARAMP survey years, overall mean coral cover estimated from towed-diver surveys decreased from 24% (SE 1.1) in 2003 to 12% (SE 1.6) in 2005. The comparable depth strata surveyed in both years and a visible drop in coral cover in the north, where elevated coral cover was previously reported in 2003, suggest that this decrease in estimated coral cover was genuine rather than an artifact of environmental heterogeneity or variable locations of survey tracks (Figs 18.9.2a and b; for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Coral Generic Richness and Relative Abundance

One REA benthic survey was conducted using the quadrat method at Arakane Reef during MARAMP 2003, and 9 coral genera were observed (Table 18.9.4.1a). One REA benthic survey was conducted using the quadrat method at Arakane Reef during MARAMP 2005, and 10 coral genera were observed.

Across the 2 MARAMP survey years, 11 coral genera were observed. *Montastrea, Pocillopora, Leptastrea,* and *Favia* were important components of the coral fauna at Arakane Reef, contributing > 10% of the total number of colonies enumerated in both survey years (Table 18.9.4.1a). *Montastrea* was the most numerically abundant taxon at ARA-01 in 2003, contributing 32.2% of the total number of colonies enumerated at that site. *Pocillopora*, *Favia* and *Leptastrea* were the next-most abundant taxa, accounting for 25.6%, 13.3%, and 10% of the total number of colonies. *Montastrea* was the most numerically abundant taxon at ARA-02 in 2005, contributing 21.5% of the total number of colonies enumerated at that site. *Porites*, *Leptastrea*, *Pocillopora* and *Favia* were the next-most abundant taxa, contributing 18.2%, 17.4%, 10.7%, and 10.7%, respectively, of the total number of colonies recorded. All other taxa contributed < 10% of the total number of colonies enumerated in both survey years.

Table 18.9.4.1a. Observations of colony densities (colonies m^{-2}), coral generic richness, size-class distribution (%) and relative abundance of coral genera from REA benthic surveys using the quadrat method conducted at Arakane Reef during MARAMP 2003 and 2005

				Size-class Distribution (%)							Abundance (%)									
Year	Site	Density (colonies 100 m^{-2})	Generic Richness (#)	0–5 cm	6–10 cm	11–20 cm	21–40 cm	41–80 cm	81–169 cm	> 160 cm	*Acropora*	*Astreopora*	*Favia*	*Goniastrea*	*Leptastrea*	*Montipora*	*Pavona*	*Pocillopora*	*Porites*	Octocorals	Other
2003	ARA-01	24	9	37.8	41.1	14.4	5.56	1.11	0	0	0	0	13.3	0	10	0	0	25.6	5.56	0	45.6
2005	ARA-02	30	10	71.9	15.7	8.26	4.13	0	0	0	0	0.83	10.7	0	17.4	0.83	0	10.7	18.2	0	41.3

Coral Size-class Distribution

During MARAMP 2003, the coral size-class distribution at ARA-01 showed that no single class contained the majority of corals. The greatest proportion of corals (41.1%) belonged to the second-smallest size class (6–10 cm; Table 18.9.4.1a). The other 4 size classes (0–5, 11–20, 21–40, and 41– 80 cm) accounted for 37.8%, 14.4%, 5.6%, and 1.1% of colonies recorded. No colonies with maximum diameters > 80 cm were recorded.

During MARAMP 2005, the coral size-class distribution at ARA-02 showed that the majority (71.9%) of corals had maximum diameters ≤ 5 cm (Table 18.9.4.1a). The next 3 size classes (6–10, 11–20, and 21-40 cm) accounted for 15.7%, 8.3%, and 4.1% of colonies recorded. No colonies with maximum diameters > 40 cm were recorded.

18.9.4.2 Algal Surveys

Algal Cover

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on Arakane Reef was 52% (SE 1.6), with mean values for the 6 surveys of 35%, 47%, 55%, 5%, 60%, and 62% (Fig. 18.9.4.2a, left top panel). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The overall estimated mean cover of crustose coralline red algae was 5% (SE 0.7), with survey means of 2%, 2%, 2%, 4%, 10%, and 13% (Fig. 18.9.4.2a, right top panel). The levels of habitat complexity most frequently noted during towed-diver surveys were medium and medium-low.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on Arakane Reef was 46% (SE 2.3), with mean values for the 3 surveys of 34%, 43%, and 60% (Fig. 18.9.4.2a, left bottom panel). The overall estimated mean for cover of crustose coralline red algae was 4% (SE 0.6), similar to the overall mean for 2003; means for individual surveys were 1%, 4%, and 5% (Fig. 18.9.4.2a, right bottom panel). For the 3 surveys, the substrate was frequently covered in red algae and cyanobacteria.

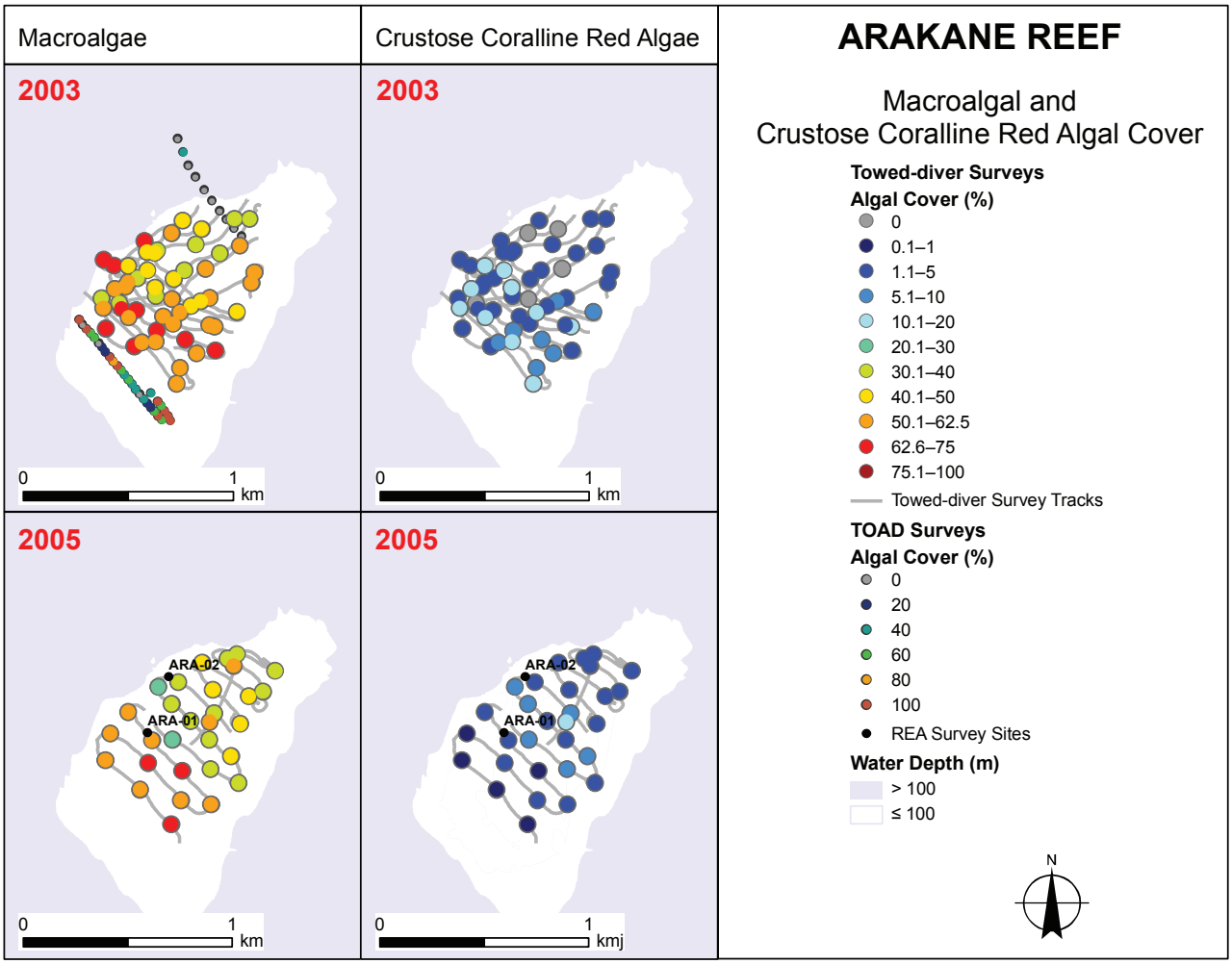


Figure 18.9.4.2a. Cover (%) observations for (*left*) macroalgae and (*right*) crustose coralline red algae from towed-diver benthic surveys conducted on Arakane Reef during MARAMP 2003 and 2005. Each large, colored point represents an estimate over a 5-min observation segments with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (turf algae were included in towed-diver surveys only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys. The 100-fm contour shown in white represents potential reef habitat.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites on the West Mariana Ridge has not been undertaken yet. Ultimately, based on microscopic analysis that may occur in the future, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2005, REA benthic surveys were conducted at 2 sites on Arakane Reef. In the field, 9 macroalgal genera (2 red, 6 green, and 1 brown), containing at least 9 species, as well as 3 additional algal functional group—turf algae, crustose coralline red algae, and cyanophytes—were observed. Macroalgal generic diversity varied slightly with 7 genera observed at site ARA-01 and 5 genera recorded at site ARA-02. The macroalgal genera *Boodlea, Liagora, Neomeris* and *Rhipidosiphon* were observed only at ARA-01, while *Dictyota* and *Valonia* were observed only at ARA-02.

The most widely distributed algal genera on Arakane Reef in 2005 were chlorophytes. Species of the genera *Halimeda* and *Microdictyon* were the most common components of algal communities (Table 18.9.4.2a), occurring in 83.3% and 91.7%

of photoquadrats sampled at both sites. Species of the genera *Jania* occurred in 16.7% of photoquadrats sampled at both sites. Species of the algal genera *Neomeris*, *Boodlea, Dictyota, Liagora, Rhipidosiphon*, and *Valonia* also were present, occurring in < 8.4% of sampled photoquadrats.

Turf algae and cyanobacteria were both exceptionally common in 2005, occurring in 100% and 95.8% of photoquadrats sampled at Arakane Reef (Table 18.9.4.2a). Turf-algal communities were found in 100% of sampled photoquadrats at both sites, and cyanobacteria were observed in 91.7%–100% of sampled photoquadrats.

	Occurrence (%)									
Site	*Amphiroa*	*Jania*	*Schizymenia*	*Halimeda*	*Microdictyon*	*Neomeris*	*Lobophora*	*Crustose Coralline Red Algae*	*Cyanobacteria*	*Turf Algae*
ARA-01	0	25	0	75	100	16.7	0	0	100	100
ARA-02	0	8.33	0	91.7	83.3	0	0	16.7	91.7	100

Table **18.9.4.2a.** Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys conducted on Arakana Reef during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed.

18.9.4.3 Macroinvertebrate Surveys

During MARAMP 2003, species of *Tridacna* giant clams were observed in all 6 towed-diver surveys conducted on Arakane Reef (Fig. 18.9.4.3a, left panel), with an overall mean density of 0.1 organisms 100 m^{-2}. The greatest mean density from a towed-diver survey was 0.156 organisms 100 m^{-2}; segment densities ranged from 0 to 0.542 organisms 100 m^{-2}.

During MARAMP 2005, giant clams were observed in all 3 towed-diver surveys conducted on Arakane Reef (Fig. 18.9.4.3a, right panel), with an overall mean density of 0.078 organisms 100 m^{-2}. The greatest mean density from a towed-diver survey was 0.172 organisms 100 m^{-2}; segment densities ranged from 0 to 0.408 organisms 100 m^{-2}.

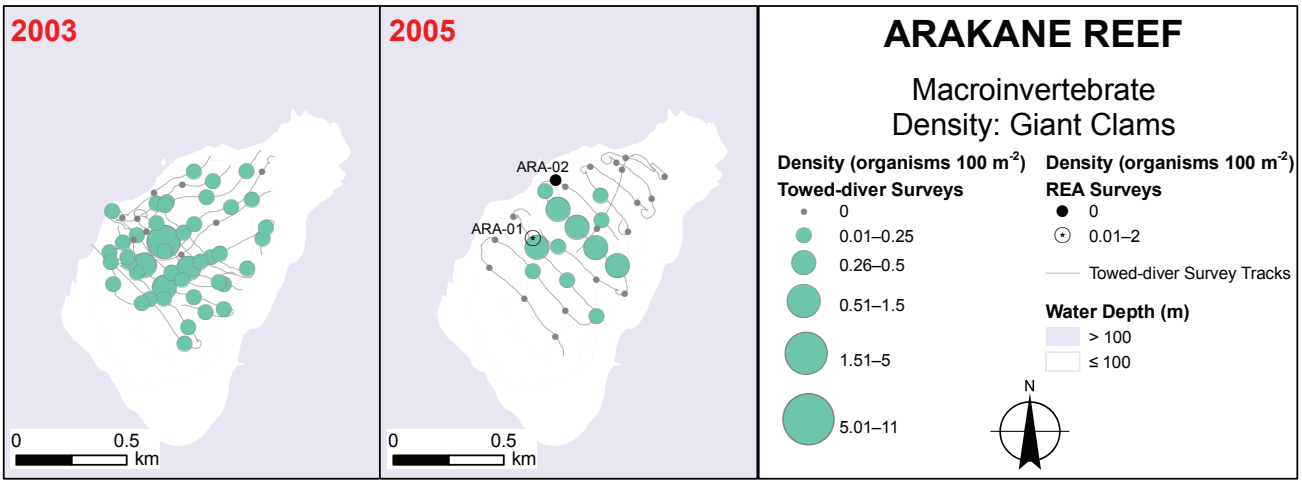


Figure 18.9.4.3a. Densities (organisms 100 m^{-2}) of giant clams from towed-diver benthic surveys conducted on Arakane Reef during MARAMP 2003 and 2005. The 100-fm contour shown in white represents potential reef habitat.

Crown-of-thorns seastars were not observed on Arakane Reef during MARAMP 2003 or 2005.

During MARAMP 2003, sea cucumbers were observed in only 1 of the 6 towed-diver surveys conducted on Arakane Reef. The mean density was 0.003 organisms 100 m^{-2}; segment densities ranged from 0 to 0.061 organisms 100 m^{-2}. Sea cucumbers were not observed in towed-diver surveys conducted during MARAMP 2005.

During MARAMP 2003, sea urchins were observed in all 6 towed-diver surveys conducted on Arakane Reef (Fig. 18.9.4.3b, left panel), with an overall mean density of 12.41 organisms 100 m^{-2}. The greatest mean density from a towed-diver survey was 17.39 organisms 100 m^{-2}; segment densities ranged from 4.38 to 26.97 organisms 100 m^{-2}.

During MARAMP 2005, sea urchins were observed in all 3 towed-diver surveys conducted on Arakane Reef (Fig. 18.9.4.3b, right panel), with an overall mean density of 8.83 organisms 100 m^{-2}. The greatest mean density from a towed-diver survey was 11.44 organisms 100 m^{-2}; segment densities ranged from 3.15 to 36.31 organisms 100 m^{-2}.

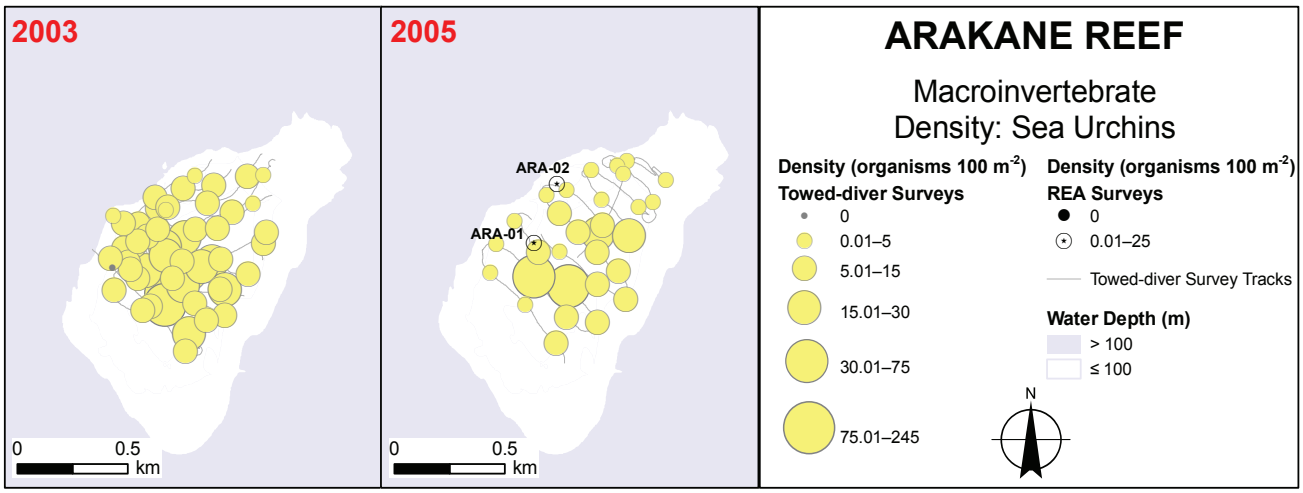


Figure 18.9.4.3b. Densities (organisms 100 m^{-2}) of sea urchins from towed-diver benthic surveys conducted at Arakane Reef during MARAMP 2003 and 2005. The 100-fm contour shown in white represents potential reef habitat.

18.9.4.4 Reef Fish Surveys

During MARAMP 2003, 6 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted on Arakane Reef. The overall estimated mean biomass, calculated as weight per unit area, was 0.77 kg 100 m^{-2} (SE 0.46). Observed

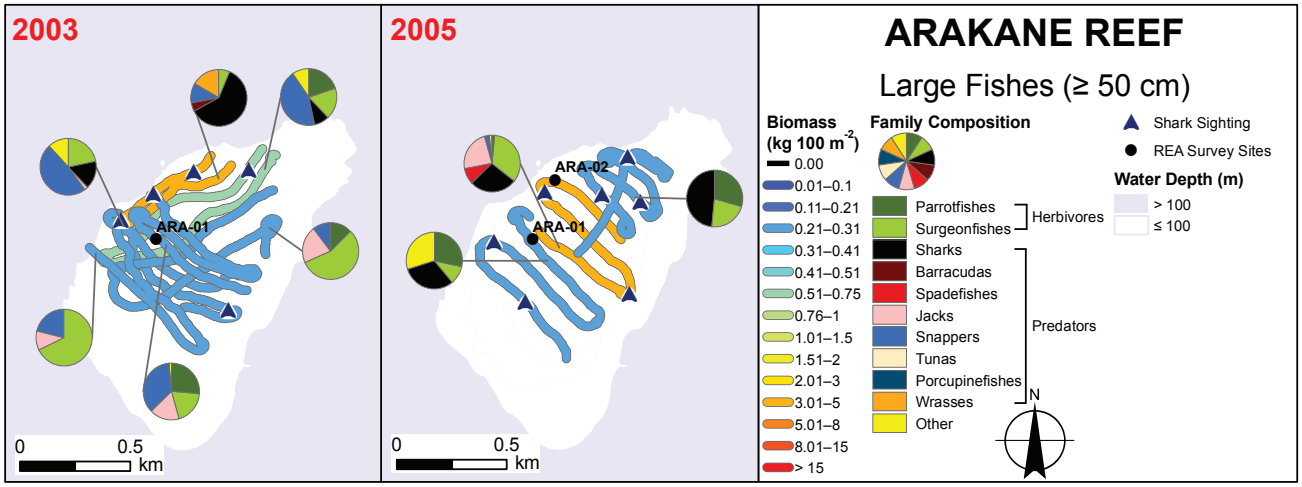


Figure 18.9.4.4a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys conducted on Arakane Reef during MARAMP 2003 and 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of survey area over which it is shown. The 100-fm contour shown in white represents potential reef habitat.

large-fish biomass tended to be higher along the northern region of the reef (Fig. 18.9.4.4a, left panel). Reef sharks and nurse sharks (Ginglymostomatidae) accounted for 42% or 0.33 kg 100 m^{-2} of overall large-fish biomass. Nurse sharks alone contributed to the greatest proportion of overall mean biomass of large fishes, with a single large (200 cm in TL) tawny nurse shark (*Nebrius ferrugineus*) contributing 65% of shark biomass. During this survey period, 6 sharks were observed: 4 whitetip reef sharks, 1 grey reef shark, and 1 tawny nurse shark. Snappers accounted for the second-greatest proportion (19%) of overall large-fish biomass. The twinspot snapper was the only snapper species recorded, with 31 individuals seen. Notable observations included 2 sightings of the humphead wrasse.

During MARAMP 2005, 3 towed-diver surveys for large-fishes (≥ 50 cm in TL) were conducted on Arakane Reef (Fig. 18.9.4.4a, right panel) The overall estimated mean biomass was 1.37 kg 100 m^{-2} (SE 1.14). Reef sharks and surgeonfishes accounted for 32% and 29%, or 0.44 kg 100 m^{-2} and 0.39 kg 100 m^{-2}, of overall large-fish biomass. During this survey period, 8 sharks were observed: 7 whitetip reef sharks and 1 grey reef shark, with those species making up 43% and 57% of shark biomass. The sleek unicornfish accounted for 73% or 0.32 kg 100 m^{-2} of surgeonfish biomass, with > 40 individuals observed during a single survey. Jacks also were commonly observed in 2005, contributing 21% of overall large-fish biomass, 98% of which was made up of a school of bigeye trevally seen during a single survey.

Overall, large-fish biomass on Arakane Reef was similar to the average of other northern reef areas in the Mariana Archipelago (Fig. 18.9.4.4b). Reef sharks and nurse sharks accounted for the largest proportions of large-fish biomass for the 2 MARAMP survey periods, and the whitetip reef shark was the most abundant shark species.

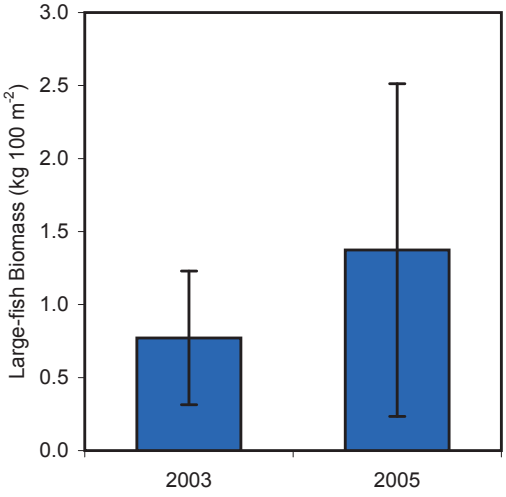


Figure 18.9.4.4b. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys conducted at Arakane Reef during MARAMP 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Total fish biomass for the single REA site surveyed for fishes of all sizes and species on Arakane Reef during MARAMP 2003 was 2.11 kg 100 m^{-2} (Table 18.9.4.4a). Wrasses accounted for the greatest proportion (49%) or 1.03 kg 100 m^{-2} of total fish biomass. The bluntheaded wrasse alone accounted for more than 80% or 0.84 kg 100 $m^{-2}$of wrasse biomass. Jacks accounted for the second-greatest proportion (16%) of total fish biomass. The bluefin made up 69% or 0.24 kg 100 m^{-2} of jack biomass. No sharks were encountered during the single REA survey conducted in 2003.

From the single REA survey conducted on Arakane Reef during MARAMP 2003, species richness was 25.3 species 100 m^{-2}, and 42 species in total were observed (Table 18.9.4.4a). Wrasses and damselfishes were the 2 most diverse families with 7 and 6 species observed. The Johnston Island damselfish (*Plectroglyphidodon johnstonianus*) was the most abundant damselfish species, and the bluntheaded wrasse was the most abundant species overall, with 88 individuals 100 m^{-2} observed.

Table 18.9.4.4a. Total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method on Arakane Bank during MARAMP 2003 and 2005.

Year	Site	Richness (species 100 m^{-2})	Biomass (kg 100 m^{-2})												
			Total	Parrotfishes	Surgeonfishes	Sharks	Soldierfishes	Groupers	Jacks	Fusiliers	Snappers	Triggerfishes	Wrasses	Damselfishes	Other
2003	ARA-01	25.3	2.11	0.11	0.12	0	0	0.1	0.34	0	0.01	0.07	1.03	0.08	0.24
2005	ARA-02	20.5	9.14	0	0.39	5.39	0	0.03	0	0	0	0.13	0.25	0.2	2.74
2005	ARA-01	23	3.57	0.53	0.34	0.35	0	0.06	0	0	0	0.4	1.18	0.51	0.2

Mean total fish biomass for the 2 REA sites surveyed on Arakane Reef during MARAMP 2005 was 6.36 kg 100 m^{-2} (SE 2.78). Reef sharks accounted for the greatest proportion (45%) of total fish biomass (Table 18.9.4.4a), and the whitetip reef shark was the only shark species encountered. The 3 whitetip reef sharks observed contributed 2.87 kg 100 m^{-2} of total fish biomass. Stingrays (Dasyatidae) accounted for the second-greatest proportion (18%) of total fish biomass, with a single blotched fantail ray (*Taeniura meyeni*) contributing 1.17 kg 100 m^{-2} to total fish biomass. Wrasses and surgeonfishes also were commonly observed, contributing 0.71 kg 100 m^{-2} and 0.37 kg 100 m^{-2} to total fish biomass.

From the 2 REA surveys conducted during MARAMP 2005, species richness was similar among sites surveyed on Arakane Reef (Table 18.9.4.4a), with a 33 species observed at ARA-01 and 28 species seen at ARA-02. As in 2003, wrasses and damselfishes were the 2 most diverse families with 11 and 10 species observed. Wrasses again dominated counts, and the bluntheaded wrasse was the most abundant species overall, with 97 individuals 100 m^{-2} recorded. The midget chromis was the most abundant damselfish species.

For both MARAMP survey years, wrasses and damselfishes were the 2 most diverse families, with an average of 9 and 8 species observed. Wrasses were the most abundant fishes, and the bluntheaded wrasse dominating counts during both survey periods.

18.10 Summary

This section presents an overview of the status of coral reef ecosystems on the reefs and banks of the CNMI and some of the key natural processes influencing coral reefs on these banks. This summary of the integrated ecosystem observations collected by the CRED and its partners during biennial MARAMP cruises in 2003, 2005, and 2007 provides sound scientific information about the conditions of the coral reef ecosystems on CNMI's reefs and banks to enable resource managers, policymakers, scientists, and other key stakeholders to make more informed decisions about the long-term conservation of the coral reef ecosystems on these areas.

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats of the reefs and banks of the CNMI. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter.

This section highlights key attributes of the coral reef ecosystems on the reefs and banks of the CNMI:

Ahyi Seamount

- Ahyi Seamount is a stratovolcano located ~ 17 km south of Farallon de Pajaros on the active Mariana Arc. It is part of the Volcanic Unit of the Marianas Trench Marine National Monument.
- In 2001, the detection by a seismic station of an explosive eruption in the vicinity of this summit suggests that this seamount may still be volcanically active.
- During MARAMP 2007, Ahyi seamount was partially mapped using multibeam sonar, adding to multibeam data that had been collected by the NOAA VENTS program. These data reveal that Ahyi Seamount is a steep-sided, conical seamount, with a minimum depth of < 80 m.
- Limited optical data collected during TOAD surveys conducted on the southern flanks of this seamount revealed a hard substrate. No hard corals were observed.

Supply Reef

- Supply Reef is a stratovolcano located ~ 25 km north of Maug on the active Mariana Arc and joined to Maug by a low saddle at a depth of ~ 1800 m. Together these 2 features form a twin volcanic massif.

- No volcanic activity has been recorded at Supply Reef.

- During MARAMP 2007, Supply Reef was mapped using multibeam sonar, adding to multibeam data that had been collected by the NOAA VENTS program. These data reveal that Supply Reef is steep-sided and conical, with ridges along the flanks and a minimum depth of ~ 10 m.

- The summit of this reef is ~ 300 m in diameter, with a lumpy topography. The flanks on Supply Reef have uniformly steep slopes, with the highest slopes (> 50°) recorded on the sides of ridges.

- The towed-diver survey conducted on and near the summit during MARAMP 2003 suggested habitat of medium-high to high complexity, characterized by low sand cover (< 5%) and high (30–50%) live-hard-coral cover, compared to levels observed at other areas in the Mariana Archipelago. The overall mean live-hard-coral cover from this survey was 39%. TOAD surveys conducted on the flanks north and south of the summit indicated similarly hard substrates.

- Wave model output shows seasonal variation with the highest ambient wave heights occurring through winter and the lowest through summer. Episodic wave events of high (> 4 m) wave heights, associated with the typhoon season of August–December also were recorded by a WTR deployed at Supply Reef.

- Mean cover of macroalgae from the single towed-diver survey conducted in 2003 was 19%, and crustose-coralline-red-algal cover was 35%.

- Mean biomass of large fishes, based on the single towed-diver survey in 2003, was 2.99 kg 100 m^{-2}. Jacks and reef sharks contributed the greatest proportions (49% and 28%) to large-fish biomass.

Zealandia Bank

- Zealandia Bank is a stratovolcano located ~ 25 km northeast of Sarigan Island on the active Mariana Arc. It is part of the Volcanic Unit of the Marianas Trench Marine National Monument.

- Zealandia Bank is elongated in shape and formed by 2 adjacent volcanic pinnacles ~ 1 km apart. During low tide, 1 of 2 pinnacles is ~ 1 m above sea level. Ridges radiate from the north and east of this bank. In 2004, fumarolic activity was detected at Zealandia Bank, suggesting that this area is still volcanically active.

- Wave model output shows seasonal variation with the highest ambient wave heights occurring through winter and the lowest through summer. Episodic wave events of high (> 4 m) wave heights, associated with the typhoon season of August–December also were recorded by WTRs deployed at Zealandia Bank from 2003 to 2007. Wave events in 2004 were 1 m higher than similar events at Supply Reef, because Zealandia has a more southerly location and is closer to the latitudes where typhoons are generated.

- Analyses of video footage obtained from the single TOAD survey conducted at depths of ~ 70–120 m on Supply Reef suggested a variable substrate, and no live hard corals were seen.

Esmeralda Bank

- Esmeralda Bank is a stratovolcano that is located 57 km southwest of Saipan and is one of the southernmost active volcanoes in the Mariana Arc. Esmeralda Bank is one of 21 seamounts protected within the Volcanic Unit of the Marianas Trench Marine National Monument.

- Multibeam data obtained over Esmeralda Bank show that the summit of the bank is formed by the rim of a crater, which appears to be breached to the west by a wide channel that runs into deeper water.

- No dive surveys were conducted on Esmeralda Bank but three TOAD surveys were conducted on the north crater rim. Only 1 of the 189 analyzed video frames revealed any live hard coral.

Marpi Bank

- Marpi Bank is located ~ 18 km north of Saipan and is part of the remnant Mariana frontal arc formed during the late Eocene and early Miocene epochs (15–20 million years ago).

- Multibeam data acquired over Marpi Bank reveal a flat-topped bank, ~ 7 km long by 3 km wide, elongated in a northeast-southwest direction, with a minimum depth of 53 m. Like Saipan, Tinian, Rota, Aguijan, and Tatsumi Reef, Marpi Bank probably is made up of uplifted limestone overlying an older volcanic core.

- High-resolution multibeam bathymetry acquired on the bank-top reveals mounds and channels, which may indicate coral habitat.

Stingray Shoal

- Stingray Shoal is a remnant volcanic seamount located on the northern end of the West Mariana Ridge, with a minimum depth of 13 m. Stingray Shoal is part of the Volcanic Unit of the Marianas Trench Marine National Monument.

- During MARAMP 2003, observations from both towed-diver surveys and TOAD video analyses revealed a predominantly hard substrate on Stingray Shoal, with very few areas exhibiting sand cover of > 5%. Towed-diver surveys on Stingray Shoal recorded habitat of medium-high to high complexity with consistently high cover of live hard corals (all but 2 survey segments had cover 40%–100%) over what was described by divers as continuous, well-developed reef. Mean live-hard-coral cover over this reef, from towed-diver surveys, was 55%, the highest level recorded for an island or bank during any of the 3 MARAMP survey years.

- Estimated macroalgal cover from the 4 towed-diver surveys conducted on Stingray Shoal averaged 34%, and overall mean cover of crustose coralline red algae was 2%.

- Deep depths limited the duration of towed-diver surveys on Stingray Shoal, and macroinvertebrates were observed in low densities there, relative to levels found at other surveyed areas in the Mariana Archipelago. Giant clams, sea cucumbers, and sea urchins were observed with mean densities of 0.002, 0.006, and 0.84 organisms 100 m^{-2}. No crown-of-thorns seastars were observed.

- Estimated biomass of large fishes on Stingray Shoal, based on towed-diver surveys conducted in 2003, was high compared to other reef areas in the Mariana Archipelago, with an overall mean of 5.15 kg 100 m^{-2}. Reef sharks accounted for the highest proportion (52%) of large-fish biomass, with the greatest contribution coming from the grey reef shark.

Pathfinder Reef

- Pathfinder Reef is a remnant volcanic ridge located on the southern part of the West Mariana Ridge, with a minimum depth of 10 m. It is located ~ 150 km west of Saipan.

- Towed-diver and TOAD surveys conducted over Pathfinder Reef revealed a predominantly hard substrate and habitat complexity characterized as medium-low to medium-high.

- Estimates of live-hard-coral cover from towed-diver surveys conducted during MARAMP 2003 and 2005 were high compared to levels seen at other reef areas surveyed in the Mariana Archipelago, with overall means of 24% and 25%.

Coral cover was consistent, with a range of 10.1%–40% for all but a single survey segment. Analyses of video footage obtained from TOAD surveys suggested that live coral cover was more variable with values in a range of 0%–100%.

- Stressed-coral cover, recorded on Pathfinder Reef during towed-diver surveys in 2005, was < 1%. Based on the 3 REA benthic surveys conducted in 2003 and 2005, coral generic richness ranged from 11 to 15 genera per site.

- Mean macroalgal cover from towed-diver surveys on Pathfinder Reef was 37% in 2003 and 29% in 2005. Mean cover of crustose coralline red algae in 2003 and 2005 was 6% and 10%.

- In both 2003 and 2005, giant clams were observed on Pathfinder Reef at moderate densities, with means of 0.093 and 0.052 organisms 100 m^{-2}. As on Stingray Shoal and Arakane Reef, densities of sea cucumbers were low on Pathfinder Reef, relative to levels found at other areas surveyed in the Mariana Archipelago, with means of 0.019 and 0.007 organisms 100 m^{-2} in 2003 and 2005. In contrast, densities of sea urchins were high compared to results from other reef areas in the Mariana Archipelago, with means of 9.79 and 5.10 organisms 100 m^{-2} in 2003 and 2005. No crown-of-thorns seastars were observed.

- Mean biomass of large fishes, from towed-diver surveys conducted on Pathfinder Reef in 2003, was moderately high compared to the levels observed at other reef areas in the Mariana Archipelago, with an overall estimated mean of 1.44 kg 100 m^{-2}. In 2005, observed biomass was much lower with an overall mean of 0.54 kg 100 m^{-2}. Across both years pooled, the greatest contribution to biomass was made by reef sharks. A notable sighting in 2005 was a single large (100 cm in TL) humphead wrasse.

- Based on the limited number of REA surveys for fishes of all sizes and species conducted on Pathfinder Reef, total fish biomass was moderate in 2003, with a sample mean of 4.72 kg 100 m^{-2}, but somewhat higher in 2005 with a sample mean of 7.18 kg 100 m^{-2}. In both survey years, the greatest contribution to overall biomass was made by snapper. Only 1 species, the twinspot snapper, was observed. Species richness ranged from 19.5 to 29.5 species 100 m^{-2} over the 2 MARAMP survey years.

Arakane Reef

- Arakane Reef is a small (~ 1.8 x 1 km), shallow bank on the West Mariana Ridge and located ~ 110 km southwest of Tinian.

- Towed-diver surveys conducted on this reef during MARAMP 2003 and 2005 suggested habitat was dominated by hard substrate and uniformly of medium-low to medium complexity.

- Overall mean cover of live hard corals, estimated from towed-diver surveys, was 24% in 2003 but only 12% in 2005. Analyses of video footage obtained from TOAD surveys suggested live coral cover within a range of 0%–100% cover, with live coral cover higher in the southern survey than in the other two surveys on this reef. Divers surveying Arakane Reef described a high abundance of soft and fire corals.

- Coral generic diversity was measured during a single REA survey at different REA sites in 2003 and 2005, with 9 and 10 genera observed.

- Mean macroalgal cover from towed-diver surveys on Arakane Reef was 52% in 2003 and 46% in 2005. Mean cover of crustose coralline red algae in 2003 and 2005 was 5% and 3%.

- In both 2003 and 2005, giant clams were observed on Arakane Reef at moderate densities, with means of 0.098 and 0.078 organisms 100 m^{-2}. As on Stingray Shoal and Pathfinder Reef, densities of sea cucumbers were low on Arakane Reef, relative to levels found at other areas surveyed in the Mariana Archipelago, with a mean of 0.029 organisms 100 m^{-2} in 2003 and none observed in 2005. In contrast, densities of sea urchins were high compared to results from other reef areas in the Mariana Archipelago, with means of 12.25 and 8.83 organisms 100 m^{-2} in 2003 and 2005. No crown-of-thorns seastars were observed.

- Mean biomass of large fishes, from towed-diver surveys conducted on Arakane Reef in 2003 and 2005, was moderate compared to levels observed at other northern reefs in the Mariana Archipelago, with overall estimated means of 0.77 and 1.37 kg 100 m^{-2}. The greatest contribution to biomass was made by reef sharks and nurse sharks in 2003 and surgeonfishes in 2005.

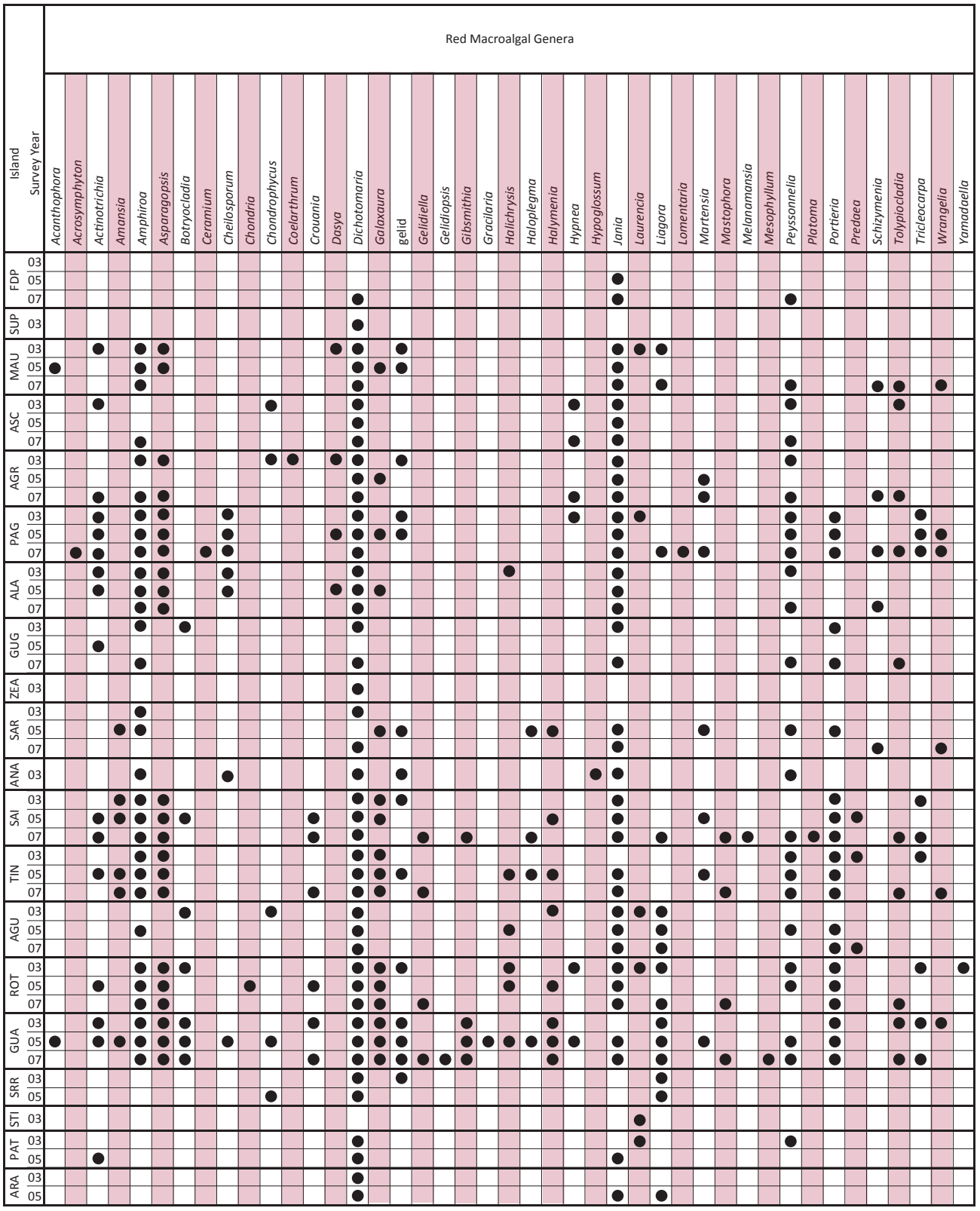
- Based on the limited number of REA surveys for fishes of all sizes and species conducted on Arakane Reef, estimated total fish biomass was 2.11 and 6.36 kg 100 m^{-2} in 2003 and 2005. Observed species richness was fairly consistent between the 2 MARAMP survey years, with 25 species 100 m^{-2} observed at a single site in 2003 and 28 and 33 species 100 m^{-2} recorded at the 2 REA sites surveyed in 2005.

APPENDICES

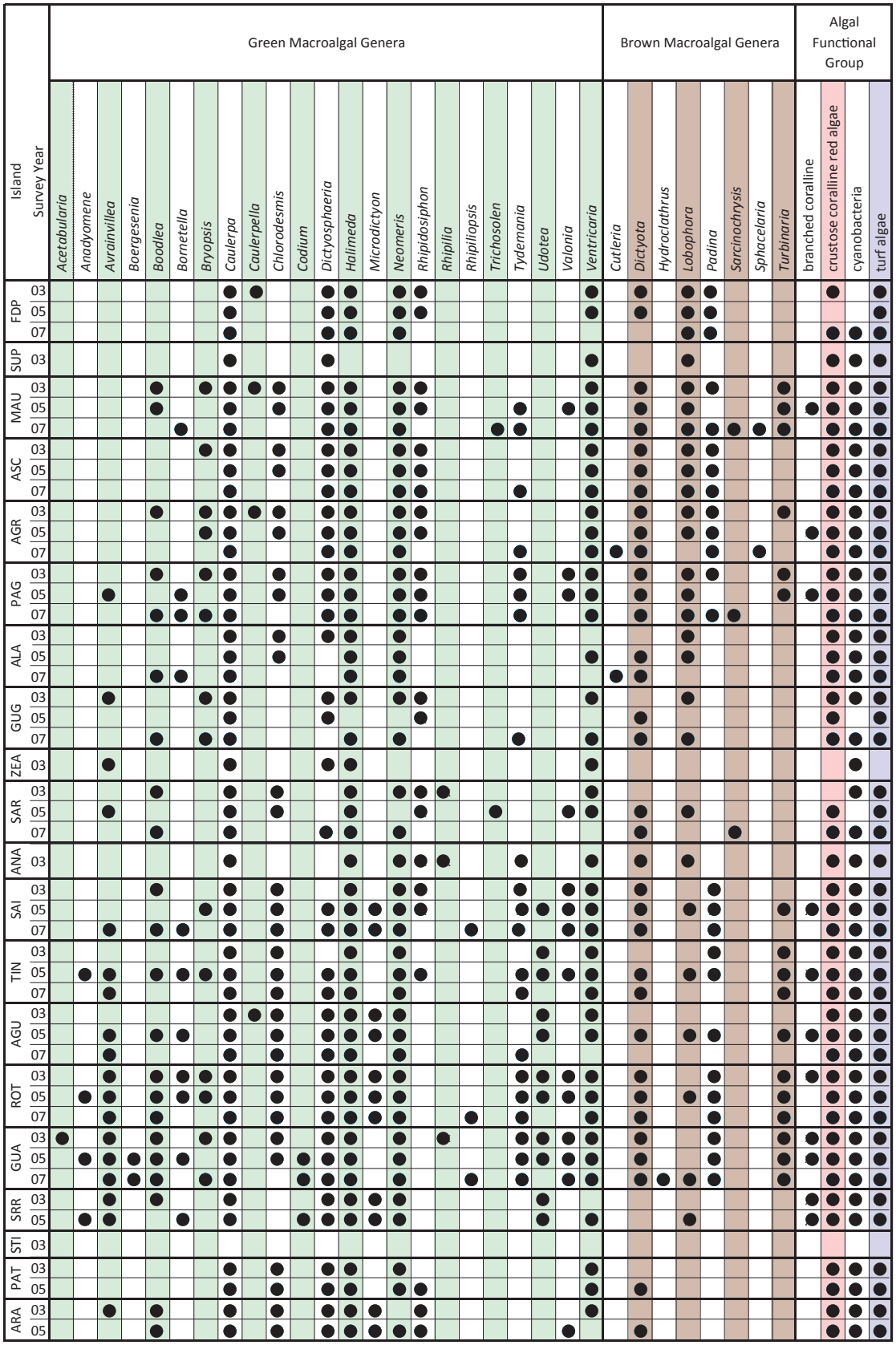
Appendix A. Anthozoan genera recorded as part of the REA benthic surveys conducted on forereef habitats in the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

Anthozoan Genera	Island																	
	Farallon de Pajaros	Maug	Asuncion	Agrihan	Pagan	Alamagan	Guguan	Sarigan	Anatahan	Saipan	Tinian	Aguijan	Rota	Guam	Santa Rosa	Pathfinder	Arakane	Island Total
Acanthastrea	●	●	●	●	●	●	●	●	●	●	●		●	●				13
Acropora	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			15
Alveopora										●			●					2
Astreopora	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	17
Cladiella														●				1
Coralimorphia										●								1
Coscinaraea										●	●	●						3
Cycloseris						●				●	●		●	●				5
Cyphastrea	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	17
Diploastrea														●				1
Echinophyllia		●			●					●	●	●						5
Echinopora		●		●	●	●	●	●		●	●	●	●					10
Euphyllia			●		●					●								3
Favia	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	17
Favites	●	●	●	●	●	●		●		●	●	●	●	●	●	●		14
Fungia		●	●	●	●					●	●	●	●	●		●		10
Galaxea		●	●	●	●	●	●	●	●	●	●	●	●	●				13
Gardineroseris				●	●			●		●		●						5
Goniastrea	●	●	●	●	●	●	●	●	●	●	●	●	●	●				14
Goniopora		●	●	●	●	●	●	●		●	●		●	●	●			12
Heliopora		●	●	●	●	●	●	●			●	●	●	●		●	●	13
Hydnophora		●	●	●	●	●	●	●	●	●		●	●	●				12
Leptastrea	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	17
Leptoria	●	●	●	●			●	●		●	●	●		●				10
Leptoseris			●		●	●	●			●	●	●			●			8
Lobophyllia		●	●	●							●			●				5
Lobophytum										●	●	●	●	●				5
Merulina			●						●									2
Millepora		●	●	●	●	●	●	●	●	●	●	●		●		●	●	14
Montastrea	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	17
Montipora	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	17
Octocoral														●				1
Other Soft Corals														●	●			2
Oulophyllia					●					●	●		●	●				5
Palythoa										●		●	●					3
Pavona	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		16
Platygyra	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		16
Plesiastrea										●	●							2
Pocillopora	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	17
Porites	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	17
Psammocora	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	17
Sarcophyton										●			●	●				3
Scapophyllia		●	●	●	●			●			●			●				7
Scolymia					●							●						2
Sinularia										●	●	●	●	●				5
Sterionephthya														●				1
Stylocoeniella		●	●	●	●		●		●	●	●	●	●	●				11
Stylophora	●	●	●	●	●	●				●	●	●	●	●	●	●		13
Turbinaria		●		●	●	●		●	●	●	●	●	●					10
Zoanthus											●							1
Total Genera	17	29	29	29	32	25	23	25	20	39	36	32	31	36	17	16	11	

Appendix B. Green and brown algal genera and algal functional groups recorded as part of the REA benthic surveys conducted on forereef habitats in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. The number of genera reported for each REA site may increase as detailed taxonomic laboratory analyses of voucher specimens become available (lab-based taxonomic identification of all algal species collected at REA sites in the northern islands, Sarigan to Farallon de Pajaros, is about 90% complete with hundreds of species identified so far).



Appendix C. Green and brown algal genera and algal functional groups recorded as part of the REA benthic surveys conducted on forereef habitats in the Mariana Archipelago during MARAMP 2003, 2005, and 2007. The number of genera reported for each REA site may increase as detailed taxonomic laboratory analyses of voucher specimens become available (lab-based taxonomic identification of all algal species collected at REA sites in the northern islands, Sarigan to Farallon de Pajaros, is about 90% complete with hundreds of species identified so far).



Appendix D. Ranks of each biological component for each geographic region and overall ranks for 2005 and 2007, based on towed-diver surveys conducted on forereef habitats during MARAMP 2005 and 2007 and used in the Archipelagic Coral Reef Condition Index, Archipelagic Benthic Condition Index, and Archipelagic Fish Condition Index. These index ranks reflect the status of a biological component for each geographic region, *relative to other regions across the Mariana Archipelago.*

		Reef Index		Benthic										Fish			
Island	Geographic Region	2005	2007	Cover of Live Hard Corals		Cover of Crustose Coralline Red Algae		Cover of Stressed Corals		Cover of Macroalgae		Density of Crown-of-thorns Seastars		Density of Large Fishes (> 50 cm TL)		Biomass of Large Fishes (>50 cm TL)	
	Northeast	35	38	43	(-10)	43	(12)	32.5	(-1)	48.5	(9)	47	(18)	26	(2)	22	(-18)
	Northwest	6	3	15.5	(5)	16	(-2)	16	(18)	17.5	(-33)	16	(-10)	8	(12)	9.5	(15)
	Southeast	4	28	13	(-16)	38	(16)	8.5	(-13)	14	(-26)	29	(28)	25	(-32)	17	(-24)
Agrihan	Southwest	17	23	26	(-2)	28.5	(-5)	11.5	(19)	34.5	(-9)	24	(-6)	24.5	(-5)	23	(0)
	North	34	36	20	(-12)	4	(0)	21	(10)	42.5	(13)	43.5	(-15)	40	(4)	37.5	(-9)
Aguijan	South	41	43	30	(-8)	37	(6)	44	(-2)	32.5	(-1)	37	(-26)	38	(-10)	41	(8)
	Northeast	9	9	7.5	(1)	27.5	(9)	28	(-2)	1	(0)	28.5	(-7)	11	(0)	15.5	(-3)
	Northwest	12	2	9.5	(13)	15.5	(-7)	21.5	(15)	1	(0)	13.5	(7)	15.5	(7)	14.5	(11)
	Southeast	13	15	21	(14)	41.5	(13)	11.5	(-11)	1	(0)	24.5	(9)	19.5	(1)	17	(-18)
Alamagan	Southwest	20	12	25.5	(11)	43	(-4)	31.5	(9)	1	(0)	17.5	(19)	21.5	(13)	15	(2)
	Northeast	11	13	22.5	(-1)	43.5	(-1)	19	(-32)	12	(22)	6.5	(11)	15	(2)	13.5	(-5)
	Northwest	10	21	6	(-10)	22.5	(-9)	22	(-36)	48.5	(3)	40	(8)	11	(-10)	12	(0)
	Southeast	2	6	43	(14)	45.5	(-7)	6.5	(1)	1	(0)	1.5	(1)	5.5	(-1)	4	(-6)
Asuncion	Southwest	7	20	24	(16)	4.5	(-7)	20.5	(-9)	40	(-18)	36	(-8)	15	(-6)	11	(-16)
	Northeast	19	14	53	(4)	37.5	(-33)	2.5	(-3)	1	(0)	26.5	(-39)	20.5	(21)	16.5	(31)
	South	29	10	50	(2)	25	(-22)	9	(2)	1	(0)	21.5	(-5)	25.5	(25)	24.5	(37)
	Southeast	30	8	48	(8)	32	(-42)	4.5	(7)	1	(0)	7.5	(3)	24.5	(33)	28	(36)
Farallon de Pajaros	West	31	7	41.5	(-11)	31.5	(-19)	5	(0)	1	(0)	42	(18)	19	(32)	21.5	(37)
	East	46	52	16	(-24)	22.5	(-7)	43	(-8)	53	(-4)	53.5	(-1)	51	(2)	51.5	(-1)
	North	53	49	6	(-8)	42	(20)	44	(-4)	49	(-4)	39	(18)	54	(2)	55	(0)
	Northwest	50	47	20	(-22)	37	(-4)	44.5	(1)	46.5	(3)	34	(16)	53	(2)	50.5	(5)
	South	51	53	24.5	(-25)	50.5	(1)	50	(4)	27.5	(-53)	53.5	(1)	52	(8)	53.5	(5)
Guam	West	49	51	50	(-6)	37	(16)	54.5	(-1)	41.5	(-1)	36.5	(-5)	48	(4)	44.5	(-11)
	Northwest	16	21	17	(26)	5	(-4)	16	(-10)	19	(36)	16	(6)	25.5	(-9)	35	(-18)
Guguan	Southwest	23	27	28	(26)	30	(-6)	21.5	(-25)	19.5	(37)	18	(22)	37.5	(5)	24	(-30)
	East	1	1	14.5	(5)	11	(-4)	20.5	(15)	1	(0)	10.5	(-9)	8.5	(3)	6	(2)
	East Caldera	26	18	6	(-6)	30.5	(17)	17	(14)	28.5	(-7)	13.5	(-11)	28.5	(11)	34	(14)
	North	3	11	9.5	(3)	27	(14)	27.5	(15)	1	(0)	18	(0)	12	(-18)	13	(-14)
	North Caldera	27	35	6	(2)	52.5	(1)	14	(6)	41	(-10)	37.5	(-13)	30	(-2)	32.5	(-7)
	West	13	5	11.5	(19)	10	(-4)	21.5	(25)	24.5	(3)	20	(6)	11	(4)	14	(2)
Maug	West Caldera	22	25	6	(0)	38	(-26)	8.5	(11)	43	(0)	42	(-6)	20	(-4)	30	(10)
	East	21	28	22	(-14)	4	(-4)	20	(4)	54.5	(3)	48.5	(13)	21.5	(-9)	26	(-4)
	North	24	17	29.5	(-11)	22.5	(3)	35.5	(-5)	52	(0)	42	(14)	8	(14)	16.5	(11)
	South	38	34	29	(10)	21.5	(-33)	27.5	(-19)	52.5	(5)	37.5	(19)	34	(4)	30.5	(13)
Pagan	West	25	31	38.5	(13)	9.5	(1)	12.5	(1)	46	(-4)	25	(6)	31.5	(-11)	31	(-2)
	North	48	41	55	(2)	55	(0)	54.5	(3)	1	(0)	1	(0)	49	(8)	49.5	(9)
	Northwest	32	48	46	(-8)	41.5	(-9)	47.5	(-7)	32.5	(5)	37.5	(17)	36	(-26)	31	(-24)
	South	36	37	42.5	(1)	20	(20)	39	(18)	38.5	(3)	13.5	(-19)	35.5	(-7)	37	(-6)
	Southeast	52	50	50	(-4)	43	(-10)	52	(-4)	17	(32)	42	(16)	48	(-6)	50.5	(-5)
Rota	West	8	31	44	(-22)	8.5	(15)	32.5	(27)	42	(8)	4	(-2)	17	(-32)	20	(-36)
	East	39	16	47	(12)	14	(6)	30.5	(-23)	32.5	(13)	32.5	(-33)	22	(34)	26	(36)
	North	44	33	47	(14)	49.5	(13)	50.5	(-3)	27.5	(-1)	38.5	(-33)	30	(26)	26.5	(9)
	Northwest	43	45	26.5	(-7)	10	(-8)	40.5	(-5)	37	(-6)	46	(-2)	48	(2)	47.5	(3)
	South	47	44	41	(-8)	17.5	(5)	22	(-20)	42.5	(23)	52	(0)	52.5	(-3)	43.5	(17)
	Southeast	28	40	42.5	(7)	26.5	(47)	39	(-4)	38.5	(7)	39.5	(-3)	23	(-38)	37.5	(-19)
Saipan	West	5	46	16	(-6)	15.5	(-17)	19.5	(-9)	15	(-28)	40	(-6)	28.5	(-53)	39.5	(-29)
	East	18	19	18.5	(1)	44.5	(5)	22.5	(1)	1	(0)	33	(16)	26.5	(-3)	18	(0)
	Northwest	33	30	26	(2)	34.5	(-11)	29.5	(3)	1	(0)	18	(14)	42	(4)	34.5	(3)
Sarigan	Southwest	15	4	28.5	(13)	36	(16)	21.5	(-3)	12.5	(23)	22	(26)	5.5	(3)	7	(6)
	Northeast	45	39	47.5	(3)	29	(8)	50.5	(1)	34.5	(21)	35.5	(9)	41	(14)	34	(-14)
	Northwest	39	26	26.5	(-13)	16.5	(29)	38.5	(5)	11.5	(21)	21	(-32)	37.5	(17)	40.5	(13)
	Southeast	37	24	38.5	(1)	22	(10)	48	(-2)	35	(-12)	23.5	(19)	24	(0)	28.5	(27)
Tinian	Southwest	42	42	43.5	(1)	14	(18)	46	(14)	26.5	(3)	30.5	(-35)	40.5	(-7)	49.5	(1)
	MEDIAN			26.5		28.5		22.5		27.5		30.5		25.5		28	

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Errata

Erratum 1—Correction in Chapter 3: "Archipelagic Comparisons," Section 3.1: "Geopolitical Context," P. 1, Table 3.1a:

The brown tree snake symbol was changed from black to grey in the "Animal Threats" column of the rows for Saipan, Tinian, and Rota. A legend for the new grey symbol was added, stating "Brown tree snake sighted but not established." A personal communications was added to the citations in the table caption, "M Onni, CNMI Division of Fish and Wildlife, pers. comm."

Although sightings of the brown tree snake (*Boiga irregularis*) have been reported for Saipan, Tinian, and Rota (Marianas Avifauna Conservation Working Group 2008), efforts by the Brown Tree Snake Program of the Commonwealth of the Northern Mariana Islands (CNMI) Division of Fish and Wildlife (DFW) to keep populations from becoming established outside of Guam have been effective, as the last live snake captured and dead snake found in the CNMI were recorded on Saipan in 2000 and on Rota in 2009, respectively (M Onni, CNMI DFW, pers. comm.)

Erratum 2—Correction in Chapter 4: "Guam & Adjacent Reefs," Section 4.1.4: "Economy," P. 7, lines 1 and 2:

This sentence was redacted: "Two fishing methods have been banned: (1) use of scuba and artificial light for spearfishing and (2) use of monofilament gill nets."

These two fishing methods have not been banned in Guam.

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