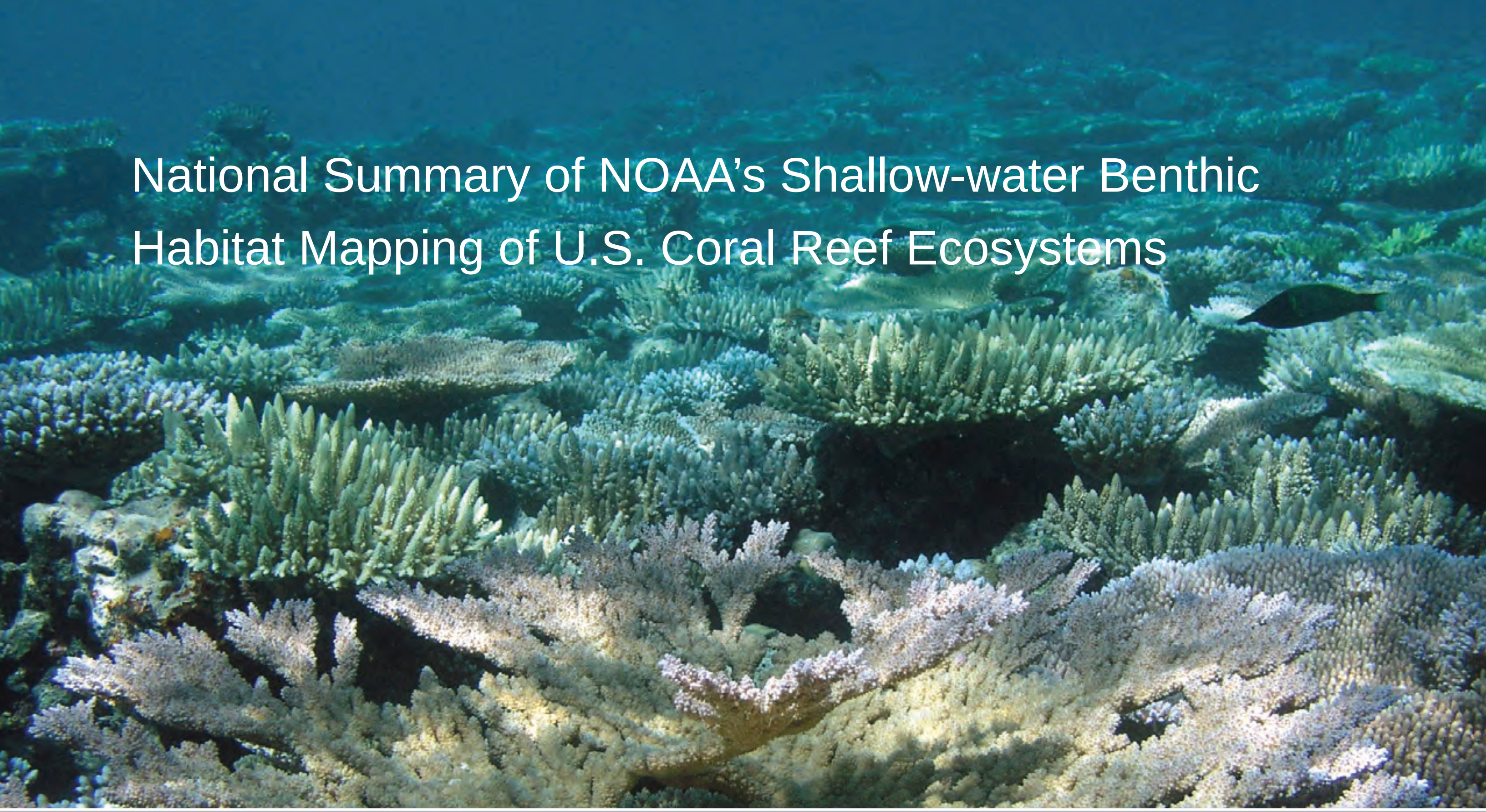
National Summary of NOAA's Shallow-water Benthic Habitat Mapping of U.S. Coral Reef Ecosystems



NOAA National Centers for Coastal Ocean Science

Center for Coastal Monitoring and Assessment

Mark E. Monaco

Timothy A. Battista

Matthew S. Kendall

Lisa M. Wedding

Alicia M. Clarke

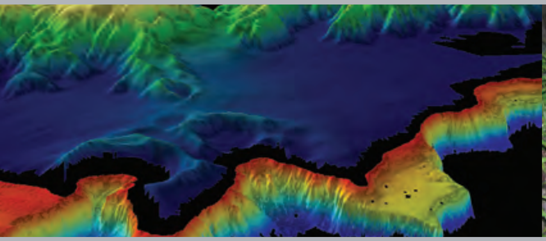
Analytical Laboratories of Hawaii, LLC

S. Miles Anderson

NOAA Office of National Marine Sanctuaries

Technical Programs and Support Division

Steven O. Rohmann

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National Summary of NOAA's Shallow-water Benthic Habitat Mapping of U.S. Coral Reef Ecosystems

Prepared for the NOAA Coral Reef Conservation Program by:
The Biogeography Branch
Center for Coastal Monitoring and Assessment
NOAA National Centers for Coastal Ocean Science
Silver Spring, MD, USA

August 2012

AUTHORS
Mark E. Monaco
S. Miles Anderson
Timothy A. Battista
Matthew S. Kendall
Steven O. Rohmann
Lisa M. Wedding
Alicia M. Clarke

CONTRIBUTORS
Sarah D. Hile
Ken Buja

Dedication

This report is dedicated to the late Miles Anderson of Oahu, Hawaii who, through his outstanding and extremely professional approach, enabled NOAA's National Ocean Service (NOS) to map nearly all shallow-water coral reef ecosystems in the U.S. Miles provided the NOS coral reef ecosystem mapping team with energy, guidance and technical skill to complete the most robust effort to map and characterize coral ecosystems from the U.S. Caribbean to the islands of the Western Pacific. His tireless efforts resulted in developing a state-of-the-art approach to mapping coral reef ecosystem habitats that is used by mapping specialists across the country. For the first time, NOS has a solid understanding of the spatial extent of the nation's coral reef ecosystem to aid in the management of these delicate natural resources. Miles' ability to work with people, ranging from senior-level politicians to local island villagers, was amazing to watch. He galvanized communities to support the development of habitat maps and constantly worked to make sure the NOS mapping products were useful and relevant. The NOS team was very fortunate to have met and worked with Miles over the last decade and we are very proud in our collective success in mapping the nation's coral reef ecosystems.

S. Miles Anderson
1947-2010

About this Document

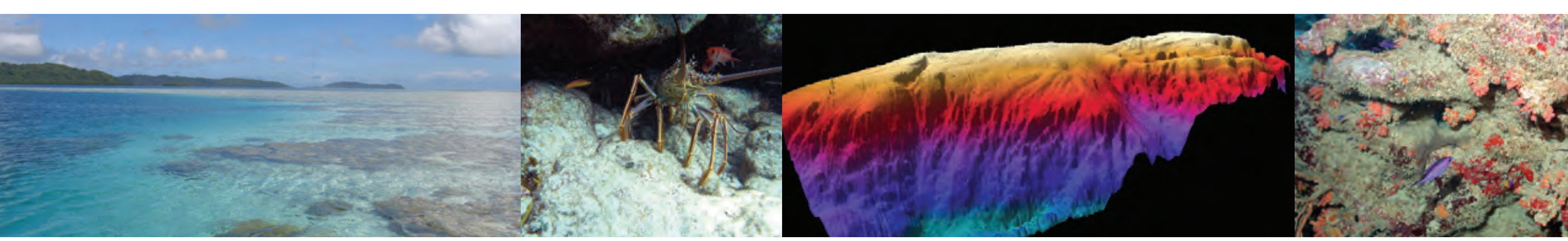
This document presents a comprehensive overview of results from more than a decade of work by the NOAA National Ocean Service (NOS) to map the shallow-water coral reef ecosystems across the U.S. The report details: (1) mapping methodologies and techniques developed; (2) final results of shallow-water benthic habitat mapping efforts in each of the 10 U.S. coral reef ecosystem areas; (3) regional and local applications of the maps and related products; and (4) national-level summary statistics on the total acreage of habitats mapped and existing data gaps. The report also introduces new and developing NOS mapping technologies.

The efforts discussed here were led by the National Centers for Coastal Ocean Science (NCCOS), the Office of National Marine Sanctuaries, Coral Reef Conservation Program, and the Coastal Services Center. NCCOS has been proactive in collaborating with other NOAA line offices as well as federal, state and nongovernmental organization partners to maximize cost-sharing efforts and reach its goals. Their funding has made it possible to complete areas that would have otherwise been unobtainable through federal funding alone.

Live hyperlinks to related products (indicated by blue text) are embedded throughout this report and are accessible when viewing this document as a PDF. For more information about this report and others like it, please visit the NCCOS web site, http://coastalscience.noaa.gov/, or direct comments to:

Mark Monaco, PhD, Director
Center for Coastal Monitoring and Assessment
NOAA National Centers for Coastal Ocean Science
Telephone: 301.713.3020 x160
E-mail: Mark.Monaco@noaa.gov

Chris Caldow, Biogeography Branch Chief
Center for Coastal Monitoring and Assessment
NOAA National Centers for Coastal Ocean Science
Telephone: 301-713-3028 x164
E-mail: Chris.Caldow@noaa.gov



Contents

Executive Summary

Photo credit: S. Miles Anderson, Analytical Laboratories of Hawaii, LLC

Coral reef ecosystems are some of the most complex and important ecosystems in the marine environment. They are also among the most biologically diverse and economically valuable ecosystems on earth, producing billions of dollars in food, as well as providing a suite of ecological services, such as recreation and tourism activities and coastal protection from storm and wave action. Yet, despite their value and importance, these fragile ecosystems are declining at an alarming rate (Waddell and Clarke (eds.) 2008) due to a myriad of threats both natural and man-made, including climate change, fishing pressure, and runoff and sedimentation. In response, the Unites States Coal Reef Task Force was established in 1998 by Presidential Executive Order 13089 to lead U.S. efforts to preserve and protect the nation's coral reef ecosystems.

In order to better understand the current state of coral reef ecosystems and successfully mitigate the impacts of stressors, informational products, such as benthic (or sea floor) habitat maps, are critical. Benthic habitat maps support the ability to prioritize areas for further study and protection, and offer a baseline to evaluate the changes in ecosystems over time. In 2000, the United States Coral Reef Task Force charged NOAA with leading federal efforts to produce comprehensive digital maps of all U.S. shallow-water (approximately 0 to 30 m in depth) coral reef ecosystem habitats.

The purpose of this document is to provide a comprehensive jurisdictional and national summary of the shallow-water coral reef ecosystem mapping efforts led by NOAA's National Ocean Service (NOS) National Centers for Coastal Ocean Science (NCCOS), the Office of National Marine Sanctuaries and the Coral Reef Conservation Program. This report:

- Summarizes the methods and habitat classification schemes from the NOS benthic habitat mapping efforts;
- Documents the extent of habitats that comprise coral reef ecosystems in 10 U.S. Caribbean, Florida and Pacific jurisdictions;

- Highlights location-specific applications of the benthic habitat maps to support ecosystem-based science and management; and
- Outlines future priorities for shallow-water benthic habitat mapping.

Since 2000, NOS and its partners have developed analytical tools and protocols for mapping shallow-water coral reef ecosystems in U.S. states, territories and freely associated states. Detailed information from these mapping efforts has been previously published in reports on each island and/or jurisdictional area. Thus, this document serves as a comprehensive summary of the previous studies and provides key information in a single report.

The scope of this report encompasses 10 areas of highly productive and diverse coral reef regions stretching from the Pacific Ocean to the Atlantic Ocean and Caribbean Sea. Each area is unique in the composition of its benthic habitats and marine life. They are:

1. U.S. Virgin Islands
2. Puerto Rico
3. Southern Florida and the Florida Keys
4. Main Hawaiian Islands
5. Northwestern Hawaiian Islands
6. American Samoa
7. Palmyra Atoll (Pacific Remote Island Areas)
8. Commonwealth of the Northern Mariana Islands
9. Guam
10. Republic of Palau

Additional finer-scale, localized mapping products have been created for other areas (e.g., Majuro, Marshall Islands and Buck Island, St. Croix, U.S. Virgin Islands), but are not discussed here. For more information about these efforts, visit: http://ccma.nos.noaa.gov/about/biogeography.

NOS and its partners have mapped over 12,100 km^2 of coral reef ecosystems in U.S. states and territories over the past 12 years. This includes approximately 5,000 km^2 of hard bottom habitats, such as coral reef, rubble and rock formations and another 7,100 km^2 of soft bottom habitats, such as sand and mud. The total area mapped by jurisdiction varied considerably. The region with the largest mapped area by a wide margin is the Florida Reef Tract, with over 6,000 km^2 of mapped habitats. In this area NOS has ongoing benthic habitat mapping studies in collaboration with the State of Florida. The next largest region is the Northwestern Hawaiian Islands with approximately 2,000 km^2 mapped followed by Puerto Rico and the Main Hawaiian Islands.

NOS' benthic habitat maps have greatly enhanced efforts to preserve and manage coral reef ecosystems within and among jurisdictions, each of which face unique challenges. They have assisted local and national coral reef managers, scientists and decision makers in:

- Evaluating the efficacy of existing marine protected areas (MPA), aiding in the design of MPA expansion, and providing details needed for the planning and design of new MPAs;
- Constructing sampling designs for coral reef ecosystem monitoring and assessment programs; and
- Developing strategies to minimize the impacts from growing human communities that depend on the ecological services provided by coral reefs (e.g., food).

In St. John, U.S. Virgin Islands, NOS benthic habitat maps are being used to support potential boundary modifications of the Virgin Islands Coral Reef National Monument. A transfer of area is being considered by the National Park Service to add a biologically productive area to the MPA. Scientists and leaders in Samoa and American Samoa are using NOS benthic habitat maps to delineate boundaries for a system of proposed MPAs and to support a territorial initiative to protect 20% of the archipelago's reefs. Additionally, NOS mapping data and products contributed to the design and designation of the Pacific Remote Islands Marine National Monument (2009) that includes Palmyra Atoll, and the successful bid to recognize the Northwestern Hawaiian Islands (also known as the Papahanaumokuakea Marine National Monument) as the nation's first UNESCO Mixed World Heritage Site in 2010.

For many jurisdictions, the maps continue to guide the development of scientific sampling designs to identify and assess the conditions of, and changes to, coral reef ecosystems and associated fauna. In the U.S. Virgin Islands and Puerto Rico, the maps are a critical component in the planning of annual scientific missions to characterize and monitor the distribution, abundance and size of reef fish and macro-invertebrates (i.e., conch, lobster , sea urchin, etc.). Data from these monitoring missions, led by NCCOS and supported by the Coral Reef Conservation Program, have helped managers in the U.S. Caribbean estimate damages from vessel groundings, evaluate zoning strategies, and understand the impacts of runoff and contaminants on marine animals and plants. The benthic habitat map for South Florida and the Florida Keys are an instrumental tool used to assess the effectiveness of no-take areas where fishing is prohibited. They are also used throughout the Florida Keys to evaluate the condition and distribution of *Acropora*, an Endangered Species Act-listed coral genus, and to support research on the impacts of invasive lionfish.

The benthic habitat maps are a key source of spatial information used to evaluate proposed infrastructure expansion projects to accommodate growing island populations. In Guam, where high-density commercial, civilian and military development threatens the surrounding marine ecosystem, scientists and planners use the maps to identify high-value coral reef ecosystems that spatially coincide with proposed construction sites. Palau resource managers face similar challenges due to the island's booming tourism industry and the infrastructure needed to support it.

These are just some examples of the many useful applications of the NOS benthic habitat mapping products detailed in this report. These mapping products provide some of the most detailed and accurate descriptions of the physical and biological characteristics of the nation's diverse coral reef communities and equip on-the-ground managers, scientists and decision makers with information that is integral to effective ecosystem-based management strategies.

Where possible, hyperlinks to related data and resources (indicated by blue text) are directly accessible throughout this report when viewing the document as PDF. Comprehensive reports, digital benthic habitat maps in an atlas format for each of the 10 coral reef areas highlighted here, as well as all mapping data and metadata, imagery, video and management tools are available at, http://ccma.nos.noaa.gov/about/biogeography/.

Introduction

Photo credit: NCCOS/CCMA Biogeography Branch

Since 2000, NOAA National Ocean Service (NOS) has developed analytical tools and protocols for mapping shallow-water (approximately 0 to 30 m) coral reef ecosystems in U.S. states, territories and freely associated states across the Atlantic Ocean, Caribbean Sea and the Pacific Ocean. The products derived from these mapping efforts provide the most detailed and accurate descriptions of the physical and biological characteristics of the nation's diverse coral reef communities. The resulting products equip local managers with marine resource data that are integral to effective ecosystem-based management strategies.

The purpose of this document is to provide a comprehensive island, regional and national summary of the shallow-water mapping efforts led by NOS' National Centers for Coastal Ocean Science (NCCOS), Center for Coastal Monitoring and Assessment, Biogeography Branch, the Office of National Marine Sanctuaries and the NOAA Coral Reef Conservation Program. Objectives include:

- Summarize the methods and habitat classification schemes from NOS mapping efforts;
- Document the aerial extent of primary habitats that comprise coral reef ecosystems in the U.S. Caribbean, Florida and Pacific Ocean;
- Highlight location-specific applications of benthic maps; and
- Outline future priorities for shallow-water benthic habitat mapping.

With the exception of South Florida and the Florida Keys Reef Tract, which is still being completed, the information in this document has been previously published in detailed reports on each island and/or regional area. Thus, this document serves as a comprehensive summary of the previous studies and provides the key information in a singular report.

Background

The management of coral reef ecosystems is a challenging and complex balancing act. Managers must strike a balance between ecosystem protection and allowing people to enjoy and use these beautiful natural resources. Coral reef ecosystems provide a suite of socioeconomic and ecological goods and services that benefit people, including: recreation and tourism activities, protection from storm and wave events, and are primary sources of food for some localities. Due to their ecological importance and the continued decline in coral reef ecosystem condition, the United States Coral Reef Task Force was established in 1998 by Presidential Executive Order 13089 to lead U.S. efforts to preserve and protect coral reef ecosystems. The Coral Reef Task Force committed to produce comprehensive digital maps of all U.S. shallow and selected, priority deep water (>30 m) coral reef habitats and NOAA was directed to lead this body of work. Coral reef mapping efforts were coordinated through the task force's Mapping and Information Synthesis Working Group, composed of representatives from numerous federal, state/territory and commonwealth agencies, as well as academic organizations and nongovernmental organizations.

For the purpose of developing detailed habitat maps, coral reef ecosystems were defined by the U.S. Coral Reef Task Force as those integrated biological and physical habitats that include hard and soft corals and other commonly associated habitats such as seagrass, algae, mangroves and soft sediments (Monaco et al. 2001). By nature, the management of coral reef ecosystems is, in part, a spatial issue, as these ecosystems range in scale from large continuous structures to discrete features surrounding islands and adjacent to continents. Timely, accurate and consistent benthic habitat maps greatly enhance efforts to preserve and manage coral reef ecosystems within and among jurisdictions. With comprehensive maps and habitat assessments provided by NOS, coral reef managers have been more effective in designing and implementing a variety of conservation measures, including:

- Long-term monitoring programs with accurate temporal baselines from which to track changes;
- Place-based conservation measures, such as marine protected areas and development of coastal and marine spatial plans; and
- Targeted research to better understand the socioeconomic, oceanographic and ecological processes affecting coral reef ecosystem function and condition.

The benthic mapping approach was designed to ensure relevance and applicability to meet management needs. It included identifying and delineating benthic features in georeferenced, remotely sensed imagery and assessing the thematic accuracy of the resulting map. An accurate, georeferenced map is critical when characterizing and monitoring the condition of coral communities over time. It is important to recognize that "mapping" was comprised of many activities, including delineating shoreline, surveying to obtain ground truthing data, defining habitat classification systems and producing digital habitat maps.

Although NOS led the national mapping efforts, the studies were conducted through a series of local, state, commonwealth, territory, academic and private sector partners. These entities collectively developed applied map products and utilized the resulting maps to conduct research and monitoring in support of coral ecosystem management needs. A suite of technologies were

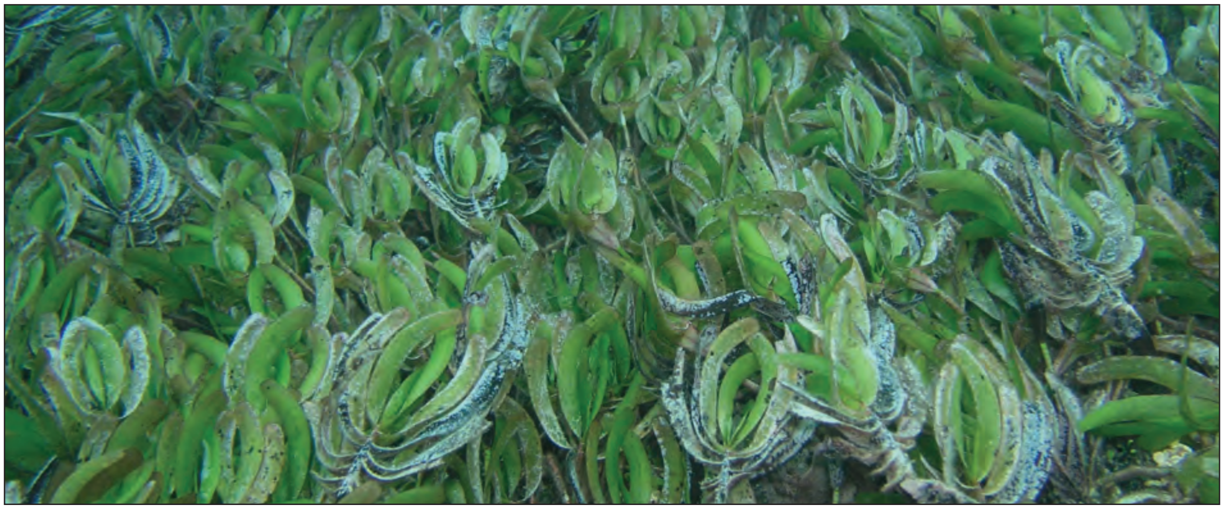


Figure 1. Seagrass beds are one of the many benthic habitat types mapped in this process. Photo credit: S. Miles Anderson.

required to develop accurate benthic habitat maps at spatial scales necessary for management, but within time and budget constraints. Low-altitude aerial photography, hyperspectral imagery and color satellite imagery were used in a variety of areas to provide the imagery that was primarily classified by visual interpretation. Efforts to characterize and map coral reef ecosystems required a scheme for classifying the benthic habitats found in each area to be mapped. To meet this need, NOS led several island and regional efforts to develop the classification schemes based on the features that could be seen in the various types of remote sensing imagery (Kendall et al. 2001; Coyne et al. 2000a, b). In general, the classification schemes were fairly consistent across regions, especially in the most general categories of the hierarchical classification, such as hard bottom, soft bottom, algae and seagrass (Figure 1).

Geographic Coverage

The U.S. is responsible for managing and conserving extensive shallow-water coral reef ecosystems within its maritime boundaries in close cooperation with local governments (Waddell 2005). The scope of this report encompasses 10 areas of highly productive and diverse coral reef regions stretching from the Pacific Ocean to the Atlantic Ocean and Caribbean Sea (Figures 2 and 3). Each area is unique in the composition of its benthic habitats and marine life. The 10 primary coral reef areas of the U.S., its territories, commonwealths and freely associated states featured in this report are:

1. U.S. Virgin Islands
2. Puerto Rico
3. Southern Florida and the Florida Keys
4. Main Hawaiian Islands
5. Northwestern Hawaiian Islands
6. American Samoa
7. Palmyra Atoll (Pacific Remote Island Areas)
8. Commonwealth of the Northern Mariana Islands
9. Guam
10. Republic of Palau

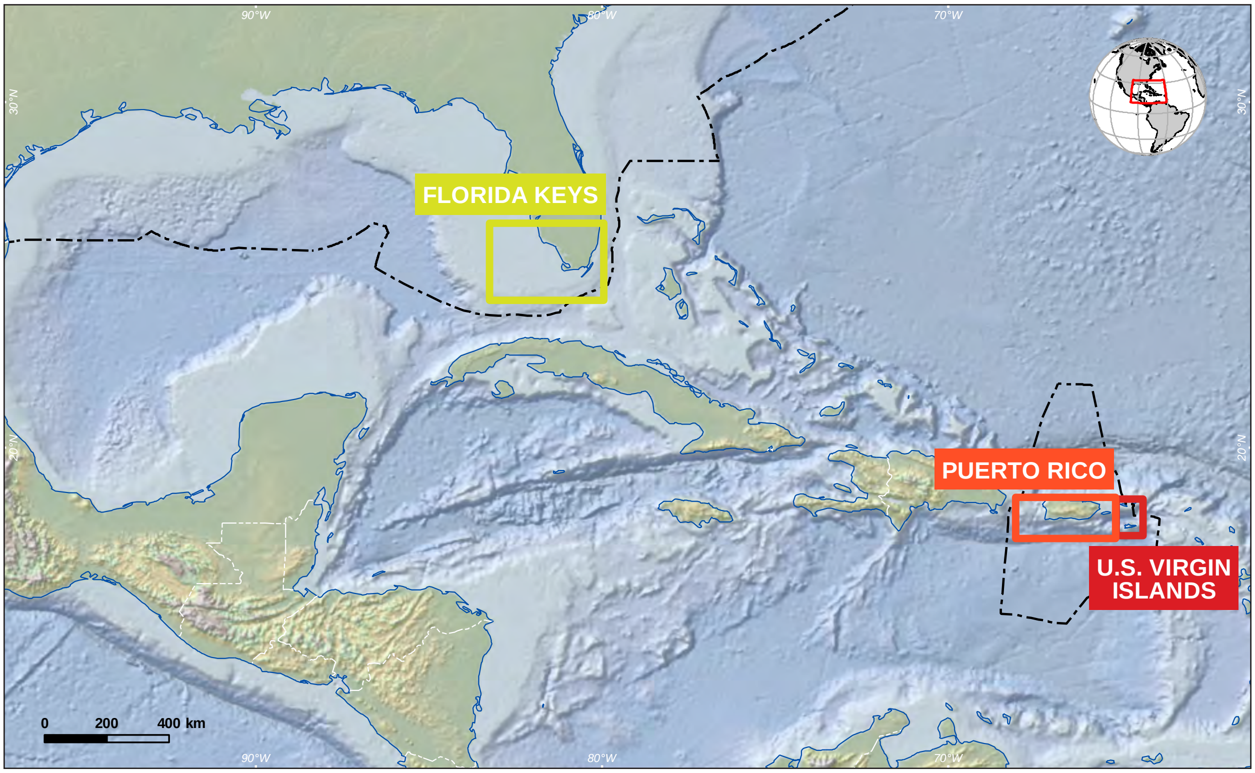


Figure 2. Locations of shallow-water U.S. coral reef ecosystems mapped by NOS and featured in this report in the Atlantic Ocean, Gulf of Mexico and Caribbean. Credit: Ken Buja.

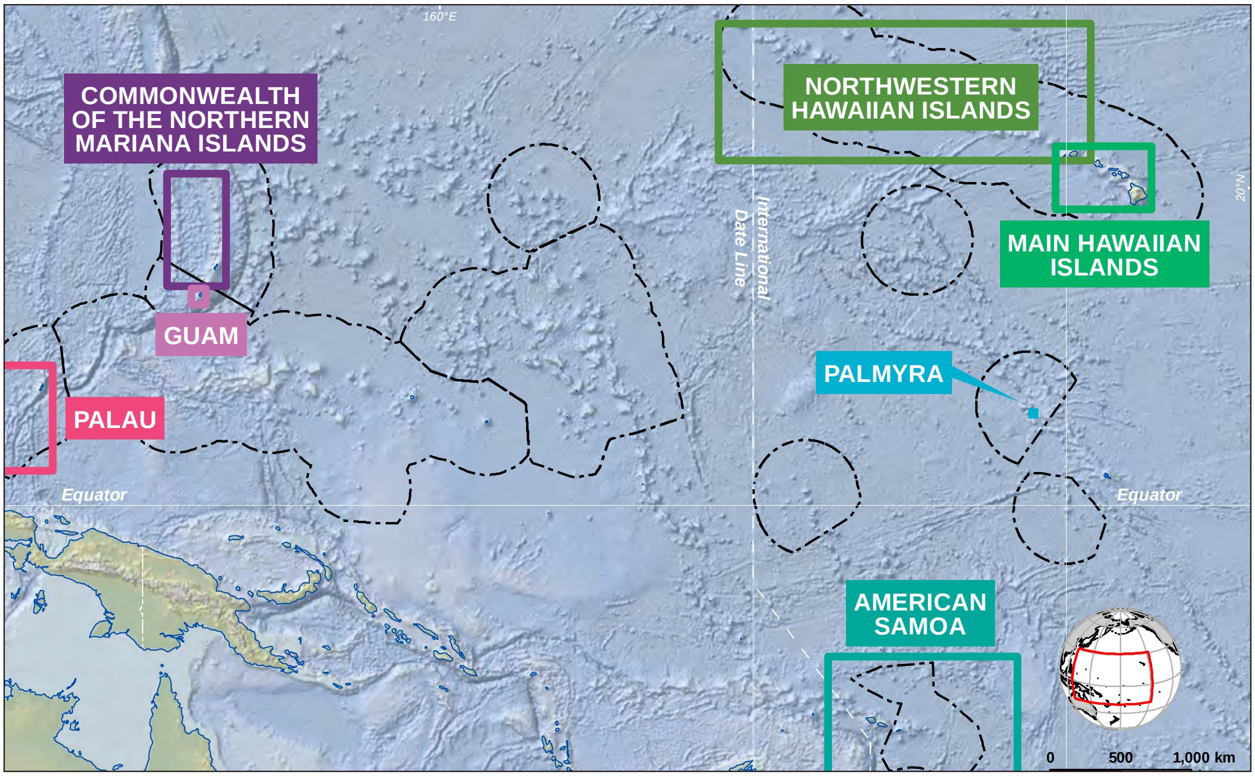


Figure 3. Locations of U.S. shallow-water coral reef ecosystems mapped by NOS and featured in this report in the Pacific Ocean. Credit: Ken Buja.

Mapping Products

A key component of the mapping efforts undertaken by NOS is the ability to serve information and data to managers, scientists, academics and the public quickly and efficiently online and through user-friendly tools derived from the raw data. The online presence for mapping data and reports from each of the 10 primary coral reef areas presented in this document is listed in Table 1. Each site outlines the scope of the work and provides easy access to all relevant products, including PDFs of the benthic habitat maps, aerial or satellite imagery, accuracy assessment data, detailed descriptions of mapping techniques and classification schemes, as well as related publications. Users can also request CDs, DVDs and hard copies of many products. Additionally, NOS scientists and GIS specialists worked closely with users and stakeholders to develop supplemental online resources to make the most of the information presented in the benthic habitat maps. The following tools are customizable mechanisms for delivering mapping data:

- BIOMapper (or Biogeography Integrated Online Mapper): a series of fully interactive, online features designed to let users explore benthic habitat mapping data for various locations (i.e., St. John, U.S. Virgin Islands).

Online: St. John, U.S. Virgin Islands BIOMapper http://ccma.nos.noaa.gov/explorer/biomapper/biomapper.html?id=StJohn

- Habitat Digitizer Extension: A GIS tool that uses a hierarchical classification scheme to delineate features by visually interpreting georeferenced images, such as aerial photographs, satellite images and side scan sonar. Users can: create custom classification schemes; digitize polygons, lines and points using standard ArcGIS editing tools; and attribute the features using a dialog containing the user-created scheme.

Online: http://ccma.nos.noaa.gov/products/biogeography/digitizer/

- Aerial Photography Search: A search tool of recent and historic aerial photos from the U.S. Virgin Islands and the Main Hawaiian Islands.

Online: http://www8.nos.noaa.gov/biogeo_public/aerial/search.aspx

- Google Earth and Google Maps-based access to over 5,400 underwater video clips, still images and satellite images from Florida .

Online: http://ccma.nos.noaa.gov/ecosystems/coralreef/fl_mapping/#products (see links under "Data").

Report Organization

Subsequent chapters of this report detail mapping methodologies developed by NOS and summarize the final results of shallow-water benthic habitat mapping efforts in each of the 10 U.S. coral reef ecosystem areas. The information reported is based on the most comprehensive maps available for each location. Additional finer-scale mapping products have since been produced for localized areas (i.e., Buck Island, St. Croix and Majuro, Marshall Islands) but are not discussed in this report.

Chapter 2 provides a comprehensive overview of the six-step mapping process, including the development and evolution of the classifications schemes used for habitat attribution at each location.

Table 1. The online locations for the shallow-water mapping products generated by NCCOS, the Coral Reef Conservation Program, the Office of National Marine Sanctuaries and partners.

Jurisdiction	Web Resources	Status
U.S. Virgin Islands and Puerto Rico	http://ccma.nos.noaa.gov/ecosystems/coralreef/usvi_pr_mapping.aspx	Completed in 2002
Florida	http://ccma.nos.noaa.gov/ecosystems/coralreef/fl_mapping/ http://flkeysbenthicmaps.noaa.gov/data_download.html	1992 - present
Main Hawaiian Islands	http://ccma.nos.noaa.gov/ecosystems/coralreef/main8hi_mapping/	Completed in 2003 and 2007
Northwestern Hawaiian Islands	http://ccma.nos.noaa.gov/ecosystems/coralreef/nwhi_mapping.aspx	Completed in 2003
American Samoa, Guam and the Commonwealth of the Northern Mariana Islands	http://ccma.nos.noaa.gov/ecosystems/coralreef/us_pac_mapping.aspx	Completed in 2005
Palmyra Atoll (Pacific Remote Island Areas)	http://ccma.nos.noaa.gov/ecosystems/coralreef/palmyra/	Completed in 2011
Republic of Palau	http://ccma.nos.noaa.gov/products/biogeography/palau/	Completed in 2007

Mapping results discussed in this report are organized by geographic location, or jurisdiction, in Chapters 3-12. The geomorphic structure, biological cover, and reef zonation for each location are described and discussed in the broader context of the geomorphological and biological setting of the region. Due to the small variations in mapping approach among island groups (e.g. evolution of classification schemes), and often significant differences in reef morphology, the focus of each jurisdictional chapter is customized to describe key findings for each area. In addition, examples of how the benthic habitat maps have been applied to regional coral reef ecosystem management, scientific, and conservation efforts are also provided for each location. It must be noted that there have been many applications for the NOS benthic habitat maps; however, in many instances their applied value occurs behind-the-scenes and goes undocumented in publications and peer-reviewed scientific literature. As a result, publications are cited detailing the application of the NOS maps when possible, but in other cases a cross section of known applications are discussed but references for them are unavailable. Lastly, the final chapter of this report provides summary statistics on the acreage of habitats mapped, highlights new mapping technologies and data gaps. Full reports for each of the 10 coral reef areas highlighted in this summary document, as well as all mapping data and metadata, imagery, video and management tools are available at: http://ccma.nos.noaa.gov/about/biogeography/.

MAP PRODUCTION PROCESS & METHODS

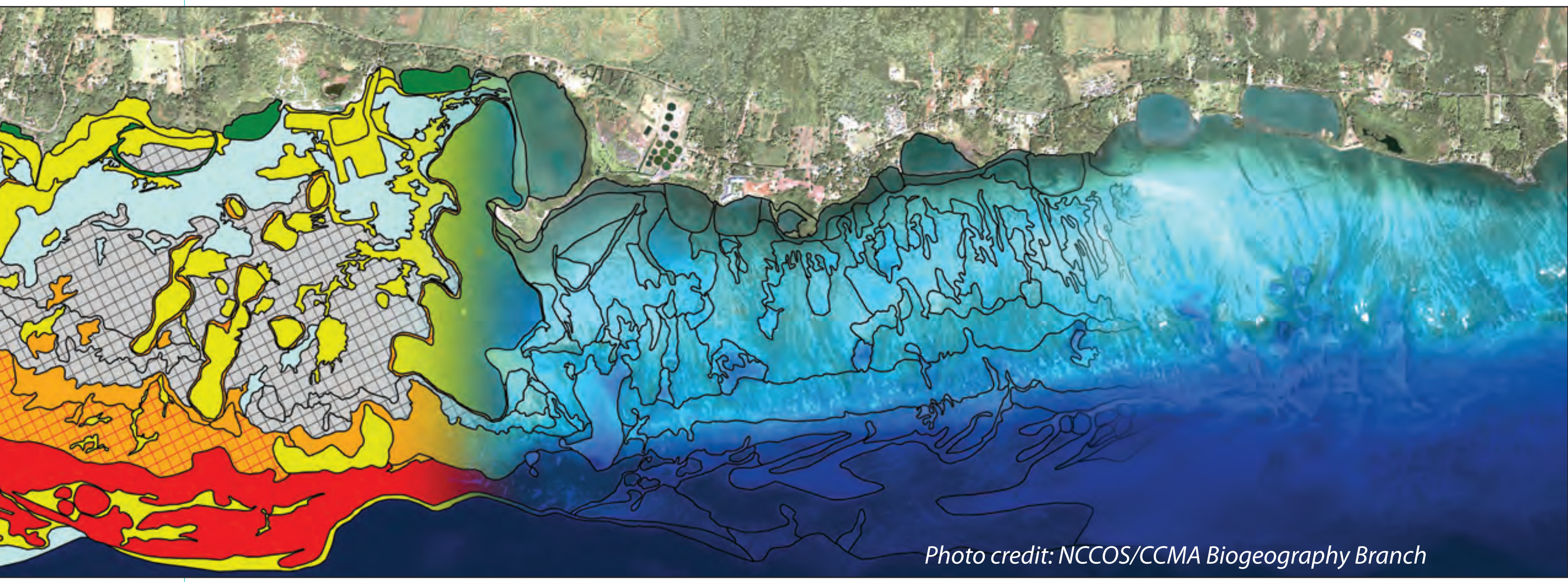


Photo credit: NCCOS/CCMA Biogeography Branch

Mapping Process Overview

To meet the U.S. Coral Reef Task Force goals of mapping U.S. shallow-water coral ecosystems, a variety of data acquisition techniques (i.e., ship-based multibeam, satellite and aerial imagery, etc.) are required in conjunction with data processing and analytical expertise using GIS. Since 2000, National Ocean Service (NOS) has developed and refined tools and protocols for mapping nearshore coral reef ecosystems. The shallow-water benthic habitat maps discussed in this report are derived primarily from satellite imagery and aerial photographs. A general overview of the shallow-water benthic habitat mapping process is illustrated in Figure 4 and described in more detail in the following paragraphs:

1. Imagery Acquisition – The first step in map creation is the acquisition and processing of a comprehensive dataset of remotely sensed imagery. All imagery is geo-positioned to ensure acceptable spatial accuracy in the mapping product.

2. Habitat Boundary Delineation – The first draft of the benthic habitat map is generated by delineating all features that could be identified by visual inspection of the remotely sensed imagery. During the creation of this first draft, discrete points are placed on the map through visual interpretation or computer analysis that are representative of all the color and texture signatures in the imagery. In addition, sites that are difficult to distinguish in the imagery and that warrant further field investigation are identified. These sites are labeled as ground validation positions.

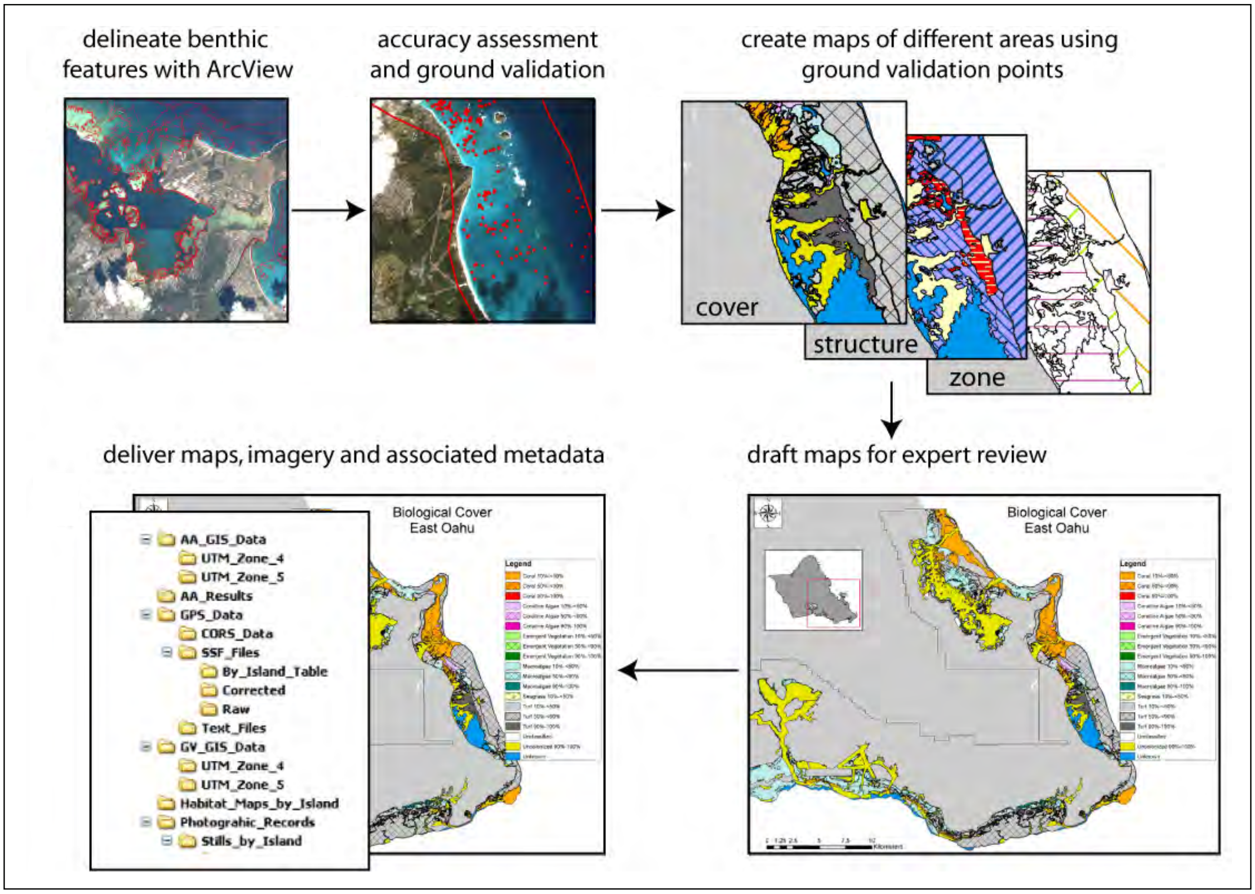


Figure 4. Flowchart illustrating the general benthic habitat mapping process developed by NOS. Source: Battista et al. 2007.

3. Ground Validation – During this stage, the map producer explores the selected locations with a suite of assessment techniques depending on the depth and accessibility of each site. A combination of underwater video, free diving, snorkeling and surface observations are used to survey the ecological characteristics at each location. This information is analyzed and the initial maps are edited to generate a second draft map improved by the field observations.

4. Expert Review—The second draft map is then reviewed by local marine biologists, coral reef scientists and resources managers. Comments are integrated into the map products to generate the reviewed, semi-final draft map.

5. Accuracy Assessment – An independent team of NOS scientists, contractors and/or independent coral reef scientists not associated with map creation conducts field investigations at pre-defined random sites to assess the classification accuracy of the draft map. Sites are generated with a stratified random sampling design for a statistically rigorous assessment of individual classification categories and overall map accuracy.

6. Final Product Creation – Final benthic habitat maps are generated by correcting any inaccuracies revealed by the accuracy assessment. Additionally, all associated datasets—including GIS files, field video and metadata—are packaged and provided to partners and the public.

Imagery Used for Coral Reef Ecosystem Mapping

In 2000, NOS conducted studies to determine what techniques and technologies were most suitable for the mapping of shallow-water coral ecosystems. In all cases, NOS' procedures involved using visual interpretation of source imagery or, more recently, computer analysis of acoustic data to generate benthic habitat maps. Source imagery for mapping came from a suite of technologies, including color aerial photography or high-resolution, commercially available color satellite imagery (e.g., QuickBird II or IKONOS), airborne LiDAR bathymetry and associated backscatter, and ship-based acoustic sonar and associated backscatter imagery. Imagery was initially screened during quality control for low cloud cover, sun glint and turbidity conditions amenable to identification of seafloor features. Additionally, procedures used to ensure the accurate positioning and consistent spatial and spectral characteristics of the source imagery are discussed.

Overview of NOAA Benthic Habitat Classification Scheme for Habitat Attribution

In order to undertake any coral ecosystem mapping activity, a habitat classification scheme is required. A habitat classification scheme is a structured system of arranging habitat types into defined groups or classes based on similarities and differences in ecological characteristics. The initial task in any mapping effort is to clearly identify these classes and describe their attributes. The scheme is used to guide the delineation and definition of habitats throughout the map creation process. The NOS habitat classification scheme defines benthic communities on the basis of five primary coral reef ecosystem attributes:

- Geographic Zone: Zone refers only to each benthic community's location within the system (e.g., reef crest) and does not address substrate or cover types that are found within it.
- Geomorphologic structure: Structure refers only to predominate physical structural composition of the feature and does not address location (e.g., on the shelf or in the lagoon) or the biological community colonizing its surface (e.g., live coral).
- Biological cover: Spatial extent of dominant biota expressed as a percentage of total area measured (e.g. live coral, seagrass).
- Coral Cover: Coverage of living coral on hardbottom expressed as a percentage of total area measured.
- Percent Hardbottom: Proportion of each polygon occupied by hardbottom.

Structure and cover are organized hierarchically to describe features at varying levels of detail such that numerous habitats are encompassed by more broadly defined habitat classes. This hierarchy provides users with the ability to expand and collapse the detail of the structures described in the habitat map to meet individual needs. NOS is currently exploring the ability to export the coral reef ecosystem habitat scheme to the Coastal and Marine Ecological Classification Standards recently adopted by the Federal Geographic Data Committee. Every feature in the benthic habitat map is assigned a designation from each level of the scheme, where imagery and ground validation allow. Because each island group features some unique geomorphological structures and habitat types, the terminology used to describe habitat types is customized from location to location. The recently updated shallow-water benthic habitat map of St. John, U.S. Virgin Islands, completed in 2009, illustrates a wide range of cover and structure types identified according to a recent NOS classification scheme (Figures 5 and 6). The following cover and structure photos and text are taken from Zitello et al. (2009).

The classification scheme is also influenced by the minimum mapping unit requirements and the spatial and spectral characteristics of the source data (e.g., aerial photography). The minimum mapping unit is the smallest polygon or feature delineated in the map. It is based on a number

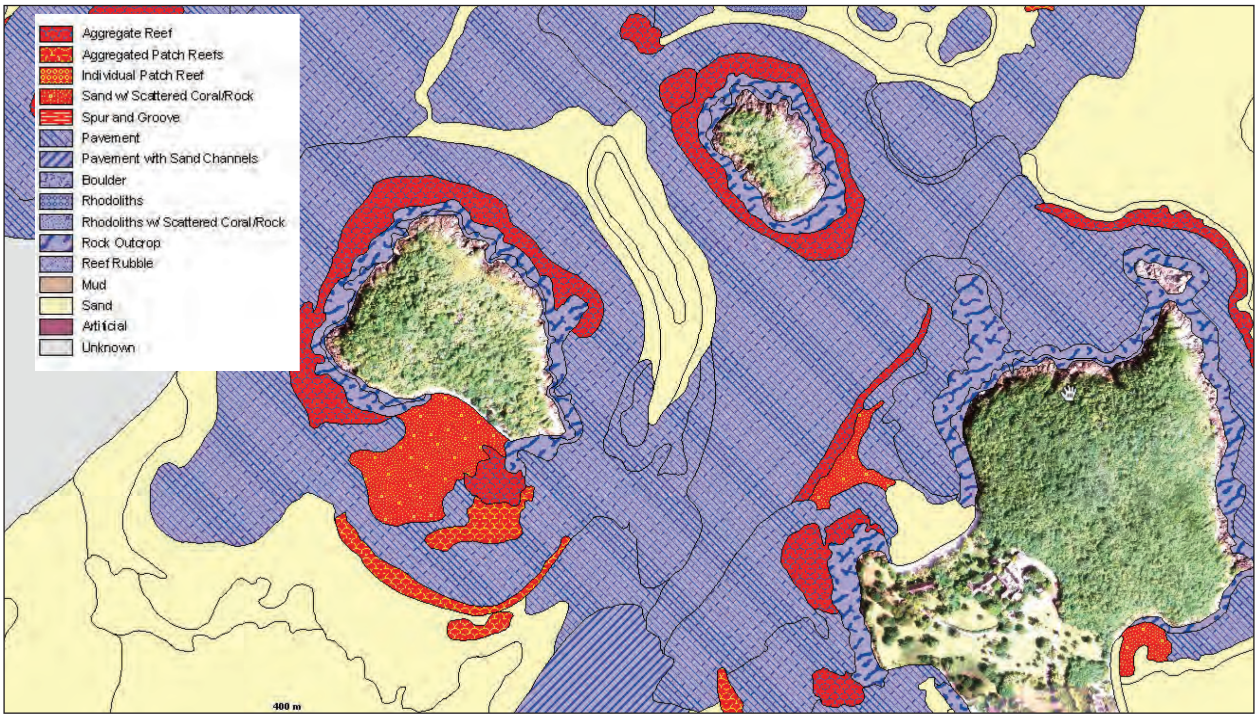


Figure 5. A portion of the shallow-water benthic habitat map from St. John, U.S. Virgin Islands(above) and example biological structure classes (below). Source: Zitello et al 2009.

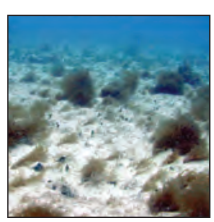
Aggregate Reef: Continuous, high-relief coral formation of variable shapes lacking sand channels.

Aggregate Path Reefs: Clustered patch reefs that individually are too small or too close together to map separately.

Individual Patch Reef: Coral formations that are isolated from other coral reef formations by bare sand, seagrass or other habitats.

Sand with Scattered Coral and Rock: Primarily sand bottom with scattered rocks or small, isolated coral heads that are too small to be delineated individually.

Spur and Groove: Structure having alternating sand and coral formations.

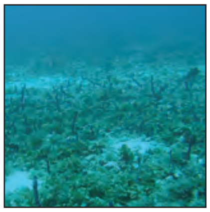


Pavement: Low-relief, carbonate rock with coverage of algae, hard coral, gorgonians, zooanthids or other sessile vertebrates that are dense enough to partially obscure the underlying surface.

Figure 5 (continued from page 10). Example biological structure classes (below). Source: Zitello et al 2009.

Boulder: Aggregations of loose carbonate or volcanic rock fragments that have been detached or transported from their native beds.

Mud: Fine sediment often associated with river discharge and build up of organic material in areas sheltered from high-energy waves and currents.

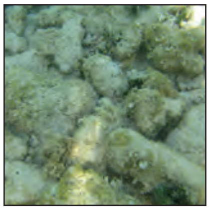


Rhodoliths: Aggregation of cylindrical, disk-like or irregular shaped calcareous nodules averaging roughly 6 cm in diameter.

Sand: Coarse sediment typically found in areas exposed to currents or wave energy.

Rock Outcrop: A primarily continuous exposure of solid carbonate blocks or volcanic rock extending offshore from the island bedrock.

Artificial: Man-made habitats such as submerged wrecks, large piers, submerged portions of jetties and the shoreline of islands created from dredge spoil.



Reef Rubble: Dead, unstable coral rubble often colonized with macroalgae.

Unknown: Major structure indistinguishable due to turbidity, cloud cover, water depth or the interference with an optical signature of the seafloor.

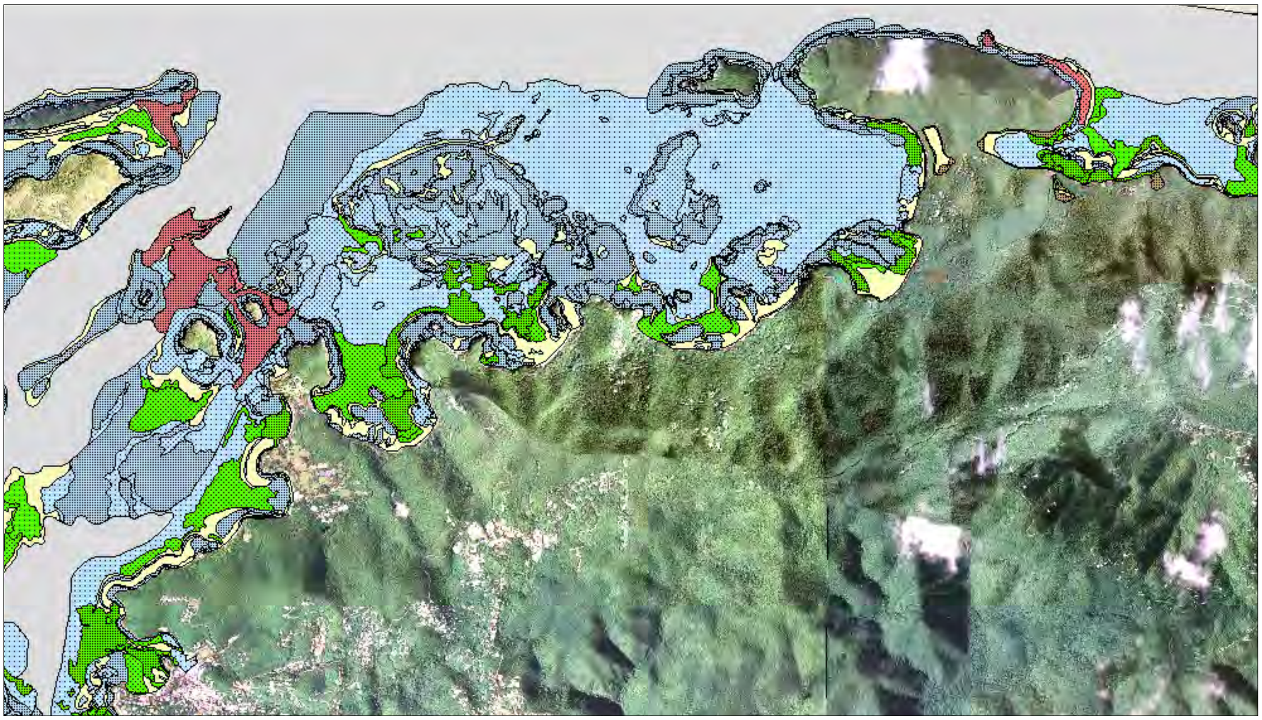
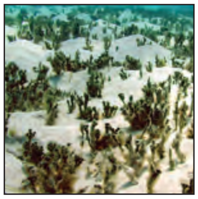


Figure 6. A portion of the shallow-water benthic habitat map from St. John, U.S. Virgin Islands (above) and example biological cover classes (next page). Source: Zitello et al. 2009.

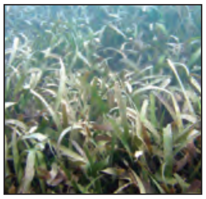
Figure 6 (continued from page 11). Example biological structure classes (below). Source: Zitello et al. 2009.



Algae: Substrates with 10% or greater distribution of any combination of numerous species of red, green or brown algae.

Live Coral: Substrates colonized with 10% or greater live, reef-building corals.

Mangrove: Comprises semi-permanently, seasonally or tidally flooded coastal areas occupied by a species of mangrove.



Seagrass: Habitat dominated by 10% or more of any single species of seagrass or a combination of several seagrass species.

No Cover: Substrates not covered with a minimum of 10% of any of the other biological cover types (i.e., sand , as pictured here).

Unknown: Substrates where biological cover is indistinguishable due to one or more factors including turbidity, cloud cover, water depth or other interference.

of considerations, including: the needs of the coral reef management communities, the ability to accurately interpret features in the imagery and the level of effort needed to complete map production.

Historically, NOS has generated maps with a 4,047 m^2 minimum mapping unit, or 1 acre. However, more recently coral reef ecosystem managers have expressed interest in a smaller minimum mapping unit. As a result, NOS is currently working to meet this management need and has released a technical memorandum that describes a mapping effort based on a non-hierarchical scheme and smaller minimum mapping unit of about 1,000 m^2, or 0.25 acres (Zitello et al. 2009).

Evolution of NOAA Classification Schemes

Since it first began mapping coral reef ecosystem habitats, NOS has developed several habitat classification schemes with extensive input from the academic, management and conservation communities. As needed, each scheme was modified based on local knowledge to incorporate improvements in NOS' understanding of the interrelationship between habitat and the organisms that live on and use those habitats. Because of geological and biological differences in locations, differences in the technologies used to collect mapping-related data, the desire to describe reef ecosystems as layers in a GIS and advances in mapping procedures over time, classification schemes were often customized from region to region. The following paragraphs describe specific changes in the classification schemes by jurisdiction.

Florida (1992 - present)

Starting in 1992, NOS and the Florida Fish and Wildlife Conservation Commission developed a hierarchical classification scheme for the Florida Keys composed of 24 mutually exclusive classes of benthic communities in four major habitat categories: corals, seagrasses, hardbottom and bare substrate. Visual interpretation of aerial photography was used to generate the map. (FMRI 2000). In 2005, NOS initiated an effort to remap the shallow-water benthic habitats of southern Florida. A classification scheme similar to that developed for the Main Hawaiian Islands was initially employed (Kendall et al. 2001). Starting in 2009, a non-hierarchical scheme has been used for the mapping effort (Zitello et al. 2009).

U.S. Virgin Islands and Puerto Rico (2002)

In 2002, NOS completed benthic habitat maps of the U.S. Virgin Islands and Puerto Rico. The classification scheme defines benthic communities based on two attributes: large geomorphological zones and smaller features within zones. Every polygon on the benthic map was assigned a structure within a zone. Zone indicates polygon location and structure indicates composition of each benthic community delineated. Nine mutually exclusive zones were identified from land to open water, corresponding to insular shelf and coral reef geomorphology. Twenty-six distinct and non-overlapping structure types were identified. Structure refers only to each benthic community's substrate and/or cover type and does not address location (e.g., on the shelf or in the lagoon). Structures are defined in a collapsible hierarchy ranging from four broad classes (e.g., submerged vegetation, unconsolidated sediment, coral reef/hard bottom and other), to more detailed categories (e.g., mangrove, seagrass, algae, individual patch reefs, bedrock, etc.), to patchiness of some specific features (e.g., 50-70% cover of seagrass). Visual interpretation of aerial photography was used to generate the maps.

Northwestern Hawaiian Islands (2003)

In 2003, NOS completed benthic habitat maps of the Northwestern Hawaiian Islands using high resolution, IKONOS color satellite imagery. A hierarchical classification scheme was used to define and delineate the shallow-water benthic habitats in the Northwestern Hawaiian Islands. The classification scheme was designed to categorize benthic habitat by substrate category (unconsolidated and hardbottom), structure (e.g., linear reef or pavement) and cover (e.g., coral or macroalgae). Shallow-water coral reef ecosystems also were grouped into larger geomorphological systems, such as atoll and bank, and geographic zones, such as lagoon and back reef. A total of 30 unique classes of benthic habitat were included in the Northwestern Hawaiian Islands classification scheme. High-resolution, color satellite imagery was used for mapping the benthic habitats. Digital processing of the spatial and spectral information from the satellite imagery made it possible to establish a minimum mapping unit of approximately 100 m^2 (1/40 acre). Combining digital image processing and establishing a small minimum mapping unit enabled benthic features to be characterized that would not otherwise have been mapped using alternative methods.

American Samoa, Guam and the Commonwealth of the Northern Marianas Islands (2005)

In 2005, NOS completed shallow-water benthic habitat maps of the islands and atolls of American Samoa, Guam and the Commonwealth of the Northern Marianas Islands. A hierarchical classification scheme was created to define and delineate shallow-water benthic habitats of these locales. The benthic features were classified using a hierarchical, two tiered classification scheme consisting of a geomorphologic reef structure and biological cover. Structure refers only to predominant physical structure (e.g., coral reef and hardbottom, unconsolidated sediment, other delineations and unknown) of the feature. The structure types also include detailed classes (e.g., sand, mud, spur and groove, individual and aggregated patch reef, aggregate reef, scattered coral/rock in unconsolidated sediment, pavement, rock/boulder [volcanic and carbonate], reef rubble, pavement with sand channels, artificial and unknown). Cover type refers only to predominant biological component (e.g., coral, seagrass, macroalgae, coralline algae, turf algae, emergent vegetation, uncolonized and unknown), colonizing the surface of the feature. The cover types also include a density modifier representing the percentage of predominate cover type (10%-<50% sparse, 50%-<90% patchy, 90%-100% continuous). The separation of biological cover and geomorphological structure represents an evolution compared to previous versions of the classification schemes. Additional modifications to the scheme were made during the mapping process to ensure that each category definition reflected the intended habitats and zones encountered in the field as accurately as possible.

Main Hawaiian Islands, Palau (2007) and Palmyra Atoll (2011)

NOS completed benthic habitat maps of the islands of the Main Hawaiian Islands and the Republic of Palau in 2007 and completed a benthic habitat map of Palmyra Atoll in 2011. The classification scheme used for these three locations was similar to that used to map American Samoa, Guam and the Commonwealth of the Northern Marianas Islands. Habitat zone indicates polygon location. Zones were identified from land to open water corresponding to typical insular shelf and coral reef geomorphology. These zones include: shoreline intertidal, vertical wall, lagoon, back reef, reef flat, reef crest, fore reef, bank/shelf, bank/shelf escarpment, channel, dredged, unknown and land.

U.S. Virgin Islands

Photo credit: NCCOS/CCMA/ Biogeography Branch

Introduction

The U.S. Virgin Islands are at the northern edge of the Caribbean Sea east of Puerto Rico. They are the westernmost of the Leeward Islands in the Lesser Antilles. Island size in the Lesser Antilles is small relative to the Greater Antilles and consequently shelf morphology is narrower, watershed size is smaller, river and stream discharge is lower and the scope of land-based threats shift in this region of the Caribbean to reflect smaller geographies.

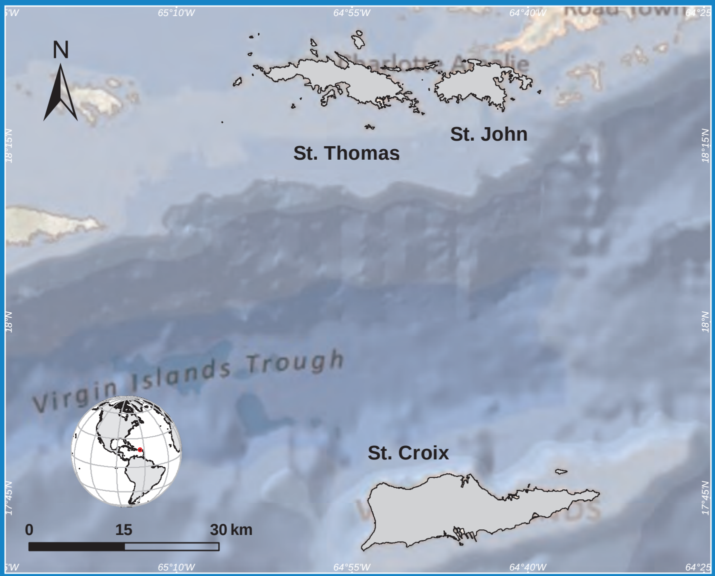


Figure 7. Map of the U. S. Virgin Islands. Credit: Ken Buja and Sarah D. Hile.

This U.S. territory consists of three main islands plus many other small cays and rocks (Figure 7). Two of the islands, St. Thomas and St. John, share the same insular shelf and Cretaceous origins as Puerto Rico (~100 million years ago), whereas the larger third island of St. Croix, is on a geologically separate insular platform ~50 km to the south. The islands seen today were formed by a series of volcanic eruptions, uplifts, fluctuations in sea level and accretion of reef formations created in the context of the easterly trade winds. The coral reef ecosystem built upon these geologic foundations is a mosaic of habitats, including fringing reefs, patch reefs, carbonate pavements, mangrove forests, bank barrier reefs, seagrass meadows and other coral communities.

Mapped Geology and Benthic Habitat

Over 485 km^2 of benthic features were mapped in the U.S. Virgin Islands in 2000-2001 using aerial photography (Kendall et al. 2001; Table 1). The major structure type with the largest area overall was coral reef and colonized hardbottom, which comprised ~61% of the mapped area (Figures 8 and 9). While submerged aquatic vegetation accounted for over 33 % of the area mapped, this includes patchy seagrass and macroalgae, which may include considerable areas of bare sand. Dominant detailed structure types included colonized pavement with sand channels (~25% of area mapped), colonized pavement (21%), seagrass (17%) and macroalgae (16%; Figure 10). Other important detailed structure types include linear reefs (4.9%) and mangrove forests (< 1%). Linear reefs are often considered the highest quality reefs with greatest rugosity and fish diversity. Mangroves are often considered important habitat for juvenile fish and play an important role in buffering coastal systems from storms and filtering runoff. Benthic cover was not mapped separately in the U.S. Virgin Islands as was done for some other jurisdictions.

Typical zonation and width of mapped habitats varied by island and coastal region. The northwest coast of St. Croix between Christiansted

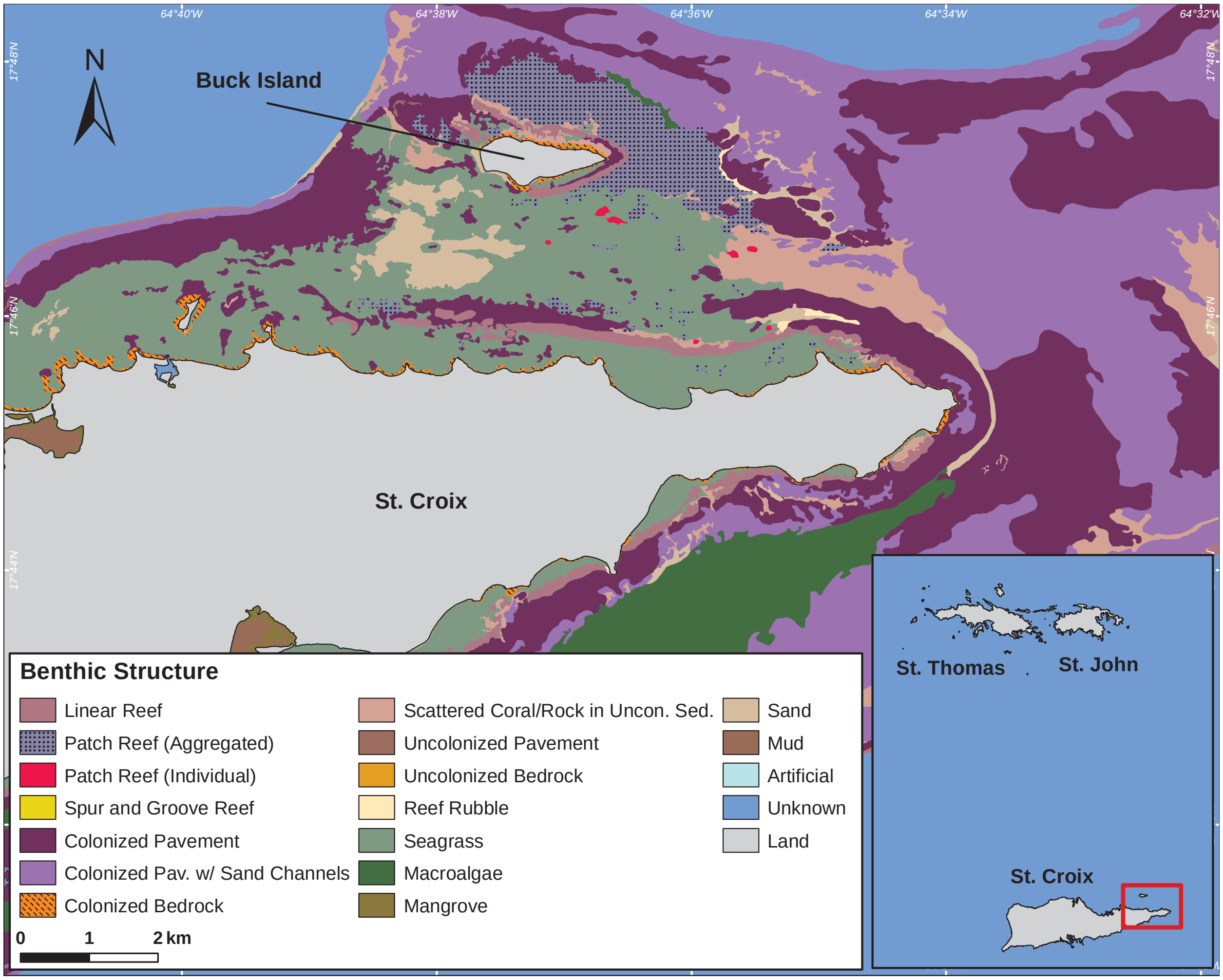


Figure 8. A portion of the habitat map showing shallow-water benthic structure near Buck Island, St. Croix, U.S. Virgin Islands. For the complete benthic habitat map of the U.S. Virgin Islands, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Figure 9. U.S. Virgin Islands general structure.

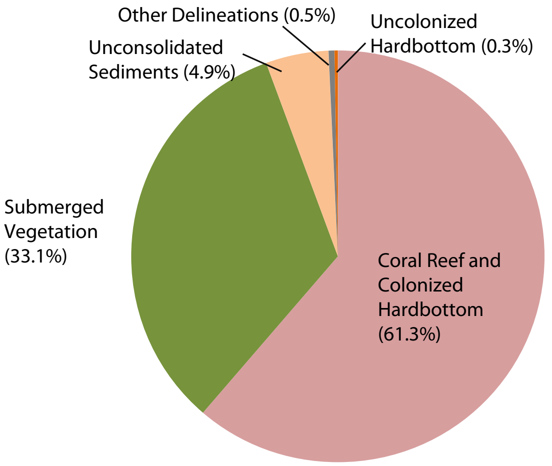
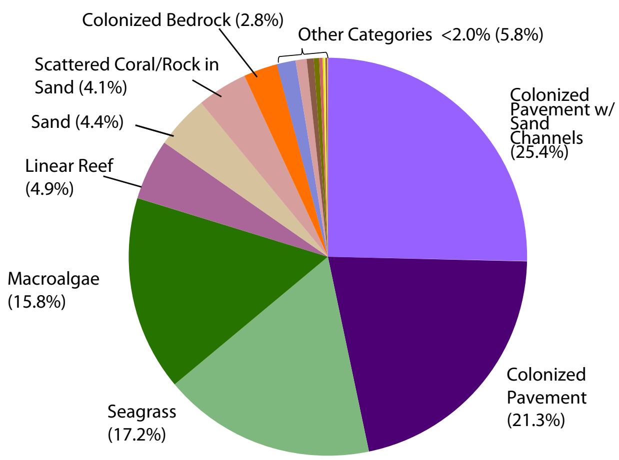


Figure 10. U.S. Virgin Islands detailed structure.



and Fredricksted is marked by a very steep and narrow shelf that plummets into deep waters only a few hundred meters from shore. Colonized bedrock dominates the shoreline/intertidal zone of the exposed region forming a narrow band 10-50 m wide. Adjacent to this is a 100-300 m wide band of colonized pavement and pavement with sand channels that makes up the small flattened part of the shelf. Very narrow linear reefs are found in the escarpment zone along portions of the northwest coast. Fringing reefs a few hundred meters to a kilometer offshore are present along much of the eastern half of St. Croix (Figure 11). These often emergent formations are typically ~100-300 m wide and enclose several seagrass dominated bays. Nearly the entire insular shelf of St. Croix was mapped, including several banks extending well offshore from the eastern and southern coasts. The largest of these is Lang Bank which extends 15 km from the eastern tip of the island. These banks are generally flat and dominated by pavement and pavement with sand channels.

In contrast to St. Croix, the coasts of St. Thomas and St. John are marked by many well protected bays between steep headlands but do not have

Figure 11. An aerial image of a fringing reef at Teague Bay in the northeast of St. Croix. Credit: Simon Pittman, NCCOS/CCMA/Biogeography Branch.

the extensive emergent fringing reef system seen on eastern St. Croix. Instead, zonation all around St. Thomas and St. John often includes a narrow band (~10-50 m wide) of bedrock adjacent to shore, especially around the many rocky headlands. In exposed areas, the bedrock is often adjacent to colonized pavement of highly variable width, followed by linear reefs sloping into deeper water. At the base of the linear reefs, the shelf gradually slopes away into deeper waters beyond the detection range of the aerial photography through habitats such as sand, scattered coral and rock in sand, seagrass and macroalgae.

Notable regions with extensive coverage of key structures include the seagrass meadows in Christiansted Harbor, Buck Island Channel and all along the southern shore of St. Croix. Seagrass covers less extensive areas of St. Thomas and St. John, and large meadows are more restricted to protected bays and along southern shores. Large mangrove forests were mapped on southeast St. Thomas, in the Reef Bay and Coral Bay regions of St. John, and the Salt River Bay, Altona Lagoon and refinery regions of St. Croix. Linear reefs form a narrow and intermittent fringe around most islands but concentrated areas include eastern St. John in and around Coral Bay, as well as the eastern half of St. Croix.

It is important to note that the summary statistics and general descriptions reported above do not include the very large area of insular shelf around St. Thomas and St. John that could not be mapped in this assessment using the aerial photo based mapping techniques. Due primarily to water depth, reef ecosystem features were not visible over the majority of these two island's shelves. This included large offshore banks and shelf edge reefs, many of which harbor extensive reef communities at the edge of the mesophotic zone.

Applications for Science and Management

Coral reef ecosystems are deteriorating around the world at an alarming rate (Wilkinson 2004) and those within the U.S. Virgin Islands are no exception (Rogers and Beets 2001; Beets and Rogers 2002). To help halt this degradation, federal and territorial government agencies have been working to establish marine protected areas and their more restrictive form, marine reserves (i.e., no-take), to shelter portions of the ecosystem from selected anthropogenic impacts. A recently designated marine protected area is the Virgin Islands Coral Reef National Monument established in 2001. These submerged lands consist of about 51 km^2 of marine habitat off the island of St. John, roughly doubling the area in and around St. John now under the jurisdiction of the National Park Service. Nearly all extractive uses and anchoring are prohibited within the monument.

While desired, ecological and biological criteria are not always feasible to consider when establishing protected areas; as was the case in developing the Virgin Islands Coral Reef National Monument. To assess the long-term effectiveness of the monument, it was necessary to map and characterize the habitats and associated fauna within and outside the monument's boundaries to provide a baseline for future comparative purposes and support adaptive management actions. The National Park Service, National Ocean Service (NOS) and the U.S. Geological Survey initiated a joint project in 2002 to develop a baseline characterization of species and their associated habitats within and outside the monument to assess changes within the ecosystem. The NOS U.S. Virgin Islands digital habitat maps were used to stratify biological sample collection by habitat and management unit to enable comparisons of fish assemblages and habitats within and outside the monument, with the intended objective of providing better scientific guidance for the management of the monument and Virgin Islands National Park (Monaco et al. 2007, 2009; Pittman et al. 2008).

Results showed areas outside the monument had significantly higher live coral cover, greater habitat complexity, supported more species, and had higher abundance and biomass of reef fishes than protected within the monument (Monaco et al. 2007). While reef sites outside of the monument cannot be considered for inclusion, an ecological correction can be made by exchanging the eastern, less biologically rich portion of the monument for the wedge of territorial sea that currently bisects the monument on the south side of St. John (Figure 12a and b). Currently, discussions are underway between the National Park Service and the U.S. Virgin Island government. As the wedge is already within the authorized boundaries of the monument, this should facilitate the boundary adjustment. Inclusion of the mid-shelf reef currently located within the wedge will increase the amount of protected coral reef and fish habitat and provide greater opportunity for resources in this marine protected area to recover from past harvest of resources and other stressors.

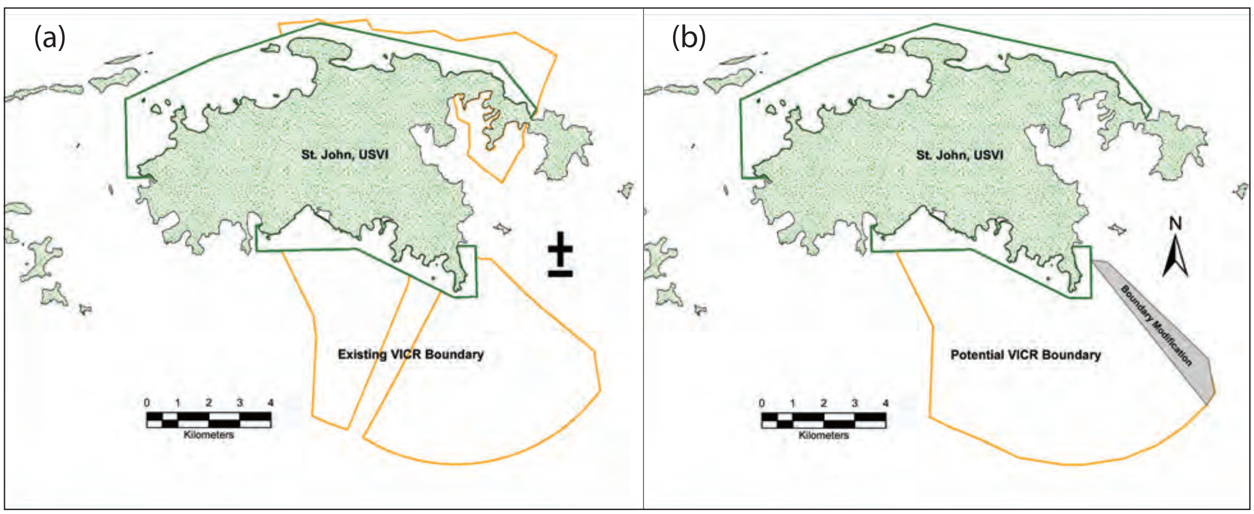


Figure 12a and b. Existing Virgin Islands Coral Reef National Monument (a) and potential modification of the monument boundary along the south shore of St. John, U.S. Virgin Islands (b). Source: Boulon et al. 2008.

Puerto Rico

Photo credit: NCCOS/CCMA Biogeography Branch

Introduction

The Commonwealth of Puerto Rico lies at the northern margin of the Caribbean Sea west of Hispañola. Puerto Rico is the easternmost of the Greater Antilles, the large islands along the northeast margin of the Caribbean tectonic plate. Island size in the Greater Antilles is large compared to the Lesser Antilles to the east and consequently shelf morphology is often wider, watershed size is larger, estuaries are more developed, river and stream discharge is greater and the scope of land-based threats shift in this region of the Caribbean to reflect smaller geographies.

The commonwealth is comprised of a number of islands, including the large main island of Puerto Rico and the smaller offshore islands, including Culebra and Vieques to the east, and Mona, Monito and Desecheo to the west, plus many other small islets and cays (Figure 13). These islands all lie on the very northern edge of the Caribbean tectonic plate. The insular shelf of Puerto Rico is very narrow on the north side of the island and faces the Puerto Rico Trench, the deepest part of the Atlantic Ocean. Elsewhere around the islands the shelf is more broad and flat. The coral reef ecosystem built upon this geologic foundation in Puerto Rico is a complex mosaic of interrelated habitats, including mangrove forests, seagrass beds and coral reefs, as well as other unique coastal ecosystems including three rare bioluminescent bays.

Figure 13. Map of Puerto Rico. Credit: Ken Buja and Sarah D. Hile.

Mapped Geology and Benthic Habitat

Approximately 1600 km² of benthic features were mapped from 2000-2001 using aerial photography (Kendall et al. 2001; Table 1). The major structure types with the largest area were coral reef/hardbottom and submerged aquatic vegetation, which together comprised ~90% of the mapped area (Figures 14 and 15). While submerged aquatic vegetation accounted for over 45% of the area mapped, this includes patchy seagrass and algae which may include considerable areas of bare sand. Dominant detailed structure types include seagrass (39%) and colonized pavement with sand channels (~20%; Figure 16). Other important detailed structure types include linear reefs (4.7%) and aggregated patch reefs (~15%), which are often considered the highest quality reefs with greatest rugosity and fish diversity. Mangrove forests covered <5% of the area mapped. Benthic cover was not mapped separately in Puerto Rico as was done for some other jurisdictions.

Typical zonation of mapped habitats varied by coastal region. The northern and northwestern regions are characterized by a very narrow shelf and heavy wave action. Sand beaches are in many areas followed by a ~50-150 m wide band of colonized bedrock. Farther offshore are typically regions of pavement with sand channels in

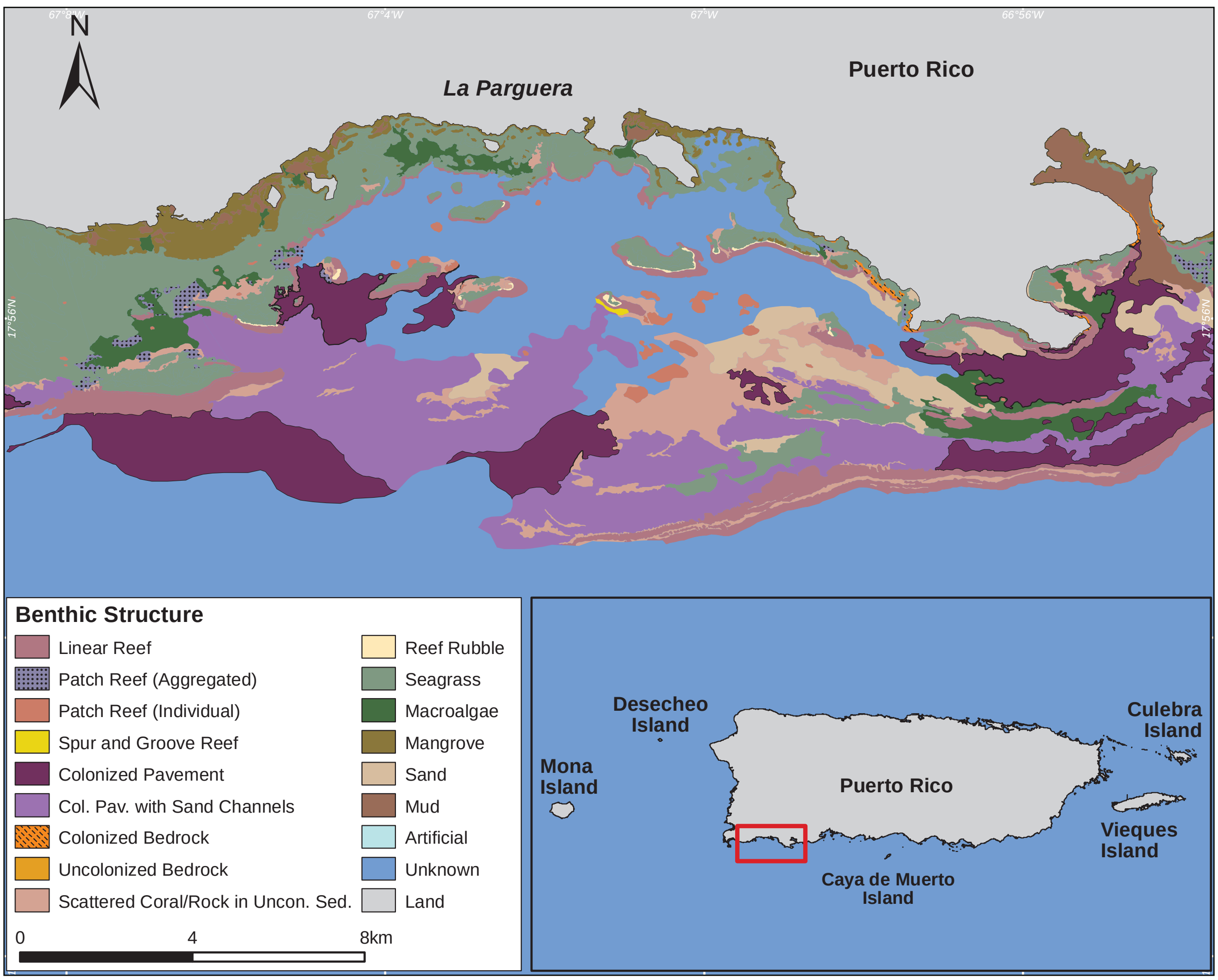


Figure 14. A portion of the benthic habitat map showing shallow-water benthic structure in southwest Puerto Rico. For the complete benthic habitat map of Puerto Rico, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Figure 15. Puerto Rico general structure.

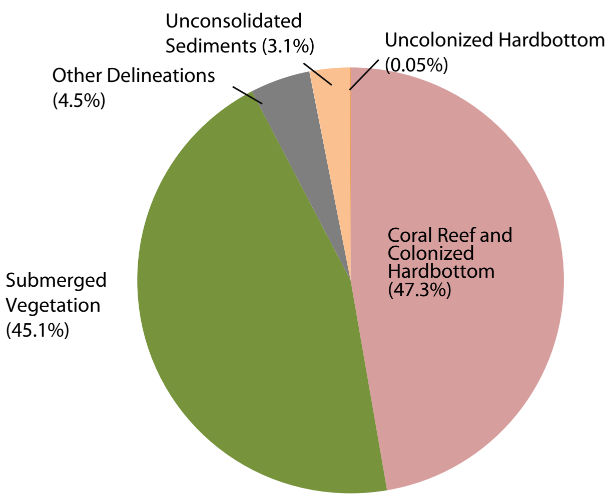
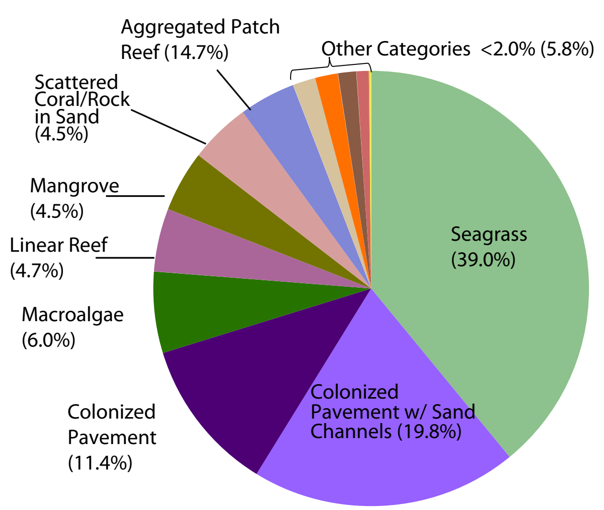


Figure 16. Puerto Rico detailed structure.



a ~100-300 m wide band followed by increasingly large areas of linear reefs progressing eastward that are typically ~100-500 m wide. The eastern shore of Puerto Rico and the shelf area around Culebra and Vieques are much wider and allow for extensive soft bottom areas, patch reefs and many protected bays and shorelines relative to the north shore. Southern and southwestern Puerto Rico is marked by several bank formations where the shelf extends ~5 to 15 km offshore. This region lacks extensive sand beaches and the colonized bedrock zone that typifies much of the north coast and shoreline around Vieques. Many mangrove lined bays with extensive seagrass and patch reef formations are partially enclosed by linear reefs along these coasts followed by broad areas of pavement and pavement with sand channels extending offshore.

Notable regions with extensive coverage of key structures include the seagrass meadows between Vieques and the east end of Puerto Rico (240 km^2) and the southwestern corner of Puerto Rico around Cabo Rojo (80 km^2). A large, continuous mangrove forest (Figure 17) was mapped east of San Juan (15.5 km^2). Areas with discontinuous mangrove forests that covered large areas included the eastern tip of Puerto Rico around Roosevelt Roads Naval Base (9.1 km^2) and the La Parguera area (4.1 km^2). The largest reef areas mapped were located primarily along the southern and southwestern edge of the island where the shelf is broad and flat and amenable to aerial photo-based mapping. The largest areas of mapped linear reef were located around the southeastern facing coasts of Vieques, along the northeast shore of Puerto Rico, and along multi-tiered formations fronting the many bays along the south coast such as near La Parguera, Guanica, Ponce and Jobos.

It is important to note that the summary statistics reported above do not include the very large area of insular shelf that could not be mapped in this assessment using the aerial photography-based approach. Due to discharge of turbid rivers, suspended sediment from wave action, water depth, clouds and other factors that prevent benthic features from being visible, 75% of the Puerto Rican insular shelf (area between the shoreline and the 30 m isobath or shelf edge) could not be mapped using the available aerial photography. Much of the north coast of Puerto Rico could not be mapped due to turbidity associated with

Figure 17. Example of mangrove cover, which is prevalent in parts of Puerto Rico. Photo Credit: NCCOS/CCMA/ Biogeography Branch.

the many rivers and heavy surf conditions that characterize this region. The central portion of the west coast had shelf features obscured by sediment-laden river discharge from Rio Guanajibo and Rio Grande de Anasco. The very small island of Monito was not photographed. A large area between the islands of Vieques and Culebra extending eastward along the shelf platform to the territorial boundary of the U.S. Virgin Islands was not mapped because bottom depth was beyond the limit of detection by aerial photography (~ 20 m). A widening variety of remote sensing technologies, including satellites, airborne hyperspectral scanners, LiDAR and shipboard multibeam sonar are rapidly improving and providing ever more detailed, accurate, and cost-effective alternatives for benthic mapping across a range of depths and water conditions. A combination of these aerial, satellite, and in-water technologies will be required to comprehensively and cost-effectively map portions of the Puerto Rican shelf mapped as "unknown" in this assessment.

Applications for Science and Management

Since completion of the benthic maps in 2001, they have been used to address a range of scientific, educational and management purposes. Hundreds of map downloads and CDs have been disseminated to individuals representing federal, commonwealth, academic, conservation, business and private interests. A small cross section of applications from the last 10 years is discussed.

A primary original purpose driving creation of benthic maps in Puerto Rico was to support identification and management of essential fish habitat for the Caribbean Fisheries Management Council. A direct link to the maps is provided on the council's web site. In a more specific example of fisheries management, these maps have been used during a fishery management council process called Southeast Data, Assessment and Review. Maps were the basis for extrapolating island-wide estimates of population size for assessing stocks of key fisheries species including Mutton Snapper (*Lutjanus analis*), queen conch

Figure 18. NOAA NOS shallow-water benthic habitat maps for Puerto Rico have been used by local management agencies to estimate queen conch population size and for queen conch stock assessments. Photo Credit: NCCOS/ CCMA/Biogeography Branch.

(*Strombus gigas; Figure 18*) and Yellowfin Grouper (*Mycteroperca venenosa*) based on habitat-derived densities (e.g., SEDAR 2007).

In other applications, benthic maps have played a role in marine protected area design and analyses of marine zoning in Puerto Rico. For example, modifications to the marine zoning around Vieques have been under consideration since the closure of the U.S. Navy base on that island. Management zones at the time of base closure were overlayed onto the benthic maps to quantify reef habitats protected in the various restricted areas (Kendall and Eschelbach 2006). Benthic maps were also the primary input into a recent theoretical investigation on optimizing marine protected area network design around Puerto Rico to incorporate aspects of ecological function (Appeldoorn and Pagan 2009). Most recently, the Grand Reserve, a newly implemented marine protected area in northeast Puerto Rico in 2011 relied, in part, on the benthic maps to identify an appropriate size and boundary configuration.

Habitat maps have also played a central role in devising assessment and monitoring strategies for coral reef ecosystems in Puerto Rico. Recent sampling designs for reef monitoring studies in southwest Puerto Rico, Vieques and Jobos Bay have relied on the benthic maps as a spatial framework to effectively stratify survey effort (e.g., Zitello et al. 2009, Pait et al. 2009, Bauer and Kendall (eds.) 2010, Pittman et al. 2010). Results of these monitoring studies on coral communities, fish distributions, contaminants and nutrients have been stratified by bottom types as depicted in the benthic maps. Maps have also been a primary information input for scientific investigations on a range of topics, such as landscape ecology (Pittman et al. 2007b), predictive mapping of fish diversity (Figure 19; Pittman et al. 2007a), spatial distribution of manatees, habitat inventory (Kendall et al. 2004) and remote sensing (Prada et al. 2008).

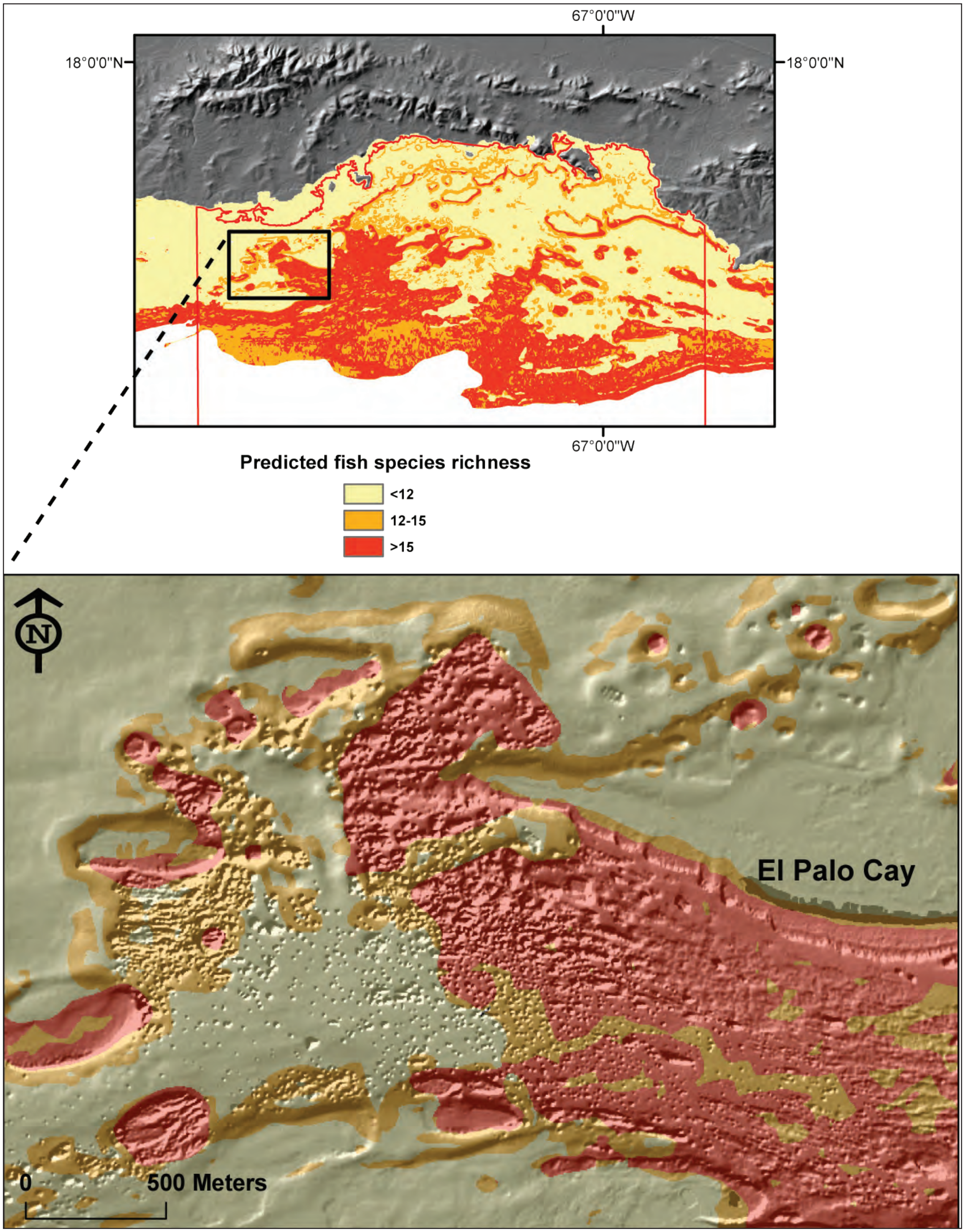


Figure 19. Predictive map of fish species richness for southwest Puerto Rico. Models used both seafloor surface complexity and the NOS benthic habitat map to accurately predict patterns of fish biodiversity. Red "hotspot" areas support highest numbers of fish species. Source: Adapted from Pittman et al. 2007a.

South Florida and the Florida Keys

Photo credit: Jiangang Luo, UM/RSMAS

Introduction

The Florida Keys form a crescent-shaped chain of limestone islands that extend from near Miami to Key West, a distance of about 240 km (Figure 20). The South Florida and the Florida Keys are situated within the subtropical region of the Western Hemisphere. The channels between the islands of the Florida Keys generate high current velocities that have sculpted sediments and underlying limestone to create a unique island and shallow-water community structure that is important for the role it plays in reproduction, feeding and growth to maturity for a vast number of marine, bird and land animals. The Florida Keys are made of Pleistocene-age Key Largo Limestone and Miami Limestone, while the northern Keys (from Dade County north to Martin County) are generally sediments on top of limestone. Key Largo limestone forms the upper Keys, while Oolite Limestone forms the Lower Keys. Approximately 18,000 years ago, as glaciation took water from the ocean, sea level dropped and the ancient coral forests of the Florida Keys died and collapsed into the islands currently found in the region. The principal reef building corals were the elkhorn (*Acropora palmata*), staghorn (*A. cervicornis*), brain and star corals. Many other calcium carbonate-forming organisms and plants, such as sea fans, mollusks and the green algae *Halimeda* that, over thousands of years, formed layer after layer of structure. Numerous federal parks and refuges (and a number of state managed areas) are located in southeastern Florida and the Florida Keys. Their combined conservation and management has done much to ensure the survival of numerous protected species in southern Florida, an area within 100 km of five million people.

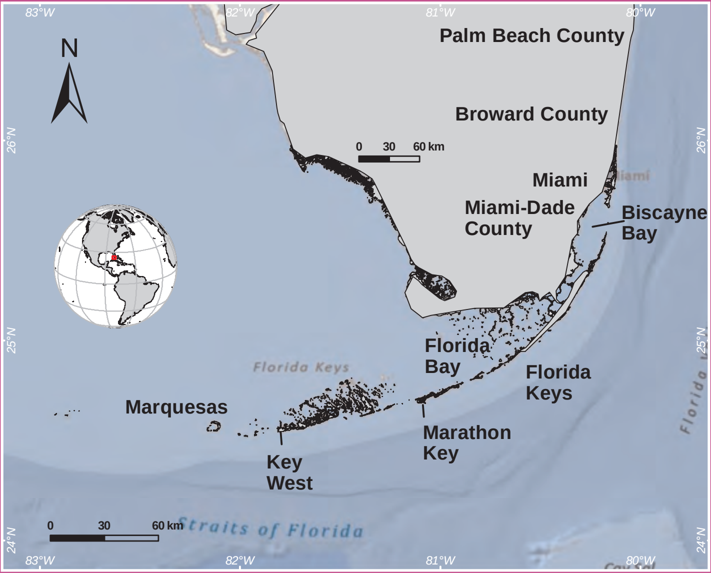


Figure 20. Map South Florida and the Florida Keys. Credit: Ken Buja and Sarah D. Hile.

Mapped Geology and Benthic Habitat

In 1998, National Ocean Service (NOS) and partners characterized coral reef ecosystem habitats in water 0–20 m deep across the Florida Reef Tract from Biscayne National Park southwest through the Marquesas and the Dry Tortugas covering 5,918 km^2 (FMRI 2000, Table 1). Water quality conditions (mostly persistent turbidity) limited visual interpretation of the aerial photography and resulted in 15% of the area, including an extensive area west of Key West within the Marquesas, not being mapped. When that portion of NOS' 1,670 km^2 habitat map (completed in 1998) has the "unknown" area subtracted, 1,440 km^2 was classified into actual habitats. Of that 1,440 km^2, over 77% (1,110 km^2) was classified unconsolidated sediment (sand and/or mud) and 328 km^2 was classified coral reef and colonized hardbottom (Figures 21 and 22).

The mud and sand areas were where seagrass and algal habitats were found. The coral reef and colonized hardbottom area was where pavement (17.5%), aggregate reef (1.5%), spur and groove (1.3%), individual patch reefs (0.7%), aggregated patch reefs (0.6%) and other structural components of the ecosystem were found (Figures 21 and 23).

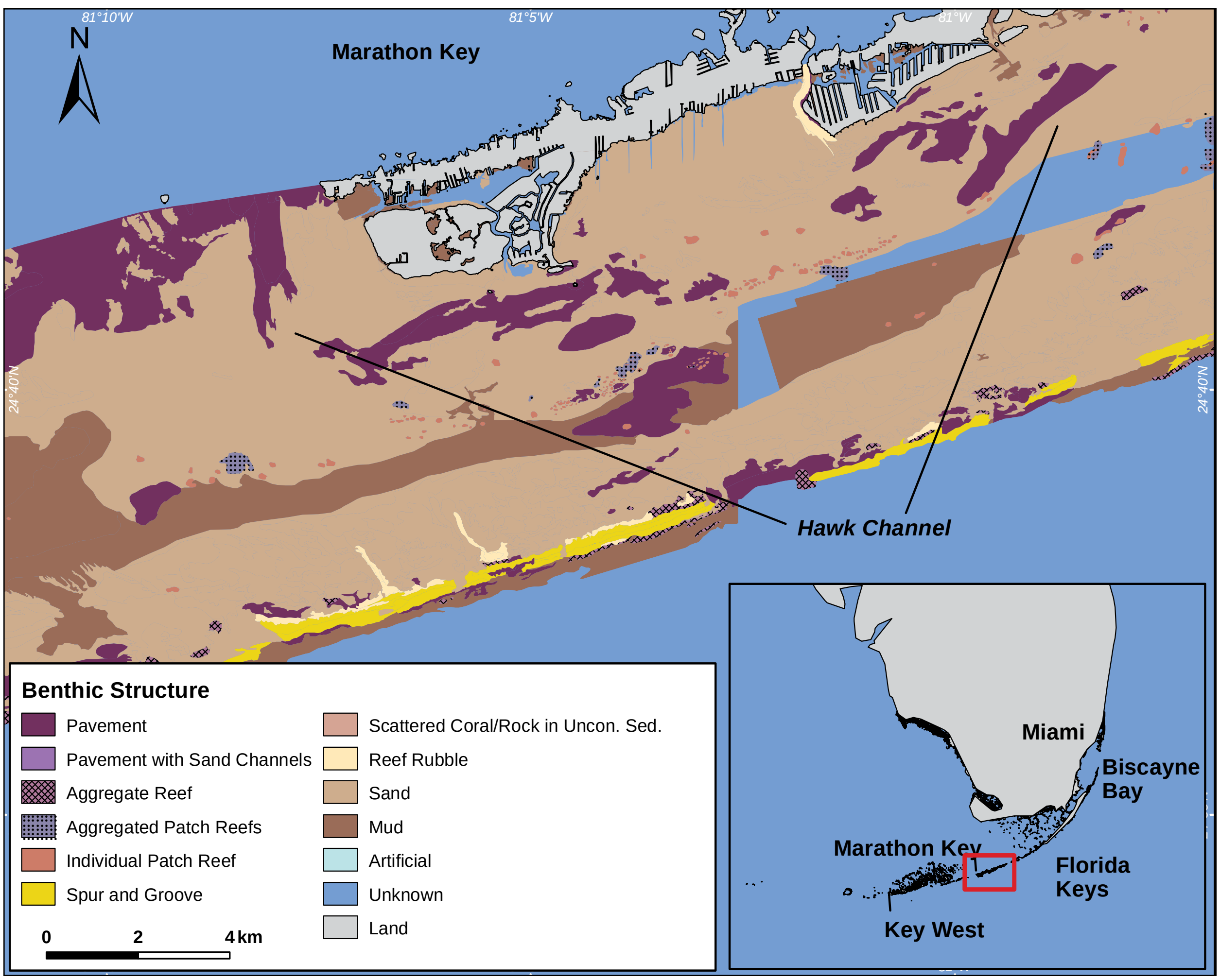


Figure 21. Portion of the benthic habitat map showing shallow-water benthic structure for an area in the Florida Keys. For more information about ongoing Florida benthic habitat mapping efforts, see online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

As discussed above, about 77% of the area mapped was sand and mud where seagrass and algal communities occur (Figure 21 and 22).

Seagrass and algal habitats have been shown to provide critical food, shelter and nursery habitat for numerous fish and crustacean species. Within Hawk Channel, as many as 2,500 or more individual patch reefs, ranging in size from ~0.07 ha (700 m^2) to larger than 0.5 ha (5,000 m^2), have been identified (Rene Baumstark, FWC pers comm.). These patch reefs are colonized by a variety of hard corals, soft coral and gorgonians.

Figure 22. Florida Keys general structure.

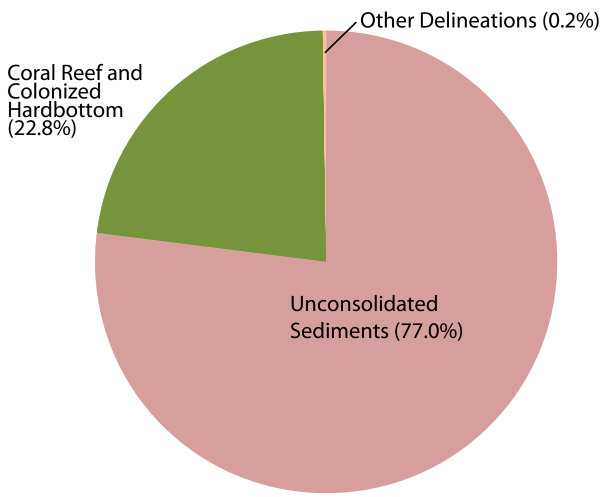
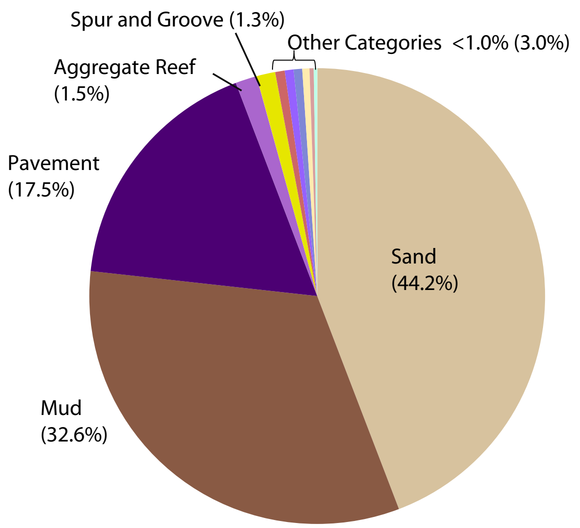


Figure 23. Florida Keys detailed structure.



Ongoing Mapping Efforts

The National Coral Reef Institute has mapped 965 km^2 of seafloor habitats in Martin, Palm Beach, and Broward Counties and is finalizing the Dade County map at this time. When completed, the National Coral Reef Institute will have mapped approximately 1,000 km^2. The Florida Fish and Wildlife Conservation Commission has mapped 5,475 km^2 of southeastern Florida, Biscayne Bay, Florida Bay, Florida Keys and Marquesas seafloor habitats. NOAA has mapped about 3,900 km^2 of Hawk Channel and Florida Bay seafloor habitats. Over the next several years, NOAA's Office of the Coast Survey plans to collect airborne bathymetric LiDAR and ship-based acoustic sonar data to support habitat mapping of the Marquesas area of the Florida Keys. The National Coral Reef Institute, Florida Fish and Wildlife Conservation Commission and NOS have used various classification schemes to map the South Florida region. Over the next several years, the maps will be standardized to produce a single, unified habitat map.

Applications for Science and Management

A recent analysis to estimate the potential extent of shallow-water coral ecosystems in U.S. waters reveals that nearly 80% are found in South Florida and the Florida Keys (Rohmann et al. 2005). Each year, roughly three million people come to the Florida Keys to snorkel, dive, fish and enjoy the warm tropical weather. Between 2001 and 2005, an estimated 6.4 million recreational fishers averaged 27.2 million marine fishing trips annually in Florida, including the Florida Keys. Johns et al. (2004) report 3.64 million person days were spent fishing on natural reefs annually in the Florida Keys. An estimated 173.3 million fish were caught and about 50% were released (NMFS, 2007; http://www.st.nmfs.noaa.gov/st1/index.html).

Figure 24. Managers rely on the NOS benthic habitat maps from South Florida and the Florida Keys regions to monitor and assess fish populations and habitats. Credit: Jiangang Luo, UM/RSMAS.

In order to support fish, spiny lobster, and other marine and terrestrial animal populations, the coral reef ecosystems of South Florida and the Florida Keys need to be in good condition and unaffected by point and nonpoint sources of pollution, climate change, overfishing, and physical damage from ships, boats and humans. Timely, comprehensive and accurate coral reef ecosystem maps provide critical information needed for new and ongoing conservation and management activities that contribute to improving the condition of these ecosystems.

Coral reef ecosystem managers express concern about overfishing of both targeted and nontargeted fish species because their removal—especially top predator species—can cause disruptions in ecosystem function (Frank et al. 2005). NOS habitat maps clearly show the location and extent of critical habitats needed by fish and other organisms to reproduce and feed (Figure 24). They are also an instrumental tool researchers have used in long-term efforts to assess the effectiveness of no-take areas where fishing is prohibited. Studies using the maps have shown these no-take areas contain more and bigger fish, ensure fish are able to reproduce, and cause spillover of more and bigger fish into areas outside the no-take areas. Starting in 2012, maps created by NOS and partners will provide critical information needed to conduct a comprehensive biogeographic assessment—the study of the distribution of organisms and ecosystems in a geographic area over time—and undertake a public participation process to possibly expand existing or identify new no-take conservation areas in the Florida Keys.

The general decline, since the mid-1990s, in the number of stony coral species found in the Florida Keys and, in particular, the decline in abundance of the reef building *Acropora* corals, is another important management concern. The benthic habitat maps are being used to support random stratified monitoring activities throughout the Florida Keys to assess the health and distribution of *Acropora* and other stony coral colonies. The mapping of patch reef location and size may assist in understanding the role of patch reefs as refugia for stony coral species. In addition, the presence of the invasive lionfish (*Pterois volitans*) in the Florida Keys exacerbates manager concerns. Lionfish have no known predators in the Florida Keys coral reef ecosystem and are known to prefer small reef fish and juveniles of important commercial and recreational species as their food. Habitat maps are being used to support research on the impacts of invasive lionfish and develop possible response activities.

Main Hawaiian Islands

Introduction

The Main Hawaiian Islands are located in the middle of the North Pacific Subtropical Gyre, centered at about 28°N. They consist of eight high volcanic islands that range in age from active lava flows on the east side of the Big Island (Hawaii Island) to Kauai, which is 7 million years old (Figure 25). The Main Hawaiian Islands comprise the southern part of the Hawaiian Archipelago consisting of eight populated, high volcanic islands approximately 630 km across. They are Earth's most isolated islands, being some 2,400 miles from both of their nearest continental land mass, North America, and the islands of Polynesia in the South Pacific.

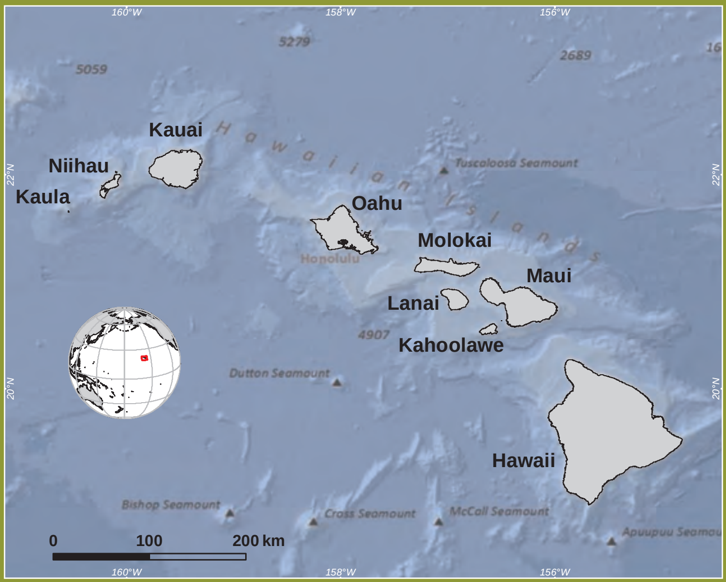


Figure 25. Map of the Main Hawaiian Islands. Credit: Ken Buja and Sarah D. Hile.

The Main Hawaiian Islands are part of a 3,200 mile long volcanic mountain chain that has been produced over the past 70-75 million years from a stationary magmatic "hot spot" that injected molten lava through the thin rigid crust of the Pacific tectonic plate as it has moved north and northwestward at rates of three to four inches a year. As the lava piled up on the surface of the oceanic crust, the largest mountains on Earth were produced. Subsequently, they then began successively to subside, fall apart, undergo erosion and eventually become surrounded and covered by coral/algal reefs as their tops changed from high islands to low islands and atolls, and ultimately to submerged seamounts. All of that happened as they moved away from the Hawaiian Hot Spot over a period of time ranging from 20 to 30 million years. The main eight high islands of Hawaii that lie at the southeastern end of the archipelago represent only some five million years of that cycle.

The geographic isolation of Hawaii has resulted in some of the highest levels of endemism in any tropical marine ecosystem on earth (Kay and Palumbi 1987, Jokiel 1987, Randall 1998). Some of these endemics are dominant components of the coral reef community, resulting in a unique ecosystem that has extremely high conservation value (DeMartini and Friedlander 2004, Maragos et al. 2004). With species loss in the sea accelerating, the irreplaceability of these species makes Hawaii an important biodiversity hotspot.

Mapped Geology and Benthic Habitat

The entire sea bottom of the Main Hawaiian Islands that extends from shoreline to 30 meters depth was mapped in 2003, with further improvements to the classification scheme in 2007. For the area of the Main Hawaiian Islands that was characterized by the NOAA benthic habitat maps (Battista et al. 2007; Table 1), approximately 30% and 70% of the geomorphic structure was classified as unconsolidated sediment (sand and/or mud) and coral reef and hardbottom, respectively (Figures 26 and 27). Of the unconsolidated sediment, the cover class was characterized by 25% sand, followed by 5% mud classes.

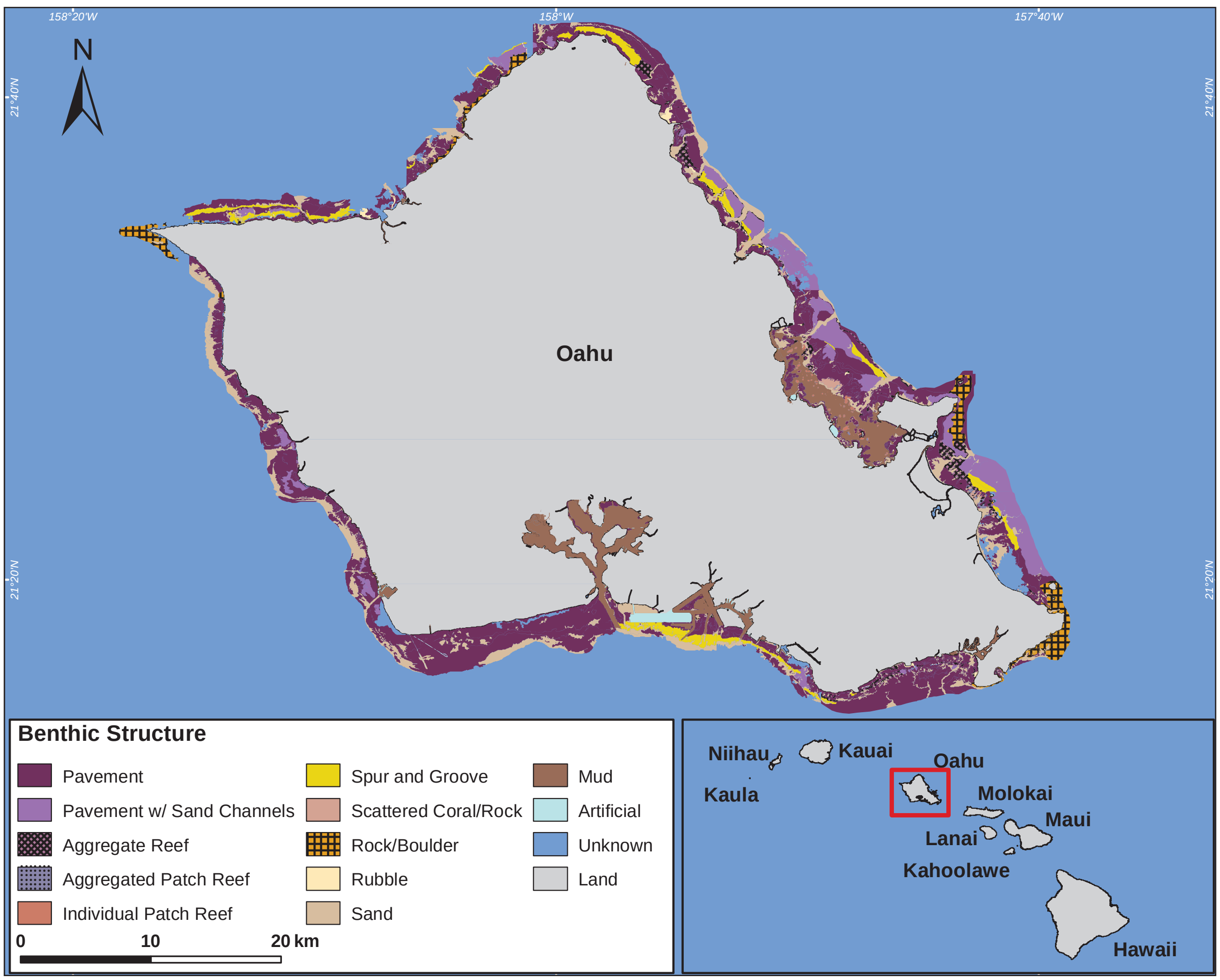


Figure 26. Habitat map showing shallow-water benthic structure of Oahu, Maine Hawaiian Islands. For the complete benthic habitat map of the Main Hawaiian Islands, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Figure 27. Main Hawaiian Islands general structure.

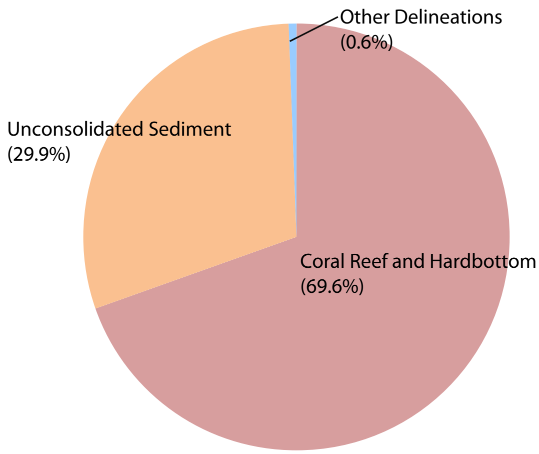


Figure 28. Main Hawaiian Islands detailed structure.

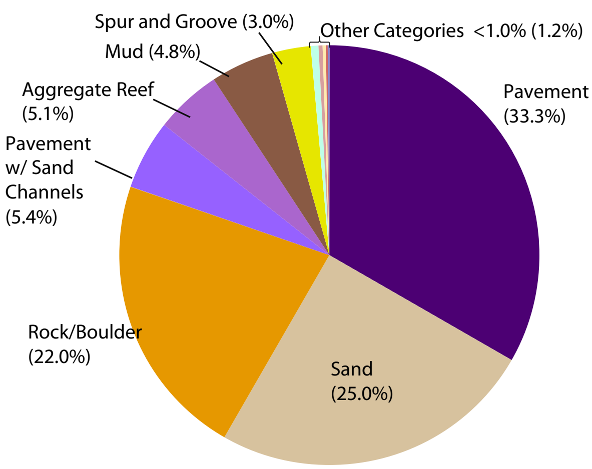


Figure 29. Main Hawaiian Islands general cover.

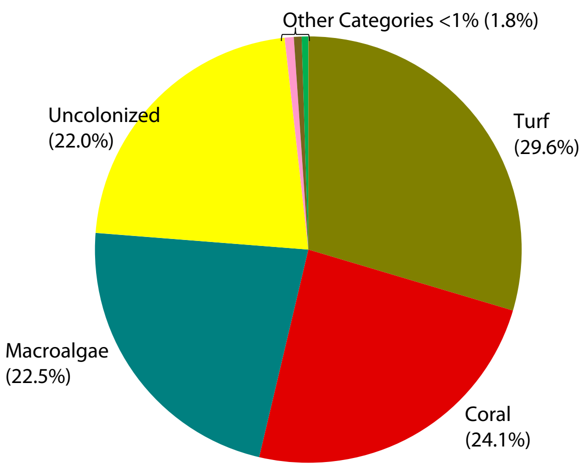
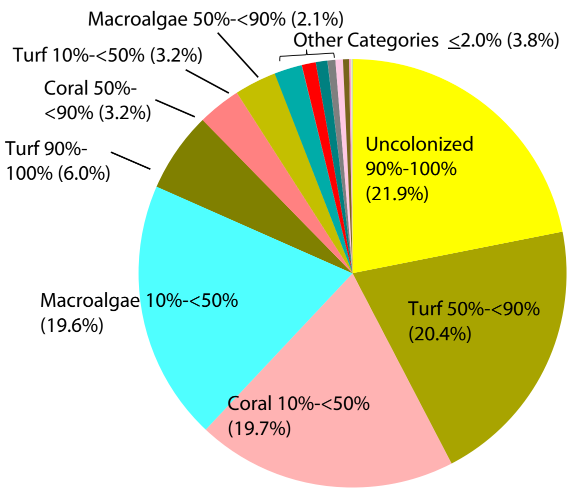


Figure 30. Main Hawaiian Islands detailed cover.



For the detailed structure category the coral reef and hardbottom class consisted mostly of pavement (~33%), sand (25%), rock/boulder habitat (22%), with aggregate reef and spur and groove habitat at 5% and 3% cover respectively (Figure 28). In general, turf (30%) and macroalgae (23%) were fairly dominant cover types in the Main Hawaiian Island coral reefs. (Figures 29-31). Of the coral cover in the Main Hawaiian Islands, the detailed cover class shows the coral 10%-<50% the most common (19.7%) and areas of high coral cover (e.g., coral 50%-<90%) at only 3.2% of the detailed cover (Figure 30).

As the Main Hawaiian Islands are located in the middle of the Pacific Ocean, Hawaii is exposed and subjected to large ocean swells and strong tradewinds contributing to the development of distinctive micro-communities that are sculpted by these dynamic natural processes. Climatological and oceanographic processes such as circulation, windward and leeward exposure, and seasonal fluctuation in ocean swell have shaped the structure and distribution of benthic marine habitats. For instance, the leeward reefs have far more developed reef environments (e.g., Kona)

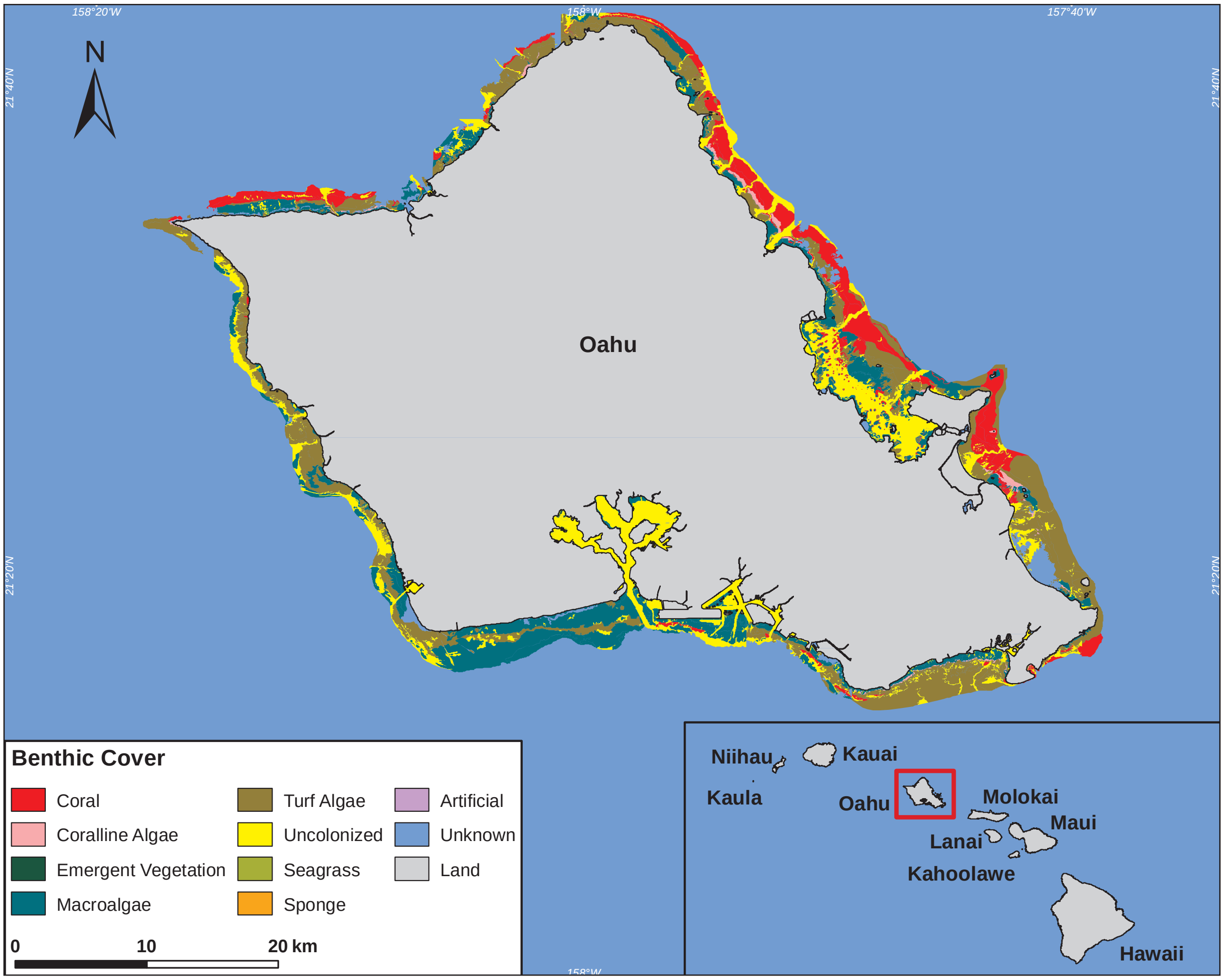


Figure 31. Habitat map showing shallow-water benthic cover of Oahu, Maine Hawaiian Islands. For the complete benthic habitat map of the Main Hawaiian Islands, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

with greater protection from large winter storms and as a result these areas are characterized by higher coral cover.

Applications for Science and Management

The benthic habitat maps for the Main Hawaiian Islands support a range of applications for regional science and management communities (Friedlander et al. 2007 a, b; 2009; Wedding et al. 2008). They were used to evaluate the efficacy of existing marine protected areas using a spatially explicit stratified random sampling design. The maps also guide *in-situ* studies of fish assemblages and benthic habitats with the resulting products evaluated in a spatial framework in order to assess the efficacy of these protected areas relative to their adjacent habitats. Results demonstrated that spatial patterns of fish assemblages in Hawaii are largely driven by their habitats and level of protection from fishing (Friedlander et al. 2007 a, b; 2009). This process, using National Ocean Service (NOS) benthic habitat maps and sampling across the range of habitats, provided a robust evaluation of existing marine protected areas. To support higher fish biomass and greater numbers and diversity of species, future protected area designs in the Main Hawaiian Islands need to include a mosaic of habitats with a range of complexities and depths to accommodate the wide range of species found on Hawaiian coral reefs. The NOS benthic habitat maps provide managers with the critical underlying information on the spatial extent of coral reef habitats to support future marine protected area design and evaluation.

Further, the benthic habitat maps have been refined in a number of locations to support local-level management objectives (Ortiz et al. 2008, Wedding et al. 2010).The availability of the ArcGIS benthic habitat digitizing extension has supported the creation of supplementary fine-scale coral reef habitat maps that are complimentary to the NOS benthic habitat maps (Wedding et al. 2010). The flexibility and availability of GIS tools provided by NOS allow for a multi-scale approach to be applied to coral reef studies by creating benthic habitat maps at different scales (e.g., varied minimum mapping units; Kendall et al. 2003).

As part of a global effort by NOAA and The Nature Conservancy to engage coral reef managers in ecosystem-based spatial management using Reef Resilience principals, researchers teamed up to train the Hawaii state and community marine managers. The benthic habitat maps provided the basis for mapping activities for the Reef Resilience workshops and were key elements designed to focus managers on habitat classification, zonation, and representation and replication of reef habitats to be prioritized for management efforts in the face of limited resource availability. Workshop participants were divided into smaller groups for the activity, and the resultant maps were not only an important tool to visualize the management of reefs at an island scale with all of the natural and anthropogenic influences, but a productive start to a much larger process. Four workshops were held on three islands between December 2011 and July 2012.

In addition, at the University of Hawaii at Manoa, students in an annual field marine biology course use the NOS benthic habitat maps to study the spatial distribution and habitat requirements of two NOAA species of concern-- Hawaiian reef coral (*Montipora dilatata)* and an inarticulated brachiopod (*Lingula reevii*). The spatial information for *M. dilatata* and *L. reevii* habitat requirements derived from habitat maps and field surveys will aid the National Marine Fisheries Service Pacific Islands Regional Office to: (1) prioritize critical areas of current and potential habitat in Kaneohe Bay for management of these species of concern (e.g., mitigation measures for consultations under Section 7 of the Endangered Species Act); (2) determine whether on-the-ground conservation measures (e.g., continued removal of alien/invasive algae) will be effective in protecting these species from further declines in Kaneohe Bay; and (3) provide an important case study in coral outplanting locations and management efforts.

Northwestern Hawaiian Islands

Photo credit: J. Watt

Introduction

The Northwestern Hawaiian Islands is an archipelago that consists of a series of islands, atolls, reefs, shallow-water banks and seamounts that start with Nihoa Island and stretch 1,193 miles west-northwest to Kure Atoll. They are part of the Hawaiian Ridge-Emperor Seamounts chain, considered to be the longest mountain chain in the world (Grigg 1983), that extends approximately 3,700 miles from the Island of Hawaii to the Aleutian Trench off the coast of Siberia. The named islands, shoals, banks and atolls (from east to west) are: Nihoa, Necker, French Frigate Shoals, Gardner Pinnacles, Maro Reef, Laysan Island, Lisianski Island, Pearl and Hermes Atoll, Midway Island and Kure Atoll (Figure 32). The Northwestern Hawaiian Islands constitute 9.6% of the total U.S. potential coral reef ecosystem area within 100 fathoms (Rohmann et al. 2005). The Northwestern Hawaiian Islands were formed over the past 70-75 million years through the same volcanic process that formed the Main Hawaiian Islands. Kure Atoll is the oldest emergent island in the Hawaiian Archipelago and the Main Hawaiian Islands are the youngest.

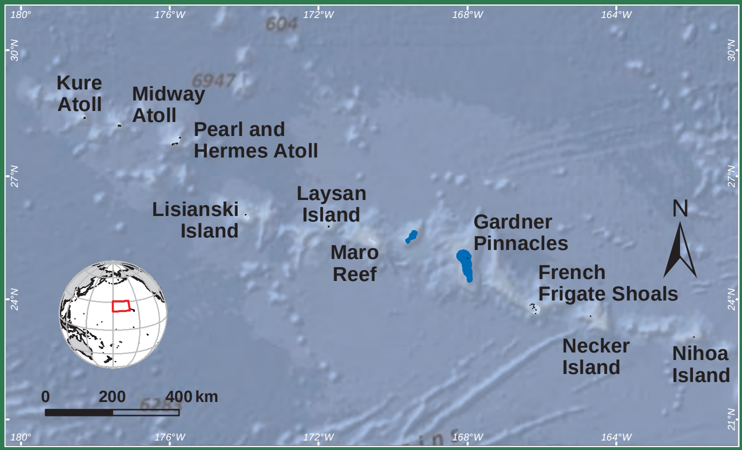


Figure 32. Map of the Northwestern Hawaiian Islands. Credit: Ken Buja and Sarah D. Hile.

The Northwestern Hawaiian Islands have a relatively pristine and unspoiled environment and a robust biotic community. The geographic isolation of these coral ecosystems, and relatively light fishing pressure has resulted in the area being one of few remaining apex predator-dominated coral ecosystems in the world (Friedlander and DeMartini 2002). Their isolation also has resulted in some of the highest tropical marine ecosystem endemism in the world. While elsewhere in the world coral reefs are threatened and stressed by human activities such as coastal development, pollution and resource over exploitation, the remote location of the Northwestern Hawaiian Islands has helped protect its coral reefs from adverse human impacts. They are still relatively pristine ecosystems with a much greater diversity in reef habitat than in the Main Hawaiian Islands.

Mapped Geology and Benthic Habitat

The National Ocean Service (NOS) has sponsored a shallow-water (0-30 m) benthic habitat mapping program, which in 2003 produced the *Atlas of the Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands* (NOAA 2003; Table 1). IKONOS high-resolution satellite imagery was used to derive benthic habitat maps, estimate depth and the color images. During this effort, NOS characterized about 4,240 km^2 of the shallow-water benthic habitats of the Northwestern Hawaiian Islands.

For the area of the Northwestern Hawaiian Islands that was characterized using the hybrid mapping approach detailed in NOAA 2003, about 45% and 40% of the geomorphic structure was classified as unconsolidated sediment (sand and/or mud) and hardbottom, respectively (Figures 33 and 34). Further examination indicates that about 44% and 33% of the unconsolidated sediment is classified

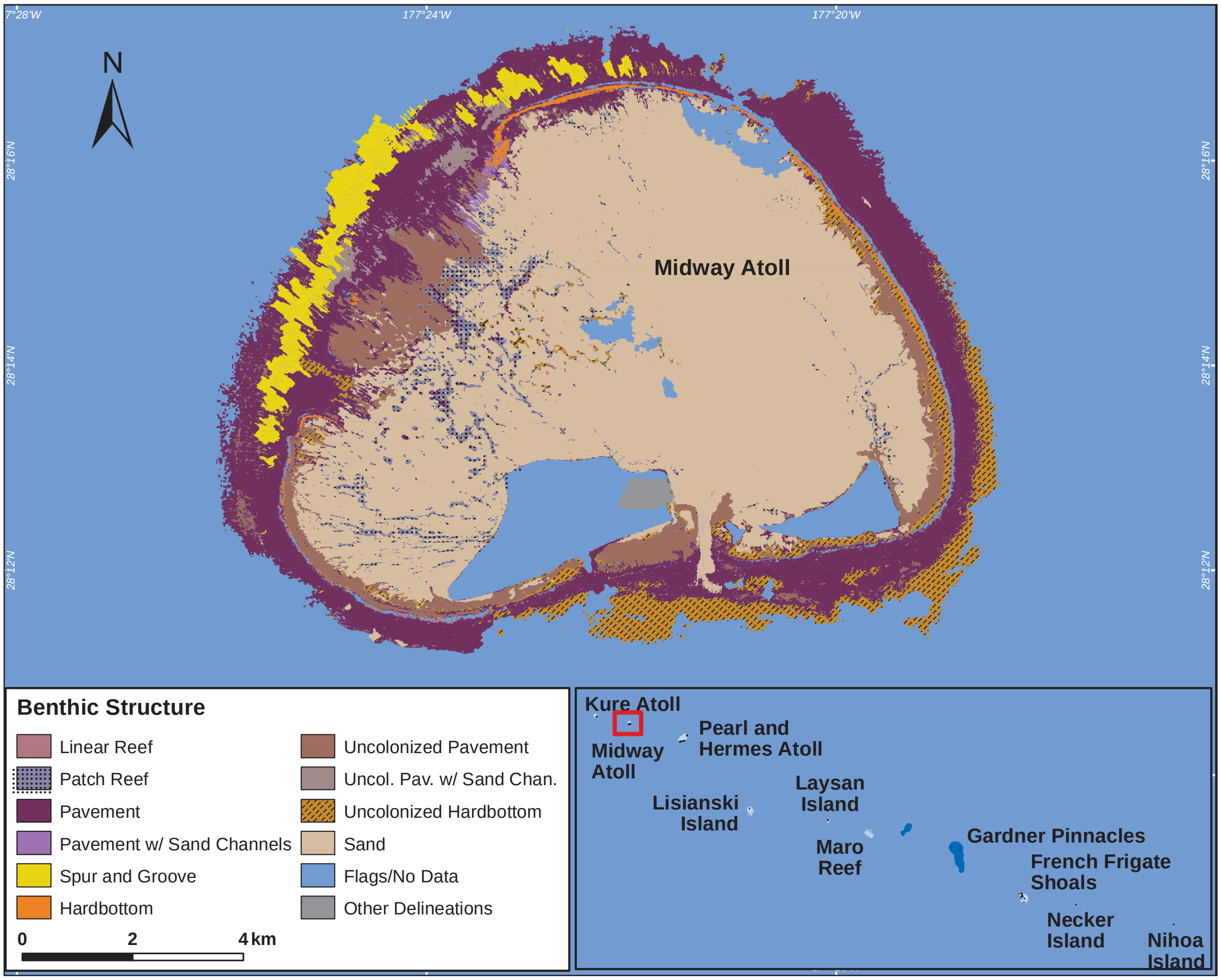


Figure 33. Habitat map showing shallow-water benthic structure of Midway Atoll, Northwestern Hawaiian Islands. For the complete benthic habitat maps of the Northwestern Hawaiian Islands, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Figure 34. Northwestern Hawaiian Islands general structure.

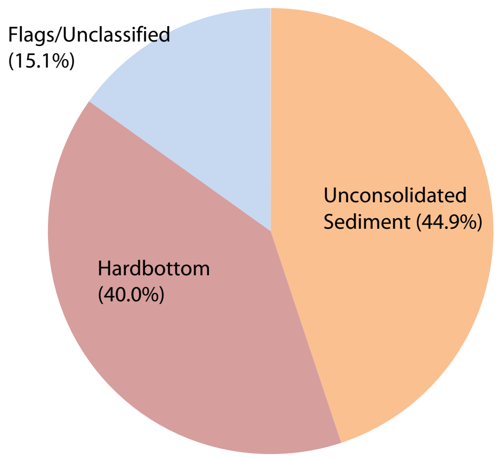
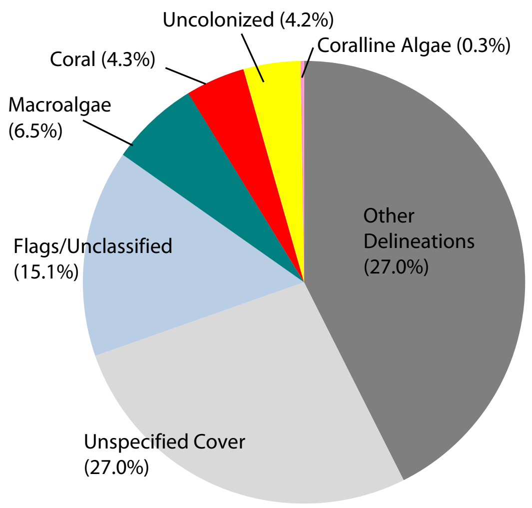


Figure 35. Northwestern Hawaiian Islands detailed cover.



as sand and mud respectively. For the biological cover class, macroalgae was the greatest coverage at 6.5%, followed by coral (4.3%) and coralline algae (0.3%; Figures 35 and 36). A total of 34% (1,435 km^2) of the Northwestern Hawaiian Islands area was classified as "no data" and about 230 km^2 being classified as "unknown."

An examination of the Northwestern Hawaiian Islands habitat maps further reveals that, because limited ground validation data were available, only about 427 km^2 of the area could be characterized as macroalgae, coral, uncolonized and crustose coralline algae. The remainder (3,810 km^2) was classified as no data, other delineations, unspecified cover or unclassified.

To date, the mapping efforts in the Northwestern Hawaiian Islands have characterized 4,240 km^2 of the shallow-water benthic habitats. There is great potential to further improve and supplement existing shallow-water mapping efforts in the Northwest Hawaiian Islands. Future mapping missions by NOS and its regional management partners (the U.S. Fish and Wildlife Service and state of Hawaii) should focus on filling in the data gaps. These future efforts should include supplementing the existing satellite imagery and conducting comprehensive field surveys to collect both ground validation and accuracy assessment data. In addition, this work should be implemented in coordination with NOAA multibeam mapping efforts.

Applications for Science and Management

NOS' IKONOS-derived benthic habitat maps currently provide an important reference for planning annual field survey campaigns in the Northwestern Hawaiian Islands. The habitat maps can assist in stratifying marine field surveys by major habitat type and help scientists to optimize biological monitoring sampling design in the monument. In addition, the benthic habitat maps are a key component of the National Centers for Coastal Ocean Science's product, A *Marine Biogeographic Assessment of the Northwestern Hawaiian Islands* (Friedlander et al. 2009). This document significantly contributed data and information that led to the successful designation of the Papahanaumokua National Monument as the first mixed UNESCO World Heritage Site in the U.S. There is great potential for further application of the benthic habitat maps in the Northwest Hawaiian Islands as future mapping missions fill

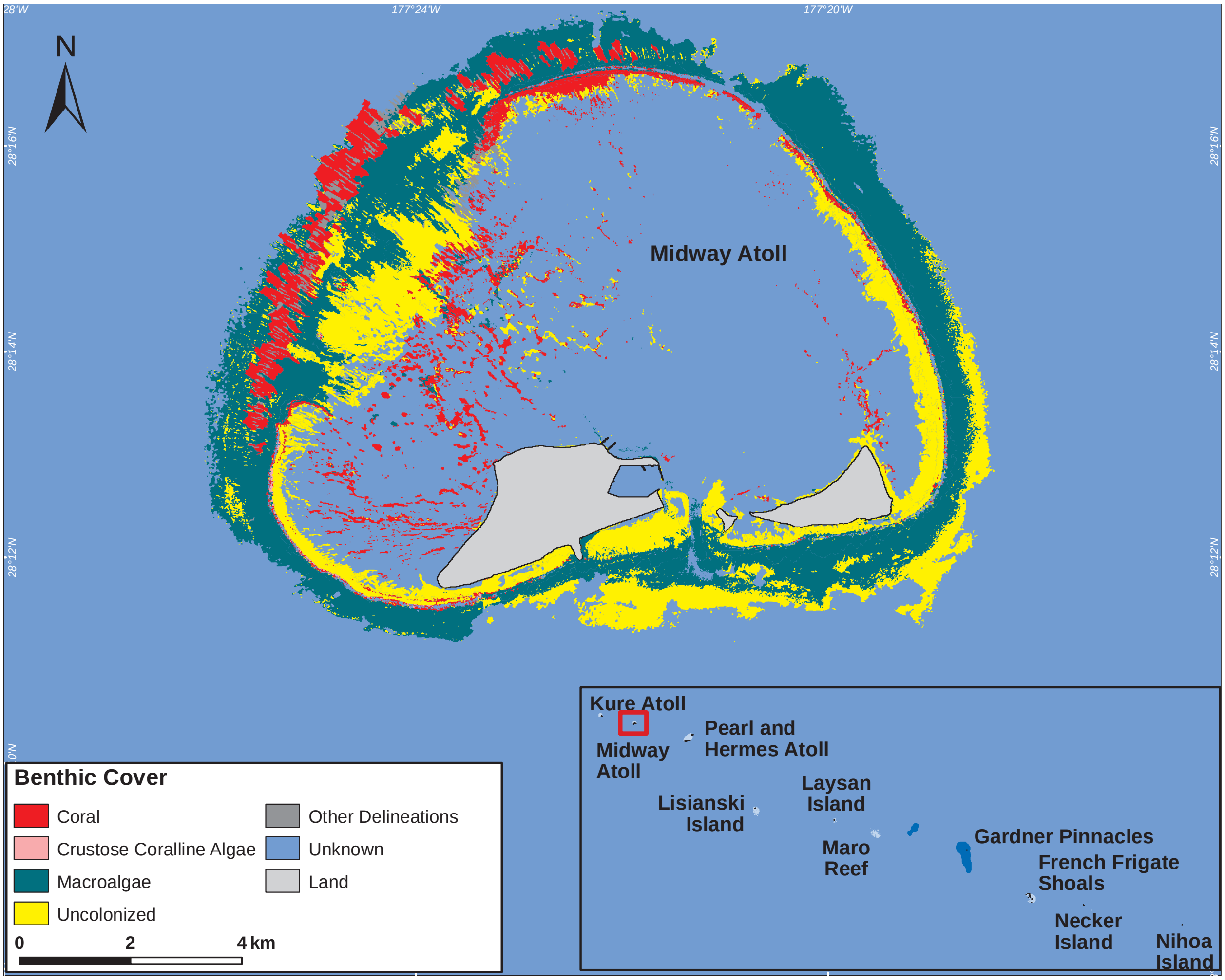


Figure 36. Habitat map showing shallow-water benthic cover of Midway Atoll, Northwestern Hawaiian Islands. For the complete benthic habitat maps of the Northwestern Hawaiian Islands, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

in data gaps and create a comprehensive habitat map of the region.

In addition, the moderate-depth multibeam mapping conducted by NOAA's Coral Reef Ecosystem Division has provided data sets that have been applied to quantify the area and location of essential fish habitat in the Northwestern Hawaiian Islands (Friedlander et al. 2009). Locations of potential adult bottomfish habitat were also spatially delineated for managers. The depth, slope and backscatter information derived from multibeam datasets were key components for the calculation and delineation of essential fish habitat and potential habitat in the Northwestern Hawaiian Islands. Spatially comprehensive benthic habitat maps will also provide additional information that can serve as a proxy to support future essential fish habitat studies in the region.

American Samoa

Introduction

The territory of American Samoa consists of seven islands in the central tropical South Pacific and is the only U.S. territory located south of the equator (Figure 37). American Samoa is comprised of five volcanic islands, including Tutuila (formed 1.5 million years ago), by far the largest, small Aunu‘u Island (not pictured in Figure 37) close by Tutuila, and the Manu’a Island group of Ofu, Olosega (both formed ~300,000 years ago) and Ta‘u (~100,000 years old), located approximately 95 km east of Tutuila. These five mountainous islands are part of a volcanic hotspot chain that also includes the much larger islands of Independent Samoa to the west, and an active undersea volcano east of Ta’u called Vailulu’u. American Samoa also includes two low-lying coral atolls; Swains, located ~350 km north of Tutuila, and Rose, located 140 km east-southeast of Ta‘u. Both of these atolls are much older than the volcanic islands derived from the Vailulu’u hotspot, are not geologically related, and are very isolated from the other islands due to the prevailing ocean currents.

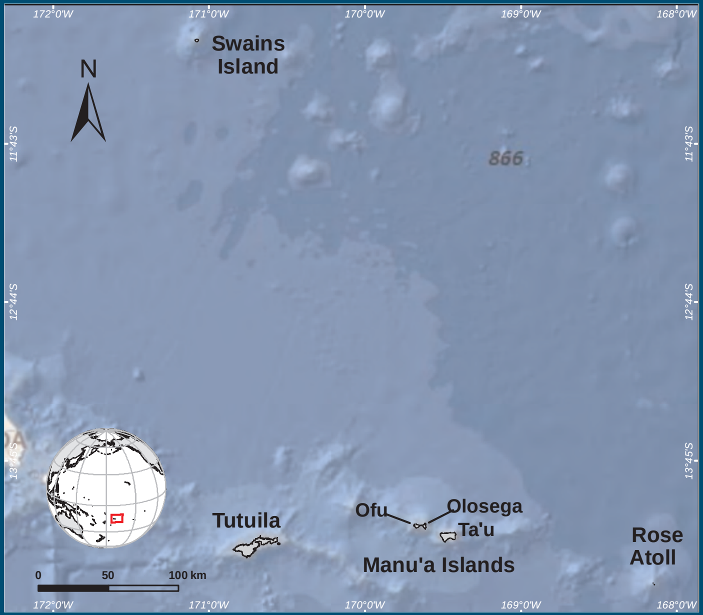


Figure 37. Map of American Samoa. Credit: Ken Buja and Sarah D. Hile.

The coral reef ecosystem built upon these geologic foundations in American Samoa is a mosaic of habitats, including fringing reefs, reef flats, slopes and other coral communities including some of the largest single coral heads known in the region (located in southwestern Ta’u). Like other Pacific island reefs, these interrelated features have formed as a result of gradual processes, including volcanic eruption, island subsidence, reef accretion and sea level fluctuations.

Mapped Geology and Benthic Habitat

In 2003, the National Ocean Service (NOS) launched an effort to map the benthic habitats of American Samoa (NOAA NCCOS 2004; Table 1). Over 72 km^2 of benthic features were mapped using IKONOS satellite imagery. The major structure type with the largest area overall was coral reef/hardbottom, which comprised ~85% of the mapped area (Figures 38 and 39). The dominant detailed structure type was pavement (41% of mapped area). Other important detailed structure types included aggregate reefs (13%) and spur and groove features (12% of mapped area), which are often considered the highest quality reefs with greatest rugosity and fish diversity in this region.

The major cover type with the largest area was coral, which comprised over half the mapped area (Figures 41-43). Coralline algae also covered a large area (>20% of mapped bottom features), as did bare, uncolonized substrate (~15%). Detailed classes indicated that coral cover was almost always in the 10-50% cover category, whereas coralline algae achieved 50-90% cover in nearly a third of the features where it was the dominant cover type (Figure 42).

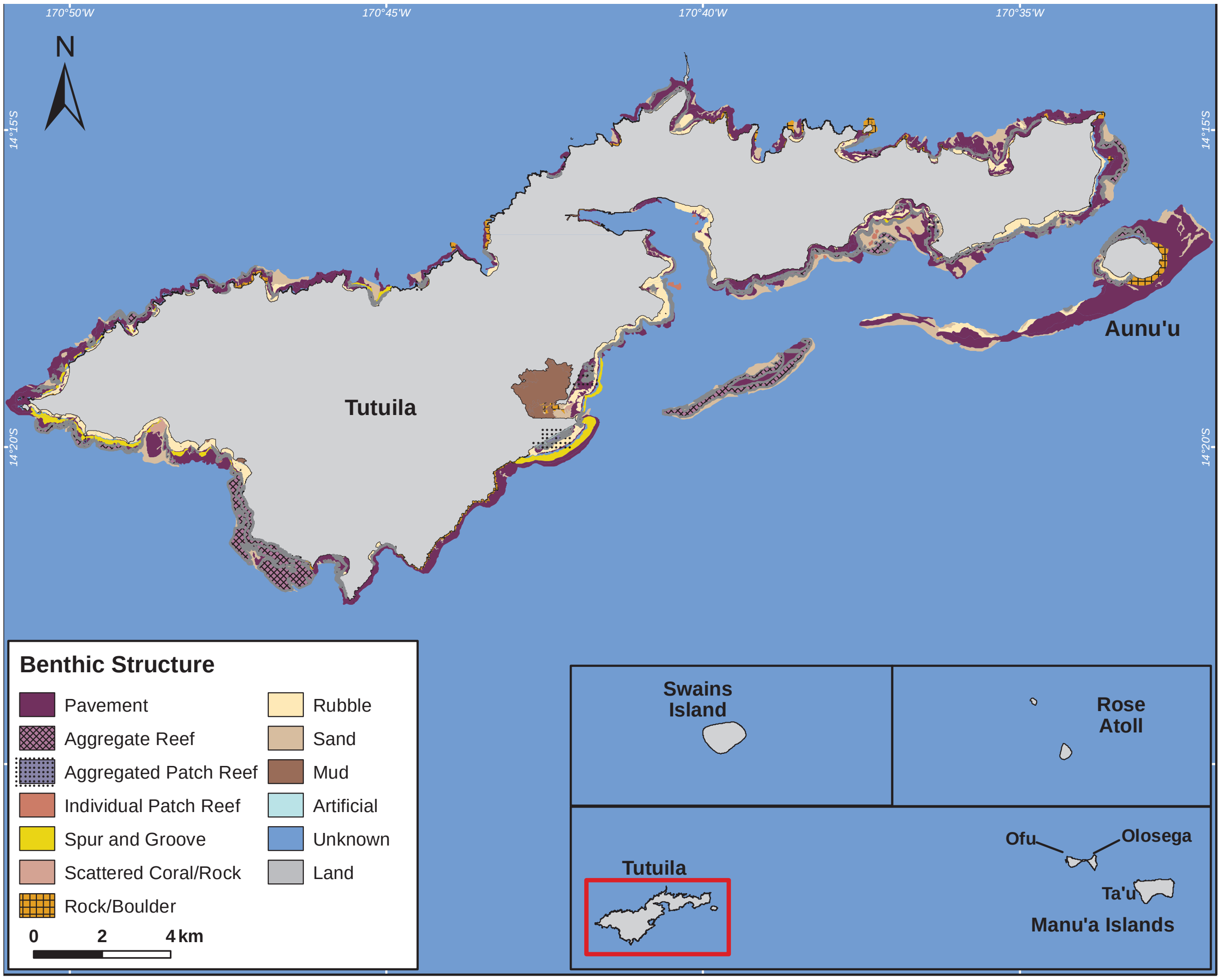


Figure 38. Habitat map showing shallow-water benthic structure of Tutuila, American Samoa. For the complete benthic habitat map of American Samoa, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Figure 39. American Samoa general structure.

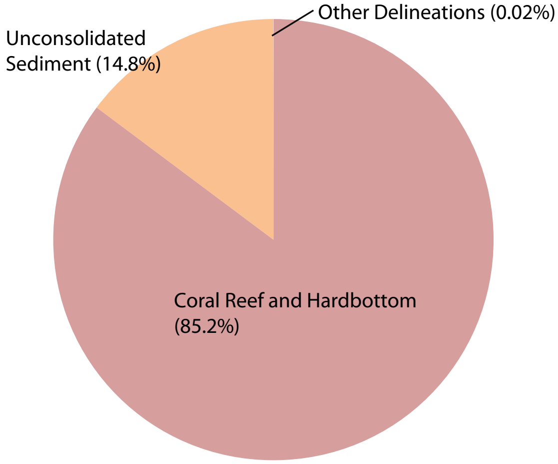


Figure 40. American Samoa detailed structure.

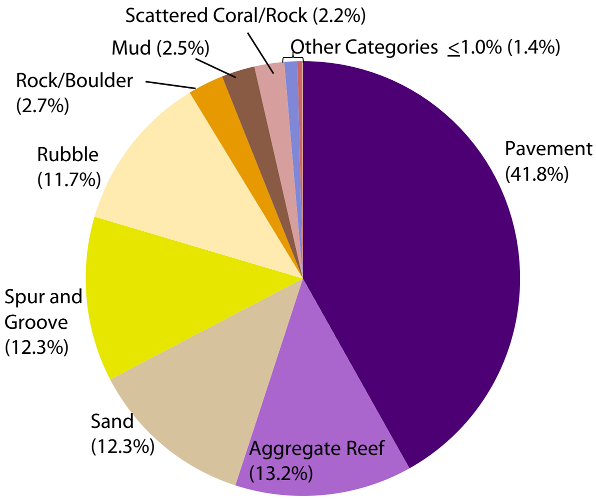


Figure 41. American Samoa general cover.

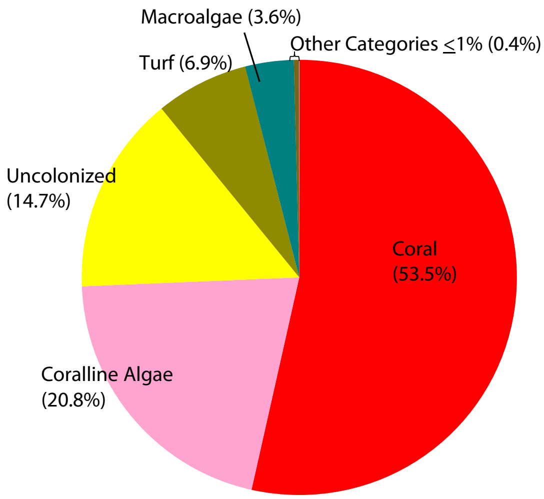
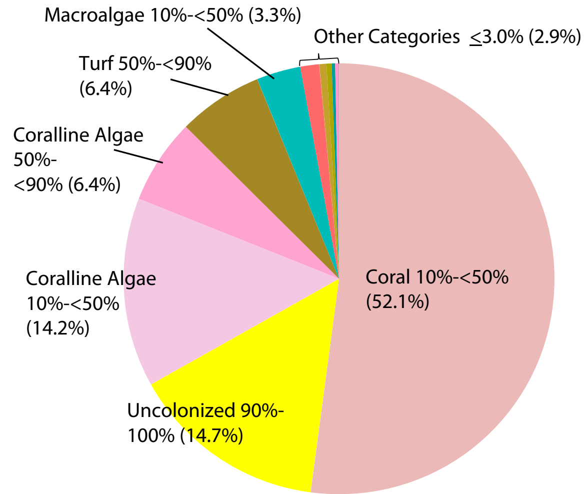


Figure 42. American Samoa detailed cover.



Typical zonation and width of mapped habitats varied by island. Rose Atoll consists of two small islets on the northeast edge of a central lagoon that is ~30 m deep and open to the ocean at the northern edge. Much of the central lagoon was unmappable with IKONOS imagery due to water depth and turbidity. The central lagoon is surrounded by a ~150-200 meter wide band of scattered coral and rock. The backreef surrounding the lagoon consists of aggregate reef, rubble and patch reefs in addition to two small islands that are surrounded by a rubble zone that is from a few meters to 150 m wide in places.

The shallowest part of the back reef consists of a 100-300 m wide band of pavement covered with coralline algae. A narrow (~50 m wide) reef crest zone consists of pavement and rubble structures covered with coralline algae followed by a similarly narrow forereef zone composed of spur and groove habitat. Swains Island is an atoll with a completely enclosed lagoon. A reef flat comprised of rubble and pavement forms a ~150 m wide ring around the island. These are surrounded by narrow (50 m wide) reef crest and forereef

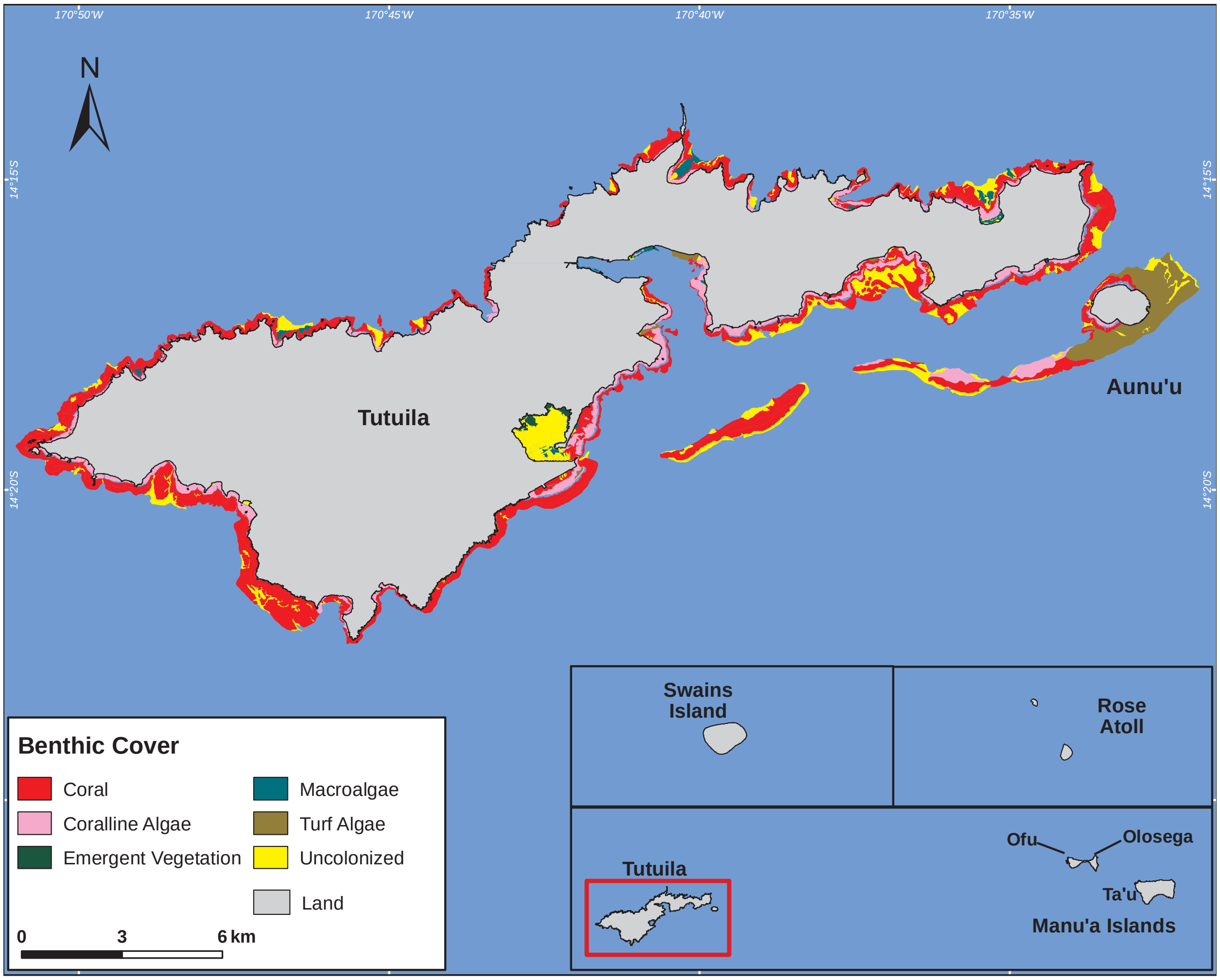


Figure 43. Habitat map showing shallow-water benthic cover of Tutuila, American Samoa. For the complete benthic habitat map of American Samoa, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

zones dominated by spur and groove structures covered with coralline algae and coral. An escarpment zone rapidly slopes into deep water outside the forereef at both Swains Island and Rose Atoll. The Manu'a Islands are steep-sided mountains and characterized by a narrow fringing reef that is only a few hundred meters wide before rapidly sloping into deep water. Beginning with a narrow (often only 10-20 meters or less) shoreline zone of rock-boulder, a rubble-dominated reef flat and reef crest rings much of Ta'u (~100 m wide), followed by a steep spur and groove forereef zone with moderate coral cover that rapidly slopes into deep water. The zonation is similar at Ofu and Olosega, although the zones are slightly wider, more patchy and diverse with several depressions in reef flat areas. Tutuila has a similar zonation in its relatively well developed fringing reefs, however this larger island has much more variable habitat widths and several other key differences in habitat distribution compared to the Manu'a Island group. There are many well-protected bays around Tutuila, with sandy beaches and much broader reef flats that often include a central channel that focuses tidal exchange and stream discharge. Forereefs tended to be aggregate reefs instead of the spur and groove structures that dominated this reef zone on the other islands. In addition, there are extensive offshore banks around Tutuila, only two of which (~2 km southeast of Tutuila) were shallow enough to be mapped with IKONOS imagery. Also notable on

Figure 44. Scientists and managers in American Samoa are using NOS benthic habitat maps to better understand and manage the habitat of the Pacific Humphead Wrasse, a species of concern under the Endangered Species Act. Credit: Alan Friedlander, U.S. Geological Survey and University of Hawaii.

Tutuila were the mangroves in the Pala lagoon area on the south central coast. This is the only large area of mangroves anywhere in American Samoa.

It is important to note that the summary statistics and general descriptions reported above do not include the very large area of insular shelf that could not be mapped in this assessment offshore of Tutuila using the IKONOS imagery. Due primarily to water depth, reef ecosystem features were not visible over the majority of the island's shelf. This included extensive offshore banks and shelf edge reefs, many of which harbor extensive reef communities at the edge of the photic zone. Recently, NOS surveyed using multibeam sonar and then classified the data into a benthic habitat map (Kendall and Poti (eds.) 2011).

Applications for Science and Management

The benthic maps of American Samoa have been used for a wide variety of purposes, a few of which are highlighted here. As with elsewhere, benthic maps are instrumental in constructing sampling designs for reef ecosystems and are used to stratify survey effort among habitat types by various monitoring agencies. The benthic maps have also been used as an information input into an economic valuation of coral reefs for American Samoa (Spurgeon et al. 2004). Benthic maps provided the total area of reef resources along various segments of coast classified by use type and intensity and were a basic component needed to calculate the value of coral reefs. Evaluating distributions of reef organisms in the context of their preferred habitats is another basic use. For example, local fisheries management agencies have used the NOS benthic maps around Tutuila to better understand the habitat and distribution of Pacific Humphead Wrasse (*Cheilinus undulatus*), a species of concern under the Endangered Species Act (Figure 44).

Benthic maps are also of central importance to marine protected area planning. The Government of American Samoa has adopted a recent initiative to protect 20% of their coral reefs as "no-take" refugia (Sunia 2000). To accomplish this objective, maps are needed to calculate when the protection goal has been reached. Similarly, the NOAA

Office of National Marine Sanctuaries Program is exploring an expansion of their protected areas in American Samoa and is using NOS benthic maps as an important input for determining appropriate locations for additional sites and boundary configurations (Kendall and Poti (eds.) 2011, U.S. Department of Commerce 2011).

Palmyra Atoll

Introduction

Palmyra Atoll is located about halfway between Hawaii and American Samoa in the equatorial Northern Pacific Ocean (Figure 45). The atoll has the largest landmass of the six Northern Line Islands (2.6 km^2 area, 7.5 km length). Rising only a few feet above sea level, Palmyra Atoll is the remaining remnant of volcanic activity some 65-120 million years ago. Palmyra consists of 54 islets that are all conneected with the exception of two and arranged in a nearly oval pattern, forming four shallow, well-protected interior lagoons. The lagoons are surrounded by 61 km^2 of shallow coral reef ecosystem (average depth 10 m) and steep escarpment flanks along the exterior periphery.

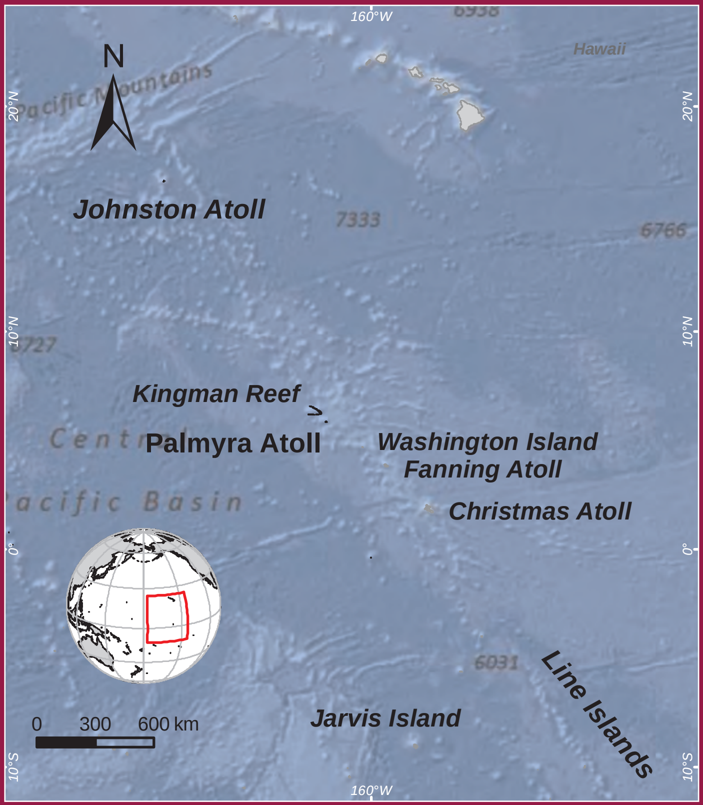


Figure 45. Map of Palmyra Atoll. Credit: Ken Buja and Sarah D. Hile.

Palmyra Atoll is home to a diverse coral reef ecosystem that includes over 130 species of stony coral and many top predators like sharks. In 2009, President George W. Bush established the Pacific Remote Islands Marine National Monument to provide conservation protection for Palmyra Atoll (as well as Howland, Baker and Jarvis Islands; Wake Atoll; and Kingman Reef). The inclusion of Palmyra Atoll into the monument was due to its unique and relatively pristine tropical marine and terrestrial flora and fauna. Its intact coral reef ecosystems also make Palmyra an ideal spot for scientific research. Scientists actively conduct research in Palmyra through the Palmyra Atoll Research Consortium and a small research camp managed by The Nature Conservancy of Hawaii.

Mapped Geology and Benthic Habitat

In 2009, the National Ocean Service (NOS) conducted a shallow water benthic habitat mapping program for Palmyra Atoll using IKONOS and QuickBird 2 satellite imagery (NOAA and Analytical Laboratories of Hawaii LLC 2010; Table 1). Benthic habitats within the lagoon portion of the atoll cover about 12 km², while the entire atoll, including the western and eastern terrace shelf extensions, includes 54.71 km² of coral reef ecosystem (Figure 46). Palmyra has a mixed barrier reef-atoll zonation pattern. Water flow and bottom depth of the interior is variable due to the considerable modifications made by the U.S. military during World War II. This includes dredged channels and artificial causeways, the latter altering the hydrodynamic water flow within the lagoon system. The north and south coasts transition seaward from land in a predictable pat-

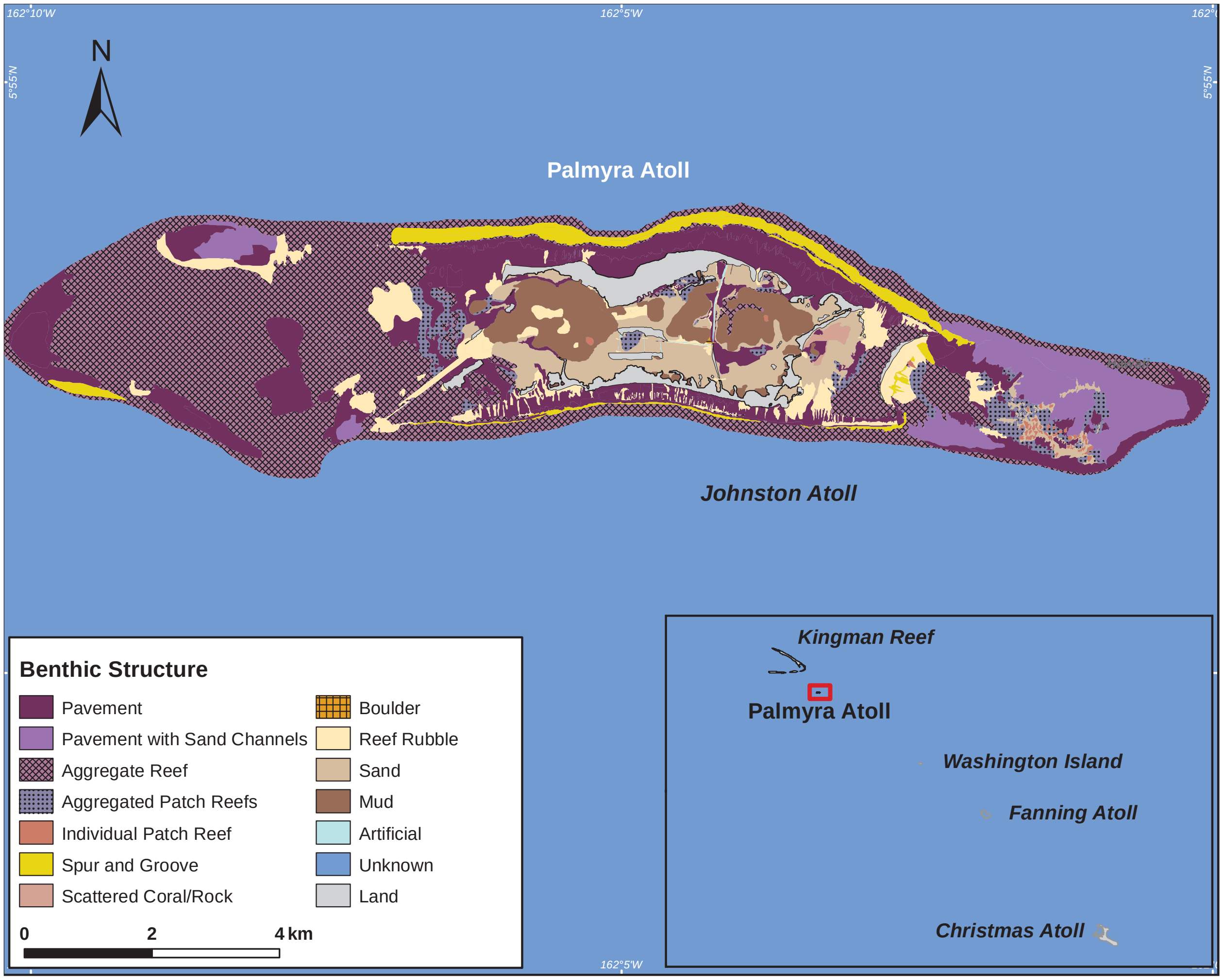


Figure 46. Habitat map showing shallow-water benthic structure of Palmyra Atoll. For more information on the benthic habitat map for Palmyra Atoll, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Figure 47. Palmyra Atoll general structure.

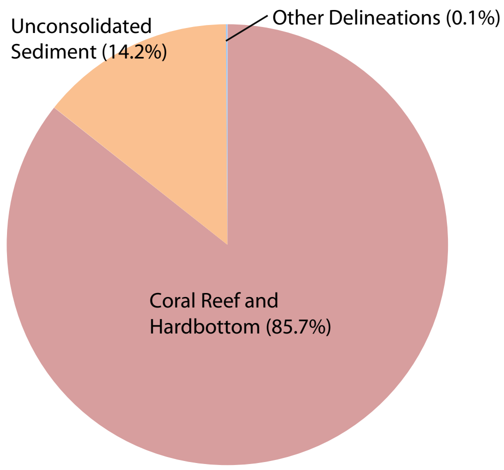


Figure 48. Palmyra Atoll detailed structure.

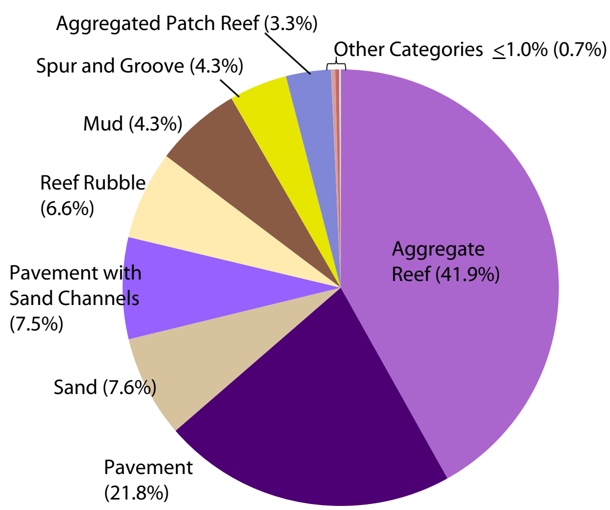


Figure 49. Palmyra Atoll general cover.

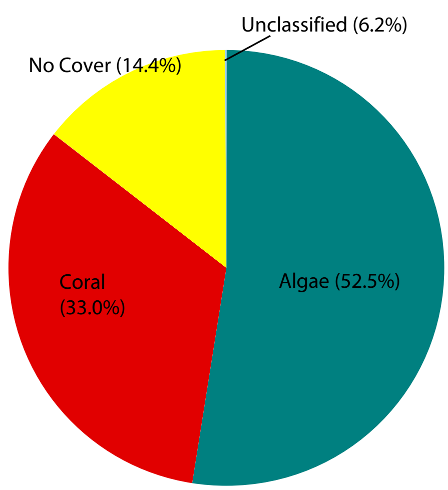
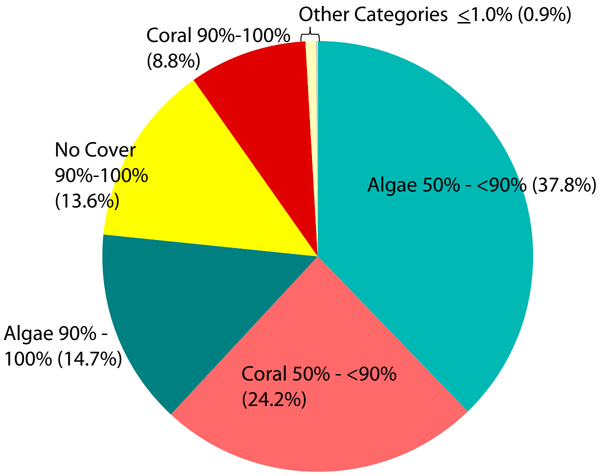


Figure 50. Palmyra Atoll detailed cover.



tern: reef flat, back reef, reef crest, forereef, bank shelf and steep shelf escarpment. While the east and west regions are characterized by extended bank shelf terraces transitioning to a steep shelf escarpment.

The major structure type with the largest area overall is coral reef/hardbottom, which comprised nearly 86% of the mapped area (Figure 47). Aggregate reef is the dominant geomorphological structure type on the atoll (41.9% of the total area, 21.06 km^2), particularly on the western terrace and bank shelf locales (Figures 46 and 48). The eastern terrace is primarily comprised of pavement with sand channels (7.5% of the total area, 3.78 km^2), likely due to exposure to disturbing wave energy. Pavement structure is found throughout the atoll, but is typical on the reef flat found along the north and south shores. Spur and groove is present in significant quantity along the northern edge of the atoll, outside the reef crest, and in smaller quantity along the southern edge of the atoll. The inner lagoons are dominated by uncolonized (sparse, patchy macroalgae and cyanobacteria) sand and mud habitat, with the exception of the far eastern lagoon, where aggregate reef is present.

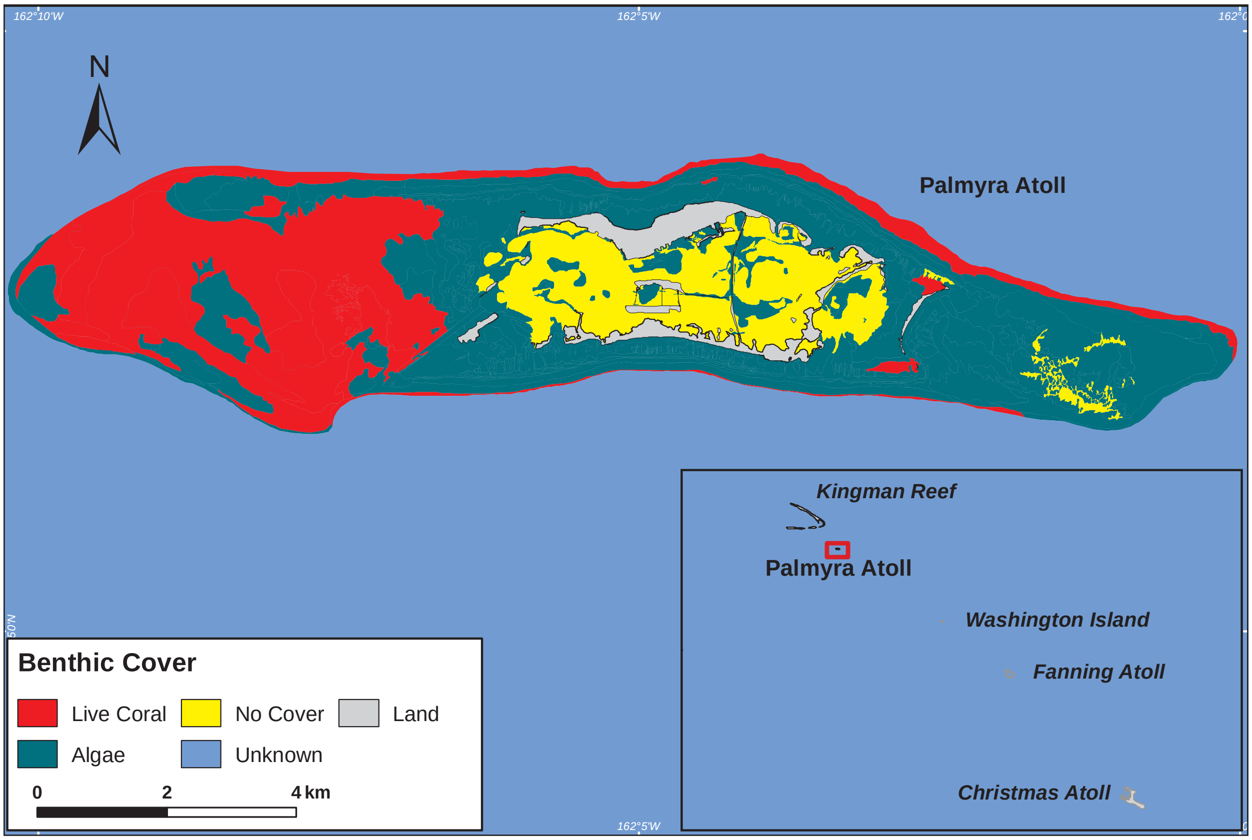


Figure 51. Habitat map showing shallow-water benthic cover of Palmyra Atoll. For more information on the benthic habitat map for Palmyra Atoll, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Medium and high density live coral is the dominant biological cover type along the western terrace and the fore-reef surrounding the atoll, with the exception of the far south-east tip (33% of the total area, 16.6 km^2), a few discrete areas within the eastern bank (Figures 49-51). Medium (50% - <90%) and high (90%-100%) density macroalgae dominate the biological cover composition of the atoll (52.5 % of the total area, 26.4 km^2, Figure 50). Macroalgae is pervasive on the reef flat surrounding the islet ring and throughout the eastern bank.

Applications for Science and Management

Palmyra Atoll is considered a de facto heritage site for comparing disturbed versus undisturbed coral reef ecosystems. For instance, the atoll has an intact apex predator-dominated fish population, which allows scientists and managers to better understand a healthy ecosystem dominated by large predators versus the condition of the most highly overfished and impacted coral reef ecosystems (Figure 52). The benthic habitat maps provide a valuable source of information to explore fish habitat utilization patterns, behaviors, abundance, trophic dynamics and carrying capacity in this system versus others.

The benthic habitat maps also provide critical planning information for optimizing biological monitoring sampling design. The Palmyra Atoll Research Consortium has used the benthic habitat maps to develop a stratified random monitoring program, following the methodologies developed in Hawaii by Friedlander et al. (2007b). In addition, the benthic habitat maps have been used to inform the placement of an acoustic array

*Figure 52. Bluefin Trevally (*Caranx melampygus*) over coral reefs in Palmyra. In many coral reef ecosystems around the world Bluefin Trevally, a top predator, face intense fishing pressure. Photo Credit: Kydd Pollock, The Nature Conservancy.*

within the lagoon and around the atoll to monitor the predator-prey dynamics in this natural laboratory. The habitat maps also provide the first quantification on benthic habitat distribution and quantity, serving as an important informational source to evaluate natural and anthropogenic changes in time (i.e., climate change). For instance, causeway removal is currently being considered to increase flow dynamics, but the maps can serve as an important predictive source as to what habitats are likely to repopulate after the mitigation.

Finally, the maps have served as an important source for monitoring disturbances over time, such as an outbreak of an invasive 'corallimorph' (*Rhodactis howesii*) on the western portion of the atoll adjacent to a decades-old shipwreck. There is concern as to the rate of corallimorph spreading, what existing habitats may be impacted, and possible mitigative measures that can be taken.

Commonwealth of the Northern Mariana Islands

Photo credit: Dave Burdick

Introduction

The 890 km long island chain, the Commonwealth of the Northern Mariana Islands, is in political union with the United States and occupies a strategic region of the Western Pacific Ocean. It consists of fourteen (not including Guam) islands about three-quarters of the way from Hawaii to the Philippines (Figure 53).

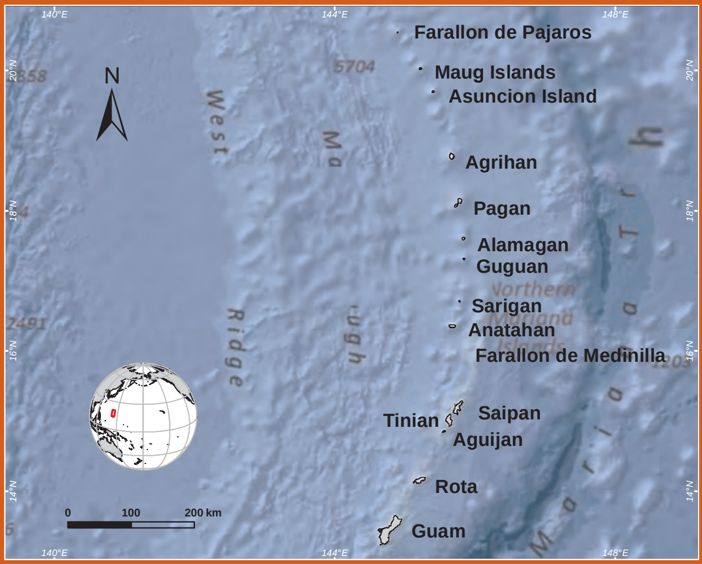


Figure 53. Map of the Commonwealth of the Northern Mariana Islands. Credit: Ken Buja and Sarah D. Hile.

The geologic conditions of the islands and shallow coral reef ecosystems of the Mariana Archipelago can be divided in to two distinct geologic groups demarcated between Farallon de Medinilla and Anatahan. These groups are: (1) the young, volcanic northern islands on the Mariana Arc, including, from south to north, Antatahan, Sarigan, Guguan, Alamagan, Pagan, Agrihan, Asuncion, Maug and Farallon de Pajaros; and (2) the old, southern islands located on the Mariana Arc, including Guam, Rota, Aguijan, Tinian, Saipan and Farallon de Medinilla (Figure 53). The young, volcanic northern islands were formed 0–5 million years ago by the subduction of the Pacific Plate under the Philippine Plate at the Mariana Trench. The islands and reef system is characterized by steep slope rock/boulder topography; periodic volcanic eruptions and landslides. The older, southern islands group was formed 15–20 million years ago. While these islands are volcanic in nature, they are primarily covered by uplifted limestone formed from ancient coral reef. These islands are characterized by surrounding low sloping terraces and fringing coral reefs.

In 2009, the three northern-most islands (Asuncion, Maug and Farallon de Pajaros), the Mariana Trench, and several volcanic features between the Mariana Arc and Trough, were designated as the Marianas Trench Marine National Monument.

Mapped Geology and Benthic Habitat

Mapping of shallow-water benthic habitats of the Commonwealth of the Northern Mariana Islands was conducted in 2005 using high-resolution, multispectral satellite imagery (NOAA National Centers for Coastal Ocean Science 2005; Table 1). Approximately 20 km² of marine habitats from Rota to Farallon de Pajaros were mapped, but banks located along the west Marina Ridge were not mapped due to their depth beyond the visual detection limit.

The southern islands of the Commonwealth of the Northern Mariana Islands (Rota, Aguijan, Tinian, Saipan, Farallon de Medinilla) have a mixed fringing reef zonation pattern, although an emergent reef crest is typically only present on the western leeward sides of the islands. The

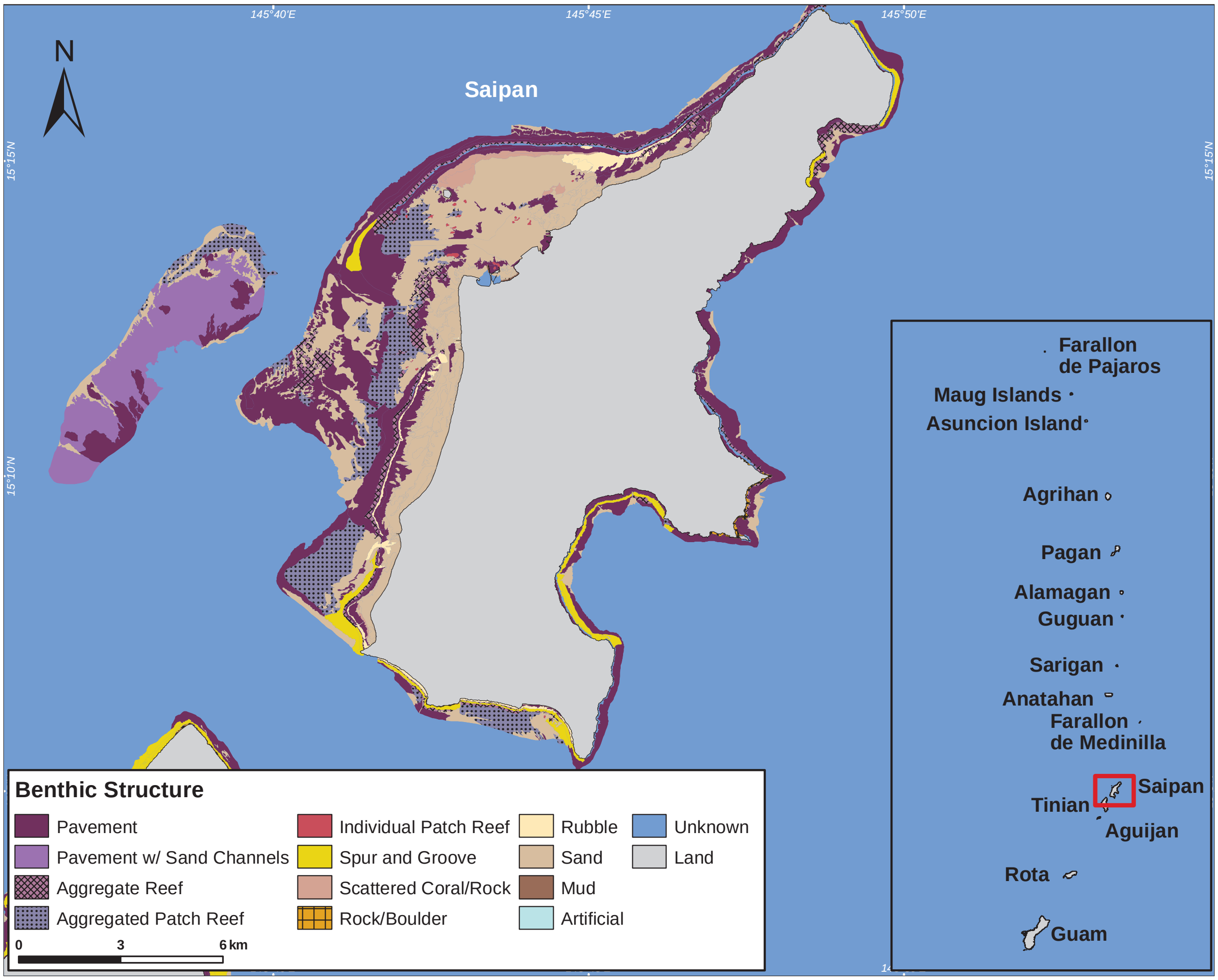


Figure 54. Habitat map showing shallow-water benthic structure of Saipan, Commonwealth of the Northern Mariana Islands. For the complete benthic habitat map of the Commonwealth of the Northern Mariana Islands, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Figure 55. Commonwealth of the Northern Mariana Islands general structure.

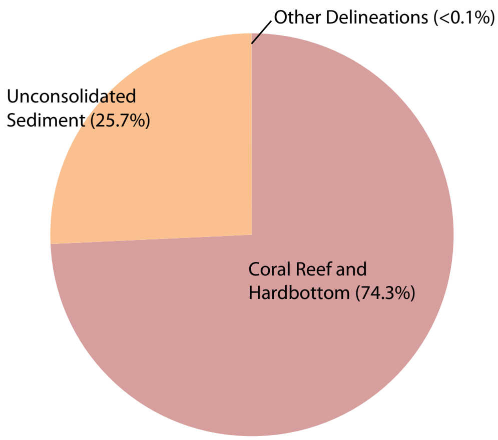


Figure 56. Commonwealth of the Northern Mariana Islands detailed structure.

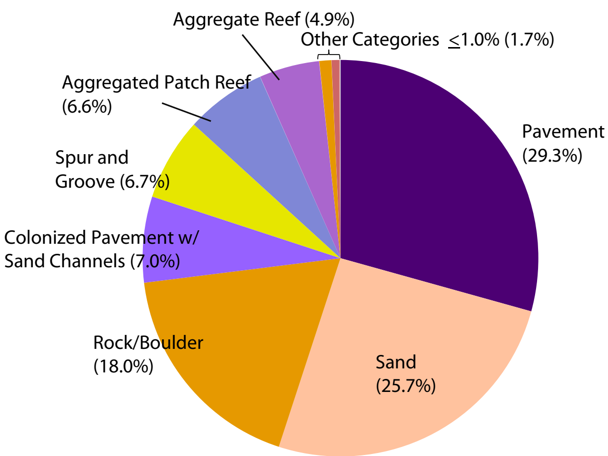


Figure 57. Commonwealth of the Northern Mariana Islands general cover.

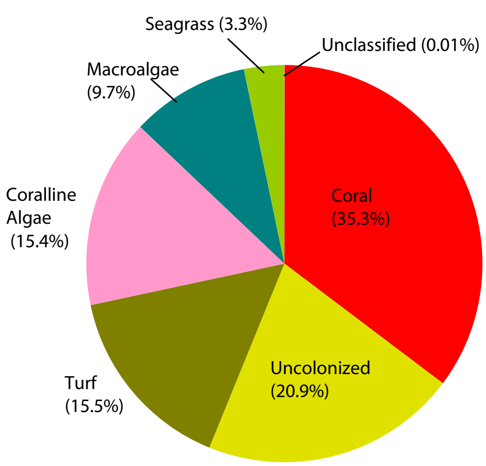
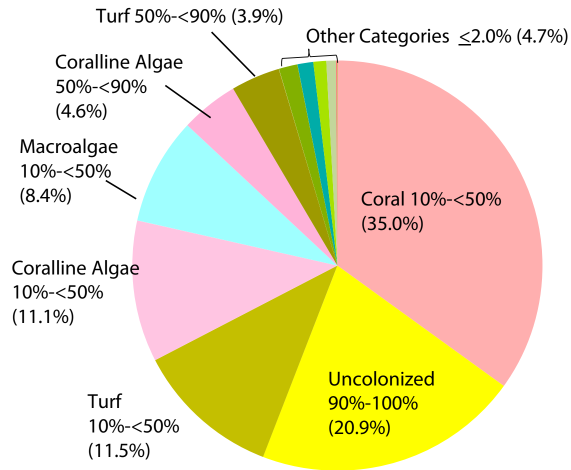


Figure 58. Commonwealth of the Northern Mariana Islands detailed cover.



fringing reef portion of the island transitions in a predictable pattern: shoreline intertidal, reef flat, reef crest, fore reef, bank shelf to bank shelf escarpment. Where a reef crest is not present, the island seascape transitions includes combinations of reef flat, fore reef, bank shelf and bank shelf escarpment. The northern islands are typified, with few exceptions, by a steep sloped bank shelf immediately from the shoreline interface.

While both the northern and southern parts of the Commonwealth of the Northern Mariana Islands are dominated by coral reef and hard bottom (74.3% of the total area, 151.5 km^2, Figures 54-56), a greater proportion is found in the southern islands (73% of the total area, 110.6 km^2). This is primarily a function of the geological conditions where the northern islands have a steep, narrow bank shelf, while the southern islands have a broad limestone platform. Of the coral reef and hardbottom, rock/boulder dominates the northern islands (80.1% of the total area, 36.3 km^2) and pavement (with and without sand channels) dominates the southern islands (42.3% of the total area, 69.2 km^2).

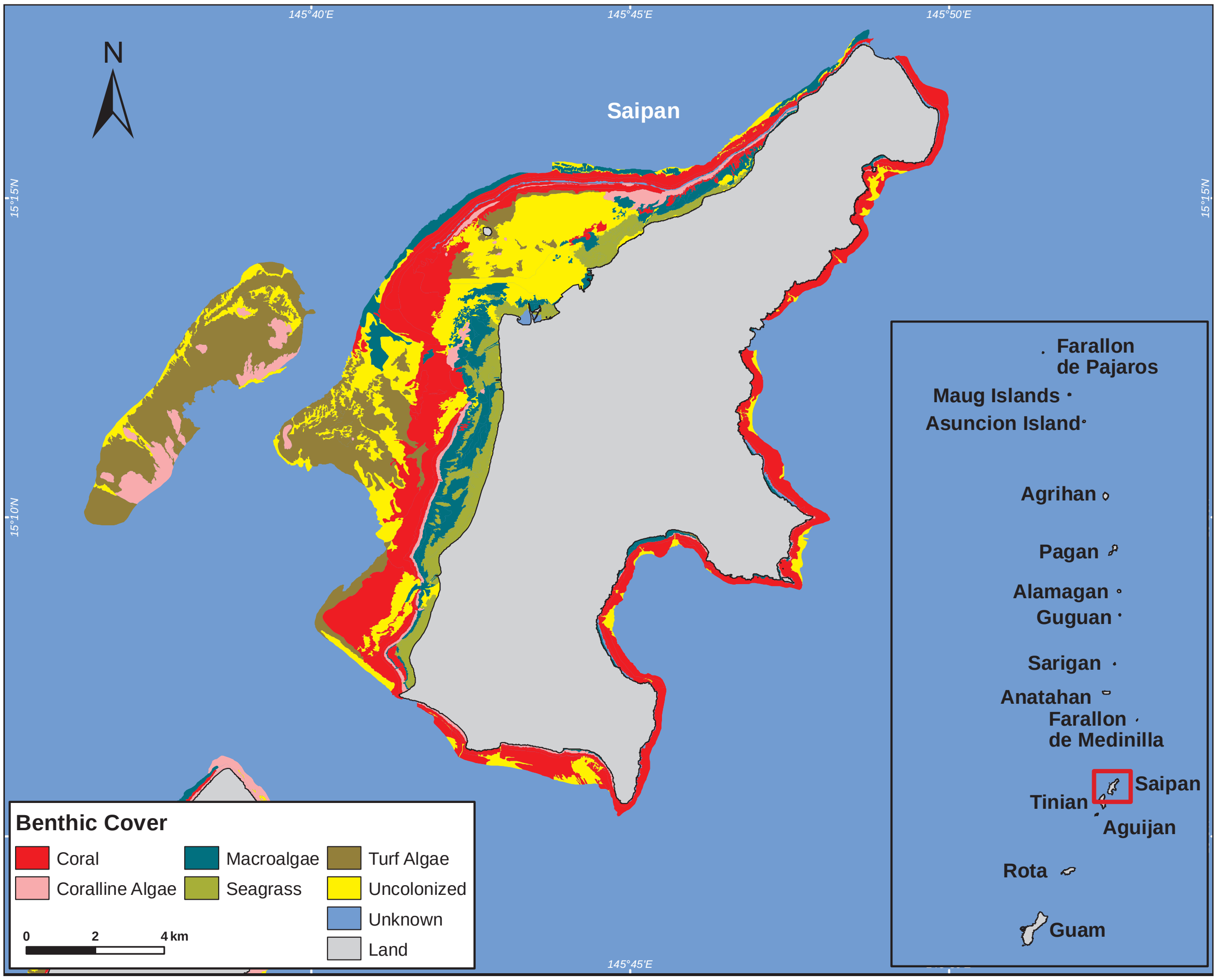


Figure 59. Habitat map showing shallow-water benthic cover of Saipan, Commonwealth of the Northern Mariana Islands. For the complete benthic habitat map of the Commonwealth of the Northern Mariana Islands, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

In general, the most common benthic cover types in the Commonwealth of the Northern Mariana Islands are coral (35.3%), uncolonized substrates (20.9%), and turf and coraline algae at 15.5% and 15.4%, respectively (Figures 57-59). In the southern islands, low (10% - <50%) density coral and uncolonized habitat are the dominate cover types (30.4% of the total area, 47.7 km^2; 24.7% of the total area, 39.2 km^2). In the northern islands, low (10% - <50%) density coral and low (10% - <50%) density turf macroalgae dominate the biological cover composition (53.3% of the total area, 6.9 km^2; 15.3% of the total area, 39.2 km^2).

Applications for Science and Management

The southern islands of the Commonwealth of the Northern Mariana Islands struggle to minimize the impacts of high resident population, number of tourist visitors and anthropogenic stressors associated with the civilian and military population. In fact, Saipan has a higher population density than even Guam (524 versus 324 persons/km^2). The cumulative impact of stressors such as sedimentation, nutrient loading, overfishing and development have a negative impact on the Commonwealth of the Northern Mariana Islands reef communities (Figure 60). While the

Figure 60. The coral reef ecosystems of the southern Commonwealth of the Northern Mariana Islands face threats from a growing population, coastal development and other anthropogenic stressors. Photo Credit: Dave Burdick.

northern islands have relatively few anthropogenic stressors due to their remoteness and low population (0-100 inhabitants), these factors also make it very difficult to detect and enforce illegal fishing activities conducted by other nations.

The benthic habitat maps provide critical informational sources for resource managers to address these aforementioned challenges. The National Ocean Service's benthic maps of the Commonwealth of the Northern Mariana Islands have been used for a wide variety of purposes. As in other areas, benthic maps are instrumental in constructing sampling designs for reef ecosystems and are used to stratify survey effort among habitat types by various monitoring agencies.

The Commonwealth of the Northern Mariana Islands has nine locally established marine reserves in addition to the Marianas Trench Marine National Monument. The availability of habitat mapping products provided a critical source of spatial information to justify and locate the designation of the marine protected areas and the monument. Maritime construction, regulatory permits, and reducing human impacts will continue to require the need for detailed habitat mapping information to assess and inform the short and long term impacts as well as the success of coral ecosystem management measures.

Guam

Photo credit: Dave Burdick

Introduction

The U.S. territory of Guam is the southernmost island of the Marina Archipelago and the largest island in Micronesia (Figure 61). Guam lies on one of a series of volcanic arcs extending north towards Japan. Though several of the northern islands in the Mariana Island chain are still volcanically active, Guam, located in the south, is not. However, the island is still tectonically active, experiencing occasional earthquakes due to its proximity to the western edge of the Pacific Plate. The Mariana Island chain was created by the colliding Pacific and Philippine Sea tectonic plates. Guam is the closest land mass to the Mariana Trench, a deep subduction zone that lies beside the island chain to the east. Challenger Deep, the deepest surveyed point in the world's oceans (at 35,797 ft or 10,911 m deep), is southwest of Guam.

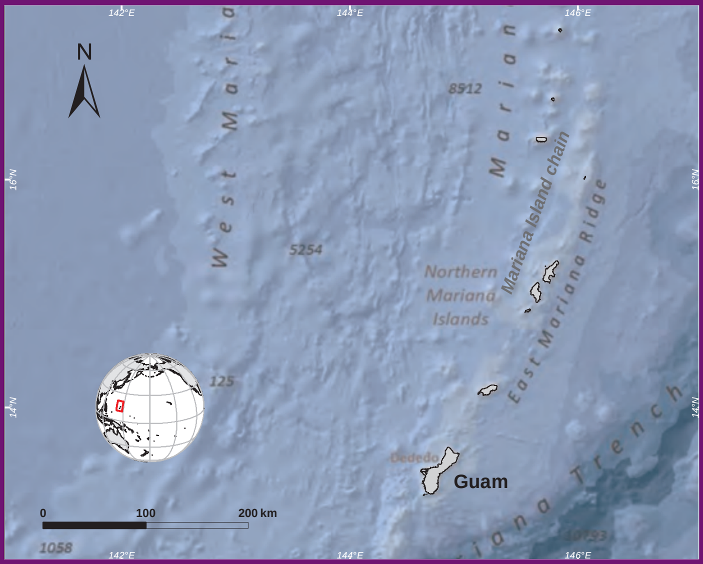


Figure 61. Map of Guam. Credit: Ken Buja and Sarah D. Hile.

The geology of Guam is quite unique as the northern half is primarily comprised of flat, uplifted limestone while the southern half is more mountainous volcanic rock formed during the mid- to late Eocene epoch (33-48 million years ago). The island is completely surrounded by a coralline limestone plateau. The northern section is characterized by steep cliff shoreline, while the shoreline of the volcanic southern section has numerous bays, canyons and valleys. Despite its small size, the island is heavily populated with civilians and an extensive U.S. military presence. While a popular tourist destination, the combination of sustained civilian and military development impacts to the coral reef ecosystem has been detrimental. The precipitous decline in live coral cover over the last 40 years is well documented. Overfishing has also led to a low fish abundance and diversity in inshore waters, including large, slow-growing herbivorous fish and iconic species such as the Napoleon Wrasse.

Mapped Geology and Benthic Habitat

Mapping of shallow-water benthic habitats of Guam was conducted in 2005 using high-resolution, multispectral satellite imagery (NOAA National Centers for Coastal Oceans Science 2005; Table 1). Approximately 105 km^2 of marine habitats from Cocos Lagoon north to Achae Point were mapped, but Banks located to the south were not mapped due to their depth beyond the visual detection limit (11-mile Reef, Galvez Bank, and Santa Rosa Reef).

A fringing reef surrounds much of island, with the exception of two barrier reef lagoons and several deep channels. Cocos Lagoon is located on the southern tip and Apra Harbor on the central west coast. Guam has high biodiversity, with over 5,100 species of marine organisms, including 1,000 spe-

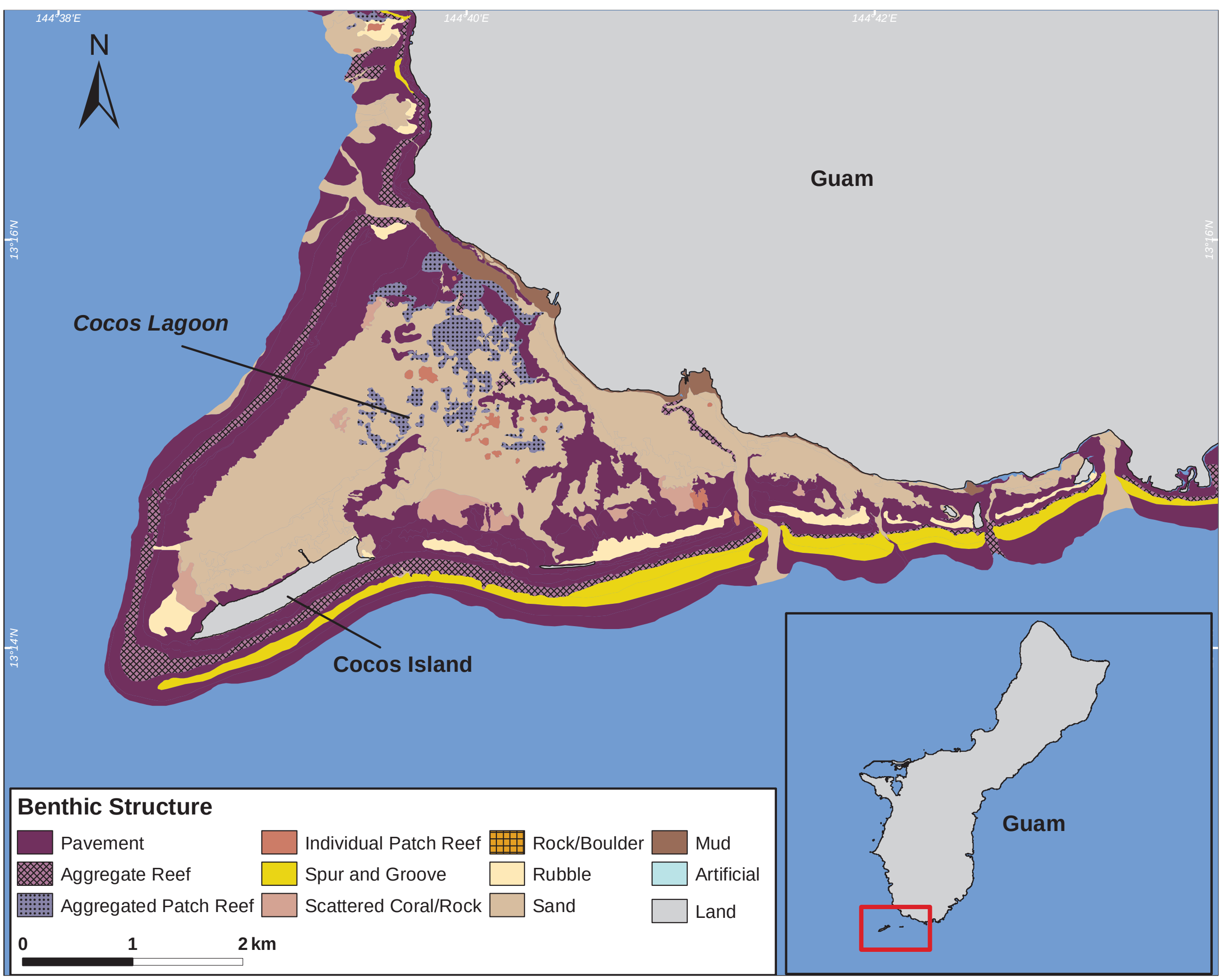


Figure 62. A portion of the habitat map showing shallow-water benthic structure for the Cocos Lagoon region of Guam. For the complete benthic habitat map of Guam, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Figure 63. Guam general structure.

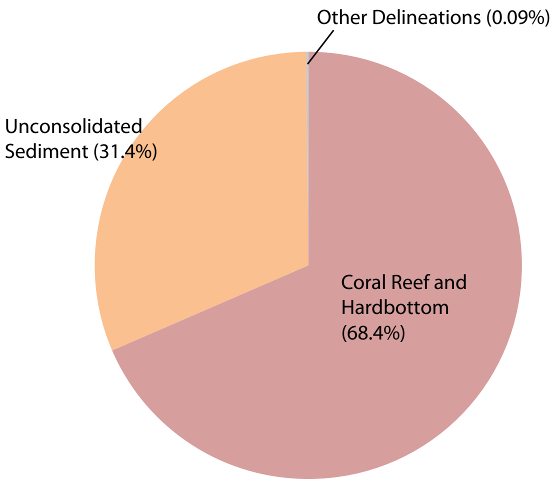


Figure 66. Guam detailed cover.

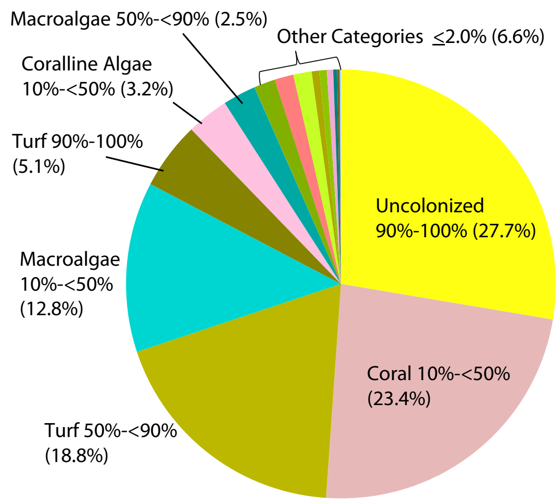


Figure 64. Guam detailed structure.

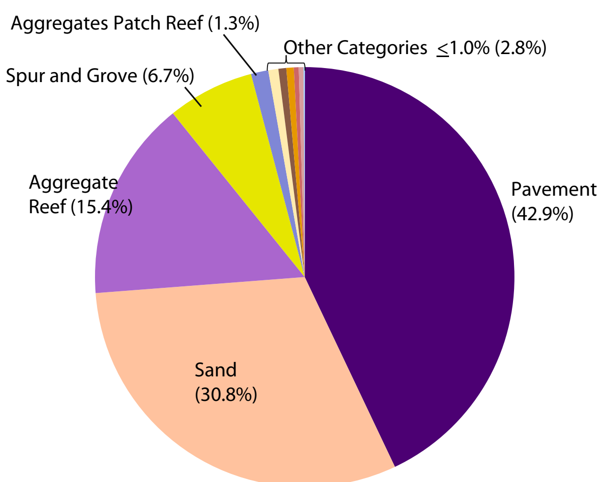
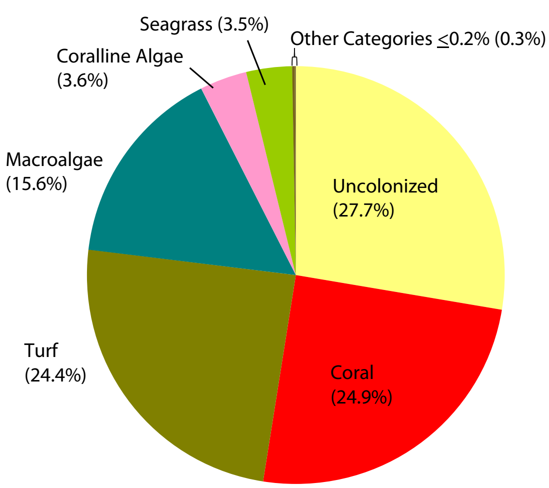


Figure 65. Guam general cover.



cies of fish and 500 species of hard corals. In addition to coral reefs, seagrass beds and mangroves are also present. While found in comparatively low quantities (total area 2 km^2), mangroves are present in Apra Harbor and the southern tip of the island. Three species of seagrass are found on Guam. Sparse patches of seagrass are found near river mouths in the south of Guam, but it is abundant in Cocos Lagoon.

Coral reef and hard bottom (68% of the total area, 71.7 km^2) as well as unconsolidated sediment (i.e., sand) dominate the geomorphological structure in Guam (31% of the total area, 32.9 km^2; Figures 62-64). Large expanses of coral reef and hard bottom are found surrounding the island, with extensive unconsolidated sand structure found within Apra Harbor on the western, leeward flank and Cocos Lagoon.

In general, uncolonized habitat, low (10% - <50%) density coral, and medium density turf algae dominate the biological cover composition of Guam (27.7% of the total area, 28.9 km^2; 23.4 % of the total area, 24.5 km^2; 18.8 % of the total area, 19.6 km^2; Figures 65-67). Uncolonized habitat and medium density turf algae is primarily found on the reef flat and bank/shelf. Low density coral is

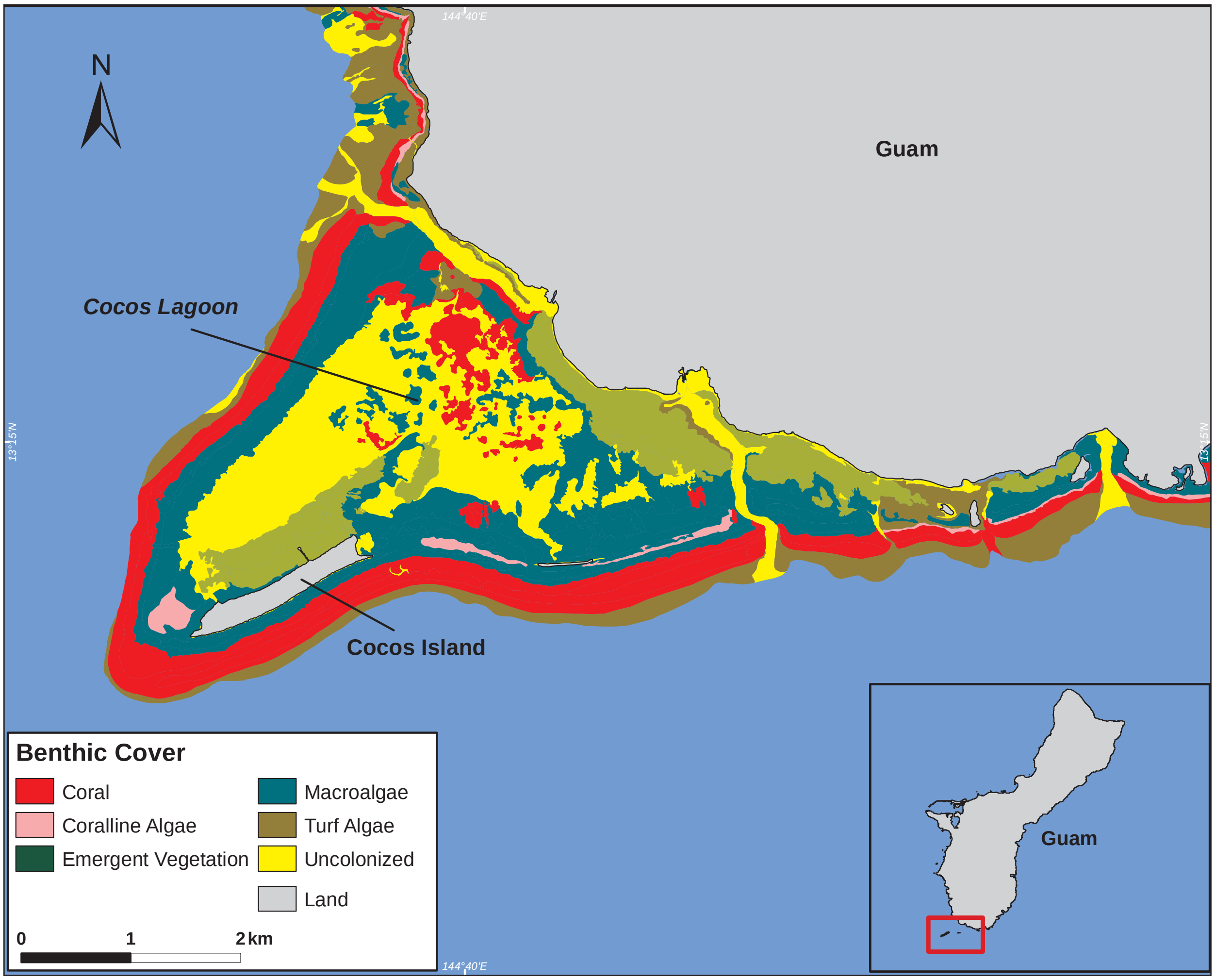


Figure 67. A portion of the habitat map showing shallow-water benthic cover for Guam Island. For the complete benthic habitat map of Guam, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

primarily found on the reef flat and reef crest. Guam has a classic fringing reef zonation pattern. The main fringing reef portion of the island transitions in a predictable pattern: shoreline intertidal, reef flat, reef crest, fore reef, bank shelf to bank shelf escarpment. The two lagoon systems are characterized by the following zonal transition: land, reef flat, lagoon, back reef, reef crest, fore reef and bank shelf. These are interspersed with several channels intersecting through the reef complex.

Applications for Science and Management

Guam Island is a highly disturbed coral reef ecosystem due to the large resident population, number of tourist visitors and anthropogenic stressors associated with the civilian and military population (Figure 68). The cumulative impact of stressors, such as sedimentation, nutrient loading, overfishing, development, planned (naval harbor expansion) and unplanned disturbances (diver destruction of reefs), has contributed to the poor condition of many of Guam's reef communities.

While Guam has five locally established marine reserves (Tumon Bay, Piti Bomb Holes, Sas Bay,

Figure 68. High-density development in Guam threatens surrounding marine ecosystems. Photo Credit: J. Jocson.

Achang Reef and Pati Point), as well as other protected areas (War in the Pacific National Historical Park, the Ritidian National Wildlife Refuge, the Orote and Haputo Ecological Reserve Areas and the Guam Territorial Seashore Park), limited management and enforcement has hindered their success. It is recognized that in order to improve the condition and health of Guam's coral reef communities, additional management measures are needed.

National Ocean Service habitat mapping products have provided a critical source of spatial information to assess the impacts of proposed military infrastructure expansion. High coral population within Apra Harbor presents a direct conflict with military efforts to dredge the harbor for deeper draft vessels and expand piers to accommodate larger class naval vessels. The habitat maps provides critical information to identify high value coral reef ecosystems and spatial coincidence with proposed construction. Additionally the maps provide the first synoptic characterization of the condition and extent of coral reef ecosystems, providing a valuable tool to assess future improvements from management measures and/or reef community decline from human impacts.

Republic of Palau

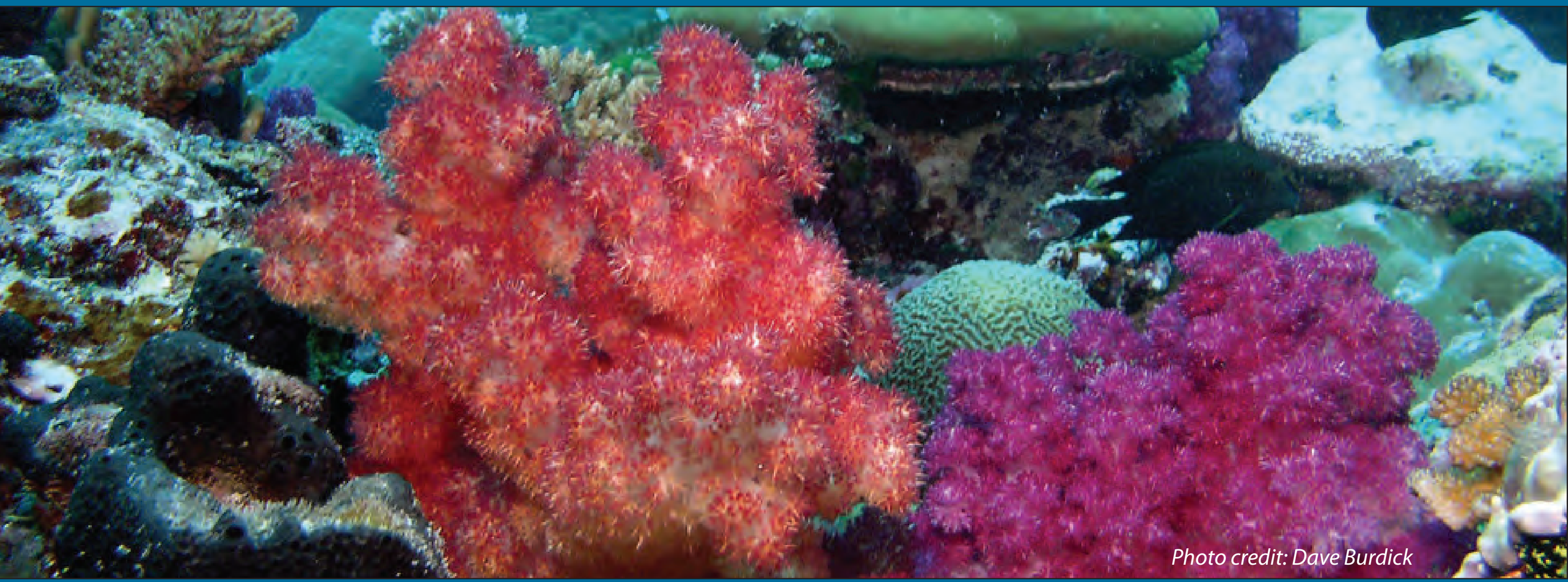


Photo credit: Dave Burdick

Introduction

The Republic of Palau (Belau) is located in the Pacific Ocean about 800 km east of the Philippines and about 1,300 km southwest of Guam. Part of the Caroline Islands group, Palau is the westernmost archipelago in Oceania, extending 160 km long in a northeast-southwest direction. It comprises a total land area of 459 km², coastline of 1,519 km, and an exclusive economic zone of 629,000 km². Palau is an archipelago comprised of over 700 islands and atolls, but only 12 of which are inhabited. Palau's most populous islands are Anguar, Babeldaob, Koror and Peleliu (Figure 69). The latter three lie enclosed within the same fringing barrier reef, while Angaur is an oceanic island several miles to the south. The Kayangel, a coral atoll, is situated north of these islands, while the uninhabited Rock Islands (not pictured in Figure 69) are situated to the west of the main island group.

Palau is a remnant of the highest peaks of the Kyushu-Palau ridge, an underwater chain of volcanic mountains which extend 2,000 km from Japan to the Island of New Guinea. The ridge rises 2 km off the adjacent basin floor, tectonic evidence of a Remnant Island Arc that was active between 42 and 32 million years ago.

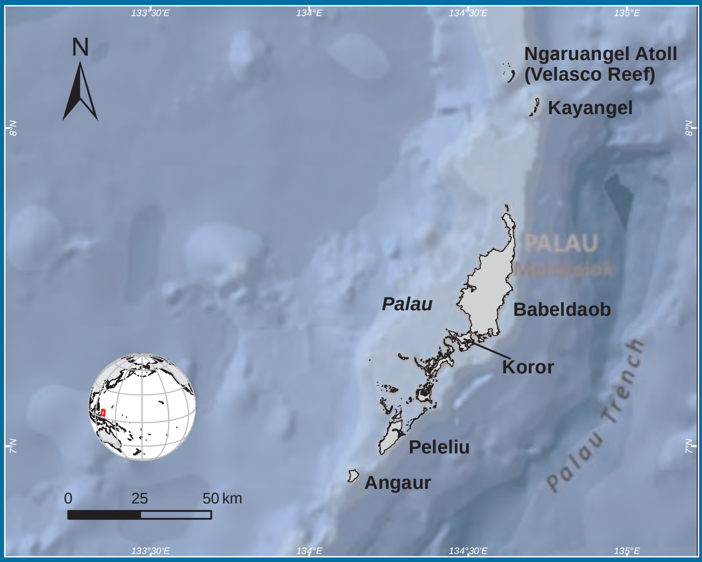


Figure 69. Map of Palau. Credit: Ken Buja and Sarah D. Hile.

Palau varies in geology and formation, but can be classified into four types of island: volcanic, reef and atoll, low platform and high limestone. Several of the islands are a combination of these four basic types. The volcanic islands (Babeldaob, Meiuns, Malakal and the western part of Koror) comprise most of the land area. Seven reef and atoll islands are located north and northeast of Peleliu. The southwest Islands are a combination of low platform islands and atolls, while the central and southern regions of the archipelago are comprised of over 300 limestone islands, the majority being the steep, coralline, limestone rock islands. These mushroom-shaped islands formed as a result of reef system uplift and Pleistocene-era sea level decline.

Palau has the most diverse coral fauna of Micronesia and the highest density of tropical marine habitats of comparable geographic areas around the world. Palau's rich marine biota include approximately 400 species of hard corals, 300 species of soft corals, 1,400 species of reef fishes, seven out of nine of the world's species of giant clam and thousands of other invertebrates (many still to be identified). In addition to coral reefs, mangroves and seagrass beds, Palau has deep algal beds, mud basins, current swept lagoon bottoms, rich tidal channels and anoxic basins within the rock islands.

Mapped Geology and Benthic Habitat

Mapping of shallow-water benthic habitats for Palau was conducted in 2007 using high-resolution, multispectral satellite imagery (Battista et al. 2007; Table 1). Approximately 1,500 km² of marine

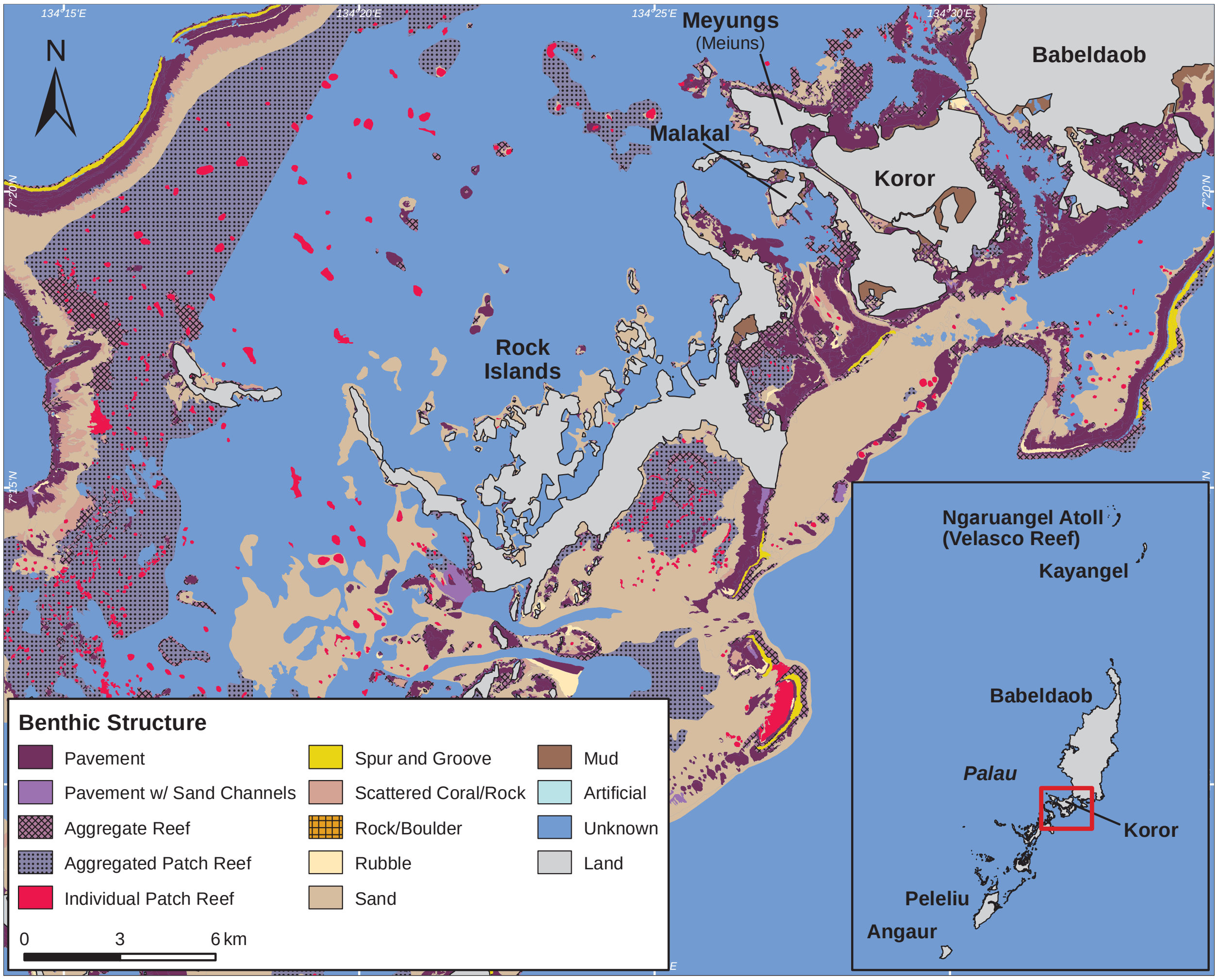


Figure 70. A portion of the benthic habitat map showing shallow-water benthic structure for the area surrounding Koror, Palau. For the complete benthic habitat map of Palau, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Figure 71. Palau general structure.

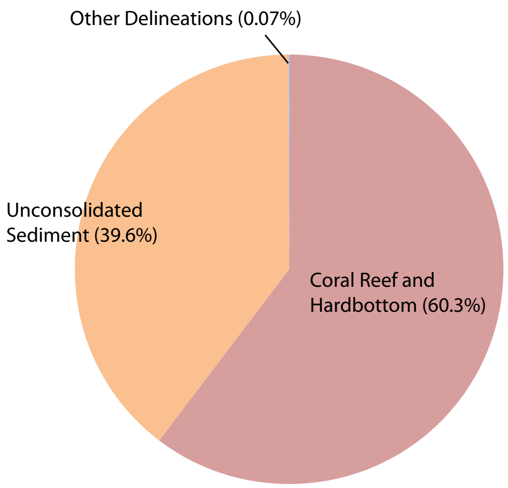


Figure 72. Palau detailed structure.

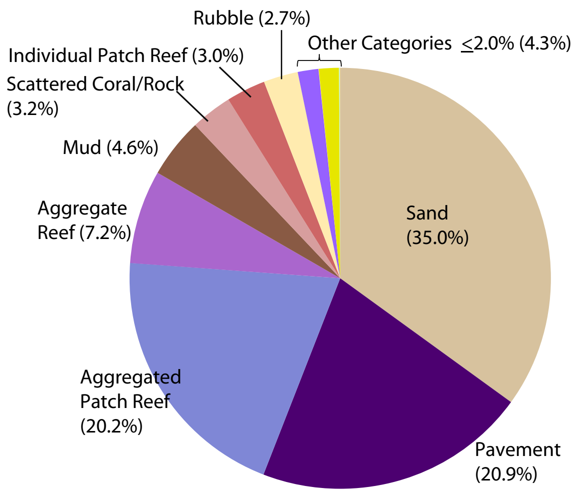


Figure 73. Palau general cover.

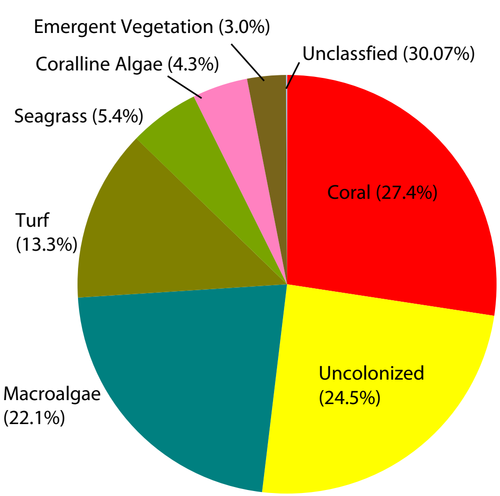
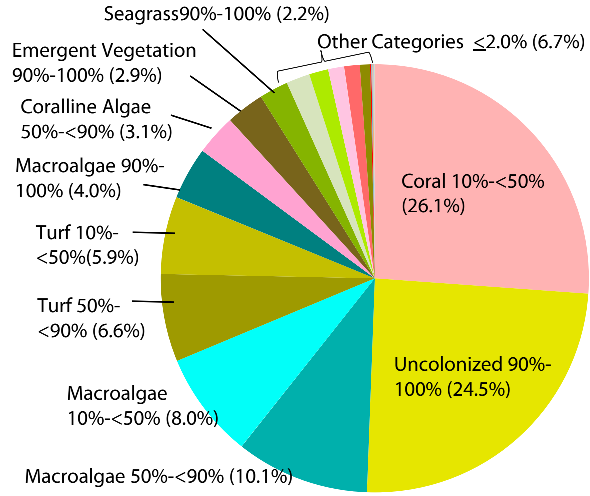


Figure 74. Palau detailed cover.



habitats from Anguar north to Ngaruangel Atoll (Velasco Reef) were mapped, but did not include Helen Reef to the south.

While unconsolidated sediment (i.e., sand) dominates the geomorphological structure in Palau (39.6% of the total area, 517 km^2; Figures 70 - 72), pavement and aggregate patch reef hard bottom structure conducive for soft and hard coral is also present in significant quantities (20.9% of the total area, 310 km^2; 20.2% of the total area, 299 km^2, Figure 72). Large expanses of these structure types occur on the western, leeward flank of the lagoon due west of Koror and the Rock Islands.

In general, low (10% - <50%) density coral and uncolonized are the dominate cover types of Palau (26.1 % of the total area, 386 km^2; 24.5% of the total area, 362 km^2, Figures 73-75). Low density coral predominates the Rock Islands and along the western extent of the lagoon. Macroalgae and turf habitat dominates in regions more heavily exposed to wave disturbance, such as the eastern flank and northern Ngerchelong Reef of Babeldoab.

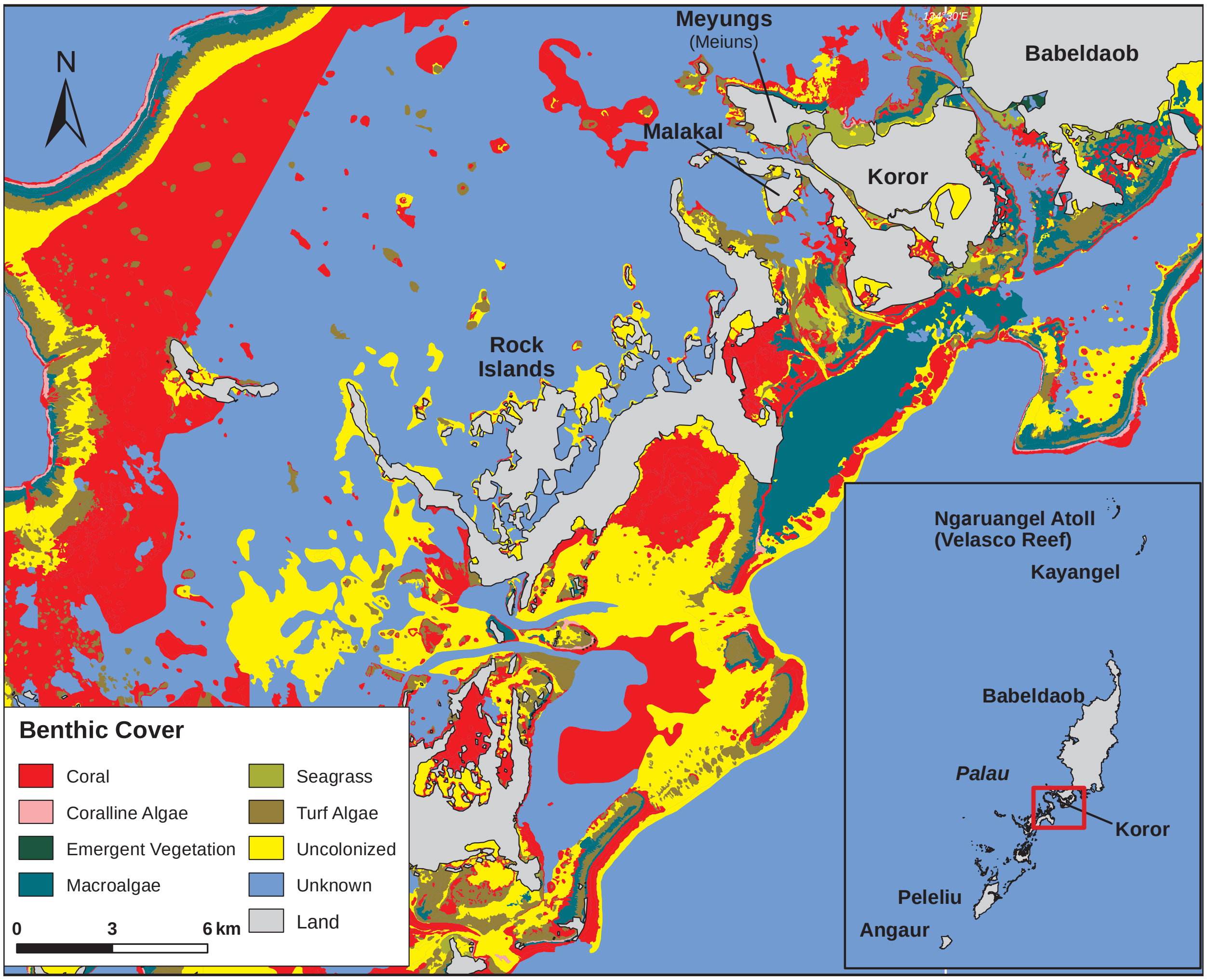


Figure 75. A portion of the benthic habitat map showing shallow-water benthic cover for Palau. For the complete benthic habitat map of Palau, see the online resources listed in Table 1. Credit: Ken Buja and Sarah D. Hile.

Palau has a mixed barrier reef-atoll zonation pattern. The main islands of Babeldaob and Koror transition in a predictable pattern: shoreline intertidal, reef flat, lagoon, back reef, reef crest, fore reef, bank shelf to bank shelf escarpment. These are interspersed with several channels intersecting through the reef complex. Reef holes are a common feature and can occur in any zone of the entire fringing reef. Also, Palau is nearly entirely surrounded by a vertical wall that commonly starts at depths of approximately 3 to 6 m and reaches depths of up to 609 m. Thus, both Reef Hole and Vertical Wall were added to the standard hierarchical classification scheme as new zones.

Applications for Science and Management

The Republic of Palau is an exceptional example of a vibrant coral reef ecosystem, due in part to its geographic isolation, but also its proactive management measures (Figure 76). Sixty-five percent of the population lives in the state of Koror, with the remaining states sparsely populated and, hence, less impacted by anthropogenic stressors. However, the completion of the Compact Road circumnavigating Babeldoab, was intended to increase accessibility to other states. Sedimentary run-off from road construction has had an immediate negative impact on near-shore coral reef habitats, however the long-term

Figure 76. Palau is home to vibrant coral reef ecosystems that support a lucrative tourism industry. On-the-ground managers use NOS benthic habitat maps as part of an ecosystem-based management strategy to conserve and better understand their unique resources. Credit: Dave Burdick.

impacts of greater accessibility to the full extent of Babeldoab is of greatest concern. Additionally, Palau's reefs fuel tourism bringing visiting divers and snorkelers from all over the world. The sheer number of visitors (68,000 visitors in 2009) and the infrastructure associated with supporting their visit (e.g. hotels, restaurants, sewage treatment) risks coral degradation.

Palau's management and research community have been very active in trying to minimize these combined effects. For instance, Palau has designated 31 marine protected areas covering nearly 40% of Palau's nearshore marine area. Locating these marine protected areas, as well as evaluating their management success, is predicated on having benthic habitat maps to evaluate habitat changes. Furthermore, the addition of future marine protected areas, as encouraged under the Micronesian Challenge, requires identifying ecological hotspots made possible by the benthic habitat map products. Monitoring the health and distribution of marine fish and habitats requires sound sampling design. The habitat maps are being utilized by management agencies to design and implement a random stratified sampling protocol based on habitat stratification of the habitat map classes.

Summary & Discussion

Photo credit: *Evan D'Alessandro, UM/RSMAS*

Since 2000, the National Ocean Service (NOS) has mapped over 12,100 km^2 of coral reef ecosystems in U.S. states and territories (Figure 77). This includes approximately 5,000 km^2 of hard bottom habitats, such as coral reef, rubble and rock formations (red bar segments in Figure 77), and another 7,100 km^2 of soft bottom habitats, such as sand and mud (green bar segments in Figure 77). The total area mapped varies widely when comparing among jurisdictions. The region with the largest mapped area by a wide margin is the Florida Reef Tract, with over 6,000 km^2 of mapped habitats. The next closest region is the Northwestern Hawaiian Islands, with approximately 2,000 km^2 mapped, followed by Puerto Rico and the Main Hawaiian Islands. The area mapped in the Main and Northwestern Hawaiian Islands combined does not encompass as large an area as has been mapped in the Florida Reef Tract. Considering only the proportion of the habitats mapped as hard bottom, the Florida Reef Tract still has the most area mapped, followed by the Northwestern Hawaiian Islands, Main Hawaiian Islands and then Puerto Rico. The Florida Reef tract is also marked by a comparatively large proportion of soft bottom habitats. The other jurisdictions make up much smaller proportions of the total mapped areas due to their relatively small size. In order of decreasing size, these include: the U.S. Virgin Islands, the Commonwealth of the Northern Mariana Islands and Guam, American Samoa, and the Pacific Remote Island Areas (Palmyra). Compared to the larger jurisdictions, these areas have a relatively greater proportion of hard bottom habitats.

Clearly this represents vast progress in understanding the distribution of coral reef habitats throughout the U.S. However, the total area mapped represents less than half of the total potential area of coral reef ecosystems defined by the 30 m depth contour. When evaluating the area of potential coral reef ecosystem remaining

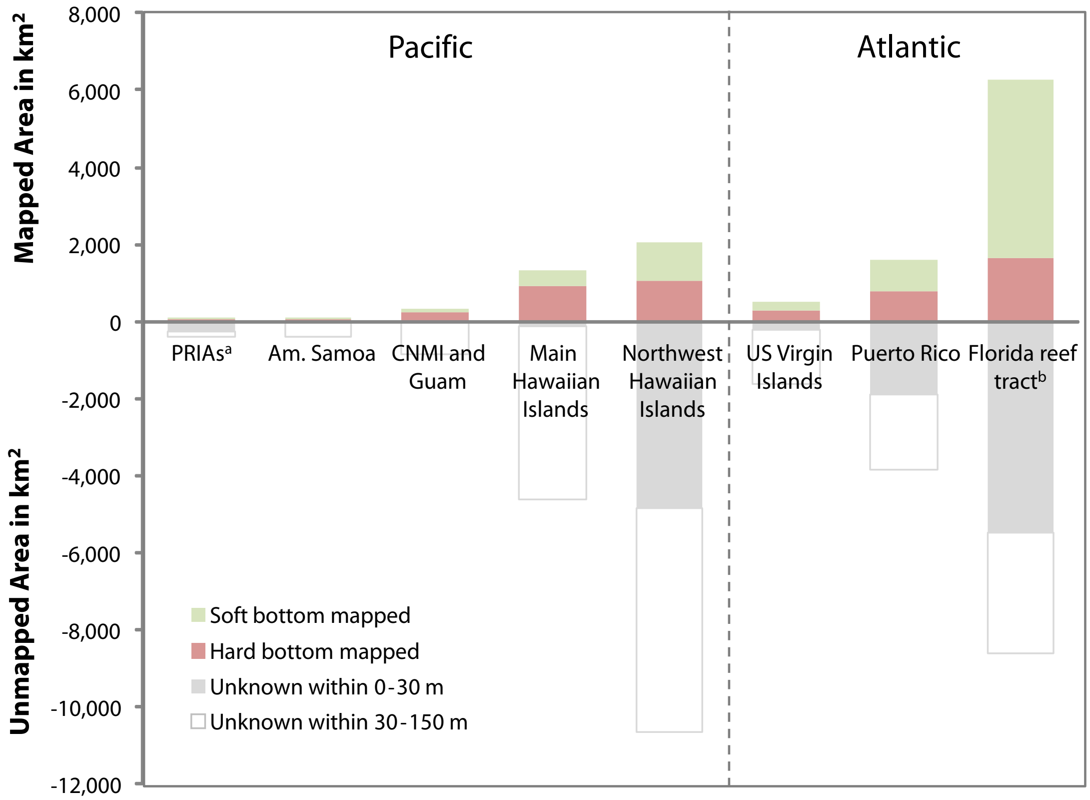


Figure 77. Total area of mapped and unmapped coral reef ecosystems in U.S. states and territories throughout the Atlantic, Caribbean and Pacific from 2000-2011. All values are in km^2.
[a] Area estimates include Howland, Baker, Jarvis, and Wake Islands, Kingman Reef, and Johnston and Palmyra Atolls.
[b] Area estimates include only a portion of the extensive West Florida Shelf (as required by the Coral Reef Conservation Program). The unknown area in Florida was intentionally limited using the approximate boundary of the Florida Keys National Marine Sanctuary. If the unknown area in Florida is extended to the 150 m depth contour associated with the West Florida Shelf up to approximately Tarpon Springs, Florida, the proportion of the total area mapped would be considerably smaller.

to be mapped, it is useful to consider the total area of sea floor where coral reefs could occur. The use of depth ranges for locations of potential reef ecosystem areas (0-30 m for shallow corals that are dependent upon sunlight, and deeper mesophotic coral reefs) has been used by a number of prior studies (Rohmann et al. 2005, Locker et al. 2010), although actual values may vary considerably depending on many local factors.

The solid grey bars in Figure 77 represent unmapped coral reef ecosystems between 0 and 30 m depth. Large regions of this shallow bottom remain to be mapped in some areas primarily due to turbid water and cloudy conditions in available remote sensing imagery. The Florida Reef Tract, the Northwestern Hawaiian Islands, Puerto Rico and the Pacific Remote Island Areas all have an especially large proportion of unmapped area for those reasons. This demonstrates the need for a continued commitment to mapping many shallow reef ecosystems. In contrast, most of the shallow reef areas have been mapped in the Commonwealth of the Northern Mariana Islands and Guam, American Samoa, the Main Hawaiian Islands and the U.S. Virgin Islands.

New Tools and Techniques Developed

Advances in Mapping Techniques

The charge of mapping the shallow-water coral reef ecosystems under U.S. jurisdiction presents NOS scientists with the opportunity to advance seafloor mapping methodologies to successfully meet the challenges of such a complex task. Since 2000, the NOS National Centers for Coastal Ocean Science (NCCOS) and its partners have advanced mapping techniques and approaches using LiDAR, multibeam and other image sources (Pittman et al. in press; Foster et al. in press). Remote sensing technology provides the data to support benthic habitat mapping and an overall approach for assessing the marine environment. Acoustic sensors have provided resource managers with a valuable tool to capture baseline information about the living marine resources. In the last decade, multibeam has been used to map benthic habitats in a number of marine managed areas across the U.S. Caribbean (e.g., Virgin Islands Coral Reef National Monument) and has overcome the difficulties associated with mapping in deep and turbid conditions. The use of new technologies and combining multiple types of remote sensing data have been developed during NOS benthic habitat mapping efforts and represent an important step in the application of remote sensing to support marine management actions.

Scientific research in this area has increased in the last decade as the number and sophistication of operational sensors grow. A collaborative project was recently completed between NCCOS, the National Park Service and other U.S. federal government, private and academic partners to produce a comprehensive habitat map of the Buck Island Reef National Monument in St. Croix, U.S. Virgin Islands. However, given the depth range of the study site, which extends from the coastline of Buck Island to 1,800 meters, there was a need to devise an innovative method that would allow for the measurement of sea floor depths as well as characterize its habitats across the entire seascape in the monument. NCCOS ultimately devised a new method that fuses the strengths of four different sonar, LiDAR and optical imagery sensors to gather the information needed. Depth, as well as other characteristics of shallow areas (0-30 m), was recorded in the monument using multispectral and LiDAR imagery. At depths of more than five meters, NCCOS used ship-based sonar technology to scan the sea bed. The derived information included the structure and biological cover, key pieces of information that resource managers need to make effective ecosystem management decisions. In early 2012, NCCOS delivered the final habitat maps, still images, videos and related applications to monument managers through the St. Croix BIOMapper, an innovative online portal designed to provide quick access to mapping information and data (Figure 78).

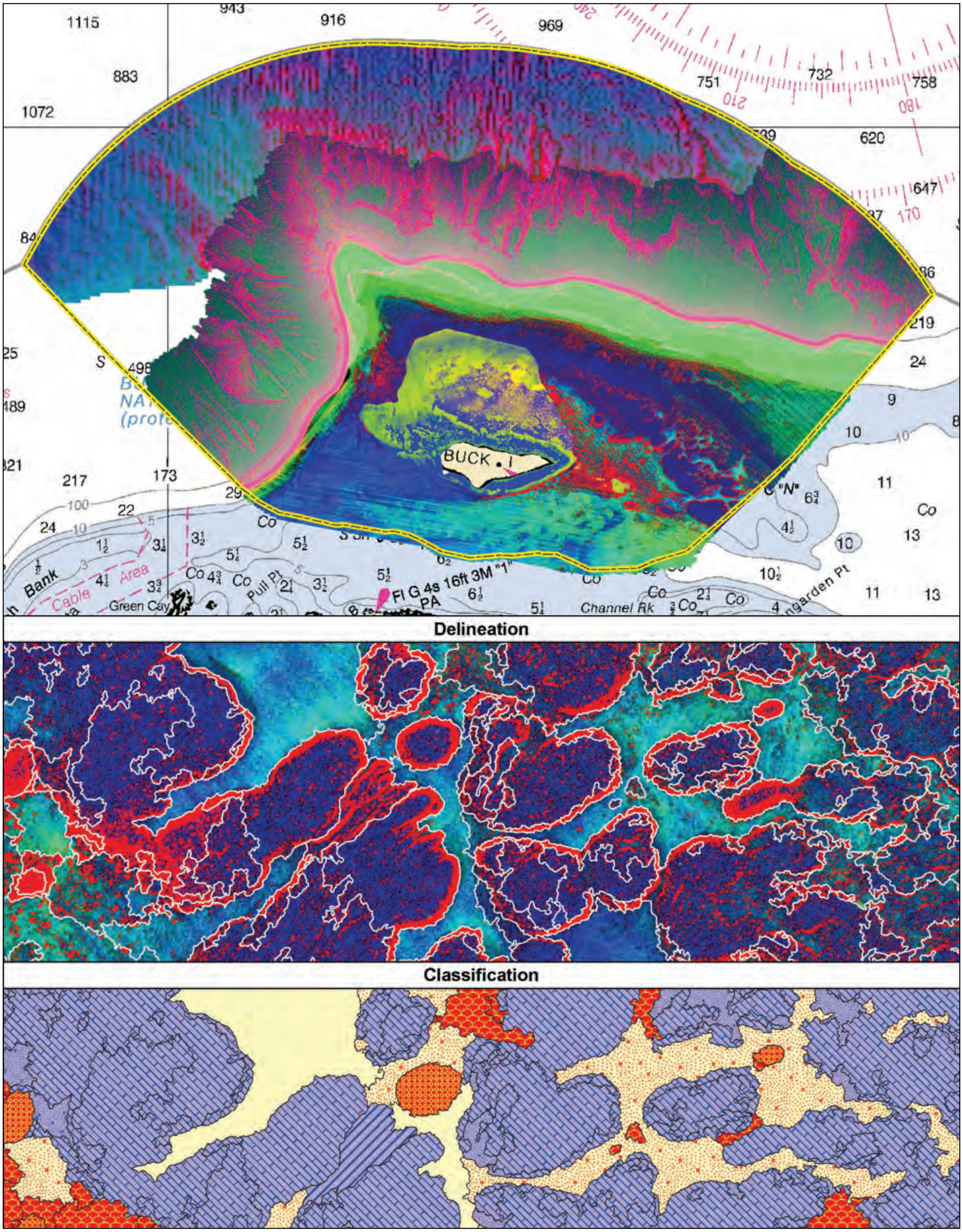


Figure 78. Maps integrating multiple acoustic sensors, multispectral and LiDAR imagery (top) to produce a seamless bathymetric product (bottom). Credit: NCCOS.

Biogeogeography Software Tools

Over the years NCCOS has also led the development of a suite of new software tools to support NOS coral reef ecosystem mapping efforts in U.S. states and territories. The major software developments included the creation of BIOMapper and the Benthic Habitat Digitizer Extension. Further, the systematic development of several hierarchical habitat classification schemes customized for unique regions (see the Map Production Process & Methods chapter) in the Pacific and Caribbean, represent a significant contribution to the coral reef mapping community.

The BIOMapper tool was developed as an interactive, online feature designed to let users explore data from benthic habitat mapping efforts in the Pacific and Caribbean (Figure 79). Currently, BIOMapper serves data from: Buck Island, U.S. Virgin Islands; Jobos Bay, Puerto Rico; Majuro, Marshall Islands; Palmyra, Pacific Remote Island Areas; Southwestern Puerto Rico; St. John, U.S. Virgin Islands; and Vieques, Puerto Rico. In 2012, data from American Samoa, the Commonwealth of the Mariana Islands, Hawaii, Palau, as well as from other areas of Puerto Rico and the U.S. Virgin Islands, will be added. There are portals for each location that provide access to a comprehensive collection of data, including aerial and acoustic imagery, benthic habitat data, survey sites, dive photography and underwater video, and related publications, as well as the ability to create customized, printable PDF maps. These data products provide a detailed, contemporary evaluation on the status, abundance and distribution of marine plants and animals for each site. The results of these efforts provide resource managers, scientists, and the public increased understanding and technical capacity for ocean exploration, management and stewardship.

The Habitat Digitizer Extension is a GIS tool designed to use a hierarchical classification scheme to delineate features by visually

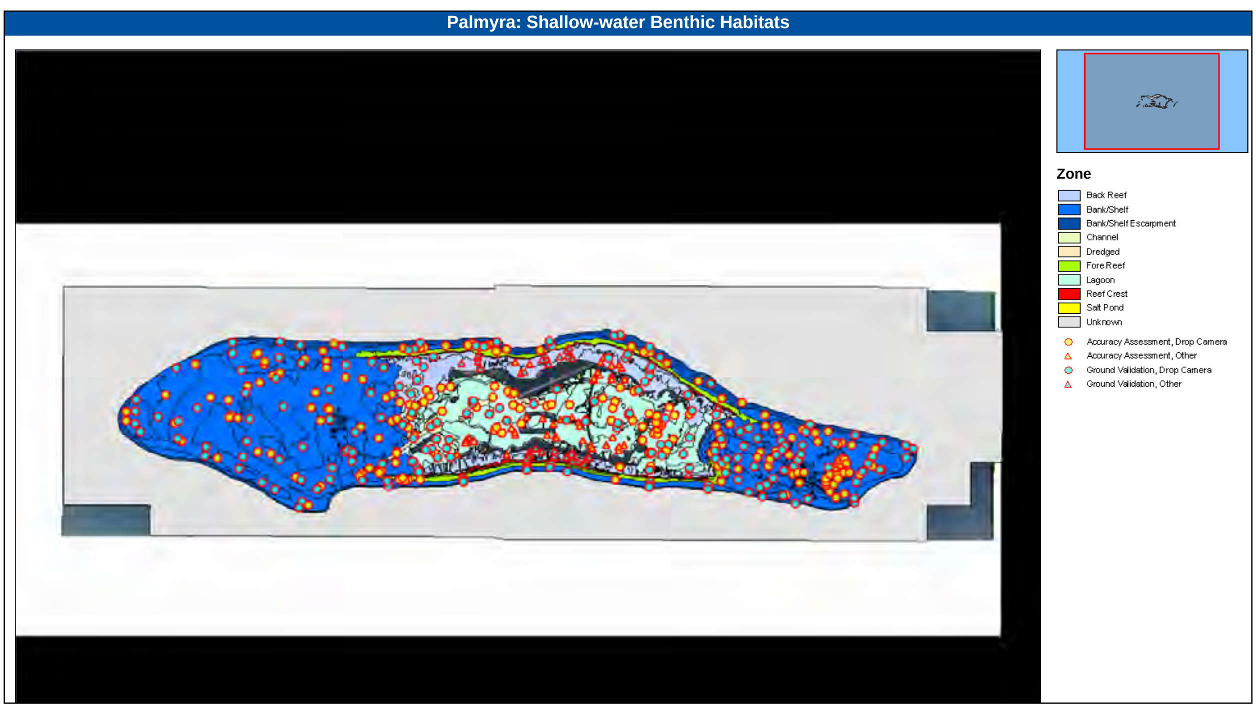


Figure 79. An example of a customized map of Palmyra generated by the Palmyra BIOMapper.

interpreting georeferenced images, such as aerial photographs, satellite images and side scan sonar. The extension allows users to create custom classification schemes, digitize polygons, lines, and points using standard ArcGIS editing tools, and attribute the features using a dialog box containing the user-created scheme. The extension allows new hierarchical classification schemes to be easily created, modified and saved for use on future mapping projects. There are several advantages to using classification schemes with a hierarchical structure: the detail of habitat categories can be expanded or collapsed, the thematic accuracy of each category/hierarchical level can be determined, and additional categories can be easily added or deleted at any level of the scheme to meet user needs. This GIS tool has been useful in benthic habitat mapping projects in the Pacific and Caribbean since it's development.

Future Priorities

NOS and its partners have made tremendous strides in addressing the goal to map all U.S. shallow-water coral reef ecosystems. However, despite the U.S. Coral Reef Task Force's initial charge to create baseline maps for all areas, several locations of significant importance still have large regions that are uncharacterized. The regions with the largest remaining areas of unmapped shallow-water (0-30 m) habitats include the Pacific Remote Island Areas (85%), the Northwestern Hawaiian Islands (70%), Florida Keys (47%) and Puerto Rico (55%). The absence of comprehensive information on these regions confounds and limits efforts to synoptically compare and contrast the condition and extent of coral reefs across their entire management purview. The Pacific Remote Island Areas and the Northwestern Hawaiian Islands Monuments are widely recognized to have some of the largest and healthiest populations of coral reef ecosystems remaining in the world due to their isolation from human disturbances. Conversely, the Florida Keys coral reef ecosystem has undergone declines in condition due to increasing anthropogenic pressure.

In addition to the shallow areas that have been the focus of much of the satellite and aerial based mapping effort to date, there are vast areas of deeper reef habitat that remain to be mapped in nearly all jurisdictions. These deeper regions in the 30-150 m depth range are shown as white bars in Figure 77. These deeper areas make up the majority of the unmapped area for many jurisdictions (American Samoa, the Commonwealth of the Northern Mariana Islands and Guam, the Main Hawaiian Islands and the U.S. Virgin Islands) and substantial proportions of others (Northwestern Hawaiian Islands, Puerto Rico and Florida). Benthic mapping in these deeper areas can only be done through techniques such as multibeam sonar.

The science of mapping has evolved dramatically through the efforts of NCCOS, the Coral Reef Conservation Program and the Office of National Marine Sanctuaries. Researchers with the center have been able to maximize the use of technologies that were previously unavailable to advance the accuracies, resolution and thematic content of products to better serve resource managers. This includes the implementation of airborne bathymetric LiDAR systems, the latest generation of high-resolution commercial satellite imagery (i.e., WorldView2 and GeoEye2), digital drop camera field validation techniques, improved classification schemes and hybrid mapping techniques discussed in the previous section.

Addressing mapping priorities will be determined by a combination of factors, the most important of which are level of funding available, management relevance, ship availability and funding leveraged from partners. The NOS coral ecosystem mapping team consults regularly with all jurisdictions to update their needs and priorities and projects are planned in collaboration with jurisdictional managers. The NOS mapping team and its partners will continue to address the above priorities in an effort to provide accurate, timely, and spatially comprehensive shallow water benthic habitat maps to support research, monitoring, and assessment that aids in the conservation of the nation's coral reef ecosystems.

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Photo credit: NCCOS/CCMA Biogeography Branch

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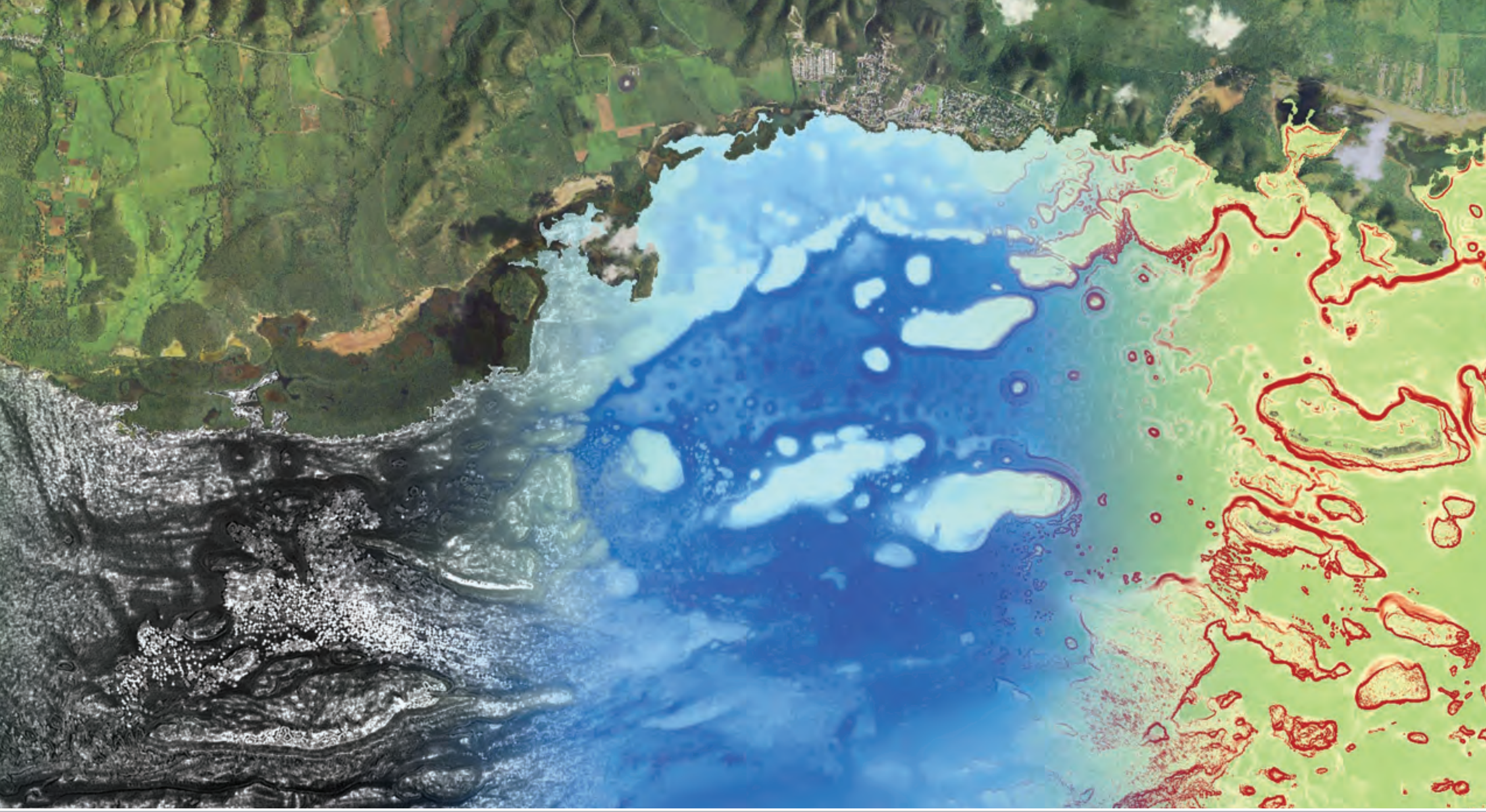

U.S. Department of Commerce

Rebecca Blank, *Acting Secretary*

National Oceanic and Atmospheric Administration

Jane Lubchenco, *Under Secretary for Oceans and Atmosphere*

National Ocean Service

David M. Kennedy, *Assistant Administrator for Ocean Services and Coastal Zone Management*




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