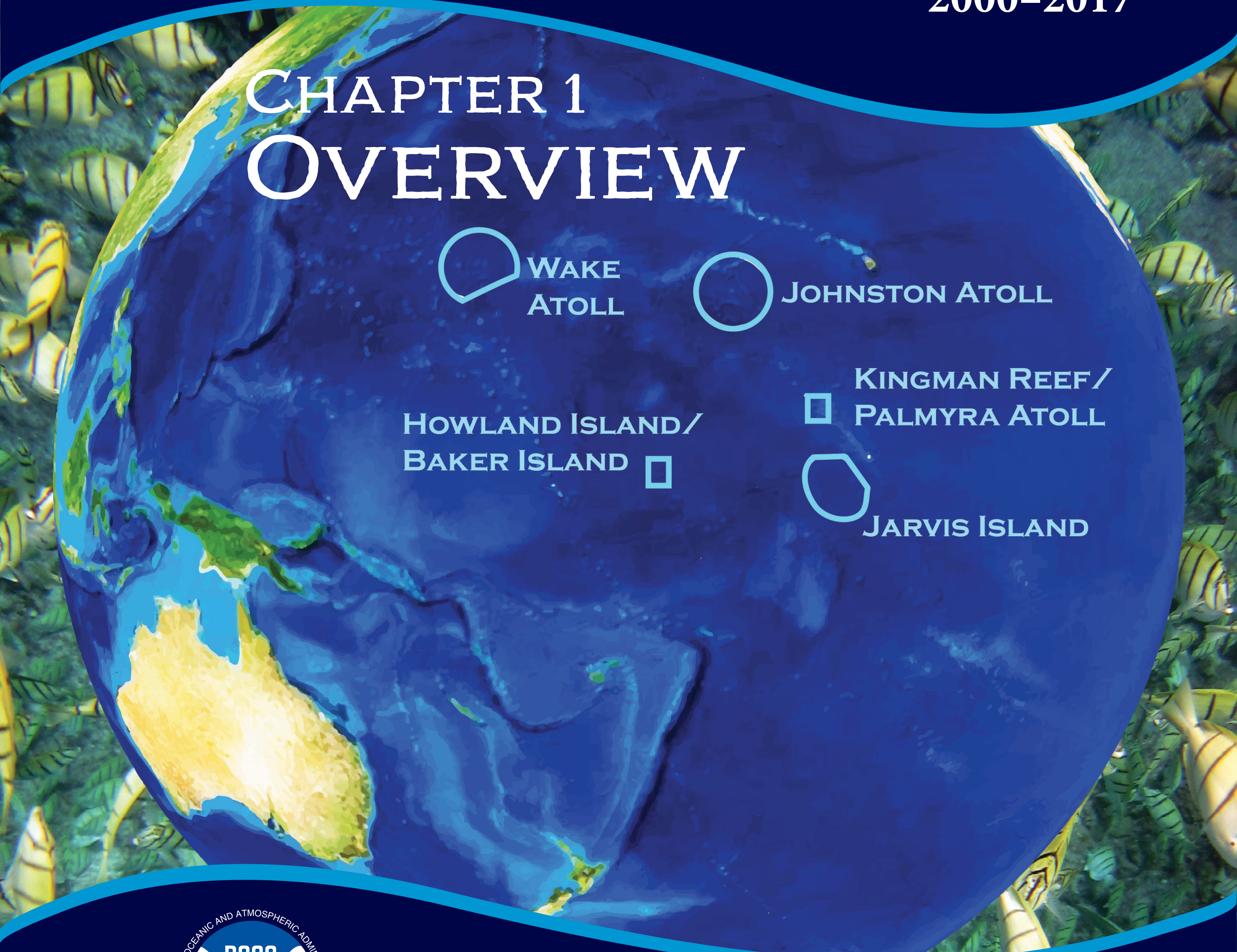
Coral Reef Ecosystem Monitoring Report for The Pacific Remote Islands Marine National Monument

2000–2017

Chapter 1
Overview



NOAA Fisheries

Ecosystem Sciences Division

Pacific Islands Fisheries Science Center

Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument 2000–2017

Chapter 1: Overview

Introduction, Report Structure, Operational Background, and Methods

Authors

Brainard, Russell E.[1]; Acoba, Tomoko[2]; Asher, Megan A.M.[2]; Asher, Jacob M.[2]; Ayotte, Paula M.[2]; Barkley, Hannah C.[2]; DesRochers, Annette[2]; Dove, Dayton[2]; Halperin, Ariel A.[2]; Huntington, Brittany[2]; Kindinger, Tye L.[2]; Lichowski, Frances[2]; Lino, Kevin C.[2]; McCoy, Kaylyn S.[2]; Oliver, Thomas[1]; Pomeroy, Noah[2]; Suka, Rhonda[2]; Timmers, Molly[2]; Vargas-Ángel, Bernardo[2]; Venegas, Roberto M.[2]; Wegley Kelly, Linda[3]; Williams, Ivor D.[1]; Winston, Morgan[2]; Young, Charles W.[2]; Zamzow, Jill[2]

[1]National Oceanic and Atmospheric Administration, Pacific Islands Fisheries Science Center
[2]University of Hawaii, Joint Institute for Marine and Atmospheric Research
[3]San Diego State University

PIFSC Special Publication SP-19-006a
2019

United States Department of Commerce, National Oceanic and Atmospheric Administration,
National Marine Fisheries Service, Pacific Islands Fisheries Science Center

NOAA Inouye Regional Center
Attn: NMFS/PIFSC/Ecosystem Sciences Division
1845 Wasp Boulevard, Building 176
Honolulu, Hawaii 96818 U.S.A.

This report is a deliverable for the NOAA Coral Reef Conservation Program's National Coral Reef Monitoring Program (NCRMP) Data, Reports, and Information Products for Management, Project ID 31186. It also contributed to the NOAA Pacific Islands Fisheries Science Center (PIFSC) Milestone P19-ESD-05 and PIFSC Accomplishment P19-ESD-36. The data used to generate this report are described in the NOAA Fisheries Enterprise Data Management tool, InPort, at the following link: https://inport.nmfs.noaa.gov/inport/item/53206. In addition, all monitoring data are archived with the NOAA National Centers for Environmental Information and most benthic habitat mapping data and products are available on the PIFSC Ecosystem Sciences Division's Pacific Islands Benthic Habitat Mapping Center website, unless otherwise specified in the InPort record.

Citations

This report as a whole may be referenced in the following manner:

Brainard RE, Acoba T, Asher MAM, Asher JM, Ayotte PM, Barkley HC, DesRochers A, Dove D, Halperin AA, Huntington B, Kindinger TL, Lichowski F, Lino KC, McCoy KS, Oliver T, Pomeroy N, Suka R, Timmers M, Vargas-Ángel B, Venegas RM, Wegley Kelly L, Williams ID, Winston M, Young CW, Zamzow J (2019) Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument 2000–2017. Pacific Islands Fisheries Science Center, PIFSC Special Publication, SP-19-006. 820 p.

This chapter may be referenced in the following manner:

Brainard RE, Acoba T, Asher MAM, Asher JM, Ayotte PM, Barkley HC, DesRochers A, Dove D, Halperin AA, Huntington B, Kindinger TL, Lichowski F, Lino KC, McCoy KS, Oliver T, Pomeroy N, Suka R, Timmers M, Vargas-Ángel B, Venegas RM, Wegley Kelly L, Williams ID, Winston M, Young CW, Zamzow J (2019) Chapter 1: Overview. In: Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument 2000–2017. Pacific Islands Fisheries Science Center, PIFSC Special Publication, SP-19-006a, 101 p. doi:10.25923/3aw7-7m67

For more information or to download a copy of this publication:

http://go.usa.gov/xpRRx

Front Cover: Surgeonfish (*Acanthurus triostegus)* at Jarvis Island. Photo: Kevin Lino, NOAA Fisheries. Map of the Pacific Remote Islands Marine National Monument.

Back Cover:
Top two rows reading top (portraying back cover of each island chapter) to bottom (portraying front cover of each island chapter), from left to right.

Palmyra Atoll: *Carcharhinus amblyrhynchos* within coral reef ecosystem. Photo: Jeff Milisen; *Chaetodon trifasciatus*. Photo: James Maragos, U.S. Fish and Wildlife Service.

Kingman Reef: *Lutjanus bohar*. Photo: James Morioka, NOAA Fisheries. *Tridacna maxima*. Photo: Megan Moews-Asher, NOAA Fisheries.

Jarvis Island: *Carcharhinus amblyrhynchos* among *Sphyraena qenie*. Photo: James Morioka, NOAA Fisheries. *Carcharhinus amblyrhynchos* and *Anthias*. Photo: Andrew E. Gray, NOAA Fisheries.

Wake Atoll: *Myripristis berndti; Bolbometopon muricatum*. Photos: Andrew E. Gray, NOAA Fisheries.

Bottom two rows reading top (portraying front cover of each island chapter) to bottom (portraying back cover of each island chapter), from left to right.

Johnston Atoll: Coral reef ecosystem. Photo: Marc Nadon, NOAA Fisheries. Coral reef ecosystem and array of reef fish. Photographer unknown.

Howland Island: *Chlorurus frontalis.* Photo: Jacob Asher, NOAA Fisheries. *Chaetodon meyeri*. Photo: Ariel Halperin, NOAA Fisheries.

Baker Island: *Acropora* and *Caranx lugubris*. *Acropora* and several *Anthias* spp. Photos: Jeff Milisen.

Map of the Pacific Remote Islands Marine National Monument.

Table of Contents

Executive Summary

The work presented within the *Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument 2000—2017* is a direct result of nearly 20 years of research in the U.S. Pacific Remote Islands Marine National Monument (PRIMNM), conducted over hundreds of field days aboard National Oceanic and Atmospheric Administration (NOAA) ships, by dozens of contributors from NOAA, University of Hawaii–Joint Institute for Marine and Atmospheric Research, and partner scientists. For their efforts, we are eternally grateful and appreciative of their work.

Here, we examine seven islands and atolls within the PRIMNM, using a variety of methods across multiple disciplines in order to gauge how these unique ecosystems have fared through time. In brief, this report describes and highlights the spatial patterns and temporal trends of marine ecosystems associated with Johnston Atoll, Howland Island, Baker Island, Jarvis Island, Palmyra Atoll, Kingman Atoll, and Wake Atoll, along with cross-comparative assessments among the islands, reefs, and atolls of the PRIMNM and other island areas of the U.S. Pacific Islands region in “Chapter 9: Pacific Remote Islands Marine National Monument in the Pacific-wide Context.”

Each island, reef, and atoll chapter, along with the Pacific-wide chapter, is constructed as follows: Introduction, Benthic Characterization, Ocean and Climate Variability, Coral Reef Benthic Communities, Cryptofauna Biodiversity (in the Pacific-wide chapter only), Microbiota, Reef Fishes, Marine Debris, and Ecosystem Integration.

Key Findings

- Given the wide geographic extent and large variance in oceanographic conditions experienced across the PRIMNM, it is more informative to consider the PRIMNM as three groupings: the northernmost oligotrophic islands of Johnston and Wake Atolls, the central transition islands of Kingman Reef and Palmyra Atoll, and the equatorial upwelling islands of Howland, Baker, and Jarvis Islands.
- Due to the combined effects of equatorial and locally-intense topographic upwelling of the eastward-flowing subsurface Equatorial Undercurrent, Jarvis Island, and to a lesser extent Howland and Baker Islands, are subject to noticeably cooler mean sea surface temperatures (SSTs) than their nearest neighbors (Palmyra Atoll and Kingman Reef). The upwelling routinely experienced by these islands further results in the highest chlorophyll *a* (chl-*a*) concentrations and associated biological productivity measured across the PRIMNM. In contrast, the lower chl-*a* concentrations observed at Wake and Johnston Atolls are similar to concentrations within the Mariana Archipelago and American Samoa, which are located in the oligotrophic gyres of the North Pacific and South Pacific.
- Higher aragonite saturation values correspond to the greater availability of carbonate ions, and thus favor the growth of corals, crustose coralline algae, and other marine calcifiers. The PRIMNM’s northernmost oligotrophic islands (Johnston and Wake Atolls) retained two of the lowest average carbonate accretion rates in the U.S. Pacific Islands, indicating low reef growth over time.

- Jarvis Island experienced a massive decline in coral cover in response to acute thermal stress associated with the 2015–2016 El Niño warming event; Jarvis has shown no substantial recovery in coral cover since. Coral cover at Baker Island and Kingman Reef also declined from 2015 to 2018, reflecting a 13% decline over 3 years at both islands.
- Calcifiers comprised approximately half of the benthic communities at Howland Island, Kingman Reef, and Baker Island. Despite Jarvis's catastrophic decline in coral cover in 2016, the recent proportion of calcifiers at Jarvis Island remains high, likely due to a marked increase in cover of crustose coralline algae (CCA) observed in 2018.
- Across the PRIMNM, the crown-of-thorns sea star (*Acanthaster planci*, COTS) was consistently observed only at Kingman Reef and Johnston Atoll, though densities at these islands fluctuated across survey years. Localized outbreaks that were synchronized in timing across central Pacific reefs appeared to be genetically independent, rather than spread via the planktonic larvae released from a primary outbreak source.
- Mean reef fish biomass varied by a factor of >15 among all U.S. Pacific islands surveyed. The equatorial upwelling and central transition islands of the PRIMNM were among the islands that retained the highest biomass, especially of piscivores and planktivores, although Wake Atoll was an exception to this trend.
- The PRIMNM has also been notable for supporting larger abundances of species listed by the Endangered Species Act (ESA), including the greatest densities of the green sea turtle (*Chelonia mydas*) observed in the U.S. Pacific.

Scientists are increasingly recognizing the magnitude of ongoing and projected effects from global warming and ocean acidification on coral reef ecosystems. As such, this report provides an essential scientific foundation for informed decision making for the long-term conservation and management of the coral reef ecosystems within the PRIMNM. By summarizing trends in ecosystem response across space and time, this report is the first step towards assessing ecosystem resilience and identifying potential underlying drivers that impede or promote such resilience. Understanding these trends can inform the prioritization among candidate areas for management, as well as among the various types of policies and management actions themselves. In conclusion, the individual island, reef, atoll and Pacific-wide comparison chapters give resource managers and policymakers an unprecedented scale of spatial status and temporal trends to examine each ecosystem throughout the PRIMNM, with the hope of protecting and conserving these unique resources for generations to come.

Acknowledgements

We would like to give credit to all National Oceanic and Atmospheric Administration (NOAA) Pacific Islands Fisheries Science Center (PIFSC) and Research Corporation of the University of Hawaii/Joint Institute for Marine and Atmospheric Research (JIMAR) scientists and staff, and the numerous partners who provided support to the Pacific Reef Assessment and Monitoring Program (Pacific RAMP) during 2000–2017, and contributed to the development of this report. We extend a special thanks to the officers and crews from the NOAA Ships *Townsend Cromwell*, *Oscar Elton Sette*, and *Hi'ialakai* who provided field support for the Pacific RAMP surveys. We further express our sincere appreciation to PIFSC, JIMAR, the NOAA Coral Reef Conservation Program (CRCP), and Pacific Islands Regional Office (PIRO) for funding and providing collaborative resources throughout these efforts.

We specifically acknowledge Malia Chow as PIRO branch chief for the Essential Fish Habitat-Pacific Marine National Monuments, along with PIRO's Heidi Hirsh and Richard Hall for their collaboration, reviews, and inputs throughout this report's genesis, along with their participation in associated workshops. We would like to recognize the United States Fish and Wildlife Service Pacific Islands Refuges and Monuments Office for their partnership throughout Pacific RAMP history and their participation in the workshops associated with the report. In addition, we appreciate their reviews and those of PIRO interns Jesi Bautista and Savannah Smith of Kupu Hawaii, who collectively provided valuable inputs toward the "History and Human Influences" sections for each island, reef, and atoll chapter. We further extend our thanks to the United States Air Force, 611th CES/CEIE, Joint Base Pearl Harbor, Hawaii for their collaborative efforts at Wake Atoll and inputs toward the report and at workshops.

We would like to recognize PIFSC Editorial Services, in particular, Jill Coyle, Katie Davis, and Hoku Johnson for their inputs throughout the editorial process, Donald Kobayashi, PIFSC, for his extensive time and insights in conducting chapter technical reviews, and PIFSC Director Michael Seki and PIFSC ESD Director Frank Parrish for their support and reviews. In addition, we wish to express our gratitude to the CRCP Coral Reef Information System and JIMAR data managers for their efforts to manage and make Pacific RAMP data publicly accessible and compliant with the Public Access to Research Results requirements.

Lastly, we are appreciative of Tom Hourigan and Dale Brown of NOAA Fisheries, two of the earliest visionaries in the establishment of the first Pacific long-term, integrated ecosystem-based monitoring program.

PIFSC has been fortunate to work with many partners who contributed to Pacific RAMP and associated efforts, and while this list is by no means comprehensive, we sincerely thank each and every one of you. Your contributions helped make this report possible, and as a result, we have collectively provided valuable inputs to the management and conservation of the coral reef ecosystems of the Pacific Remote Islands Marine National Monument.

Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument 2000–2017

Chapter 1: Overview

Introduction, Report Structure, Operational Background, and Methods

NOAA Ship Oscar Elton Sette *off of Johnston Atoll.*
Photo: James Maragos, U.S. Fish and Wildlife Service.

1.1 Introduction

*Photos from the seven Pacific Remote Islands Marine National Monument atolls, islands, and reefs from top to bottom, left to right: wahoo (*Acanthocybium solandri*) at Wake Atoll, photo: Andrew E. Gray; black jack (*Caranx lugubris*) at Jarvis Island, parrotfish (*Chlorurus microrhinos*) and benthic habitat at Kingman Reef, and surgeonfish (*Acanthurus triostegus*), photos: Kevin Lino; Christmas tree worm (*Spirobranchus giganteus*) at Baker Island, photo: Hatsue Bailey; grouper at Wake Atoll, photo: Andrew E. Gray; jack and grey reef shark (*Carcharhinus amblyrhynchos*) at Jarvis Island, photo: Ariel Halperin; butterflyfish swimming over coral head at Palmyra Atoll, photo: Ariel Halperin; small giant clam (*Tridacna maxima*) amongst coral at Kingman Reef, photo: Megan Moews-Asher; surgeonfish (*Naso lituratus*) at Johnston Atoll, photo: Paula Ayotte; benthic community at Howland Island. All photos courtesy NOAA Fisheries.*

History of Coral Reef Ecosystem Monitoring and the Pacific Reef Assessment and Monitoring Program

National coral reef conservation efforts in the United States were advanced in 1998, with the issuance of Presidential Executive Order 13089 by President Clinton to "preserve and protect the biodiversity, health, heritage, and social and economic value of U.S. coral reef ecosystems and the marine environment" (Clinton 1998). This executive order established the U.S. Coral Reef Task Force (USCRTF) and emphasized the need to undertake a comprehensive approach to research, map, and monitor all U.S. coral reef ecosystems. In 2000, the USCRTF developed the

National Action Plan to Conserve Coral Reefs (Force 2000), and the *Coral Reef Conservation Act of 2000* laid out a national framework to address the degradation of U.S. coral reef ecosystems and other coral reef conservation issues (16 U.S. Code §6401 [2000]). The NOAA Coral Reef Conservation Program (CRCP) was established in 2000 to help fulfill NOAA's responsibilities under the *Coral Reef Conservation Act* and Presidential Executive Order 13089 on Coral Reef Protection (Clinton 1998).

In response to these federal mandates and with the support of CRCP, the NOAA Southwest Fisheries Science Center's Honolulu Laboratory initiated the Pacific Reef Assessment and Monitoring Program (Pacific RAMP) in early 2000, and established the Coral Reef Ecosystem Investigation (CREI) in 2001. In 2002, NOAA, in cooperation with the USCRTF, released *A National Coral Reef Action Strategy* to address and reduce threats to coral reefs worldwide. With the establishment of Pacific Islands Fisheries Science Center (PIFSC) in 2003, CREI was converted into the Coral Reef Ecosystem Division (CRED), which implemented Pacific RAMP through 2016, when another reorganization changed CRED into the Coral Reef Ecosystem Program (CREP) under a new Ecosystem Sciences Division (ESD) within PIFSC. Further reorganization in 2017 moved the former CREP staff into other programs under ESD. In this document, we will refer to all past activities conducted by CREI, CRED, and CREP by the name ESD for simplicity.

The ESD continues to provide science in support of the mission to address and reduce threats to coral reefs by conducting a comprehensive suite of interdisciplinary monitoring and research activities, including habitat mapping, oceanographic and climate studies, and long-term monitoring of coral reef ecosystems in the U.S.-affiliated Pacific Islands (Figure 1). The ESD's goal is to provide high-quality, unbiased ecosystem-based data and information products to resource managers, policymakers, the public, and scientists on local, regional, national, and international levels in a timely manner. The ESD conducted biennial (every 2 years) Pacific RAMP surveys from 2000 to 2012, and triennial (every 3 years) surveys since 2012, in each of the U.S.-affiliated Pacific Islands management jurisdictions. Accurate and up-to-date characterizations of the status and trends of coral reef ecosystems are necessary to inform ecosystem-based management and evaluate the effectiveness of management actions for sustainable use and long-term conservation. Pacific RAMP survey results are also used to improve our understanding of ecosystem processes and the cause-and-effect mechanisms that influence the status and resilience of coral reefs.

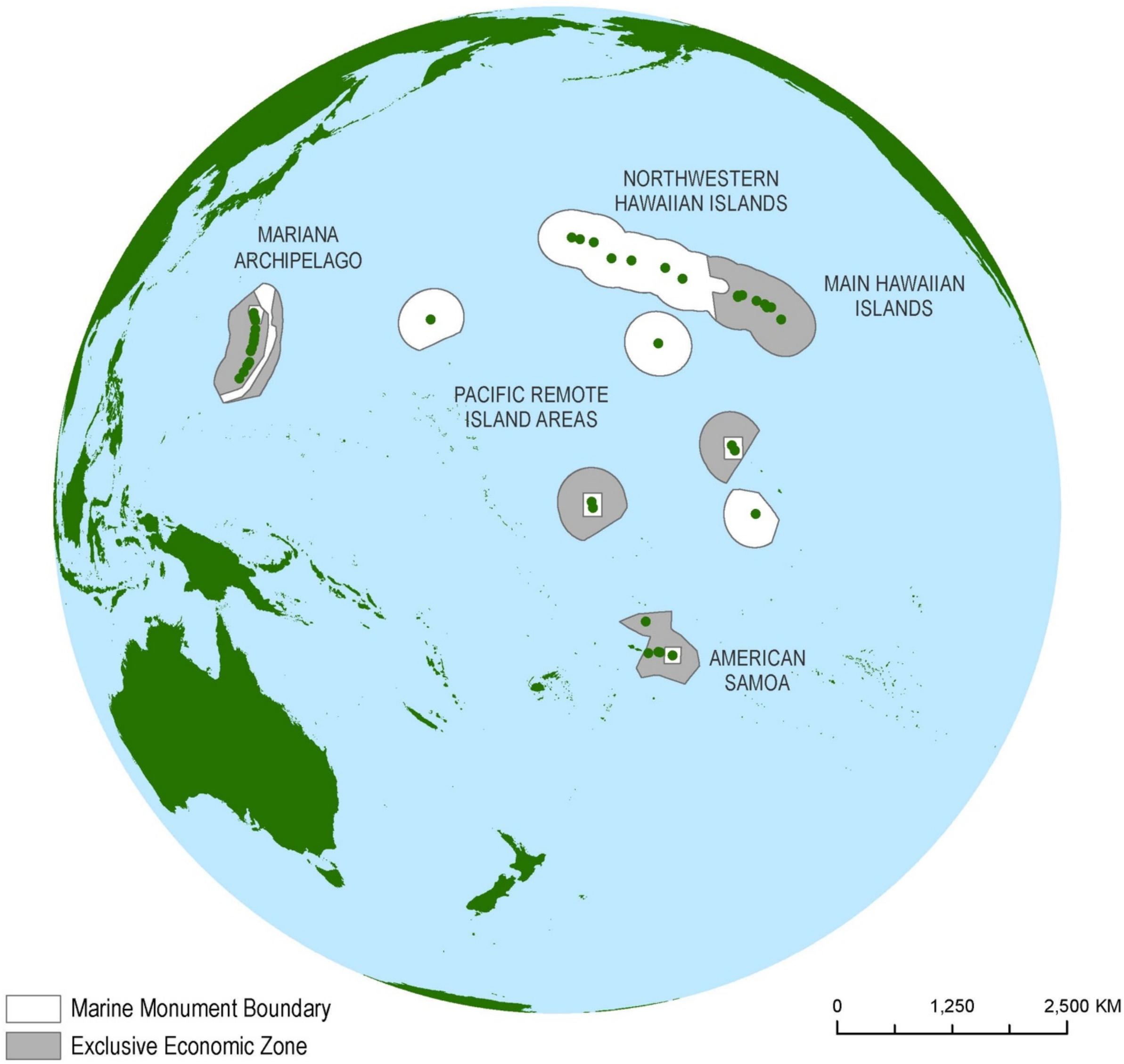


Figure 1. Ecosystem Sciences Division (ESD) area of work in the Pacific. ESD monitors the status and trends of coral reef ecosystems of ~40 islands, atolls, and shallow banks spanning the waters of American Samoa, the Hawaiian Archipelago, the Mariana Archipelago (including the Mariana Trench Marine National Monument), and the Pacific Remote Islands Marine National Monument (PRIMNM). Gray areas represent the U.S. Exclusive Economic Zones, with the white areas representing the four large Marine National Monuments (MNM) in the Pacific, including Papahānaumokuākea MNM in the Northwestern Hawaiian Islands, PRIMNM, Mariana Trench MNM, and Rose Atoll MNM in American Samoa.

ESD's integrated coral reef ecosystem monitoring uses a suite of complementary standardized methods to systematically assess corals, algae, other invertebrates, fishes, and microbes in the context of their benthic habitats and varying oceanographic and water-quality environments. These methods are used consistently across the U.S. Pacific Islands region (PIR) to enable comparative ecosystem analyses across diverse biogeographic, environmental, oceanographic, and socioeconomic (human use) gradients. Monitoring coral reef ecosystems across these complex and diverse gradients makes it possible to significantly improve our understanding of the ecosystem processes that structure coral reefs ecosystems across the PIR, and identify potential cause-and-effect mechanisms that influence the health and resilience of coral reef ecosystems over time.

Ecosystems are significantly influenced by processes both within and well beyond local jurisdictional boundaries. The Pacific RAMP aims to assist local and regional resource managers by providing essential information about these ecosystem processes that can potentially influence local and regional resources. As such, the Pacific RAMP is envisioned as a key component of the national backbone to provide broad-scale baseline assessments for the PIR. Pacific RAMP provides an improved understanding of island- and region-scale conditions that serve as context to support more frequent and finer-scale monitoring and to evaluate effectiveness of local management actions. These baseline assessments are explicitly expected to be complemented by more focused, local monitoring programs within each jurisdiction, including those jurisdictions funded by CRCP-administered coral reef monitoring grants.

The initial exploratory surveys of the Pacific RAMP in 2000–2003 provided the first-ever baseline characterizations of the biodiversity, abundance, and distributions of coral reef habitats and associated resources across the PIR. Those early surveys and the inherent logistical and budgetary constraints posed by the vast and remote PIR have shaped many aspects of the long-term Pacific RAMP. By collecting biennial and triennial “snapshot” surveys of these reef ecosystems during ship-based research expeditions, the Pacific RAMP provides observations of the status of these coral reef ecosystems to enable detection of long-term changes in conditions over time.

Ecosystem-based Management and Ecosystem-based Fisheries Management

Figure 2. Example components related to an ecosystem that need to be managed using a more holistic ecosystem approach. From coastal development, agriculture, tourism and climate change, to small- and large-scale fishing, recreation, habitats, fisheries, and protected species—the human, natural, and governmental interconnections all play a role in marine ecosystems and associated impacts and therefore need to be considered in managing for a sustainable marine ecosystem. Image courtesy United Nations Environment Programme, 2011.

Fishery and marine resource managers strive to make management decisions that will allow humans to sustainably interact with and use complex ecosystems in a manner that ensures long-term ecosystem conservation and viability for future generations. Fishery management plans have traditionally focused on single stocks or commercially important groupings of stocks. Under these types of plans, managers typically set biomass harvest or mortality rate goals with limited consideration of broader ecosystem considerations. However, there has been growing understanding that exploited marine resources must be considered as an integral component of a functioning ecosystem instead of as phenomena that operate independently of the broader ecological community and environment.

There has been a steadily increasing shift toward ecosystem-based management (EBM) in the United States (Figure 2). In 2010, President Obama promulgated Executive Order 13547 as the National Ocean Policy for the stewardship of the ocean and our coasts (President Barack Obama 2010). In 2013, the National Ocean Policy Implementation Plan stated that "the goal of EBM supported by this plan is to maintain a healthy, productive, and resilient ocean that can continue to provide the benefits and resources that humans want and need" (Sutley and Holdren 2013). In 2016, NOAA Fisheries established an ecosystem-based fisheries management (EBFM) policy and roadmap for implementation "to better inform and enable better decisions regarding trade-offs among and between fisheries (commercial, recreational, and subsistence), aquaculture, protected species, biodiversity, and habitats. Recognizing the interconnectedness of these ecosystem components will help maintain resilient and productive ecosystems (including the human communities on which they depend), even as they respond to climate, habitat, ecological, and other environmental changes" (Denit 2016). In 2019, NOAA Fisheries developed regional implementation plans to identify 5-year priority actions and milestones, including the "Pacific Islands Region Ecosystem-Based Fisheries Management Implementation Plan 2018–2022."

EBM and EBFM require efforts to monitor holistic ecosystem indicators, which include information on the status and trends of species, habitats, and environmental conditions in biophysical and human systems. The goal of these ecosystem-based monitoring programs is to balance ecological scales with management scales so that monitoring meets the needs of management decision-making processes. In 2010, CRCP unified NOAA's monitoring efforts by establishing the National Coral Reef Monitoring Program (NCRMP), which collects data across biological, climatic, and socio-economic domains. For the U.S. Pacific Islands, NCRMP augmented the ongoing Pacific RAMP surveys with long-term socioeconomic surveys aimed at better establishing linkages between the ecological status of coral reefs and the human uses and benefits of coral reef ecosystems. Over the past 19 years, NOAA's Pacific RAMP and NCRMP have been able to continually adapt to evolving management needs and changing political environments without detracting from the overarching goal of long-term coral reef ecosystem status and trends monitoring (Heenan et al. 2016).

The Pacific Remote Islands Marine National Monument

Masked booby breeding colony congregates along the shoreline at Baker Island U.S. Fish and Wildlife Service (USFWS) National Wildlife Refuge.
Photo: Laura Beauregard, USFWS.

To help protect and preserve diversity and abundance of ocean life, on January 6, 2009, President George W. Bush established PRIMNM by Presidential Proclamation #8336 under the authority of the Antiquities Act of 1906. The Pacific Remote Islands Marine National Monument (PRIMNM) was established to provide broad-scale protections to marine ecosystems and incorporated 298,017 square kilometers (km^2) within its boundaries, which extend 50 nautical miles (nm; 92.6 km) from the mean low water lines of Howland (0°48′N, 176°37′W), Baker (0°12′N, 176°29′W), and Jarvis (0°22′S, 160°03′W) Islands; Johnston (16°45′N, 169°31′W), Wake (19°17′N, 166°36′E) and Palmyra Atolls (5°52′N, 162°06′W), and Kingman Reef (6°24′N, 162°24′W; Federal Register 2009). On September 25, 2014, President Barack Obama expanded the PRIMNM through Presidential Proclamation #9173 by extending the 50-nm boundary to the 200-nm seaward limit of the U.S. Exclusive Economic Zone around Jarvis Island and Johnston and Wake Atolls (National Oceanic and Atmospheric Administration 2015). The expanded area of the PRIMNM is now approximately 1,270,000 km^2 (370,000 nm^2; Figure 3).

The PRIMNM is cooperatively managed by the Secretary of Commerce (NOAA) and the Secretary of the Interior (U.S. Fish and Wildlife Service), with the exception of Wake and Johnston Atolls, which are currently managed by the Department of Defense. National Wildlife Refuges also exist at each of the islands within the PRIMNM, with Johnston Atoll designated as a Refuge in 1926; Howland, Baker, and Jarvis Islands in 1974; and Kingman Reef and Palmyra Atoll in 2001.

The Pacific Remote Islands have a rich human history that dates back to Polynesian voyages through these waters. In the mid-1800s, some of the islands experienced active whaling and guano mining. The United States claimed most of the islands of the PRIMNM via the Guano Islands Act of 1856 (11 Stat. 119, enacted August 18, 1856, codified at 48 U.S.C. §§ 1411–1419) that enabled citizens of the United States to take peaceful possession of unclaimed islands containing guano deposits as a source for sodium nitrate for gunpowder, as well as an agricultural fertilizer. Several of the islands of the PRIMNM played active roles as staging areas during World War II and the Cold War. The history of human activities at individual islands (and atolls) within the PRIMNM will be discussed in the beginning of the respective island chapters.

The Pacific Remote Islands span significant natural gradients in oceanographic conditions. Biogeographically, the islands and atolls can be divided into three groups based on oceanographic and ecological characteristics: (1) the equatorial upwelling islands of Baker, Howland, and Jarvis; (2) the central transition islands of Kingman Reef and Palmyra Atoll; and (3) the northernmost oligotrophic islands of Wake and Johnston Atolls (Figure 3, Figure 4). The equatorial islands lie within the westward-flowing surface South Equatorial Current and are especially productive as they benefit from the combined effects of regional equatorial upwelling and localized topographic upwelling of the eastward-flowing subsurface Equatorial Undercurrent that collectively bring cool, nutrient-rich waters to the sunlit surface where photosynthesis thrives. In contrast, the northernmost islands are influenced by the westward-flowing North Equatorial Current and are situated in the nutrient-poor, or oligotrophic, waters of the central gyre that are characterized by low biological productivity. The central transition islands, located in the path of the warm, eastward-flowing North Equatorial Countercurrent and at the northern edge of the enhanced productivity region, experience a moderate level of biological productivity (Brainard et al. 2005; Miller et al. 2008).

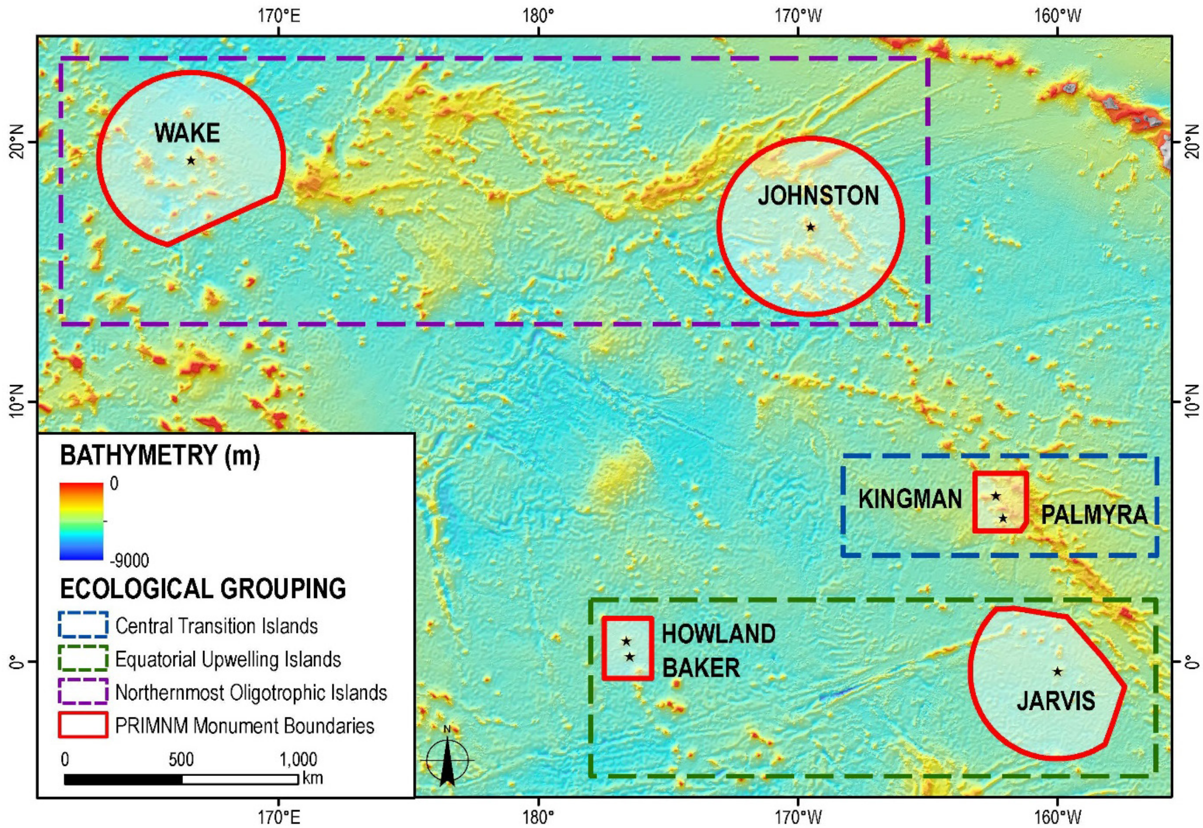


Figure 3. Pacific Remote Islands Marine National Monument boundaries and bathymetry (Smith and Sandwell 1997; Becker et al. 2009) © 2008 The Regents of the University of California.

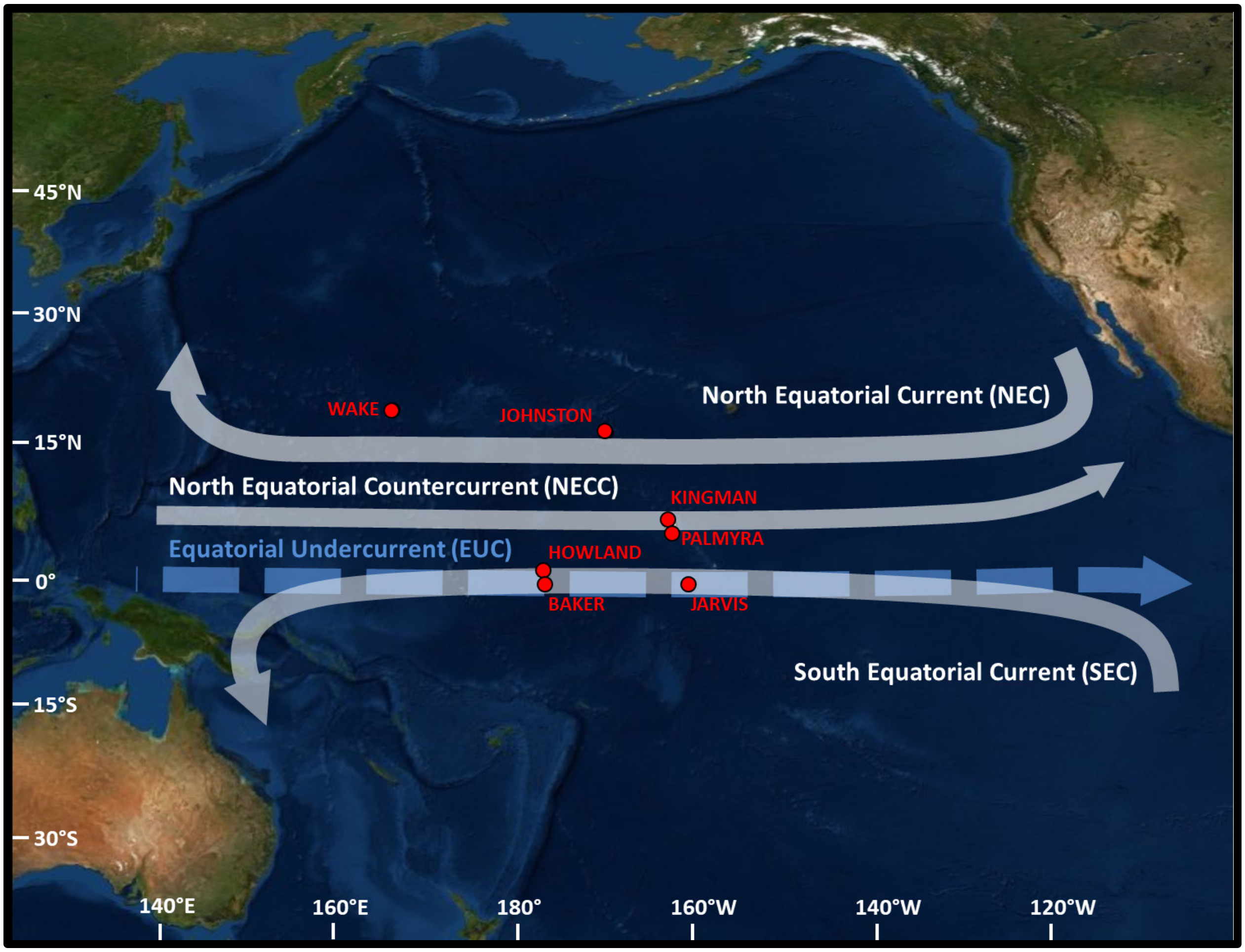


Figure 4. Major currents of the equatorial and subtropical Pacific and their influence on the Pacific Remote Islands. The westward-flowing North Equatorial Current and South Equatorial Current and eastward-flowing North Equatorial Countercurrent are surface currents, while the eastward-flowing Equatorial Undercurrent is a subsurface current (~100–200 m depth).

Each of the Pacific Remote Islands is unique in terms of size. Wake is the largest of the Pacific Remote Islands with a land area of approximately 7 km^2. The rest of the Pacific Remote Islands have land areas less than 5 km^2. While these islands are small in size, reef areas range from approximately 2 km^2 surrounding Howland Island to 94 km^2 surrounding Johnston Atoll (Table 1). With the exception of Johnston, Palmyra, and Wake Atolls, which have some limited human presence, the Pacific Remote Islands are currently uninhabited.

Table 1. Summary table of island characteristics across the Pacific Remote Islands Marine National Monument. Blue area represents the 30 m depth contour around the islands. Colors indicate land area. All areas were calculated using GIS techniques. Monument areas were calculated by NOAA's Pacific Islands Regional Office. Population estimates were collected from the U.S. Fish and Wildlife Service (USFWS) and Wikipedia. The ages of Baker, Howland, Jarvis, Kingman, and Palmyra were obtained from the Seamount Biogeosciences Network. The age of Johnston was determined through USFWS documentation, and the age of Wake was obtained from the Pacific Islands Benthic Habitat Mapping Center.

ISLAND	BAKER	HOWLAND	JARVIS	KINGMAN	PALMYRA	JOHNSTON	WAKE
Relative Shape and Size (30-m contour)							
Land Area (km²)	2	2	4	0	2	3	7
Seafloor Area 0-30 m (km²)	4	3	4	48	53	194	19
Reef Area 0-30 m (km²)	4	2	4	37	42	94	13
Seafloor Area 30-150 m (km²)	2	2	3	37	9	24	3
Monument Area (km²)	51,658		315,085	53,503		442,447	407,785
Population	0	0	0	0	4-20	4-5	94
Age (million years)	~124	~125	~111	~112	~112	~171	>160
Ecological Grouping	Equatorial Upwelling Island	Equatorial Upwelling Island	Equatorial Upwelling Island	Central Transition Island	Central Transition Island	Northernmost Oligotrophic Island	Northernmost Oligotrophic Island
Island Chain	Phoenix Islands	Phoenix Islands	Line Islands	Line Islands	Line Islands	Line Islands	Marshall Islands

Due to their remoteness, the PRIMNM is home to some of the least impacted coral reef ecosystems in the world. However, despite their remote location and on-going conservation management efforts, the coral reefs remain vulnerable to global changes in climate. Studies in the PRIMNM present a unique opportunity to understand ecological responses to climate change and ocean acidification in the absence of several anthropogenic impacts, such as overfishing and land-based pollution, which are common for many other coral reefs around the world (Friedlander et al. 2010).

Refining Pacific RAMP

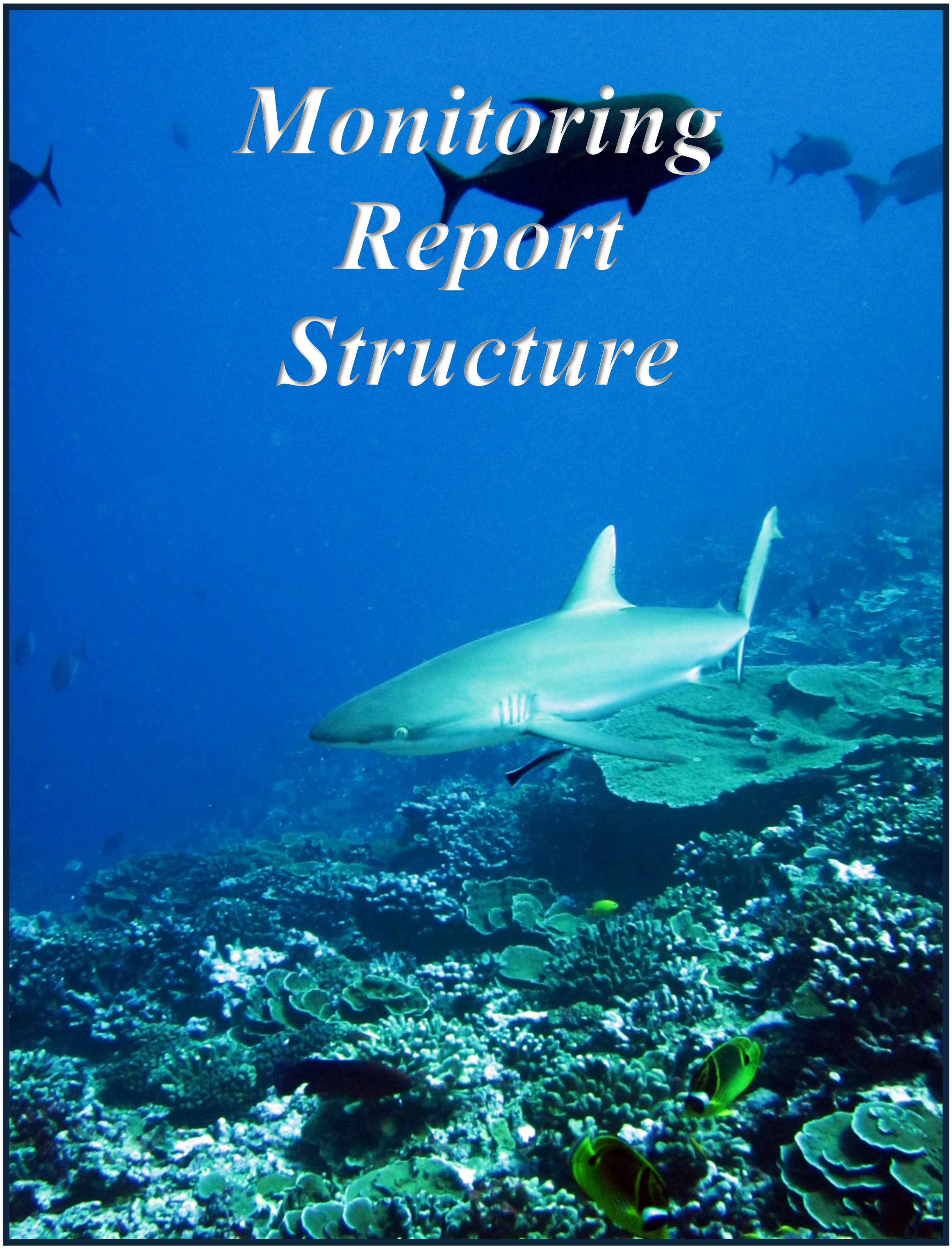
During 2000–2017, ESD conducted 39 Pacific RAMP survey cruises, including 11 survey cruises to Jarvis Island, 10 survey cruises to Howland and Baker Islands, 9 survey cruises to Palmyra Atoll and Kingman Reef, and 6 survey cruises to Johnston and Wake Atolls in the PRIMNM. As is typical for any long-term monitoring effort, ESD survey protocols have been refined over this period to improve sampling designs and prioritize the information needs of managers in light of the resources available for monitoring. For example, ecological survey methods were refined to reduce observer variability and expand the suite of monitored indicators to assess ecological impacts of ocean acidification. Details regarding the refinements to the monitoring protocols used during Pacific RAMP cruises are discussed in the methods-related sections later in this chapter.

A significant majority of the approximately 40 islands, atolls, and banks surveyed by the Pacific RAMP had virtually no prior ecological or biodiversity surveys, bathymetric or habitat maps, or in situ oceanographic observations of the coral reefs. Little or no information was available about what to expect in terms of habitats, biogeographic structures, oceanographic conditions, or species compositions, distributions, or abundances. In most instances, the initial surveys of the Pacific RAMP were exploratory assessments with the purpose of shaping this long-term monitoring program. The logistical and financial challenges presented by the vastness and remoteness of the Pacific Islands Region have played and will continue to play a key role in structuring the scope and scale of Pacific RAMP.

The primary goal of an ecosystem-based monitoring program is to characterize the status and trends of the biological communities and key ecological processes to both natural environmental variability and localized anthropogenic activities to inform and evaluate the effectiveness of ecosystem-based management decisions. In marine environments, specifically for dynamic coral reef ecosystems, this goal presents significant challenges. Patterns of natural variability are quantified over broad temporal and spatial scales, with temporal scales including diurnal, seasonal, episodic (e.g., weather and storms), interannual (e.g., El Niño Southern Oscillation), and decadal changes (e.g., Pacific Decadal Oscillation). Spatially, reef ecosystems vary over scales ranging from meters to thousands of kilometers. Ecological zones, such as intertidal, lagoonal, or barrier reef, and habitat types, such as forereef, reef crest, and backreef often vary as a function of prevailing or episodic oceanographic conditions (temperature, waves and currents, light, water quality, nutrients, terrestrial inputs, etc.).

Pacific RAMP surveys were conducted every 2 years from 2000 until 2012, and every 3 years since 2012. With the exception of oceanographic and bioacoustic moorings, which collected data nearly continuously between Pacific RAMP surveys, the Pacific RAMP cannot detect high-frequency ecological fluctuations. The triennial Pacific RAMP surveys were designed to examine ecological variability over longer terms (interannual to multi-decadal), essentially taking periodic snapshots of the condition of the ecosystems at the time that surveys were conducted there. Many years of these so-called “snapshots” are needed before rigorous discussion of long-term trends becomes possible.

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



Caranx lugubris *and* Carcharhinus amblyrhinchos *among a benthic community at Jarvis Island.*
Photo: NOAA Fisheries.

1.2 Monitoring Report Structure

Chaetodon auriga in the eastern pools of Palmyra Atoll.
Photo: James Maragos, U.S. Fish and Wildlife Service.

This report provides an overview of key spatial patterns and temporal trends of the environmental and oceanographic conditions, biological resources, and composition of coral reef ecosystems across the seven islands, atolls, and reefs of the PRIMNM. The data compiled for this report are from Pacific RAMP research surveys conducted from 2000 through 2017 by NOAA PIFSC ESD and external collaborating scientists.

This report represents one of many installments of ESD's ongoing efforts to bring resource managers and interested stakeholders the best available, ecosystem-based data to help them make informed decisions about the sustainable use and conservation of the resources they manage, in this case, coral reef ecosystem in the PRIMNM. The information herein serves three main purposes:

- Provide snapshots of the status and condition of coral reef resources around each of the islands, atolls, and reefs in the PRIMNM over the course of the survey periods.
- Provide a foundation of knowledge regarding ecosystem conditions in the PRIMNM for ongoing monitoring of temporal changes to the ecosystem.

- Serve as a resource for stakeholders and resource managers for understanding marine areas of interest and formulating evolving management questions about how to best manage and conserve marine resources in the face of climate and ocean changes.

The report consists of nine chapters, though the main body of the report consists of seven individual chapters, each dedicated to one of the islands, atolls, or reefs within the PRIMNM. Each of these chapters includes the following:

- an introduction with a historical background of human activities;
- a spatial characterization of the benthic habitats;
- the spatial status and trends of oceanographic conditions influencing the biological resources;
- spatial and temporal characterizations of the abundance, distribution, diversity, and condition of corals, macroinvertebrates, cryptobiota (Chapter 9 only), microbiota, and reef fishes; and
- a description of the relationships between these various ecosystem components as an integrated, ecosystem-based assessment of findings.

The final chapter of this report examines Pacific-wide comparisons of integrated ecosystem observations to evaluate similarities and differences among the islands of the PRIMNM, including placing the islands, atolls, and reefs of the PRIMNM within the context of the larger Pacific Islands Region that is surveyed as part of Pacific RAMP. In addition, attached to "Chapter 9: Pacific Remote Islands Marine National Monument in the Pacific-wide Context" are Appendix A, "Total Generic Richness of Hard Corals in the PRIMNM," and Appendix B, "Reef Fish Encounter Frequency in the PRIMNM."

The operational background and methodological descriptions are presented in the following sections of this chapter. The "Benthic Characterization Methods" section describes the various acoustic and optical platforms and processing approaches used to develop maps of the 3-dimensional bathymetry, character (hard-soft), and biological cover of the benthos. The "Ocean and Climate Variability Methods" section describes instruments, sampling strategies, and processing approaches used to characterize spatially- and temporally-varying oceanographic and water quality conditions. The "Survey Methods for Coral Reef Benthic Communities" "Cryptofauna Biodiversity Methods," "Microbiota Methods," and "Survey Methods for Reef Fishes" sections describe the various methods used to document the abundance, distribution, diversity, and condition of corals, algae, coral and coralline algal disease, other macroinvertebrates, cryptobiota, marine microbes, and reef fishes. The "Marine Debris Methods" conducted during Pacific RAMP expeditions describes how sightings of debris were recorded during monitoring surveys. Maps produced to support the Pacific RAMP benthic and reef fish monitoring survey design are described in the final section.

Public Access to Research Results (PARR)

PARR (Public Access to Research Results) is a White House policy enacted in 2013 that applies to all federally funded scientific research and intends to increase public accessibility to publications and digital data produced by federally funded agencies. The NOAA plan to comply with this policy states that NOAA data producers will develop metadata (i.e., data documentation), submit data to the NOAA archive, and make data publicly accessible. The ESD uses InPort (the NOAA Fisheries Enterprise Data Management tool) as the "one stop shop" to document and provide access to ESD-collected or produced datasets. Additionally, all monitoring data are archived with the NOAA National Centers for Environmental Information (linked in InPort). Most benthic habitat mapping data and products are publicly accessible on ESD's Pacific Islands Benthic Habitat Mapping Center website.

All datasets used in this monitoring report are documented in InPort ID# 53206, *Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument*. For more in-depth information, consult the scientific papers referenced throughout this report.

Basemap Template

Many of the map-based figures throughout this report include a basemap template, an example of which is shown in Figure 5. The template includes three base layers, including georegions, land/emergent reef, and 30 m and 100 m depth contours. The initial basemap in each island chapter includes the georegion labels (names), and all maps using the basemap template thereafter exclude the georegion labels so as not to distract from the data presented in the maps.

All maps in the report are oriented north unless otherwise noted.

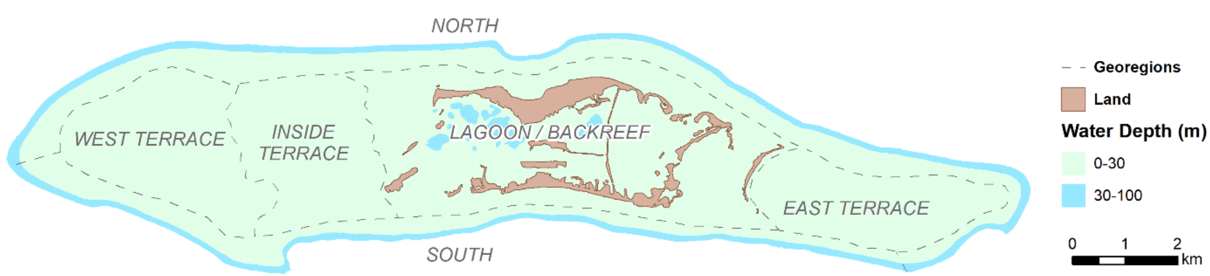


Figure 5. Example basemap template used in the island chapters of this report.

Georegions

ESD defined geographic regions, or georegions, for each of the islands, specifically *and only* to facilitate discussions about the spatial patterns of ecological and oceanographic observations that appear throughout the island chapters. Georegions were not used in any quantitative analyses (i.e., the data presented in this report are not summarized by the georegions); rather, the georegions were created to establish a consistent terminology when an author referred to specific areas around each island or atoll. Several factors were considered, and several datasets were evaluated when delineating the initial georegion boundaries—including waves, habitat and seafloor structure, benthic and reef fish communities, and satellite data and imagery—depending on the available data at the time the georegions were established. Field-going ESD staff with multiple years of experience conducting surveys in the PRIMNM were also informally consulted to refine the georegion boundaries. This was an informal process and was dependent on available data.

Land/Emergent Reef

ESD digitized land and emergent features for several of the islands and atolls of the PRIMNM using NOAA charts and satellite imagery for reference. Land features had already been created for Palmyra as part of the NOAA National Centers for Coastal Ocean Science (NCCOS) effort (2010) and for Wake as part of the topographic-bathymetric digital elevation model that was developed for the NOAA Center for Tsunami Research (Grother et al. 2010).

Water Depth

Generally, ESD created the depth strata by integrating the existing bathymetry data for the island or atoll, interpolating the gaps in the bathymetry to create a seamless bathymetry product, and classifying the seamless product into specific depth strata, including 30 m and 100 m. For the islands with significant bathymetry gaps that were difficult to interpolate, depths were digitized using NOAA charts. The depth strata serve as a backdrop for the data presented in the report. The 30 m contour was selected since all biological and nearly all oceanographic monitoring surveys were conducted within 30 m depths. The 100 m contour was included to highlight the steepness of the islands beyond 30 m depths and the depth range within the lagoons.

Small boat operations and NOAA Ship Oscar Elton Sette.
Photo: NOAA Fisheries.

Operational Background

1.3 Operational Background

Crews getting ready to be picked up by NOAA Ship Hi‘ialakai *at Johnston Atoll.*
Photo: Kelvin Gorospe, NOAA Fisheries.

This section presents the operational background of the Pacific RAMP expeditions that conducted surveys in the PRIMNM. As part of this Pacific-wide monitoring effort, ESD conducted its first surveys in the PRIMNM in 2000, with subsequent expeditions continuing through 2018 (and reported here through 2017). The first three PRIMNM expeditions were conducted from the NOAA Ship *Townsend Cromwell* in 2000, 2001, and 2002. The next two PRIMNM surveys were conducted from the NOAA Ship *Oscar Elton Sette* in 2004 and 2005. From 2006 to 2018, the Pacific RAMP expeditions in the PRIMNM were conducted from the NOAA Ship *Hi‘ialakai* (Figure 7).

The NOAA Ships *Townsend Cromwell*, *Oscar Elton Sette,* and *Hi‘ialakai*, as well as their officers and crews, have different capabilities and limitations (Figure 7). The *Townsend Cromwell*, being substantially smaller (50 m/652 displacement tons) than both the *Oscar Elton Sette* and *Hi‘ialakai* (68 m/2,014 displacement tons), could only accommodate a complement of 11 or 12 scientists and had limited abilities to carry small boats, which were mostly inflatables. The *Oscar Elton Sette* accommodates a complement of 20 scientists and supports multiple larger small boats, including the 8 m multibeam survey launch R/V *Acoustic Habitat Investigator* (*AHI;*

Figure 6). The *AHI* was carried on the stern of the *Oscar Elton Sette* and deployed using this ship's crane when in distant ports, such as Pago Pago, Saipan, or Guam, but could not be deployed and recovered at sea. The use of the *Hi'ialakai* for PRIMNM expeditions starting in 2006 increased the maximum complement to 22 scientists and significantly improved the ability to conduct benthic habitat mapping missions and diver operations. The *Hi'ialakai* had hull-mounted shallow-water and deepwater multibeam systems and was able to carry the *AHI* in dedicated davits, which allowed for deployment of the *AHI* at sea. The *Hi'ialakai* was also equipped with diesel-powered 8 m and 10 m small boats, a cascade nitrox compressor system, and a permanently installed diving recompression chamber.

Figure 6. NOAA Corps officer Keith Golden and NOAA PIFSC scientists Scott Ferguson and John Rooney aboard the R/V *AHI,* mapping the benthic habitat using acoustic sonar. Photo: Megan Moews-Asher, NOAA Fisheries.

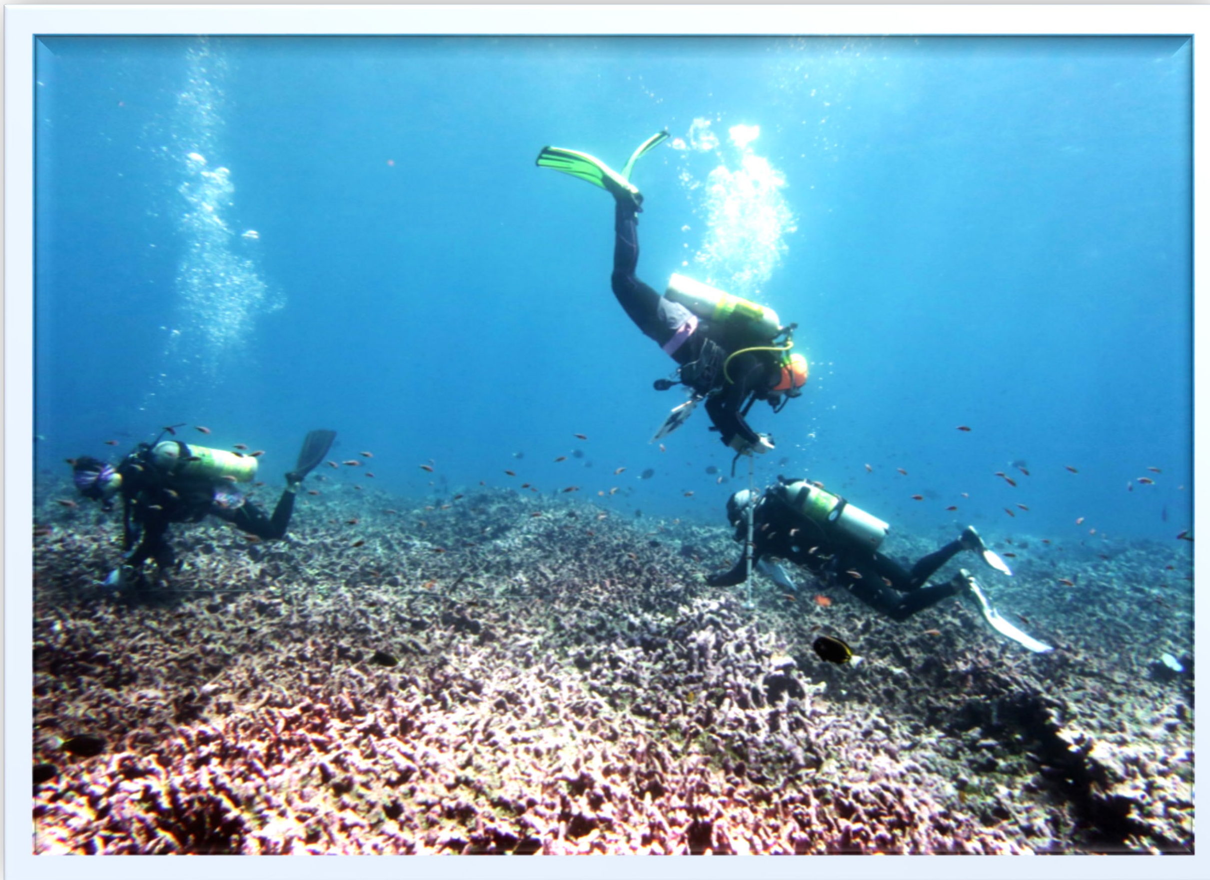
ESD has also increased its small-boat and dive-support capabilities with the addition of multiple 6 m boats (SAFE Boats International), a portable cascade nitrox compressor system, a portable recompression chamber, and incorporating the standard use of dive computers during dive operations, which was not allowed during the early years of the program.

Figure 7. The NOAA Ships used to conduct PRIMNM cruises include the *Hi'ialakai* (left), *Oscar Elton Sette* (middle), and *Townsend Cromwell* (right). NOAA photos.

A school of purple Anthias *make counting fish difficult at Howland Island.*
Photo: Jeff Milisen/NOAA Fisheries.

Pacific Reef Assessment and Monitoring Program Methods

1.4 Pacific Reef Assessment and Monitoring Program Methods



Benthic divers conduct their respective rapid ecological assessment surveys at Howland Island.
Photo: Paula Ayotte, NOAA Fisheries.

Although most of the ecological and oceanographic observations of the Pacific RAMP are now collected every 3 years (formerly every 2 years), time-series observations of key environmental conditions that influence reef processes are also made nearly continuously using an array of moored oceanographic and bioacoustic instruments. These biological and environmental observations are further complemented by a suite of benthic habitat mapping products developed collaboratively by ESD and the Biogeography Branch of the NOAA Center for Coastal Monitoring and Assessment (CCMA), National Centers for Coastal Ocean Science (NCCOS). Collectively, ESD's Pacific RAMP and benthic habitat mapping efforts are part of the NOAA Coral Reef Ecosystem Integrated Observing System (CREIOS) in the Pacific.

Objectives

There are several primary objectives for these ESD-led activities in the U.S. Pacific Islands:

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

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

- Employ complementary and overlapping methods to assess and monitor species composition, abundance, percentage of cover, size distribution, diversity, and general health of fishes, corals, algae, and other macroinvertebrates in shallow-water (<30 m) habitats.

- Assess and monitor diseases of corals and coralline algae.

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

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

Overview

Integrated ecosystem observations and monitoring of this scope were unprecedented in the waters of the PRIMNM. As such, the initial interdisciplinary research expeditions for the Pacific RAMP were exploratory in nature, often providing the first-ever baseline assessments of reef resources in these mostly remote and uninhabited regions of the Pacific. As analyses of those initial baseline assessments progressed, the Pacific RAMP shifted from an assessment phase to a long-term ecosystem-monitoring phase. The suite of methods used by Pacific RAMP also has steadily evolved to improve the quality, relevance, and utility of the interdisciplinary data streams.

Methodological Improvements

Methodological improvements in sampling protocols and survey design have been made over time among different Pacific RAMP survey cruises. Such changes are necessary and common during developmental stages of long-term monitoring programs and discussed in detail within the methods-related sections of this chapter. To improve the statistical robustness of Pacific RAMP survey data and to meet mandates in the *Magnuson-Stevens Reauthorization Act of 2006* to determine annual catch limits, Pacific RAMP adopted a stratified random design for reef fish Rapid Ecological Assessment (REA) surveys in 2008 and for benthic REA surveys in 2013. The survey domain was also expanded to encompass all hard-bottom habitat between 0 and 30 m in 2008. While these changes improved the statistical rigor and application of the data generated, there are limitations to evaluating temporal trends across differing methodologies and sampling designs.

In addition to refining sampling protocols and improving sampling designs, surveys have been expanded or added to Pacific RAMP in response to changing management priorities and an improved understanding of factors that affect coral reef ecosystems. Regular coral disease observations were added beginning in 2006. Water sampling to determine carbonate chemistry was added in 2006 to document and understand the ecological impacts of ocean acidification on coral reefs. Chlorophyll-*a* and nutrient analysis from water sampling was added in 2004 and 2005, respectively, to measure the effects of sedimentation, runoff, and other factors influencing reefs, though those efforts were discontinued in 2010. As part of the international Census of Marine Life's Census of Coral Reef Ecosystems (CReefs) project, autonomous reef monitoring structures (ARMS) were developed and deployed during Pacific RAMP in 2008. ARMS are used to establish a baseline of spatial patterns and initiate long-term monitoring of temporal changes in the biodiversity of small organisms living within the reef framework (i.e., cryptobiota, which represent >99% of the diversity of coral reef communities). With the support and collaboration of San Diego State University, water sampling to document the abundance and diversity of the microbial community of coral reefs was initiated in 2009. The use of calcification accretion units (CAUs) and bioerosion monitoring units (BMUs) was initiated in 2010 and 2013 to assess spatial patterns and monitor temporal trends in reef accretion of calcium carbonate and reef bioerosion, respectively, in an effort to better understand (1) the balance between production and removal of calcium carbonate and (2) the ability of coral reefs to survive steadily decreasing pH and aragonite saturation state (i.e., ocean acidification). Limited plankton tow surveys were initiated in 2016 to better understand the status and role of the meroplankton community supporting coral reef resilience.

Data Limitations

Operational and dive safety protocols limit the large majority of the biological observations to daylight hours and during periods of favorable sea states. Because of these operational limitations, it is probable that many species remain spatially or behaviorally isolated from our surveys. For example, nocturnal species of fishes and invertebrates or species found preferentially in high wave energy environments cannot be effectively monitored using the existing sampling protocols.

For research that relies on consistent observer objectivity and training, reducing errors and biases are obvious yet difficult challenges. Ideally, observer bias could be largely eliminated with clear protocols, proper training, and consistent observers. In reality, continuity among scientific personnel and reciprocity divers from multiple institutions is difficult to achieve. Still, ESD remains committed to minimizing observer biases by maintaining consistency in field methodologies and onsite data collection and to implementing comprehensive, evolving training protocols (such as survey cruise calibration dives) in an effort to account for and limit inter-observer variability.

Joyce Miller mapping the benthic habitat, using a multibeam echosounder on the R/V Acoustic Habitat Investigator (AHI).
Photo: Megan Moews-Asher, NOAA Fisheries.

Benthic Characterization Methods

1.5 Benthic Characterization Methods

Benthic community at Kingman Reef.
Photo: Ariel Halperin, NOAA Fisheries.

The topography of the seafloor is a key element of biological oceanography; the depth and characteristics of the seabed define the habitat for benthic organisms and are fundamental aspects of marine ecosystems. As such, accurate, high-resolution benthic habitat maps are essential tools for the effective conservation and management of coral reef ecosystems.

Bathymetric data, which include information about the depth and shape of underwater terrain, are essential for characterizing marine habitats and have a range of important management and research applications. Bathymetric data can be acquired by many techniques, each with varying degrees of accuracy and resolution. Acoustic methods (i.e., multibeam echosounders) are typically preferred to collect bathymetric data over broad spatial areas in moderate to deep-water areas, as there are depth limitations to multibeam surveying in shallow waters. This shallow limit varies and is based on (1) safety concerns related to the risks associated with navigating in shallow, potentially hazardous areas, and (2) time constraints; the area that a surface vessel can survey decreases in shallower waters (i.e., multibeam swath width becomes narrower, so less area is mapped along a survey track in shallow waters than in deeper waters). Alternatively, in shallower depths, bathymetric data can be acquired by airborne platforms (e.g., LiDAR), or estimated depths can be derived from satellite-based remote sensing data (if depth validation data are available). However, in remote locations, LiDAR tends to be logistically unfeasible or prohibitively expensive. For such locations, estimated depths have been derived as an alternative.

Backscatter data—an additional data product of multibeam echosounders (and can also be produced by LiDAR)—provide an indication of the texture and hardness of the seafloor, and can be used to describe the composition and geological character of the seafloor. Backscatter data, for example, are useful in differentiating between various types of seafloor substrate, such as hard rock versus relatively soft sediment.

High-quality bathymetric data (i.e., other than satellite-based depths) can be used to derive further morphological characteristics of the seafloor beyond depth, such as slope and rugosity (a measure of topographic roughness). These characteristics provide a measure of the complexity of the seafloor morphology, which is closely tied to fish abundance (Rogers et al. 2014) and species richness (Grigg 1994; Walker et al. 2009).

In situ optical data of the benthic habitat (e.g., still photographs or video imagery) are also useful for discerning seabed characteristics and are important to validate interpretations of derived seafloor metrics.

Used in various combinations, these different data types can yield spatially continuous information about the physical character of the seafloor that is relevant to specific groups of organisms and ecosystems more broadly. Such information is used to identify and delineate benthic habitats of key organisms and contributes to the production of benthic habitat maps.

Background

The U.S. Coral Reef Task Force identified mapping of all U.S. coral reef habitats as one of its highest priorities in the 2000 National Action Plan to Conserve Coral Reefs. Meanwhile, CRCP established a goal to map all U.S. coral reef areas to assist in the conservation and management of U.S. coral reefs. In support of these goals, ESD and the NCCOS Biogeography Branch have been leading efforts to produce benthic habitat maps of the nation's coral reef areas using a suite of technologies and methodologies to collect and generate benthic habitat mapping data and products.

The quality and geographic coverage of existing data, as well as consultation with key resource managers and stakeholders, have been used to determine habitat mapping priorities in the Pacific Islands Region. Prior to the CRCP establishing its goal, almost no modern data existed in the region; therefore, existing nautical charts served as the primary base for the initial planning process.

Overview

From 2001 to 2017, ESD—through the Pacific Islands Benthic Habitat Mapping Center (PIBHMC)—conducted mapping surveys in the Pacific Islands Region during dedicated mapping missions, expeditions that combined Pacific RAMP and mapping objectives, and expeditions that piggybacked mapping operations with other missions. Validation data (both depth and habitat) were sporadically collected throughout; however, multibeam data (bathymetry and backscatter) were primarily collected from 2002 to 2008, with *Hiʻialakai* and the *AHI* the exclusive platforms for ESD's multibeam surveys, both of which are now retired. When used in conjunction with the *Hi'ialakai*, the *AHI* could be deployed and recovered in locations far from sheltered harbors, making surveys in shallow waters possible throughout the remote areas of the U.S. Pacific Islands (Figure 8). As this report was being developed, plans for PIFSC to resume multibeam operations in the Pacific using NOAA Ship *Rainier* were being explored.

Figure 8. The survey launch R/V *AHI* and NOAA Ship *Hi'ialakai* were outfitted with multibeam echosounders that facilitated multibeam surveys across the Pacific Islands Region.

Multibeam surveys have also been conducted by other agencies in specific areas around the Pacific for Extended Continental Shelf (ECS) purposes and following the expansion of the Marine National Monuments to survey previously unmapped areas and features of special interest. For the ECS effort, multibeam data were acquired on behalf of NOAA by the Center for Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM/JHC) at the University of New Hampshire as part of the national effort to establish the full extent of the continental shelf of the U.S. Schmidt Ocean Institute's R/V *Falkor* mapped areas in the Papahānaumokuākea Marine National Monument and Johnston Atoll of the PRIMNM; NOAA Ship *Okeanos Explorer*, operated by NOAA's Office of Ocean Exploration and Research (OER), mapped areas in all the Pacific Marine National Monuments as part of its 3-year Campaign to Address Pacific Monument Science, Technology, and Ocean Needs project; and the E/V *Nautilus*, operated by the non-profit organization Ocean Exploration Trust, mapped areas within the Line Islands of the PRIMNM (Kingman, Palmyra, and Jarvis) and the National Marine Sanctuary of American Samoa.

While extensive coverage of multibeam data has been achieved in some areas of the Pacific Islands Region, significant gaps in bathymetric data coverage remain in nearshore areas where neither multibeam nor bathymetric LiDAR data are available (Miller et al. 2011) due to the previously discussed limitations. Hence, in 2008 ESD started developing and refining methods for deriving depths from satellite imagery to provide more coverage of bathymetric data in the shallow nearshore waters around each of the islands. Validation data are essential to verify depths estimated from satellite imagery. As ESD ramped up its satellite mapping efforts, it became apparent that sufficient distribution of depth validation data was not available for most locations in the remote islands across the Pacific. As such, single-beam data have been opportunistically collected by ESD around the Pacific Islands from 2012 to 2017 to support its satellite-based mapping activities.

Optical data of the seafloor (videography and photographs) and data derived from their analysis (percent of benthic cover types, such as coral and macroalgae) have been collected by ESD from 2001 to 2015 using towed-camera systems for habitat validation purposes. Towed optical assessment device (TOAD) surveys were conducted across the Pacific Islands from 2001 until the TOAD was retired in 2015 when it was replaced with a more easily deployable towed drop-camera system.

Regarding the development of benthic habitat maps for the Pacific Islands, the Biogeography Branch has historically led collaborative efforts to develop shallow-water benthic habitat maps from satellite imagery and habitat validation data. ESD also developed methods to improve classification of the seafloor for both shallow and deep-water areas using a supervised approach (i.e., requires the use of habitat validation data), that reveals greater details of the habitat (Suka and Rooney 2017). The challenge with creating these types of detailed habitat maps in remote areas (e.g., the islands and atolls in the PRIMNM) is the insufficient or complete lack of habitat validation data available for those places, with the exception of Palmyra where an intensive habitat mapping effort was conducted by NCCOS and Analytical Laboratories of Hawaii, LLC (2010). This was the impetus for ESD to develop unsupervised substrate classification approaches based on remotely-sensed (satellite and multibeam) data alone (Dove et al. 2018).

Most of the habitat-related data and products collected or generated by ESD, and the corresponding metadata (i.e., data documentation), are available on the PIBHMC website (data for the islands and atolls of the PRIMNM are available in the Pacific Remote Island Areas section).

Survey Effort

Multibeam Surveys

The *Hiʻialakai* was used to conduct shipboard multibeam surveys in the PRIMNM during three RAMP expeditions conducted in 2006, 2007, and 2015. During the 2006 and 2007 missions, the *AHI* was deployed from the *Hiʻialakai* to perform multibeam surveys in shallow, nearshore waters inaccessible to the *Hiʻialakai,* usually within approximately 10–300 m depths. Multibeam operations on the *Hiʻialakai* were conducted to complement and overlap the *AHI* shallow data, with depths exceeding 4,500 m in some areas. Opportunistic multibeam operations were also conducted by the *Hiʻialakai* in 2015 to fill minor gaps in the bathymetric data coverage in deeper waters. ESD's multibeam surveys conducted in the PRIMNM are summarized in Table 2.

While the majority of each island was mapped during the two earlier missions, gaps in multibeam data coverage exist and are the result of any number of factors, including the sonar occasionally losing bottom contact due to steep slopes; boat speeds slightly faster than the optimum rate for multibeam data acquisition; lack of overlap with the adjacent multibeam swath; boat/ship turns; hazardous areas within/near shallow fringing reefs; and impassable water depths inside lagoons.

Table 2. List of multibeam operations in the PRIMNM, including vessel, mission year, islands surveyed, mission ID, and link to access the data from the NOAA archive.

Vessel	Survey Year	Islands Surveyed	Mission ID	Documentation
AHI	2006	JOH, HOW, BAK	AHI-06-01	AHI-06-01_mb.html
AHI	2006	JAR, PAL, KIN	AHI-06-04	AHI-06-04_mb.html
Hiʻialakai	2006	JOH, HOW, BAK	HI-06-01	HI-06-01_mb.html
Hiʻialakai	2006	JAR, PAL, KIN	HI-06-04	HI-06-04_mb.html
AHI	2007	WAK	AHI-07-01	AHI-07-01_mb.html
Hiʻialakai	2007	WAK	HI-07-01	HI-07-01_mb.html
Hiʻialakai	2015	HOW, BAK	HA-15-01	InPort ID: 47822

JOH=Johnston, HOW=Howland, BAK=Baker, PAL=Palmyra, KIN=Kingman, JAR=Jarvis, WAK=Wake

Equipment

See Table 3 for a list of the sonars available for each vessel used to conduct multibeam surveys and the associated frequencies and maximum depth ranges. Surveying shallow waters presents a challenge for large vessels, such as the NOAA ships. While the two echosounders on the *Hiʻialakai* were capable of surveying in water less than 10 m deep (per the manufacturer's specifications), these depths were not attainable from the *Hiʻialakai* due to the aforementioned risks associated with navigating in shallow, nearshore areas. The *AHI*, however, equipped with a RESON SeaBat 8101-ER, was capable of surveying in shallow waters just a few meters deep under favorable conditions.

Table 3. Multibeam echosounder capabilities.

Sonar	Vessel	Frequency (kHz)	Maximum Depth (m)
Kongsberg EM 300	*Hiʻialakai*	30	5000+
Kongsberg EM 3002D	*Hiʻialakai*	300	150+
RESON SeaBat 8101-ER	*AHI*	240	300

Data acquisition and processing

In 2006 and 2007, multibeam data were collected on both the *Hiʻialakai* and the *AHI* with an ISS-2000 collection module from the Science Applications International Corporation (SAIC) and processed using SAIC SABER (Survey Analysis and Area Based Editor) processing software. In 2015, Kongsberg Maritime's Seafloor Information System (SIS) data acquisition software was employed to collect multibeam data from the *Hiʻialakai*, and the data were post processed using

SABER and QPS's (Quality Positioning Services BV) Qimera processing software. For information about PIFSC's data collection and processing procedures for multibeam surveys conducted in 2006 and 2007, see the following three documents available on the PIBHMC website: (1) *Multibeam Acquisition Overview*, (2) *Hydrographic Surveying Using the SAIC ISS-2000 System* (Simmons et al. 2001), and (3) *Multibeam Bathymetry Processing Overview*. These procedures differ from those followed for multibeam surveys conducted in 2015; refer to the documentation link provided for mission HA-15-01 listed in Table 2 for more information. Multibeam backscatter data (acoustic imagery files) collected by ESD in 2006 and 2007 were processed using software developed by the Hawai'i Mapping Research Group at the University of Hawai'i. See the *Multibeam Backscatter Processing Overview* document available on the PIBHMC website for further details on backscatter data processing. Backscatter data were not collected in 2015.

Although backscatter intensity is a valuable tool for investigating seafloor characteristics, a number of different parameter settings influence backscatter intensity values. Distinguishing the effect of one parameter from others may not be possible when processing backscatter data. The most important factors that have caused noticeable artifacts or differences in data sets are sonar frequency and settings, topographic slope, and survey procedures. As a result, backscatter data quality is variable among different sensors and around different islands, which is apparent in the data products for the islands and atolls in the PRIMNM. In particular for the PRIMNM, the shallow-water data collected from the *AHI* are of poorer quality compared with the data collected from the *Hi'ialakai*. Also, changes to acquisition parameters during the surveys conducted from the *Hi'ialakai* later in 2006 resulted in the acquisition of higher quality deep-water data around Palmyra, Kingman, and Jarvis compared with the data acquired prior to that at Johnston, Howland, and Baker.

Considering the above, ESD's backscatter data (1) generated from sonars with different frequencies were not merged (i.e., data from the *AHI* 240-kHz sonar was not merged with the *Hi'ialakai* deep water 30-kHz sonar), (2) from steep slope areas were clipped at a uniform depth, and (3) that were not collected in a manner that optimized backscatter data quality (i.e., straight lines at uniform depths) were not used to produce derivative products for an area (e.g., unsuitable for semi-automated substrate classification). In other words, if there is too much false variation in backscatter intensity, the backscatter data poorly reflect actual distinctions in substrate variation and therefore are not used (Figure 9).

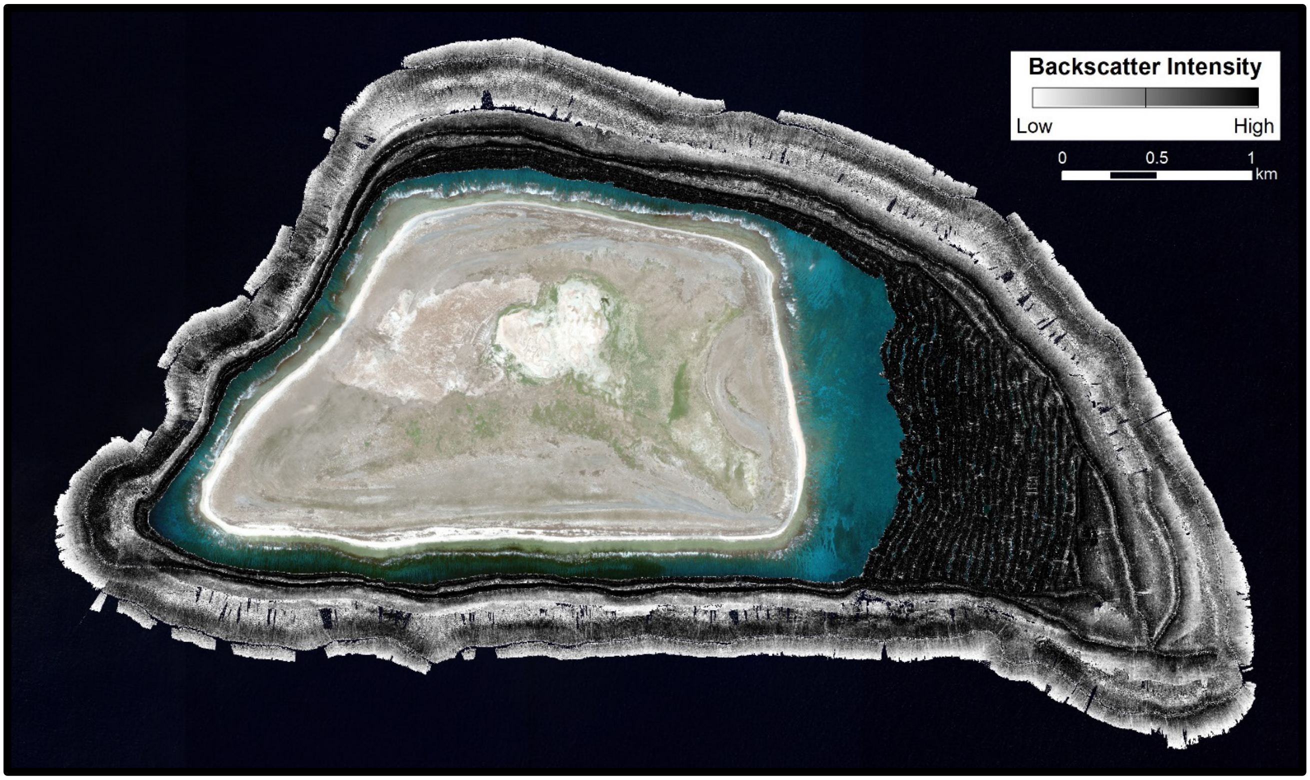


Figure 9. Map of Jarvis Island showing *AHI*-acquired backscatter data of insufficient quality for predicting seafloor substrates. Backscatter intensities around the 0.5 mi outer perimeter of the island reflect the ship tracks where the *AHI* surveyed around the steep slopes of the island rather than actual distinctions in the substrate (higher backscatter intensity on shallow side of survey track versus lower intensity on deeper side).

Data archive

Multibeam data are archived and available online following each cruise via the NOAA National Centers for Environmental Information (NCEI) NOAA Multibeam Bathymetric Data Archive. See Table 2 for a complete list of ESD's relevant multibeam operations in the PRIMNM and the corresponding links to access the mission-specific data via the bathymetry archive.

Gridded products

Once data editing and processing were complete, the multibeam data were exported and hosted on the PIBHMC website along with the corresponding map and documentation. Bathymetry grids with a cell size between 5 and 60 m were created, depending upon the appropriate resolution for the depth range (Figure 10a). In general, 5 m and 10 m resolution grids are typically used for high-resolution maps of shallower areas (maximum depths clipped between 300 and 800 m), whereas 20–60 m resolution grids are used for products that include the full extent of the data for a location, including deep-water areas. Processed backscatter data for nearshore areas collected with the *AHI* or the *Hi'ialakai* shallow-water sounders are gridded at 1 m resolution, and data collected with the *Hi'ialakai* deep-water sounder are gridded at 5 m resolution (Figure 10b).

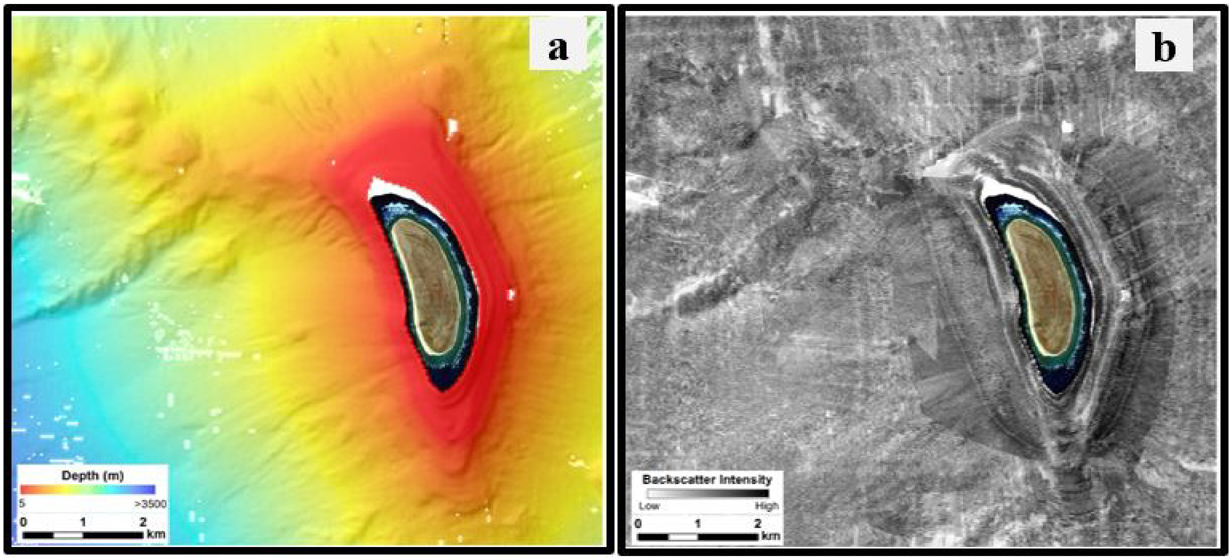


Figure 10. Example bathymetry (a) and backscatter (b) grids produced by Ecosystem Sciences Division for Howland, with IKONOS satellite imagery in the background to represent the land and shallow unmapped areas. The grids have a 30% transparency applied and are draped over a 3D representation of the bathymetry (i.e., hillshade generated in ArcGIS using default settings).

Single-beam Surveys for Depth Validation

Single-beam echo sounders were used by ESD from 2012 to 2017 to collect depth soundings, specifically to calibrate WorldView satellite imagery for the purposes of generating satellite-derived water depths and to validate the estimated depths as described later in the Satellite-derived Bathymetry section. The data are collected opportunistically during Pacific RAMP missions from small boats, and two different transducer configurations have been used over time. In 2017, soundings were collected while transiting at higher speeds in waters deeper than approximately 60 m, so these data are unreliable and are not presented in this report. An error analysis was performed to assess the accuracy of the single-beam depth soundings between 1 and 60 m by comparing the soundings to existing bathymetry data. Depending on the location, this analysis may not have been possible if the single-beam data did not at least partially overlap with other high-resolution bathymetry data (multibeam or LiDAR) for the area. Average soundings error by island and year ranged from 0.2 to 1.92 m for the single-beam data collected in the PRIMNM. The results of the *Single-beam Error Analysis* are available on the PIBHMC website. For more information about and access to the single-beam data, refer to the data documentation in InPort. These data are presented in the island chapters of the report; however, no map products are available for these data on the PIBHMC website.

Towed-camera Surveys for Habitat Validation

TOAD surveys to collect seafloor videography were conducted in the PRIMNM at depths ranging from approximately 10 to 400 m using a towed camera sled deployed from NOAA ships in 2002 and 2004. Typically, the TOAD was maintained at approximately 1–5 m above the seafloor, and the location of the tow body along the survey track was estimated by calculating the layback of the sled in relation to the ship's position; estimated positional accuracy using this method was on the order of 50 m. The raw video data for the PRIMNM islands surveyed are available for viewing or download on the PIBHMC website.

Screen grabs of the video data were later analyzed for benthic cover as described in the *Optical Analysis Overview*, available on the PIBHMC website, along with the original list of benthic habitat classifications used (the classification scheme used by ESD for all image analysis was updated in 2011). The benthic cover data are available as maps and shapefiles for download for each island and mission on the PIBHMC website.

While the TOAD data provide information about habitat, they have seldom been used for habitat validation purposes due to the manner in which the data have been collected (i.e., localized survey design and low positional accuracy). See Figure 11 for an example of the sparse TOAD data available for an island. With the exception of Palmyra, these data are not presented in the island chapters of the report; however, map products are available for select islands in the *Optical Validation* sections of the PIBHMC website.

Figure 11. Example of the habitat validation data (shown in red) available for Howland collected by ESD via towed-camera surveys, displayed over a WorldView satellite image for reference.

Habitat Characterization

In support of the goal to map all U.S. coral reef areas, ESD has been providing value-added products for the islands and atolls in the PRIMNM from the previously described source data. Using the data collected from these survey efforts, a suite of data and map products to be described in this section have been created.

Satellite-derived Bathymetry

ESD has derived estimated depths from satellite imagery to overcome the challenges associated with acquiring bathymetric information within nearshore areas of the islands and atolls in the Pacific where multibeam data are lacking. A study supported by ESD (Hochberg et al. 2007) compared a number of different methods and demonstrated the most accurate method was simple, empirical multiple linear regression against known depths (Lyzenga 1985). In general, this method is most successful in relatively shallow water (<20 m) areas where there is high-quality imagery available, there are shallow banks (as opposed to steep flanks), and overlapping depth data are available for verification (Lyzenga et al. 2006).

From 2008 to 2009, ESD adapted the Lyzenga method to derive depths using 4 m resolution multispectral IKONOS satellite imagery acquired by the CRCP from 2001 to 2003 for nearly all of the U.S. Pacific islands (Hogrefe 2008; Hogrefe et al. 2008). Depths from overlapping multibeam bathymetry collected by ESD, though spatially limited (multibeam data tend to overlap only the deeper extents of satellite-derived depths), were used to validate the estimated depths (Hogrefe 2009). In the PRIMNM, acceptable estimated depths (based on validation results) were only derived around Palmyra, Kingman, and Johnston.

In 2009, satellite technologies dramatically improved when the WorldView-2 satellite was launched, which collects 1.84 m resolution multispectral images and has eight bands in visible/near infrared wavelengths, compared with the four bands of IKONOS imagery (and the WorldView-3 satellite launched in 2014). Further, one of the new color bands, the coastal band, allows for greater clear-water depth penetration that supports bathymetric studies (DigitalGlobe 2010). Thus, ESD developed methods to estimate depths using WorldView satellite imagery (Ehses and Rooney 2015) acquired by DigitalGlobe (and available to government users through an enterprise license agreement with the National Geospatial-Intelligence Agency) based on the methods developed by Hogrefe et al. (2008).

Nearshore waters within the PRIMNM have complete coverage with WorldView satellite imagery. Selection of satellite images for depth or other analyses is an arduous process, especially for the remote islands and atolls of the PRIMNM. Numerous images for a location are visually inspected for minimal turbidity, surf/whitewater, cloud cover, and glint, though few images, if any, meet all these criteria. Oftentimes, it is not necessarily the most recent image that generates the highest quality results.

Where possible, depths have been derived for nearshore areas around the islands and atolls in the PRIMNM using this more recent (2011–2016), higher quality imagery, even if IKONOS-derived depths were already available. Gaps exist in the derived depths for each of the islands due to a lack of reliable imagery of the seafloor because areas in the imagery showing high water-column turbidity, clouds, whitewater, etc. are excluded from the analyses.

Depths from overlapping single-beam data collected in 2012, 2014, and 2015 were used to calibrate the relevant satellite imagery and to validate the satellite-derived estimated depths generated for the PRIMNM, except for Baker where depths from towed-diver surveys were used instead for calibration and validation (single-beam data were not yet processed). Based on the error analysis performed, the average agreement between the calculated (satellite-derived) and measured (single beam) depths for each island in the PRIMNM ranged from 55% to 81%. The derived bathymetry products were clipped at approximately 20 m, beyond which statistical results were typically worse.

Low accuracy is not uncommon with spectral depth mapping, especially with limited depth validation data. We must also take into consideration that single-beam data were not collected specifically for mapping purposes; rather, it is a secondary dataset collected opportunistically during small-boat based biological surveys, resulting in a sporadic distribution of the data rather than uniform spatial coverage. Nevertheless, the single-beam data are still useful for validating estimated depths, which are—despite the range in accuracy—informative given no other data exist for these remote locations. However, the application of satellite-derived bathymetry for analyses beyond broad depth mapping is quite limited.

The IKONOS and/or WorldView satellite-derived bathymetry grids produced for each island are available in the *Bathymetry* sections of the PIBHMC website.

Integrated Bathymetry

Multibeam data collected by ESD serve as the foundation for bathymetry maps produced by ESD for the Pacific Islands Region. If other bathymetric data are or become available for areas where there are gaps in ESD's multibeam data, they are combined with ESD's multibeam data to produce an integrated bathymetry grid and map, providing more complete bathymetry coverage for each island. Typically, these additional bathymetry data include satellite-derived bathymetry (usually produced by ESD), bathymetric LiDAR collected by another agency, and/or multibeam bathymetry acquired by other partners. These existing products are available for select islands in the *Bathymetry* sections of the PIBHMC website.

For purposes of this report, new or updated integrated bathymetry grids have been produced for all islands in the PRIMNM using multibeam bathymetry collected by ESD and satellite-derived bathymetry generated by ESD from IKONOS and/or WorldView imagery. Overlapping bathymetry data are ranked when compiled into seamless surfaces for an island, with multibeam data ranking higher than satellite depths in order of decreasing resolution, and depths derived from WorldView imagery ranking higher than IKONOS derived depths. These integrated bathymetry grids are only presented in the island chapters of the report and are not available online. However, as described in the previous sections, the individual source data are available on the PIBHMC website. The integrated products are available upon request.

Bathymetric Derivatives

Bathymetric data can be further analyzed to produce morphological derivatives that are useful for determining the character of the seafloor and associated benthic habitats. While numerous derivatives can be generated from these data (Watkins 2015; Suka and Rooney 2017; Lecours et al. 2017), only a subset of these derivatives, including slope (Figure 12a), rugosity (Figure 12b), and bathymetric position index (BPI) parameters (Figure 12c) are part of a standard set of products that were produced and distributed by ESD via the PIBHMC website for the Pacific Islands Region. Key bathymetric derivatives were also used to develop seafloor substrate maps as described in the next section; however, these were interim datasets and not retained.

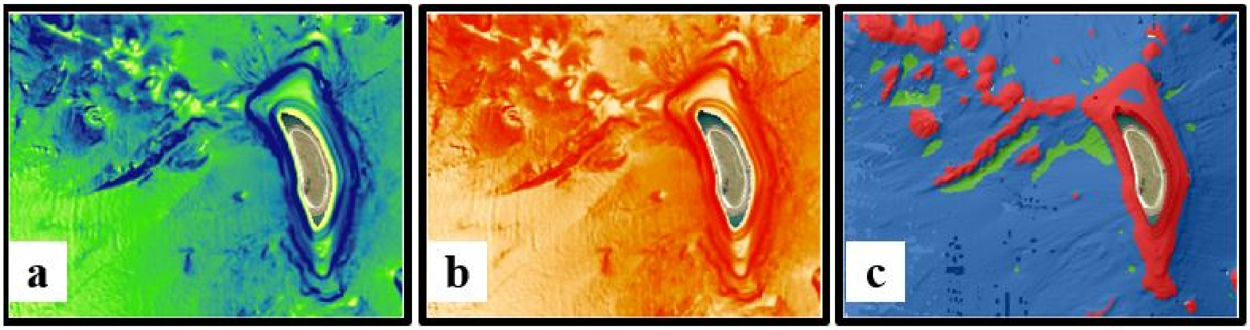


Figure 12. Examples of bathymetric derivatives shown for Howland, including slope (a), rugosity (b), and bathymetric position index (BPI) zones (c), with WorldView satellite imagery in the background to represent the land and shallow unmapped areas. BPI Zones have a 30% transparency applied and are draped over a 3D representation of the bathymetry (i.e., hillshade).

Slope

Cell values reflect the maximum rate of change (°) in elevation between neighboring cells, which is rate of change in elevation between a location and its surroundings, usually expressed in degrees. Slope was derived from multibeam bathymetry using Spatial Analyst in ArcGIS. A subset of these data are presented in the island chapters of the report. Slope products are available for select islands in the *Seafloor Characterization* sections of the PIBHMC website.

Rugosity

Cell values reflect the ratio of surface area to planimetric area for the region contained within a cell's 9-cell neighborhood. They provide indices of topographic roughness (complexity of the seafloor surface) and convolutedness (Jenness 2004). ArcGIS and the Benthic Terrain Modeler were used to derive rugosity (Wright et al. 2012). These data are not presented in the island chapters of the report; however, they are available for select islands in the *Seafloor Characterization* sections of the PIBHMC website.

Bathymetric position index (BPI)

BPI is a second order derivative of bathymetry that evaluates differences between the elevation of a focal point and the mean elevation of the surrounding cells within a user-defined area. In other words, BPI is a measure of where a location with a defined elevation is relative to the overall landscape, classified into broad scale (zones) and fine scale features (structures). A negative value represents a cell that is lower than its neighboring cells (depressions), and a positive value represents a cell that is higher than its neighboring cells (crests). The larger the cell value, the more prominent the seafloor feature differs from its surrounding areas. Flat areas or areas with a constant slope produce values near zero. ArcGIS and the Benthic Terrain Modeler were used to derive BPI (Lundblad et al. 2006). A subset of these data are presented in the island chapters of the report. BPI products are available for select islands in the *Seafloor Characterization* sections of the PIBHMC website.

Seafloor Substrate

ESD developed classification approaches to predict the broad-scale presence of hard substrates within shallow (0–30 m) and deeper-water (>30 m) environments (Dove et al. 2018). In both cases, an unsupervised machine-learning approach was used to classify the seafloor, employing available remote sensing data for each environment (i.e., satellite imagery for shallow reefs and multibeam data for deeper environs). These methods are intended to be applied where suitable habitat validation data are not broadly available, as was done for the islands and atolls of the PRIMNM.

Hard substrate is defined as areas where rock (e.g., limestone pavement or basalt), hard biogenic reef (e.g., coral reef or rhodolith beds), or large (>64 mm) unconsolidated particles (e.g., reef rubble) comprise the majority component of the seafloor. Soft substrate indicates the presence of unconsolidated sediment with predominantly smaller particles (e.g., carbonate sand).

Shallow Reef Environments

WorldView multispectral satellite imagery acquired from 2011 to 2017 was used to predict substrate character for the shallow-water areas. This classification approach involves 3 primary components: (1) geometric, radiometric, and atmospheric pre-processing; (2) removal of water column effect and production of depth-invariant indices (adapted from methods described in Mumby and Edwards [2000]), and (3) cluster analysis and classification, with steps 1 and 2 primarily performed in ENVI image analysis software and step 3 in ArcGIS. The depth-invariant indices display variations in seabed properties that are predominantly unaffected by water depth. If this step is not followed, the classification routine primarily identifies bathymetric gradients instead of substrate variation. Lastly, each of the classes in the resulting classified map (~15) were visually attributed to one of two categories, hard or soft. See NOAA Fisheries InPort record ID 54217 for further details.

Deep Water Environments

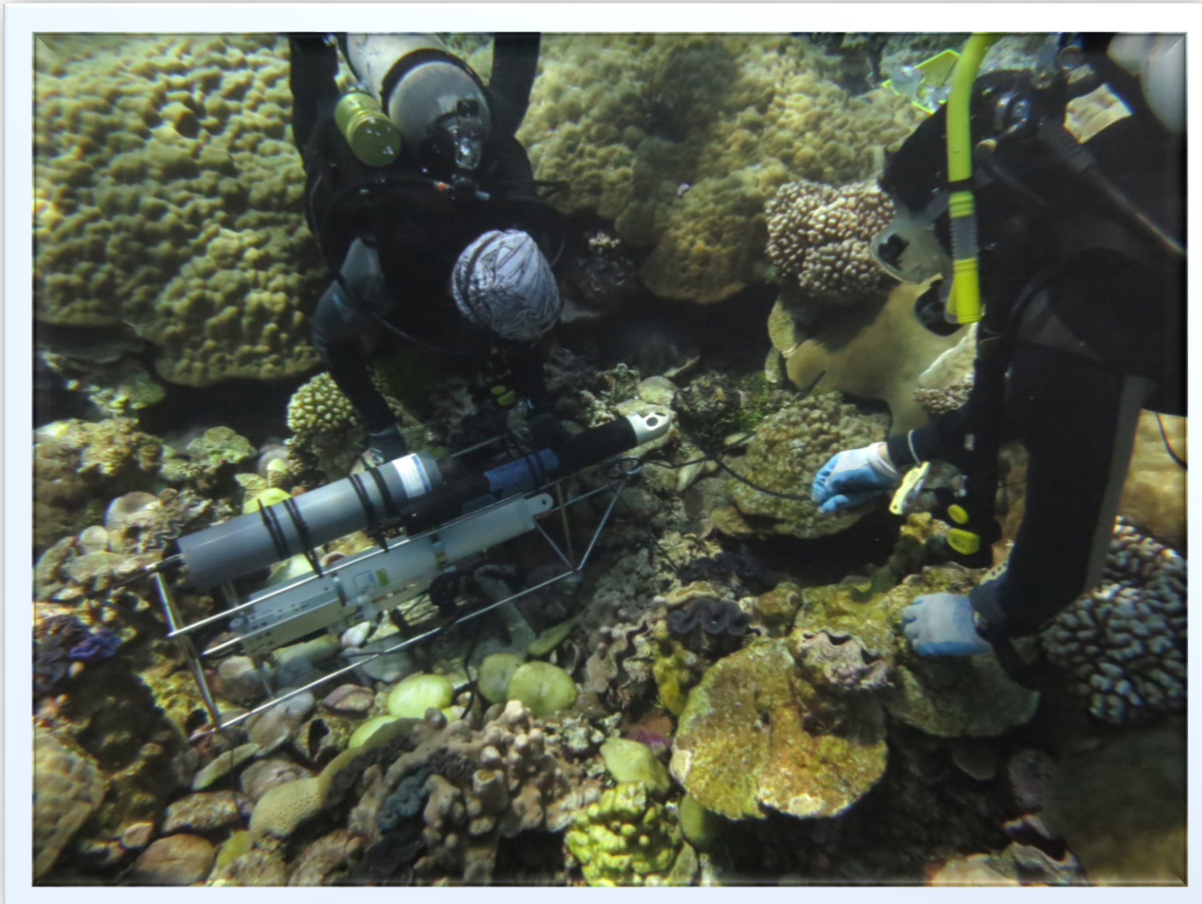
Multibeam bathymetry and backscatter were used for substrate prediction in waters deeper than approximately 30 m. A classification routine similar to the satellite-based approach was employed; however, further covariates were used as model inputs for cluster analysis within deeper waters. Three bathymetric derivatives—slope, standard deviation (SD) of mean depth (the higher the SD of the depth, the greater the rugosity), and relative distance to the mean depth (RDMV)—together with the backscatter data were included in the cluster analysis, in this case to identify groups of shared attributes among the multiple variables (Lecours et al. 2017). High slopes do not support unconsolidated sediments, so are likely to represent hard substrates. Equally, high standard deviation (a measure of rugosity) is indicative of rugged, hard substrates. RDMV provides a measure of relative bathymetric highs and lows, and therefore constrains areas of probable sedimentation (lows) versus non-deposition (highs). Most importantly, the backscatter data provide a measure of seabed texture and reflectivity, making them sensitive to hardness. Backscatter data, however, are prone to noise and are less reliable on high slopes and in rugose areas; hence, it is useful to include the bathymetric derivatives in the substrate predictions.

Similar to the satellite-derived classification, the cluster analysis and classification were performed in ArcGIS, and the resulting classes (~5) were manually assigned to hard or soft substrate by comparing the map classes with the underlying input data. Minor manual editing was conducted where obvious quality issues with the backscatter data persisted through to the classified map. See NOAA Fisheries InPort record ID 56994 for further details.

NOAA scientists Hannah Barkley and Ariel Halperin prepare equipment for use by the ocean and climate change team at Howland Island. These bottles will be filled with water samples to measure dissolved inorganic carbon composition in the ocean.
Photo: Noah Pomeroy, NOAA Fisheries.

Ocean and Climate Variability Methods

1.6 Ocean and Climate Variability Methods



NOAA divers installing oceanographic instruments at Kingman Reef.
Photo: NOAA Fisheries.

ESD monitors several oceanographic parameters and associated ecosystem response variables, including temperature, carbonate chemistry, calcium carbonate accretion and bioerosion rates, and cryptofauna and microbial biodiversity (both of which are discussed later in this chapter). Since 2000, ESD has used a variety of surface and subsurface moored instrumentation to monitor oceanography and water quality within the PRIMNM. Initial sampling efforts in 2000 focused on Conductivity, Temperature, and Depth (CTD) casts and temperature data collection. In following years, ESD further developed its nearshore and benthic time-series observations. In 2013, ESD began to execute NCRMP methodologies during RAMP research expeditions. Current data collections for NCRMP monitoring (2013–present) are described in the following instrumentation and discrete sampling efforts.

Instrumentation and Discrete Sampling

Subsurface Temperature Recorders (STRs)

Subsurface Temperature Recorders (STRs) secured to the reef collect high resolution, in situ seawater temperature time series. STRs are deployed for 2 to 3-year intervals at 1–25 m depths and are frequently recovered and redeployed at the same locations to maintain site-specific temperature time series (often 10 or more years). Starting in 2000, ESD deployed Sea-Bird Electronics (SBE)-39 temperature sensors. In 2013, ESD switched to the newer SBE-56, enabling a faster (5 min) sampling interval.

CTD Hydrocasts

CTD profilers are used to collect high resolution vertical casts of the water column from 1–30 m depths. ESD uses SBE-19plus CTDs paired with a SBE-43 dissolved oxygen probe and a Wetlabs ECO FLNTU sensor to measure fluorescence and turbidity. Hydrocasts are collected simultaneously with discrete water samples.

Discrete Water Sample Collection

ESD collects discrete seawater samples to assess coral reef water quality. Near reef, surface seawater samples are collected at 1 m depths using a 5 L Niskin bottle, stored in 500 mL glass bottles, and fixed with saturated mercuric chloride. Samples are analyzed for dissolved inorganic carbon (DIC) and total alkalinity (TA) at the NOAA Pacific Marine Environmental Laboratory (PMEL). Full carbon system chemistry—including pH and aragonite saturation state (Ω_{ar})—is calculated from TA and DIC using temperature and salinity values from paired CTD casts. Pre-2012 water sampling efforts also included nutrients, chlorophyll-*a*, and salinity bottle samples.

Calcification Accretion Units (CAUs)

Calcification Accretion Units (CAUs) quantify rates of reef calcium carbonate accretion (Vargas-Ángel et al. 2015). Each CAU is comprised of two 10 cm × 10 cm PVC plates separated by a 1-cm plastic spacer and mounted on a stainless steel rod driven into the benthos (Figure 13). CAUs are deployed in groups of five, over a 50 m^2 coral reef area, for 2–3 years. After recovery, the weight of calcium carbonate accreted by the organisms that recruited to the CAU plates (largely crustose coralline algae and corals) is used to provide an estimate of the net rate of calcium carbonate formation (g $CaCO_3$ cm^{-2} y^{-1}). The majority of CAU deployment locations are at long-term permanent ESD survey sites, and repeated CAU deployments at these permanent sites provide multi-year time series accretion data.

Bioerosion Monitoring Units (BMUs)

Bioerosion Monitoring Units (BMUs) quantify net calcium carbonate bioerosion rates. Each BMU is comprised of a clean coral skeleton block (constructed from recently dead *Porites* spp.) exactly measured and cut to a 1 cm × 2 cm × 5 cm piece and mounted atop a small PVC base. BMUs are mounted on the same stake as the CAUs (i.e., in groups of five and over the same 50 m^2 coral reef area as the CAUs) and deployed for 2–3 years (Figure 13). Each BMU is accurately measured and scanned before and after deployment by a Micro CT scanner at the

NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML). The differences between pre-deployment and post-deployment BMU weight and density are used to estimate net rates of bioerosion, and CT scans of recovered units can be used to identify the bioeroding organisms present. The majority of BMU deployment locations are at long-term permanent ESD survey sites, and repeated BMU deployments at these permanent sites provide multi-year time series bioerosion data.

Data are not presented in this report but are available upon request.

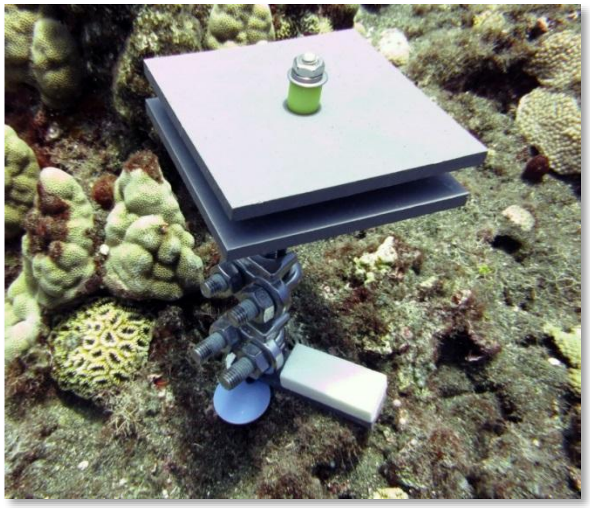


Figure 13. Newly deployed Calcification Acidification Unit (grey square plates) and Bioerosion Monitoring Unit (white rectangular block) assembly on the reef.

Ocean Acidification Diel Suite

As an extension of the NCRMP-Pacific regional and basin-wide efforts to monitor the ecological impacts of ocean acidification (OA), ESD developed an "OA diel suite" to monitor diel variations in seawater carbonate chemistry. The diel suite is a group of instruments deployed on the seafloor of permanent survey sites at a depth of 15 m for at least 24 hours and up to several weeks. The suite consists of programmable underwater collectors (PUCs), a moored CTD, an acoustic Doppler current profiler (ADCP), and a pH sensor.

PUCs pump a discrete volume of water into an individual collection bag for DIC and TA analysis. Each PUC pumps one sample at a specified date and time, so the OA diel suite is deployed with 6–9 PUCs to achieve an appropriately sampled diel time series. Near reef salinity and temperature time series are collected at 5-min intervals using a SBE-19plus CTD. Current profiles and wave spectra time series are collected at 5-min intervals using a 3-beam 1 MHz or 2 MHz Nortek Aquadopp profiler ADCP. Data are grouped into 1 m depth bins to provide depth specific information from the seafloor to the water surface. At 5-min intervals, pH is measured using the SBE/Satlantic SeaFET pH sensor. Values of pH from the SeaFET and those derived from discrete water samples collected by the PUCs are compared to evaluate SeaFET accuracy and pH trends.

Photomosaics and Structure from Motion (SfM)

Photomosaics and structure-from-motion (SfM) are large-scale photographic survey techniques that are used to characterize the composition and complexity of benthic communities. These high definition and larger scale photographs complement traditional photoquadrat benthic survey methods by providing consistent data on the percent cover, species composition, and physiological health of corals, algae, and other benthic taxa. Photomosaics and SfM collected over time can serve as large-scale archives for monitoring change on coral reefs. Academic collaborators from UCSD's Scripps Oceanographic Institution produced 2D and 3D photomosaics of 50–100 m^2 areas of reef, most of which are at the permanent NCRMP reef survey sites.

Data are not presented in this report but are available upon request.

Coral Core Collections

A coral core provides a sequential record of skeletal extension and density, allowing scientists to observe the coral's response to historical environmental and anthropogenic stress events, as well as a changing climate. ESD collects coral cores from *Porites* spp. using either a handheld pneumatic drill system capable of collecting 3.81 cm diameter cores up to 1 m long, or a surface-powered hydraulic drill capable of collecting 8.89 cm diameter cores up to 10 m long.

Data are not presented in this report but are available upon request.

Bioacoustics

The Ecological Acoustic Recorder (EAR) is a passive acoustic device designed for monitoring sound-producing marine life (marine mammals, fish, crustaceans), as well as human maritime activity (boat traffic/engine noise). The EAR is a digital, low-power system that records ambient sounds up to 30 kHz on a programmable schedule and/or can respond to transient acoustic events that meet specific criteria, such as motorized vessels passing nearby or cetacean vocalizations. EARS are deployed on the seafloor at 5–25 m depth. The EAR is no longer used within ESD, as it has been replaced by the Ocean Instruments Soundtrap 300. Sample intervals vary depending on duration of deployment and goals for acoustic capture.

Data are not presented in this report but are available upon request.

Shipboard CTD Hydrocasts

Shipboard CTD hydrocasts onboard the *Hiʻialakai* facilitate discrete water sample collection and provide high resolution vertical profiles of chemical and physical constituents found throughout the water column. A SBE-911plus has served as the cornerstone of shipboard hydrocast data collection, with a SBE-43 dissolved oxygen probe, and Wetlabs ECO FLNTU sensor measuring fluorescence and turbidity. Data are currently only collected at the surface to augment the study of the surface ocean's carbonate chemistry system, but historically casts have reached depths of 500 m.

Data are not presented in this report but are available upon request.

Shipboard ADCP, Meteorological Data, Thermosalinograph (TSG)

The *Hiʻialakai* shipboard ADCP, Ocean Innovations Ocean Surveyor provides directional ocean current data. Shipboard measurements of air temperature, wind speed and direction, barometric pressure, and relative humidity are measured from the bow and atop the pilothouse; and near-surface temperature and conductivity (salinity) measurements are collected in a seawater flow-through system with an inline SBE-21 SeaCAT TSG. Data for all parameters are continuously collected while the vessel is underway.

Data are not presented in this report but are available upon request.

Satellite-derived Oceanographic Products/Modelling

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

Satellite Remote Sensing

- NASA Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Imager
    - http://oceancolor.gsfc.nasa.gov/SeaWiFS/
    - Measures bio-optical properties of the ocean, including a calculation of chl-*a* levels, 9 km grid resolution
    - Climatology produced by ESD and NODC for OceanEye project using the period of 1998–2003
- NASA Moderate Resolution Imaging Spectrometer (MODIS)-Aqua
    - https://oceancolor.gsfc.nasa.gov/cgi/l3
    - Measures bio-optical properties of the ocean, including a calculation of chl-*a* levels, 4 km grid resolution
- NOAA High-resolution Optimum Interpolation Sea Surface Temperature (SST) V2
    - https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html
    - Measures ocean temperatures by using in situ and satellite SST data, 0.25 degree grid resolution

Ocean Modeling—Bleaching Threshold

As early as 1997, the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) began producing web-accessible, satellite-derived, near-real-time SST products to monitor conditions conducive to coral bleaching from thermal stress around the globe. These products can be found at Coral Reef Watch (CRW). SST data are provided at a resolution of 50 km × 50 km (0.5° × 0.5°).

The bleaching threshold developed by CRW serves as a general indicator for coral bleaching and is defined as 1 °C above the maximum monthly climatological SST value for a particular geographic area. It is important to note that satellite-derived SST represents the oceanographic temperatures of surface waters at a broad spatial scale, as opposed to the site- or reef-specific temperatures that are collected in situ by ESD (using STRs) at increasing depths.

Ocean Modeling—Wave Watch III

NOAA Wave Watch III is a third-generation, full-spectral ocean wind-wave model that provides historical and near real-time open-ocean, deep water modeled spectral wave data (height, period, and direction). Model outputs can generally be applied on spatial scales >1–10 km and beyond the depths of the surf zone (Tolman 1999).

Discontinued Oceanography and Water Quality Datasets

Hoeke et al. (2009) describes ESD's integrated oceanographic observing system established prior to NCRMP and outlines the historical precedent for ESD coral reef monitoring efforts. Instruments that are no longer deployed include the following:

Multi-parameter Moored Meteorological/Oceanographic/Coral Bleaching Warning Buoy

Moored buoys provided high-resolution data on SST, barometric pressure, wind speed, and wind direction. Enhanced versions additionally provided salinity, UV-B, and PAR. Subsets of these data were transmitted daily via satellite telemetry.

Sea Surface Temperature (SST) Buoy

Moored SST buoys provided high-resolution SST data with a SBE-39 attached to the bottom of the buoy at a nominal depth of 0.3 m. Data were collected at a 30-min sampling interval. Hourly means were internally calculated and transmitted via satellite telemetry once a day.

Ocean Data Platform (ODP)

The ODP provided water column directional current profiles and wave spectra using a SonTek 3-beam 1000 kHz acoustic Doppler profiler and provided high resolution temperature and conductivity time series observations using a SBE-37 MicroCAT C-T. The instruments were deployed on the seafloor at depths of 15–40 m.

Wave and Tide Recorder (WTR)

The Wave and Tide Recorder (WTR) provided high-resolution wave and tide records using SBE-26plus. Sample intervals varied depending on duration of deployment. Instruments were deployed on the seafloor at depths of 10–25 m.

Current meters

Subsurface moorings provided high-resolution current velocity and direction at locations of interest, including reef flats and shallow reef passes/channels. The Nortek Aquadopp provided full-depth, directional, current profiles and wave spectra using a 3-beam 1 MHz or 2 MHz acoustic Doppler profiler. The Aanderaa Data Instruments single point current meter (RCM-9) provided high-resolution current profiles at a single deployment depth.

Survey Design

ESD conducts stratified-random discrete water sampling for carbonate chemistry monitoring, but focuses instrument-related monitoring efforts at the permanent NCRMP reef survey sites at depths of 1 m, 5 m, 15 m, and 25 m (Figure 14, top). Permanent sites are typically established at north, south, east, and west points around the island or atoll of interest at 15 m depths.

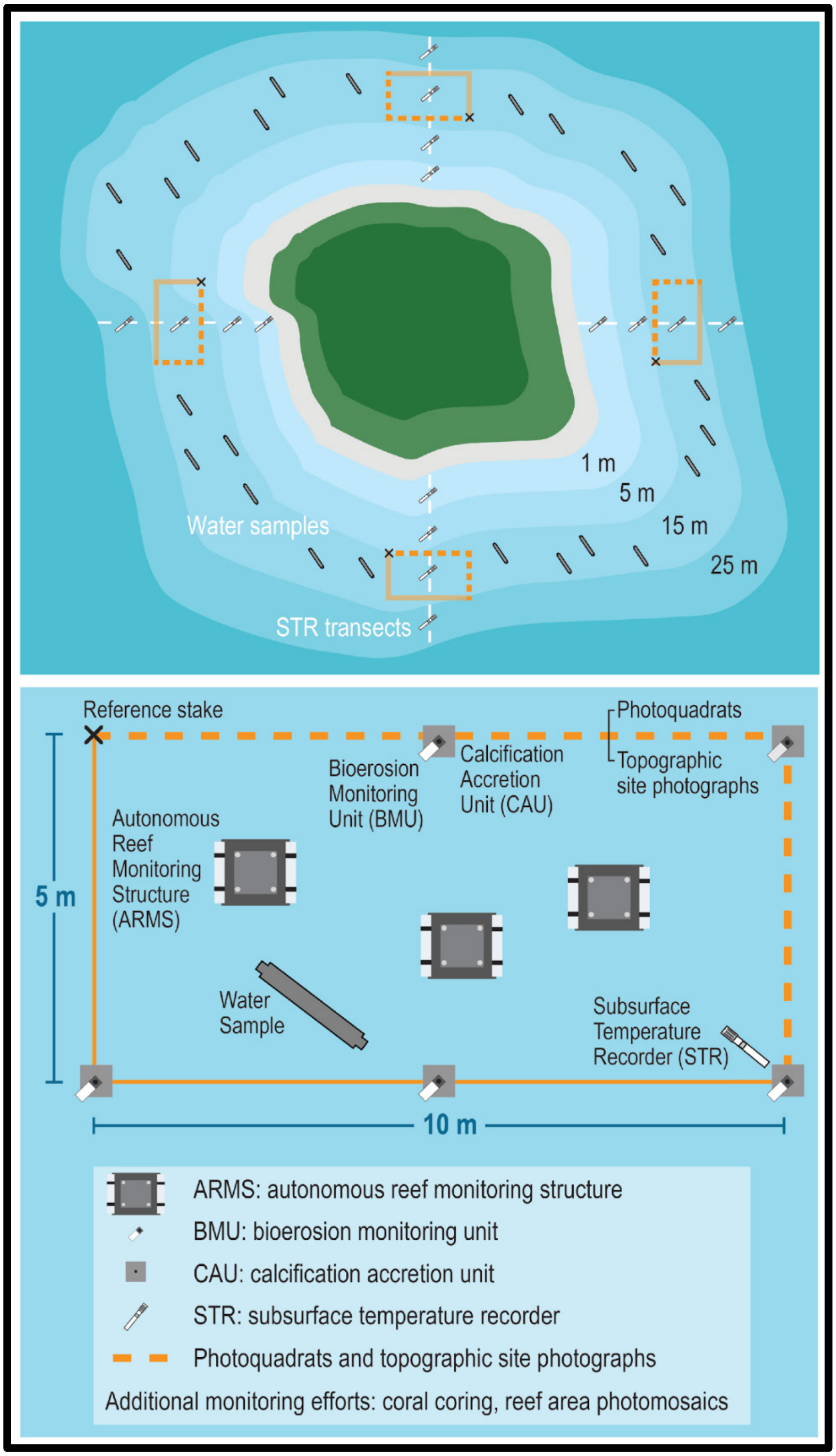
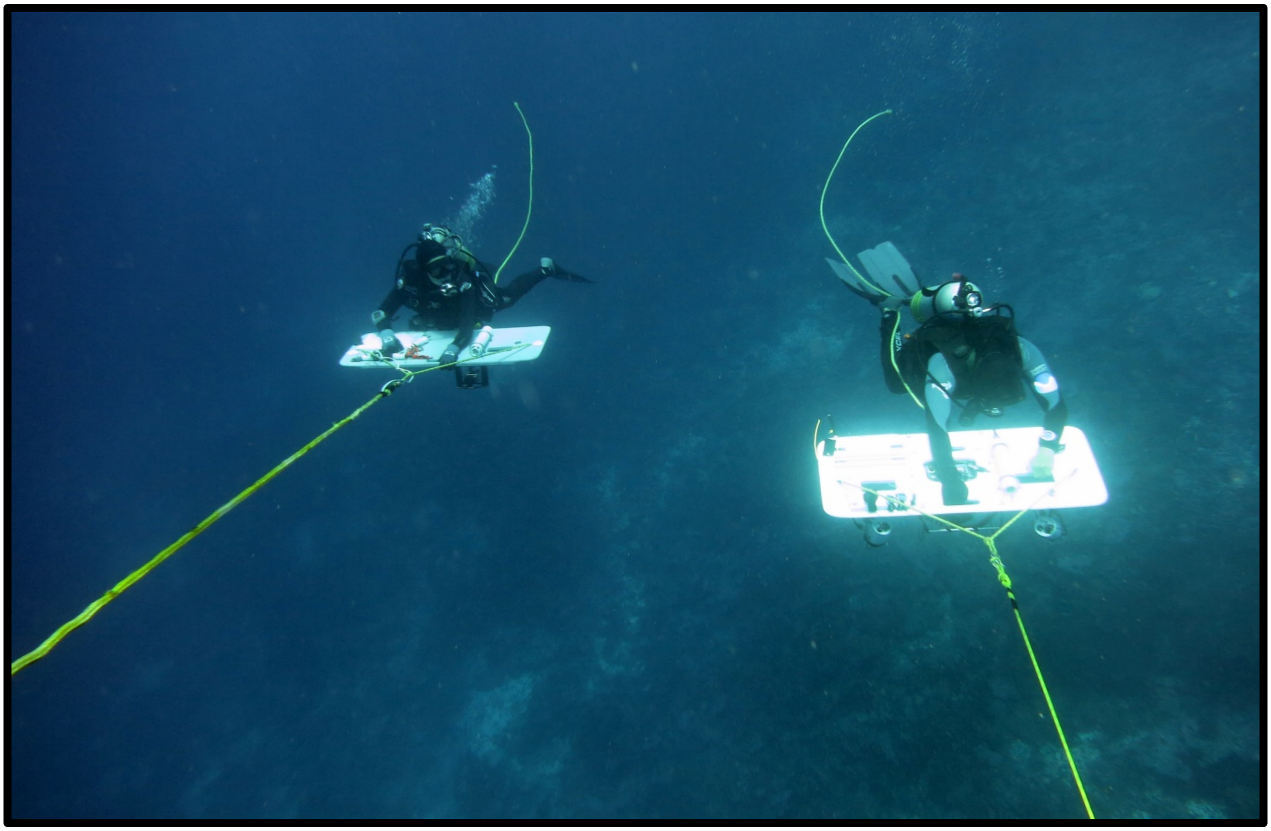


Figure 14. Schematic of ocean and water quality sampling design (top), and detailed placement of instruments within the long-term permanent survey sites (bottom).

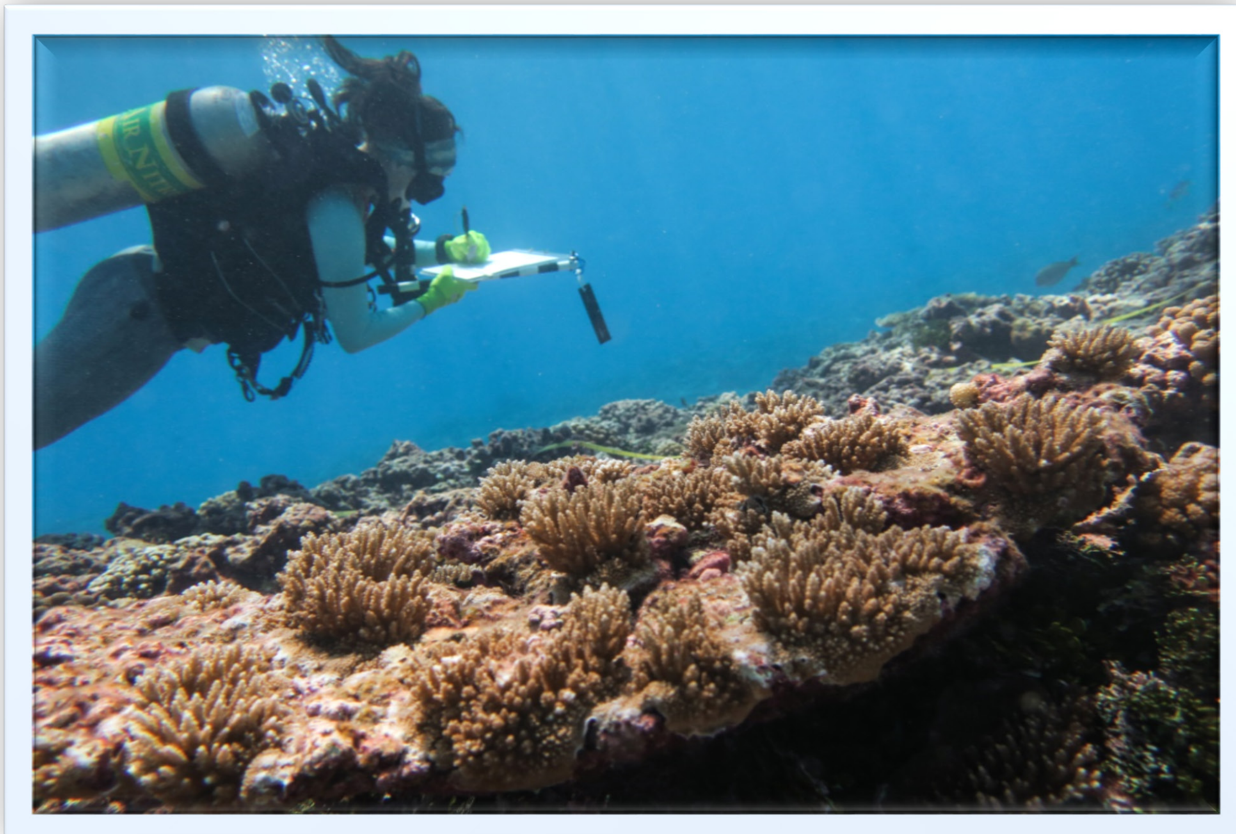
Instruments within the permanent survey sites are deployed on the reef for a period of 2–3 years. The suite of data collection and instruments shown in Figure 14 (bottom) monitor carbonate chemistry (water sample/CTD hydrocasts), cryptic biodiversity (3 ARMS), bioerosion rates (5 BMUs), calcification rates (5 CAUs), and seawater temperature variability (1 STR). Additional microbial sampling, coral core collections, and photomosaic surveys may also occur within these sites. The site's rectangular shape is estimated with measuring tapes and delineated on the reef during site installation by temporarily placing tapes and markers from a permanently installed reference stake. Along the nearshore 10 m side of the survey site and the downslope 5 m side, the measuring tapes mark every meter of the 15 m transect used for photoquadrat documentation, urchin counts, and reef structure/rugosity measurements. SCUBA divers photograph the reef at 1 m intervals on both sides of the tape (30 total photographs over the 15 m transect), as well as conduct an urchin count and evaluation of reef rugosity along the same transect. Around the perimeter of the survey site, at 5 m intervals, the CAUs and BMUs are deployed. Within the survey box the ARMS and SBE-56 are deployed. Divers collect a discrete seawater sample (15 m depth) using a 5 L Niskin bottle. A second discrete water sample is collected at the surface (1 m depth) directly above the survey site. Immediately upon returning to the dive boat, a CTD hydrocast is conducted to within a few feet of the seafloor using a SBE-19 plus. Next, the surface (1 m) and reef (15 m) seawater samples are processed for DIC, TA, nutrients, and/or salinity analyses. Upon returning to the ship at the end of the day, a shipboard CTD hydrocast and discrete water sample are collected 10–15 km offshore from the permanent survey site.



Divers are towed by a small boat to survey benthic habitats and large mobile fish species at Baker Island. Photo: Marie Ferguson, NOAA Fisheries.

Survey Methods for Coral Reef Benthic Communities

1.7 Survey Methods for Coral Reef Benthic Communities



NOAA benthic diver Brittany Huntington measures the size and condition of numerous juveniles of branching Acropora *spp.*
Photo: Chelsie Counsell, Hawai'i Institute of Marine Biology, courtesy NOAA Fisheries.

Data for the three main benthic categories addressed in the report—corals, algae, and other macroinvertebrates—were acquired using two types of surveys: benthic Rapid Ecological Assessment (REA) surveys and towed-diver surveys (TDS). During the 15 PRIMNM surveys cruises conducted between 2001 and 2017, a total of 658 benthic REA surveys were conducted at specific reef sites, while 683 TDS were performed around the islands and reefs. Overviews of REA surveys and TDS, with descriptions of sampling design and survey methods specific to each ecological discipline, are presented below.

Towed-diver Surveys

Towed-diver surveys (TDS) began in the PRIMNM in 2001. They were used to characterize benthic communities and to quantify the abundance and spatial distribution of ecologically important macroinvertebrate taxa over an area that is much broader than the areas surveyed using benthic REA methods. Importantly, towed-diver surveys also accessed exposed coastlines (e.g., windward-facing shores and high-swell conditions) that were not always surveyed using REA techniques.

TDS targeted outer-reef habitats. A series of TDS covered the perimeter around each surveyed island/reef system along a relatively constant isobath (typically between 10 and 20 m). At smaller islands/reef systems, multiple circumnavigations using TDS were possible targeting different depths (e.g., 5, 15, and 25 m). Each individual towed-diver survey typically covered approximately 1.5–2.5 km of distance. In this report, TDS estimates of benthic cover are only shown from 5–17 m target depths to facilitate comparisons between methods, habitats among islands, and changes in composition at a single island over time. Macroinvertebrate data from TDS are shown for all available tow depths.

TDS towed a pair of divers behind a small boat, with one diver tasked with benthic data collection and one diver gathering data on large fishes (see the section "Survey Methods for Reef Fishes" later in this chapter). Benthic divers made visual estimates within an 8 m swath (Figure 15). TDS observations were recorded separately per 5-min "segment" (10 segments per complete 50-min tow), with mean segment length of approximately 220 m. To georeference the data collected during TDS, a GPS receiver located on the small boat was programmed to record longitude and latitude coordinates every 5 sec. Segments are used as the unit of replication for analysis of TDS data. A detailed methodology for the TDS can be found in Kenyon et al. (2006) and Lino et al. (2018).

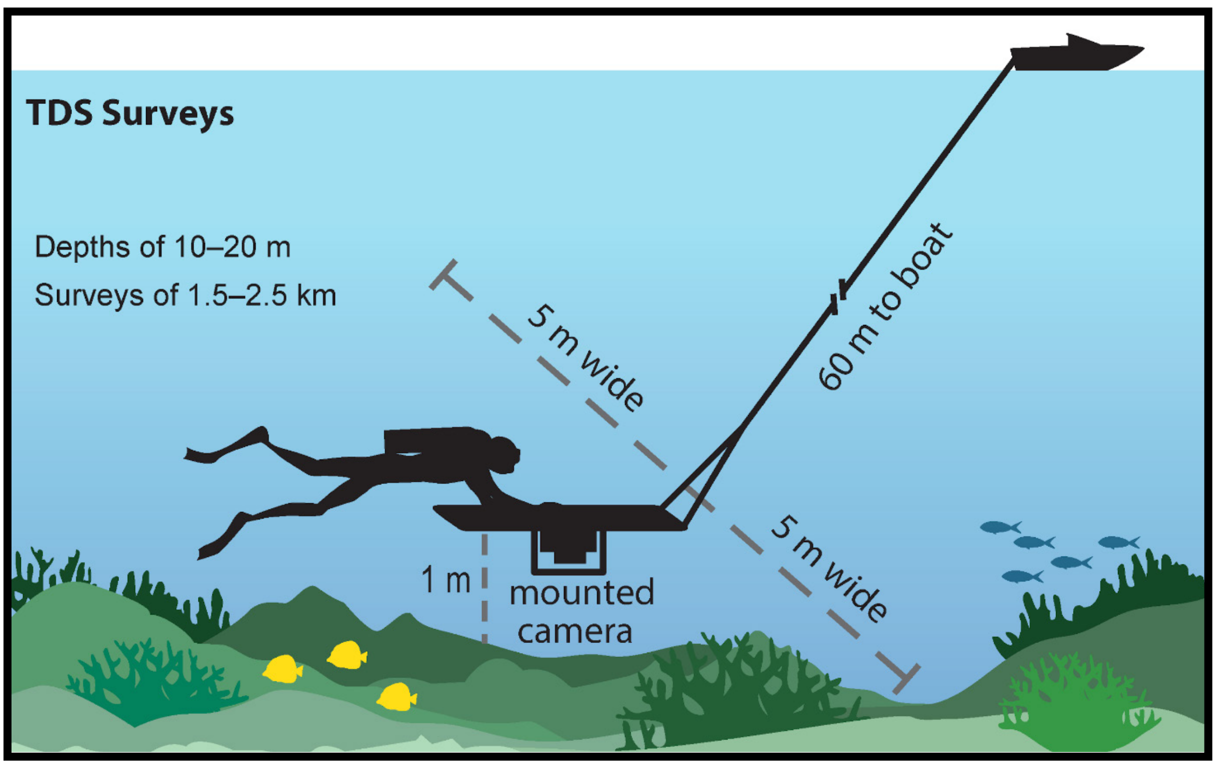


Figure 15. Schematic of towed-diver surveys. Surveys are conducted typically at 10–20 m depths over distances of 1.5–2.5 km. Benthic divers survey an 8 m swath (4 m on either side of the tow line) from approximately 1 m above the benthos (the fish diver survey swath is shown).

Over time, TDS have collected data on an assortment of benthic parameters (Brainard et al. 2012); for the purposes of this report, only a relevant subset are reported. Benthic divers estimated the benthic cover (binned estimates) of coarse benthic community groups per segment, including hard coral, macroalgae, and crustose coralline algae (CCA; Table 4). Because towed-diver surveys use visual estimates for cover, results can be subject to observer variability both within and among survey years. These estimates were recorded to the nearest percentage during 2003 and within 10 percentage bins from 2004 onwards (Table 5). For binned estimates, the midpoint of the bin was used for analysis. Turf algae were included in estimates of 'macroalgae' from 2003 to 2006. Turf was then recorded in a separate category in subsequent years to avoid overestimating macroalgal cover. It should be noted that calcified macroalgae *Halimeda* were consistently included in the macroalgae cover estimates over time. CCA was added as a category in 2005. Benthic divers also recorded counts of crown-of-thorns sea stars (COTS), giant clams, sea cucumbers, and sea urchins observed in the segment. Sea cucumber abundance was discontinued from surveys in 2014 due to difficulty maintaining consistency among habitats and between observers. All macroinvertebrates, except COTS, were counted singly up to 25 and then binned as follows: 26–50, 51–100, 101–250, 251–500, 501–1,000, and more than 1,000 organisms. COTS were counted singly up to 100 organisms and then binned into the same higher classes. Given the size and often cryptic nature of certain macroinvertebrates, such as sea urchins and giant clams, the density values presented in this report may under-represent the number of individuals present.

Table 4. Benthic towed-diver survey metrics. Quantified metrics for each benthic community group are shown.

Benthic Communities	**Quantified Metric**
Benthic Cover	Cover (%) of live hard corals
	Cover (%) of stressed corals
	Cover (%) of crustose coralline red algae
	Cover (%) of macroalgae (in 2001–2006, combination of macroalgae and turf algae; 2008–present macroalgae only)
Macroinvertebrates	Abundance of crown-of-thorns sea stars, giant clams, sea cucumbers, and sea urchins

Table 5. Percent cover bins for towed-diver survey. Midpoint of the bin range was used in analysis.

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

In addition to the primary observations for each ecological discipline, towed divers were tasked at various times with recording unusual or important sightings that included significant biological or habitat gradients, shipwrecks, unexploded ordinance or munitions, and derelict fishing gear or other types of marine debris located on the seafloor.

Data from each survey segment were graphically projected onto maps using the midpoint for each survey segment. For estimates of benthic cover, values were estimated as the midpoint of the binned observation range. Macroinvertebrate densities were estimated as the number of individuals observed within 100 m^2.

Rapid Ecological Assessment Surveys

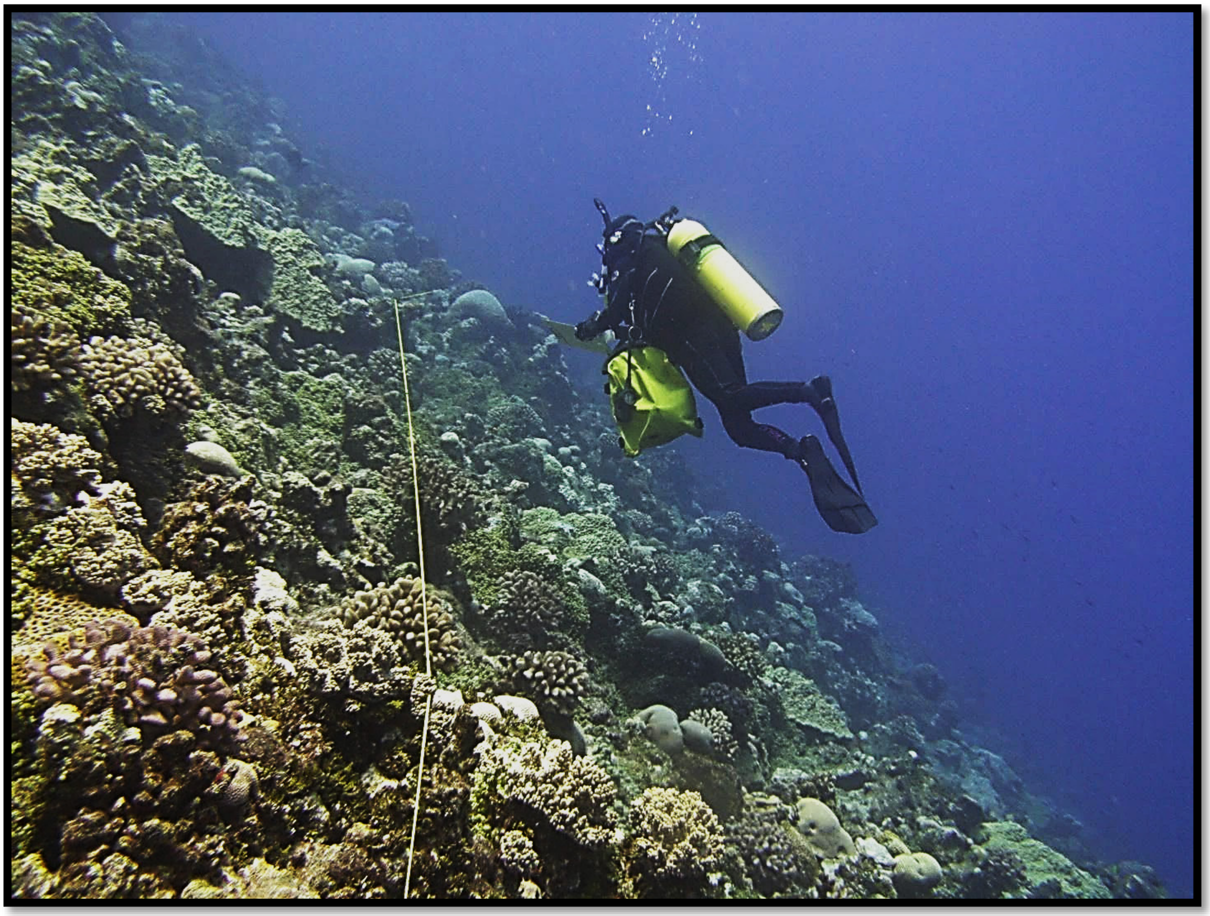


Figure 16. NOAA diver conducting benthic Rapid Ecological Assessment (REA) survey at Wake Atoll. Photo: Bernardo Vargas-Ángel, NOAA Fisheries.

Rapid Ecological Assessment (REA) surveys were used to survey corals, algae, select macroinvertebrates, and protected species (Figure 16; Table 6). Over time, these surveys have collected data on an assortment of benthic parameters (Brainard et al. 2012); however, only a subset of relevant metrics are presented in the island-specific chapters. In addition, REA methodologies and protocols evolved over time, reflecting improvements to the survey design, sampling techniques, and data quality. Given these changes in methods, comparisons between survey estimates are precluded.

Table 6. Benthic Rapid Ecological Assessment Survey metrics. Metrics collected for each benthic group of data are shown.

Benthic Group	Quantified Metric
Corals	Cover (%) of live stony corals
	Coral density (# colonies m^{-2})
	Size-class distribution of corals
	Extent and prevalence of coral disease and bleaching
	Extent of partial mortality (old and new)
Algae	Cover (%) of macroalgae, crustose coralline algae, and turf algae
	Distribution and occurrence of coralline-algal disease
Protected Species	Sighting of Endangered Species Act (ESA)-threatened coral species (2015–present)

REA: Repeat Sites

A number of REA sites (~6 to 20; depending on island/atoll size) were haphazardly selected at the time of the first cruise at each location (2005 for Wake, 2004 for all other islands) and, when possible, the same site coordinates were resampled during PRIMNM cruises until 2012 (hereafter referred to as “repeat sites”). Transect placement within a site was also haphazard, and placed varied from year to year. Site selection was not random, but in consultation with the resource management agencies and, in many cases, placed at long-term monitoring sites previously established by the U.S. Fish and Wildlife Service. The following aims were considered during REA repeat site selection: (1) a range of survey sites representative of the benthic habitats around each island or reef system; (2) a mixture of sites with a range of anthropogenic impacts from high to low; and (3) sites that could be compared to and complement previous assessment and monitoring work conducted by other agencies.

Between 2004 and 2012, most REA surveys were conducted at repeat sites along the forereef slopes of islands at depths of 10–20 m, with additional surveys conducted in some backreef and lagoon habitats.

The nonrandom nature of site selection places limits on the degree to which biotic metrics can be extrapolated through statistical inference to the larger population around an island. Since transects were not placed at the exact same location year after year at repeat sites, we therefore do not make inter-annual comparisons at nominal sites in this report.

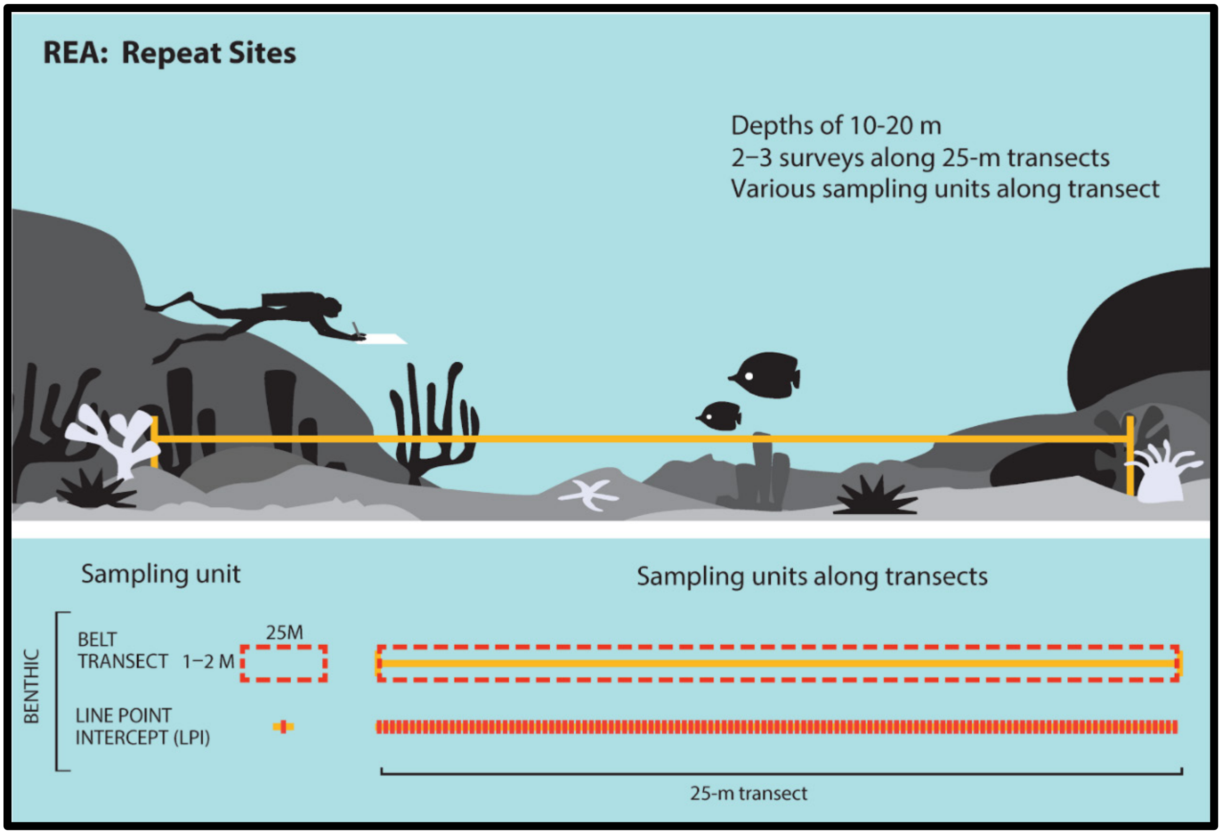


Figure 17. Schematic of Rapid Ecological Assessment repeat site surveys (used from 2004 to 2012). Belt transects were used to survey the coral population. Line point intercept (at 20 cm intervals illustrated in schematic) was used to survey benthic community cover.

The belt-transect method was used to quantitatively assess generic richness, colony density, and size class of stony coral colonies (scleractinia, hydrozoa, and the blue coral *Heliopora coerulea*). At each site, two 25 m transects were haphazardly laid against the prevailing current, following the 15–20 m isobath. Transects were placed in line separated by a 5–10 m space (Figure 17). Between 2004 and 2008, the width of the transect was subjectively determined by the perceived colony density; a width of 1 m was used in high-density areas, while a width of 2 m was used in low-density areas. At each REA site, the coral diver surveyed two 25 m transect lines, recording all coral colonies whose centers fell within each belt transect. Colonies were identified to genus level and size estimated as one of seven size classes: ≤5 cm, 6–10 cm, 11–20 cm, 21–40 cm, 41–80 cm, 80–160 cm, and >160 cm (Mundy 1996). When estimating coral-colony boundaries, consideration was given to tissue color, interfaces (e.g., skeletal ridges) with neighboring colonies of the same species, and variations in growth forms. If determinations of individual colony boundaries could not be made on these criteria alone, conspecific areas of live tissue separated by more than 10 cm were counted as separate colonies. All scleractinian, hydrozoan, and octocorals were included in this census.

In 2010–2012, five 2.5 m^2 segments (beginning at points: 0 m, 5 m, 10 m, 15 m, and 20 m) were surveyed along each of the two 25 m transect lines. In each segment, all coral colonies whose center fell within 0.5 m of either side of the transect line were identified to the genus or species level, and two planar-size metrics collected (i.e., maximum diameter and maximum diameter perpendicular to the maximum diameter). The extent (percentage of colony affected) of "recent" and "old" partial mortality was estimated for each colony. In addition, cases of bleaching and disease were recorded and supplementary information collected, including extent, severity (1 = faded, 2 = pale, 3 = blotchy, 4 = fully discolored, 5 = stark white), as well as photographic documentation.

Beginning in 2006, coral diseases and coralline-algal diseases, as well as predation scars from COTS (*Acanthaster planci*) or corallivorous snails, such as *Drupella*, were also quantified using the belt-transect method at each REA site. Within a belt transect or segment, all coralline-algal diseases were enumerated and classified into five general categories: coralline lethal orange disease, coralline fungal disease, coralline white band syndrome, coralline target phenomena, and coralline cyanobacterial disease, following Vargas-Ángel (2010). At each site, occurrence of coralline-algal disease was estimated, in lieu of prevalence, as the number of cases (counts) relative to the percent of CCA cover at each transect/survey site, as follows: DO_I = [(total no. cases of a specific disease) ÷ (% CCA cover)].

From 2006 to 2008, coral disease surveys followed Brainard et al. (2005) and Aeby (2006), whereby at the beginning of each dive, subjectively perceived abundance of coral disease dictated the width of the belt. Prevalence of coral disease was computed as the percentage of diseased colonies (counts) relative to the estimated total number of colonies in the survey area. Due to the heterogeneity inherent at each site, the extrapolation of colony numbers can result in overestimates of colony densities and underestimates of disease prevalence; for those reasons these data are not presented. Later, between 2009 and 2012, surveys were conducted within the five 2.5 m^2 segments per transect. Prevalence was estimated as the percentage of diseased colonies relative to the total number of colonies tallied per site. All diseased coral colonies were enumerated, measured, identified to the genus level, and assigned to one of six disease state categories (Vargas-Ángel and Wheeler 2008): skeletal growth anomalies, white syndrome (acute tissue loss), subacute tissue loss, pigmentation response, fungal infections, and other impaired health conditions (including patchy or thermal bleaching, algal and cyanophyte infections, tube-worm infestations, and syndromes of unknown etiology). A measure of lesion extent was quantified for select disease states (including bleaching and skeletal growth anomalies) as the percentage of colony affected and severity was assessed on a semi quantitative scale ranging from 1 (mild) to 5 (acute), following Work and Aeby (2006). Additionally, lesions attributable to predation from COTS, corallivorous snails, or fish were also identified and enumerated. Disease counts were complemented with digital photography and tissue collections for future histological examination and verification.

Detailed descriptions of coral diseases and coralline algae diseases, as well as predation scars and bleaching, can be found at the ESD website (Vargas-Ángel 2010).

Line-point-intercept Surveys

The line-point-intercept method (Hill and Wilkinson 2004) was used to assess the percentage of cover for live corals and other benthic elements at REA sites surveyed between 2006 and 2012. A coral diver swam along the two 25 m transect lines recording at 50 cm intervals (2005–2008) and 20 cm intervals (2010–2012) with all benthic elements falling directly underneath the transect lines (Figure 17). Benthic elements were assigned to one of nine categories: live corals (scleractinian, hydrocorals, and *Heliopora coerulea*), dead corals, carbonate pavement, rock, crustose coralline red algae, macroalgae (both calcified and fleshy), coral rubble, sand, and other sessile invertebrates. Benthic organisms were identified to the lowest taxonomic level possible. Cover of turf algae was derived from estimates of cover of dead corals, pavement, and rock.

REA: Stratified Random Sampling

Beginning in 2013, REA survey methodology shifted from using repeat sites to stratified random sampling (StRS). A two-stage survey scheme following Cochran (1970) was employed; the details of two-stage stratified random sampling design and implementation are described by Smith et al. (2011) and Swanson et al. (Swanson et al. 2018). StRS sites are stratified by reef-zone (forereef, protected slope, backreef, lagoon) and depth: shallow (<6 m), mid (6–18 m), and deep (18–24 m). Survey effort was proportional to the amount of hard bottom within each stratum, such that more sites were sampled in strata containing larger amounts of hard bottom habitat. Estimates for strata were generated from site means and weighted by strata area. Island-scale and population-domain estimates (means and totals) were calculated using weighted strata means. Sites were randomly selected within each stratum for each cruise rather than resampled.

Surveys at each site were conducted within two 18 m belt transects (Figure 18). Adult coral colonies (≥5 cm) were surveyed within four (1.0 m × 2.5 m) segments at 5 m increments along each 18 m transect in the following manner: 0−2.5 m; 5.0−7.5 m; 10−12.5 m; and 15−17.5 m. Colonies were identified to the lowest taxonomic level possible (species or genus), measured (maximum diameter to the nearest cm), and morphology was noted. In addition, partial mortality and condition of each colony was assessed. Partial colony mortality was quantified as the percent of dead tissue (classified as “old dead” or “recent dead”) and attributed to cause of mortality when known. Conditions affecting each colony (i.e., disease and bleaching) were noted, along with the extent (percent of colony affected) and severity (ranging from moderate to acute).

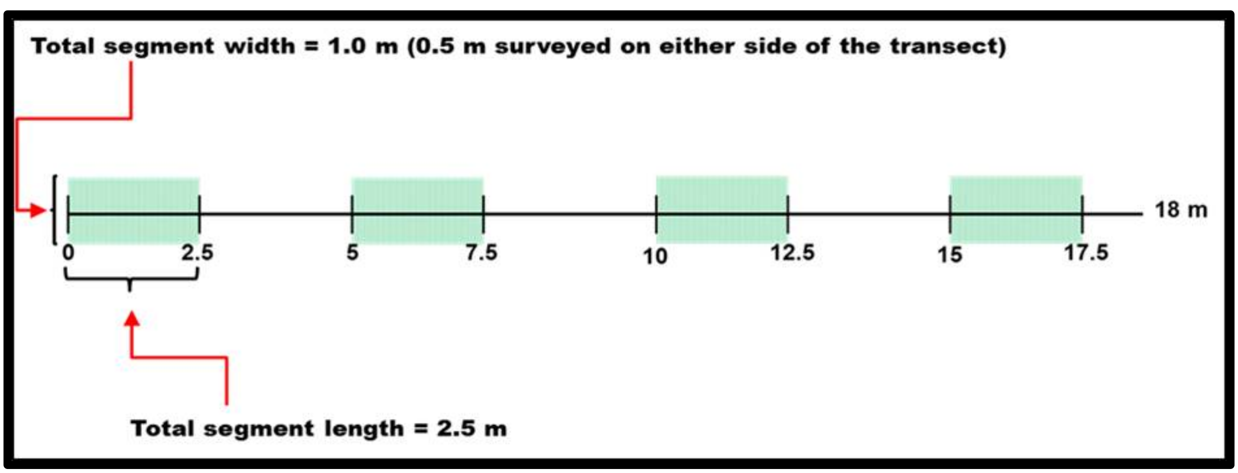


Figure 18. Schematic of stratified random REA belt transect surveys used to survey the coral population.

Juvenile coral colonies (<5 cm) were surveyed within three (1.0 m × 1.0 m) segments along the same two transects: 0–1.0 m, 5.0–6.0 m, and 10.0–11.0 m. Juvenile colonies were identified by a distinct tissue and skeletal boundary that distinguished them from fragments of larger adult colonies. Each juvenile colony was identified to the lowest taxonomic level possible (genus or species) and measured (both the maximum and perpendicular diameter to the nearest 2 mm).

Coralline-algal diseases and syndromes were quantified within each belt transect and classified into the same five general categories used during REA: repeat site surveys (2004–2012) and occurrence calculated using the previously described approach.

Benthic image analysis
Starting in 2014, benthic cover and community composition were derived from still photographs collected every 1 m from the 1 m to the 15 m mark along the same two REA transect lines. Benthic imagery was collected at additional stratified random sites for fish assemblage surveys, using the same approach but along one 30 m transect. The 30 photographs taken per site, were later analyzed, implementing the web-based software Coral Point Count with Excel extensions (Kohler and Gill 2006) and CoralNet (Beijbom et al. 2015). Benthic cover of each photograph was evaluated by randomly overlaying ten points on each image and identifying the organism or type of substrate beneath, with 300 points per site. Benthic elements falling under each point were identified to genus/morphology for hard corals, and to genus/functional group for algae, invertebrates, and other taxa following Lozada-Misa et al. (2017).

Generating island-scale estimates from the stratified design

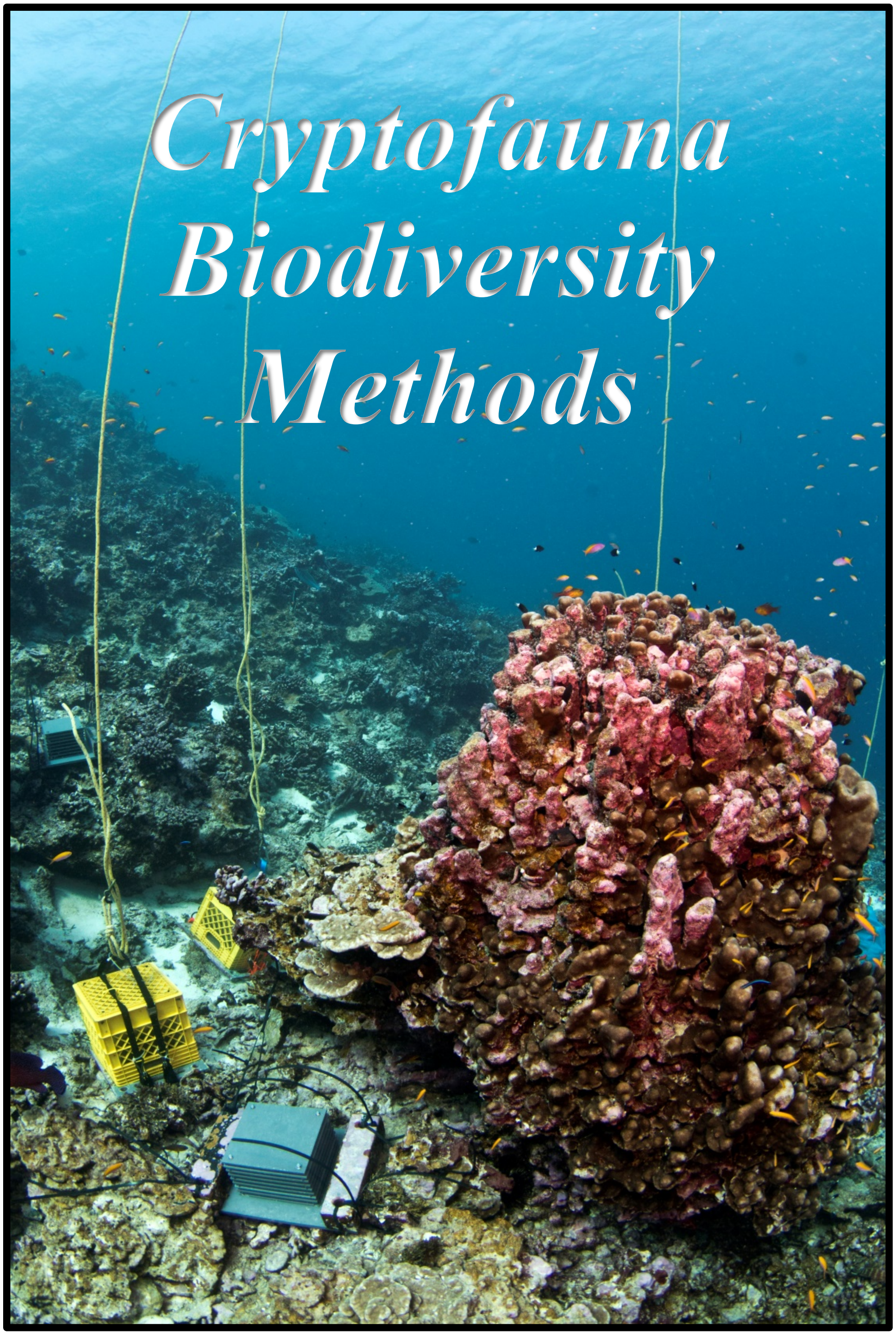
Summary statistics (e.g., mean and variances) of survey quantities (e.g., percent cover, colony density) are calculated by first averaging values within each stratum before calculating the reporting unit values. A weighted average method to calculate summary statistics is used because survey strata vary in size within each reporting unit. Estimates of the mean and variance for each survey quantity considered are calculated based on the observed values at sampled sites within each stratum. Then, aggregate estimates of the quantities across all strata are calculated using the formulas below. For example, with respect to colony density, we have

1. pooled mean colony density (*X)* across S strata: $X = \sum_{1}^{S} (X_i * w_i)$ and;
2. pooled variance of colony density (VAR) across S strata: $VAR = \sum_{1}^{S} (VAR_i * w_i^2)$

where X_i is the estimate of mean colony density within stratum i, VAR_i is the estimated variance of X_i, and w_i is the stratum-weighting factor. Strata weighting factors were based on the size of strata (i.e., if a stratum is 50% of the total area in an island, then the weighting factor is 0.5) and total of all weighting factors in an island sums to 1 (Smith et al. 2011).

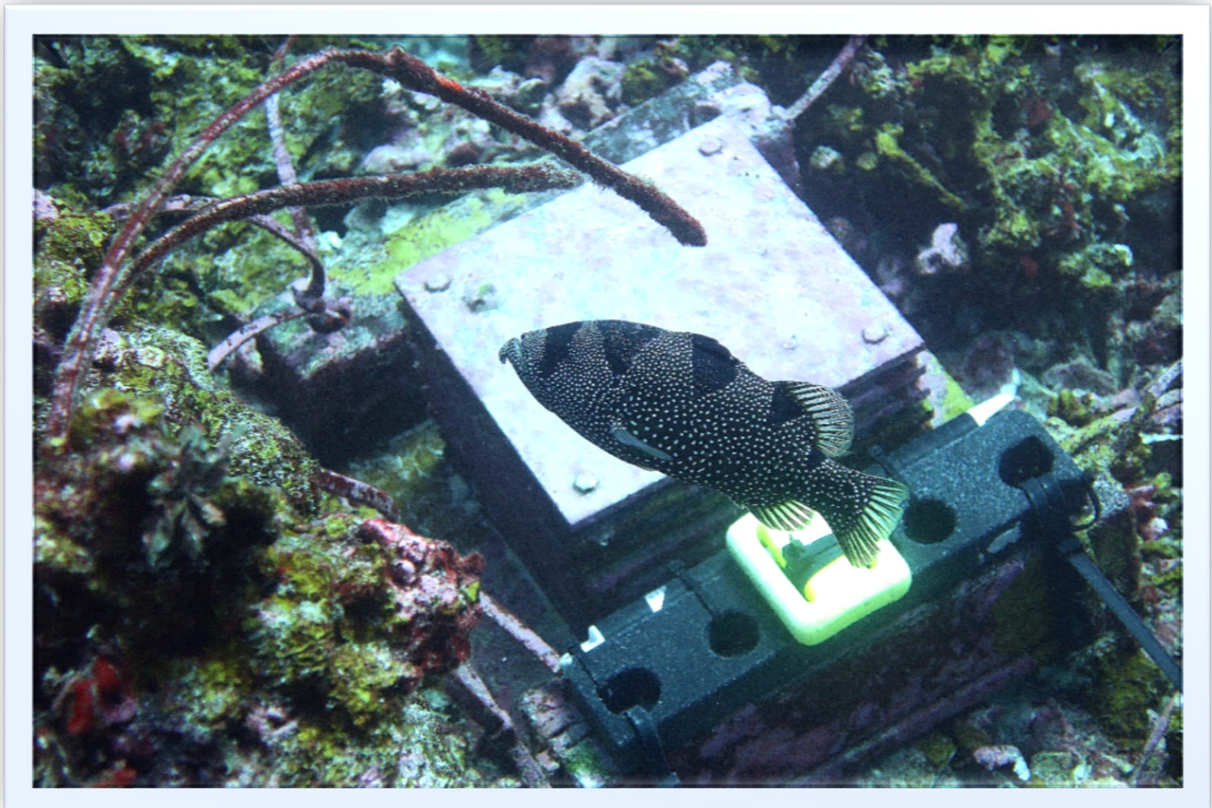
Gridded figures of percent hard coral cover were generated by spatially binning all coral cover data across all survey years (2001–2017) and methods (TDS, line point-intercept (LPI), repeat sites, and StRS benthic and fish photoquadrats) into 500 m × 500 m grid cells, with the mean value presented in each cell. Raw time series of coral cover are also presented by georegion around each island. Finally, gridded long-term coral cover trend analyses were also computed using all data across all survey years and methods per 500 m × 500 m grid cells, using a linear regression model, reporting the slope as a per 10-year metric. To report a grid's trend value, it was required that each reported cell have at least one observation in each of three, 5-year bins (i.e., 2000–2005, 2006–2010, and 2011–2015).

All data handling and analyses were performed using raw site data extracted from the NOAA ESD Oracle database and processed using a set of routine processing scripts written in R (R Core Team 2013).



Autonomous reef monitoring structures are ready for collection at Jarvis Island.
Photo: Jeff Milisen, NOAA Fisheries.

1.8 Cryptofauna Biodiversity Methods



Spotted soapfish at Jarvis Island swims over autonomous reef monitoring structure.
Photo: Kevin Lino, NOAA Fisheries.

Autonomous Reef Monitoring Structures (ARMS)

Autonomous Reef Monitoring Structures (ARMS) are three dimensional (23 cm × 23 cm × 23 cm) standardized habitats used to examine the small, diverse, and functionally important group of marine organisms known as the cryptobiota (Figure 19; Knowlton et al. 2010; Ransome et al. 2017). ARMS are deployed in groups of three within the same 50 m^2 coral reef area as the CAUs and BMUs. They are encapsulated with a mesh-lined crate upon recovery to contain all organisms that have recruited to these artificial habitats. ARMS are processed by disassembling the plates and filtering the water through a 2 mm sieve. Sieved motile organisms are then sorted to morphospecies, photographed, counted, identified, and preserved. Specimens were examined through the imagery and/or under a microscope by additional taxonomists back on land to increase the taxonomic resolution of the collected organisms.

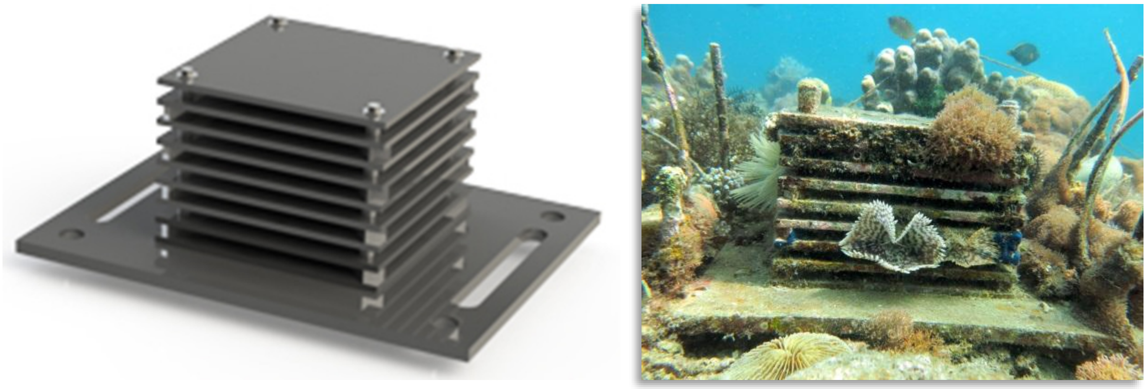
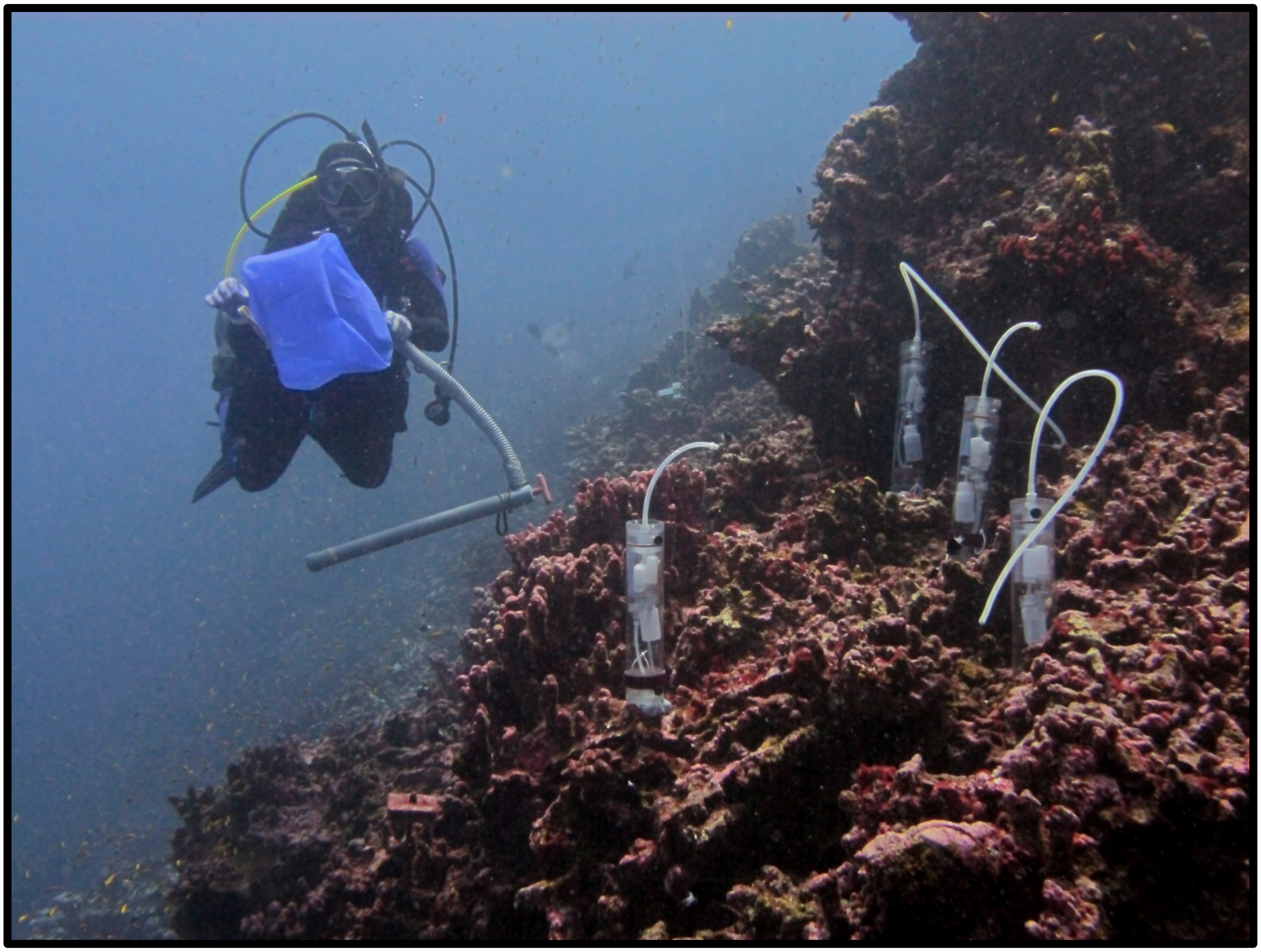


Figure 19. Computer Aided Design image of an assembled Autonomous Reef Monitoring Structures (ARMS) (left) and an image of an ARMS unit after 3 years on the reef (right).



Microbial biologist Lauren Mathews from San Diego University takes microbial samples at Jarvis.
Photo: James Morioka, NOAA Fisheries.

Microbiota Methods

1.9 Microbiota Methods

Corals at Palmyra Atoll.
Photo: Chelsie Counsell, NOAA Fisheries.

Microbial Biodiversity

ESD's academic collaborators from San Diego State University and the University of Hawaii provide benefit to the assessment and monitoring of coral reefs by monitoring benthic community microbial taxonomic and functional composition and by calculating fluxes of energy between the reef microbial community, benthic, and pelagic macro-biota. These efforts allow for characterization of coral reef ecosystems from a molecular to an ecosystem-wide scale across the PRIMNM and U.S. islands of the Pacific.

Microbial biodiversity sampling includes analyses of discrete water samples from various Niskin bottle collections. SPE-DOM (Solid Phase Eluted Dissolved Organic Matter) and benthic community evaluation offer a deeper characterization of the organic matter pool on reefs.

Collection of Water Chemistry Using Minidon Niskin Bottles

Primary goal and procedural overview: This method provides most of the long term monitoring samples (water chemistry: organic carbon, inorganic nutrients; microbial activity and composition: abundances and biomass, autotroph:heterotroph, and diversity). At every reef site, samples were collected from the (1) reef benthos, (2) reef matrix, and (3) reef water column. Offshore samples were collected opportunistically whenever the ESD sampled there. Water samples were processed according to the procedures outlined in Haas et al. (2014).

Molecular Characterization of Dissolved Organic Matter (DOM Metabolomics)

Primary goal and procedural overview: These analyses, which isolate DOM from seawater with low salt contamination for downstream analysis by LC-MS (liquid chromatography–mass spectrometry), yield information concerning both the quality and quantity of DOM in benthic-associated seawater providing deeper characterization of the organic matter pool on reefs. Protocols for collection and processing of SPE-DOM can be found in Petras et al. (2017).

Collection of Benthic Viral and Microbial Metagenomes

Primary goal and procedural overview: As part of the long-term monitoring efforts of microbial community structure on reefs, this protocol replaces the 80-liter water collections in cubies (cube-shaped containers) and TFF concentration methods completed from 2009 to 2015. These samples characterize benthic-associated bacterial and viral composition for estimates of community diversity and function on reefs of varying condition. Protocols for collection, processing, and analyses can be found in Knowles et al. (2016).

Collection of Coral:Algal Interaction Tissue Biopsies (Microbial Coral Biopsy)

Primary goal and procedural overview: The microbiologist collected one coral:algal biopsy transect across coral-algal interaction interfaces per site (goal: 2–4 punch transects per island depending on island size). Biopsies are processed to yield coral and algal metagenomes, metatranscriptomes, viromes, and metabolomes. These samples were collected at reef sites, but not necessarily at NCRMP sites.

These collections (1) replace the collections of rubble and algae (i.e., smashed reef) that were collected on previous cruises and (2) provide a spatial dataset for investigating mechanisms of coral resistance to algal competition at coral–algal interaction interfaces. Protocols for sampling and data processing can be found in Hester et al. (2016) and Quinn et al. (2016).

NOAA diver Louise Giuseffi conducts fish surveys at Howland Island.
Photo: Kevin Lino, NOAA Fisheries.

Survey Methods for Reef Fishes

1.10 Survey Methods for Reef Fishes

*Floral wrasse (*Cheilinus chlorourus*) at Wake Atoll.*
Photo: Andrew Gray, NOAA Fisheries.

ESD collects data on the reef fish communities. These datasets are acquired using two types of surveys: fish Rapid Ecological Assessment (REA) surveys and towed-diver surveys (TDS). During the 15 PRIMNM surveys cruises conducted between 2001 and 2017, a total of 1,326 fish REA surveys were conducted at specific reef sites, while 683 TDS were performed around the islands and reefs. Overviews of REA and TDS and descriptions of sampling design and survey methods specific to each ecological discipline are presented below.

Towed-diver Surveys

Towed-diver surveys (TDS) began in the PRIMNM in 2001 and are used to characterize large bodied fishes, greater than 50 cm total length (TL), over an area that is much broader than the areas surveyed using REA methods. Importantly, towed-diver surveys also are able to access exposed coasts (e.g., windward-facing shores and high-swell conditions) that cannot always be surveyed using REA techniques.

TDS target outer-reef habitats around the island perimeter where large fishes tend to be more abundant. A series of TDS cover the perimeter around each surveyed island/reef system along a relatively constant isobaths (typically between 10 and 20 m). At smaller islands, multiple circumnavigations using TDS were possible targeting different depths (e.g., 5 m, 15 m, and 25 m). Each individual towed-diver survey typically covered approximately 1.5–2.5 km of distance.

Only data from 10–20 m target depths TDS and with length of at least 500 m are shown in this report to facilitate comparisons among islands.

TDS tow a pair of divers behind a small boat, with one diver tasked with fish data collection and one diver gathering benthic data (Figure 15). Divers make visual estimates within a 10 m swath (Figure 15). Each survey took approximately 50 min, with 4–6 surveys typically completed per field day. TDS observations are recorded separately per 5-minute "segment" (10 segments per complete 50-min tow), with mean segment lengths of approximately 220 m. To georeference the data collected during TDS, a GPS receiver located on the small boat was programmed to record longitude and latitude coordinates every 5 sec. Segments are used as the unit of replication for analysis of TDS data. A detailed methodology for the TDS can be found in Richards et al. (2011).

During TDS, fish divers estimated the number, species, and size of all fishes greater than 50 cm TL moving across or within their tow transect. Divers also recorded the presence of species of interest in the general vicinity of tow transect, even when those species were not within the tow transect areas. Those observations are recorded as "presence" data and not used in any estimates that quantify density per unit area. Diver observations for each 5-min survey segment were graphically projected onto ArcGIS maps using the midpoint for each survey segment. Because TDS use visual estimates for assessing fish abundance and size, results can be subject to observer variability both within and among survey years.

In this report, fish observations from TDS are restricted to key taxa of interest that are generally infrequently observed using REA methods, including sharks, humphead wrasse (*Cheilinus undulatus*), and bumphead parrotfish (*Bolbometopon muricatum*).

Rapid Ecological Assessment Surveys

Rapid Ecological Assessment (REA) surveys were used to survey fish communities beginning in 2003. Fish REA surveys are investigations that provide data at a high degree of quantitative and taxonomic resolution for reef fishes. The REA methodologies and survey design evolved, reflecting improvements in the survey design, sampling techniques, and data quality. Given inherent differences in study designs over time, comparisons cannot be readily made across varying methodologies and designs.

REA: Repeat Sites

From 2001 through 2009, the majority of REA surveys were conducted at sites along the forereef slopes of islands at depths of 10–20 m, with additional surveys conducted in some backreef, lagoon, and protected slope habitats. These REA sites were haphazardly selected, generally at the time of the first expedition at each location (2001 for most islands, 2005 for Wake, 2004 for Johnston), but some sites were added during later visits. Where possible, the sites were resampled during subsequent research cruises. However, sites were not physically marked (e.g., with transect pin) and were only relocated using the latitude and longitude recorded during the first survey. Transect placement within a site was also haphazard and varied from year to year. Site locations were selected largely haphazardly within the target depth range, with the intention of broadly spreading sites around the island to the extent that was operationally feasible. A very small number of repeat site locations in the PRIMNM were chosen at the request of local managers or researchers.

Belt Transect Surveys

At each REA site, the reef fish dive team consisted of two divers. Divers typically laid out three, 25 m transects per site, approximately in line along the depth contour and separated by approximately 5–10 m. The fish divers recorded all fishes 20 cm or greater TL within an 8 m-wide belt per transects. On completing the outward swim, divers performed a return swim along the transect line, recording all fishes smaller than 20 cm TL in 4 m-wide belts (Figure 20). Fishes of all sizes were identified to the lowest taxonomic level possible, generally species, and assigned to 5-cm size bins. During belt-transect surveys, all reef-associated fishes were counted, including those in the water column (e.g., planktivores). Coastal pelagic species (e.g., clupeids [sardines], belonids [beakfishes], and antherinids [silversides]) seen near the ocean surface were not recorded. The outward swim of larger fishes took typically about 3–5 min to complete per transect, while the return survey of small fishes took about 5–10 min or more to complete per transect.

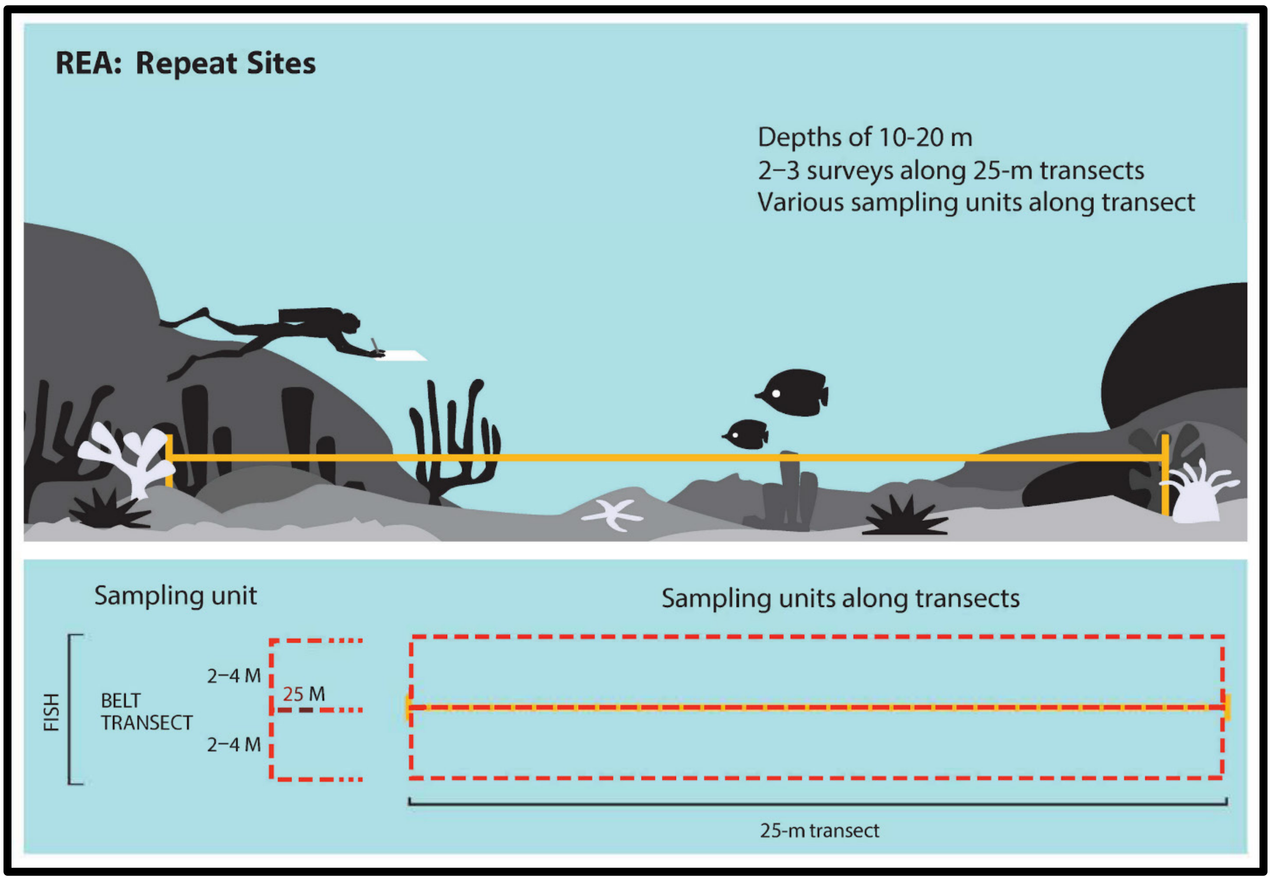


Figure 20. Schematic of fish Rapid Ecological Assessment repeat site surveys. Belt transects were used to survey the reef fish community.

As with benthic REA surveys at repeat sites, supplementary sites were added opportunistically on subsequent cruises, and those data are summarized in this report. Site selection for these supplemental REA sites was generally haphazard, but limited by operational constraints.

The nonrandom nature of site selection places limits on the degree to which biotic metrics can be extrapolated through statistical inference to the larger population around an island. As site and transect locations were not identical from year to year, we do not make inter-annual comparisons at nominal sites in this report.

REA: Stratified Random Sampling

Belt-transect surveys continued at REA repeat sites through 2009. However, a new fish REA survey design (stratified random from 0 to 30 m) and sampling method (stationary point count [SPC]) were introduced in 2008. Notably, in 2008 and 2009, both REA fish methods were used at a subset of sites to allow for some calibration between methods.

Stationary Point Count (SPC) Surveys

Beginning in 2008–2009, fish REA sites were randomly located within a domain encompassing all hard-bottom reef habitats in less than 30 m of water at each island. Each island was stratified by reef-zone (forereef, protected slope, backreef, lagoon) and by depth bin (into shallow: <6 m; moderate: 6–18 m; and deep: 18–30 m), with sampling density (i.e., number of surveys) heavily weighted towards sampling outer-reef zones (the forereef and protected slope). Survey sites are never revisited in this scheme; instead, sites are unique to each expedition.

Details of the stationary point count method are provided in Ayotte et al. (2011), but summarized here. At each SPC site, surveys were made by a team of divers (generally two divers) recording observations of fishes in one or two "SPC-pairs." Each SPC-pair consisted of two adjacent visually estimated 15 m diameter cylindrical plots extending from the substrate to the limits of vertical visibility (Figure 21). The divers laid out a 30 m transect line along the substrate, following the depth contour. Markings at 7.5 m, 15 m, and 22.5 m enable the two divers to locate the midpoint (7.5 m or 22.5 m) and two edges (0 and 15 m or 15 and 30 m) of their adjacent survey cylinders. Each count consisted of two components: (1) a 5-min species enumeration period in which the divers recorded the taxa of all species observed within their cylinders; followed by (2) the tallying portion of the count, in which divers systematically worked through their species lists, recording the number and estimated size (TL, to the nearest cm) of each individual fish. The tallying portion was conducted as a series of rapid visual sweeps of the plot, with one species/grouping counted per sweep. To the extent possible, divers remained at the center of their cylinders throughout most of the count. Small, generally site-attached and semi-cryptic species were left to the end of the tally period, at which time the divers swam through their plots counting those species. SPC surveys were not conducted if horizontal visibility was less than 7.5 m.

In addition, divers recorded observations in or around their cylinders throughout the course of the survey as a way track presence of species of interest. In the relatively infrequent cases where more than one SPC-pair was conducted at a site, the SPC-pairs were haphazardly located approximately 10–30 m away from each other.

At all SPC sites, after the fish survey was complete, divers visually estimated benthic cover within their cylinders to functional group (e.g., coral, sand). Once all other portions of the survey were complete, divers conducted a benthic photoquadrat transect. As with the benthic REA surveys, still digital photographs were collected every meter, from the 1-meter to the 30-meter mark along the REA transect line. These photoquadrat images were scored identically to those collected during benthic REA surveys, and the resulting data were analyzed together with the benthic REA survey images to evaluate benthic cover over space and time. However, to date, images from SPC surveys in the PRIMNM prior to 2014 have not been analyzed due to staffing limitations. Hence, for fish REA sites where photoquadrat data were either not collected or not yet analyzed, the visual estimates of benthic cover taken by the fish divers were also incorporated into island assessments of benthic cover.

Further detail on survey methods is available in the stationary point count methods protocol document (Ayotte et al. 2011) and data descriptor paper (Heenan et al. 2017).

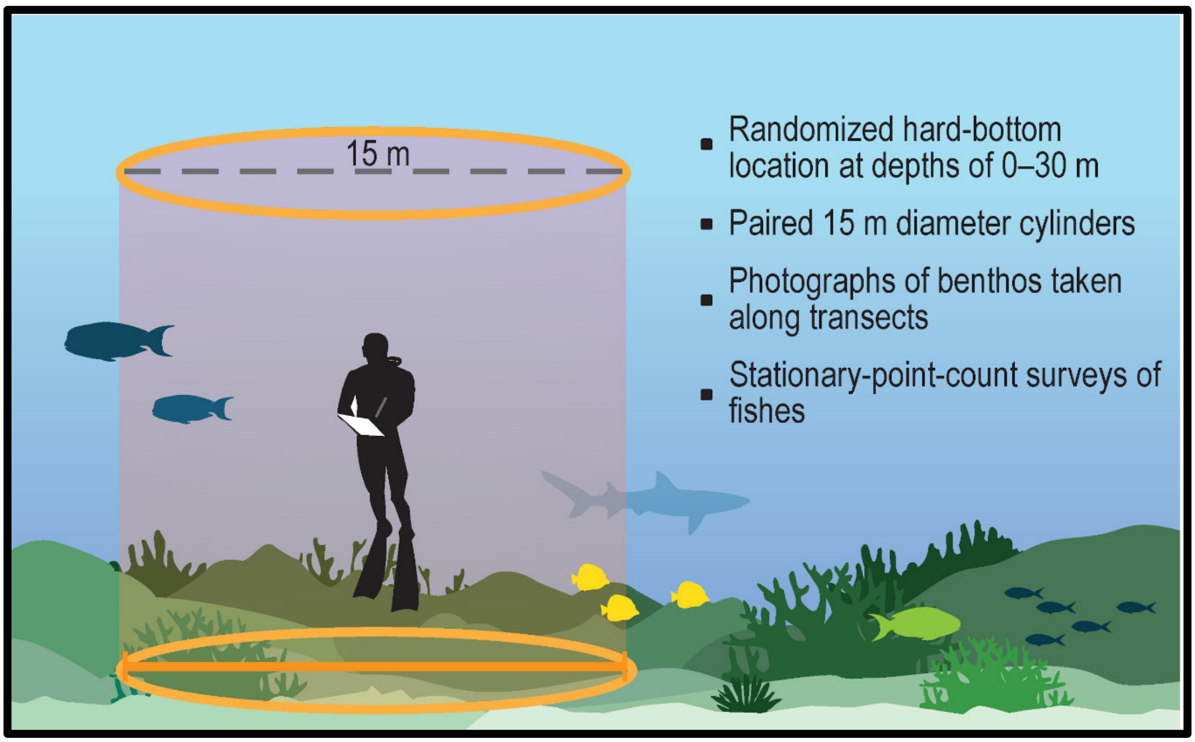


Figure 21. Schematic diagram of stationary point count method used for fish Rapid Ecological Assessment surveys beginning in 2008.

For all fish survey methods described, divers recorded number, size (TL), and taxa of the fishes observed. Size estimates were converted to weight estimates using published length-weight conversion parameters taken from a range of sources (Kulbicki et al. 2005; Froese and Pauly 2010). As each survey involves a known area of reef, the total number or weight of fishes can be converted to abundance or biomass estimates (i.e., number or weight per unit area). In belt surveys, fish sizes were estimated within 5 cm bins, and the mid-points of those bins used to estimate weight. Towed diver size bins have changed over time. For that reason and others, only towed diver abundance data, or actual locations of encounters of interest, are presented in this report. Those locations (e.g., of observations of species of interest) are the mid-points of the segments on which that species was observed.

Throughout the report, fish assemblage data are typically pooled into either "all fishes" or into "consumer groups" and occasionally by family. The four consumer groups are based on diet information taken largely from FishBase (Froese and Pauly 2010): primary consumers (herbivores and detritivores); secondary consumers (omnivores and benthic invertivores); planktivores; and piscivores (Sandin and Williams 2010).

Generating island-scale estimates from the stratified design

Island-scale estimates of summary statistics (e.g., mean and variance) for stratified random fish survey metrics are calculated identically to the benthic REA survey data described previously.

All data handling and analyses were performed using raw survey data extracted from the NOAA ESD Oracle database, processed using a set of routine analysis scripts written in R (Heenan et al. 2017).

*A flounder (*Bothus mancus*) hiding in a shipwreck at Wake Atoll.*
Photo: Andrew Gray, NOAA Fisheries.

1.11 Marine Debris Methods

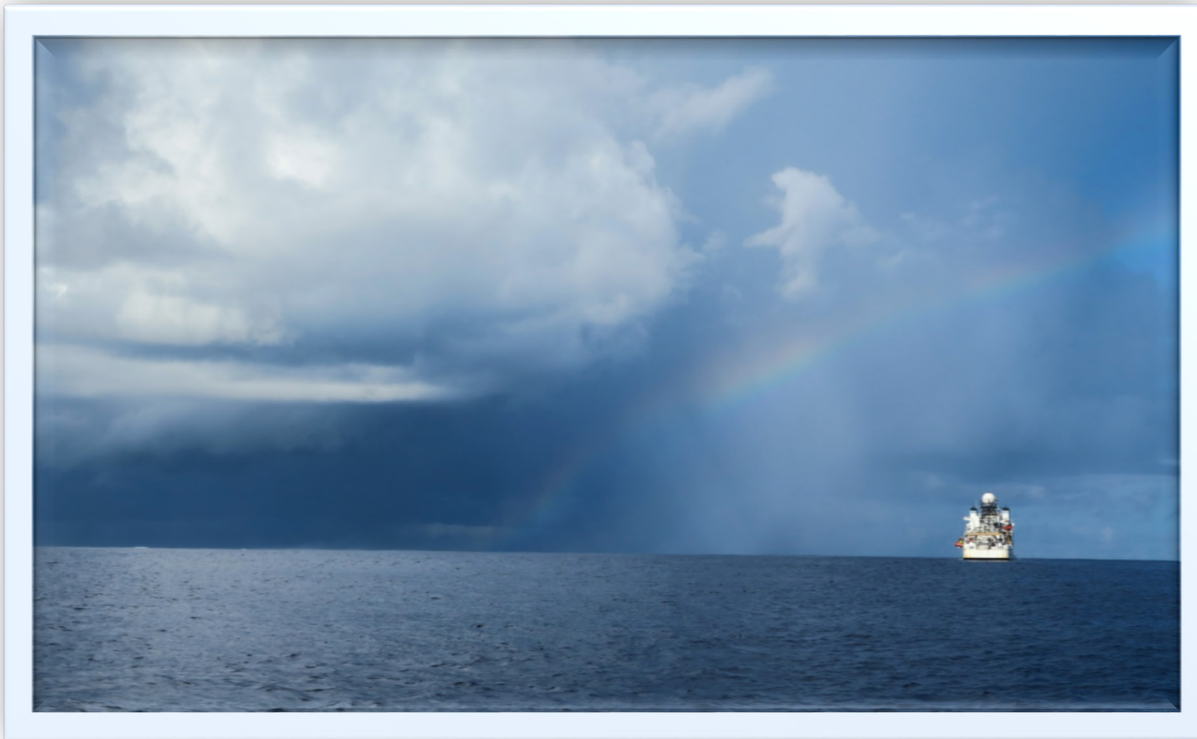
Shark entangled in marine debris in Howland.
Photo: Adel Heenan, NOAA Fisheries.

As a secondary data set, towed-diver surveys numerically tallied marine debris when sightings fell within the 8 m width of the survey swath for each 5-min survey segment. Debris items included but were not limited to the following types: (1) derelict fishing gear, (2) munitions, or unexploded ordinances, (3) shipwrecks, and (4) other man-made objects, whether of nautical or terrestrial origins. The secondary nature of this marine debris data set means that potential observations may have been missed by divers overwhelmed by other priorities at a given time. Therefore, observations of debris presented in this report are positive identifications, but absence of observations does not imply lack of debris (Brainard et al. 2005; Heenan and Williams 2013; Williams et al. 2015).

Gnathodentex aureolineatus *at Palmyra Atoll.*
Photo: Andrew E. Gray, NOAA Fisheries.

Maps to Inform the Monitoring Survey Design

1.12 Maps to Inform the Monitoring Survey Design



NOAA Ship Hiʻialakai *with a rainbow in the background at Kingman Reef.*
Photo: Chelsie Counsell, NOAA Fisheries.

For Pacific RAMP surveys of fish and corals, ESD adopted a stratified-random survey design (see *REA: Stratified Random Sampling* described in the "Survey Methods for Coral Reef Benthic Communities" and "Survey Methods for Reef Fishes" sections). Monitoring surveys are stratified by depth and reef zone and restricted 0 m to 30 m depths in hard-bottom habitats. Here we describe the individual survey strata.

Depth Strata

The depth strata maps presented in each of the island chapters were prepared in a similar fashion to the water depth layers included in the basemaps, excluding the interpolation step. The existing bathymetry datasets for each island were merged together and classified into 7 bins, with breakpoints at 6 m, 18 m, 30 m, 150 m, 500 m, 1,000 m, and greater than 1,000 m. The first three strata comprise the shallow, mid, and deep depth strata, respectively, used for the Pacific RAMP stratified-random survey design. ESD adopted these depth strata from Papahānaumokuākea Marine National Monument, where a stratified-random sampling design in the Northwestern Hawaiian Islands was first implemented. The data presented in the depth strata maps correspond to the mapped seafloor area presented in the depth strata tables.

The estimated seafloor area presented in the same table was calculated from the interpolated seamless bathymetry product (unknown areas were interpolated from the surrounding known areas). The largest gaps in coverage from 0 to 1,000 m depths usually occurred within 0–30 m. Depending on the size and extent of the bathymetry coverage gaps, it was not always possible to estimate the seafloor area for the 6 m or the 18 m strata with confidence for several of the islands and atolls in the PRIMNM. In these cases, the first few strata presented in the table were instead binned into 0–18 m or 0–30 m.

Reef Zones

Reef zones did not exist for the islands and atolls of the PRIMNM, with the exception of Palmyra (NCCOS 2010) and were therefore delineated by ESD to support the stratified-random survey design. Reef zones include forereef, protected slope, backreef, and lagoon. The outer-reef zones, including forereef and protected slope, are typically surveyed during Pacific RAMP monitoring surveys; however, depending on the location, lagoon and backreef areas have also been surveyed. Protected slope is habitat that is somewhat protected: not protected enough to be a lagoon, but not exposed enough to be considered forereef. The forereef habitat has fully exposed shallow habitat (i.e., leads up to breaking waves and land), and the protected forereef is somewhat protected by submerged reef, but does not reach breaking waves or land.

Satellite imagery was primarily used to manually digitize the zones, as well as nautical charts, bathymetry data, and habitat information from the biological monitoring surveys (REA and towed diver). As previously discussed, the best available WorldView satellite images were acquired for each location for depth and habitat mapping purposes. Despite this, depending on the date of the imagery, it was difficult to discern the precise extent of the reef crest/reef flat zones that extend from the shoreline out to breaking waves due to seasonal changes in wave action. Additionally, other reference data may not have been available because wave action prohibits the estimation of depths in these areas and because ESD does not conduct surveys in these habitats.

Substrate

At the time the survey strata were established for the islands and atolls of the PRIMNM, substrate maps did not yet exist, except for Palmyra (NCCOS 2010). For all other locations, areas within 30 m depths that are classified as hard or unknown bottom type are included in the survey strata. Since all areas within 30 m depths were unknown substrate for the six other locations in the PRIMNM, survey strata were restricted by depth only for these places.

Surveyable Seafloor Area

For purposes of this report, updated surveyable seafloor area was calculated for all islands and atolls in the PRIMNM using the new substrate maps, the interpolated seamless bathymetry, and the reef zones. The calculated areas comprise all hard or unknown substrate within 0–30 m depths for the surveyed reef zones applicable to each island or atoll (e.g., all reef zones have been surveyed at Johnston and Kingman, whereas only forereef habitats have been surveyed at the other islands and atolls).

Octopus blending into the benthos at Jarvis Island.
Photo: Andrew Gray, NOAA Fisheries.

References

1.13 References

Aeby GS (2006) Baseline levels of coral disease in the Northwestern Hawaiian Islands. Atoll Res Bull 534:471–488.

Ayotte P, McCoy K, Heenan A, Williams I, Zamzow J (2011) Coral Reef Ecosystem Division standard operating procedures: data collection for Rapid Ecological Assessment fish surveys. Pacific Islands Fisheries Science Center Administrative Report H-11-08, 24 p.

Becker JJ, Sandwell DT, Smith WHF, Braud J, Binder B, Depner J, Fabre D, Factor J, Ingalls S, Kim S-H, Ladner R, Marks K, Nelson S, Pharaoh A, Trimmer R, Von Rosenberg J, Wallace G, Weatherall P (2009) Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS. Mar Geod 32:355–371. doi:10.1080/01490410903297766

Beijbom O, Edmunds PJ, Roelfsema C, Smith J, Kline DI, Neal BP, Dunlap MJ, Moriarty V, Fan T-Y, Tan C-J, Chan S, Treibitz T, Gamst A, Mitchell BG, Kriegman D (2015) Towards Automated Annotation of Benthic Survey Images: Variability of Human Experts and Operational Modes of Automation. PLoS One 10:e0130312. doi:10.1371/journal.pone.0130312

Bell TE (1995) Remote sensing. IEEE Spectr 32:24–31. doi:10.1109/6.367967

Brainard R, Maragos J, Schroeder R, Kenyon J, Vroom P, Godwin S, Hoeke R, Aeby G, Moffitt R, Lammers M, Gove J, Timmers M, Holzwarth S, Kolinski S (2005) The State of Coral Reef Ecosystems of the U.S. Pacific Remote Island Areas. In: Waddell JE (ed) The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2005, NOAA Tech. NOAA Technical Memorandum NOS NCCOS 11, Silver Spring, MD, pp 338–372

Brainard RE, Asher J, Blyth-Skyrme V, Coccagna E, Dennis K, Donovan MK, Gove JM, Kenyon J, Looney EE, Miller JE, Timmers MA, Vargas-Angel B, Vroom PS, Vetter O, Zgliczynski B, Acoba T, DesRochers A, Dunlap MJ, Franklin EC, Fisher-Pool PI, Braun CL, Richard BL, Schopmeyer SA, Schroeder RE, Toperoff A, Weijerman M, Williams I, Withall RD (2012) Coral Reef Ecosystem Monitoring Report of the Mariana Archipelago: 2003-2007. Honolulu, Hawaii

Clinton W (1998) Executive Order 13089 Coral ReeOrder, Executivef Protection. Fed Regist 63:32701–32703.

Cochran WG (1970) Sampling Techniques, 3rd edn. John Wiley & Sons, New York

Denit K (2016) NOAA Fisheries Ecosystem-based Management Road Map. Washington D.C.

DigitalGlobe (2010) The Benefits of the Eight Spectral Bands of WorldView-2.

DOC/NOAA/NOS/NCCOS/CCMA/Biogeography Branch and Analytical Laboratory of Hawaii LLC (2010) Palmyra Atoll Coral Reef Habitat Mapping Completion Report. Silver Spring, MD

Dove D, Acoba T, DesRochers A (2018) Seafloor Substrate Characterization from Shallow Reefs to the Abyss: Spatially-continuous seafloor mapping using multispectral satellite imagery, and multibeam bathymetry and backscatter data within the Pacific Remote Islands Marine National Monument and the main Hawaiian Islands. Pacific Islands Fisheries Science Center, PIFSC Internal Report, IR-18-018, 37 p.

Ehses JS, Rooney JJ (2015) Depth Derivation Using Multispectral WorldView-2 Satellite Imagery. NOAA Tech Memo NMFS-PIFSC-46 24. doi:10.7289/V5668B40

Force USCRT (2000) National Action Plan to Conserve Coral Reefs.

Friedlander AM, Sandin SA, DeMartini EE, Sala E (2010) Spatial patterns of the structure of reef fish assemblages at a pristine atoll in the central Pacific. Mar Ecol Prog Ser 410:219–231.

Froese R, Pauly D (2010) FishBase. World Wide Web electronic publication. www.fishbase.org.

Grigg RW (1994) Effects of sewage discharge, fishing pressure and habitat complexity on coral ecosystems and reef fishes in Hawaii. Mar Ecol Prog Ser 103:25–34.

Grother PR, Taylor LA, Eakins BW, Carignan KS, Warnken RR, Lim E, Caldwell RJ (2010) Digital Elevation Models of Wake Island: Procedures, Data Sources and Analysis. Boulder, CO

Haas AF, Knowles B, Lim YW, McDole Somera T, Kelly LW, Hatay M, Rohwer F (2014) Unraveling the Unseen Players in the Ocean - A Field Guide to Water Chemistry and Marine Microbiology. J Vis Exp. doi:10.3791/52131

Heenan A, Williams ID (2013) Monitoring Herbivorous Fishes as Indicators of Coral Reef Resilience in American Samoa. PLoS One 8:e79604. doi: 10.1371/journal.pone.0079604

Heenan A, Gorospe K, Williams I, Levine A, Maurin P, Nadon M, Oliver T, Rooney J, Timmers M, Wongbusarakum S, Brainard R (2016) Ecosystem monitoring for ecosystem-based management: using a polycentric approach to balance information trade-offs. J Appl Ecol 53:699–704. doi:10.1111/1365-2664.12633

Heenan A, Williams ID, Acoba T, DesRochers A, Kosaki RK, Kanemura T, Nadon MO, Brainard RE (2017) Long-term monitoring of coral reef fish assemblages in the Western central pacific. Sci Data 4:170176. doi:10.1038/sdata.2017.176

Hester ER, Barott KL, Nulton J, Vermeij MJA, Rohwer FL (2016) Stable and sporadic symbiotic communities of coral and algal holobionts. ISME J 10:1157–1169. doi:10.1038/ismej.2015.190

Hill J, Wilkinson C (2004) Summary for Policymakers. In: Intergovernmental Panel on Climate Change (ed) Climate Change 2013 - The Physical Science Basis. Cambridge University Press, Cambridge, pp 1–30

Hochberg E, Vogt S, Miller J, Hogrefe K (2007) Remote sensing of shallow water bathymetry for integration with multibeam SONAR data. ftp://ftp.soest.hawaii.edu/pibhmc/website/webdocs/documentation/PRIDE_poster.pdf. Accessed 7 Nov 2017

Hoeke RK, Gove JM, Smith E, Fisher-Pool P, Lammers M, Merrit D, Vetter OJ, Young CW, Wong KB, Brainard RE (2009) Coral reef ecosystem integrated observing system: In-situ oceanographic observations at the US Pacific islands and atolls. J Oper Oceanogr 2:3–14.

Hogrefe K (2008) Derivation of Near-shore Bathymetry from Multispectral Satellite Imagery Used in a Coastal Terrain Model for the Topographic Analysis of Human Influence on Coral Reefs. Oregon State University

Hogrefe K (2009) Error Analysis of Bathymetric Data Derived from IKONOS Imagery Location: Tutuila Island, American Samoa.

Hogrefe KR, Wright DJ, Hochberg EJ (2008) Derivation and Integration of Shallow-Water Bathymetry: Implications for Coastal Terrain Modeling and Subsequent Analyses. Mar Geod 31:299–317. doi:10.1080/01490410802466710

Jenness JS (2004) Calculating landscape surface area from digital elevation models. Wildl Soc Bull 32:829–839. doi:10.2193/0091

Kenyon JC, Brainard RE, Hoeke RK, Parrish FA, Wilkinson CB (2006) Towed-diver surveys, a method for mesoscale spatial assessment of benthic reef habitat: a case study at Midway Atoll in the Hawaiian Archipelago. Coast Manag 34:339–349. doi:10.1080/08920750600686711

Knowles B, Silveira CB, Bailey BA, Barott K, Cantu VA, Cobian-Guëmes AG, Coutinho FH, Dinsdale EA, Felts B, Furby KA, George EE, Green KT, Gregoracci GB, Haas AF, Haggerty JM, Hester ER, Hisakawa N, Kelly LW, Lim YW, Little M, Luque A, McDole-Somera T, McNair K, De Oliveira LS, Quistad SD, Robinett NL, Sala E, Salamon P, Sanchez SE, Sandin S, Silva GGZ, Smith J, Sullivan C, Thompson C, Vermeij MJA, Youle M, Young C, Zgliczynski B, Brainard R, Edwards RA, Nulton J, Thompson F, Rohwer F (2016) Lytic to temperate switching of viral communities. Nature 531:466–470. doi:10.1038/nature17193

Knowlton N, Brainard RE, Fisher R, Moews M, Plaisance L, Caley MJ (2010) Coral Reef Biodiversity. In: Life in the world's oceans : diversity, distribution, and abundance. Wiley, p 361

Kohler KE, Gill SM (2006) Coral Point Count with Excel extensions (CPCe): A Visual Basic program for the determination of coral and substrate coverage using random point count methodology. Comput Geosci 32:1259–1269. doi:10.1016/j.cageo.2005.11.009

Kulbicki M, Guillemot N, Amand M (2005) A general approach to length-weight relationships for New Caledonian lagoon fishes. Cybium 29:235–252.

Lecours V, Devillers R, Simms AE, Lucieer VL, Brown CJ (2017) Towards a framework for terrain attribute selection in environmental studies. Environ Model Softw 89:19–30. doi:10.1016/j.envsoft.2016.11.027

Lino K, Asher J, Ferguson M, Gray A, McCoy K,Timmers M, Vargas-Ángel B (2018) Pacific Islands Fisheries Science Center Ecosystem Sciences Division standard operating procedures: data collection for towed-diver benthic and fish surveys. Pacific Islands Fisheries Science Center, PIFSC Administrative Report, H-18-02, 76 p. doi:10.25923/59sb-sy51.

Lozada-Misa P, Schumacher BD, Vargas-Ángel B (2017) Analysis of benthic survey images via CoralNet: a summary of standard operating procedures and guidelines. Pacific Islands Fisheries Science Center, PIFSC Administrative Report, H-17-02, 169 p. doi:10.7289/V5/AR-PIFSC-H-17-02.

Lundblad ER, Wright DJ, Miller J, Larkin EM, Rinehart R, Naar DF, Donahue BT, Anderson SM, Battista T (2006) A benthic terrain classification scheme for American Samoa. Mar Geod 29:89–111. doi:10.1080/01490410600738021

Lyzenga DR (1985) Shallow-water bathymetry using combined lidar and passive multispectral scanner data. Int J Remote Sens 6:115–125. doi:10.1080/01431168508948428

Lyzenga DR, Malinas NP, Tanis FJ (2006) Multispectral bathymetry using a simple physically based algorithm. IEEE Trans Geosci Remote Sens 44:2251–2259. doi:10.1109/TGRS.2006.872909

Miller J, Maragos J, Brainard R, Asher J, Vargas-Angel B, Kenyon J, Schroeder R, Richards B, Nadon M, Vroom P, Hall A, Keenan E, Timmers M, Gove J, Smith E, Weiss J, Lundblad E, Ferguson S, Lichowski F, Rooney J (2008) The State of Coral Reef Ecosystems of the Pacific Remote Island Areas. In: Waddell JE, Clarke AM (eds) The state of coral reef ecosystems of the United States and Pacific Freely Associated States: 2008, NOAA Tech. NOAA Technical Memorandum NOS NCCOS 73, Silver Spring, MD, pp 353–386.

Miller J, Battista T, Pritchett A, Rohmann S, Rooney J (2011) Coral Reef Conservation Program mapping achievements and unmet needs.

Mundy C (1996) A quantitative survey of the corals of American Samoa. St. Lucia

National Oceanic and Atmospheric Administration (2009) Establishment of the Pacific Remote Islands Marine National Monument. Fed Regist 74:1565–1575.

National Oceanic and Atmospheric Administration (2015) Pacific Remote Islands Marine National Monument expansion. Fed Regist 80:15693–15696.

Petras D, Koester I, Da Silva R, Stephens BM, Haas AF, Nelson CE, Kelly LW, Aluwihare LI, Dorrestein PC (2017) High-resolution liquid chromatography tandem mass spectrometry enables large scale molecular characterization of dissolved organic matter. Front Mar Sci. doi:10.3389/fmars.2017.00405

President Barack Obama (2010) Executive Order 13547 Stewardship of the Ocean, Our Coasts, and the Great Lakes.

Quinn RA, Vermeij MJA, Hartmann AC, d'Auriac IG, Benler S, Haas A, Quistad SD, Lim YW, Little M, Sandin S, Smith JE, Dorrestein PC, Rohwer F (2016) Metabolomics of reef benthic interactions reveals a bioactive lipid involved in coral defence. Proc R Soc B Biol Sci. doi:10.1098/rspb.2016.0469

R Core Team (2013) R: A language and environment for statistical computing.

Ransome E, Geller JB, Timmers M, Leray M, Mahardini A, Sembiring A, Collins AG, Meyer CP (2017) The importance of standardization for biodiversity comparisons: A case study using autonomous reef monitoring structures (ARMS) and metabarcoding to measure cryptic diversity on Mo'orea coral reefs, French Polynesia. PLoS One 12:e0175066. doi:10.1371/journal.pone.0175066

Richards BL, Williams ID, Nadon MO, Zgliczynski BJ (2011) A towed-diver survey method for mesoscale fishery-independent assessment of large-bodied reef fishes. Bull Mar Sci 87:55–74. doi:10.5343/bms.2010.1019

Rogers A, Blanchard JL, Mumby PJ (2014) Vulnerability of coral reef fisheries to a loss of structural complexity. Curr Biol 24:1000–1005. doi:10.1016/j.cub.2014.03.026

Sandin SA, Williams I (2010) Trophic Classifications of reef fishes from the tropical U.S. Pacific (Version 1.0).

Simmons W, Nadeau R, Byrne S, Lemke S (2001) Hydrographic surveying using the SAIC ISS-2000 system. In: U.S. Hydrographic Conference 2001. pp 1–9

Smith SG, Ault JS, Bohnsack JA, Harper DE, Luo J, McClellan DB (2011) Multispecies survey design for assessing reef-fish stocks, spatially explicit management performance, and ecosystem condition. Fish Res 109:25–41. doi:10.1016/j.fishres.2011.01.012

Smith WHF, Sandwell DT (1997) Global sea floor topography from satellite altimetry and ship depth soundings. Science (80-) 277:1956–1962.

Suka RR, Rooney JJ (2017) Acoustic characterization of mesophotic coral reef ecosystems of West Hawai‘i.

Sutley NH, Holdren JP (2013) National Ocean Policy implementation plan. Washington D.C.

Swanson D, Bailey H, Schumacher B, Ferguson M, Vargas-Ángel B (2018) Ecosystem Sciences Division standard operating procedures: data collection for rapid ecological assessment benthic surveys. doi:10.25923/39jh-8993

Tolman HL (1999) WaveWatch-III version 1.18: Post-processing using NCAR graphics.

Vargas-Ángel B (2010) Crustose coralline algal diseases in the U.S.-affiliated Pacific Islands.

Coral Reefs 29:943–956. doi:10.1007/s00338-010-0646-x

Vargas-Ángel B, Wheeler B (2008) Coral health and disease assessment in the US Pacific territories and affiliated states. In: Proceedings of the 11th International Coral Reef Symposium. p 5

Vargas-Ángel B, Richards CL, Vroom PS, Price NN, Schils T, Young CW, Smith J, Johnson MD, Brainard RE (2015) Baseline assessment of net calcium carbonate accretion rates on U.S. Pacific Reefs. PLoS One 10:e0142196. doi:10.1371/journal.pone.0142196

Walker BK, Jordan LKB, Spieler RE (2009) Relationship of reef fish assemblages and topographic complexity on Southeastern Florida coral reef habitats. J Coast Res 10053:39–48. doi:10.2112/SI53-005.1

Watkins RL (2015) A methodology for classification of benthic features using WorldView-2 Imagery. Honolulu, Hawaii

Williams ID, Baum JK, Heenan A, Hanson KM, Nadon MO, Brainard RE (2015) Human, oceanographic and habitat drivers of Central and Western Pacific Coral Reef Fish Assemblages. PLoS One 10:e0120516. doi:10.1371/journal.pone.0120516

Work T, Aeby G (2006) Systematically describing gross lesions in corals. Dis Aquat Organ 70:155–160. doi:10.3354/dao070155

Wright D, Pendleton M, Boulware J, Walbridge S, Gerlt B, Eslinger D, Sampson D, Huntley E (2012) ArcGISBenthic Terrain Modeler (BTM), v. 3.0. In: Environ. Syst. Res. Institute, NOAA Coast. Serv. Center, Massachusetts Off. Coast. Zo. Manag.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

NOAA
FISHERIES