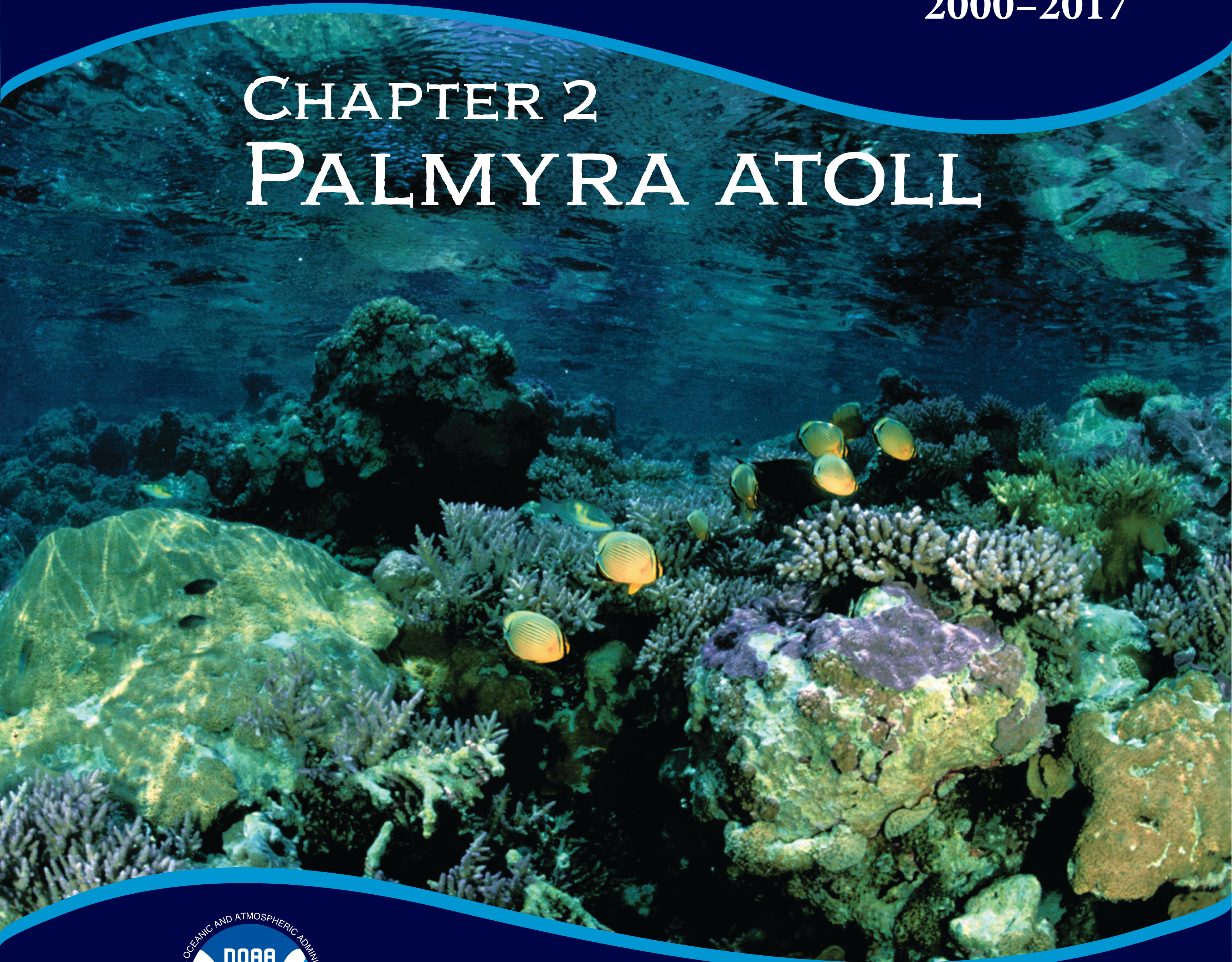
# Coral Reef Ecosystem Monitoring Report for The Pacific Remote Islands Marine National Monument 2000–2017

# Chapter 2 Palmyra Atoll




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 2: Palmyra Atoll


**Authors**

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## Citations

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Front Cover: Butterflyfishes (*Chaetodon trifasciatus)* on a coral reef at Palmyra Atoll. Photo: James Maragos, U.S. Fish and Wildlife Service.

Back Cover: Grey reef shark (*Carcharhinus amblyrhynchos*) swimming over coral reef at Palmyra Atoll. Photo: Jeff Milisen, NOAA Fisheries.

## 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 under 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 2: Palmyra Atoll

*Aerial view of Palmyra Atoll.*
*Photo: Kydd Pollock, U.S. Fish and Wildlife Service – Pacific Region.*

## 2.1 Introduction

### Report Overview

The *Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands Marine National Monument 2000–2017* 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 Pacific Remote Islands Marine National Monument (PRIMNM). The data compiled for this report are from Pacific Reef Assessment and Monitoring Program (Pacific RAMP) research surveys conducted over the period from 2000 through 2017, by the National Oceanic and Atmospheric Administration (NOAA) Pacific Islands Fisheries Science Center (PIFSC) Ecosystem Sciences Division (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. 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." For more background information on the report as a whole, operational background, Pacific RAMP methods, and Public Access to Research Results, refer to "Chapter 1: Overview."

### Chapter Overview

Palmyra Atoll, located in the central Pacific at 5°53′N, 162°05′W, is an exposed seamount summit within the Line Islands volcanic chain of the central Pacific. It is considered a true atoll as it has more than 60 $km^2$ (15,000 acres) of shallow and deep reefs encircling multiple lagoons and supporting about 26 islets (Figure 1; United States Fish and Wildlife Service 2017). Palmyra has broad, relatively shallow forereef terraces extending several kilometers to the east and west of the atoll.

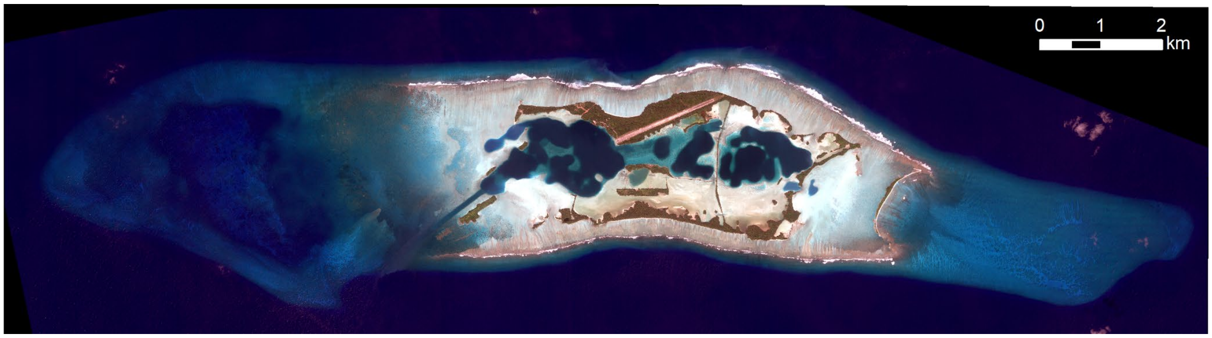



**Figure 1. Satellite image of Palmyra Atoll, November 14, 2014. © DigitalGlobe Inc. All rights reserved)**

This chapter provides a compilation of information to assist managers in making informed decisions relating to Palmyra Atoll and its coral reef ecosystems. "Benthic Characterization" sets the stage, followed by summarized data and trends for "Ocean and Climate Variability," "Coral Reef Benthic Communities," "Microbiota," "Reef Fishes," and "Marine Debris." Information from these sections is then tied together in the "Ecosystem Integration" section to provide a better understanding of the interactions and relationships between ecosystem components at Palmyra Atoll.

To aid discussions about the spatial patterns of ecological and oceanographic observations that appear throughout this chapter, six geographic regions, hereafter referred to as georegions, were defined for Palmyra (Figure 2). Most map-based figures throughout this chapter use the basemap template as shown in Figure 2, which includes georegions, land features, and the 30 and 100 m depth contours (isobaths).

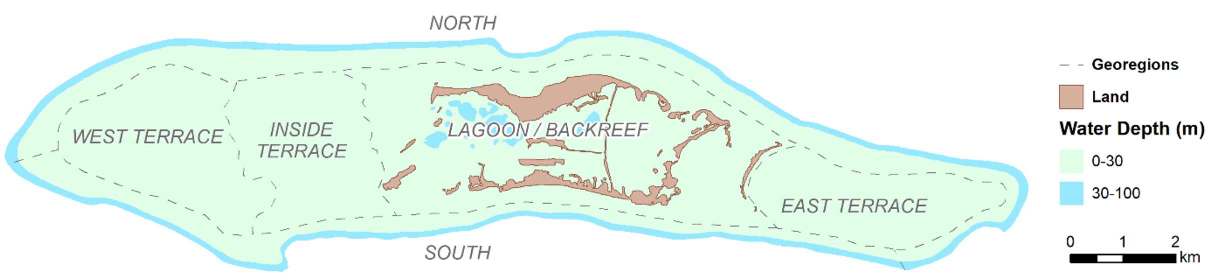



**Figure 2. The six geographic regions, or georegions, for Palmyra Atoll: North, South, West Terrace, Inside Terrace, Lagoon/Backreef, and East Terrace.**

## History and Human Influences

The first recorded sighting of Palmyra Atoll was in 1798, by Captain Edmund Fanning of the American sealing ship *Betsy* (Fanning 1924). More definitively, in 1802, the USS *Palmyra,* captained by Cornelius Sawle, shipwrecked on the reef, which was subsequently named after the vessel (United States Fish and Wildlife Service 2017). No artifacts or evidence of Polynesian, Micronesian, or other pre-European native settlements before 1802 have been found at Palmyra, an undisturbed atoll with numerous small islets forming a perimeter around three distinct lagoons (Dawson 1959).

During the mid-19th century, coastal populations of harvested whales were decreasing, prompting the whaling industry to make its way into the fertile Pacific before the supply and competitive new fuel sources made commercial whaling economically unfeasible. Palmyra has been owned and/or claimed by a number of different entities over time, including the Kingdom of Hawaii, before being claimed by the United States in 1898, and again in 1912 (United States Department of Interior 2006). In 1911, Judge Henry E. Cooper took ownership of the Atoll's islands, using it to grow coconuts (Pacific Islands Ocean Observing System 2018). In 1922, while Cooper maintained ownership of two of the islands (collectively referred to as "Home Island") the Fullard-Leo family acquired the remaining land at Palmyra and established the Palmyra Copra Company to harvest the abundant coconuts (The Nature Conservancy 2018).

In 1939, Pan Am began running commercial passenger and mail float planes through Palmyra as part of their Honolulu/Pago Pago/New Zealand route and used Palmyra as a refueling stop. The facilities were managed by the Civil Aeronautics Authority (precursor to the Federal Aviation Administration). President Franklin D. Roosevelt then officially placed "Palmyra Island, Territory of Hawaii, Under the Control and Jurisdiction of the Secretary of the Navy" (President Franklin D. Roosevelt 1940). In 1941, the Palmyra Naval Air Station was established. From 1941 to 1945, the island was occupied by the U.S. Navy, with upwards of 6,000 servicemen stationed there during World War II (Dawson 1959). This infrastructure buildup permanently altered the hydrodynamic flow patterns within the atoll lagoon system and altered the water circulation and ecosystems in the Lagoon/Backreef georegion (Dawson 1959; Maragos 1993; Maragos et al. 2008; Collen et al. 2009). They constructed multiple buildings and dredged a navigable deepwater channel exposing the lagoon to the open ocean, enabling ships to enter the protected anchorages inside the lagoon. The military further constructed causeways between islands, built new islands, and added to large existing islands with dredged coral. This included two primary runways on Cooper Island, an emergency runway on Sand Island, and two runway islands that were never finished (Collen et al. 2009). Causeways formed a perimeter road around the lagoons and bisected the eastern and central sections, essentially creating a fourth, eastern lagoonal ecosystem. Post World War II, materials from the air station were burned or discarded into the lagoon, and unexploded ordinance was left behind (United States Geological Survey 2018). In 1962, Palmyra was used for observation by 40–50 people during nuclear bomb testing at Johnston Atoll, located 1450 km to the northwest (Johnson 2018).

More recently, the longline vessel F/V *Hui Feng No. 1* grounded on the West Terrace of Palmyra Atoll in 1991 (United States Fish and Wildlife Service 2017). The shipwrecked *Hui Feng No. 1* triggered an invasive proliferation of the corallimorph *Rhodactis howesii,* which may have been fueled by the leaching of otherwise limited nutrients, such as iron, into the environment (Work et al. 2008; Kenyon 2011). The U.S. Fish and Wildlife Service (USFWS) removed the shipwreck and iron debris as the first step in restoring the reef by cutting off the nutrient supply. The area was declared clean and free of debris in 2013 (United States Fish and Wildlife Service 2017). Corallimorph removal efforts and monitoring of the recovery process led by USFWS are still ongoing within the West Terrace.

In November 2000, the islands of Palmyra Atoll (excluding Home Island, which is still owned by the Cooper family) were purchased from the Fullard-Leo family by The Nature Conservancy (TNC) for the purpose of conservation and to develop a low use ecotourism program. In January 2001, the tidal lands, submerged lands, and marine waters surrounding the emergent lands of

Palmyra out to the 12 nm Territorial Sea Boundary became designated as the Palmyra Atoll National Wildlife Refuge. The refuge was established to protect and preserve the natural character of fish, wildlife, plants, coral reef communities, and other resources associated with the various ecosystems of Palmyra. In 2002, the USFWS purchased the majority of the emergent land at Palmyra Atoll from TNC for inclusion in the refuge, excluding Cooper/Menge and Home Islands. After several new research projects were proposed and initiated in 2005, a TNC research station capable of supporting as many as 20 researchers was constructed at Palmyra Atoll in 2006 to study a range of environmental issues. In 2009, President George W. Bush established PRIMNM to protect and preserve the marine environment around Baker, Howland, and Jarvis Islands, Wake, Johnston, and Palmyra Atolls, and Kingman Reef for the care and management of the historic and scientific objects therein (National Oceanic and Atmospheric Administration 2009).

For several decades, Palmyra has been subject to recreational visitation by sailboats and motorboats. Recreational activities currently permitted by the USFWS include snorkeling, diving, limited sport fishing, and wildlife observations. Prior to 1998, longline fishing effort was limited in the Palmyra Atoll area. This increased between 1998 and 2003, with much of the effort focused to the north, east, and northeast. There were increased catch rates of bigeye tuna (*Thunnus obesus)* northeast and northwest of the atoll that may be attributed to oceanographic changes relative to winter El Niño events (Howell and Kobayashi 2006). Limited catch-and-release sport fishing for bonefish and limited offshore pelagic fishing for local consumption are currently allowed within the refuge (Brainard et al. 2005). Since the establishment of the refuge in 2001, commercial fishing has been illegal within 12 nm of Palmyra. However, limited blue-water sustenance fishing is allowed with a primary catch of yellowfin tuna (*Thunnus albacares*) and wahoo (*Acanthocybium solandri*) on the south and west sides of the atoll. Non-target species, such as red snapper and grey reef sharks, have been recorded as bycatch and released when possible.

In June 2011, the USFWS, TNC, and Island Conservation worked to successfully rid the island of its invasive rat population. These vermin likely suppressed seabird numbers and predated native forest seeds, which may have reduced nutrient input into the atoll. The eradication of rats, along with a paired forest restoration project, is anticipated to increase  native species, such as trees, seabirds, land crabs, and other terrestrial land invertebrates documented to be connected to the marine environment via nutrient pathways (Young et al. 2013). While Palmyra hosts one of the best remaining examples of *Pisonia* forest in the world, it too has experienced a decline in recent decades similar that observed globally. The loss of *Pisonia*, which may be due to damages inflicted by alien insect infestations, limits seabird nesting areas. Palmyra's remote location lies beyond the influence of other major urban centers, associated pollutants, and shipping lanes (Brainard et al. 2005).

In the scope of management, Palmyra Atoll is deemed an incorporated territory of the United States, meaning that it is subject to all provisions of the U.S. Constitution and is permanently under American sovereignty. Cooper Island and ten other land parcels are owned by TNC and are managed as nature reserves. The westernmost islets along the southern shore are known as Home Island and are privately owned by descendants of the Cooper family. The remainder of Palmyra is classified as federal land and waters actively managed by the USFWS as a National Wildlife Refuge. In addition, the marine environment is cooperatively administered under the jurisdiction of the Secretary of Commerce (NOAA) and the Secretary of the Interior (USFWS) from Honolulu, HI. For all other purposes, Palmyra is one of the U.S. Minor Outlying Islands. In 2014, Presidential Proclamation 9173 expanded the boundaries for many of the islands/atolls of the PRIMNM, including Palmyra. The PRIMNM is currently one of the largest marine protected areas in the world (Executive Office of the President 2014).

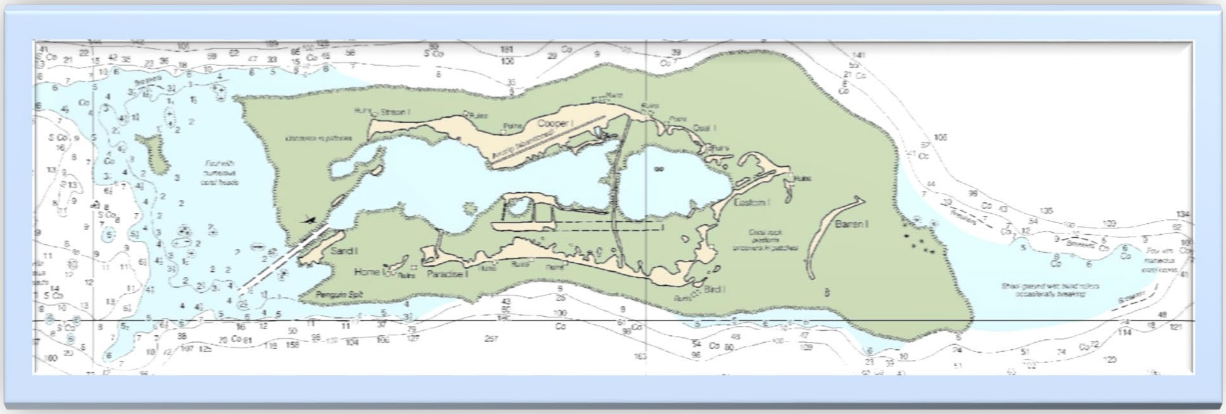
## Geology and Environmental Influences

Palmyra Atoll, along with Johnston Atoll, Kingman Reef, and Jarvis Island, is geologically part of the northwest-southeast trending Line Islands submarine ridge/seamount chain, Palmyra and Kingman being part of the Northern Line Islands group. Palmyra Atoll is located 67 km (36 nm) southeast of Kingman Reef and 566 km (306 nm) north of the Equator (United States Department of Interior 2006) and, along with Wake and Johnston Atolls, is considered a "coral atoll," consisting of coral reefs encircling deep lagoons and supporting many islets. Palmyra is the least progressed of the atolls, with its many islets surrounded by a barrier reef and consisting of several lagoons. Palmyra is influenced by the westward flowing North Equatorial Current (NEC) and eastward North Equatorial Countercurrent (NECC). During the summer, the Intertropical Convergence Zone affects Palmyra's weather and sea conditions, resulting in predominantly light, variable winds, high precipitation, and humidity. In the wintertime, the easterly trade winds and seas become stronger (Brainard et al. 2005).

*Acropora and surrounding reef at Palmyra Atoll.*
*Photo: Jeff Milisen/NOAA Fisheries.*

# ***Benthic Characterization***

## 2.2 Benthic Characterization



*NOAA Nautical Chart of Palmyra Atoll.*
*Source: [NOAA, 6th Ed., May 2006]*

In this section, the benthic habitats of Palmyra Atoll are characterized for the depth range from 0 to 1,000 m, using integrated and synthesized data from numerous sources.

### Survey Effort

NOAA has been collecting benthic habitat mapping data for the nearshore areas around Palmyra since 2002, using a variety of methods as described in the "Benthic Characterization Methods" section of the Overview chapter. These methods include multibeam bathymetric and backscatter surveys, single-beam surveys for depth validation, and towed-camera surveys for habitat validation. In addition, field surveys conducted by the National Centers for Coastal Ocean Science (NCCOS) are discussed (DOC/NOAA/NOS/NCCOS/CCMA/Biogeography Branch and Analytical Laboratory of Hawaii LLC 2010).

#### *Multibeam Surveys*

Mapping surveys were conducted around Palmyra during the 2006 Pacific RAMP research cruise using multibeam sonar systems aboard the NOAA Ship *Hi'ialakai* (Simrad EM 300 and EM 3002D) and R/V *AHI* (Reson 8101-ER). A portion of the area had been mapped in 2005 by the University of Hawaii R/V *Kai'imikai O Kanaloa*, though that area was re-surveyed by the *Hi'ialakai* to provide higher resolution bathymetry and backscatter imagery to the collective multibeam coverage. Bathymetric and backscatter data were collected for depths between approximately 3 and 3,500 m and used to derive mapping products covering a total of approximately 1,082 km$^2$. Approximately 38.6 km$^2$ of the area between 0 and 30 m depths was not surveyed because the shallower areas of the reef terraces, back reef, and lagoon were inaccessible to survey with vessel-mounted multibeam systems.

Two of the resulting gridded bathymetric products are a 5 m high-resolution grid of the lagoon, shelf, and slope habitats to allow for the identification of fine-scale features to a depth of 300 m, and a coarser 40 m mid-resolution grid that includes the full extent of the multibeam bathymetric data collected (Figure 3). The data and supporting documentation are available on the Palmyra Bathymetry page of the Pacific Islands Benthic Habitat Mapping Center (PIBHMC) website.

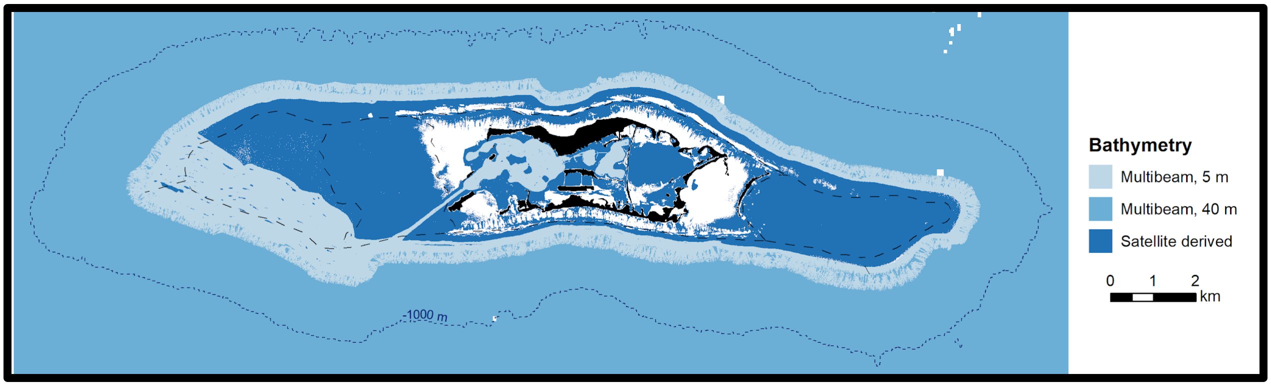



**Figure 3. Bathymetric coverage map for Palmyra Atoll showing extent of high- (5 m) and mid-resolution (40 m) gridded multibeam data acquired by the Ecosystem Sciences Division (ESD) in 2006 (lighter blues), and estimated bathymetry derived by ESD from satellite imagery (dark blue). The dotted dark blue line represents the 1,000 m depth contour. Gaps in bathymetric coverage are shown in white and land features in black. Satellite-derived bathymetry is discussed later in this section.**

The backscatter data from the shallower surveys conducted from the R/V *AHI* were gridded at 1 m resolution, while the deeper surveys conducted from the *Hiʻialakai* were gridded at 5 m resolution. Acoustic backscatter intensities reveal characteristics of the seabed around Palmyra that can be related to topography and slope. The 1 m resolution backscatter data are useful for habitat interpretation in shallow waters; the deeper backscatter data have quality issues, including high noise levels and patchiness in the coverage (e.g., off the shelf break in ~30–300 m depths along the slope). The 5 m resolution backscatter data had near complete coverage with only minor data gaps. The data and supporting documentation are available on the Palmyra Backscatter page of the PIBHMC website.

### *Single-beam Surveys*

Single-beam sonar data were acquired around Palmyra from depths between approximately 0.5 and 300 m in 2012, and between approximately 5 and 160 m in 2015 (Figure 4). As ocean conditions varied each year, the errors associated with the data also varied (0.62 and 0.24 m, respectively).

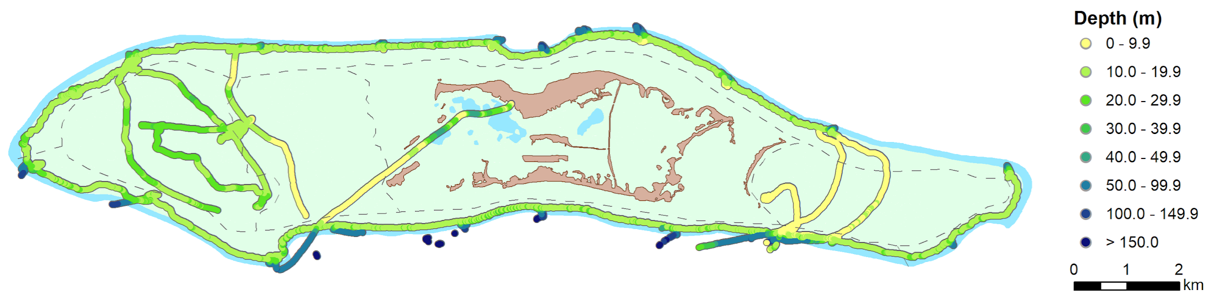



**Figure 4. Depth validation data for Palmyra Atoll collected by the Ecosystem Sciences Division in 2012 and 2015.**

### *Towed-camera Surveys / Habitat Validation*

Habitat validation data in the form of underwater video and still photographs were acquired primarily around the West Terrace georegion of Palmyra from depths between approximately 10 and 170 m by ESD in 2002 and 2004 using the Towed Optical Assessment Device (TOAD). In 2009 and 2010, NCCOS acquired habitat validation data around Palmyra from depths between 0 and 30 m at precisely located coordinates by recording visual observations of the habitat (i.e., benthic habitat assessments) and using a video drop camera (Figure 5).

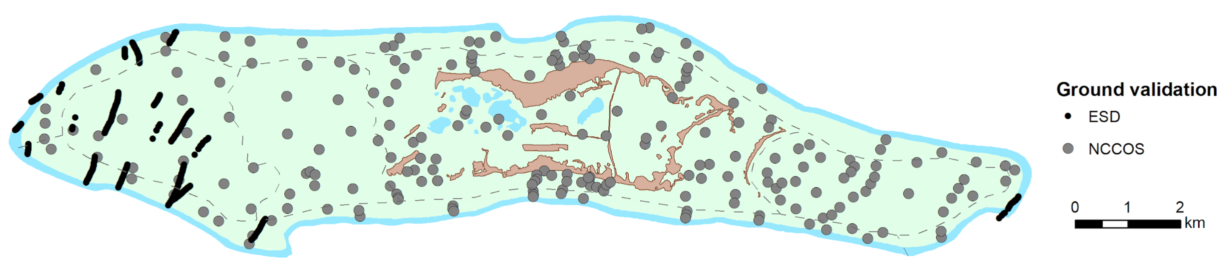



**Figure 5. Habitat validation data for Palmyra Atoll collected by the Ecosystem Sciences Division (ESD; black dots) and the National Centers for Coastal Ocean Science (NCCOS; grey dots).**

A subset of the TOAD images collected were classified into substrate types (e.g., sand, rubble, boulder), biological cover type (e.g., coral, macroalgae, coralline algae), and coral growth morphology (e.g., branching, columnar, encrusting) to produce a map of percent cover for observed scleractinian coral at the image collection point. The data and supporting documentation are available on the Palmyra Optical Validation page of the PIBHMC website.

NCCOS conducted benthic habitat assessments at 476 sites. The high density and relatively even spatial coverage of these observations provided important data for creating detailed thematic benthic habitat maps. A subset of these data (217 sites) provided habitat validation for creation of a habitat map derived from satellite images—including geomorphological structure (e.g., boulder, aggregate reef, and spur and groove) and biological cover (e.g., coral, seagrass, macroalgae, coralline algae, and turf)—for water depths between 0 and 30 m around Palmyra. The remainders of the sites were used for the accuracy assessment of the resulting habitat classes (methods described on the Benthic Habitat Mapping of Palmyra Atoll project website). These data are available via the Palmyra BIOMapper, a web portal developed by NCCOS for exploring benthic habitat mapping data.

## Habitat characterization

### *Satellite-derived Bathymetry*

ESD derived estimated depths between 0 and 25 m from IKONOS satellite imagery acquired in 2001 to fill gaps in the shallow-water bathymetric coverage around Palmyra. ESD later derived estimated depths between 0 and 16 m from WorldView-2 satellite imagery acquired in 2014. Depth soundings collected in 2012 and 2015 (Figure 4) were used to validate the satellite-derived depths, resulting in 80% agreement between the overlapping soundings and estimated depths. The data and supporting documentation are available on the Palmyra Bathymetry page of the PIBHMC website. Though these estimated depths provide useful information for areas with little or no bathymetric measurements, they have limited use for other mapping purposes. See Figure 3 for the extent of satellite-derived depths generated by ESD that partially filled the gap in existing bathymetric coverage.

### *Integrated Bathymetry*

ESD's multibeam bathymetry and satellite-derived depths were combined to produce an integrated bathymetric map for Palmyra (Figure 6).

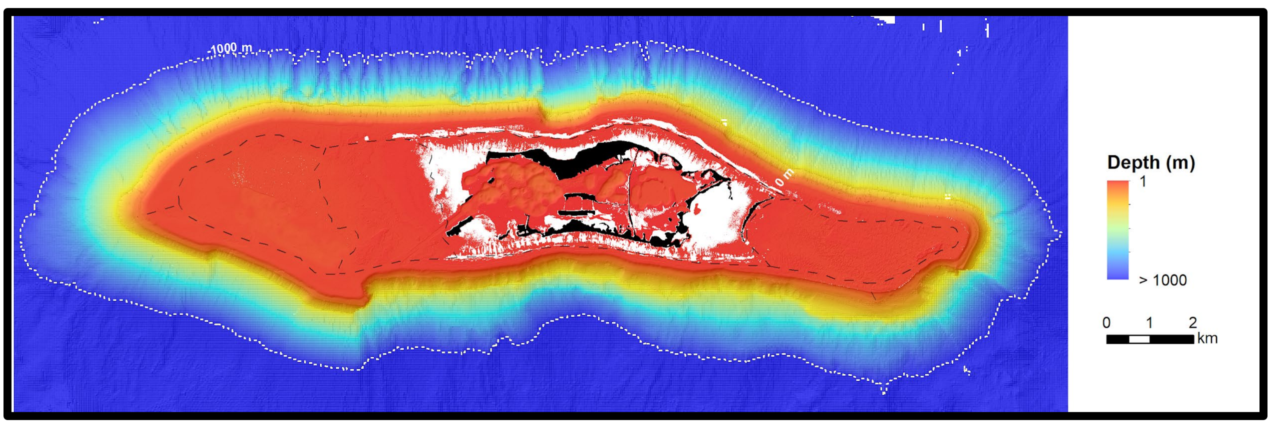



**Figure 6. Integrated bathymetric map focusing on depths from 0 m to ~1,000 m for Palmyra Atoll, with gaps in bathymetric coverage shown in white and land features in black. The dotted white line represents the 1,000 m depth contour.**

The bathymetric data for the shelf around Palmyra revealed submerged banks (terraces) to the west and east of the atoll, with depths primarily less than 50 m. These East and West Terraces contrasted with the deeper inner lagoons and the steep, narrow north- and south-facing forereef slopes. The Lagoon/Backreef georegion, nearly enclosed by islets and fringing reefs, is accessed via the dredged channel in the southwest and shows large variations in depth—from small pockets of impassable waters due to exposed reefs at low tide to maximum depths exceeding 50 m in some areas. The bank edges and forereef slopes had canyon-like incisions, most prominent along the northern bank and extending to deeper depths. Beyond the terraces and reef slopes, the seafloor dropped dramatically around the entire atoll to depths greater than 3,000 m.

### *Bathymetric Derivatives*

No bathymetric derivatives (e.g., slope, rugosity, or bathymetric position index layers) are currently available for Palmyra.

### *Seafloor Substrate*

ESD generated predicted seafloor substrates (i.e., hard or soft bottom) for Palmyra in 2018 (Figure 7). The source data used to produce the substrate map for Palmyra for water depths to 1,000 m include multibeam bathymetric and backscatter data from the 2006 surveys and WorldView-2 satellite imagery acquired in 2014. The data and supporting documentation are available on the Palmyra Seafloor Characterization page of the PIBHMC website.

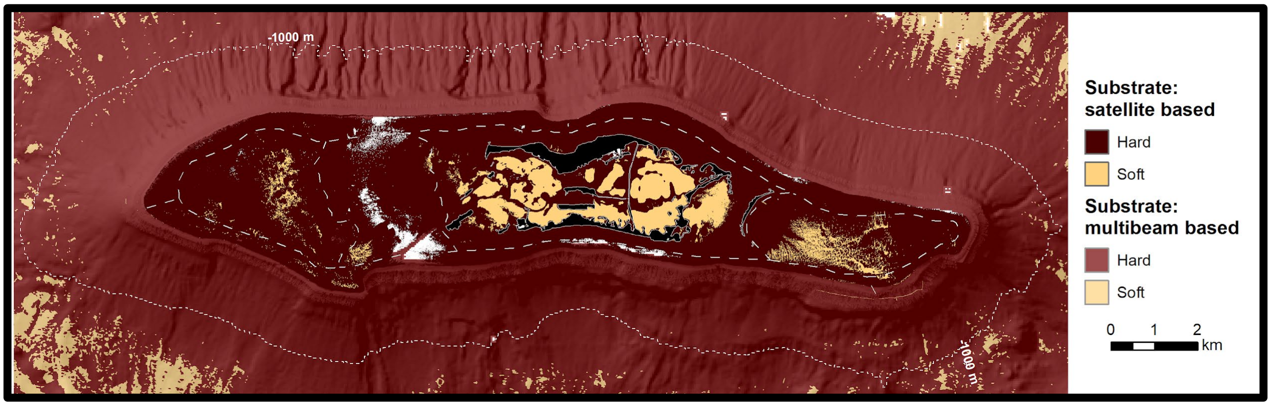



**Figure 7. Seafloor substrate map of Palmyra Atoll showing hard- and soft-bottom habitats. Generally, depths from ~0 to 30 m were derived from WorldView-2 satellite imagery, and depths >30 m were based on gridded multibeam bathymetric and backscatter data (40 m and 5 m resolution, respectively). The dotted white line represents the 1,000 m depth contour. Gaps in substrate coverage are shown in white and land features in black.**

Due to variability in coverage and data quality of the multibeam and satellite-derived data for Palmyra, the substrates for the nearshore areas were produced by combining the substrate classifications from both data types. Predictions from the most suitable data type for a particular setting were used. The forereef and backreef classifications were primarily generated from the satellite-derived predictions (0–30 m), and multibeam-based classifications were only used within the deeper parts of the Lagoon/Backreef georegion. While multibeam data also exist from the shelf break (~30 m) to 300 m down the seamount slope, poor data coverage and quality precluded using these data. Finally, limited manual mapping was conducted in areas where the satellite-derived predictions were deemed inaccurate and where no multibeam data exist. These problems were primarily observed in shallow lagoonal areas where darker, silty sediments found adjacent to the islets within the lagoons were incorrectly classified as hard substrate (darker areas are typically interpreted as hard substrate). In these scenarios, manual delineation of substrate was required to override the machine-learning predictions.

In shallow-water areas, expected substrates include carbonate sands (varying in grain size), mud, rubble, packstone and possible dredging artifacts, patch reefs, and reef rubble. Palmyra's landscape underwent a series of significant modifications over the years, especially after the U.S.

Navy took control prior to World War II (Dawson 1959). As a result of dredging, use of patch reef material to enlarge the islands, and other construction activities, some of that material likely ended up on some of the reef flats. Soft-bottom areas around Palmyra are likely composed of carbonate sand sediment originating from corals, mollusks, and calcareous algae, with availability limited primarily by growth and decay of reef organisms (Tucker and Wright 2009). The general sediment transport at Palmyra is from east to west as water passes over the reef flats into the Lagoon/Backreef georegion and often exits through the dredged boat channel (Collen et al. 2009). The sheltered lagoonal areas tend to have lower hydrodynamic flow compared with the areas outside the atoll, thereby allowing for more sediment deposition and higher rates of bioturbation. Soft-bottom areas were found within both the shallow and deep portions of the Lagoon/Backreef georegion, with higher deposition rates in the deep areas. In the deeper areas outside of the reef crest, hard substrates were almost exclusively observed associated with variable reef morphologies and pavement; gullies associated with coarser, potentially hard sediment and steep slopes were also evident.

### *Case Study: Substrates versus Habitats*

NCCOS produced a comprehensive benthic habitat map of Palmyra to 30 m depths over a total seafloor area of 50.26 km$^2$ using satellite imagery (IKONOS and Quickbird II) and habitat validation data (DOC/NOAA/NOS/NCCOS/CCMA/Biogeography Branch and Analytical Laboratory of Hawaii LLC 2010). The benthic habitat data include zones (e.g., bank /shelf, forereef, lagoon), geomorphological structures (e.g., aggregate reef, mud, spur and groove), and biological cover (e.g., algae, live coral). Since habitat maps of this nature did not exist for the PRIMNM, with the exception of Palmyra, ESD adapted methods to generate seafloor substrates for each of the islands of the PRIMNM from satellite imagery for shallow-water areas and from multibeam data for deeper-water habitats.

The NCCOS habitat maps for Palmyra were useful in assessing the reliability of the satellite-derived substrate predictions. See Figure 8 for a comparison between the satellite-derived substrates and the NCCOS benthic structure map. Panel A shows the variability in satellite-derived substrates in the East Terrace georegion of Palmyra prior to clustering of the classes into either hard or soft designations. The substrate predictions between the hard- and soft-bottom classes serve as a proxy for the proportion of sandy bottom substrate. When these substrate predictions (A) were compared with the structures delineated in the NCCOS habitat map (B), the in-between substrate classes in A corresponded to aggregate and patch reef areas, which are not uniformly hard or soft bottom, in B. Therefore, these pre-clustered substrate classes for Palmyra provide additional information about the seabed beyond the hard/soft designation.

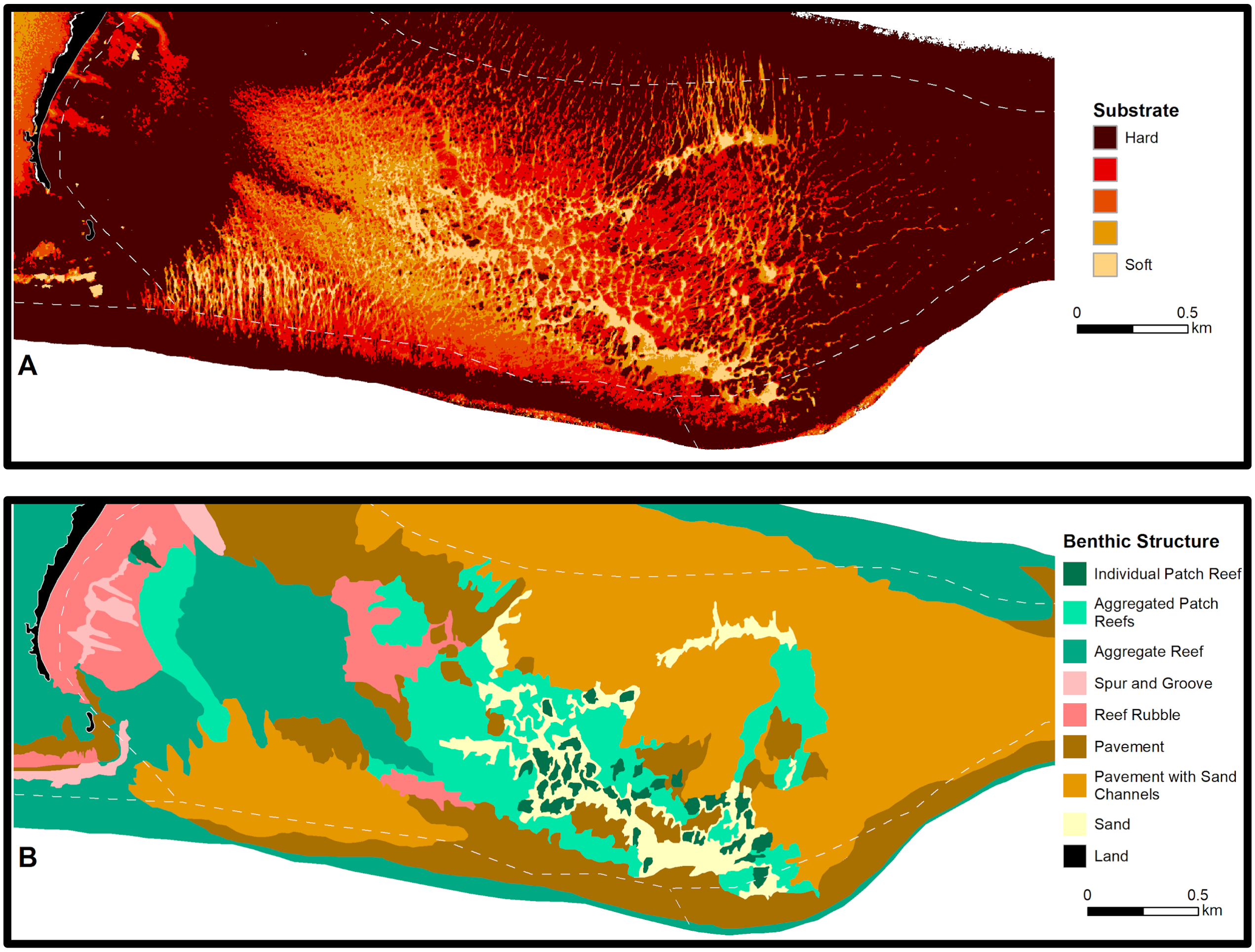



**Figure 8. (A) Satellite-derived substrate predictions with land features shown in black compared with (B) detailed benthic structures from the benthic habitat map developed by the National Centers for Coastal Ocean Science for Palmyra Atoll, demonstrating how substrate classes in between the hard/soft threshold preserve useful additional information about the seabed (i.e., mixed areas of hard- and soft-bottom types shown in the orange-to-red classes in panel A correspond to benthic structures, such as aggregate and patch reefs, spur and groove, and reef rubble areas, delineated in panel B).**

## Maps to Inform the Coral Reef Fish and Benthic Monitoring Survey Design

Many biological communities are naturally structured by depth and habitat (i.e., reef zone), often due to differences in associated environmental parameters, such as light, temperature, salinity, and wave energy. The current Pacific RAMP stratified-random survey design restricts monitoring surveys to hard-bottom habitats in the 0 to 30 m depth range, stratified by both depth and reef zone.

### *Depth Strata*

The integrated bathymetry shown in Figure 6 has been used to classify depth bins (Figure 9) from 0 to 1,000 m. For the Pacific RAMP surveys, depth strata have been defined as shallow

(>0–6 m), mid (>6–18 m), and deep (>18–30 m). Estimated seafloor areas for each of the depth strata are included in Table 1.

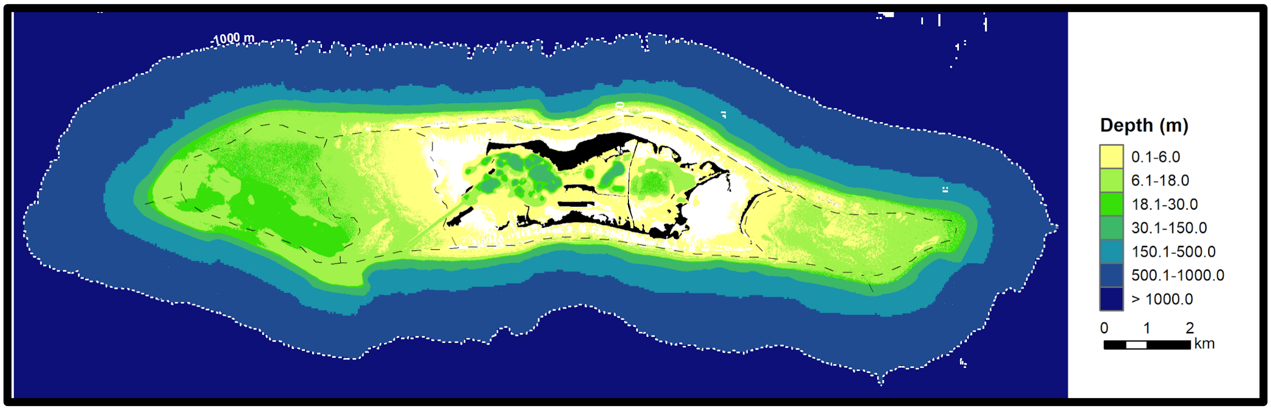



**Figure 9. Depth strata map for Palmyra Atoll from 0 m to 1,000 m, with gaps in bathymetric coverage shown in white and land features in black. The dotted white line represents the 1,000-m depth contour.**

The actual mapped seafloor area for select depth strata at Palmyra differs from the estimated seafloor area (Table 1). Remaining gaps in the integrated bathymetry were estimated to enable calculation of pertinent population abundance statistics using the stratified-random design. Around Palmyra, 86% of the seafloor between 0 and 30 m depths was mapped, leaving an approximately 7.0 $km^2$ gap in the shallowest (>0–6 m) depth strata. The map of the seafloor from 30 to 1,000 m depths was nearly spatially complete.

**Table 1. Land and seafloor area by depth strata from 0 to 1,000 m depths for Palmyra Atoll. Seafloor area statistics include actual mapped area ($km^2$) and estimated seafloor area ($km^2$) based on interpolation of the integrated bathymetric map for Palmyra. Land area is 2.6 $km^2$.**

| Depth (m) | Estimated Seafloor ($km^2$) | Mapped Seafloor ($km^2$) |
|---|---:|---:|
| >0–6 | 22.8 | 15.8 |
| >6–18 | 19.3 | 19.2 |
| >18–30 | 7.8 | 7.8 |
| **Subtotal: >0–30** | **49.9** | **42.8** |
| >30–150 | 8.6 | 8.6 |
| >150–500 | 20.2 | 20.1 |
| >500–1,000 | 56.0 | 56.0 |
| **Total: >0–1,000** | **134.7** | **127.6** |

### *Reef Zones*

To support the stratified-random design for Pacific RAMP monitoring surveys, reef zones have been identified for Palmyra based on the zones delineated from the shore to the shelf edge in the benthic habitat map produced by NCCOS. The original zones were pooled into five reef zones, including forereef, backreef, reef crest/reef flat, lagoon, and land, to optimize the sampling effort for Pacific RAMP monitoring surveys (Figure 10). Forereef zones include bank/shelf and bank/shelf escarpment areas; lagoon zones include channels and dredged areas; and land zones include salt ponds.

Only forereef habitats were typically surveyed, because these habitats most commonly occur in coral reef areas. Therefore, results from surveys at Palmyra can be compared with results from surveys across all coral reefs of the U.S. Pacific Islands. Moreover, hazards navigating near the shallow areas within the Lagoon/Backreef georegion and limited access into the lagoon hindered surveys in these habitats at Palmyra.

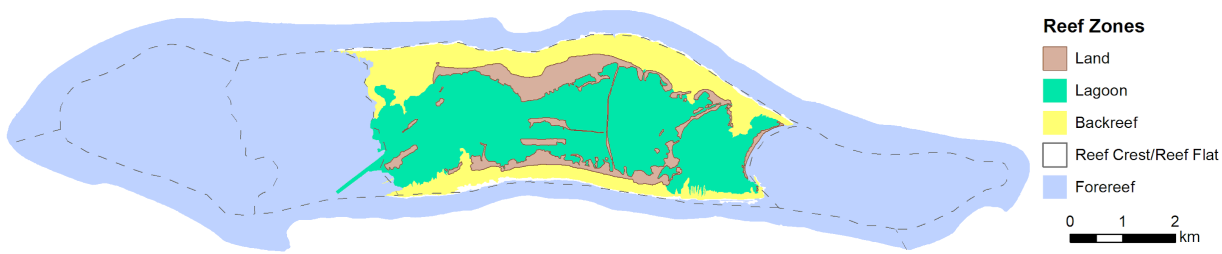



**Figure 10. Reef zones for Palmyra Atoll based on the zones delineated in the benthic habitat map produced by the National Centers for Coastal Ocean Science.**

### *Substrate*

Only hard-bottom substrates were targeted for stratified-random reef fish and benthic monitoring surveys of Pacific RAMP. Substrates for the current survey strata for Palmyra were based on the major structures from the NCCOS benthic habitat map for Palmyra (Figure 11). The seafloor surrounding Palmyra outside of the lagoon is predominantly hard substrate. Within the lagoon, unconsolidated sediments are the dominant substrate.

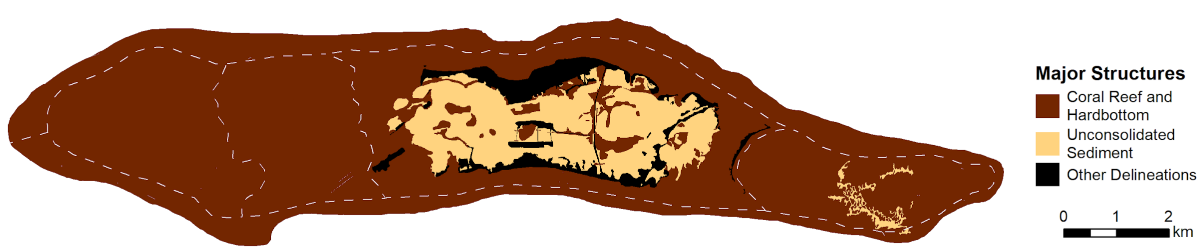
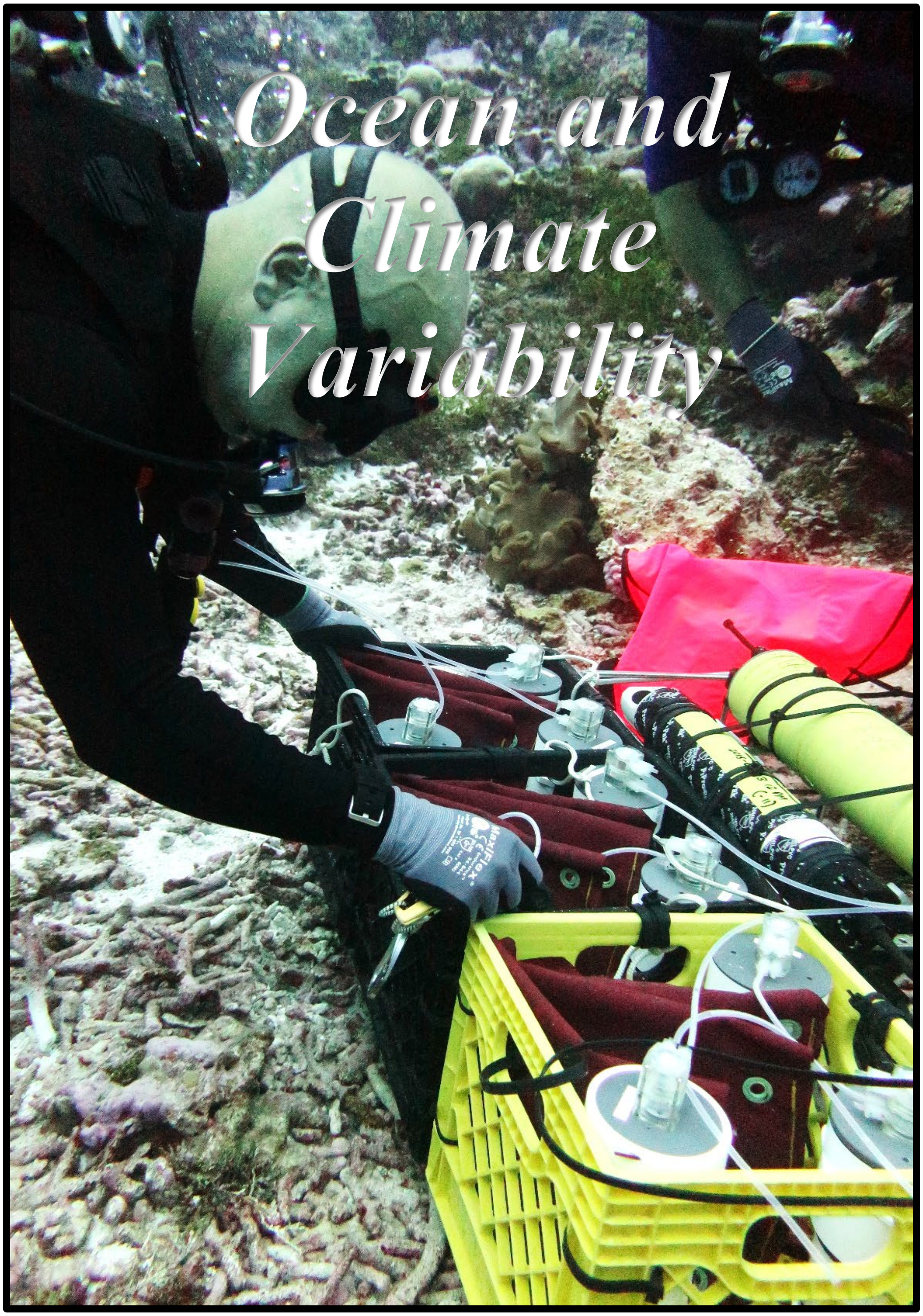



**Figure 11. Hard- and soft-bottom substrates for Palmyra Atoll, based on the major structures delineated in the National Centers for Coastal Ocean Science benthic habitat map.**

*Survey Strata*

Figure 12 shows the strata used by the benthic and fish teams for the stratified-random surveys at Palmyra. The strata, which include depth, reef zones (not shown), and bottom type (i.e., substrate), are well defined with no significant gaps in the survey domain. The depths, estimated for the express purpose of defining the depth strata, were combined with a detailed benthic habitat map that includes seafloor structure (hard bottom) and zones. The surveyable area at Palmyra, including the forereef, hard-bottom habitats in the 0 to 30 m depth range, encompasses approximately 33 km$^2$.


**Figure 12. Survey strata for fish and benthic surveys, including substrate and depth strata (defined for Pacific Reef Assessment and Monitoring Program stratified-random surveys as shallow [>0–6 m], mid [>6–18 m], and deep [>18–30 m]) for Palmyra Atoll. The few unknown substrate areas, primarily in the deeper depths along the map perimeter, are shown in grey, and land features are shown in black. Depths >30 m are excluded from the survey strata, which at Palmyra includes the deeper areas of the Lagoon/Backreef georegion shown in white.**




*NOAA Diver Ariel Halperin installs an instrument package on the reef at Palmyra Atoll to measure oceanographic changes throughout tidal/daily cycles.*
*Photo: Hannah Barkley, NOAA Fisheries.*

## 2.3 Ocean and Climate Variability

*NOAA diver secures subsurface temperature recorders installed at Palmyra Atoll.*
*Photo: NOAA Fisheries.*

### Survey Effort and Site Information

Ocean conditions in the central tropical Pacific are most heavily influenced on seasonal and interannual time scales by the latitudinal meandering of equatorial ocean currents and by basin-scale ocean change associated with oscillations in Pacific climate phenomena. Palmyra Atoll's oceanographic regime is impacted by seasonal shifts in the westward-flowing North Equatorial Current and the eastward-flowing North Equatorial Countercurrent. During summer months, weather and sea conditions are influenced by the migrating Intertropical Convergence Zone, where Palmyra experiences light and variable winds, extremely high precipitation (4.5 m of rain per year) and daytime temperatures averaging 29 °C (85 °F). During the winter, Palmyra experiences moderate easterly trade winds and seas (Miller et al. 2008). The greatest driver of interannual variability is the El Niño Southern Oscillation (ENSO). The cycling between warm El Niño events and cool La Niña events every few years produces significant fluctuations in temperature, rainfall, wind strength, wave activity, and the intensity of deep-water upwelling to the surface ocean (Hamann et al. 2004).

Large-scale fluctuations in equatorial Pacific climate and ocean conditions drive dramatic changes in the nearshore waters that bathe Palmyra Atoll's coral reefs. Seasonal and ENSO-driven variability lead to differences in temperature, water column mixing, nutrient concentrations, and seawater chemistry that affect the health and function of coral reef ecosystems. These environmental oscillations are occurring on a backdrop of global climate change, as concentrations of carbon dioxide in the atmosphere are altering the temperature and chemistry of the seawater in these coral reef habitats. Episodic high temperatures, largely driven by El Niño events, have led to increases in the frequency and intensity of coral bleaching in the past few decades. In addition, the dissolution of carbon dioxide in ocean surface waters sets off a chain of chemical reactions in seawater that decrease pH and make it more difficult for corals and calcifying reef organisms to grow. Understanding the shifts in ocean conditions that are occurring and the sensitivity of coral reef ecosystems to these changes is critical for projecting their survival under 21$^{st}$ century climate change.

Since 2000, Pacific RAMP has monitored the oceanographic environments of coral reef ecosystems in the PRIMNM. These efforts have collected data on key parameters using: (1) a diverse suite of moored instruments, (2) nearshore conductivity, temperature, and depth (CTD) vertical profiles of water column structure, (3) discrete water samples to assess dissolved nutrients, chlorophyll-a, and carbonate chemistry, and (4) estimates of calcium carbonate accretion, bioerosion rates, and coral growth and skeletal density to examine the balance between production and removal of calcium carbonate on the reef (Figure 13, Figure 14, Figure 15, Figure 16, and Figure 17). A summary of the environmental survey efforts around Palmyra from 2000 to 2016 is shown in Table 2. Refer to "Chapter 1: Overview" for oceanographic instrumentation specifics and water sample collection methodologies.

We complemented field data collections with satellite remote sensing data sets and model products to provide the large-scale climate and oceanographic context for our in situ observations. Specifically, we used the Oceanic Niño Index (ONI, the standard index of ENSO activity), sea surface temperature (SST) anomalies from the Optimum Interpolation SST data set, the Degree Heating Week (DHW) index from Coral Reef Watch, chlorophyll-*a* (chl-*a*, a proxy for primary productivity) anomalies from the Sea-Viewing Wide Field-of-View Sensor and Moderate Resolution Imaging Spectroradiometer Aqua, and global WaveWatch III model output to explore multi-decadal variability in ocean wave conditions.

**Table 2. Summary of the oceanographic and environmental data collection efforts at Palmyra Atoll by year over the period 2000 through 2016. The following instruments were deployed: coral reef early warning system (CREWS), sea surface temperature (SST) buoy, subsurface temperature recorder (STR), Seabird Electronics MicroCAT (SBE-37), ecological acoustic recorder (EAR), acoustic Doppler current profiler (ADCP), Satlantic SeaFET pH sensor (SeaFET), wave and tide recorder (WTR), calcification accretion unit (CAU), bioerosion monitoring unit (BMU), and autonomous reef monitoring structures (ARMS). Diel suites sampling included moored conductivity-temperature-depth (CTD) and discrete water samples. CTD casts, shallow (near reef) and deep (offshore), had corresponding discrete water samples, shallow (near reef) and deep (offshore). Coral cores were collected from *Porites* spp. Numbers indicate the quantity of instruments deployed (D) and retrieved (R) as D/R, water samples and diel suite collections, CTD casts, and coral cores per year.**

| Year | Instruments | | | | | | | | | | | Diel Suite | | CTD Casts | | Water Samples | | Coral Cores |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CREWS | SST | STR | SBE-37 | EAR | ADCP | SeaFET | WTR | CAU | BMU | ARMS | Moored CTD | Water Samples | Shallow | Deep | Shallow | Deep | *Porites* spp. |
| **2000** | - | - | - | - | - | - | - | - | - | - | - | - | - | 28 | - | - | - | - |
| **2001** | - | - | - | - | - | - | - | - | - | - | - | - | - | 10 | - | - | - | - |
| **2002** | 1/1 | - | 1/- | - | - | - | - | - | - | - | - | - | - | 19 | - | - | - | - |
| **2004** | 1/- | - | 4/1 | - | - | - | - | - | - | - | - | - | - | 52 | - | - | - | - |
| **2006** | 1/1 | 1/- | 9/4 | - | - | - | - | - | - | - | - | - | - | 63 | - | 48 | - | - |
| **2008** | 1/1 | 1/- | 13/9 | - | 1/- | - | - | - | - | - | 12/- | - | - | 26 | 14 | 38 | 6 | - |
| **2009** | - | - | 7/- | - | 1/1 | - | 2/1 | - | - | - | - | - | - | - | - | - | - | - |
| **2010** | -/1 | 1/- | 27/20 | 6/- | 1/1 | 4/- | 2/4 | 2/- | 40/- | - | 9/12 | - | - | 14 | 20 | 20 | 100 | 3 |
| **2011** | - | 1/1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **2012** | - | - | 28/39 | -/6 | 1/1 | 2/6 | - | -/2 | 40/40 | - | 9/9 | - | - | 8 | 16 | 16 | 80 | - |
| **2015** | - | -/1 | 18/22 | - | -/1 | 1/1 | 1/1 | - | 35/31 | 15/- | 9/9 | 1 | 8 | 15 | - | 20 | - | - |
| **2016** | - | - | 7/- | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **Total** | 4/4 | 4/2 | 114/95 | 6/6 | 4/4 | 7/7 | 5/5 | 2/2 | 115/71 | 15/- | 39/30 | 1 | 8 | 235 | 50 | 142 | 186 | 3 |

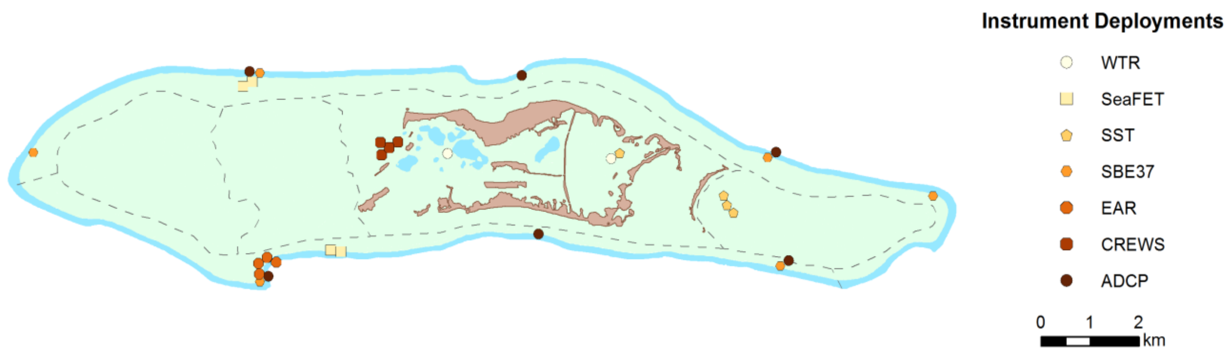



**Figure 13. Deployment locations of wave and tide recorders (WTR), Satlantic SeaFET pH (SeaFET) sensors, sea surface temperature (SST) buoys, Seabird Electronics MicroCATs (SBE-37), ecological acoustic recorders (EAR), coral reef early warning system (CREWS) buoys, and Nortek acoustic Doppler current profilers (ADCP) around Palmyra Atoll. Instrument deployments at the same location over multiple years have been plotted adjacent to one another and organized around their shared location on the map.**

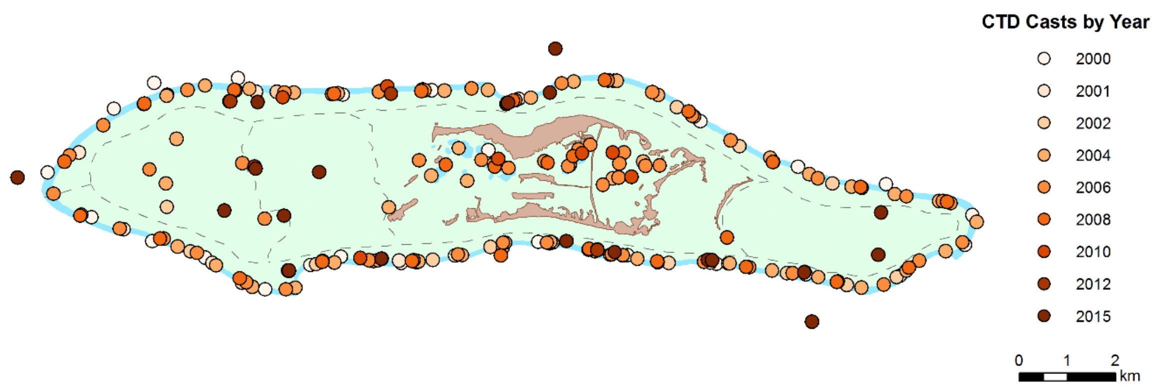



**Figure 14. Locations of nearshore conductivity-temperature-depth (CTD) hydrocasts, measuring water column salinity and temperature from the ocean surface to a depth of ~30 m around Palmyra Atoll. Casts in earlier years (2000–2010) prioritized sampling the entire perimeter of the forereef and lagoon, while later efforts (2012–2015) focused on permanent instrumentation sites (sites with subsurface temperature recorders, autonomous monitoring reef structures, and/or calcification accretion units).**

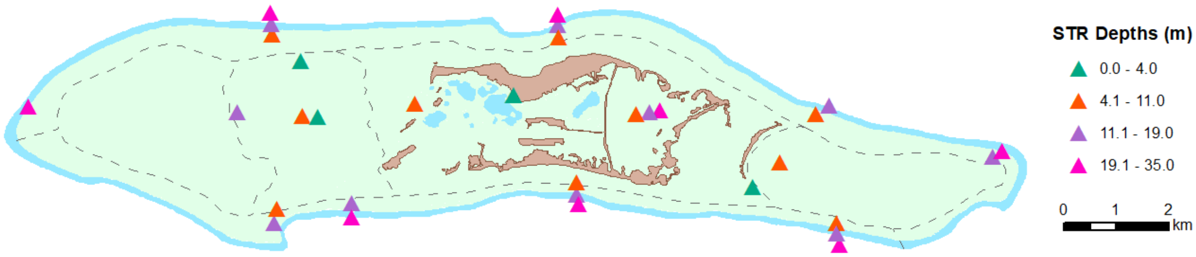



**Figure 15. Locations of subsurface temperature recorders (STRs) deployed on the reef substrate in depths ranging from 1 to 35 m depths around Palmyra Atoll. Multiple STRs may have been collected at the same location over multiple years; however, they are represented by a single marker on the map.**

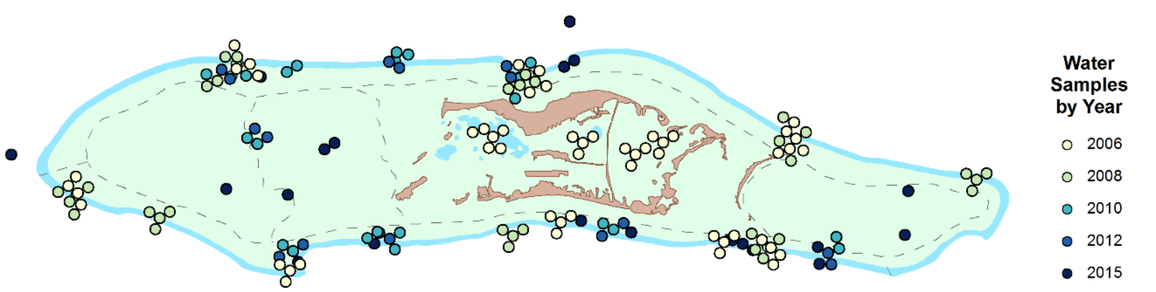



**Figure 16. Locations of discrete seawater sample collections from 1 to 35 m depths around Palmyra Atoll. Samples evaluated for various analytes: dissolved inorganic carbon, total alkalinity, chlorophyll-*a*, and dissolved inorganic nutrients. Water samples collected at the same location over multiple years have been plotted adjacent to one another and organized around their shared location on the map.**

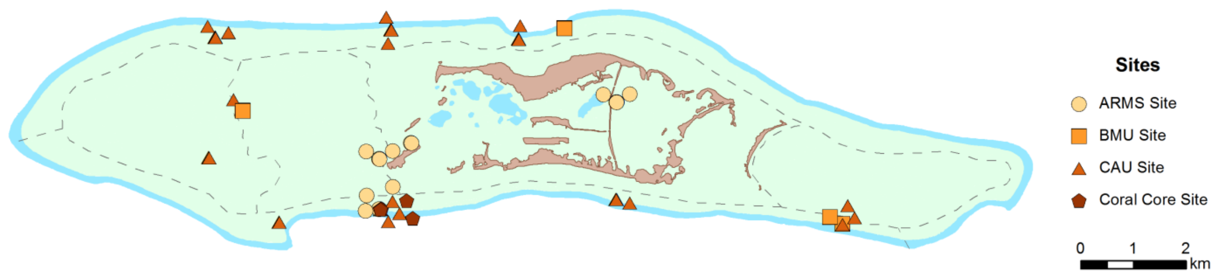



**Figure 17. Locations of autonomous reef monitoring structures (ARMS, 3 per site), bioerosion monitoring units (BMU, 5 per site), calcification accretion units (CAU, 5 per site), deployed on the reef at ~15 m depths around Palmyra Atoll. Coral cores of *Porites* spp. collected opportunistically at depths from 5 to 15 m. Instrument deployments at the same location over multiple years have been plotted adjacent to one another and organized around their shared location on the map.**

## Oceanographic Observations

Oceanographic conditions around Palmyra are predominantly driven by interannual warming and cooling associated with ENSO. The ONI, SST anomalies, DHWs, and chl-*a* anomalies in recent decades are presented in Figure 18. The ONI shows the variability and frequency of strong warm (positive, El Niño) and cool (negative, La Niña) thermal anomalies, with higher SSTs persisting during El Niño warm events and lower SSTs during La Niña cool events (Figure 19a). While patterns in Palmyra SST largely track variability in ENSO, there are notable breaks from a strong correlation. In particular, Palmyra experienced relatively low SST anomalies compared to the magnitude of the ONI during the extreme 1997–1998 El Niño event.

The coral reefs at Palmyra Atoll have experienced several episodes of ENSO-driven high temperatures over the past four decades, visualized as DHW in Figure 18c. DHWs estimate the amount of thermal stress that has accumulated in an area over a 12-week period by summing and integrating the magnitude and duration of temperatures exceeding the local coral bleaching threshold defined as 1 °C above the maximum monthly mean. SST anomalies above this threshold can drive significant coral bleaching when sustained for several weeks to months, with moderate bleaching predicted when DHW >4 °C-weeks and severe bleaching expected when DHW >8 °C-weeks. The cumulative DHWs during this period related directly to strong warming observed in the ONI (Figure 18a), with DHWs accumulated at Palmyra in response to El Niño events in 1991–1992, 2004–2005, 2009–2010, and 2015–2016.

An inverse relationship exists between ENSO-driven variability in SST and phytoplankton chl-a pigment concentration, where increased temperatures were associated with decreased concentrations of chl-a (Figure 18d, Figure 19b). During La Niña, enhanced equatorial upwelling of anomalously cool, nutrient-rich deeper waters, drives high chl-a concentrations and, by extension, greater plankton biomass. During strong El Niño conditions, warm surface waters stratify the water column and suppress the upwelling of nutrient-rich waters, resulting in decreased chl-a concentrations. These patterns were particularly evident during the transitions from strong El Niño to strong La Niña in 1998, 2005, 2007, and 2010.

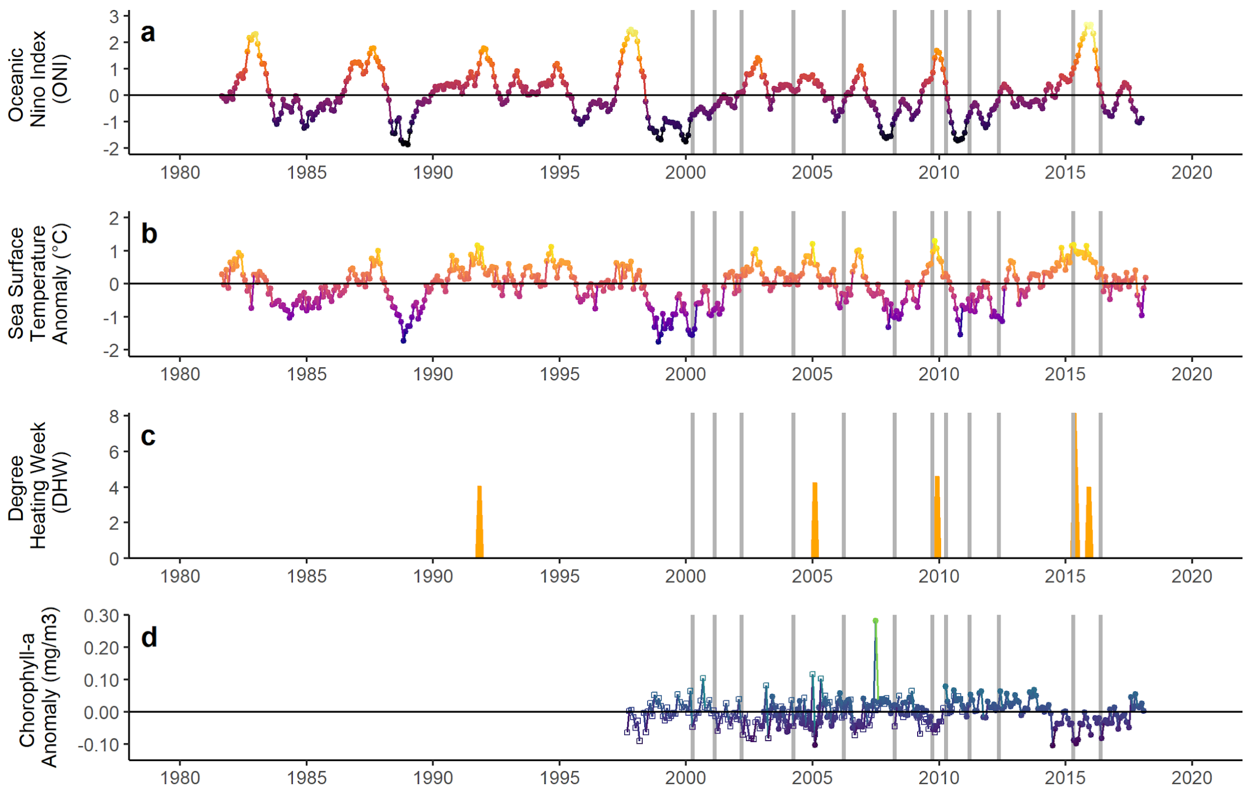



**Figure 18. Time series of oceanographic conditions at Palmyra Atoll: (a) a 3-month rolling mean of Oceanic Niño Index (ONI) from September 1981 to April 2018 in the El Niño 3.4 region (5°N–5°S, 120°W–170°W), (b) sea surface temperature (SST) anomalies from September 1981 to April 2018, (c) Cumulative Degree Heating Week (DHW) from 1985 to 2017, and (d) phytoplankton chlorophyll-*a* pigment (chl-*a*) concentrations from 1997 to 2017. Available data for ONI, SST, DHW, and chl-*a* were extracted for a box around Palmyra Atoll (Latitude North: 5.991291 to 5.769 and Longitude West: -162.261936 to -161.907118). Shading for SST and chl-*a* data indicates the magnitude of the anomaly, and vertical bars show the dates of field data collections.**

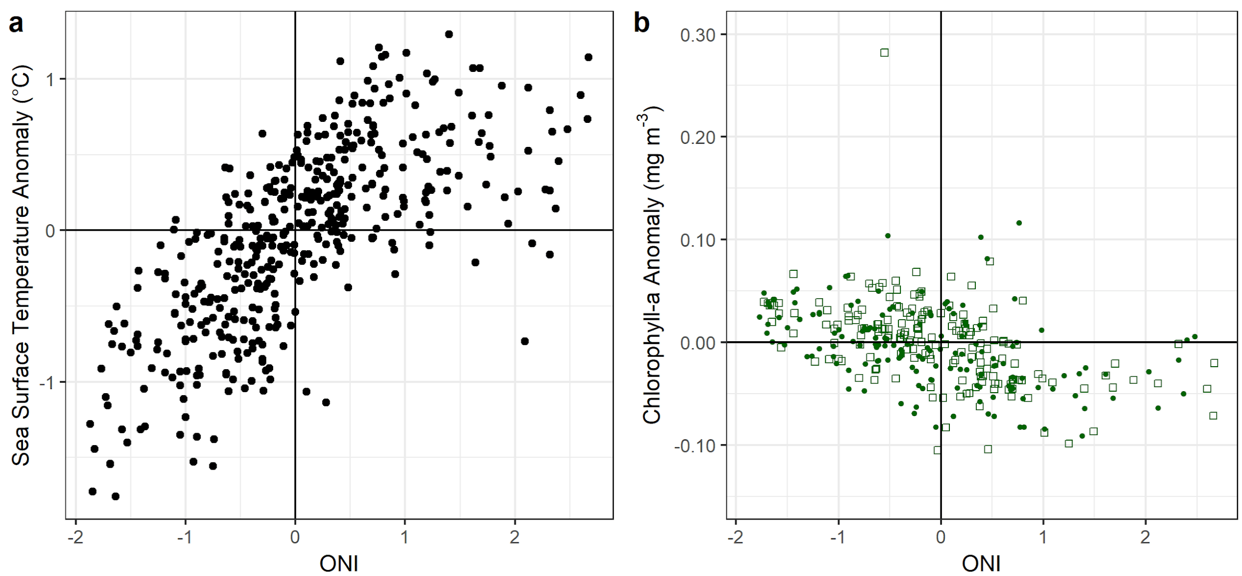



**Figure 19. Relationship between monthly-averaged oceanographic conditions at Palmyra Atoll: (a) Oceanic Niño Index (ONI) vs. sea surface temperature (SST) anomaly, and (b) ONI vs. satellite-derived chlorophyll-*a* (chl-*a*; Sea-Viewing Wide Field-of-View Sensor in boxes and Moderate Resolution Imaging Spectroradiometer in circles) anomaly data. Available data for ONI, SST anomaly, and chl-*a* were extracted for a box around Palmyra Atoll (Latitude North: 5.991291 to 5.769 and Longitude West: -162.261936 to -161.907118).**

## Water Column Observations

The physical properties and stratification of Palmyra's water column varied both temporally, with phases of ENSO, and spatially, between the exposed forereef and more sheltered lagoon. Figure 20 shows the location of shallow-water CTD casts conducted in the nearshore waters around Palmyra and inside the lagoon in 2006 (63 casts) and 2008 (26 casts). Cast data document measurable differences in temperature, salinity, and density profiles between weak (2006) and moderate (2008) La Niña years. Temperatures in 2006 were about 1 °C warmer, and salinity and density were slightly lower relative to 2008 (Figure 21).

In both 2006 and 2008, there was little vertical stratification on the forereef (Figure 21). Around the northwest corner of the atoll, lower temperatures, higher salinities, and associated higher seawater densities were observed relative to the rest of the reef, suggesting greater mixing with deep water or localized upwelling. In the protected lagoon, temperatures were much warmer (up to 1 °C higher), and temperature, salinity, and density profiles revealed greater stratification of the water column due to reduced vertical mixing.

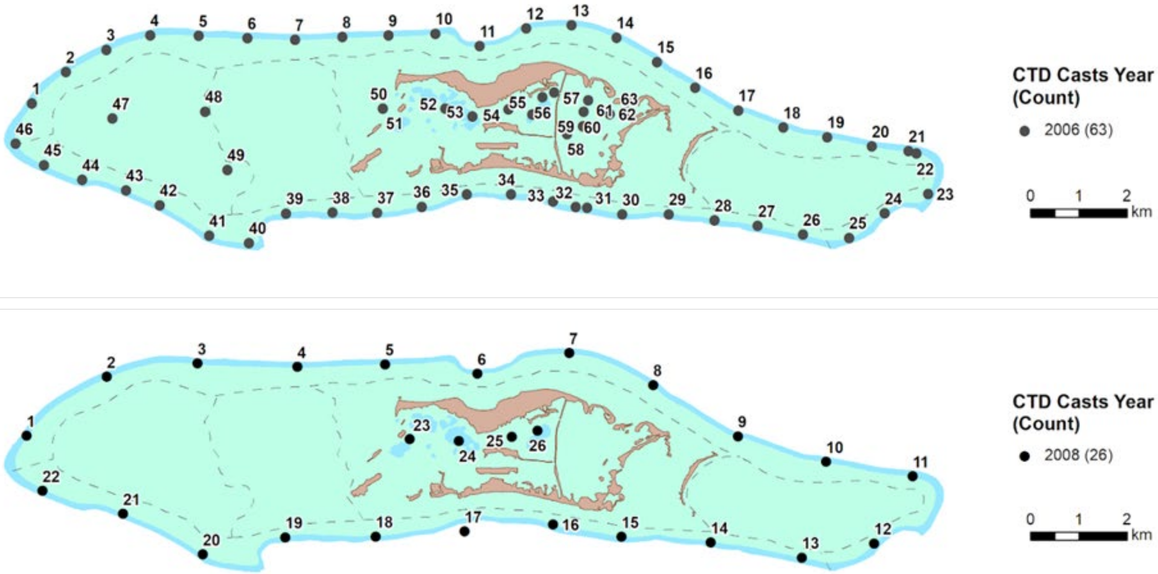



**Figure 20. Shallow-water conductivity-temperature-depth (CTD) sampling locations around Palmyra Atoll. CTDs were conducted during March of 2006 (63 casts) and March of 2008 (26 casts). The casts are numbered sequentially in a clockwise direction around the island and lagoon system from left to right, respectively.**

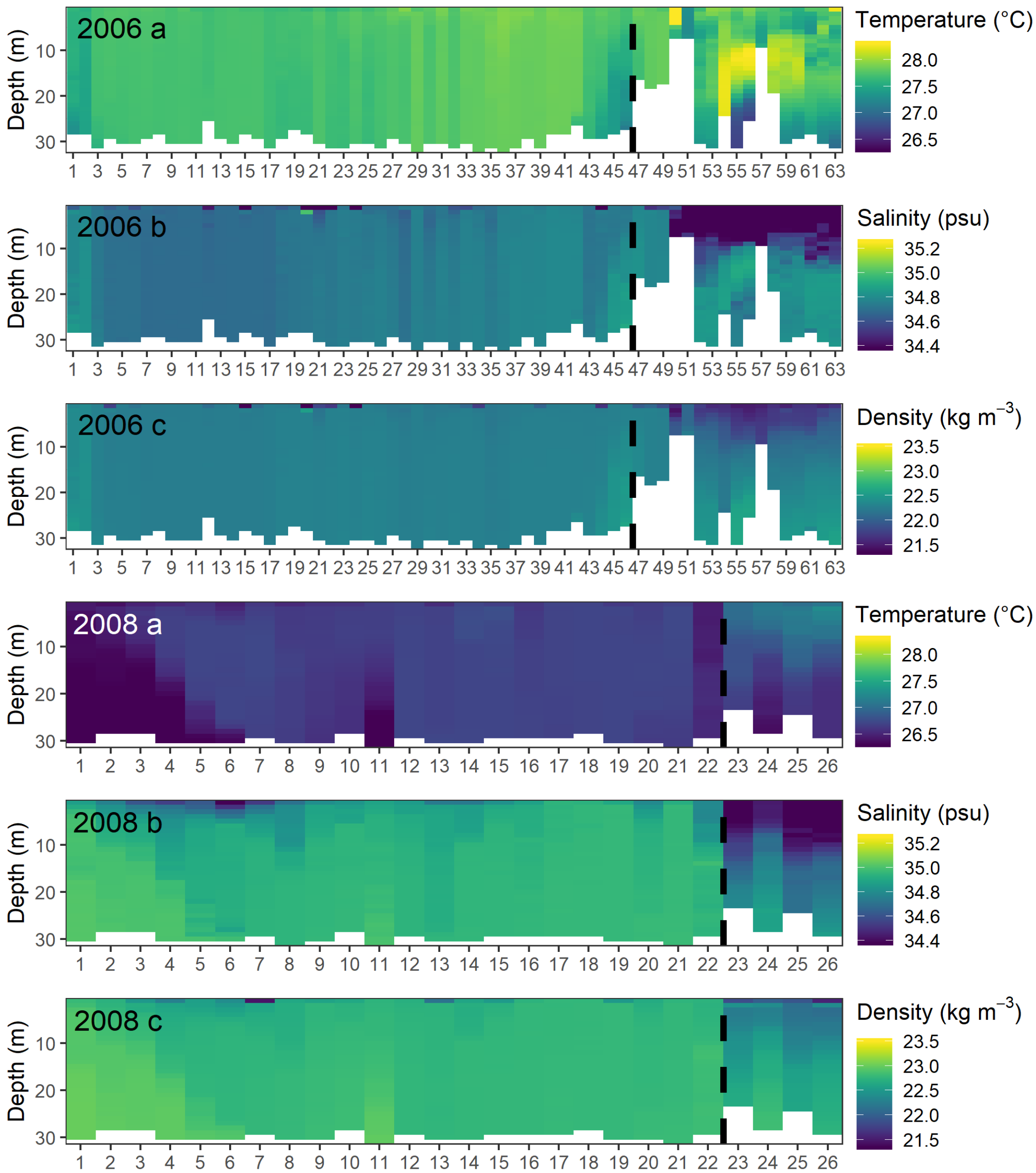



**Figure 21. Profiles from shallow-water conductivity-temperature-depth casts around Palmyra Atoll in 2006 (top three panels) and 2008 (bottom three panels) for (a) temperature (°C), (b) salinity (psu), and (c) sigma-t density (density of seawater at atmospheric pressure in kg m$^{-3}$ -1,000), from the surface to depths of ~32 m. Dashed line divides around the islands and Lagoon casts. The casts are numbered sequentially in a clockwise direction around the island, and from left to right as part of the Lagoon system located in the center of the island. The top three panels show March of 2006 profiles 1–49 (around island), and 50–64 (Lagoon), while the bottom three panels show March of 2008 profiles 1–22 (around island), and 23–26 (Lagoon).**

Between 2002 and 2017, a total of 114 moored subsurface temperature recorders (STRs) collected temperature time series at depths between 1 and 35 m (Figure 15). This suite of STRs provides in situ vertical thermal structure observations to characterize the temperature regimes experienced by Palmyra's coral reefs. The maximum temperature of 30.1 °C occurred at Palmyra

South (between 11.1 and 19.1 m), while the minimum of 25.2 °C is associated with Palmyra West (between 4.1 and 11.0 m; Figure 22). The seasonal maxima were reached at Palmyra East during the fall, with a mean of 30.5 °C at the surface (between 0 and 4.0 m) and a minimum mean of 25.4 °C during fall at the deepest range (between 19.1 and 35.0 m). The West and East sides of the island had similar homogeneous thermal conditions with depth. The Lagoon sites were more thermally stratified, with highest temperatures in the near-surface layer (0–4.0 m).

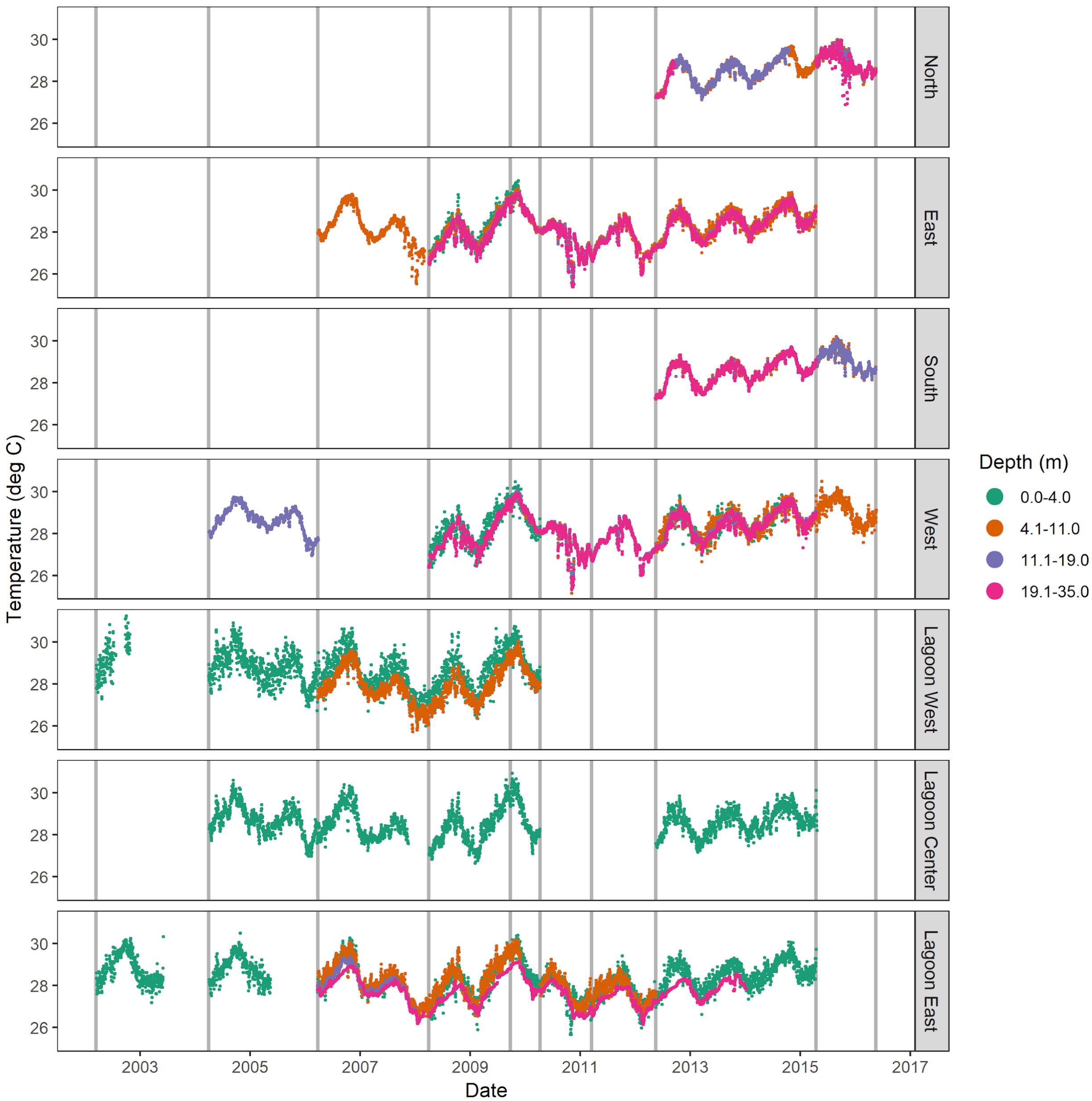



**Figure 22. Daily subsurface temperature recorder time-series observations of temperature over the period between 2002 and 2016, collected around Palmyra Atoll (North, South, West, and East) and inside its lagoon (West, Center, and East). Four different depth ranges were defined at each of these locations: green (0–4.0 m), orange (4.1–11.0 m), purple (11.1–19.0 m), and pink (19.1–35.0 m). Vertical bars show dates of field sampling efforts.**

## Wave Energy

Ocean wave dynamics strongly influence the environmental conditions of coastal habitats. The energy generated by ocean waves varies over a broad range of time scales, including tidal, multi-day storm events, seasonal, interannual, and decadal, and spatial differences in the direction, magnitude, and frequency of waves around an island or atoll can have significant impacts on the sub-island distribution of coral reef communities. Hourly wave data from 2010 to 2016 are shown in Figure 23 and Figure 24. The north side of Palmyra experienced more waves with longer periods (the length of time between crests) and heights (the distance from trough to crest) from December through February (Figure 23, left panels). The south and east sides of Palmyra were exposed to more waves with both higher periods and heights in July through September (Figure 23, right panels). The mean annual integrated wave power shows that the North and East georegions of Palmyra are most impacted by wave patterns (Figure 24).

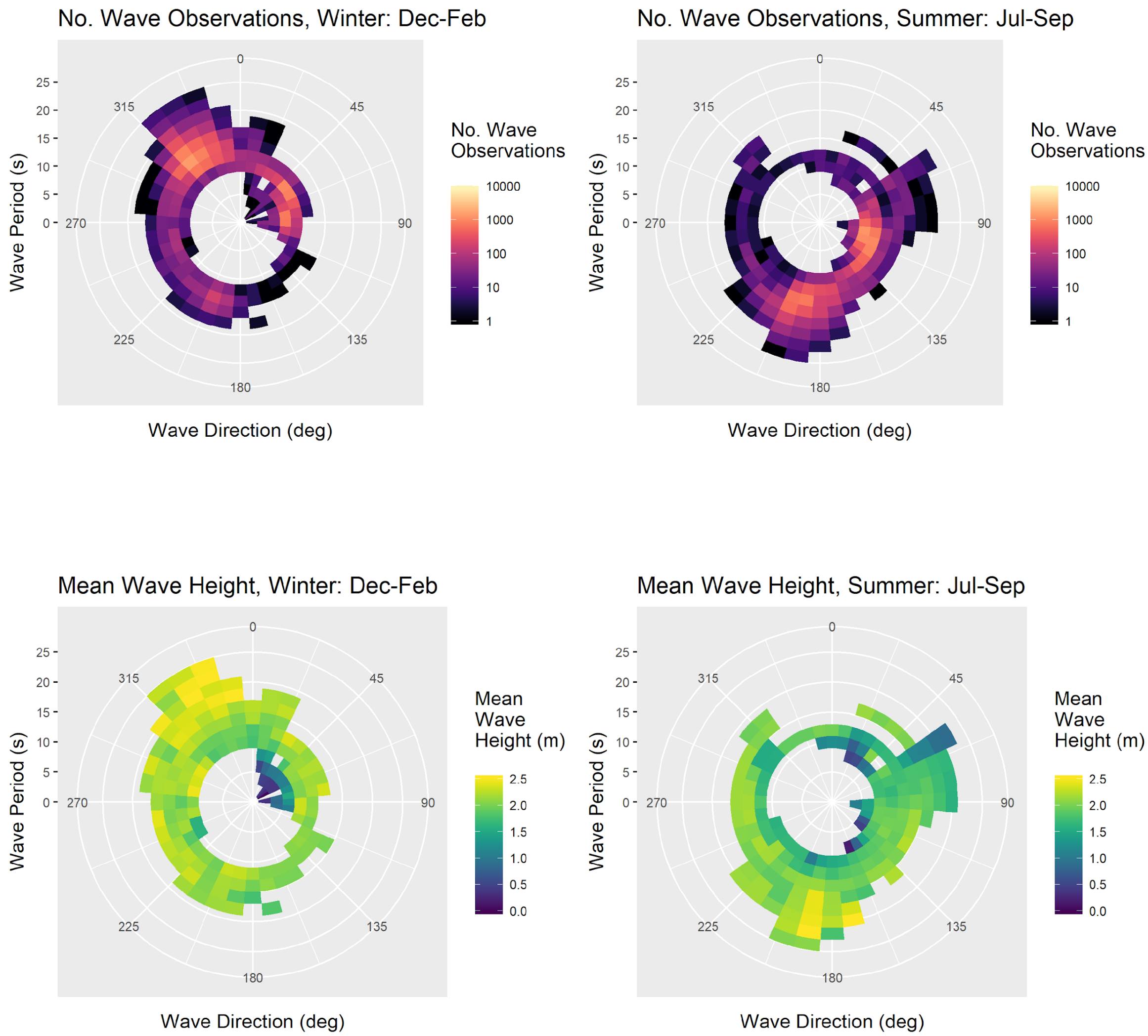



**Figure 23. Wave Watch III data from 2010–2016 for the region around Palmyra Atoll. Top panels: Polar plot of hourly wave data from December to February (left panel) and July to September (right panel). Bottom panels: Polar plot of derived mean wave height between December–February (left panel), and between July and September (right panel). The position of wave data around the 360-degree circle (in 10-degree bins) displays the direction from which the waves hitting Palmyra travel. Zero degrees indicate that waves arrive from due north and 180 degrees from due south. The height of each directional bin from the center shows the wave period (greater distances from center represent longer wave periods), and the shading shows the number of hourly observations (top) and mean wave height (bottom) for each direction and period.**

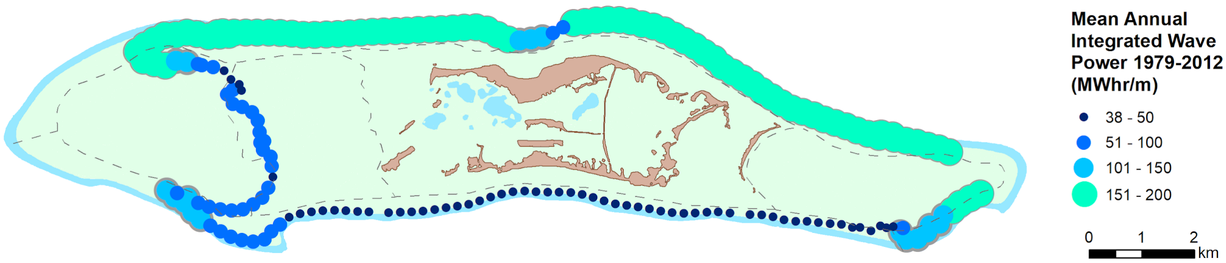



**Figure 24. Mean annual integrated wave power (MWhr/m) at Palmyra Atoll. Data from 1979 to 2012 correspond to modified Wave Watch III by coastline shadowing using the incident wave swath method (Clark and Oliver, in prep).**

## Carbonate Chemistry

Aragonite saturation state ($\Omega_A$) is a measure of the degree to which seawater is saturated with respect to the carbonate mineral aragonite, where $\Omega_A$ values above 1 indicate supersaturated conditions. $\Omega_A$ is often used as a more biologically-relevant alternative to pH because it reflects the availability of the carbonate ion ($CO_3^{2-}$) building blocks which calcifying organisms need in order to construct their calcium carbonate ($CaCO_3$) shells and skeletons. Greater values of $\Omega_A$ correspond to higher $CO_3^{2-}$concentrations and thus favor the growth of corals, crustose coralline algae (CCA), and other reef calcifiers. However, under the process of ocean acidification, with increased dissolution of carbon dioxide in seawater, the seawater pH, $\Omega_A$, and concentrations of $CO_3^{2-}$ all decrease. This makes it more difficult for corals and calcifying reef organisms to grow.

Weak interannual variability in $\Omega_A$ has been observed at Palmyra, which is largely related to the variability in ENSO. Observed $\Omega_A$ values ranged from 3.2 (2012) to 4.0 (2015 and 2010) in the South, West, and North of the island, respectively (Figure 25). No water samples for carbonate chemistry have been obtained from the lagoon. The overall highest values in $\Omega_A$ were measured during strong El Niño conditions in 2015, likely driven by the shutdown of upwelling that usually brings deep, lower-$\Omega_A$ water to the surface and by coral bleaching, which decreases the biological drawdown of $\Omega_A$ present on a healthy reef, thus causing $\Omega_A$ to rise. Conversely, $\Omega_A$ values during moderate La Niña in 2012 were much lower than those measured in 2015. $\Omega_A$ and pH values for the reef waters around Palmyra were near or slightly below the median of values observed by ESD across the U.S. Pacific Islands region since 2010 (Figure 26).

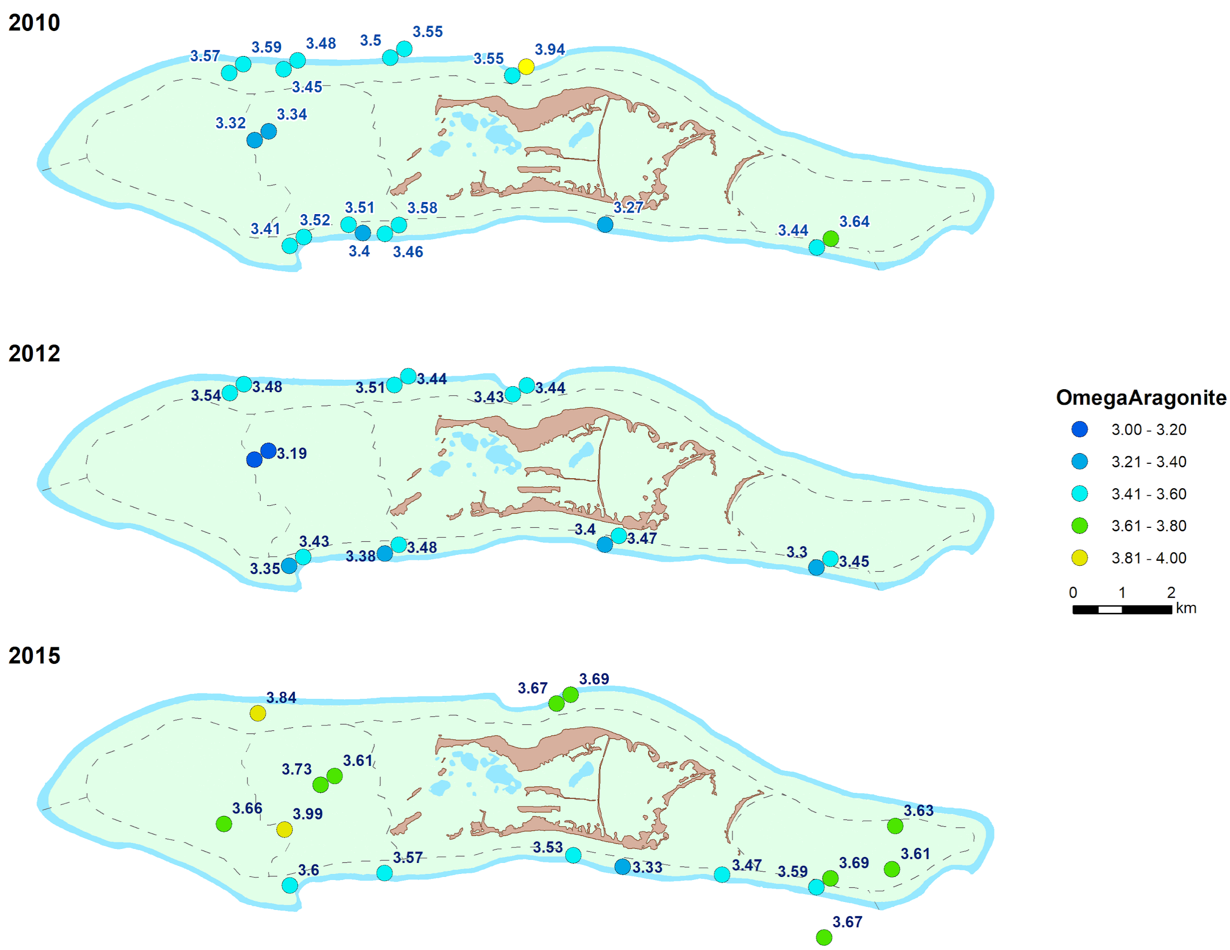



**Figure 25. Spatial distribution of aragonite saturation state ($\Omega_A$) observations during 2010, 2012, and 2015 around Palmyra Atoll.**

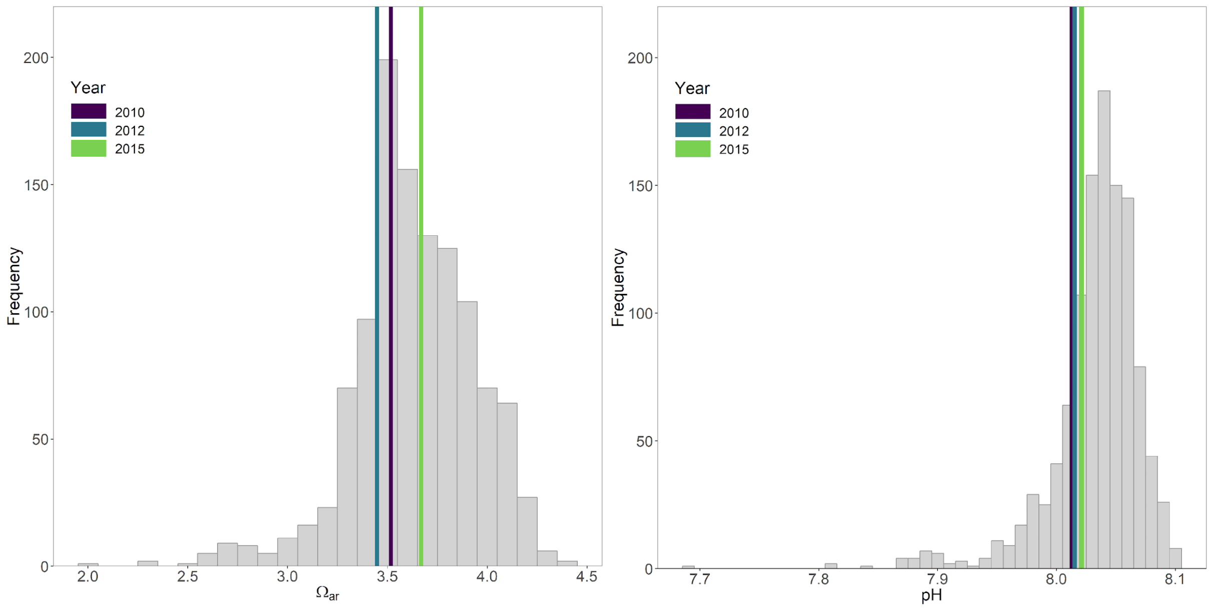



**Figure 26. Histogram of all aragonite saturation state ($\Omega_A$; left panel) and pH (right panel) values measured from discrete seawater samples collected across the U.S. Pacific Islands region from 2010 to 2017 (gray). Overlaid vertical bars show the median values for 2010 (purple), 2012 (blue), and 2015 (green) samples for Palmyra Atoll.**

## Diel Variation

The spatial and temporal patterns in carbonate chemistry observed on a coral reef are a direct result of the dynamic interplay between nearshore environmental conditions and biological processes occurring both day and night. Abiotic factors (e.g., variation in light levels, transport of water across the reef with waves, tides, and currents, and oceanographic activity like upwelling and internal wave action) interact with and influence the rate of metabolic processes (e.g., photosynthesis, respiration, calcification, and dissolution) and together alter the chemistry of the seawater that interacts with benthic communities. Some of the most dramatic changes in reef chemistry occur over the diel cycle as the result of day-to-night changes in the reef environment and shifts in biological activity. Recently, the opportunistic collection of 24-hour data through remotely deployed instrumentation has allowed us to contextualize our traditional discrete water sampling (which occurs only during daylight) with measured ranges of diel variation. These combined data sets allow for the inference of metabolic processes affecting the coral reef ecosystem.

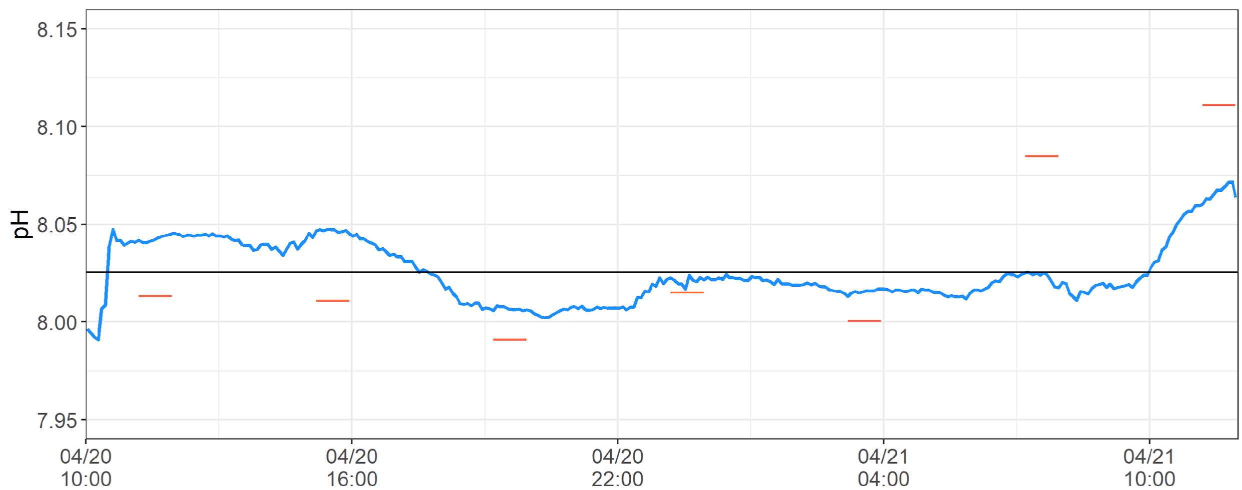



**Figure 27. Diel variability in pH over the period April 20–21, 2015 for Palmyra Atoll. Red bars represent pH observations from discrete water samples collected every 4 hours using portable underwater collectors. The blue line represents a continuous observation of pH collected using an ocean pH sensor, and the black line shows the mean of the continuous pH measurements.**

We measured temporal changes in seawater pH, driven by variability in reef metabolic processes, with a continuously monitoring pH sensor and discrete seawater pH samples collected every 4 hours by portable underwater collectors (PUCs) on April 20–21, 2015 (Figure 27). Discrete carbonate chemistry samples generally produce more reliable estimates of pH than those measured by instruments, and data from water samples can be used to calculate other carbonate parameters that paint a more complete picture of the nearshore environment and coral reef health (e.g., $\Omega_A$, $pCO_2$). However, instruments are able to sample much more frequently than discrete samplers. Therefore, discrete PUC samples can be used to calibrate the continuous time series captured by a pH sensor and calculate the full carbonate system chemistry. Values of pH from the continuous pH instrument time series and those calculated from discrete PUC water samples were reasonably close in value and captured the same overall patterns in the diel cycle at Palmyra. However, water samples and instrument data diverged toward the end of the deployment, with the pH sensor underestimating the increase in pH that occurred around 7 a.m. on April 21. This discrepancy is likely due to instrument error.

The diel pH time series demonstrates that photosynthesis was a dominant process occurring during daylight hours, raising pH by removing $CO_2$ from the seawater. Respiration then dominated at night and into the early morning, leading to a temporary decrease in pH as $CO_2$ was added back into the water. As photosynthesis rates increased the next morning, pH rose again, reaching levels slightly higher than the previous day by the end of data collection at noon. The particularly high pH water measured in the morning of April 21 could also reflect the tidal outflow of high-pH lagoon water over the forereef.

## Net Carbonate Accretion

Calcification accretion units (CAUs) are simple, two-plate fouling structures that are deployed for 2–3 years and then analyzed for the total weight of $CaCO_3$ accreted by the calcareous organisms that recruit to the plates (largely, CCA and hard corals). CAUs provide an assessment of the net rate of $CaCO_3$ formation that results from the competing processes of carbonate precipitation by calcifying organisms and the removal of material by physical (e.g., strong waves) and/or biological (e.g., parrotfish, burrowing bivalves) erosion. $CaCO_3$ accretion is essential for reefs because it builds the structural framework for coral reef ecosystems and provides essential habitat for reef organisms. However, accretion rates are strongly influenced by nearshore environmental conditions. In particular, calcification rates of corals and CCA are sensitive to changes in carbonate chemistry and decrease with decreasing pH and $\Omega_A$ (Pandolfi et al. 2011). Refer to "Chapter 1: Overview" for CAU design specifics and deployment methodologies.

CAUs were deployed from 2010 to 2012 and from 2012 to 2015 around Palmyra to assess spatial and temporal variability in accretion. Significant spatial differences in carbonate accretion rates were consistently observed during both deployment periods. Higher accretion rates typically occurred in the west, southwest, and southeast (Figure 28), areas where relatively high $\Omega_A$ levels favor calcification (Figure 25). The highest accretion rate was observed at the southwest of the entrance channel into Palmyra Lagoon over the period 2010–2012 and the northwestern reef slope over the period 2012–2015, while the lowest carbonate accretion rate was observed over the period 2012–2015 to the north of the atoll (Figure 29). No samples have been obtained from the Lagoon. Compared to the rest of the Pacific, accretion rates at Palmyra are higher than most surveyed sites, consistent with observations of near or above-median pH and $\Omega_A$.

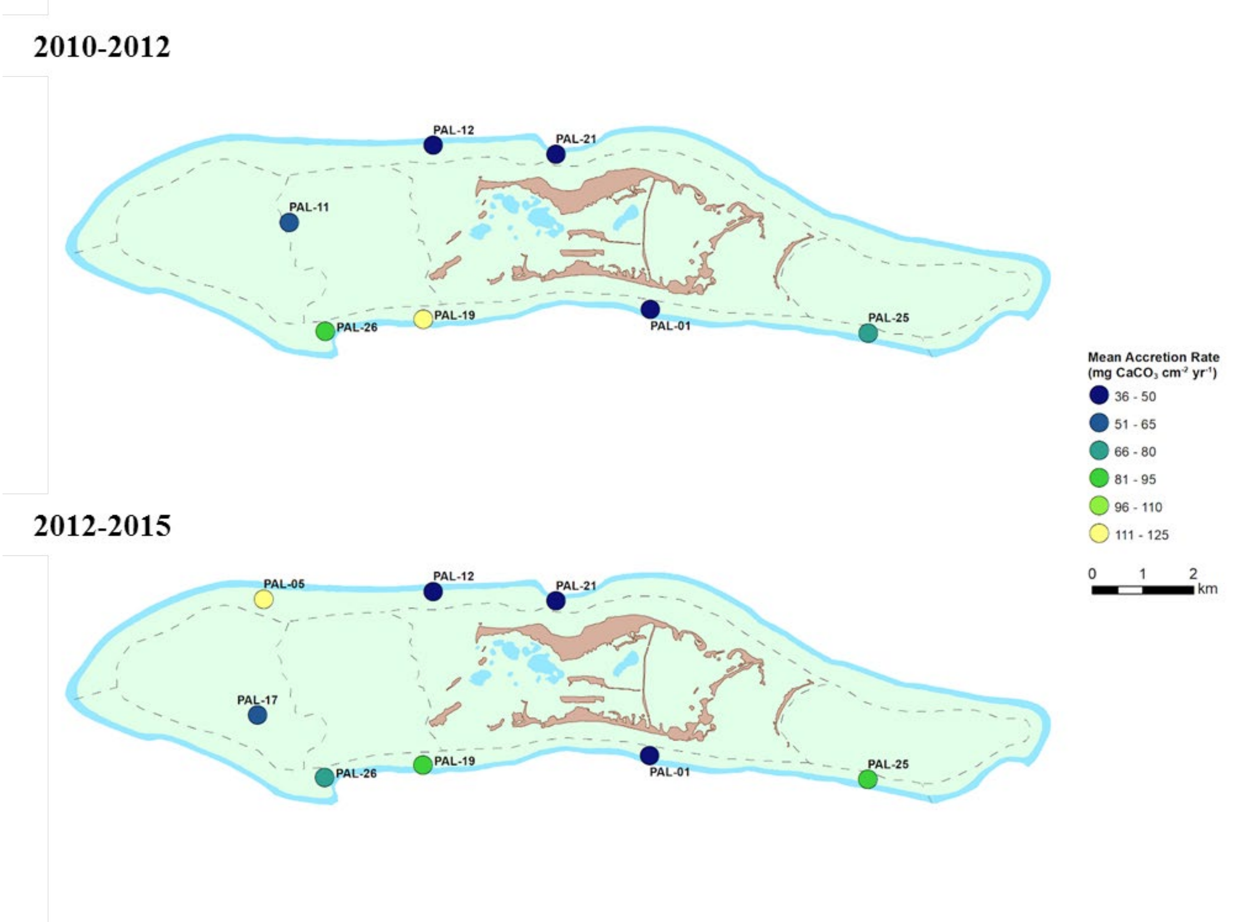



**Figure 28. Spatial distribution of mean carbonate accretion rate (mg $CaCO_3$ cm$^{-2}$ yr$^{-1}$) at Palmyra Atoll during 2010–2012 (top panel) and 2012–2015 (bottom panel). The calcification accretion units are labeled by location code.**

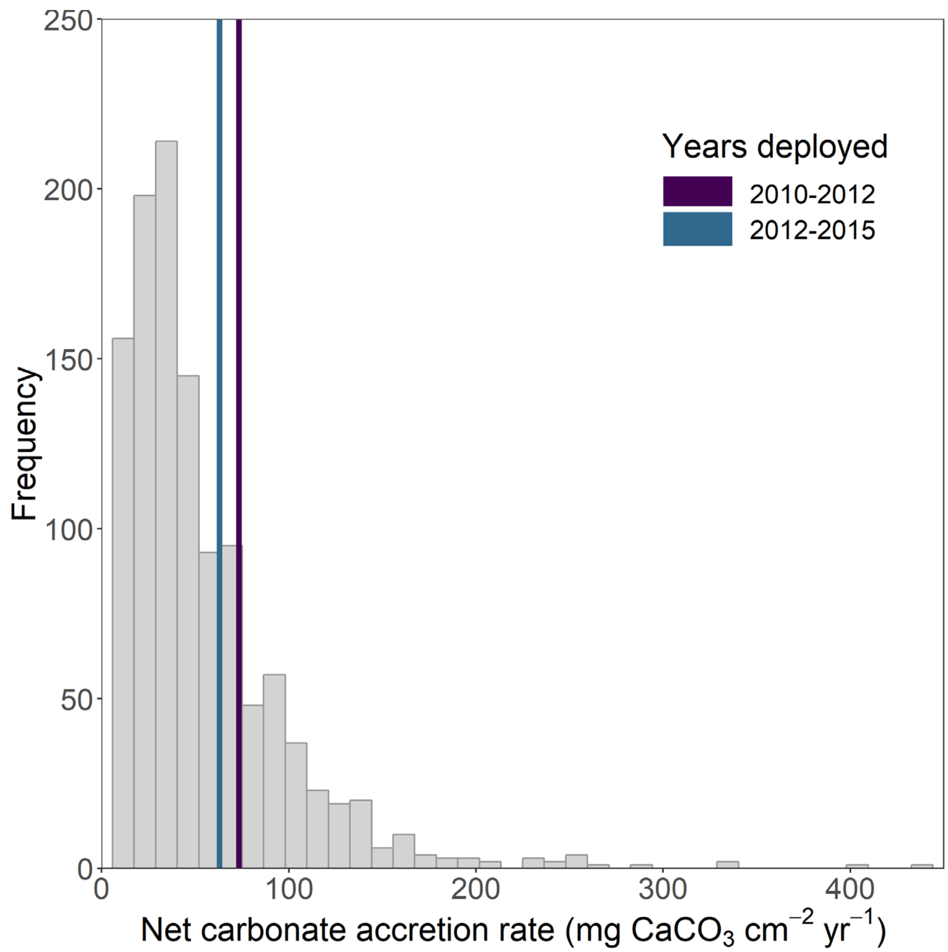



**Figure 29. Histogram of all net carbonate accretion rates (mg $CaCO_3$ cm$^{-2}$ yr$^{-1}$) measured by all calcification accretion units during the period 2010–2017 across the U.S. Pacific Islands region (gray), and median values for 2010–2012 (purple) and 2012–2015 (blue) samples for Palmyra Atoll.**

Chaetodon auriga *in the southeastern portion of the Lagoon/Backreef georegion at Palmyra Atoll. Photo: James Maragos, U.S. Fish and Wildlife Service.*

# *Coral Reef Benthic Communities*

## 2.4 Coral Reef Benthic Communities

*A juvenile humbug damselfish seeking a shelter within the branches of a Staghorn coral (*Acropora *spp.)*
*Photo: NOAA Fisheries.*

### Survey Effort and Site Information

To characterize benthic habitats and the coral populations around Palmyra Atoll, data were collected using Rapid Ecological Assessment (REA) surveys and towed-diver surveys (TDS) during eight survey efforts conducted between 2001 and 2015 (Table). REA surveys at Palmyra were primarily performed at repeat sites at mid-depth (>6–18 m) until 2015, when a stratified random sampling (StRS) design was adopted to generate more statistically-robust island-scale estimates of coral reef benthic communities. The use of a StRS study design allowed for an allocation of survey effort across multiple depth strata (shallow: >0–6 m; mid: >6–18 m; and deep: >18–30 m). The stratified-random sites were more widely and evenly distributed around the island than the former repeat sites (Figure 30). Benthic REA surveys implemented the line-point-intercept method (LPI) from 2006 through 2012 and the photoquadrat method in 2015 to estimate percent cover of benthic communities. Photoquadrat surveys were also conducted at fish

REA sites in 2015, yielding a significantly greater sample size to determine benthic cover. The belt-transect (BLT) method was used from 2004 through 2015 to estimate the abundance, distribution, condition, and diversity of the coral populations (with progressive updates to the methods detailed in “Chapter 1: Overview”). Benthic TDS were conducted primarily around the island perimeter at predominantly mid-depth forereef habitats to estimate the percent cover of benthic functional groups, the density of ecologically- or economically-important macroinvertebrates, and occurrences of potentially significant ecological events, such as widespread bleaching, outbreaks of disease, and abundance of invasive or nuisance species.

**Table 3. The total number of Rapid Ecological Assessment (REA) sites and towed-diver survey (TDS) segments completed by year and strata (if applicable) at Palmyra Atoll. Numbers in parentheses (bold) indicate the number of surveys conducted at mid-depths (>6–18 m). *Note: In 2015, REA survey methodology changed from repeat sites to stratified random sampling (StRS). StRS sites are located across three depth strata: shallow (S), mid (M), and deep (D).**

| | | **REA** | |
|---|---|---|---|
| **Year** | **TDS** | Coral Populations | Benthic Communities |
| **2001** | 73 (**64**) | - | - |
| **2002** | 111 (**100**) | - | - |
| **2004** | 192 (**148**) | (**6**) | - |
| **2006** | 174 (**123**) | (**11**) | 13 (**11**) |
| **2008** | 229 (**186**) | (**11**) | 14 (**11**) |
| **2010** | 261 (**198**) | (**12**) | 17 (**12**) |
| **2012** | 218 (**170**) | (**12**) | 15 (**12**) |
| **2015*** | 191 (**161**) | 13 (S)<br>19 (M)<br>7 (D) | 28 (S)<br>49 (M)<br>40 (D) |

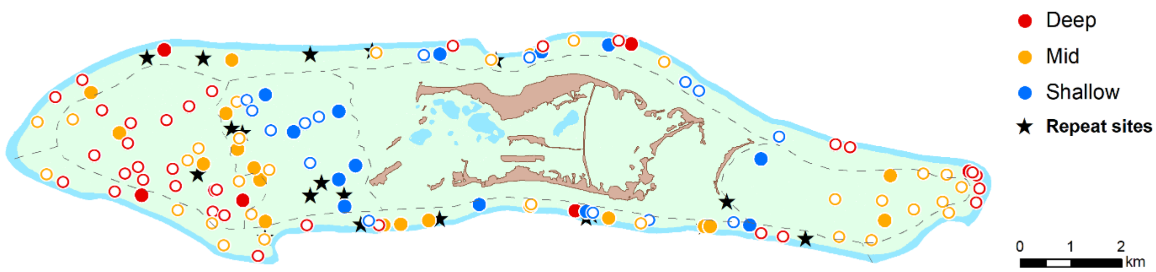



**Figure 30. Palmyra Atoll benthic Rapid Ecological Assessment survey locations. Repeat sites (stars) were sampled from 2004 through 2012 and stratified random sampling (StRS) sites were sampled in 2015 (blue, yellow, and red circles for shallow [>0–6 m], mid [>6–18 m], and deep [>18–30 m] depth strata). Photoquadrats for assessing benthic communities were collected at all StRS sites (open circle with white fill and solid circles). Coral population surveys were only conducted at sites indicated by solid circles.**

## Recent State of Benthic Cover

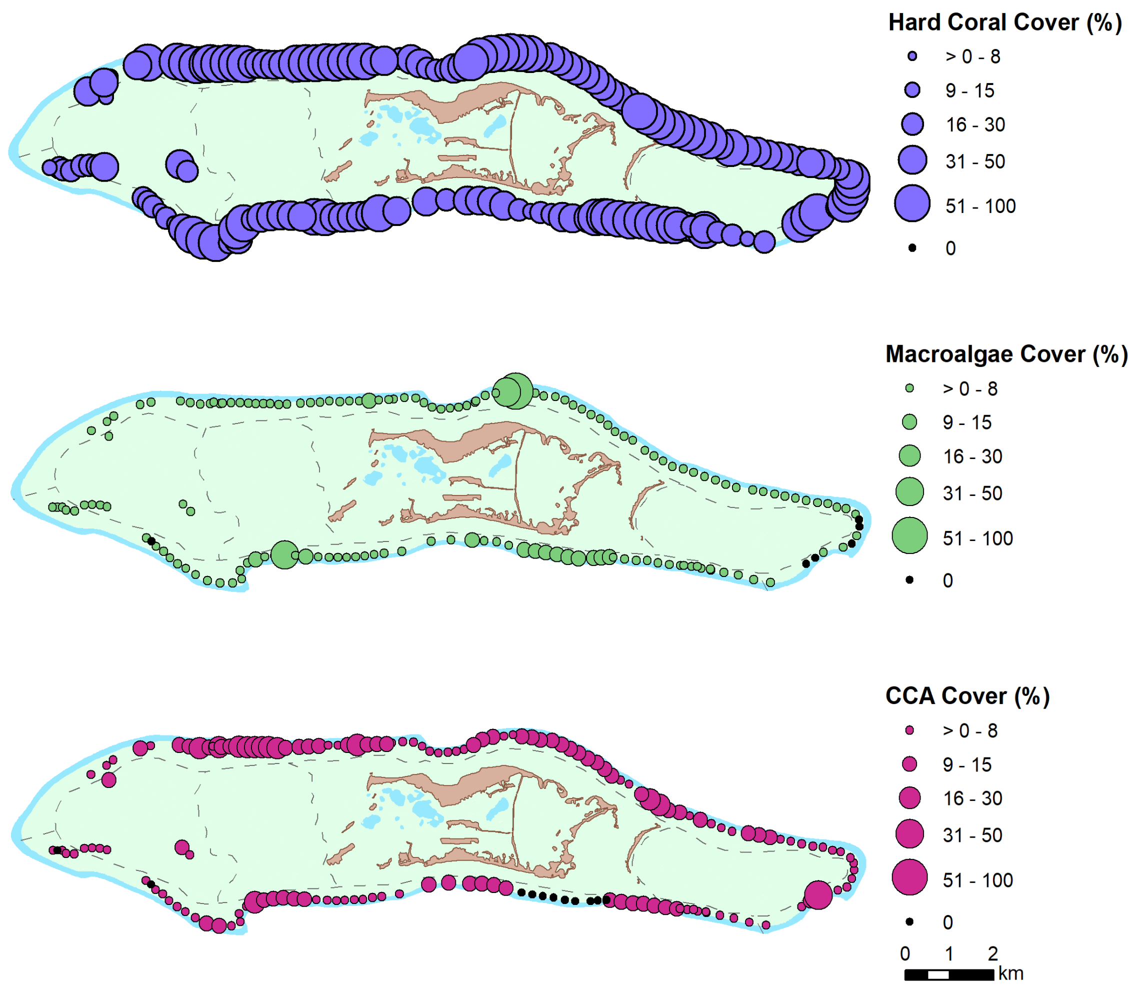



**Figure 31. Visual estimates and spatial distribution of mid-depth (>6–18 m) hard coral, macroalgae, and crustose coralline algae (CCA) cover (%) at Palmyra Atoll from towed-diver surveys in 2015.**

While the benthic composition observed during TDS in 2015 varied spatially around Palmyra, hard coral was the dominant benthic functional group (mean = 42.7% ± 2.6 SE), followed by CCA (mean = 10.4% ± 1.4 SE), and macroalgae (including encrusting and calcified macroalgae; mean = 4.4% ± 1.1 SE; Figure 31). Hard coral ranged from 15% to 69%, with lower cover observed in the west. TDS estimates of macroalgal cover (including the calcified alga *Halimeda*) were typically between 1% and 8%; however, higher macroalgal cover (up to 56%) tended to occur adjacent to emergent land. Green macroalgae of the genus *Halimeda* has been observed to be an important algal component at Palmyra (Braun et al. 2008; Smith et al. 2016), and sites with high macroalgal cover were likely partially attributable to this macroalga. CCA cover was spatially variable, ranging from 0% to 35%. The observed absence of CCA from several consecutive tow segments along the south-facing forereef coincided with relatively high estimates of macroalgae which could have made it difficult for the moving towed diver to observe the CCA.

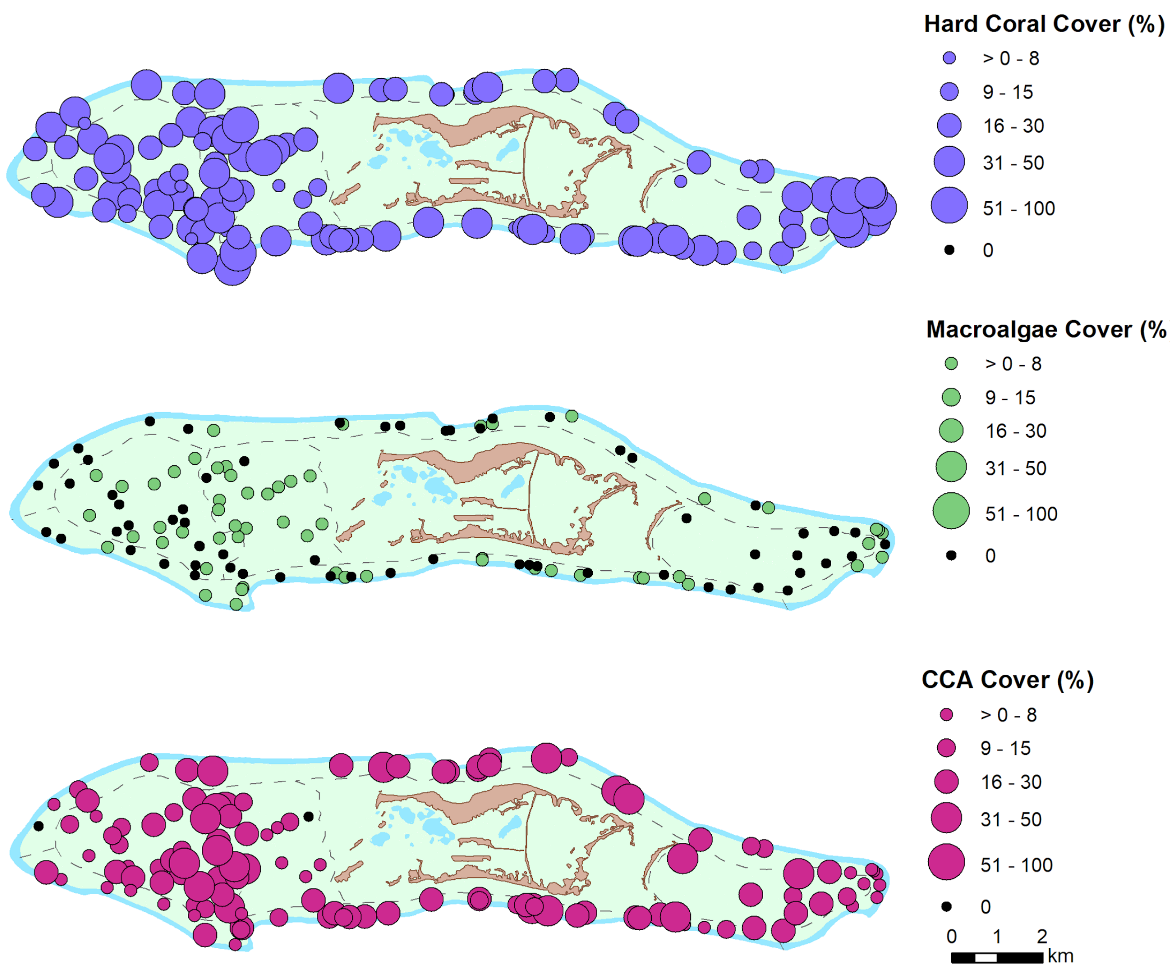



**Figure 32. Site level estimates of hard coral, fleshy macroalgae (excluding calcified and encrusting macroalgae), and crustose coralline algae (CCA) cover (%) at Palmyra Atoll from stratified random sampling photoquadrat surveys conducted at all depth strata combined (>0–30 m) in 2015.**

Cover estimates from StRS photoquadrat surveys show similar spatial patterns to the TDS, where hard coral was the dominant functional group, followed by spatially-variable CCA cover, and uniformly low macroalgal cover (Figure 32). Hard coral cover was consistently high (~15–50%) atoll-wide with some of the highest cover (>30%) concentrated on the tip of the East Terrace. Fleshy macroalgal cover (excluding calcified and encrusting macroalgae) remained consistently low across Palmyra, with no site having more than 2% cover. *Halimeda* ranged from 1% to 8% throughout most of the atoll, with a few occurrences of 9–13% cover in the southeast. CCA cover was variable among sites.

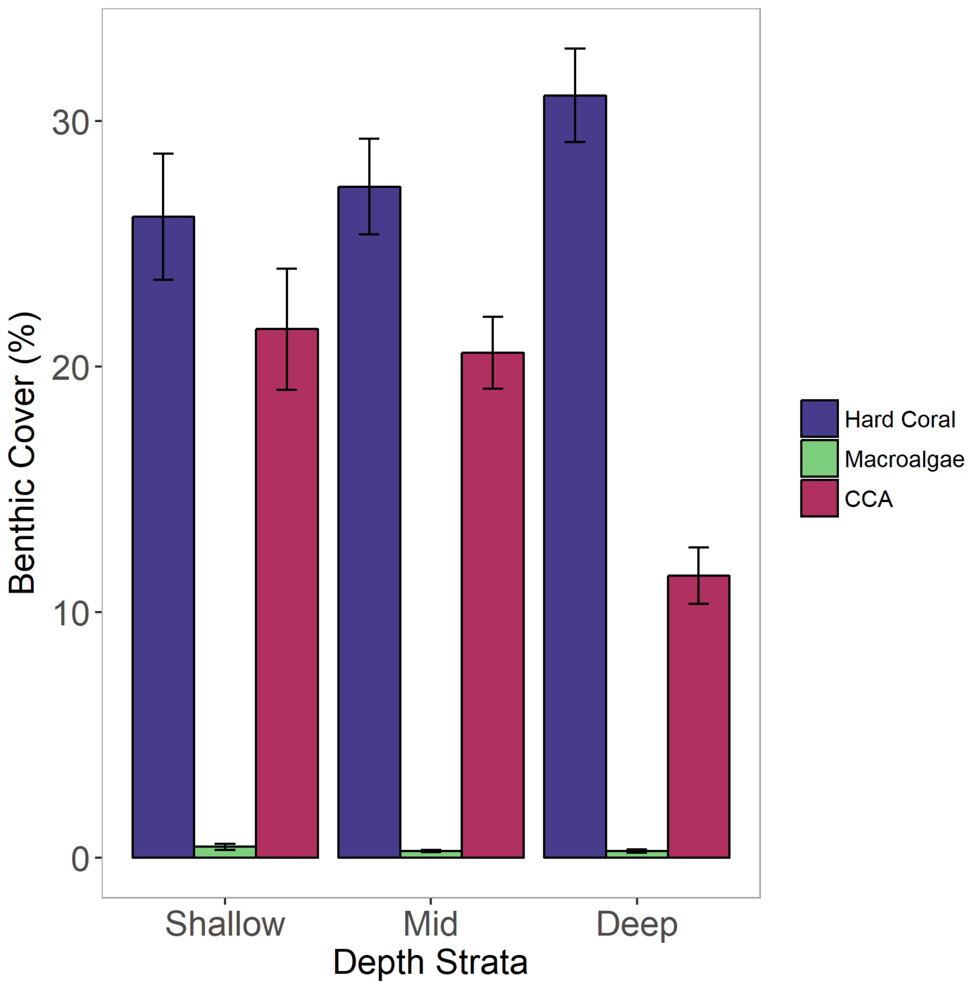



**Figure 33. Strata-level mean benthic cover (± 1 SE) at Palmyra Atoll by benthic functional groups of hard coral, fleshy macroalgae (excluding calcified and encrusting macroalgae), and crustose coralline algae (CCA) for shallow (>0–6 m), mid (>6–18 m), and deep (>18–30 m) depth strata from stratified random sampling photoquadrat surveys conducted in 2015.**

During the 2015 photoquadrat surveys at Palmyra, hard coral had higher percent cover than fleshy macroalgae (excluding calcified and encrusting) and CCA in all depth strata (Figure 33). Macroalgae had the lowest percent cover of each benthic functional group at all depths. While CCA cover was similar between shallow and mid-depth sites (mean = 21.2% ± 2.5 SE and 20.8% ± 1.6 SE, respectively), CCA cover was significantly lower at deep sites (mean = 11.3% ±

1.2 SE). Mean fleshy macroalgae cover was low across the three depth strata, with values less than 0.5%. Mean hard coral covers were slightly higher with deeper depth strata, from shallow (mean = 26.1% ± 2.6 SE) sites to deep (mean = 31% ± 2.0 SE) sites. Across depth strata, mean hard coral cover around Palmyra was among the highest observed during the 2014–2015 StRS surveys across the PRIMNM islands. Percent cover ranged from 9.5% ± 1.3 SE to 34.3% ±1.7 SE for the different islands.

## Time Series of Benthic Cover

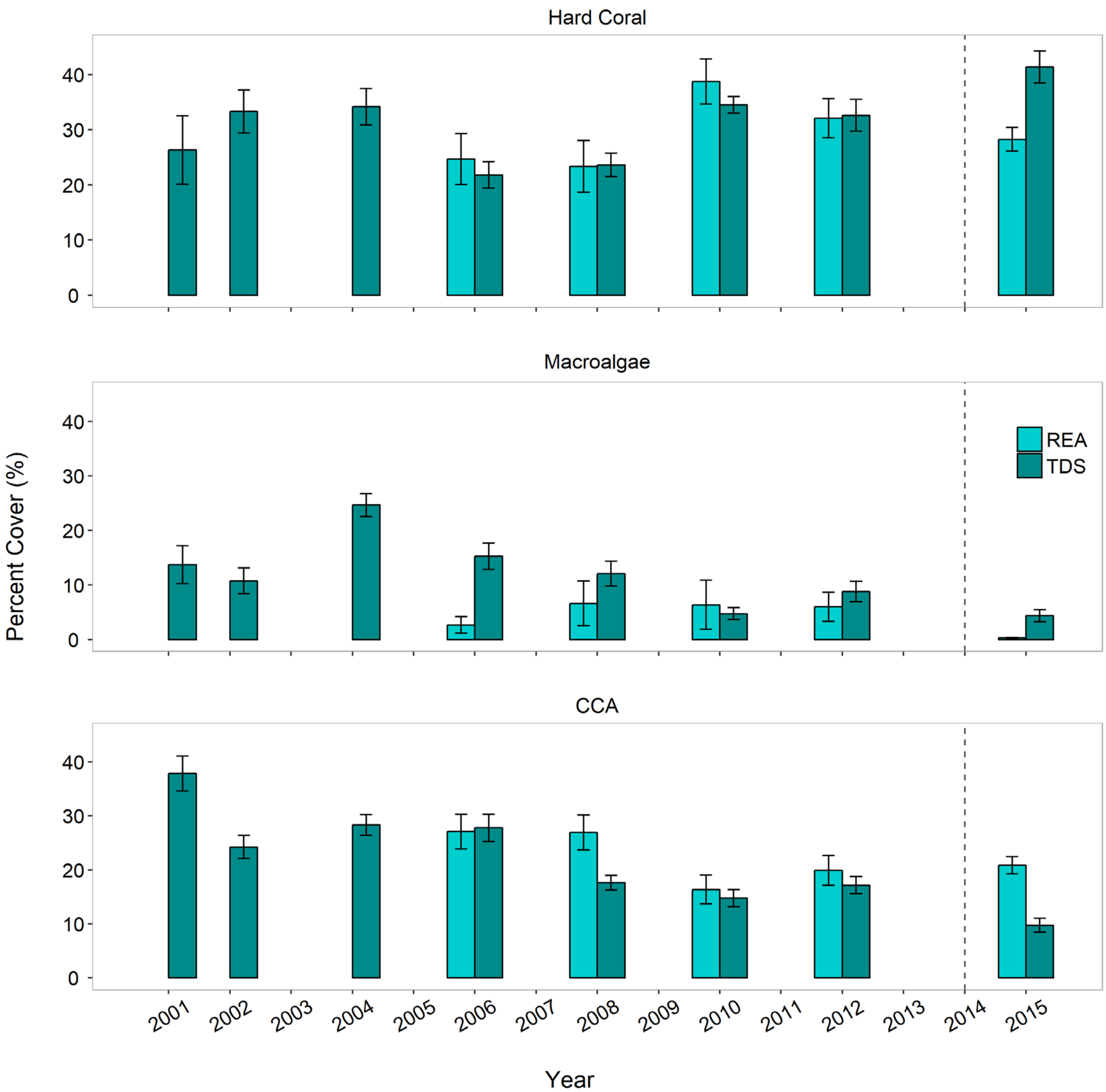



**Figure 34. Time series of mean (± 1 SE) hard coral, macroalgae, and crustose coralline algae (CCA) cover at Palmyra Atoll (%) by survey method (Rapid Ecological Assessment [REA] and towed-diver surveys [TDS]) conducted at the mid-depth stratum (>6–18 m) from 2001 through 2015. In 2014 (dashed line), REA methodology changed from line-point-intercept surveys at repeat sites to photoquadrat surveys at stratified random sampling sites. *Note: TDS macroalgae data include calcified and encrusting macroalgae; the REA macroalgae data exclude it.**

Patterns of mean coral cover were dynamic over time (2001–2015) but remained above 20% for all survey years, regardless of survey method (Figure 34). Both REA and TDS surveys observed declines in coral cover in 2006 and 2008, followed by a substantial increase in 2010. In 2015, following the implementation of the StRS survey design, REA photoquadrat methods observed substantially lower coral cover than TDS. These latter differences likely originate from the nature and spatial coverage of the surveys (TDS vs REA photoquadrat), as well as observer biases as corroborated by similar differences between methods obtained at Jarvis Island and Kingman Atoll during the 2015 Pacific RAMP expedition. Attribution of the above-mentioned patterns is difficult to ascertain due to the 2–3 year intervals between Pacific RAMP surveys. However, cool thermal anomalies reported during La Niña events in 2005, 2007, and 2010 could explain the temporal coral cover declines observed at Palmyra in the survey years following these thermal events.

Atoll-wide, CCA cover decreased over time with both REA and TDS methods. The two methods generated similar estimates of CCA cover, with the exception of 2008 and 2015, when REA observed greater CCA cover than TDS (Figure 34). Fleshy macroalgal cover observed during REA surveys was consistently low over time. TDS, which included fleshy macroalgae and calcified and encrusting macroalgae, unsurprisingly exceeded the REA means due to this methodological difference. In recent survey years, both TDS and REA methods observed very low cover of macroalgae (Figure 34).

Figure 35a illustrates the spatial synthesis of mean coral cover averaged across all survey years (2001–2015) and methods (i.e., TDS, LPI, and StRS photoquadrats). Across all survey years, hard coral cover has remained stable and high (>30%) along the Northeast, Northwest, Southeast, and West Terrace and somewhat lower (<20%) in the Inside and East terraces (Figure 35b). The extensive dredging, land build up, and permanent alterations to Palmyra’s Lagoon hydrodynamic flow patterns that took place during the U.S. WWII Pacific Campaign are likely attributable to the lower coral cover patterns near the shallow terraces. Coral cover decadal trend analysis (Figure 35c) shows discrete increases occurred along the eastern, northwestern, and southwestern facing forereef habitats, and decreases along the West Terrace.

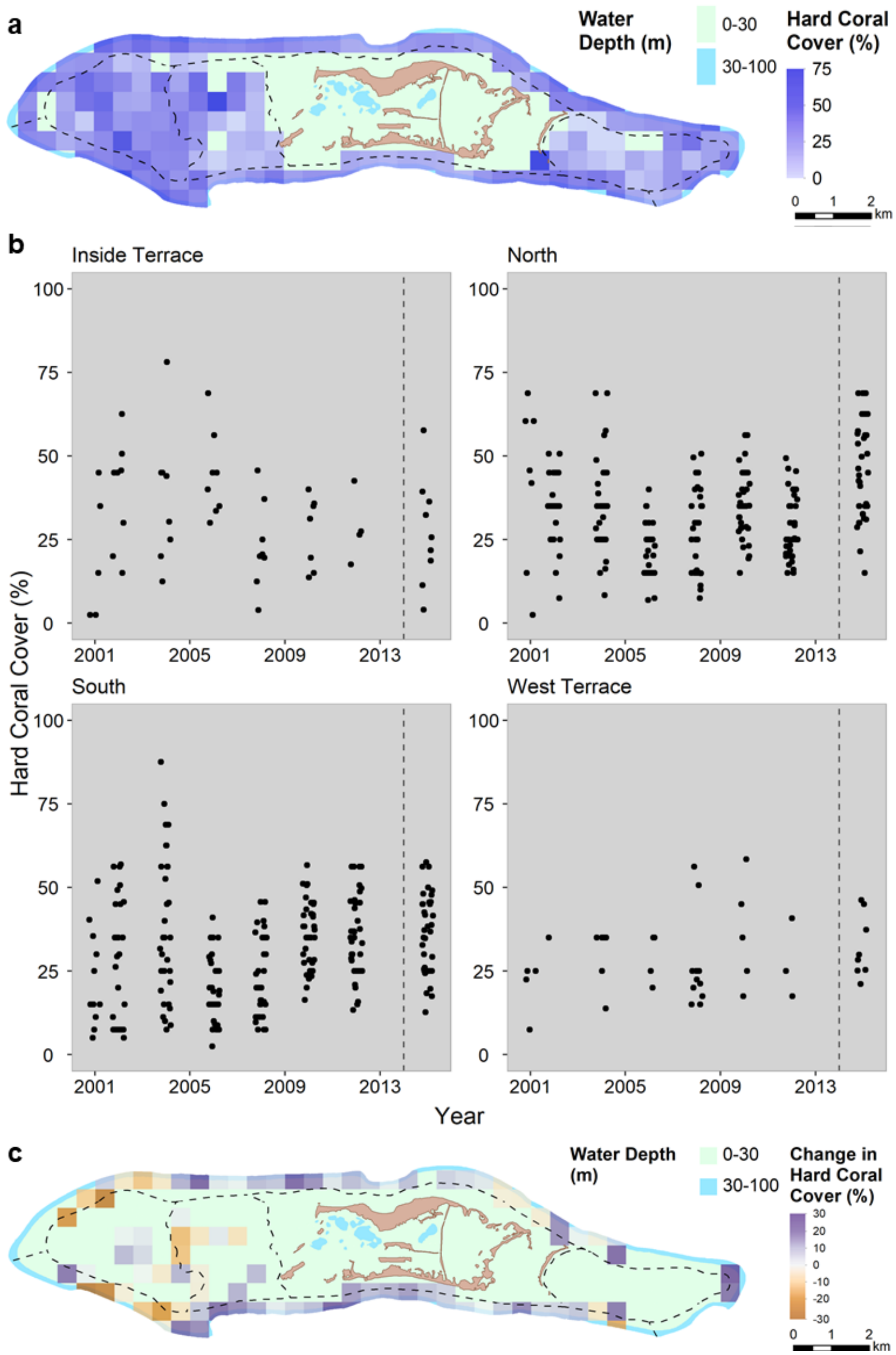



**Figure 35. Spatial patterns and temporal trends of gridded (500 m × 500 m) mean coral cover at Palmyra Atoll across survey years (2005–2015) and methods (towed-diver surveys, line-point-intercept (LPI), and stratified random sampling (StRS) benthic and fish photoquadrats). (a) Mean hard coral cover per 500 m by 500 m grid cell across all survey years; (b) temporal change in hard coral cover per 500 m by 500 m grid cell, only including cells with at least a 10-year span of data and at least 3 observation years; and (c) time series of hard coral cover by georegion. In 2014 (dashed line), Rapid Ecological Assessment survey methodology changed from LPI at repeat sites to photoquadrat surveys at StRS sites. See Survey Methods for Coral Reef Benthic Communities in "Chapter 1: Overview" for further details.**

### Time Series of Algal Disease

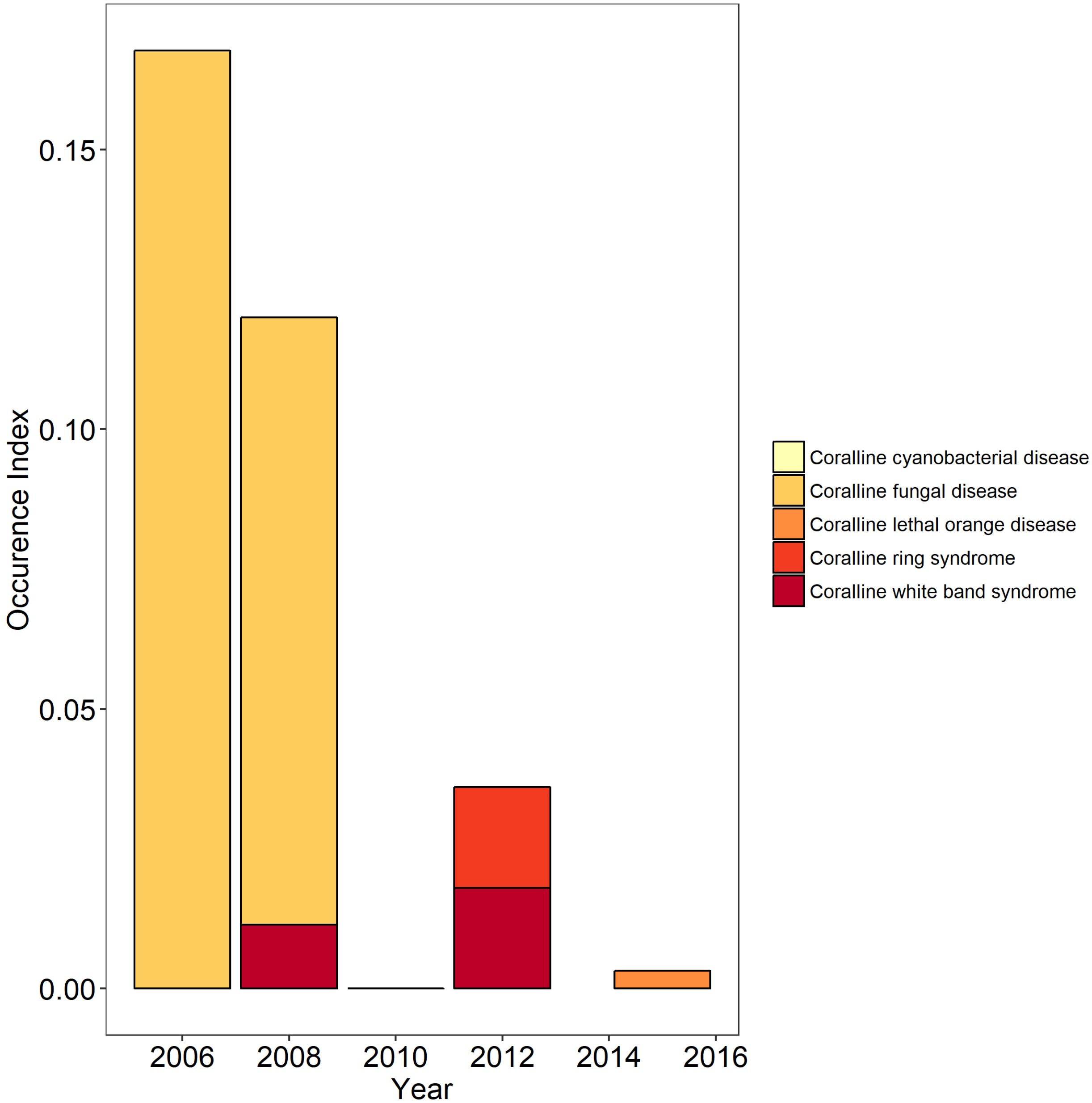



**Figure 36. Time series of crustose coralline algae disease occurrences at Palmyra Atoll for all depth strata combined (>0–30 m) from Rapid Ecological Assessment belt-transect surveys conducted from 2006 through 2015.**

CCA disease occurrence index is the proportion of the number of disease cases relative to the CCA percent cover. Values close to or greater than one suggest high disease occurrence; comparatively, numbers close to zero indicate low occurrence. CCA disease occurrence was variable over time, with a decreasing trend from 2006 to 2015 (Figure 36). In 2006 and congruent with other observations reported throughout the PRIMNM islands and American Samoa (Vargas-Ángel 2010), the occurrence of disease at Palmyra was notably higher, although only one type of disease was observed: coralline fungal disease (0.17). This disease decreased somewhat in 2008 (0.12) and was reported absent in 2010 and all subsequent survey years. Notably, changes in the occurrence of the CCA diseases between 2008 and 2010 were concomitant with a nearly 40% reduction in the cover of CCA (Figure 34). No CCA diseases were reported in 2010, but the occurrence of coralline white band syndrome increased slightly from 2008 to 2012, and coralline ring syndrome was only observed in 2012. In 2015, coralline lethal orange disease (CLOD) was the only disease observed; this was the only instance of CLOD presence at Palmyra over the period from 2006 to 2015. Coralline cyanobacterial disease has not been reported since the inception of CCA disease surveys in 2006.

## Recent Coral Abundance

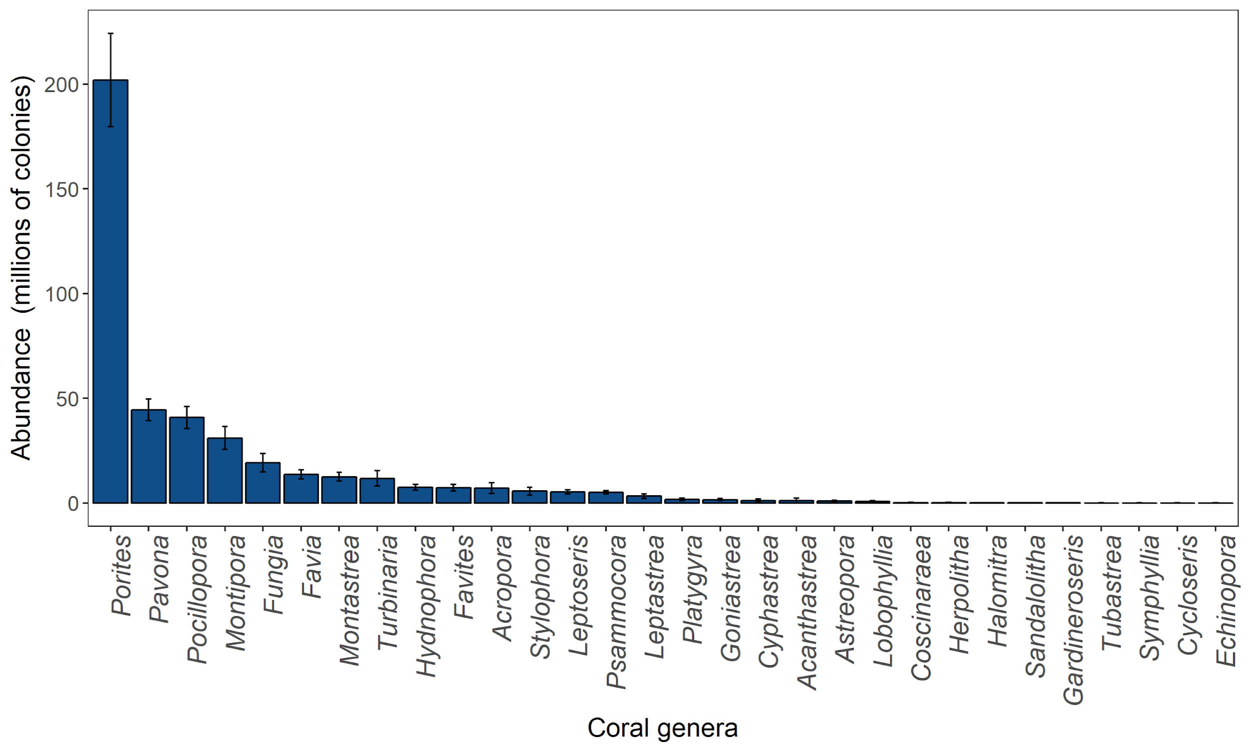



**Figure 37. Island-scale abundance (± 1 SE) estimates by coral genera for all depth strata combined (>0–30 m) at Palmyra Atoll from Rapid Ecological Assessment belt-transect surveys conducted in 2015.**

Island-scale abundance estimates for coral genera were extrapolated from the REA transect colony densities over the area of hard bottom habitat found in the survey strata (0–30 m). In terms of coral colony abundance across all three depth strata, *Porites* was the dominant genus observed at Palmyra in 2015*,* which had four times more colonies than the next most numerous genus *Pavona* (Figure 37). Of the 30 genera recorded, *Echinopora* was the least abundant.

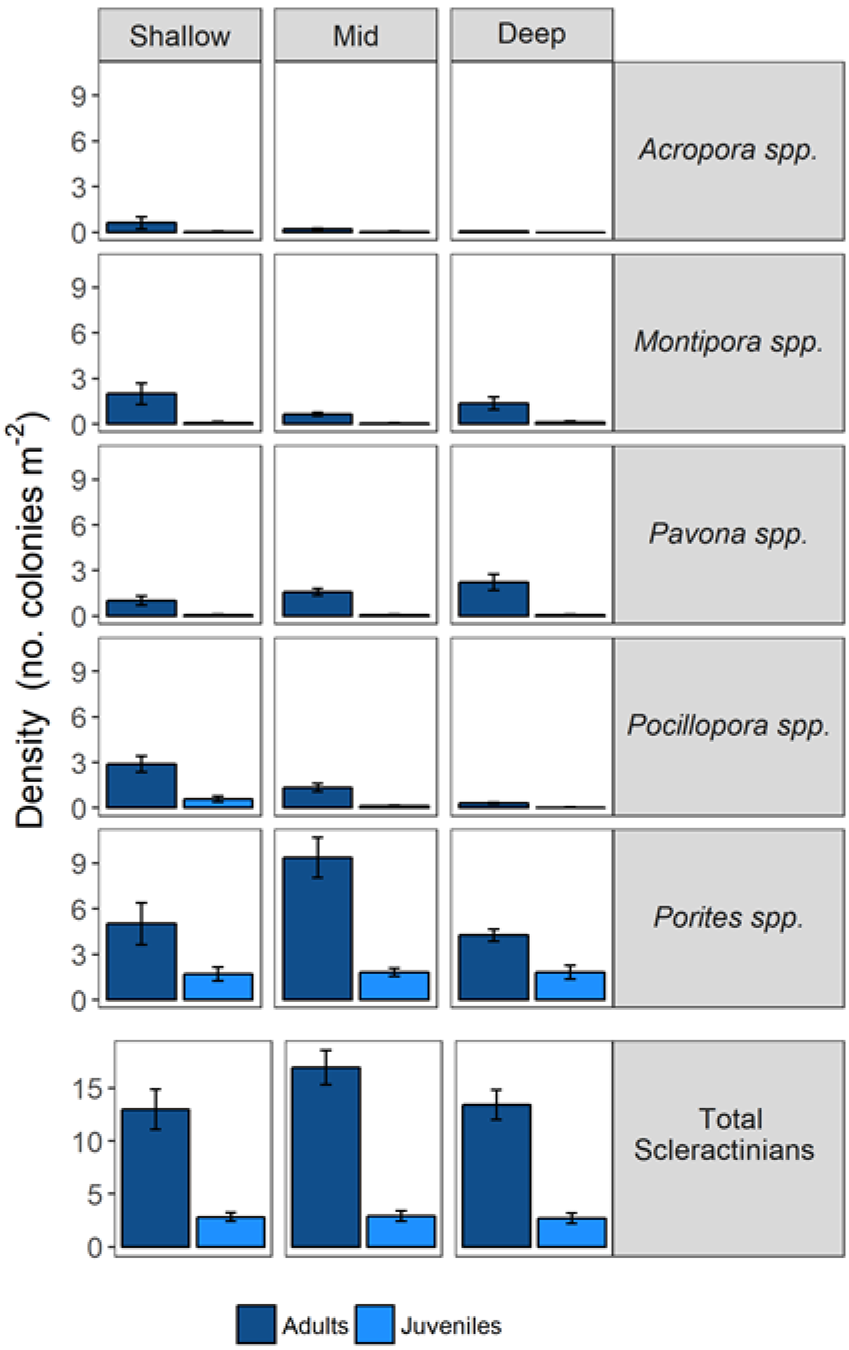



**Figure 38. Mean (± 1 SE) adult and juvenile colony density from Rapid Ecological Assessment surveys conducted at Palmyra Atoll in 2015 for shallow (>0–6 m), mid (>6–18 m), and deep (>18–30 m) depth strata for five coral genera abundant in the Pacific Remote Islands Marine National Monument (*Acropora* spp., *Montipora* spp., *Pavona* spp., *Pocillopora* spp., and *Porites* spp.) to facilitate comparison among islands.**

Adult colonies (>5 cm) dominated the coral community at Palmyra, irrespective of genus and depth, while juveniles (colonies <5 cm) comprised about 15–20% of the coral population (Figure 38). For the rest of the PRIMNM islands surveyed in the 2014–2015 period, juvenile colonies represented approximately 10–50% of the coral population. Juvenile abundance can be indicative of strong coral recruitment, an attribute associated with high reef resilience (McClanahan et al. 2012). For all genera combined, the population density of adults was highest at mid-depth sites (mean = 17 colonies/$m^2$ ± 1.6 SE), while juvenile densities were similar across depths. This trend was largely driven by high *Porites* colony densities at mid-depths, since this taxon exhibited the highest density of adult coral colonies across taxa and depth strata. Mean density of juvenile *Porites* colonies was similar across the depth strata, with a narrow range from deep (mean = 1.8 colonies/$m^2$ ± 0.4 SE) to shallow sites (mean = 1.7 colonies/$m^2$ ± 0.4 SE).

The higher mean density of *Porites* in the mid-depth stratum may be due to decreased competition from faster-growing genera such as *Pocillopora, Montipora,* and *Acropora* that thrive in shallow, well-lit habitats. *Pocillopora* adults and juveniles had highest colony densities at shallow depths (mean = 2.9 colonies/$m^2$ ± 0.5 SE and 0.6 colonies/$m^2$ ± 0.2 SE, respectively). *Montipora* had the highest colony density in the shallow depth strata for both adults (mean = 2.0 colonies/$m^2$ ± 0.7 SE) and juveniles (mean = 0.09 colonies/$m^2$ ± 0.06 SE). Of these five common genera, *Acropora* had the lowest colony density at Palmyra. Adult *Acropora* had the highest colony density in the shallow depth strata (mean = 0.6 colonies/$m^2$ ± 0.4 SE), while juveniles had the highest colony density in the mid-depth strata (mean = 0.4 colonies/$m^2$ ± 0.4 SE). The highest colony density of *Pavona* adults was in the deep depth strata (mean = 2.2 colonies/$m^2$ ± 0.5 SE), whereas *Pavona* juveniles had higher colony density in the mid-depth strata (mean = 0.07 colonies/$m^2$ ± 0.04 SE).

These genus-specific differences suggest that community composition shifts across survey depths, with different species dominating along the forereef habitats around Palmyra. These shifts likely reflect different life histories of these genera, which impact their habitat range as well as competitive abilities. However, the low colony densities of coral genera at various depths may imply larger colonies are present in these areas, not necessarily that the percent cover of coral is lower.

There were two potential sightings of corals listed under the Endangered Species Act (ESA) of 1973 at Palmyra. In 2012, one *Isopora crateriformis* colony was reported in the Inside Terrace and in 2015; one *Pavona* cf. *diffluens* was reported in the mid-depth strata within the East Terrace. Neither sighting was corroborated by photographs or voucher specimens. NOAA Fisheries recognizes *P. diffluens* as a species that is limited to the Indian Ocean and listed as Threatened under the ESA. NOAA Fisheries considers colonies resembling *P. diffluens* in the Pacific Ocean to be a different, currently undescribed species of *Pavona* (National Oceanic and Atmospheric Administration 2005). A table showing total generic richness of hard corals in the PRIMNM can be found in Appendix A of “Chapter 9: PRIMNM in the Pacific-wide Context.”

## Time Series of Coral Abundance and Condition

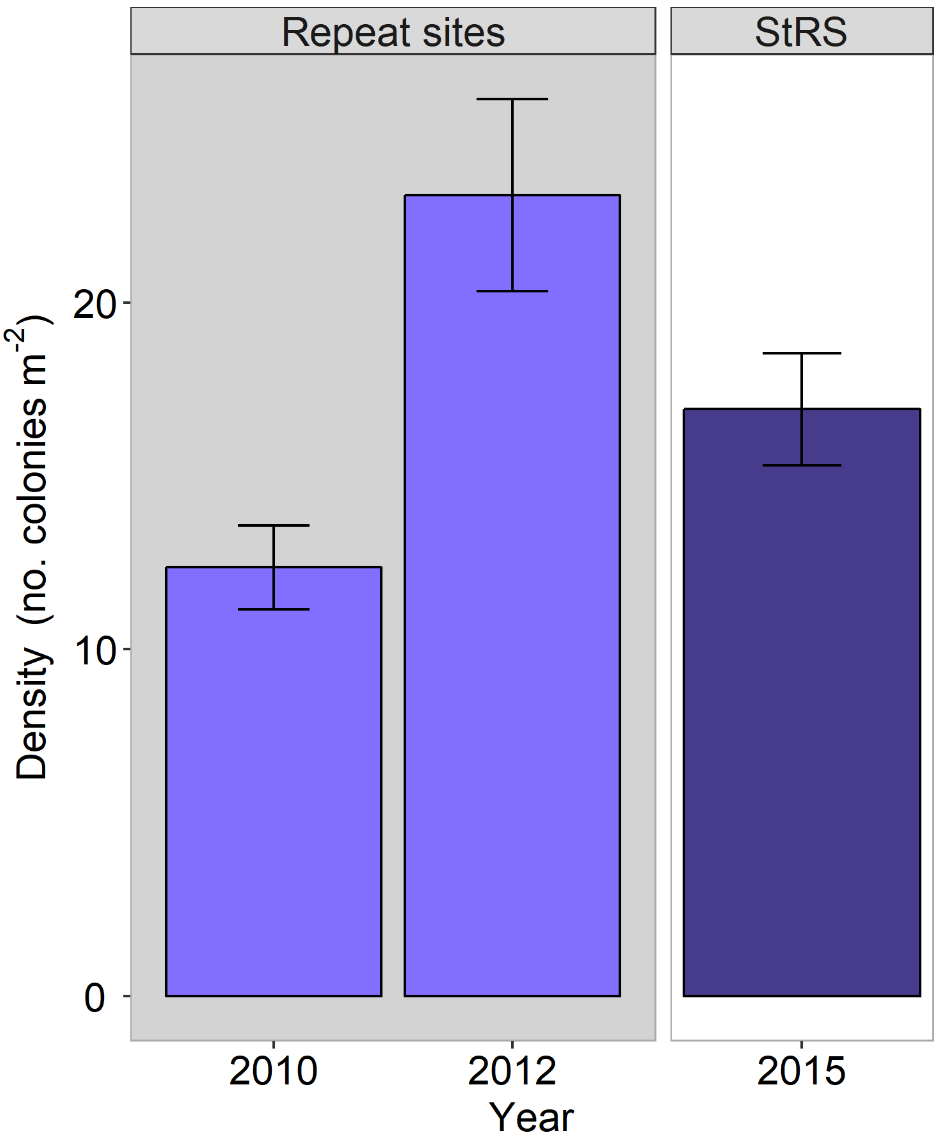



**Figure 39. Time series of mean adult colony density (± 1 SE) at Palmyra Atoll, from mid-depth (>6–18 m) strata Rapid Ecological Assessment belt-transect surveys by survey design, repeat sites or stratified random sampling (StRS), conducted from 2010 through 2015.**

Based on data collected at repeat sites, island-wide mean coral colony density increased from 2010 to 2012 (mean = 12.4 colonies/m$^2$ ± 1.2 SE and 23 colonies/m$^2$ ± 2.8 SE, respectively; Figure 39). Decrease in mean colony densities from 2012 to 2015 likely reflect the methodological updates to the protocols by which individual colonies were identified in the field. Due to inherent differences between survey designs, direct comparisons between data from repeat and random sites are inappropriate.

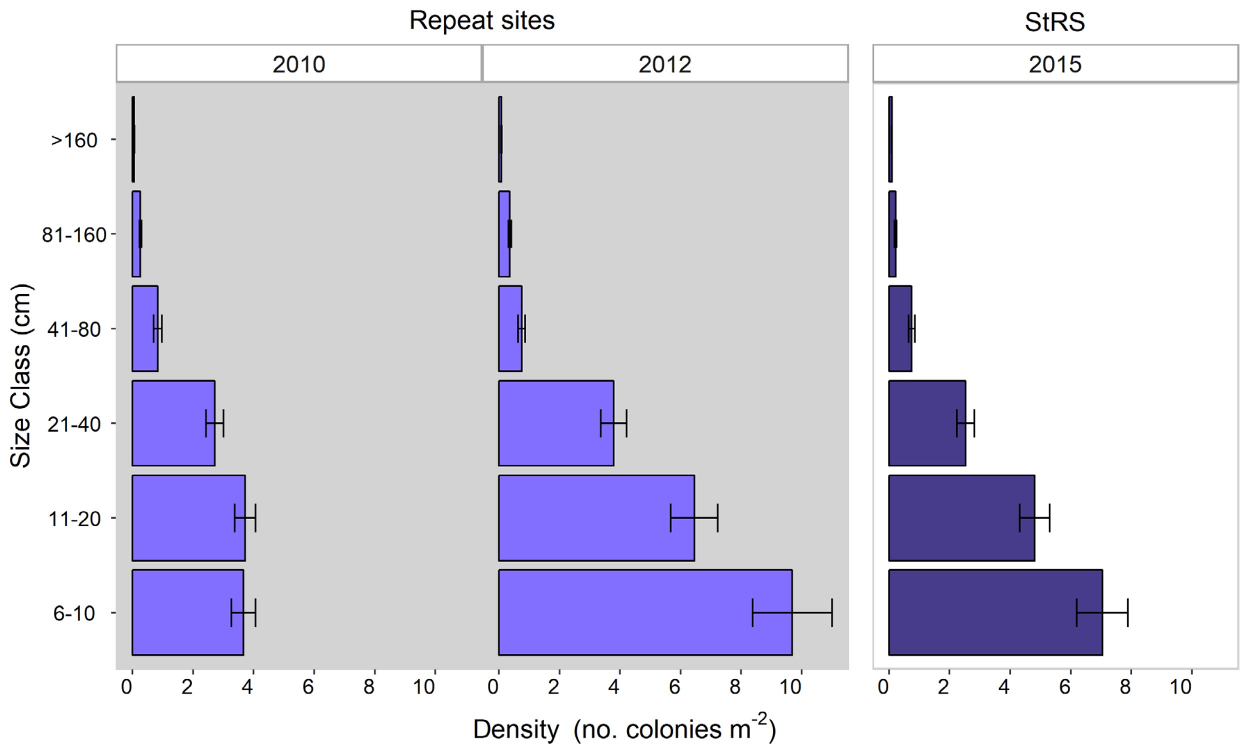



**Figure 40. Time series of mean adult colony density (± 1 SE) at Palmyra Atoll by size class from mid-depth (>6–18 m) strata Rapid Ecological Assessment belt-transect surveys by survey design, repeat sites or stratified random sampling (StRS) sites, conducted from 2010 through 2015.**

While the densities of coral colonies within the 6–10 and 11–20-cm size classes were similar in 2010, the 6–10-cm size class showed the highest colony density of all classes in both 2012 and 2015 (Figure 40). Colony density within the 6–10-cm size class more than doubled from 2010 (mean = 3.6 colonies/m$^2$ ± 0.4 SE) to 2012 (mean = 9.7 colonies/m$^2$ ± 1.3 SE), while the 11–20-cm size class also substantially increased. For each survey year, colony densities tended to decrease with size classes of increasing length.

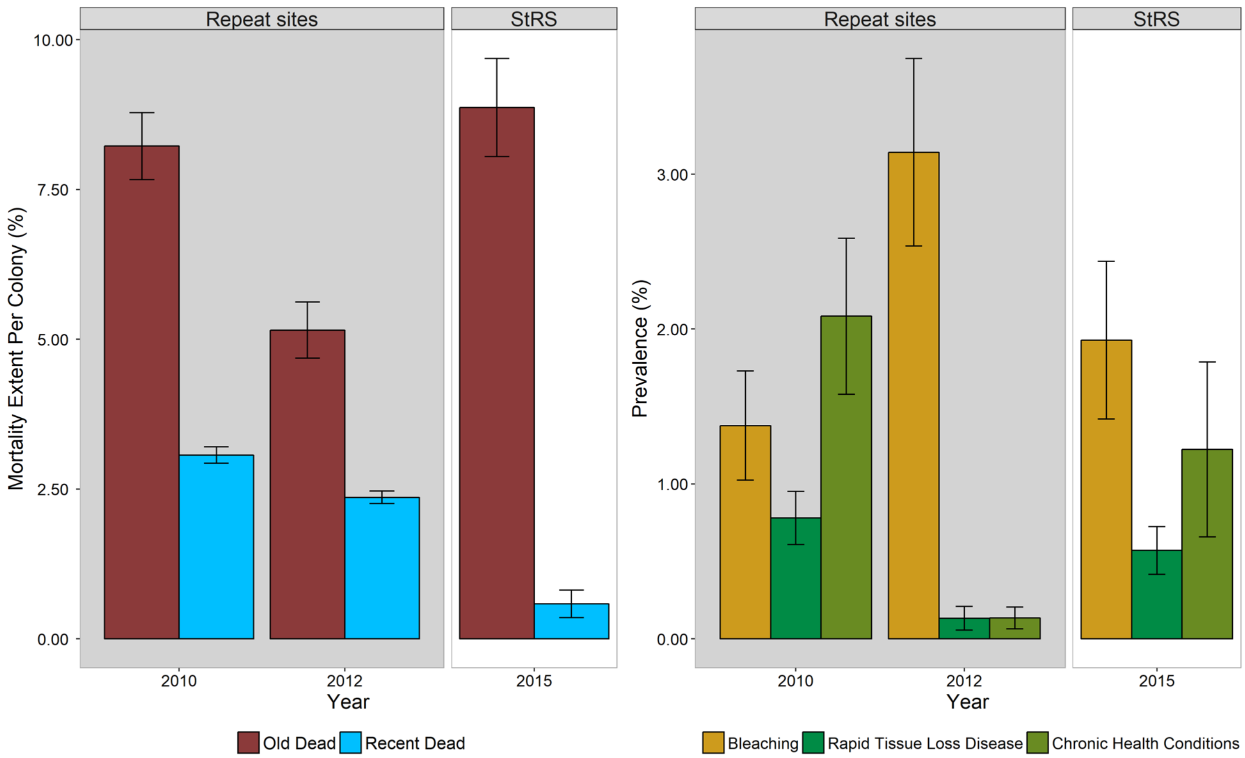



**Figure 41. Time series of mean (± 1 SE) (a) percent partial mortality and (b) prevalence of bleaching, rapid tissue loss diseases, and chronic health conditions at Palmyra Atoll based on mid-depth (>6–18 m) strata Rapid Ecological Assessment surveys by survey design, repeat sites or stratified random sampling (StRS) sites, conducted from 2010 through 2015.**

Island-wide mean percentage of both old and recent mortality decreased between 2010 and 2012, yet in the absence of active outbreak conditions, old dead remained greater than recent dead during both years (Figure 41). In 2015, the extent of old dead (mean = 8.9% ± 0.8 SE) was the highest for all years surveyed, while recent dead was the lowest (mean = 0.6% ± 0.2 SE). Mean bleaching prevalence increased from 2010 to 2012 (1.4% ± 0.4 SE and 3.1% ± 0.6 SE, respectively); but declined in 2015 (1.9% ± 0.5 SE). Despite the reported bleaching event in 2009 (Williams et al. 2010), bleaching prevalence was the lowest in 2010. Overall and across survey years, the prevalence of coral diseases was low at Palmyra. The island-wide mean prevalence of rapid tissue loss diseases decreased greatly from 2010 to 2012 (0.8% ± 0.2 SE; 0.1% ± 0.08 SE, respectively), then increased in 2015 (0.6% ± 0.2 SE), but not to levels as high as in 2010. The prevalence of chronic compromised health conditions also decreased from 2010 (mean = 2.1% ± 0.5 SE) to 2012 (mean = 0.1% ± 0.07 SE), rising slightly again in 2015 (mean = 1.2% ± 0.6 SE). While the differences in survey designs necessitate caution when interpreting differences in data between 2012 and 2015, the relatively consistent levels of coral mortality and condition suggest that coral populations at Palmyra have remained healthy and stable over time.

## Benthic Macroinvertebrates

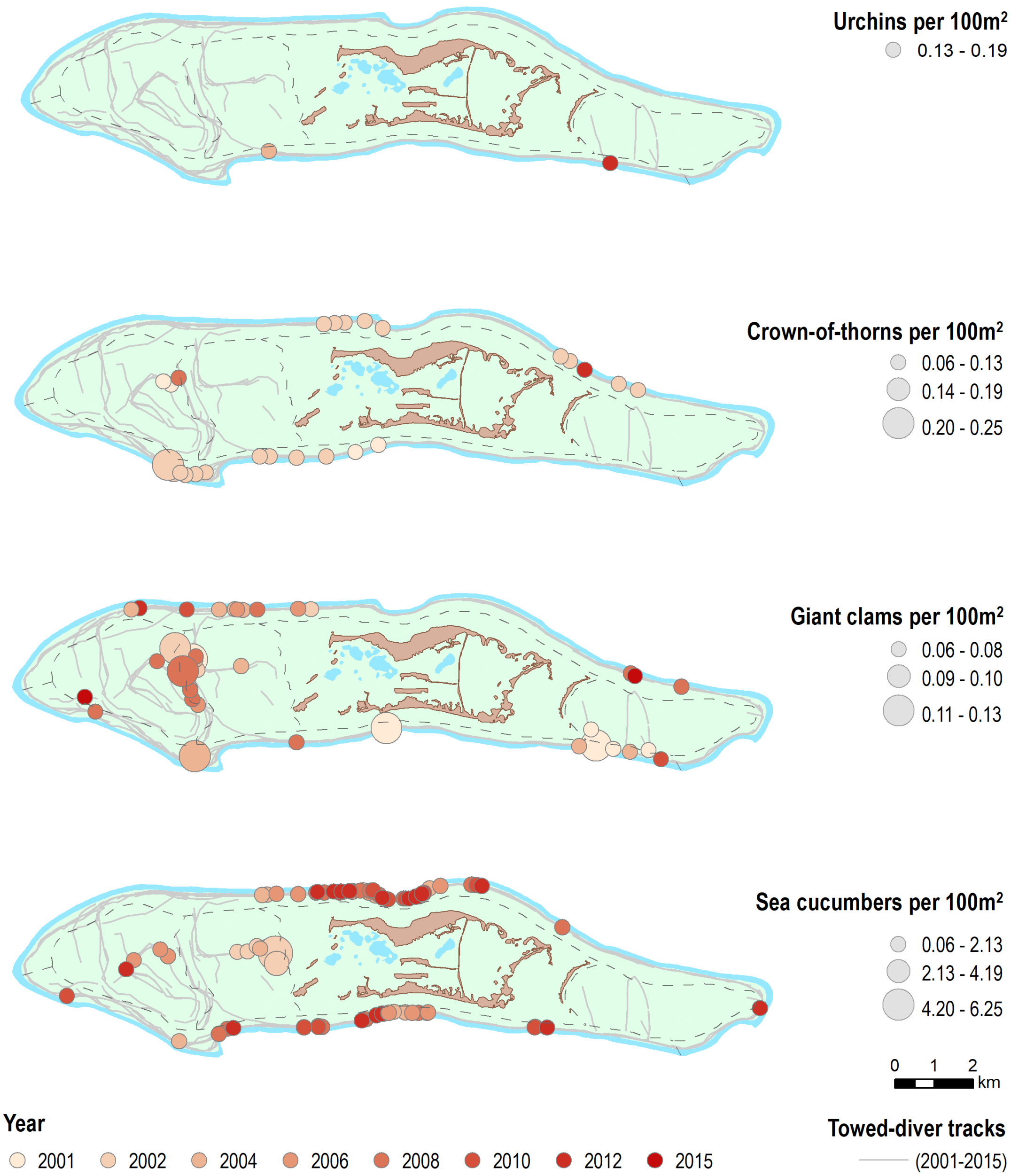



**Figure 42. Density of conspicuous ecologically or economically important macroinvertebrates (urchins, crown-of-thorns sea stars, giant clams, and sea cucumbers) observed per segment from benthic towed-diver surveys conducted throughout all depth strata (>0–30 m) around Palmyra Atoll from 2001 through 2015. Sea cucumber observations were discontinued in 2014.**

Though sea urchins were rarely spotted during TDS at Palmyra, two sightings occurred in the South georegion; one in 2004 and one in 2012 (Figure 42). The lack of urchins recorded is likely due to their cryptic nature in association with the high densities of other sessile organisms.

The densities of crown-of-thorns sea star (COTS) were variable throughout the study period 2001–2015. COTS sightings peaked in 2002 when they were observed during multiple segments along the southwest, north, and northeast forereefs and were observed at near-outbreak level (TDS COTS outbreak densities ≥1,500 indiv/km$^2$; (Moran et al. 1992) during a single tow segment in the southwest forereef. Comparatively fewer individuals were recorded in 2001, 2008, and 2012, and none were recorded in 2004, 2006, 2010, and 2015 (Figure 42).

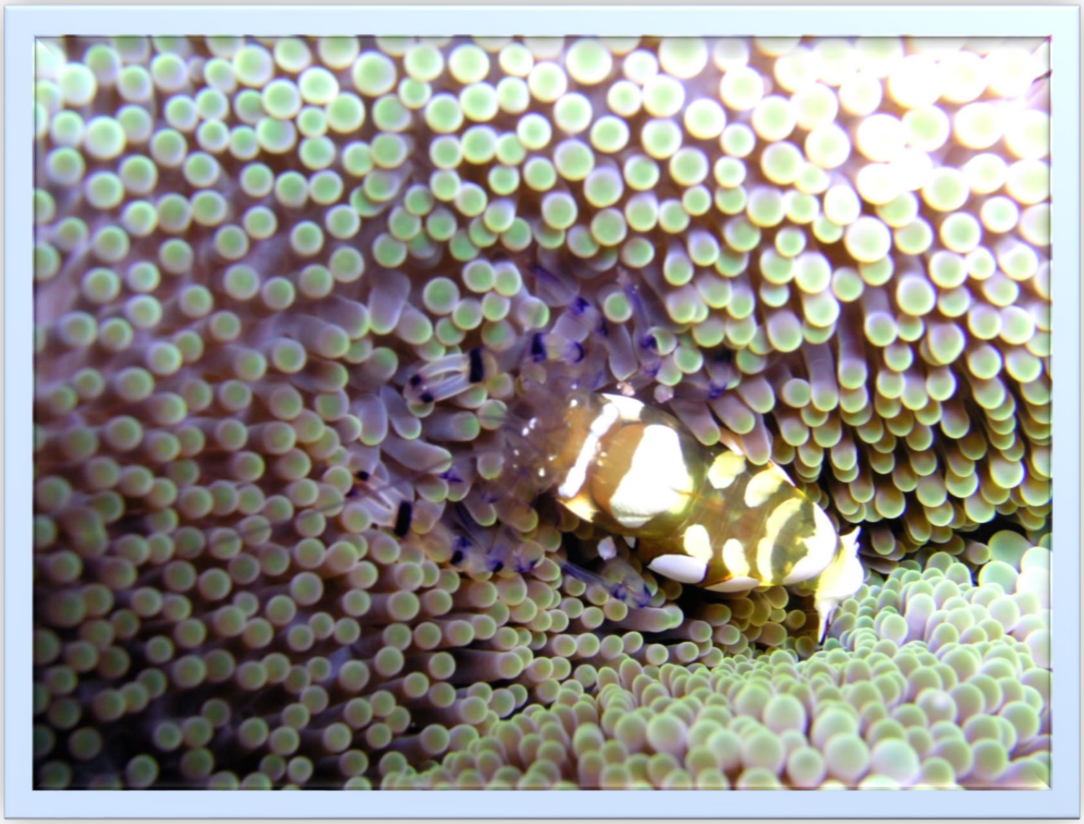
While the densities of giant clams [currently 7 species of *Tridacna* under status review; (National Oceanic and Atmospheric Administration 2017)] were generally low, they were observed by towed divers during each survey year, with the most occurrences in 2008. The highest density of giant clams observed on a single segment was 0.1 indiv/100 m$^2$, which occurred in 2001, 2002, 2004, and 2008. Giant clams were generally observed in the West Terrace, as well as along the northwest and southeast regions.

Sea cucumber densities had the broadest spatial coverage over time of all macroinvertebrates recorded, despite being discontinued from TDS in 2014. They were observed every survey year, with the exception of 2001. The most sea cucumbers were found in 2008 and 2012, mainly in the North and South georegions. The highest density of sea cucumbers observed on a segment was 6 indiv/100 m$^2$ in 2002 during a tow in the Inside Terrace.

*A microscopic view of* Montipora patula *polyps at Palmyra Atoll.*
*Photo: Austin Greene, Hawai`i Institute of Marine Biology/NOAA Fisheries.*

# *Microbiota*

## 2.5 Microbiota



Periclimenes *and* Stichodactyla *in the southeastern portion of the Lagoon/Backreef at Palmyra Atoll. Photo: Megan Moews-Asher, NOAA Fisheries.*

Palmyra Atoll is an intact reef habitat where the limited resources characteristic of relatively oligotrophic tropical waters is efficiently recycled to sustain the ecosystem. The reef microbiota facilitates the cycling of essential nutrients by breaking down organic materials released by photosynthetic benthic macroorganisms. Beginning in 2010, the assessment and monitoring of the reef microbiota at Palmyra Atoll was incorporated data collection efforts of Pacific RAMP, allowing for characterization of coral reef ecosystems from a molecular to an ecosystem scale across the entire U.S. Pacific Islands region.

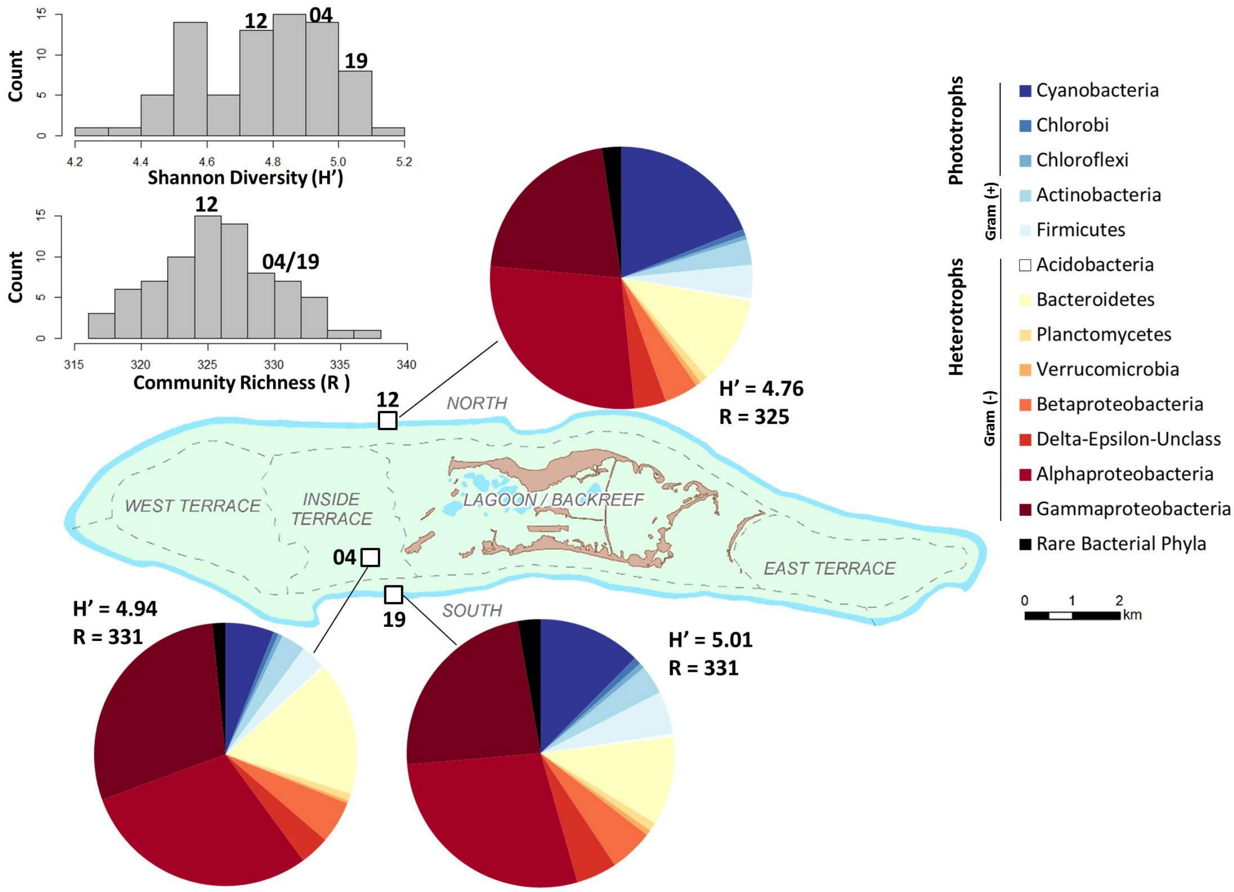



**Figure 43. Microbial composition and diversity at Palmyra Atoll. The microbial taxonomic groups are shown at phylum level. Community Richness and Shannon Diversity were calculated at the genus level. H', Shannon Index. R, Rarified Richness. Comparison of microbial diversity on three Palmyra reefs collected in 2012 (Sites 12, 4, and 19) overlaid on a histogram of all Richness and Diversity observations across the U.S. Pacific islands collected during Pacific Reef Assessment and Monitoring Program missions between 2012 and 2014 (n = 77 reef sites).**

## Microbial Composition and Diversity

Microbial communities in reef waters were collected from Pacific RAMP sites across all U.S. Pacific Islands from 2012 to 2014 and extracted for shotgun sequence metagenomic libraries. Microbial community composition at Palmyra Atoll was characterized by higher community richness and evenness on average compared to other U.S. islands across the Pacific (Figure 43). The community structure of the microbes at Palmyra reflected the complex and nutrient-rich organic material released by coral-dominated systems and the enhanced niche space characteristic of intact reef habitats, which promotes biodiversity across macro- and microbiota.

## Microbial Biomass on Reefs

Habitats dominated by reef-building organisms (i.e., stony corals and calcified algae), such as Palmyra Atoll, illustrate a functional role that suppresses the flow of energy through the microbial pathways and promote movement through particulate pathways channeling energy and nutrients towards metazoan food webs. In contrast, non-calcifying organisms, like fleshy macro and turf algae (observed in higher abundances on human-impacted reef systems), release high amounts of bioavailable dissolved organic carbon and select for larger, fast growing microbial communities that utilize these higher energetic organic resources to sustain their greater metabolic demands. The associated changes in microbial community structure and growth strategies when benthic community composition shifts from corals to algae, shunts much more of the energy produced by the system towards decomposition pathways with enhanced respiration of organic compounds to carbon dioxide. This phenomenon is referred to as microbialization (McDole et al. 2012).

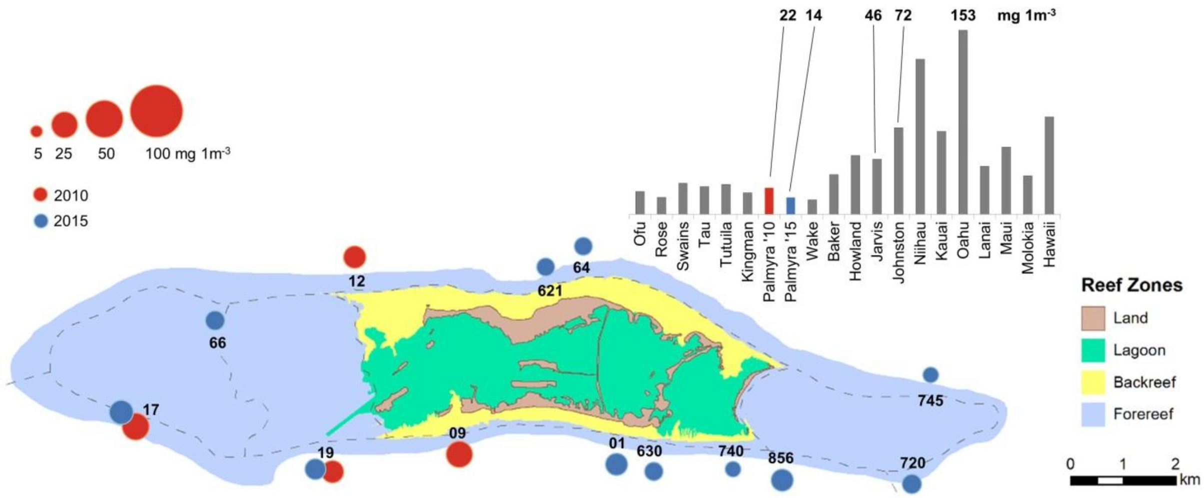



**Figure 44. Microbial biomass collected at Palmyra Atoll in 2010 and 2015 (n = 25). Cell volume was estimated based on measurements of cell length and width and cell abundances were enumerated using epi-fluorescent microscopy. Biomass is reported as milligrams per cubic meter (mg $m^{-3}$). The 2010 data were published in (McDole et al. 2012).**

Reef water samples were collected from all Pacific RAMP sites across the U.S. Pacific Islands beginning in 2008, with the first Palmyra samples measured in 2010. Microbial biomass at Palmyra Atoll, similar to other remote atolls (e.g., Rose and Wake), was lower than remote equatorial islands (Jarvis, Howland, and Baker) that experience significant upwelling. Reef degradation towards algae-dominated states promotes greater cell biomasses and higher proportions of fast growing heterotrophic taxa (as observed on the main Hawaiian Islands), which exhibited up to an order of magnitude more microbial biomass in the overlying reef waters (i.e., Palmyra in 2015 = 14 mg $m^{-3}$ and Oahu in 2008 = 153 mg $m^{-3}$). The microbial communities on degraded reefs (with higher coverage of fleshy seaweeds) are associated with increased energy requirements and lower efficiency, which deplete the availability of energetic resources to higher trophic levels (Figure 44).

*A swarm of convict tang or Manini in Hawaiian* (Acanthurus triostegus) *at Palmyra Atoll.*
*Photo: Kaylyn McCoy, NOAA Fisheries.*

# *Reef Fishes*

## 2.6 Reef Fishes

*Humphead wrasse* (Cheilinus undulatus) *at Palmyra Atoll.*
*Photo: Tate Wester, NOAA Fisheries.*

### Survey Effort and Site Information

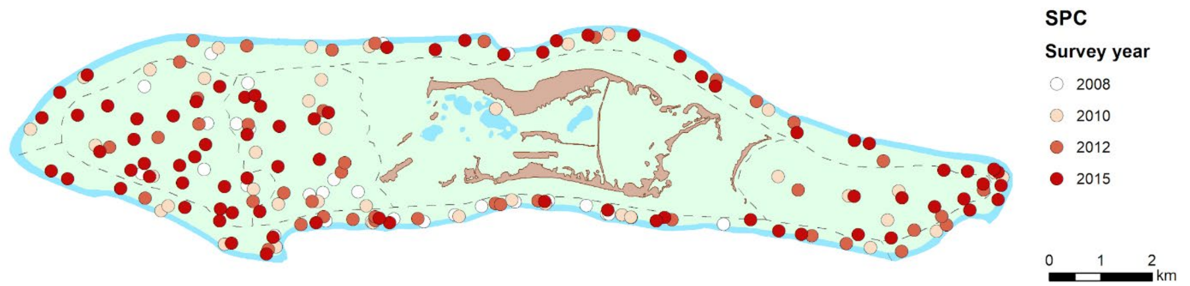
Palmyra reef fishes were surveyed on eight occasions between 2001 and 2015 (Table 3). In each case, surveys were a mix of comprehensive small-area surveys—belt-transect (BLT) or stationary point count (SPC)—and broad-scale (~2.2 km) towed-diver surveys (TDS) that focused on large-bodied fishes (>50 cm total length).

TDS were conducted primarily around the island perimeter, where large fishes tend to be most abundant (Figure 48). BLT surveys, which were utilized between 2001 and 2008, were mostly conducted at haphazardly-located, predominantly mid-depth (~10–15 m) forereef sites, with the southern forereef being more frequently surveyed than other areas (Figure 45). In 2008, Pacific RAMP initiated the transition from BLT surveys to the current SPC survey method and at the same time moved to a stratified-random survey design encompassing only hard-bottom habitats in <30 m water depths (Figure 45). Since that time, there have also been concerted efforts to increase the number of survey sites per visit. Forty or more sites have been surveyed each visit since and including 2010, compared to 12 or fewer repeat sites prior to 2008 (Table 3). One consequence of the shift in survey design is that SPC sites have been much more widely spread around the island than the BLT surveys. These sites encompass reef habitats around the eastern edge of the island that had not been surveyed previously, as well as additional sites located on the terrace areas that make up a large portion of the Palmyra reef habitat (Figure 45). Because of a mix of low sample size and some inconsistency in the application of the BLT survey method in the program's earliest years, data prior to 2003 are not used to generate quantitative estimates, such as density. Similarly, BLT data gathered at the time to the protocol changed to the stratified-random design in 2008, cannot be meaningfully compared with earlier BLT data gathered at fixed locations. Thus, the time series shown were primarily built from TDS for the period 2002–2015, and from the SPC surveys conducted for the period 2008–2015.

Relatively few fish surveys of any kind have been conducted in Palmyra lagoon and backreef habitats, i.e., within the reef crest (Figure 45). Due to the limited amount of survey time available at Palmyra each year, surveys focused on outer-forereef and shelf areas, i.e., the forereef habitats that are most suitable for large-scale comparison among all islands and regions surveyed as part of Pacific RAMP.

**Table 4. Reef fish survey effort for Palmyra Atoll. Data are number of surveys by year and method. Towed-diver surveys (TDS) transects were ~2 km long by 10 m wide (~20,000 $m^2$), typically in mid-depth forereef habitats for fishes >50 cm total length (TL). In contrast, during belt-transect (BLT) and stationary point count (SPC) surveys, divers count all fishes within small areas of reef (~350–600 $m^2$ per survey).**

| | All Fishes | | Large Fish (>50cm TL) |
|---|---|---|---|
| **Year** | **BLT** | **SPC** | **TDS** |
| **2001** | 5 | - | 5 |
| **2002** | 10 | - | 13 |
| **2004** | 10 | - | 21 |
| **2006** | 12 | - | 21 |
| **2008** | 28 | 28 | 22 |
| **2010** | - | 40 | 25 |
| **2012** | - | 42 | 22 |
| **2015** | - | 78 | 20 |



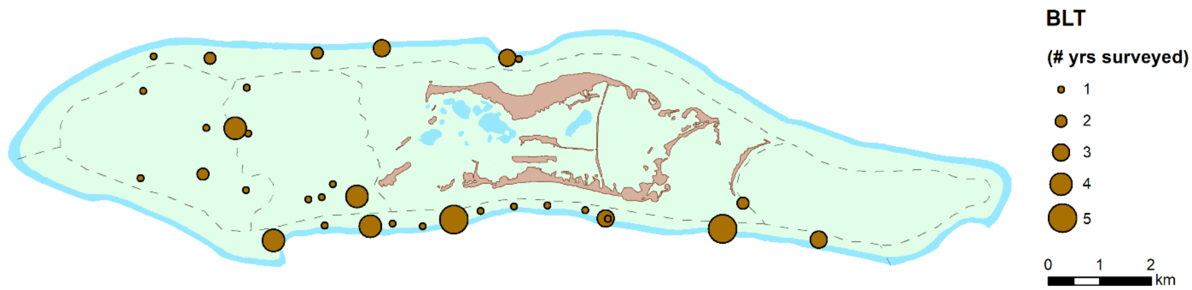




**Figure 45. Location of stationary point count (SPC) sites by year (top) and belt-transect (BLT) surveys by number of years surveyed (bottom) for Palmyra Atoll.**

## Distribution of Reef Fish Biomass and Abundance

Reef fish biomass was generally highest on outer forereef habitats, particularly around the southwest and southeast of the island (Figure 46). That pattern was largely driven by higher biomass of planktivores and piscivores, particularly reef sharks in those areas (Figure 46 and Figure 48).

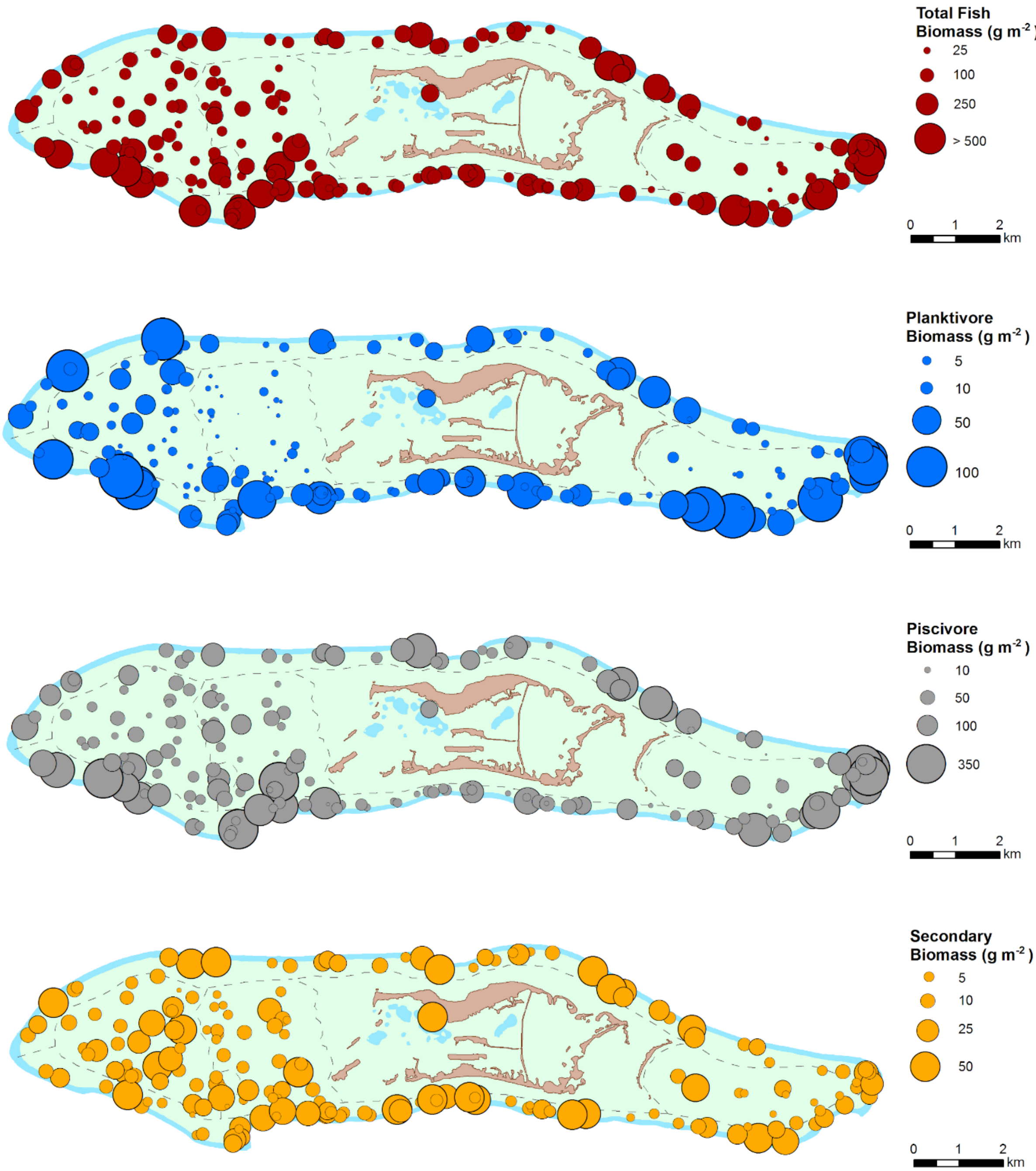



**Figure 46. Biomass maps of Total Fish (first map), Planktivore (second map), Piscivore (third map), and Secondary Consumer Groups (fourth map) from stationary point count surveys at Palmyra Atoll over the period from 2008 to 2015. Secondary consumers include primarily omnivores and invertivores, comprising many abundant and generally small-bodied species.**

Although they were relatively common on all outer forereef areas, the South georegion of Palmyra Atoll has been notable for very high numbers of anthias and other small-bodied planktivores, such as fusiliers, at many sites. In contrast, sites within the Inside Terrace and East Terrace generally had few planktivores (Figure 46).

As with other functional groups, herbivore biomass tended to be relatively low at East Terrace sites (Figure 47). That was true for parrotfishes and, to an even greater extent, for surgeonfishes. Biomass at sites in the Inner Terrace was boosted by occasional encounters with large schools (200+ individuals) of the convict tang (*Acanthurus triostegus*), and by high abundance of the striated surgeonfish (*Ctenochaetus striatus*) at many sites. Schools of milkfishes (*Chanos chanos*) were recorded occasionally along the outer forereefs in the southwestern region.

In all regions, the most common parrotfish was the bullethead parrotfish (*Chlorurus spilurus*), but—particularly on outer forereefs and the West Terrace—a significant portion of the parrotfish biomass was also comprised of large-bodied species, such as the redlip parrotfish (*Scarus rubroviolaceus*) and the steephead parrotfish (*Chlorurus microrhinos*).

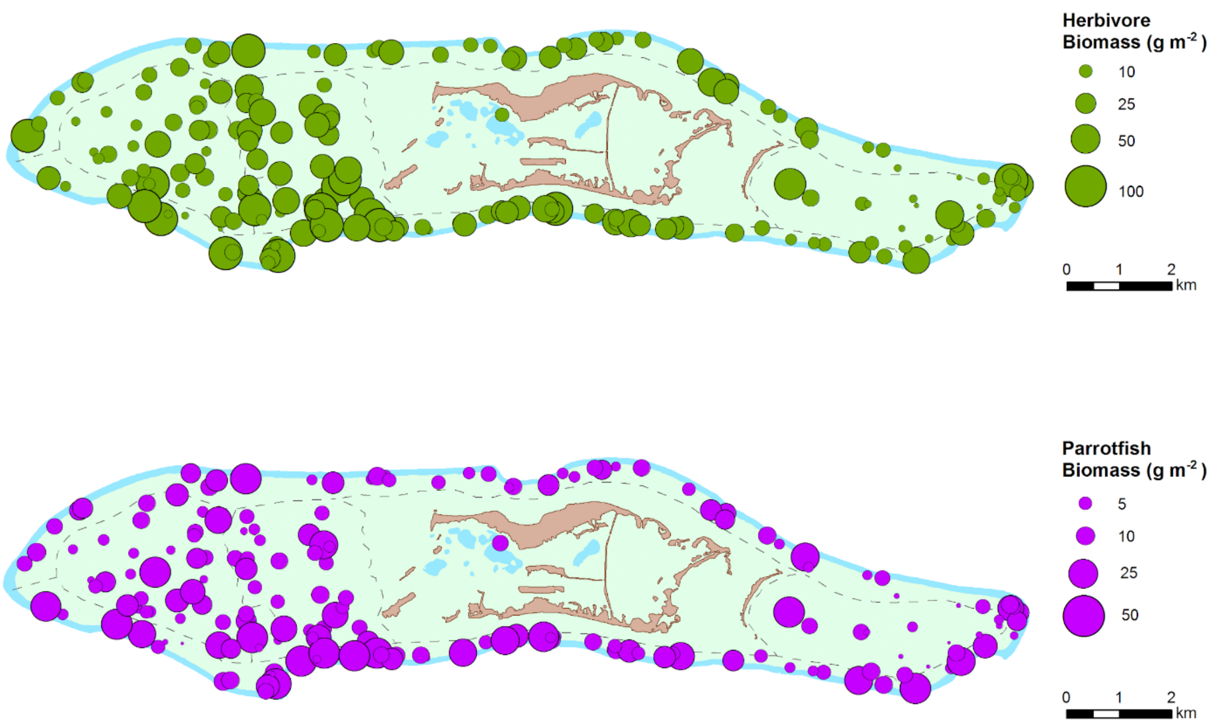



**Figure 47. Total Herbivore (top) and Parrotfish (bottom) biomass from stationary point count surveys at Palmyra Atoll over the period from 2008 to 2015.**

Gray reef sharks (*Carcharhinus amblyrhynchos*) were the most commonly observed shark species on Palmyra's northern and southern outer forereef areas, followed by blacktip reef sharks (*Carcharhinus melanopterus*). In contrast, blacktip sharks were the dominant species in terrace areas, particularly in the West Terrace, where they constituted nearly 90% of all sharks recorded. Overall, sharks were observed on nearly 40% of all TDS segments (~220 m long sub-units of the survey) along both northern and southern outer forereefs, but at only 20% or fewer segments within the terraces (Figure 48).

Biomass of other predatory species was more evenly distributed around the atoll. Common species included the bluefin trevally (*Caranx melampygus*), the most frequently encountered jack species, and the two-spotted red snapper (*Lutjanus bohar*), the most abundant piscivorous snapper. However, *L. bohar* were infrequently observed at East Terrace sites.

Humphead wrasses (*Cheilinus undulatus*) were regularly observed by survey divers in most years. Like many other large-bodied species, their distribution and abundance are generally best represented by TDS data (Figure 48). Humphead wrasses were observed on nearly 20% of all tow segments conducted along the north and south outer forereef areas, with particularly high abundance around the eastern end of Palmyra (Figure 48). However, they were infrequently recorded during TDS in terrace areas.

Bumphead parrotfishes (*Bolbometopon muricatum*) have only been observed twice during Pacific RAMP surveys at Palmyra—both times during TDS near the western end of the atoll. A school of 6 individuals was observed on the West Terrace in 2002, and a group of 3 individuals on the southern outer forereef in 2006 (Figure 48).

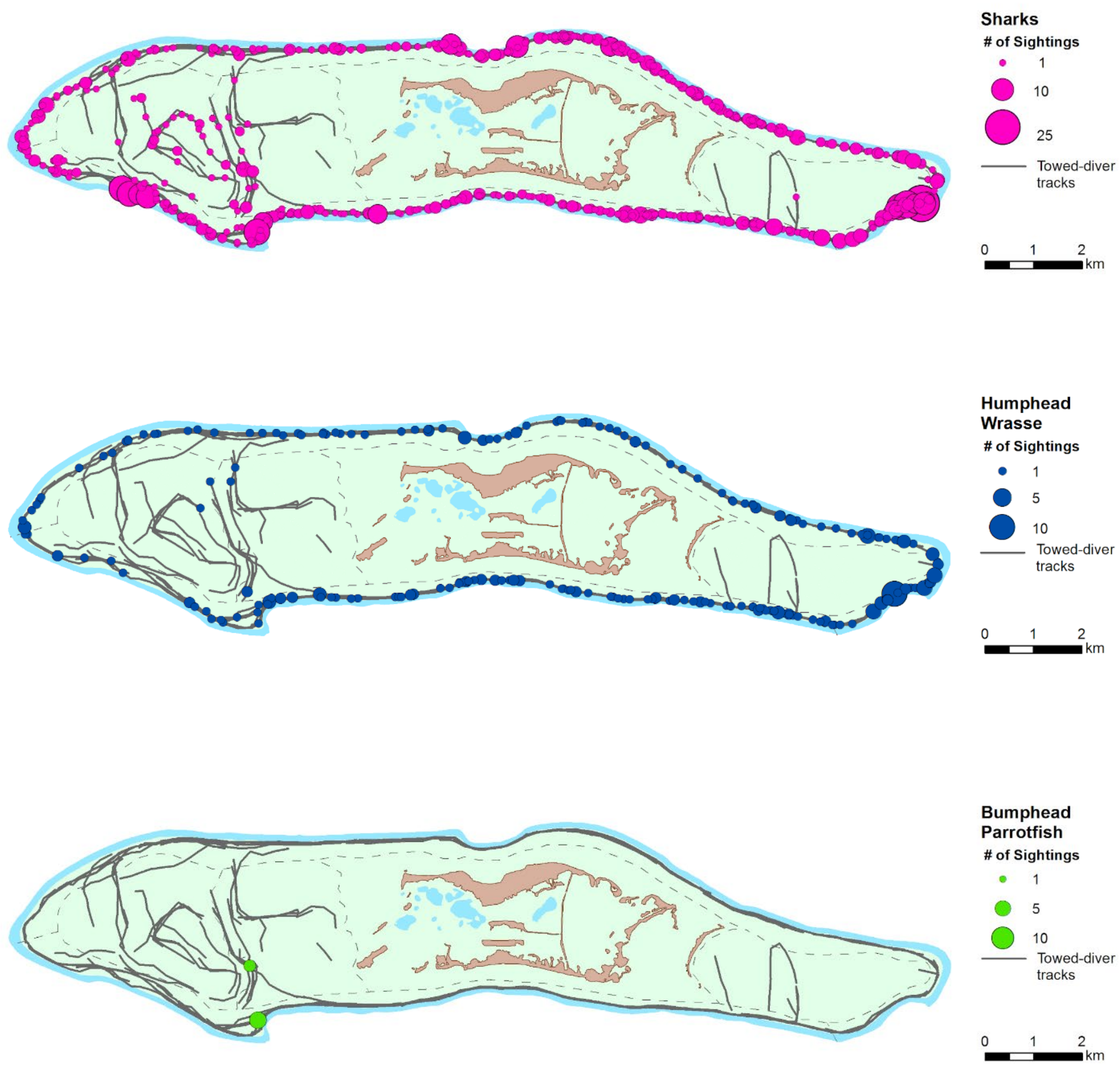



**Figure 48. Towed-diver survey sightings of sharks (top), humphead wrasse (middle), and bumphead parrotfish (bottom) at Palmyra Atoll from 2001 to 2015.**

## Distribution of Other Species of Interest

Manta rays (*Mobula* spp.) have been routinely sighted during TDS at Palmyra—they were observed during approximately 3% of all tow segments. The majority of those observations have been in outer forereef areas (i.e., the North and South georegions). The cluster of observations towards the southwest of Palmyra appears to be associated with the channel located there (Figure 49).

Sea turtles were also commonly observed during TDS. Green sea turtles (*Chelonia mydas*) have been recorded during approximately 13% of towed-diver segments, and hawksbill sea turtles

(*Eretmochelys imbricata*) during approximately 1% of all segments. Green sea turtles were most frequently observed in the Inside Terrace (29% of segments there), but were also commonly encountered on outer-reef TDS to the north and south of the emergent land areas of the island, with much lower sighting frequency on segments towards the eastern and western ends of Palmyra (Figure 49). It is harder to draw conclusions about typical distribution of hawksbill turtles, as they were only observed on 18 of the 1,435 segments surveyed (Figure 49).

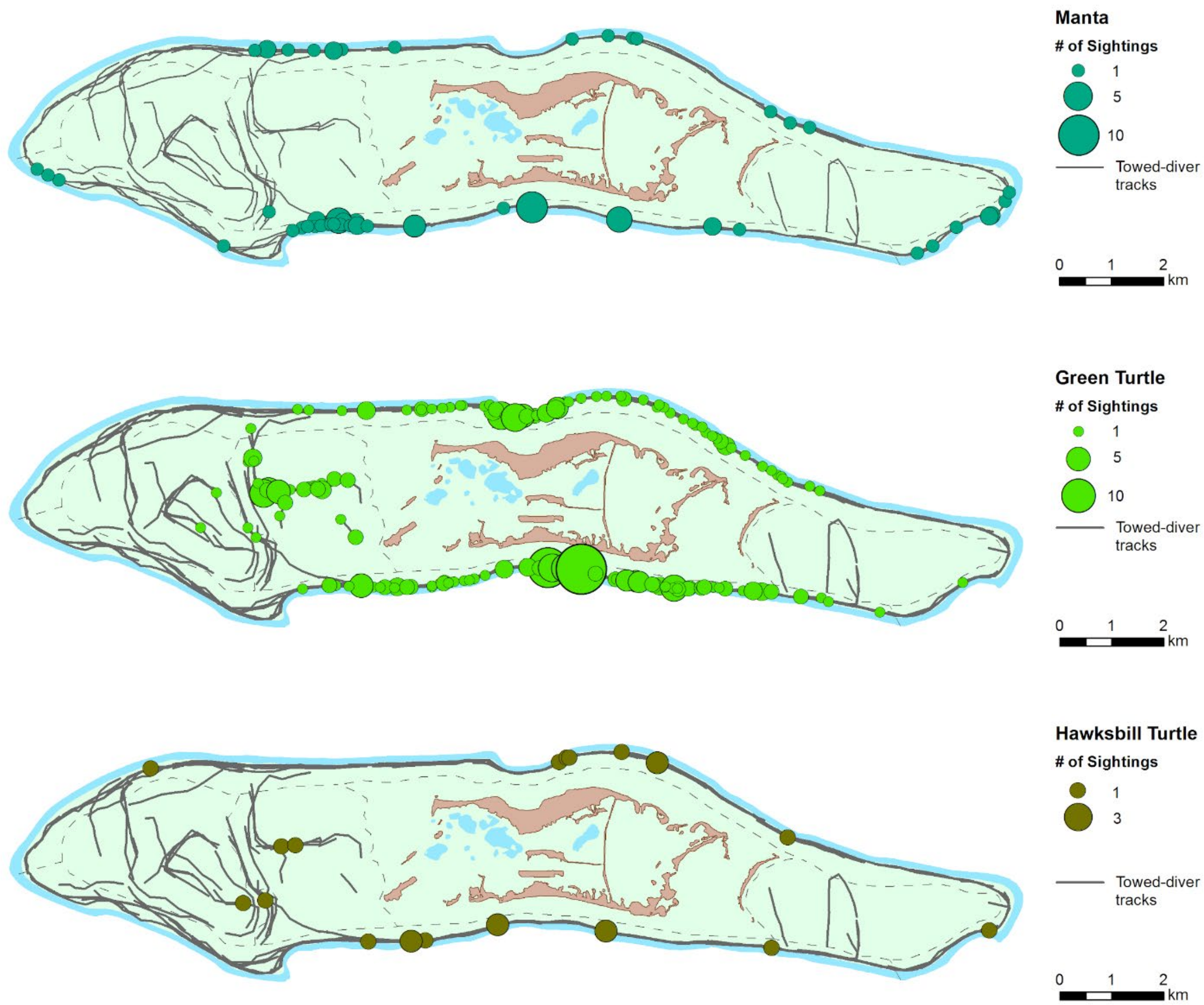



**Figure 49. Towed-diver survey sightings of manta rays (top), green turtles (middle), and hawksbill turtles (bottom) at Palmyra Atoll over the period from 2001 to 2015. Green sea turtles sightings include observations recorded as (unspecified) turtle, as the great majority of turtles seen at Palmyra were green turtles.**

## Reef Fish Time Series

Time series of reef fish biomass, incorporating data from both BLT and SPC surveys, are shown in Figure 50. The size of the confidence intervals indicates insufficient data from earlier survey years to distinguish statistically significant temporal trends. Based on the SPC data that were collected between 2008 and 2015, fish biomass tended to be higher in 2010 and 2012 for several groups of fishes, but there is no indication of any clear trend between 2008 and 2015 (Figure 50).

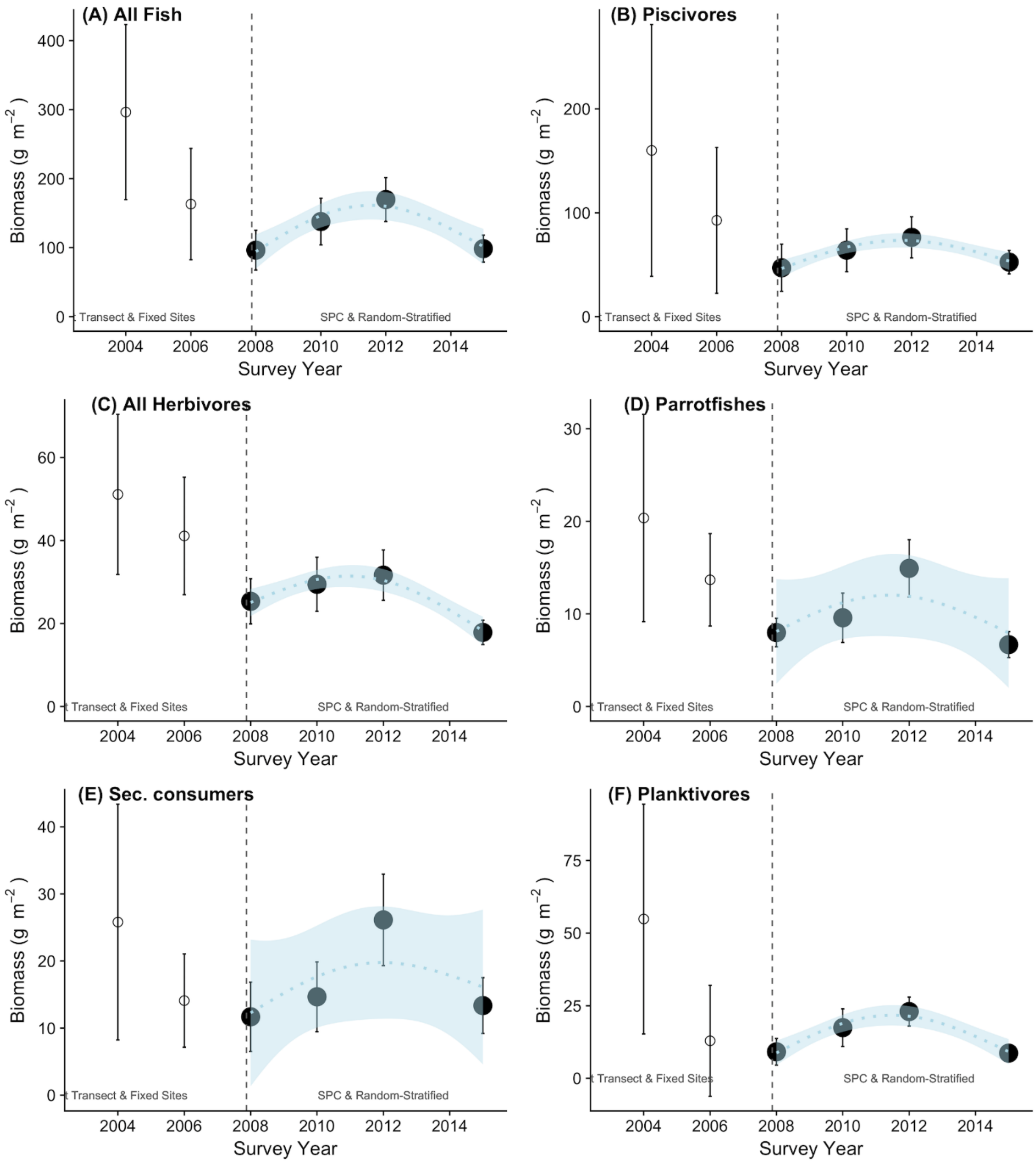



**Figure 50. Time series of reef fish biomass at Palmyra Atoll for (A) all fish, (B) piscivores, (C) all herbivores, (D) parrotfishes, (E) secondary consumers, and (F) planktivores. Data are shown for belt-transect surveys conducted at a limited number of mid-depth forereef sites in 2004 and 2006, and stationary point count surveys conducted at randomly located sites encompassing all hard-bottom forereef in water depths <u>≤</u>30 m over the period from 2008 to 2015. Circles indicate mean values, and vertical error bars represent 95% confidence intervals per time period. The light blue dotted trend line and confidence intervals that have been added for visualization purposes are derived from generalized additive models of biomass against survey year. Biomass values from the different periods cannot be directly compared due to differences in methods and survey locations.**

Based on TDS data, there were no clear temporal trends in overall shark or jack abundance at Palmyra. The peak of jack abundance, in 2004, occurred as a result of encounters with large schools of rainbow runners (*Elagatis bipinnulata*) during two surveys along northern outer reefs. The peak in 2012 was due to a single encounter with several hundred bigeye trevally (*Caranx sexfasciatus*) in the South georegion of the atoll. Those species were also observed in other years, but not recorded in such large numbers. Thus, the high variability in recorded abundance among years was likely due to inherent natural variability and patchiness of several roving, predatory species (Figure 51).

Counts of humphead wrasse during TDS transects were notably low in 2015 compared to earlier years (Figure 51). However, humphead wrasses were frequently observed "off-transect" that year. Specifically, only five individuals were recorded within TDS transects in 2015, but 39 were observed "off-transect" (i.e., in the general vicinity of the TDS).

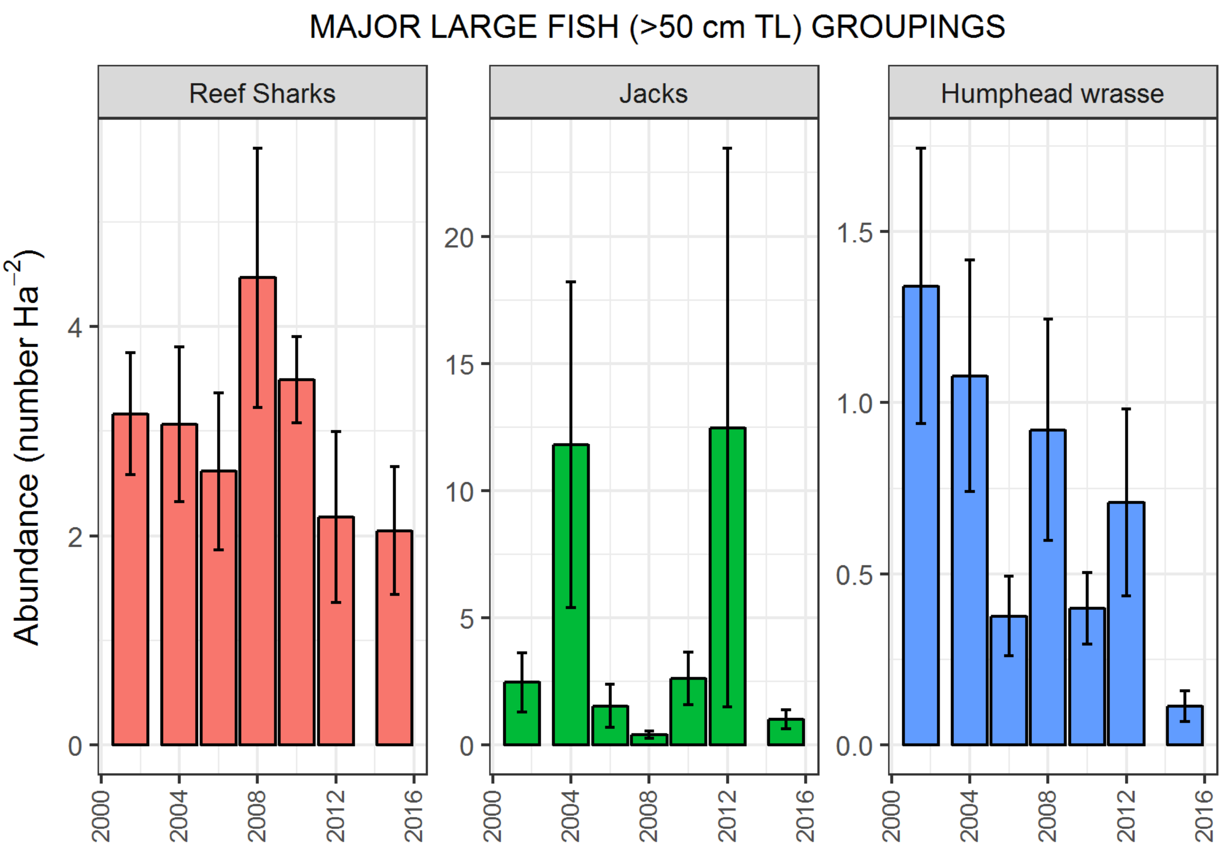



**Figure 51. Bar plots by year for reef sharks, jacks, and humphead wrasse from towed-diver survey (TDS) data at Palmyra Atoll over the period from 2001 to 2015. Note that 2001 and 2002 data were pooled due to low sample sizes in those years. In order to improve consistency among years, trends were derived only from TDS >500 m in length, which were conducted in forereef habitats between 10 and 20 m deep. Data shown are mean and standard error (SE).**

### Species Lists, Encounter Rates and Diversity

Mean species richness (i.e., the mean number of species observed per survey) ranged between 28 and 39 species per survey (Figure 52)—with 2012 being atypically high (as mean richness was between 28 and 30 in all other survey years). Such large short term variability in species richness is likely primarily due to small differences in the make of survey teams among years. Evenness was relatively similar across years—varying between 0.58 and 0.68—but notably lower in 2012 (Figure 52). Lower evenness in 2012 could be a consequence of relatively high biomass of planktivores in that year (Figure 50) as very high abundance of small planktivores would indicate the overall fish assemblage was more dominated by a small group of species than in other years.

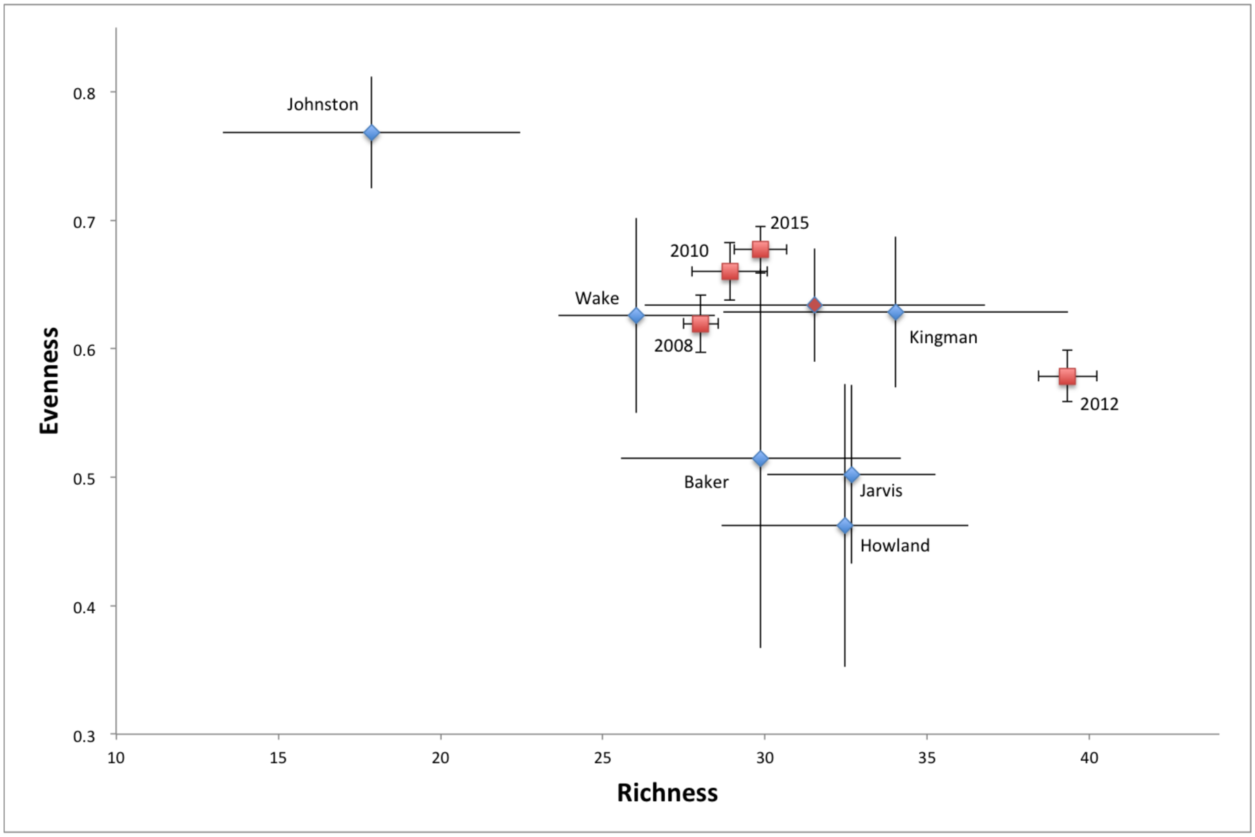



**Figure 52. Richness vs evenness. Red squares are species richness (the number of species encountered) and evenness (how equally distributed is abundance among species present—lower values indicate communities that are numerically dominated by few species, and high values indicate situations where many similarly abundant species are present) values at Palmyra Atoll by year (± SE), blue circles represent mean (± SD) of richness and evenness values for other islands in the Pacific Remote Islands Marine National Monument across all years. The single red dot represents the mean values of richness and evenness at Palmyra across all years. For consistency among islands, only data from forereef sites are included.**

Seven species of fish recorded during surveys at Palmyra are listed as endangered, vulnerable, or near threatened by the International Union for Conservation of Nature (IUCN) Red List (International Union for Conservation of Nature 2017), and six of those were regularly encountered by survey divers. As described above, *Carcharhinus amblyrhynchos*, *C. melanopterus,* and *Cheilinus undulatus*, were routinely observed during TDS, particularly in the outer reef areas. Although somewhat less common, IUCN-listed eagle rays, *Aetobatus narinari*, and manta rays (*Mobula* spp.) were also observed during TDS. Another IUCN-listed species, the Chevron butterflyfish, *Chaetodon trifascialis*, is strongly associated with table *Acropora* corals, which were rare on the forereefs where most of the surveys were conducted.

However, those corals and chevron butterflyfish were highly abundant in some backreef and lagoon habitats.

Three ESA-listed species were observed at Palmyra: Green and Hawksbill sea turtles, *Chelonia mydas* and *Eretmochelys imbricata*, and the scalloped hammerhead, *Sphyrna lewini*. Manta rays (*Mobula* spp.), which were frequently observed at Palmyra, potentially comprise two similar species that divers are not able to reliably distinguish in visual surveys—one of those, *Mobula birostris*, is listed under the ESA; the other, *M. alfredi*, is not. A complete list of fish species observed each year is given in Appendix B of “Chapter 9: Pacific Remote Islands Marine National Monument in the Pacific-wide Context.”

# *Marine Debris*

## 2.7 Marine Debris

*Invasive corallimorph* (Rhodactis howesii) *covering debris and wreckage at Palmyra Atoll.*
*Photo: Susan White, U.S. Fish and Wildlife Service.*

Marine debris was noted sporadically at Palmyra Atoll during TDS conducted from 2001 through 2015 (Figure 53). Various forms of marine debris were recorded 28 times during the benthic TDS. This does not encompass all debris found at Palmyra, given that the debris observations were only haphazardly included in the surveys, and it is also possible that the same debris was noted in consecutive survey years. Fishing line made up the majority of the sightings.

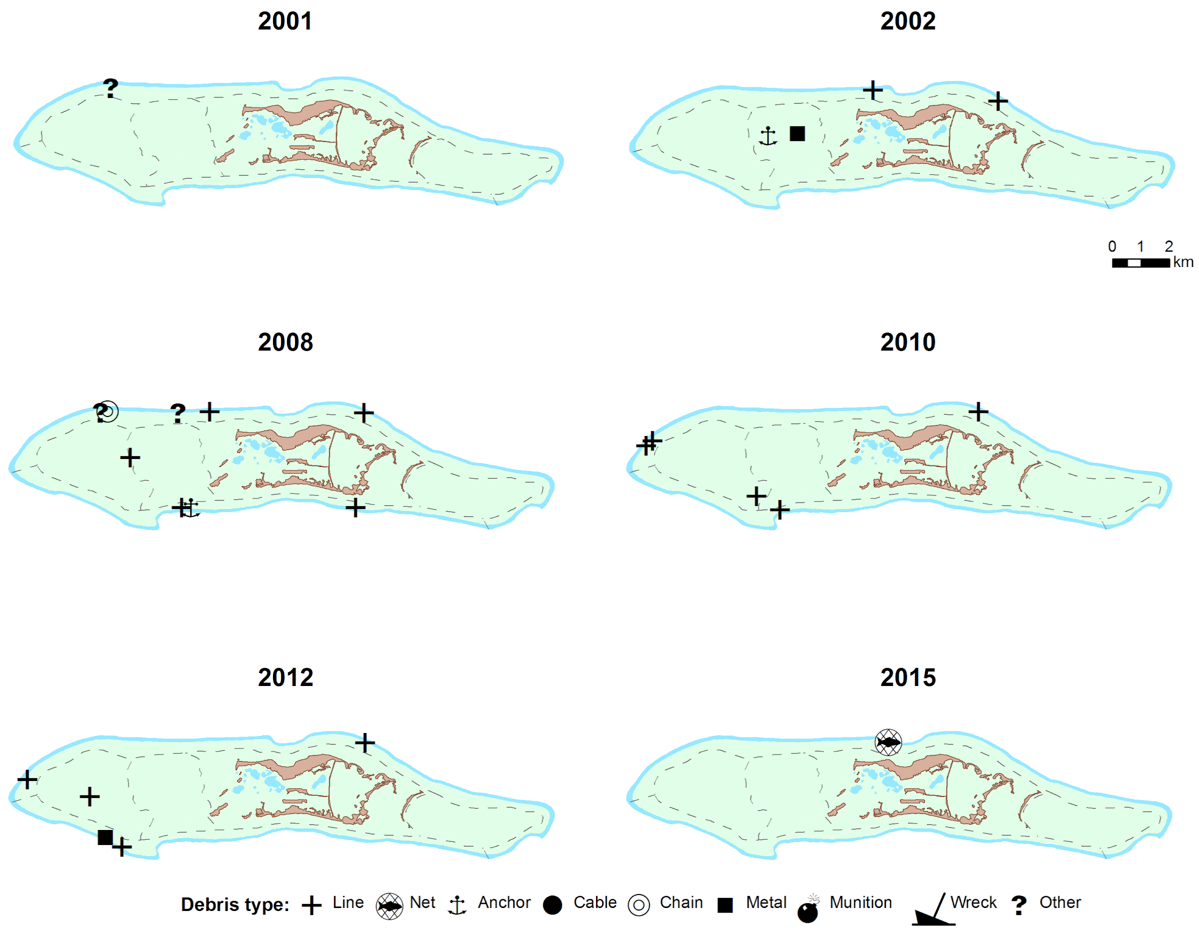
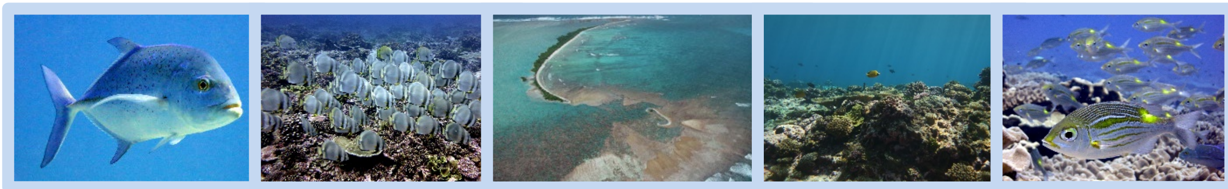



**Figure 53. Marine debris sightings, including line, net, anchors, chain, metal, and miscellaneous debris around Palmyra Atoll over the period from 2001 through 2015, as recorded during benthic towed-diver surveys.**

*A school of neon fusiliers (*Pterocaesio tile*) dart through Palmyra Atoll's forereef habitat.*
*Photo: Evan Barba, Hawai`i Institute of Marine Biology, courtesy NOAA Fisheries.*

# *Ecosystem Integration*

## 2.8 Ecosystem Integration



*Photos left to right at Palmyra Atoll:* Caranx melampygus*, Photo: Kevin Lino, NOAA Fisheries;* Platax orbicularis *on reef, Photo: Andrew E. Gray, NOAA Fisheries; Aerial view © Flickr/Island Conservation; coral reef at the western terrace, Photo: Chelsea Counsell, HIMB/NOAA Fisheries;* Gnathodentex aureolineatus *on the reef, Photo: Andrew E. Gray, NOAA Fisheries.*

### Oceanic Drivers of Benthic and Fish Populations

Although it has historically experienced substantial physical and environmental alterations, Palmyra Atoll has maintained healthy, thriving coral reefs with reef-fish assemblages that have remained relatively stable over the course of the Pacific RAMP surveys. These reefs were likely supported by the surrounding warm waters with high aragonite saturation states and accretion rates, high levels of productivity sustained by intermittent upwelling, as well as the absence of chronic human disturbances, such as land-based sources of pollution and exploitation of marine resources. Palmyra's reefs were characterized by benthic communities dominated by calcifying organisms (~60% of benthic cover), including hard corals (28.5%), crustose coralline algae (18.9%), and calcified macroalgae (*Halimeda* and *Peyssonnelia*) that were present in unusually high abundance (12%) compared to all other reefs of the PRIMNM. Microbial community abundance associated with these reefs was low, but diverse, as is typical of healthier reefs with lower abundances of both macroalgae and known coral pathogens.

Interannual variability in oceanographic conditions at Palmyra Atoll is largely ENSO-driven, yet this variability tends to remain relatively moderate compared to other Pacific regions located closer to the equator. During La Niña conditions, enhanced upwelling resulted in anomalously cool, nutrient-rich surface waters fueling striking boosts in oceanic productivity that corresponded with subsequent increases in observed reef-fish biomass in 2010 and 2012. Further, the number of fish species observed per survey (e.g., survey richness) was also relatively high in 2012, perhaps as a consequence of increased fish abundance that led to enhanced detection of species. Palmyra also supported three species listed under the ESA: green and hawksbill sea turtles (*Chelonia mydas* and *Eretmochelys imbricata*) and the scalloped hammerhead (*Sphyrna lewini*), and potentially the manta ray, *Mobula birostris*.

During El Niño events, the weakening of upwelling resulted in warmer, more oligotrophic surface waters at Palmyra Atoll, with sea surface temperatures reaching levels typically associated with thermal stress of corals every few years. Based on the survey data from the 2010 El Niño event (the only El Niño event during which RAMP surveys also took place), coral bleaching indeed occurred at moderate levels (Williams et al. 2011). Hard coral, however, has remained the dominant functional group of Palmyra's benthic communities, which suggests that these reefs have historically been capable of recovering from disturbances such as thermal events.

## Spatial Variation within the Atoll

High energy, northerly swell creates a prominent distinction between the wave-exposed northern coast and more protected southern coast of Palmyra Atoll. Soft corals, which are often associated with higher levels of hydrodynamic flow, were observed in greater abundances across exposed habitats. In contrast, surveys indicated coral cover had substantially increased only in the South georegion, perhaps due in part to the protected environment or the notably higher saturation states and accretion rates measured throughout the southern coast. Surveys further indicated the outer forereef of the South georegion supported greater abundances of planktivorous fishes, likely due to relatively high currents and plankton-rich waters that resulted from a combination of wave energy from the North forcing water to wrap around the atoll, and upwelling that supplied nutrient-rich waters. These same general conditions (high currents and abundant prey) likely further supported the higher biomass of roving predators (primarily reef sharks) observed in the outer forereef of the South georegion. The spatial patterns of key macroinvertebrates also corresponded with areas influenced by upwelling, but in reef areas that were more protected from wave energy. Greater densities of both giant clams and the crown-of-thorns sea star were consistently recorded throughout the forereef of the South and West Terrace georegions (when sufficiently detected).

The Inside Terrace georegion was exposed to outflow from the Lagoon, which consisted of strongly stratified water with high surface temperatures that underwent dynamic changes in carbonate chemistry due to long residence times. Mixing of this water as it reaches forereef areas likely resulted in the observed higher temperatures, lower accretion rates, and greater temporal variability in aragonite saturation state. This in turn may have influenced the highly variable composition of benthic communities observed within this georegion. Both the Inside Terrace and West Terrace georegions also contained higher abundances of herbivorous fishes that may have been supported by the observed higher abundances of turf algae.

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