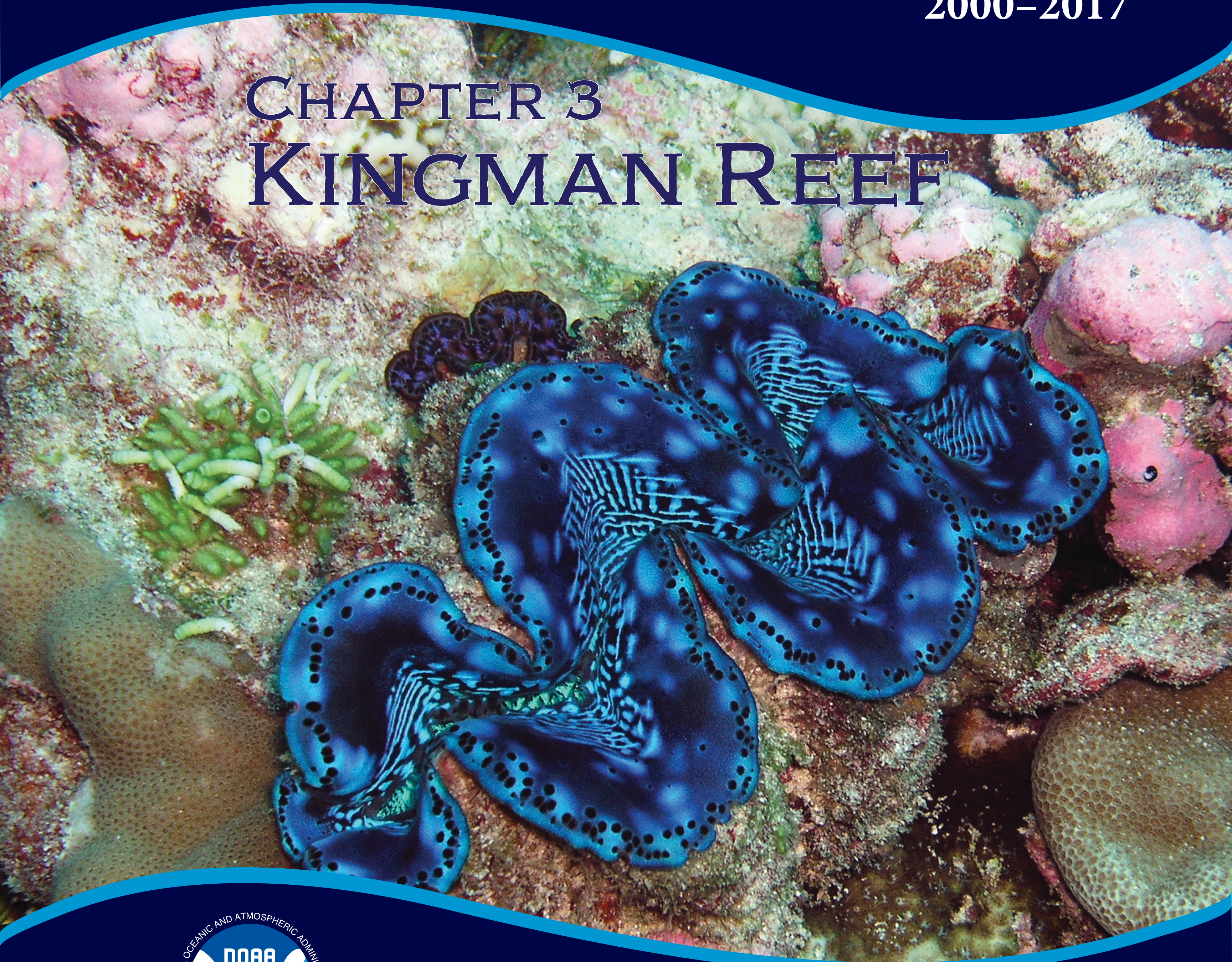
Coral Reef Ecosystem Monitoring Report for The Pacific Remote Islands Marine National Monument 2000–2017

Chapter 3 Kingman Reef



Ecosystem Sciences Division

Pacific Islands Fisheries Science Center

NOAA FISHERIES

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

Chapter 3: Kingman Reef

Authors

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Citations

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Front Cover: Small giant clams (*Tridacna maxima)* are commonly seen with an array of vibrant colors and patterns at Kingman Reef. Photo: Megan Moews-Asher, NOAA Fisheries.

Back Cover: A two-spot red snapper (*Lutjanus bohar*) comes in close to inspect a diver's camera at Kingman Reef. Photo: James Morioka, NOAA Fisheries.

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Executive Summary

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

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

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

Key Findings

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

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

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

Acknowledgements

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

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

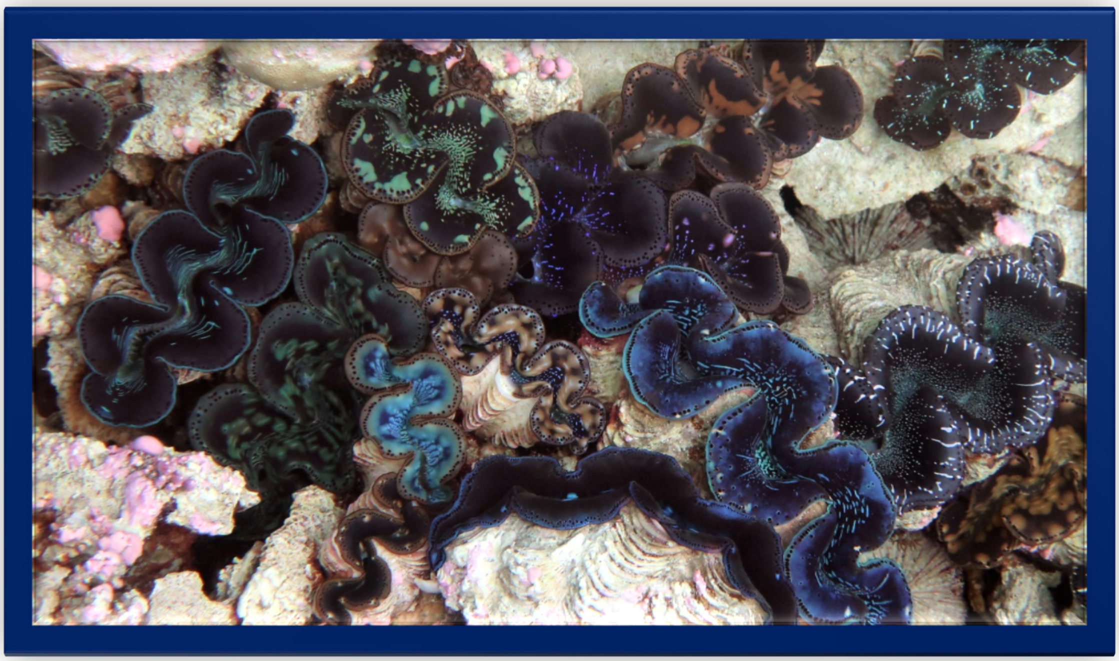
We would like to recognize PIFSC Editorial Services, in particular, Jill Coyle, Katie Davis, and Hoku Johnson for their inputs throughout the editorial process, Donald Kobayashi, PIFSC, for his extensive time and insights in conducting chapter technical reviews, and PIFSC Director Michael Seki and PIFSC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

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

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

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

Chapter 3: Kingman Reef



A group of brilliant, iridescent small giant clams (Tridacna maxima) concentrated within Kingman Reef's lagoonal backreef.
Photo: Ariel Halperin, NOAA Fisheries.

3.1 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

Kingman Reef is the northernmost of the Northern Line Islands lying 67 km (36 nm) northwest of Palmyra Atoll in the North Pacific Ocean at 6°23′N 162°25′W. The pyramid shaped reef extends a maximum of 18 km (9.5 nm) east-west and 9 km (5 nm) north-south with little emergent land and no inhabitants (Figure 1). The perimeter of mostly submerged reef crest at Kingman encompasses 75 km^2 (29 mi^2) of reef habitat, including a large, relatively deep lagoon. Although no permanent land is found at Kingman, two small emergent coral rubble spits that shift with changing wave conditions occur on the northeastern and southeastern sides of the reef (USFWS United States Fish and Wildlife Service 2013).

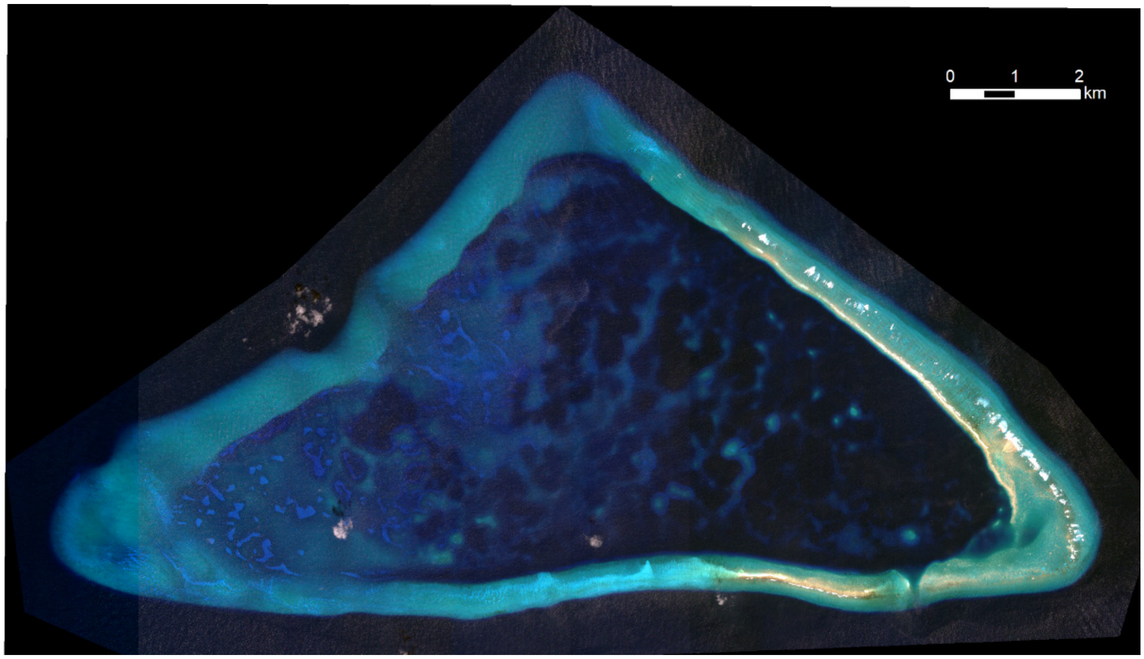


Figure 1. Satellite image of Kingman Reef, November 10, 2015. (© DigitalGlobe Inc. All rights reserved)

This chapter provides a compilation of information to assist managers in making informed decisions relating to Kingman Reef 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 among ecosystem components at Kingman.

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

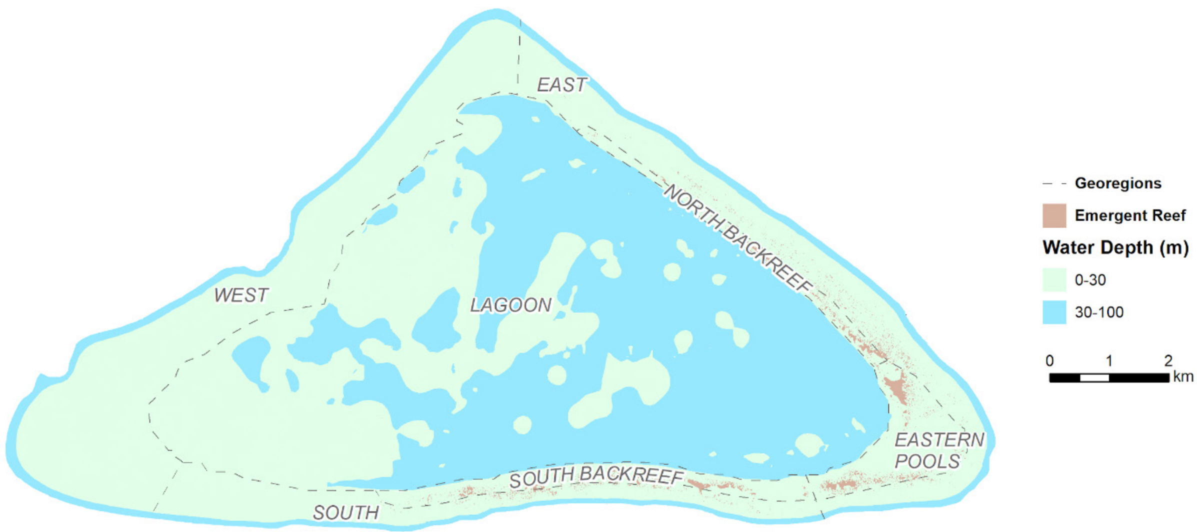


Figure 2. The seven geographic regions, or georegions, for Kingman Reef: West, South, South Backreef, Eastern Pools, East, North Backreef, and Lagoon.

History and Human Influences

Kingman Reef was discovered by American Captain Edmund Fanning of the ship *Betsey* in 1798, but is named after Captain W. E. Kingman who was the first to describe it in 1853. Due to the lack of emergent land, no artifacts or evidence of Polynesian, Micronesian, or other pre-European native settlements have been found at Kingman. Despite the lack of land or guano, Kingman was claimed in 1860 by the United States Guano Company, under the name "Danger Reef" via the Guano Islands Act of 1856 (Bryan 1942). The reef has a long history of reported sightings, as well as reported ship strikes and wrecks. The British steamship *Tartar* struck the reef at Kingman in 1874, and the British ironbark *Henry James* wrecked in 1888, stranding passengers and crew for six weeks. The barque *Lady Lampson* ran aground in 1893, and the British Navy vessel *Penguin* surveyed the reef in 1897. Kingman was formally annexed to the United States in 1922 by Lorrin A. Thurston as an agent of the Palmyra Copra Company.

In 1934, President Franklin D. Roosevelt issued an Executive Order placing Kingman Reef under the control and jurisdiction of the U.S. Navy. The lagoon was used in 1937 and 1938 as a halfway station between Hawaii and American Samoa by Pan American Airways (Pan Am). The flying boats had a supply ship stationed at Kingman to provide fuel, lodging, and meals for the layover before Pan Am ended the flights in 1938. In 1941, President Roosevelt issued another Executive Order making Kingman a U.S. National Defensive Sea Area which prohibited private vessels from entering the waters within 3 nautical miles of the reef (United States Department of Interior).

In 2000, the Department of the Interior accepted administrative jurisdiction over Kingman Reef from the Department of the Navy, and in 2001, the Kingman Reef National Wildlife Refuge was established and joined what, at the time, was called the Pacific Remote Islands National Wildlife Refuge Complex, and later became the Pacific Islands Refuges and Monuments Office. In 2009, President George W. Bush, through Proclamation 8336, established PRIMNM to protect and preserve the marine environment from 0 to 50 nm around Baker, Howland, and Jarvis Islands, Wake, Johnston and Palmyra Atolls, and Kingman Reef, for the proper care and management of the historic and scientific objects therein (National Oceanic and Atmospheric Administration 2009). As part of the PRIMNM designation, the Refuge boundaries were extended to include the waters and submerged lands from 0–3 nm to 12 nm. The Monument waters and submerged and emergent lands from 0–50 nm are cooperatively managed by the U.S. Fish and Wildlife Service (USFWS) and NOAA.

In 2007, a fishing vessel estimated to be 26 m long was discovered grounded at Kingman. The origins of the vessel remain unknown. Since its discovery, the vessel has broken down significantly, but the iron left from the components of the large engine room still pose a threat to the reef ecosystem (United States Fish and Wildlife Service 2014). Noting the leaching of contaminants from the shipwreck at Kingman was likely supporting the growth of invasive organisms, Kingman Reef wreck removal operations were enacted in 2013, with the goal of removing the abandoned wreck thereby reducing the contaminants in the water and improving wildlife habitat in the areas. A total of 44,000 pounds of wood, metal, and fiberglass debris were removed from the unknown fishing vessel before removal operations ended in 2014 (United States Fish and Wildlife Service 2014).

Geology and Environmental Influences

Kingman Reef, which is located 67 km (36 nm) northwest of Palmyra Atoll, is influenced seasonally by the eastward-flowing North Equatorial Countercurrent (NECC) and the westward-flowing North Equatorial Current (NEC). During the summer months when weather and sea conditions are strongly influenced by the Intertropical Convergence Zone, Kingman experiences predominantly light and variable winds, high precipitation, and a humid tropical climate with daytime temperatures averaging 29 °C (85 °F). During the winter months, Kingman experiences moderately strong easterly trade winds (Brainard et al. 2005).

Seeing through the seafloor of Kingman Reef from the small boat.
Photo: Brittany Huntington, NOAA Fisheries.

Benthic Characterization

3.2 Benthic Characterization

NOAA Nautical Chart of Kingman Reef.
Source: NOAA, 2nd Ed., Dec. 2008.

In this section, the benthic habitats of Kingman Reef are characterized for the depth range from 0 m 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 Kingman Reef since 2006, using a variety of methods as described in the "Benthic Characterization Methods" section of "Chapter 1: Overview." These methods include multibeam bathymetric and backscatter surveys, and single-beam surveys for depth validation.

Multibeam Surveys

Mapping surveys were conducted around Kingman Reef during the 2006 Pacific RAMP research cruise using multibeam sonar systems aboard the NOAA ship *Hiʻialakai* (Simrad EM 300 and EM 3002D) and R/V *AHI* (Reson 8101-ER). Bathymetric and backscatter data were collected for depths between approximately 3 and 3,500 m and used to derive mapping products covering approximately 926 km^2. Approximately 52.6 km^2 of the area between 0 and 150 m depths remained unmapped, mostly due to time and weather constraints and also because the shallowest areas were inaccessible to survey with vessel-mounted multibeam systems. *AHI*-based mapping efforts primarily focused on mapping around the outer reef margin and defining the southeast pass and edges of the inner reef, and a few transects were also collected across the center of the Lagoon.

Two of the resulting gridded bathymetric products are a 5 m high-resolution grid of the reefs, banks, shelf, and slope habitats that allow for the identification of fine-scale features to a depth of 300 m, and a coarser 20 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 Kingman Bathymetry page of the Pacific Islands Benthic Habitat Mapping Center (PIBHMC) website.

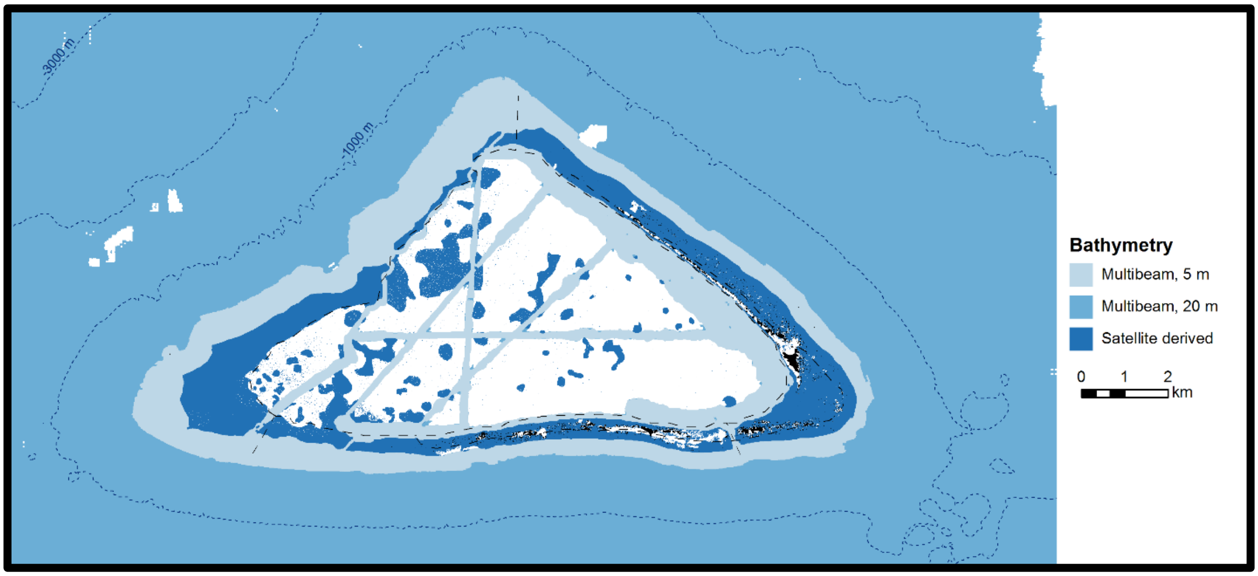


Figure 3. Bathymetric coverage map for Kingman Reef showing extent of high- (5 m) and mid-resolution (20 m) gridded multibeam data acquired by the Ecosystem Sciences Division (ESD) in 2006 (lighter blues), and estimated bathymetry derived by the ESD from satellite imagery (dark blue). The dotted dark blue lines represent the 1,000 m depth contours. Gaps in bathymetric coverage are shown in white and emergent 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 backscatter data from the deeper surveys conducted from the *Hiʻialakai* were gridded at 5 m resolution. Acoustic backscatter intensities reveal characteristics of the seabed around Kingman Reef that can be related to topography and slope. While these data are useful for geomorphology and habitat interpretation, both the shallow and deeper backscatter data have quality issues, including high noise levels and patchiness in the coverage. The data and supporting documentation are available on the Kingman Backscatter page of the PIBHMC website.

Single-beam Surveys

Single-beam sonar data were acquired around Kingman Reef from depths between approximately 0 and 118 m in 2012, with a soundings error of approximately 1 m (Figure 4).

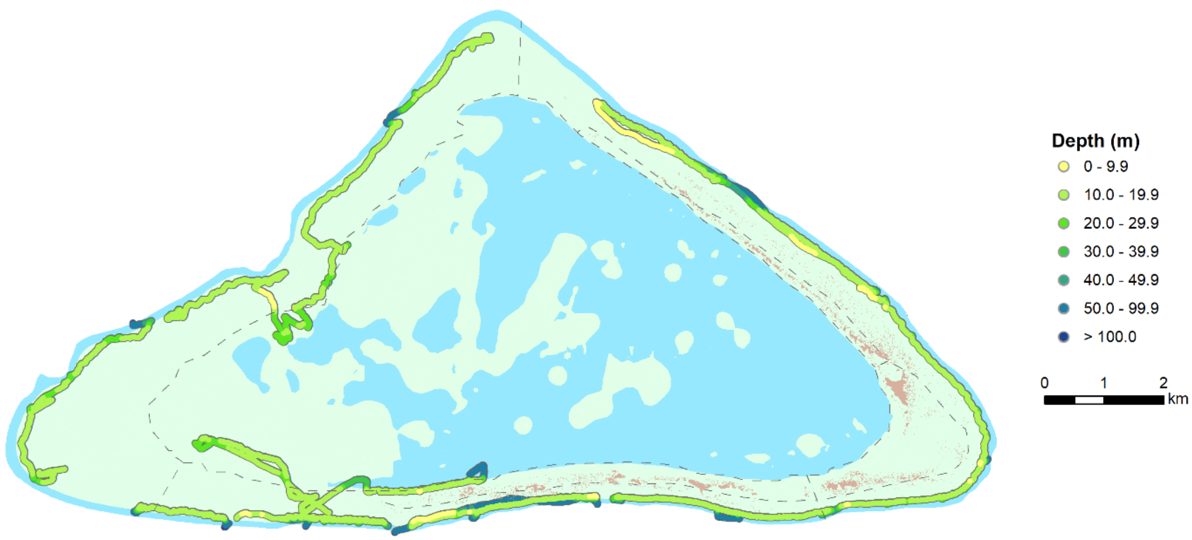


Figure 4. Depth validation data for Kingman Reef collected by the Ecosystem Sciences Division in 2012.

Towed-camera Surveys

No habitat validation data for habitat mapping purposes were collected at Kingman Reef.

Habitat characterization

Satellite-derived Bathymetry

ESD derived estimated depths between 0 and 25 m from IKONOS satellite imagery acquired in 2003 to fill gaps in the shallow-water bathymetric coverage around Kingman Reef. ESD later derived estimated depths between approximately 1 and 15 m from WorldView-2 satellite imagery acquired in 2015. Depth soundings collected in 2012 (Figure 4) were used to validate the satellite-derived depths, resulting in 68% agreement between the overlapping soundings and estimated depths. The data and supporting documentation are available on the Kingman Bathymetry page of the PIBHMC website. Though these estimated depths provide useful information for areas with little or no bathymetric measurements, the low depth accuracy limits the use of these data for other mapping purposes. See Figure 3 for the extent of satellite-derived depths generated by ESD that partially filled the bathymetric coverage gap around Kingman.

Integrated Bathymetry

ESD's multibeam bathymetry and satellite-derived depths were combined to produce an integrated bathymetric map for Kingman Reef (Figure 5).

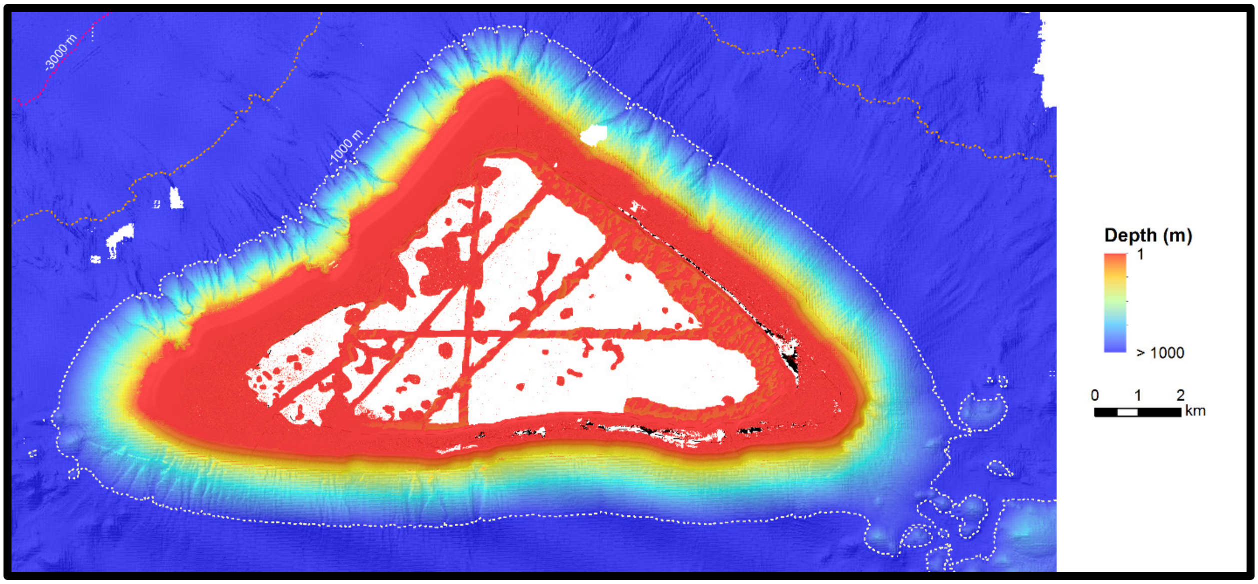


Figure 5. Integrated bathymetric map focusing on depths from 0 to ~1,000 m for Kingman Reef, with gaps in bathymetric coverage shown in white and emergent features in black. The dotted lines represent the 1,000 m (white), 2,000 m (orange), and 3,000 m (red) depth contours.

The bathymetric data around Kingman Reef are characterized by the triangular shape of the atoll reef structure, with shallow reefs encircling a large central lagoon. Three channels cut through the reef structure—one each in the North Backreef and West georegions and La Paloma Channel located between the Eastern Pools and South georegions. Part of the reef is awash during low tide, and areas of the reef can be dry with a small amount of emergent coral rubble during low-water stands (Figure 5). Seafloor depths inside the Lagoon georegion range from a few meters below sea level to deeper than 50 m; however, the overall seafloor structure is largely uncertain for that area because of the limited available data. The seafloor surrounding Kingman is variable and complex with steep slopes, though it lacks a broad shallow terrace structure outside the reef crest that is observed at other locations in the PRIMNM (e.g., Palmyra Atoll). Canyon-like channels incise most of the bank edges in the West, South, and East georegions and extend to depths deeper than 3500 m. The seafloor extending beyond the southern points of the West and East georegions has small seamount features rising to depths of 1,000–1,500 m, many of which appear to be volcanic in origin (Maragos et al. 2008).

Bathymetric Derivatives

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

Seafloor Substrate

ESD generated predicted seafloor substrates (i.e., hard or soft bottom) for Kingman Reef in 2018 (Figure 6). The source data used to produce the substrate map for Kingman for water depths to 1000 m include multibeam bathymetric and backscatter data from the 2006 *Hi'ialakai* surveys and WorldView-2 satellite imagery acquired in 2015. The data and supporting documentation are available on the [Kingman Seafloor Characterization] page of the PIBHMC website.

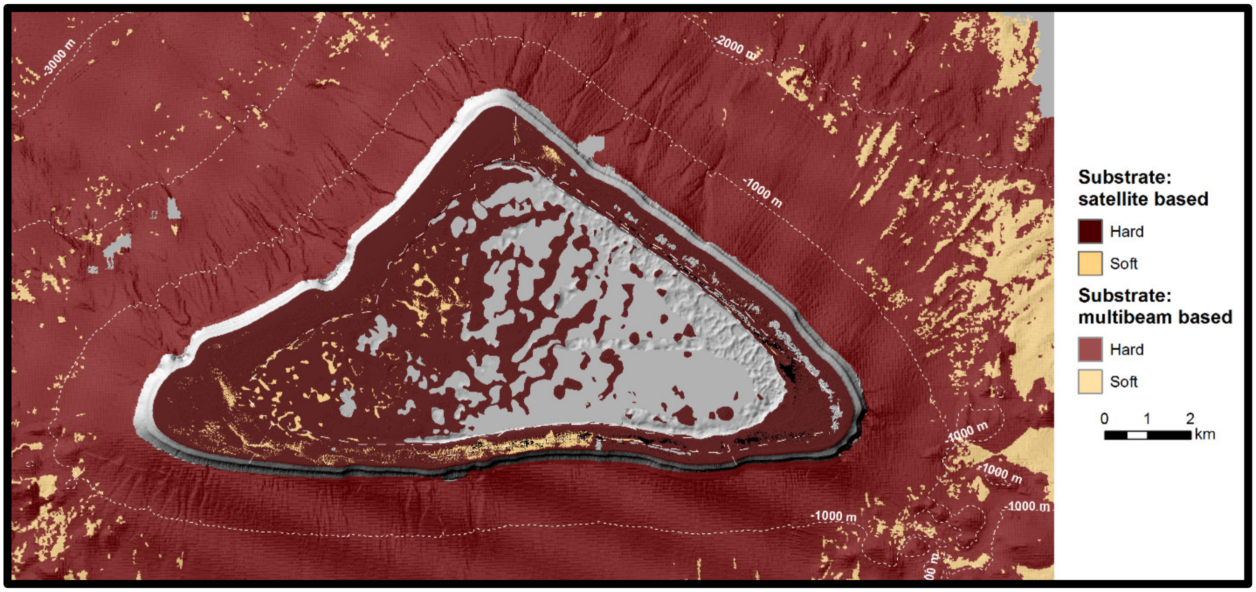


Figure 6. Seafloor substrate map of Kingman Reef showing hard- and soft-bottom habitats. Depths from ~0 m to 30 m were derived from WorldView-2 satellite imagery, and depths >30 m were based on gridded multibeam bathymetric and backscatter data (20 m and 5 m resolution, respectively). The dotted white lines represent 1,000 m interval depth contours. Gaps in substrate coverage are shown in grey and emergent features in black.

Substrate classifications were generated from the satellite-derived predictions for depths from 0 to 30 m and from the multibeam-derived predictions for depths >30–1,000 m. A significant gap exists in the Lagoon georegion of the shallow substrate map because areas too deep to classify using the satellite-based method were removed from the analysis. A gap also exists between the deepest extent of the shallow substrate map and the shallowest extent of the deeper substrate map. Though the multibeam data acquired from the *AHI* surveys partially (inside the Lagoon georegion) or completely overlap these gaps, the *AHI* data were not used to derive substrates because the backscatter data produced erroneous results.

The substrate map indicates the majority of the seafloor around Kingman Reef to 1,000 m depths is hard substrate with patches of soft-bottom habitat—most likely composed of sand—within the Lagoon georegion and surrounding reef areas. Sand bars and shallow reefs in the Backreef and Eastern Pools georegions separate the Lagoon georegion from the shallow forereef areas along the exterior edges of the reef structure.

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

Many biological communities are 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 5 was used to classify depth bins (Figure 7) from 0 to 1,000 m for Kingman Reef. 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 by available depth strata are included in Table 1.

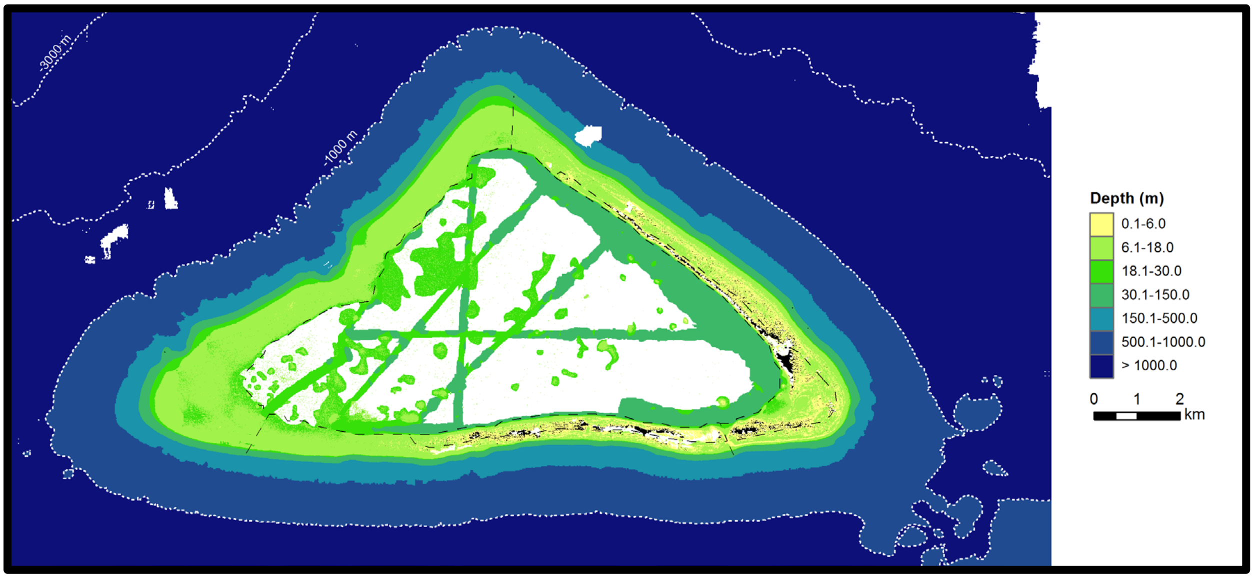


Figure 7. Depth strata map for Kingman Reef from 0 m to 1000 m, with gaps in bathymetric coverage shown in white and emergent features in black. The dotted white lines represent 1,000 m interval depth contours.

The bathymetric data gaps at Kingman Reef precluded derivation of a complete 6 m or 18 m isobath; therefore, the estimated seafloor areas for the shallow, mid, and deep depth strata are not provided in Table 1. At Kingman, 65% of the seafloor between 0 and 150 m depths was mapped, leaving a gap approximately 30.1 km^2. The map of the seafloor from 150 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 Kingman Reef. Seafloor area statistics include actual mapped area (km^2) and estimated seafloor area (km^2) based on the integrated bathymetric map for Kingman. Seafloor areas are not provided for the depth strata between 0 and 30 m depths due to bathymetric data gaps. Emergent reef area is <0.1 km^2.

Depth (m)	Estimated Seafloor (km^2)	Mapped Seafloor (km^2)
>0–6	–	5.0
>6–18	–	21.4
>18–30	–	11.0
Subtotal: >0–30	**48**	**37.4**
>30–150	37	17.5
>150–500	18	17.4
>500–1000	69	69.1
Total: >0–1000	**172**	**141.4**

Reef Zones

To support the stratified-random design for Pacific RAMP monitoring surveys, reef zones have been delineated for Kingman Reef, including forereef, backreef, protected slope, and lagoon (Figure 8). Satellite imagery was primarily used to manually digitize the zones.

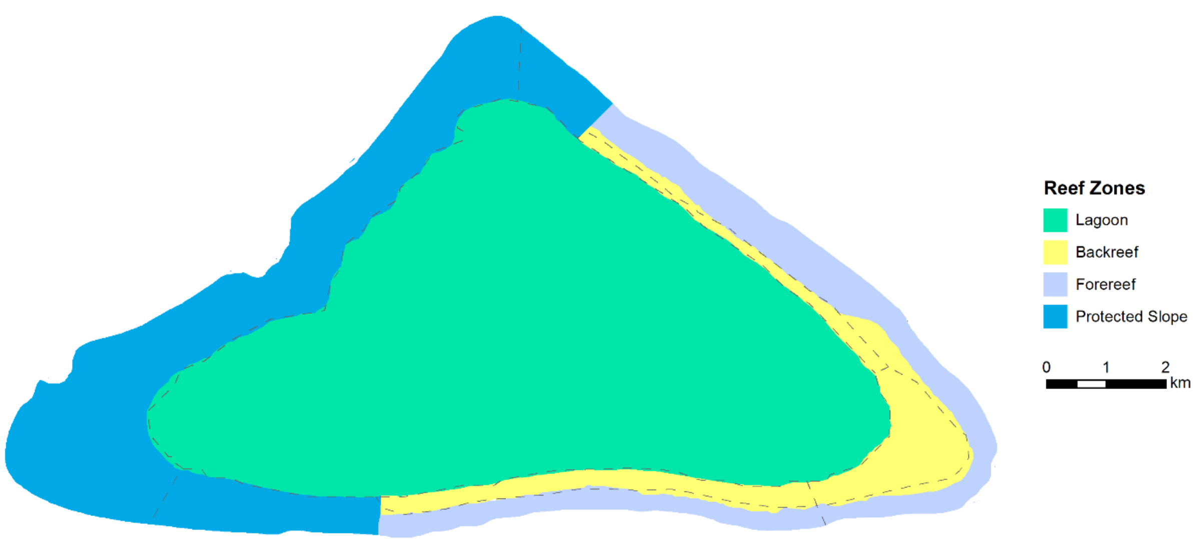


Figure 8. Reef zones for Kingman Reef.

Substrate

Only hard-bottom substrates were targeted for stratified-random reef fish and benthic monitoring surveys of Pacific RAMP. However, at the time the survey strata were established for Kingman Reef, substrate maps did not exist. As previously discussed, predicted seafloor substrates have since been developed for Kingman and will be incorporated into the survey strata in advance of the Pacific RAMP surveys at Kingman scheduled for 2021. In general, the nearshore seafloor area around Kingman is comprised mostly of hard-bottom habitats mixed with patches of soft-bottom substrates in all georegions (Figure 6).

Survey Strata

To date, the survey strata used for the stratified-random fish and benthic surveys were based on depth only (Figure 7). The new substrate and reef zone maps together with the depth strata indicate approximately 45 km^2 of surveyable seafloor is available within hard-bottom (or unknown) habitats in the 0 to 30 m depth range at Kingman Reef.

NOAA diver deploys instrument at Kingman Reef.
Photo: Ariel Halperin, NOAA Fisheries.

Ocean and Climate Variability

3.3 Ocean and Climate Variability

NOAA oceanographer positions a sea surface buoy and anchor into position at Kingman Reef. Photo: NOAA Fisheries.

Survey Effort and Site Information

Kingman Reef is a triangle-shaped geologic feature with limited shallow reef area around the perimeter and isolated patch reefs in the lagoon. The eastern rim of the reef (Eastern Pools and North/South Backreef georegions) is comprised of several narrow strips of emergent rubble and shallow forereef (<10 m) that enclose a relatively deep lagoon, while the much deeper (~15–20 m) submerged reef crest or terrace of the West georegion of Kingman allows free exchange of oceanic waters with the open lagoon. With this somewhat unique free exchange or open circulation and deep lagoon at Kingman, monitoring efforts have focused on the protected backreef slopes and exposed forereefs and, to a lesser extent, the central lagoon.

On a regional scale, Kingman Reef is impacted by the seasonal latitudinal shifts in the westward-flowing NEC and the eastward-flowing NECC. During seasons when the NECC approaches Kingman from the warmer, more biologically-diverse Western Pacific, waters can flow over the submerged western terrace directly and into the lagoon. Conversely, the westward-flowing NEC approaches Kingman from the less diverse Eastern Pacific and flows around the forereef habitats.

Additionally, weather and sea conditions are seasonally modulated by the latitudinal shifts of the Intertropical Convergence Zone, which brings heavy convective rains and light winds during the summer months and strong trade winds during the winter months. The El Niño Southern Oscillation (ENSO) is considered the strongest driver of interannual variability at Kingman, as 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 intense regional and local upwelling.

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 occur on a backdrop of global climate change, as concentrations of carbon dioxide in the atmosphere are altering the temperature and chemistry of 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 that decrease pH making it more difficult for corals and calcifying reef organisms to grow.

Since 2000, Pacific RAMP efforts have monitored the oceanographic conditions of coral reef ecosystems influencing Kingman Reef. Data have been collected for 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, coral growth, and skeletal density to examine the balance between production and removal of calcium carbonate on the reefs (Figure 9, Figure 10, Figure 11, Figure 12, and Figure 13). A summary of the environmental survey efforts around Kingman Reef from 2000 to 2015 is shown in Table 2. Refer to "Chapter 1: Overview" for oceanographic instrumentation specifics and water sample collection methodologies.

Field data collections were coupled with remote sensing data sets and model products to provide the large-scale climate and oceanographic context for the in situ observations. Remote sensing data sets used include 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 conditions.

Table 2. Summary of the ocean and climate survey efforts at Kingman Reef by year from 2000 through 2015. The following instruments were deployed: coral reef early warning system (CREWS) buoy, sea surface temperature (SST) buoy, subsurface temperature recorder (STR), ecological acoustic recorder (EAR), acoustic Doppler current profiler (ADCP), calcification accretion unit (CAU), and autonomous reef monitoring structures (ARMS). Diel suite deployment was carried out for carbonate chemistry monitoring. Conductivity-temperature-depth (CTD) casts, shallow (near reef) and deep (offshore), have corresponding discrete water samples, shallow (near reef) and deep (offshore). Coral cores of *Porites* spp. were collected by either a pneumatic or hydraulic drill. Numbers indicate the quantity of instruments deployed (D) and retrieved (R) as D/R, water samples, CTD casts, and coral cores per year.

	Instruments							Diel Suite		CTD Casts		Water Samples		Coral Cores
Year	**CREWS**	**SST**	**STR**	**EAR**	**ADCP**	**CAU**	**ARMS**	**Moored CTD**	**Water Samples**	**Shallow**	**Deep**	**Shallow**	**Deep**	***Porites* spp.**
2000	–	–	–	–	–	–	–	–	–	13	–	–	–	–
2001	–	–	–	–	–	–	–	–	–	32	–	–	–	–
2002	1/-	–	–	–	1/-	–	–	–	–	16	–	–	–	–
2004	-/-	1/-	5/-	–	-/1	–	–	–	–	44	–	–	–	–
2006	–	1/1	7/5	–	-	–	–	–	–	73	–	56	–	–
2008	–	1/-	9/7	1/-	1/-	–	9/-	–	–	82	24	72	83	–
2010	–	1/-	10/9	1/1	1/1	40/-	9/9	–	–	56	2	16	10	5
2012	–	-/1	13/10	1/1	-/1	40/40	9/9	–	–	8	4	16	20	4
2015	–	–	13/13	-/1	–	25/35	-/9	1	9	15	–	18	–	–
Total	**1/-**	**4/2**	**59/34**	**3/3**	**3/3**	**105/75**	**27/27**	**1**	**9**	**339**	**30**	**182**	–	**9**

Figure 9. Deployment locations around Kingman Reef of an acoustic Doppler current profiler (ADCP), coral reef early warning system (CREWS) buoy, an ecological acoustic recorder (EAR), and sea surface temperature (SST) buoy. 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.

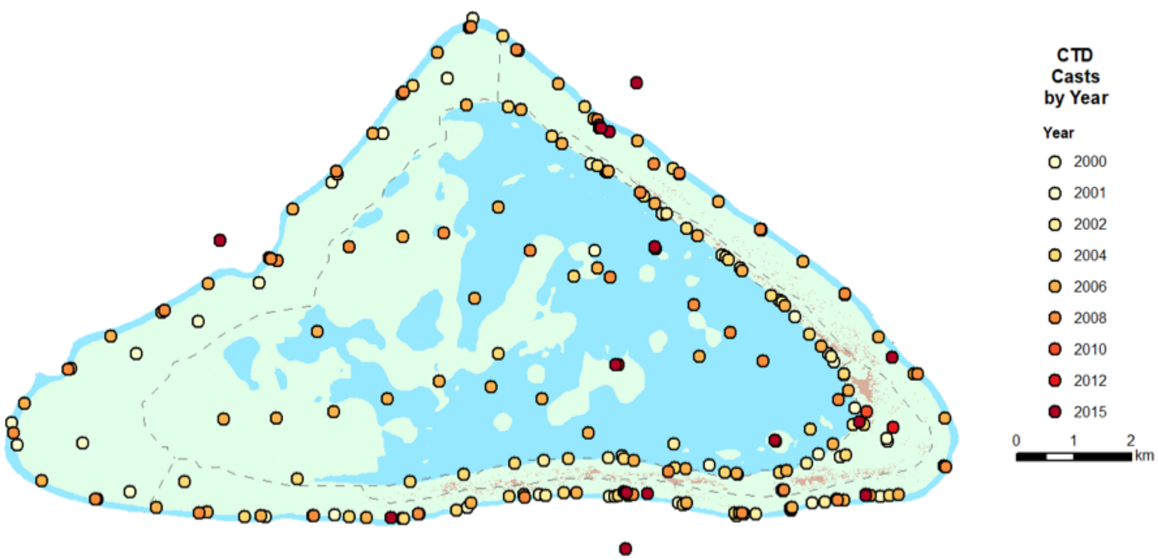


Figure 10. Locations of nearshore conductivity-temperature-depth (CTD) hydrocasts, measuring water column salinity and temperature from the ocean surface to depth of ~30 m around Kingman Reef. Casts in earlier years (2000–2010) prioritized sampling the entire perimeter of the forereef, while later efforts (2012–2015) focused on permanent instrumentation sites (sites with subsurface temperature recorders, autonomous reef monitoring structures, and/or calcification accretion units).

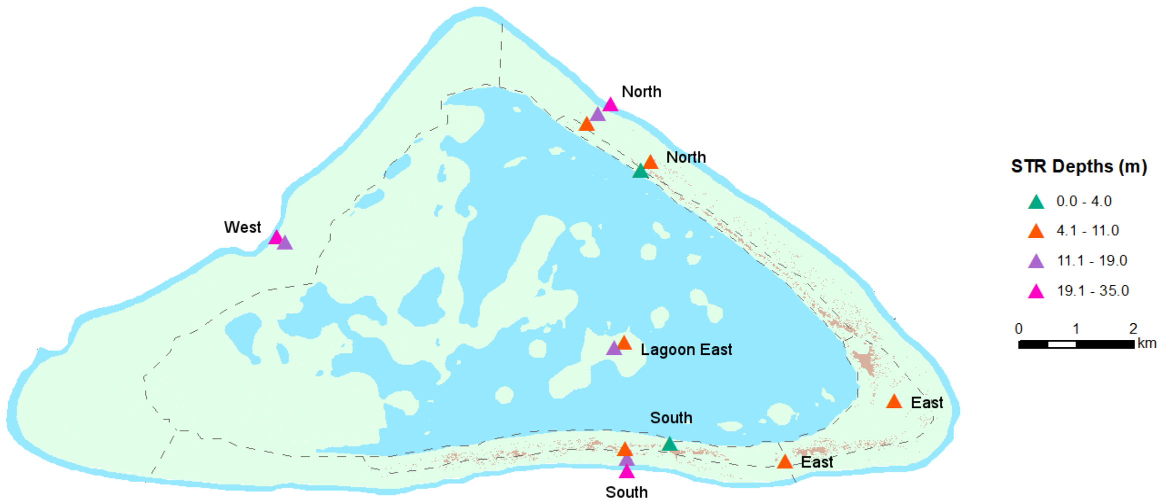


Figure 11. Locations of subsurface temperature recorders (STRs), deployed on the reef substrate in depths ranging from 1 to 35 m depths around Kingman Reef. Multiple STRs may have been collected at the same location over multiple years; however, they are represented by a single marker on the map. STR locations are labeled by the cardinal direction assigned for analysis (North, East, South, West, and Lagoon East, see Figure 18).

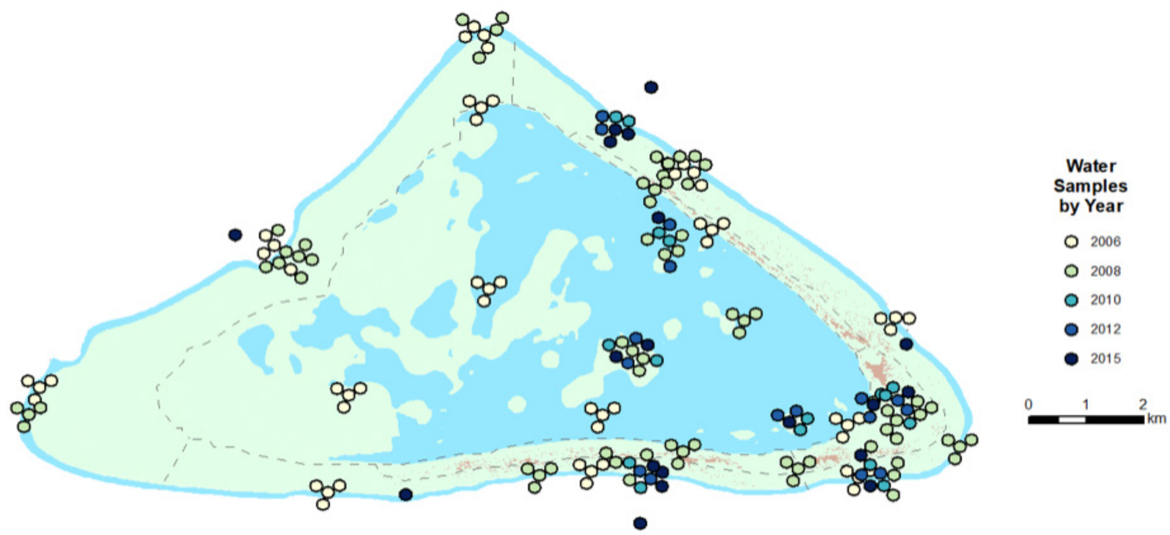


Figure 12. Locations of discrete seawater sample collections from 1 to 35 m depths around Kingman Reef. Samples evaluated for various analytes: dissolved inorganic carbon, total alkalinity, chlorophyll-*a*, and dissolved inorganic nutrients. Water samples collected at the same location over multiple years have been plotted adjacent to one another and organized around their shared location on the map.

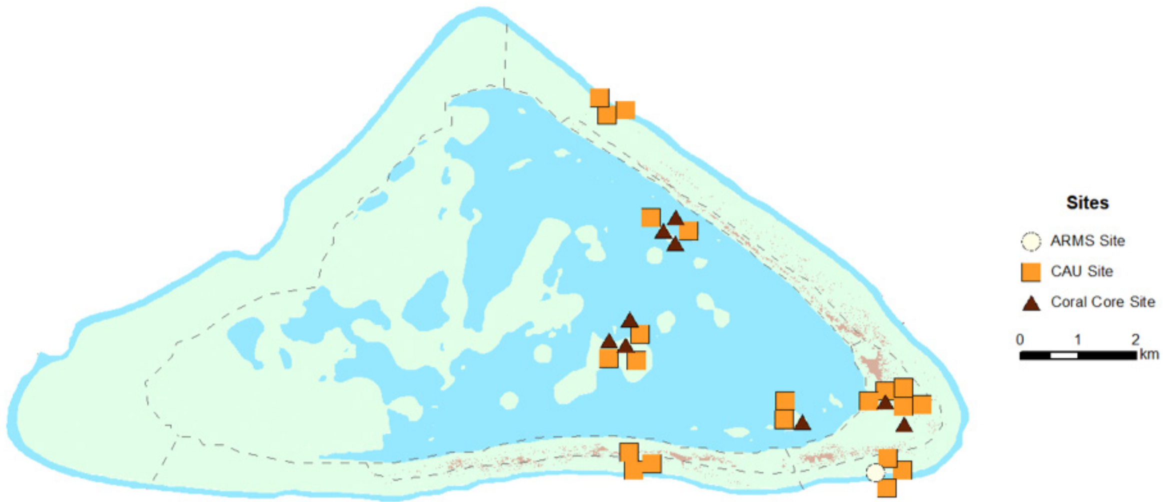


Figure 13. Locations of autonomous reef monitoring structures (ARMS, 3 per site), and calcification accretion units (CAU, 5 per site), deployed on the reef at approximately 15 m depths around Kingman Reef. Coral cores of *Porites* spp. collected opportunistically at depths from 5 to 15 m. Instrument 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 Kingman Reef show a relationship with interannual warming and cooling associated with ENSO (Figure 14). However, because Kingman's location at a latitude of 6°23′N is outside of the equatorial region, it experiences a weaker coupling with ENSO and stronger seasonal cycle than the equatorial islands within the PRIMNM (e.g., Jarvis, Howland, and Baker Islands). Being outside of the equatorial waveguide also means that it is not in the path of the eastward-flowing subsurface Equatorial Undercurrent and, therefore, does not experience the strong topographic upwelling of the equatorial islands. Being 6 degrees north of the Equator, it also experiences substantially less equatorial upwelling caused by the divergence of the trade wind-driven Ekman currents by the earth's rotation. The available ONI, SST anomalies, DHWs, and chl-*a* anomalies during the period from 1981 to 2017 are shown in Figure 14. The ONI shows the variability and frequency of strong warm (positive) and cool (negative) SST anomalies, with higher SSTs persisting during El Niño warm events and lower SSTs during La Niña cool events (Figure 15a). While the temporal patterns of SST anomalies at Kingman largely track variability in ENSO as indicated by ONI, there were notable breaks that caused weaker correlations. In particular, Kingman experienced relatively low SST anomalies compared to the magnitude of the ONI during the extreme 1997–1998 El Niño event, a pattern also observed at nearby Palmyra Atoll.

The coral reefs at Kingman Reef have experienced only mild episodes of ENSO-driven high thermal stress over the past four decades, visualized as DHW in Figure 14c. DHWs estimate the amount of thermal stress that has accumulated in an area over a 12-week period by summing any temperature exceeding the maximum monthly mean by 1 °C. 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 individual cumulative DHW events that were observed during the period from 1985 through 2017 were correlated to warming events observed in the regional ONI (Figure 14a), with DHWs >4 °C-weeks accumulated at Kingman in response to El Niño events in 2004–2005, 2009–2010, and 2015–2016. DHWs of this magnitude are not expected to cause significant bleaching or mortality.

An inverse relationship appears to have existed between ENSO-driven variability in SST anomalies and chl-*a* anomalies, where positive temperature anomalies corresponded with negative chl-*a* anomalies (Figure 14d and Figure 15b). During La Niña events, enhanced equatorial upwelling of anomalously cool, nutrient-rich deeper waters occurred and the surface waters were advected north toward Kingman, where increased chl-*a* concentrations were observed. During strong El Niño conditions, warm surface waters stratified the water column and suppressed the upwelling of nutrient-rich waters, resulting in decreased chl-a concentrations at Kingman.

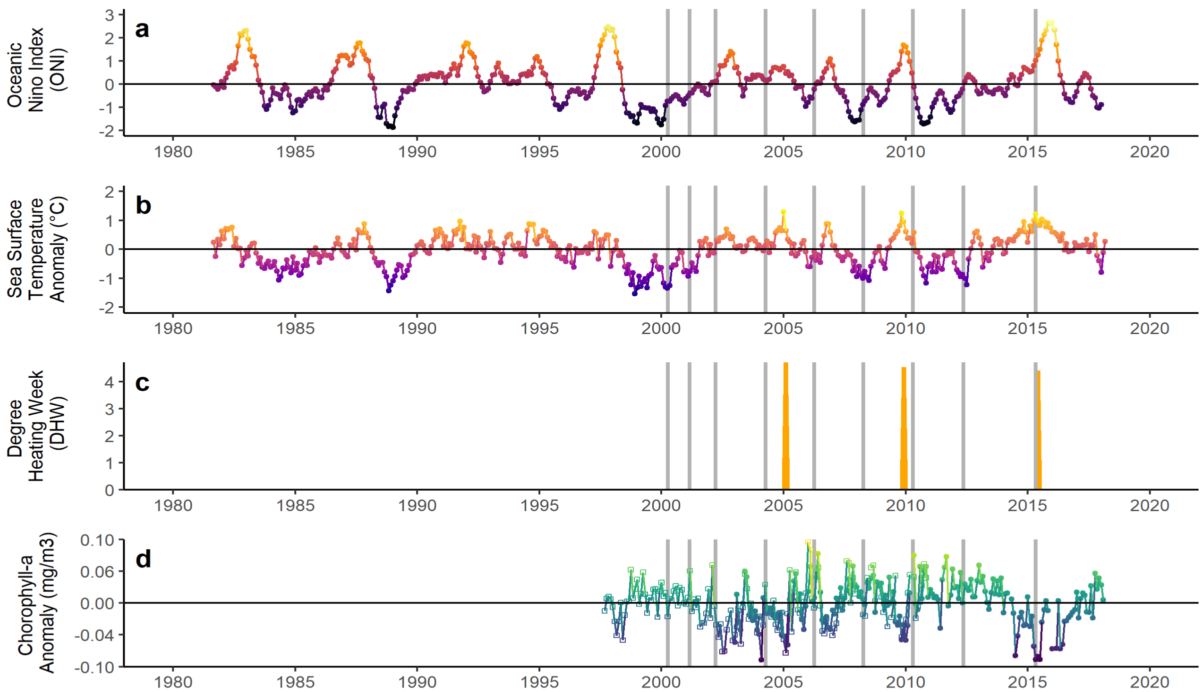


Figure 14. Time series of oceanographic conditions at Kingman Reef: (a) a 3-month rolling mean of Oceanic Niño Index (ONI) from September 1981 to April 2018 in the El Niño 3.4 region (5°N–5°S, 120°W–170°W), (b) sea surface temperature (SST) anomalies from September 1981 to April 2018, (c) Cumulative 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 Kingman (6°17.2′N to 6°32.8′N and 162°34.3′W to 162°14.4′W). Shading for SST and chl-a data indicates the magnitude of the anomaly. The grey vertical bars within each time series denote the occurrence of survey missions to Kingman.

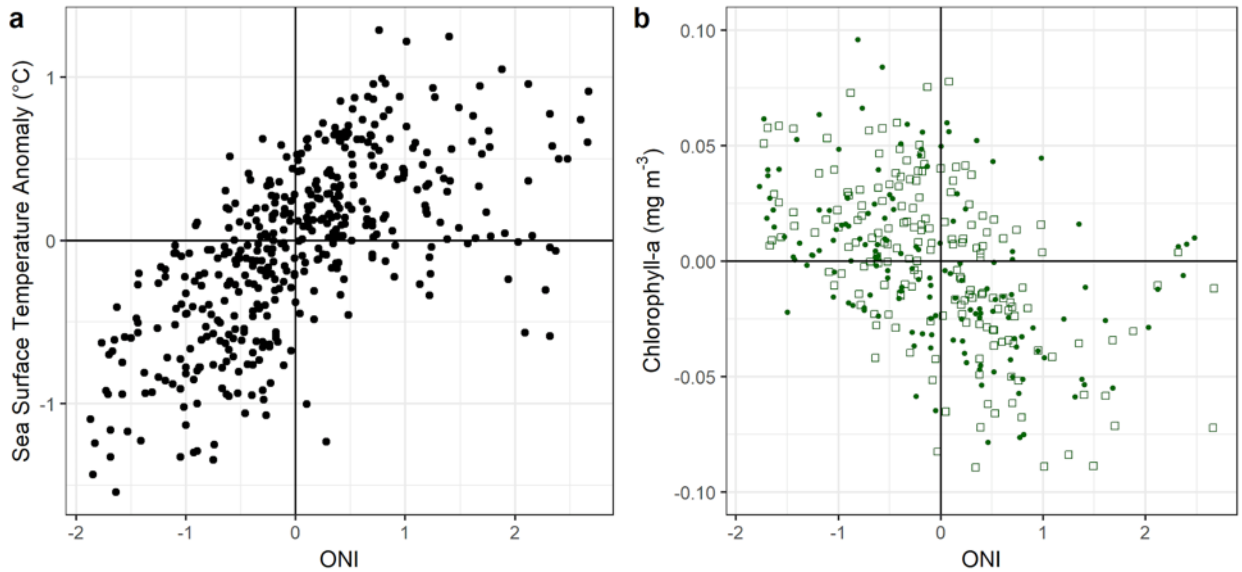


Figure 15. Relationship between monthly-averaged oceanographic conditions at Kingman Reef: (a) Oceanic Niño Index (ONI) vs. sea surface temperature (SST) anomaly, and (b) ONI vs. satellite-derived chlorophyll-*a* (chl-*a*; Sea-Viewing Wide Field-of-View Sensor in boxes and Moderate Resolution Imaging Spectroradiometer in circles) data. Available data for ONI, SST anomaly, and chl-*a* were extracted for a box around Kingman (6°17.2′N to 6°32.8′N and 162°34.3′W to 162°14.4′W).

Water Column Observations

The physical and chemical properties of the water column around Kingman Reef varied both temporally and spatially around the region due to both regional and local oceanographic processes. Figure 16 shows the location of shallow-water CTD hydrocasts conducted in the nearshore waters around Kingman in 2001 (30 casts) and 2006 (72 casts). Nearshore waters around Kingman's forereefs appeared generally vertically well-mixed during both of these years, though there were spatial differences and areas that were locally stratified (Figure 17). For example, the water column of the south-facing forereefs in the South and East georegions were warmer, less saline, and more stratified than other georegions in 2001. In addition, unlike Palmyra, there was also little observable difference in these water properties between the exposed forereefs, the more protected backreef slopes, and the lagoons during the 2006 surveys, suggesting a high degree of water exchange and mixing between the outer reef and inner Lagoon georegion. Interestingly, there was a relatively narrow region of higher salinities in the West georegion and the western portion of the Lagoon georegion during the 2006 surveys. Both of these sets of CTD hydrocasts were collected during periods of weak to moderate La Niña conditions.

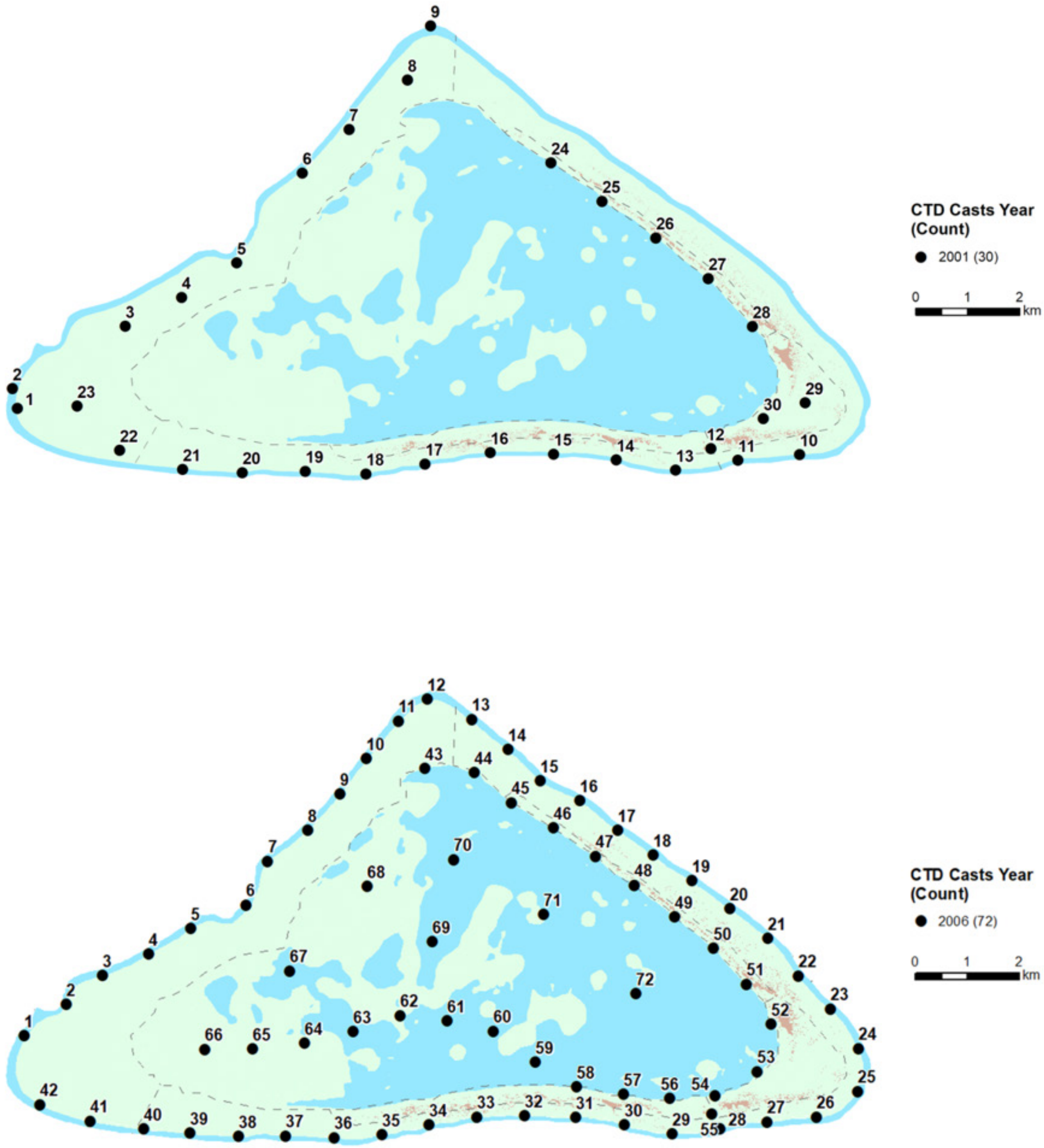


Figure 16. Shallow-water conductivity-temperature-depth (CTD) sampling locations around Kingman Reef. CTDs were conducted during 2001 (30 casts), and 2006 (72 casts). The casts are numbered sequentially in a clockwise direction.

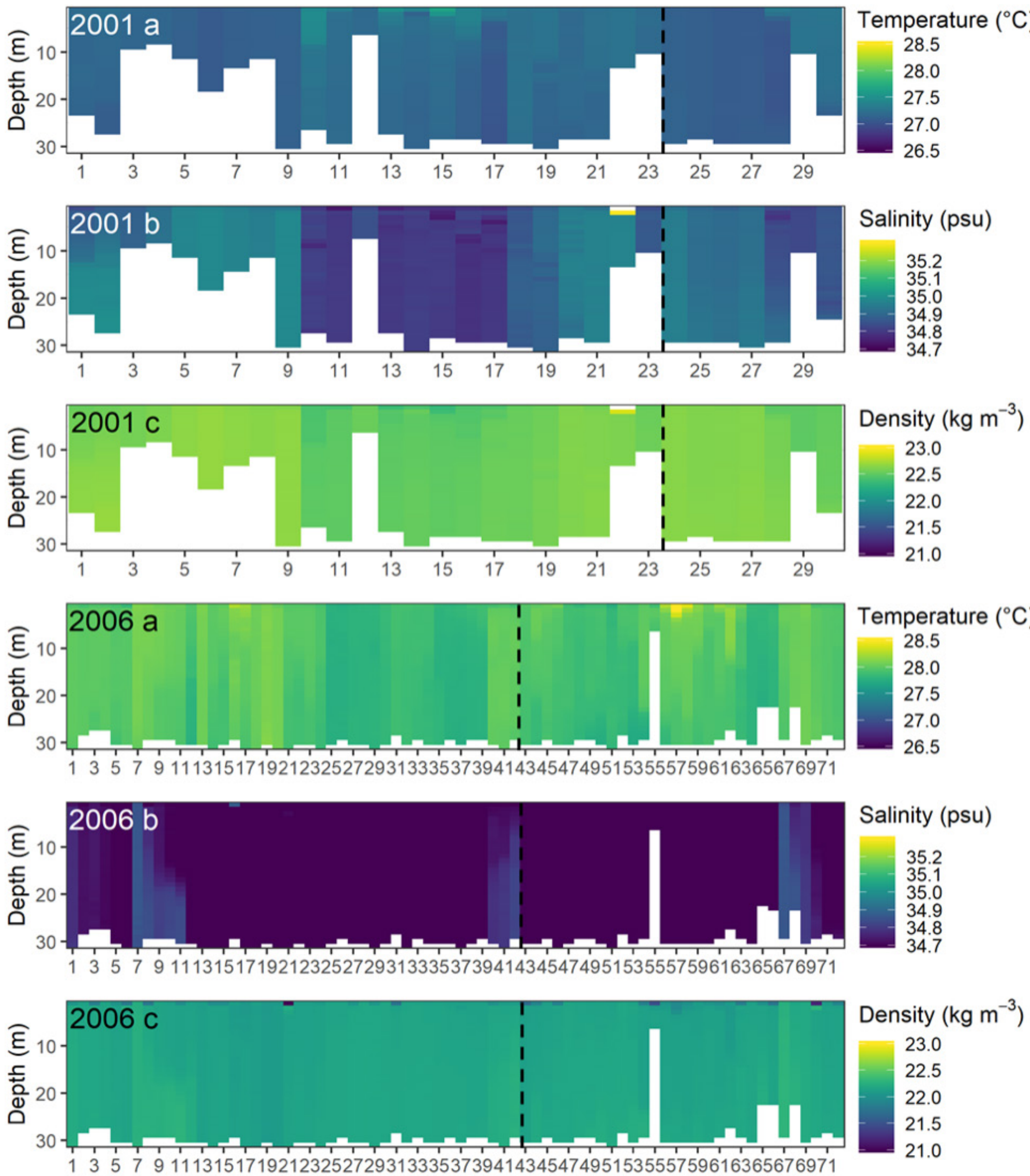


Figure 17. Profiles from shallow-water conductivity-temperature-depth (CTD) casts around Kingman Reef in 2001 (top three panels) and 2006 (bottom three panels) for (a) temperature (°C), (b) salinity (psu), and (c) sigma-t density (density of seawater at atmospheric pressure in kg m^{-3} -1,000), from the surface to depths of ~35 m. The casts are numbered sequentially in a clockwise direction around the island. The top three panels show 2001 profiles 1–30, while the bottom three panels show 2006 profiles 1–72. The vertical dotted lines in all panels delineate the forereef CTD casts from the lagoon casts.

Between 2000 and 2017, a total of 34 moored subsurface temperature recorders (STRs) collected temperature time series at depths between 1 and 31 m (Figure 11). This suite of STRs provided in situ vertical thermal structure observations to characterize the temperature regimes experienced by the coral reefs around Kingman at smaller spatial scales and greater depths than is possible using satellite SST data alone. The coral reefs at Kingman experienced temporal variability of temperature over diurnal, seasonal, and interannual scales, though the seasonal cycle appeared to be the dominant scale of variability with typical temperature differences between summer and winter of 1–3 °C (Figure 18). The range of seasonal variability was modulated by interannual variability associated with ENSO-driving temperatures between 25 °C (during winter/La Niña conditions) and 30 °C (during summer/El Niño conditions). Regionally-driven seasonal and interannual variability were coherent in both magnitude and timing across each of the instrumented sites on different sides of Kingman. The warmest observations in the instrumented record occurred during the moderate 2009–2010 El Niño. Low-temperature pulses were observed in late 2008, 2010, and 2012. These episodic cooling events were most likely driven by tropical instability waves, which form at the unstable boundary between the upwelled equatorial cool tongue waters and the warmer off-equatorial waters during La Niña periods and push fronts of cold equatorial water northward toward Kingman. The water column was mostly vertically well-mixed, with weak localized stratification.

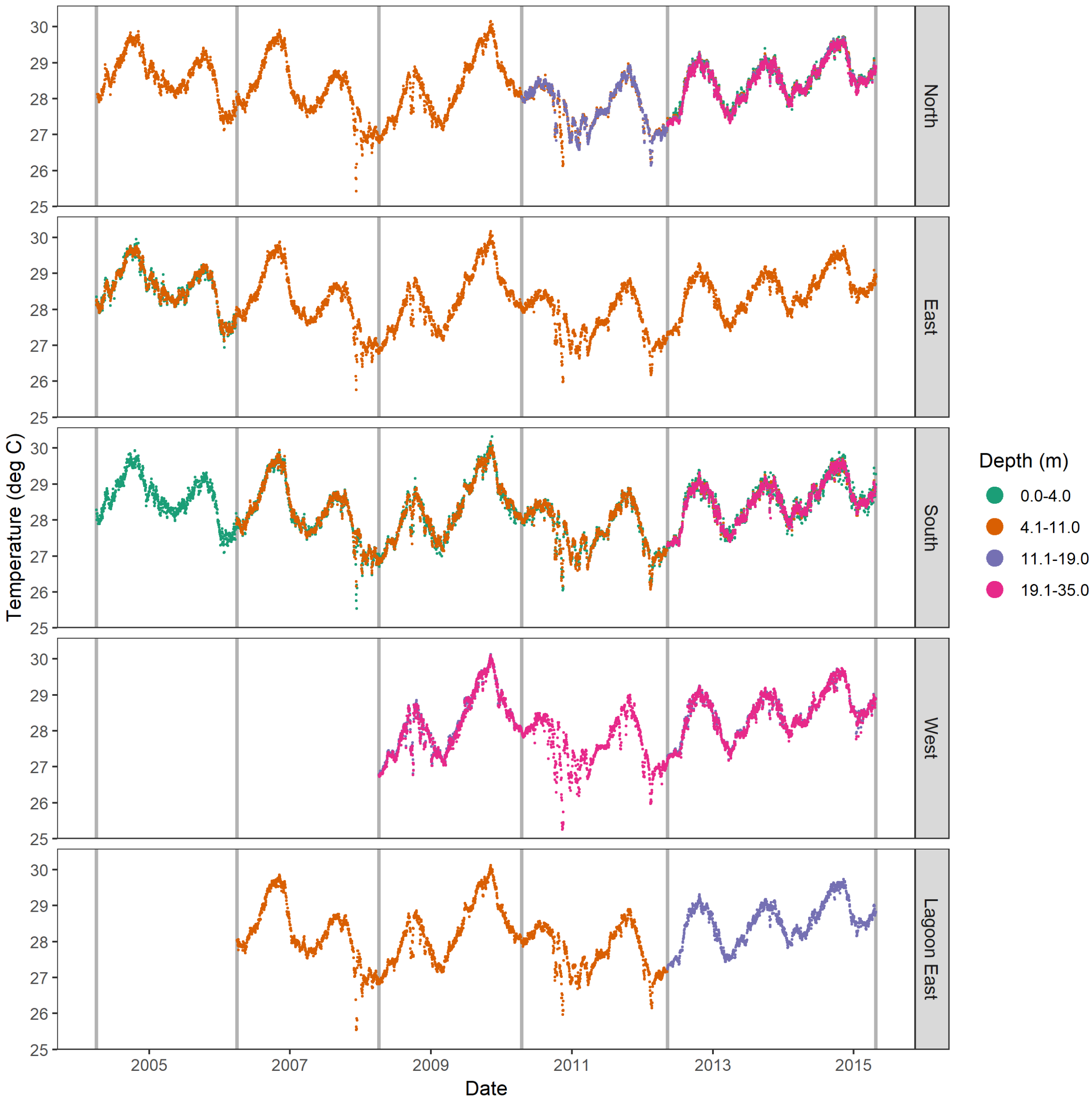


Figure 18. Daily subsurface temperature recorder time-series observations of temperature between 2002 and 2017, collected around Kingman Reef (North, East, South, West, and Lagoon East). Four different depth ranges were defined at each of these locations: green (0–4.0 m), red (4.1–11.0 m), blue (11.1–19.0 m), and magenta (19.1–35.0 m). The grey vertical bars within each time series denote the occurrence of survey missions to Kingman.

Wave Energy

Ocean wave dynamics strongly influence the environmental conditions of coastal habitats. The energy generated by ocean waves varies from tidal and diurnal scales to seasonal and interannual time scales, 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 benthic and fish communities. Hourly wave data for 2010–2016 are shown in Figure 19. The northwest side of Kingman Reef experienced more waves that had a longer period (the length of time between crests) and height (the vertical distance from trough to crest) from December through February (Figure 19, left panels). The south and east sides were exposed to more waves with both a higher period and height during the summer months of July through September (Figure 19, right panels). The mean annual integrated wave power shows that the West and East georegions of Kingman were most impacted by wave patterns, while the South georegion appeared to be relatively sheltered (Figure 20).

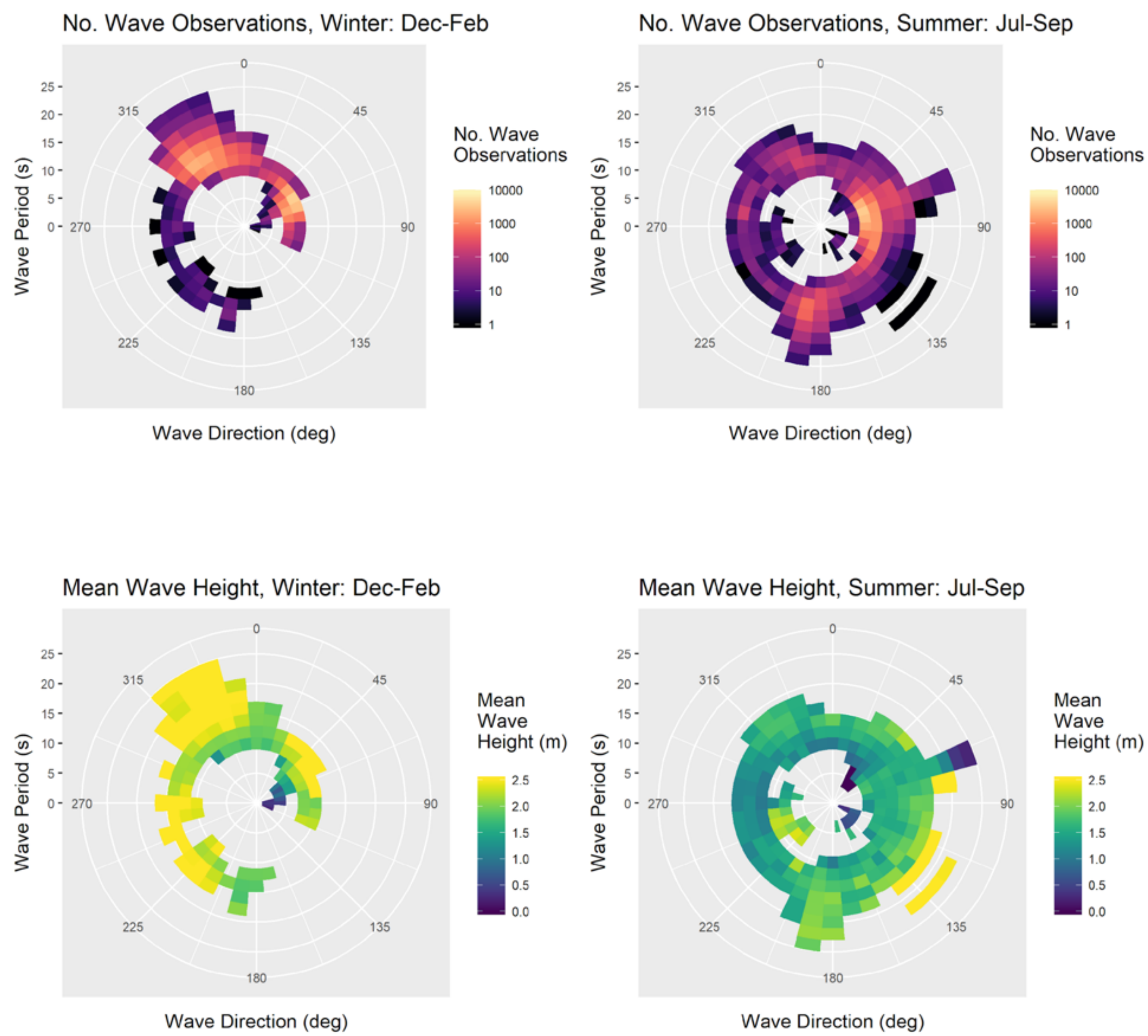


Figure 19. Wave Watch III data from 2010–2016. Top panels: Polar plot of the number of wave observations coming from different directions between December–February (left panel), and between July–September (right panel). Bottom panels: Polar plot of derived mean wave height between December–February (left panel), and between July–September (right panel). The position of wave data around the 360° circle (in 10° bins) displays the direction from which the waves hitting Kingman Reef travel. Zero degrees indicate that waves arrive from due north and 180° 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.

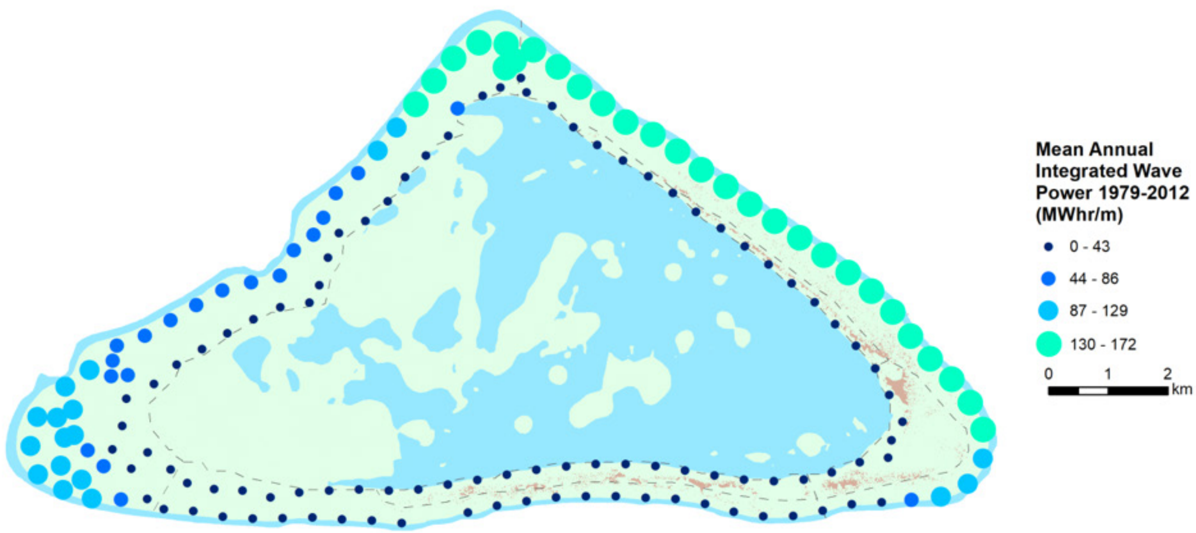


Figure 20. Mean annual integrated wave power (MWhr/m of wave front) at Kingman Reef. Data from 1979 to 2012 correspond to modified Wave Watch III by coastline shadowing using the incident wave swath method.

Carbonate chemistry

Aragonite saturation state (Ω_A) is a measure of the degree to which seawater is saturated with respect to the carbonate mineral aragonite, where Ω_A values above 1 indicate supersaturated conditions. Ω_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 Ω_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, Ω_A, and concentrations of CO_3^{2-} all decrease. This makes it more difficult for corals and calcifying reef organisms to grow.

The direct effects of equatorial upwelling at Kingman Reef are relatively minor due to its higher latitude; therefore, Ω_A values were primarily modulated by large-scale, regional, and local oceanographic processes like ENSO, coral reef metabolic processes (such as calcification-dissolution relationships at specific reef systems), and local variability in water quality. The overall highest values in Ω_A were measured May 2015, during the very early stages of what became the extreme 2015–2016 El Niño, possibly driven by the suppression of upwelling that usually brings deep, lower-Ω_A water to the surface in equatorial regions. Conversely, Ω_A values during more ENSO-neutral conditions in 2012 were lower than those measured in 2010 and 2015. Ω_A values for the reef waters around Kingman were higher in 2010 and 2015, and in 2012, near or slightly below the median of values observed by ESD across the U.S. Pacific Islands region (Figure 21). The pH values for the reef waters around Kingman were lower than the median of values observed by ESD across the U.S. Pacific Islands region for each of the three survey years (Figure 22), but 2012 scored lowest when compared to other Kingman survey years.

Spatial patterns in the carbonate chemistry observations around Kingman Reef were generally consistent over the 3 survey years of observations with slightly higher values of Ω_A and pH in forereef areas than the backreef and central lagoon areas. The lowest values were consistently observed in the Eastern Pools georegion, which has the longest residence times due to the surrounding shallow reefs that likely caused additional biological drawdown from calcification and respiration processes as waters flowed over them into the Eastern Pools. Additionally, prevailing northeast winds at Kingman can cause localized upwelling on the western edge of the emergent land, bringing deeper, lower-Ω_A waters to the surface.

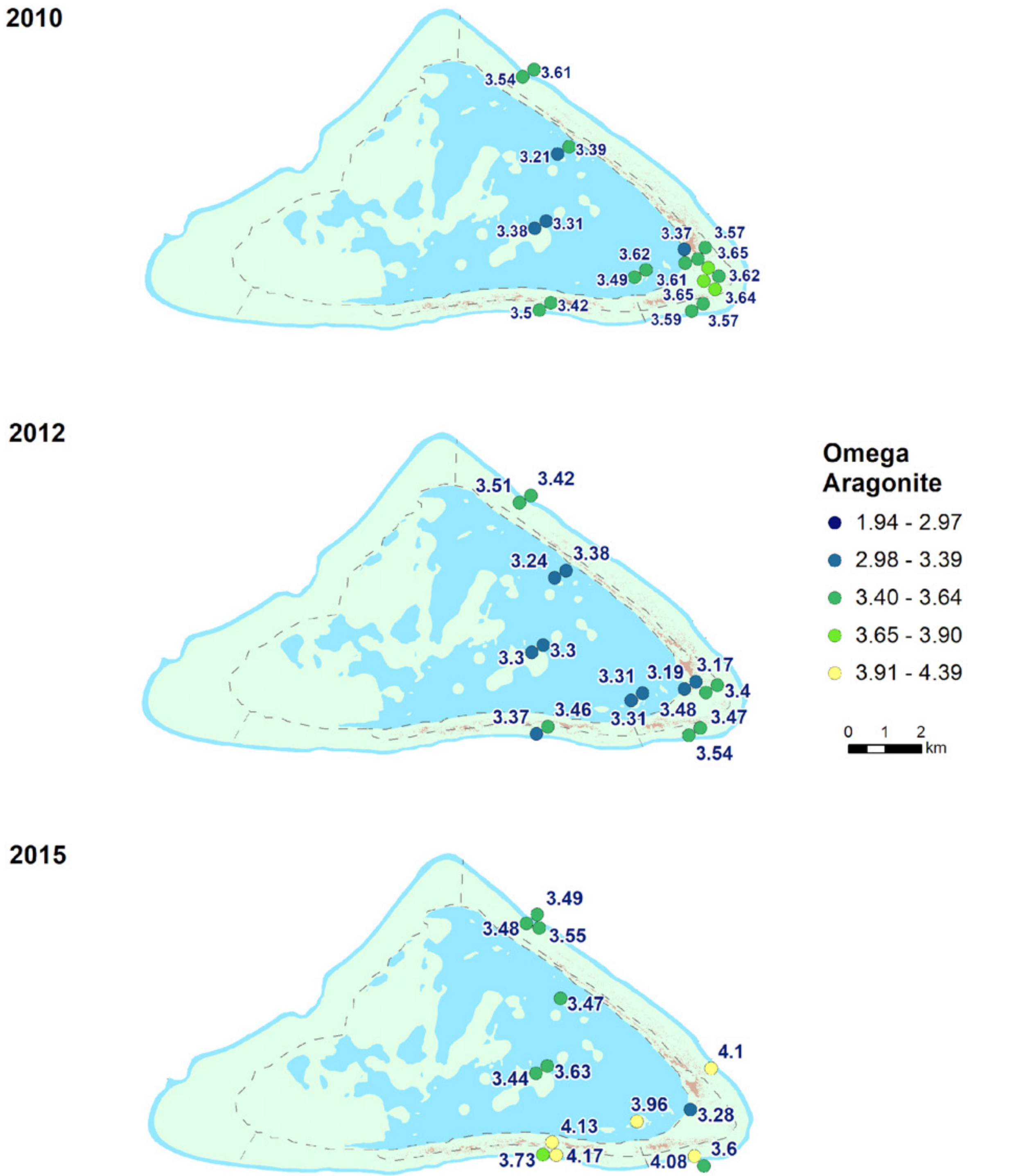


Figure 21. Spatial distribution of aragonite saturation state (Ω_A), observations during 2010, 2012, and 2015 around Kingman Reef.

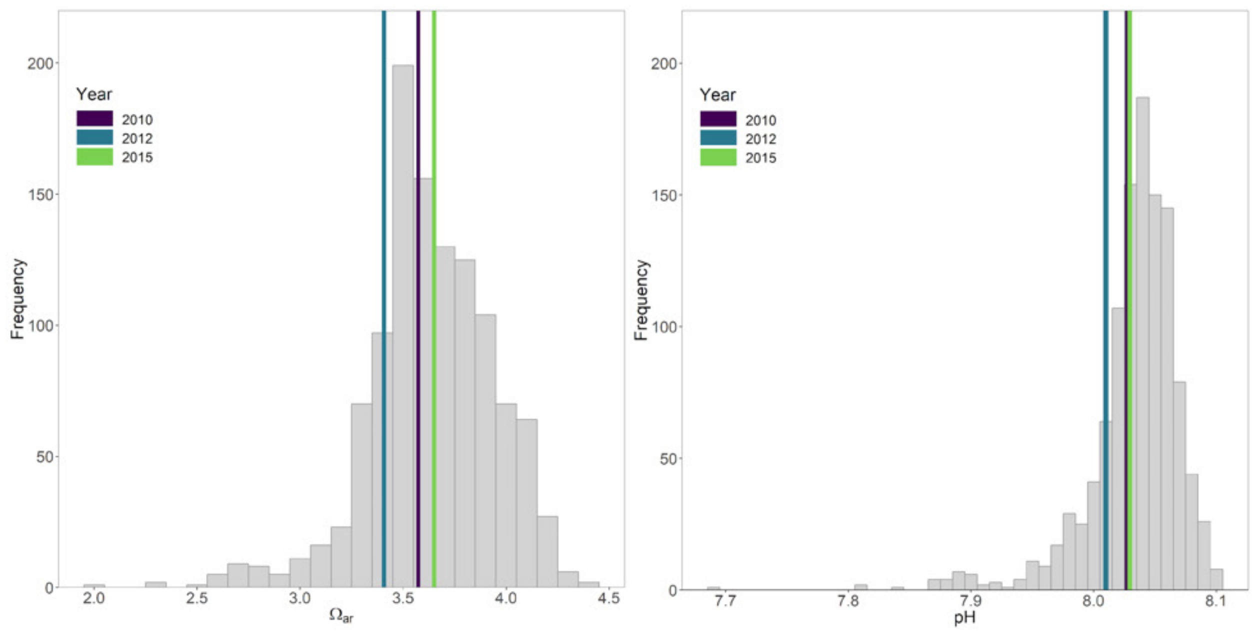


Figure 22. Histogram of all aragonite saturation state (Ω_A; left panel) and pH (right panel) values measured from discrete seawater samples across the U.S. Pacific Islands region from 2010 to 2017 (gray). Overlaid vertical bars show the medians of Kingman Reef data in 2010 (purple), 2012 (blue), and 2015 (green).

Net Carbonate Accretion

Calcification accretion units (CAUs) are simple, two-plate fouling structures that are staked to the reef substrate 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 a proxy for the net rate of $CaCO_3$ accretion 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 dynamic nearshore environmental conditions. In particular, calcification rates of corals and CCA are sensitive to changes in carbonate chemistry and decrease with decreasing pH and Ω_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 Kingman Reef to assess spatial and temporal variability in accretion. Carbonate accretion rates varied across deployment sites, although spatial patterns were generally consistent across years (Figure 23). During both sample periods, CAUs located within the Eastern Pools georegion of Kingman's reef system had the lowest accretion rates (Figure 23), which is consistent with expectations based on the lower observed values of Ω_A discussed above (Figure 21) and pH. Interestingly, despite these observations of low accretion rates from the CAU plates in the Eastern Pools georegion, that area has consistently had exceptionally high abundance of calcifying giant clams, as discussed in the "Coral Reef Benthic Communities" section (Figure 37), contrary to expectations. These contradictory findings demonstrate that expectations derived primarily from simplified laboratory-based species response experiments that generally show that calcification should decrease with decreasing Ω_A and pH, may not always apply in nature where many different interactive environmental drivers (e.g., temperature, nutrient concentrations, light levels) and ecological factors (e.g., predation, competition) are acting. Overall, accretion rates were higher from 2012 to 2015 than 2010 to 2012, which could have been due to generally weaker region-scale equatorial upwelling of cooler, lower pH and lower Ω_A water during the latter years (Figure 14).

Compared to the rest of the Pacific, accretion rates at Kingman Reef were greater than most surveyed sites (Figure 24). This may be due to the relatively steady input of oceanic waters flushing the reefs with smaller positive inputs from high nutrient concentrations driven by local upwelling of deeper lagoon waters, which can fuel productivity and increase calcification rates of coral and CCA (Cohen and Holcomb 2009; Drenkard et al. 2013).

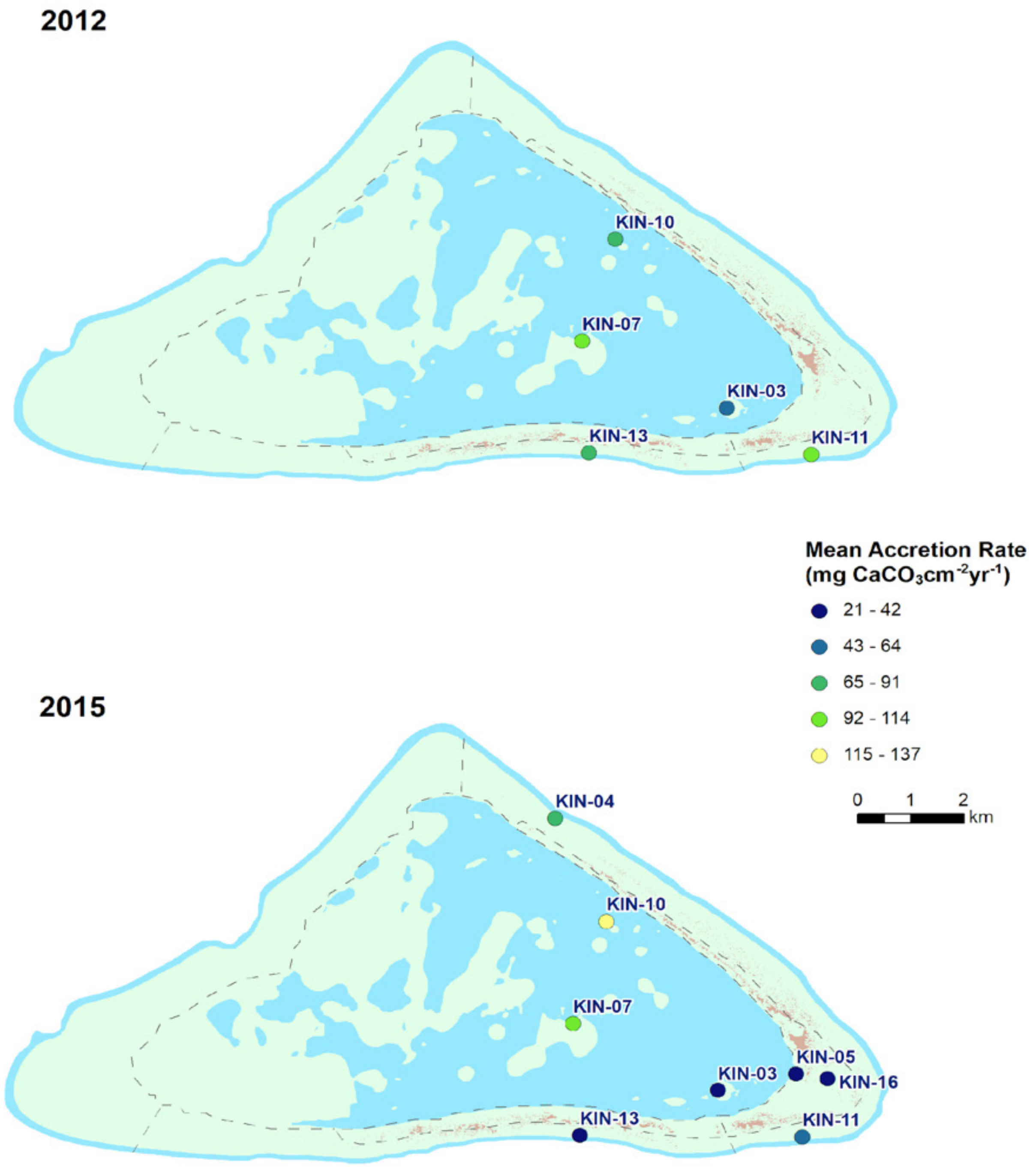


Figure 23. Spatial distribution of mean carbonate accretion rate (mg $CaCO_3$ cm^{-2} yr^{-1}) at Kingman Reef during 2010–2012 (top panel) and 2012–2015 (bottom panel). The calcification accretion units are labeled by location code.

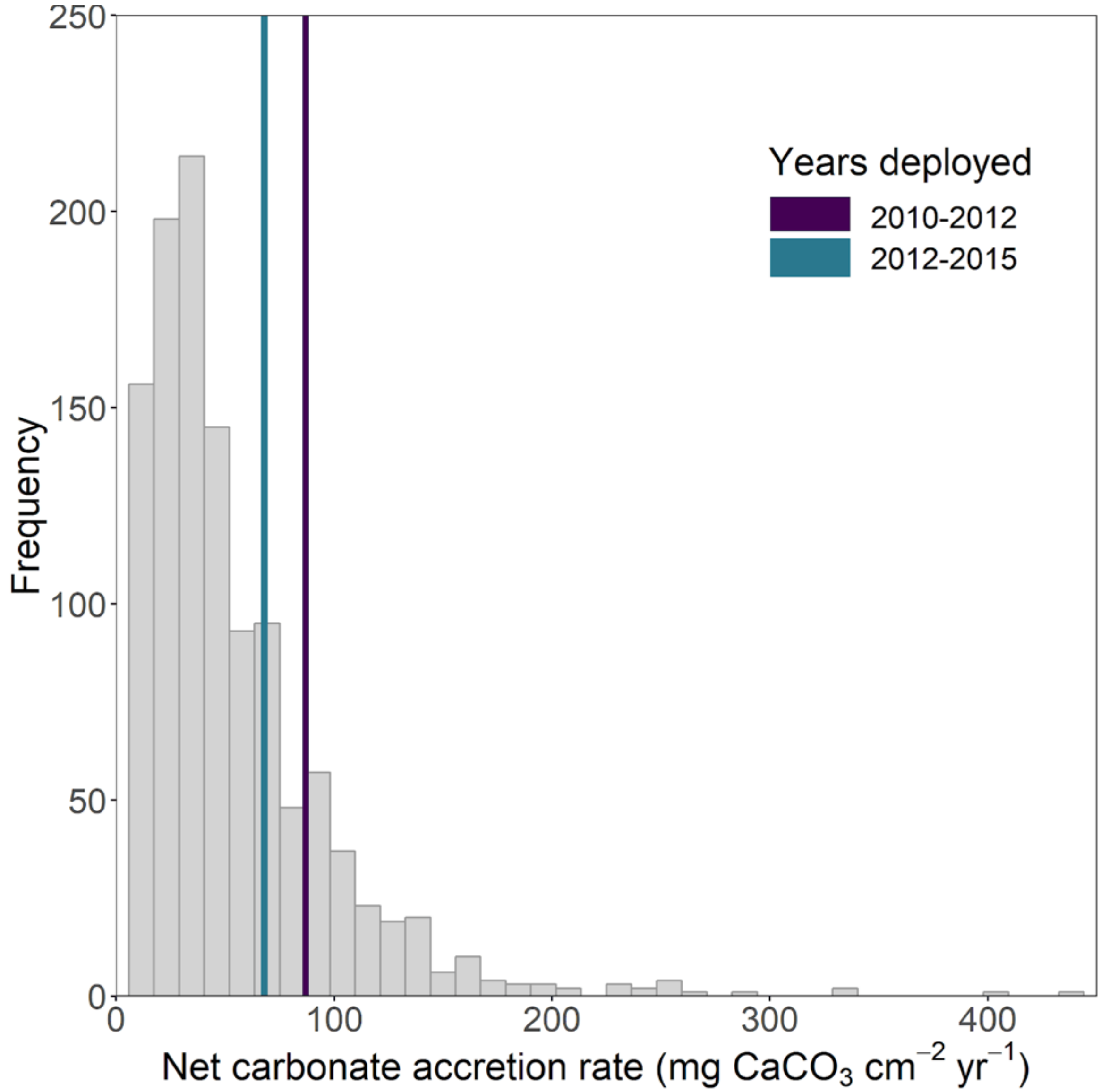
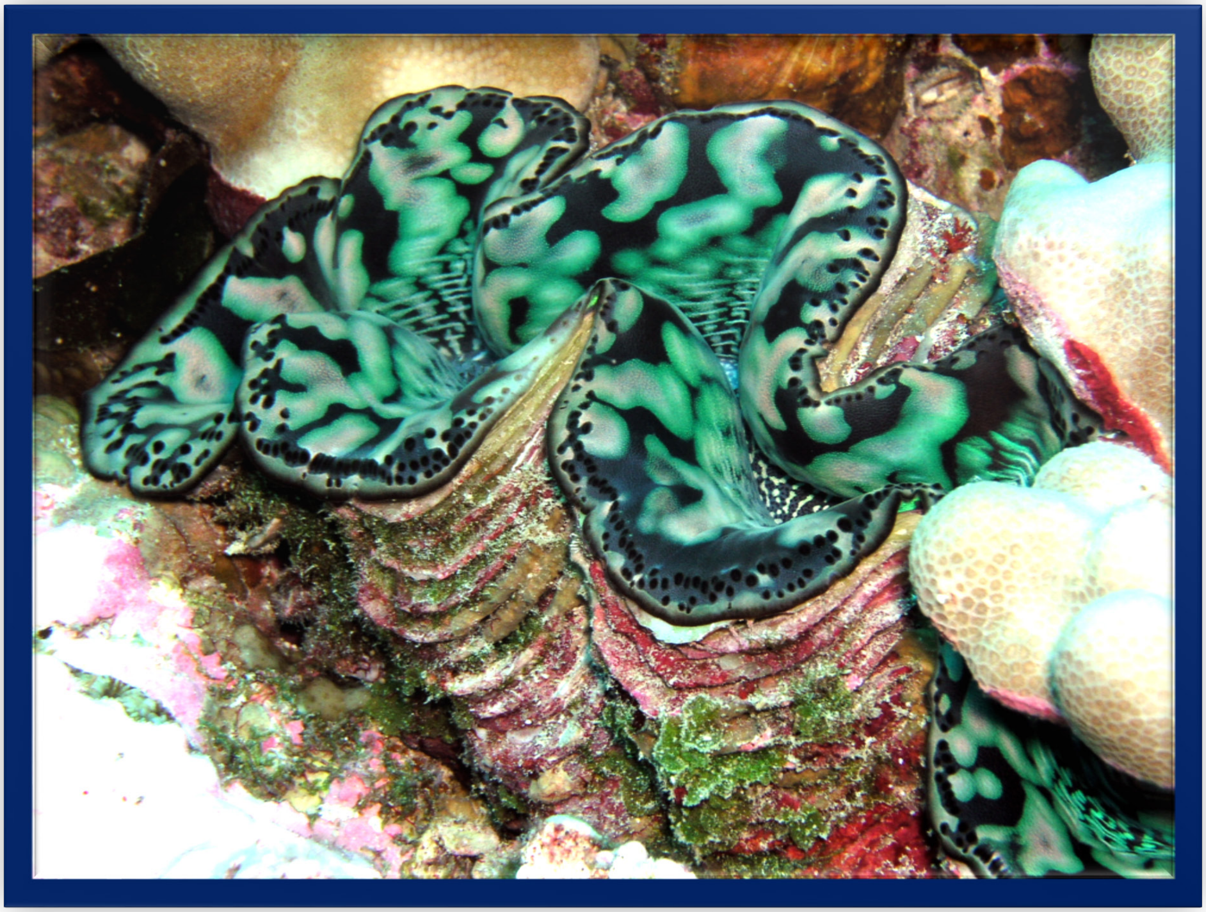


Figure 24. **Histogram of all net carbonate accretion rates (m $CaCO_3$ cm^{-2} yr^{-1}) measured by all calcification accretion units during the period 2010–2017 across the U.S. Pacific Islands region (gray), and median values for 2010–2012 (purple) and 2012–2015 (blue) samples for Kingman Reef.**

A steephead parrotfish (Chlorurus microrhinos) cruises over the reef at Kingman Reef.
Photo: Edmund Coccagna, NOAA Fisheries.

Coral Reef Benthic Communities

3.4 Coral Reef Benthic Communities



Maxima, or small giant clam (Tridacna maxima) at Kingman Reef.
Photo: Megan Moews-Asher, NOAA Fisheries.

Survey Effort and Site Information

To characterize benthic habitats and the coral populations around Kingman Reef, data were collected using Rapid Ecological Assessment (REA) surveys and towed-diver surveys (TDS) during eight survey efforts conducted between 2001 and 2015 (Table 3). REA surveys at Kingman were primarily performed at repeat site' at mid-depth (>6–18 m) until 2015, when a stratified-random sampling (StRS) survey design was adopted to generate more statistically-robust island-scale estimates of coral reef benthic communities. The use of a StRS design allowed for an increased number of survey sites 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 25). Benthic REA surveys implemented the line-point-intercept method 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 greater sample size to determine benthic cover. From 2004 through 2015, the belt-transect (BLT) method was used 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) survey sites and towed-diver survey (TDS) segments completed by year and strata (if applicable) at Kingman Reef. 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 were located across three depth strata: shallow (S), mid (M), and deep (D).

Year	TDS	REA	
		Coral Populations	Benthic Communities
2001	104 (71)	–	–
2002	91 (85)	–	–
2004	173 (148)	2	–
2006	203 (166)	5	14 (5)
2008	198 (138)	3	11 (3)
2010	209 (157)	5	16 (5)
2012	219 (179)	6	15 (6)
2015*	158 (149)	2 (S) 10 (M) 6 (D)	6 (S) 30 (M) 17 (D)

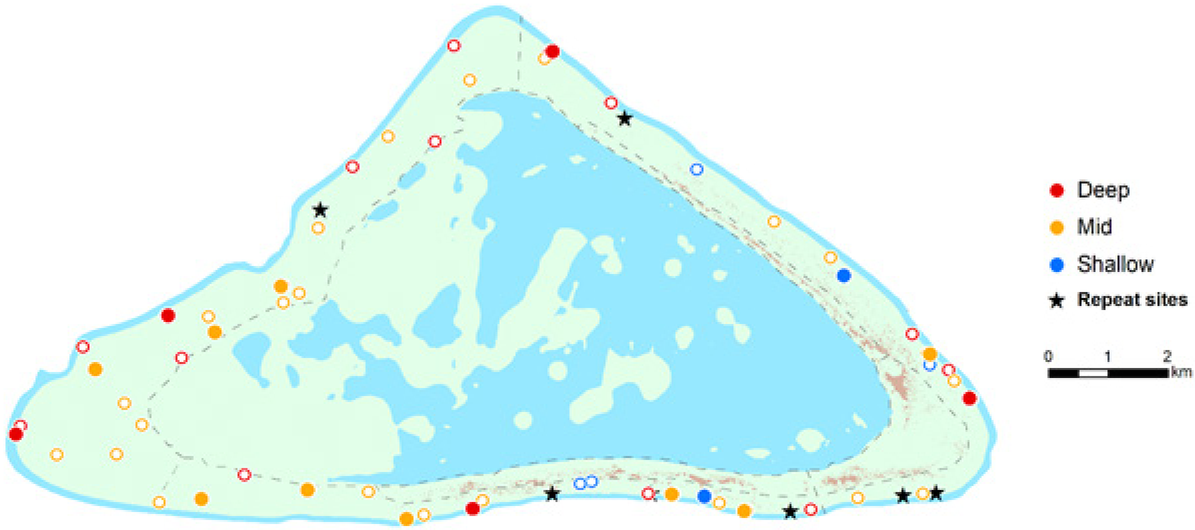


Figure 25. Kingman Reef benthic Rapid Ecological Assessment survey locations. Repeat sites (stars) were sampled from 2004 through 2012 and stratified-random sampling (StRS) sites were sampled in 2015 (blue, yellow, and red circles for shallow [>0–6 m], mid [>6–18 m], and deep [>18–30 m] depth strata). 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

Hard coral cover was uniformly high (mean = 46.9% ± 2.1 SE) and observed on all segments during mid-depth TDS in 2015 at Kingman Reef (Figure 26). Site-level estimates based on StRS photoquadrat surveys also showed that hard coral was the dominant benthic functional group (mean = 34.4% ± 1.7 SE) at Kingman; however, StRS indicated a greater spatial heterogeneity in coral cover compared to the TDS method (Figure 27). Despite the broad range of coral cover observed among StRS photoquadrat sites, there was no clear spatial pattern around Kingman. Spatial observations of macroalgae cover were consistently low on tow segments (mean = 1.8% ± 0.6 SE; Figure 26) and at StRS sites (mean = 0.3% ± 0.05 SE; Figure 27). CCA cover was variable amongst segments and sites. CCA cover from TDS (mean = 10.4% ± 3.2 SE) tended to be lower along the mid-depth reefs of the West georegion than other regions, but there was no consistent spatial pattern of CCA from StRS surveys (mean = 11.8% ± 1.2 SE).

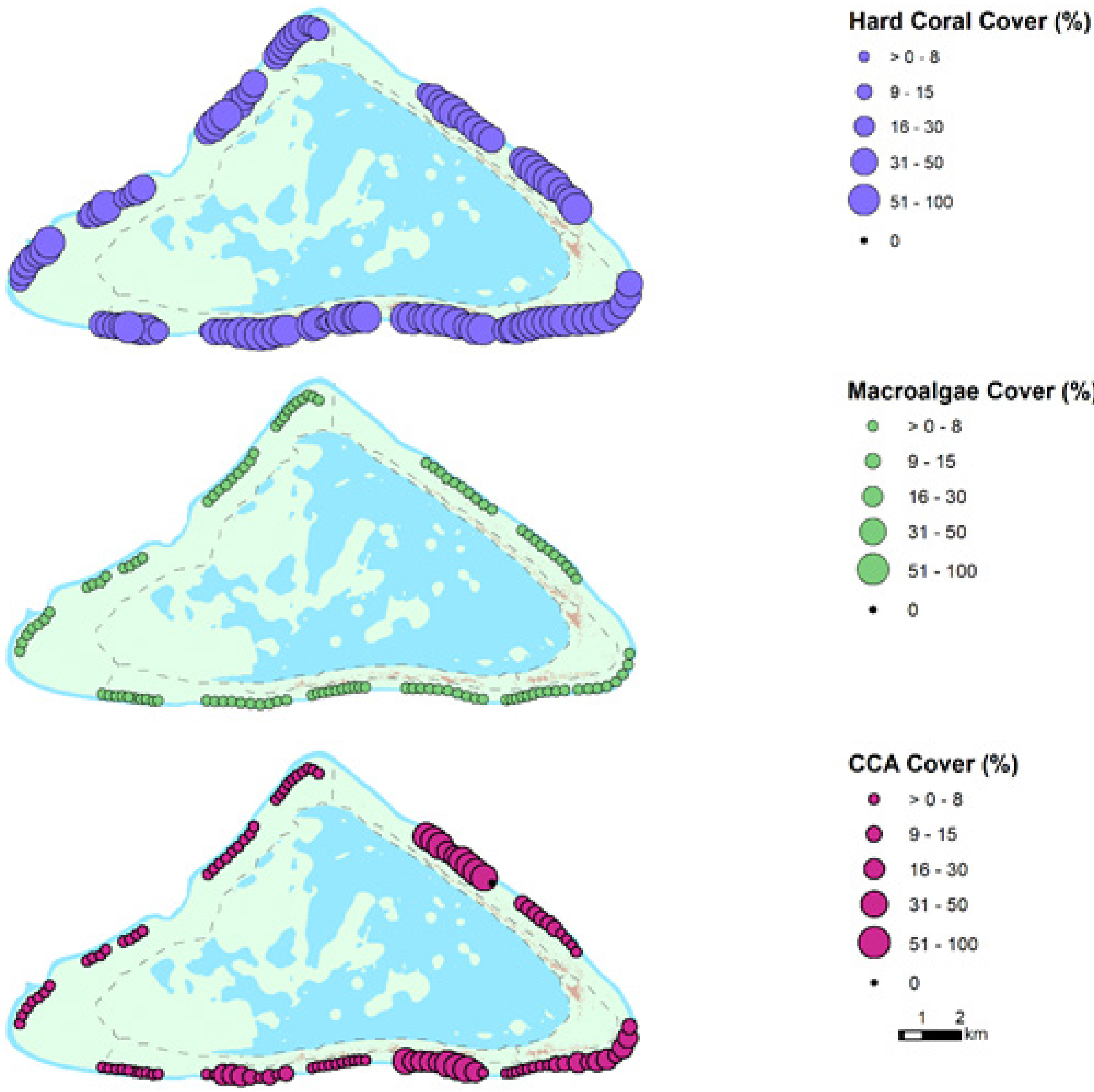


Figure 26. Visual estimates and spatial distribution of mid-depth (>6–18 m) forereef hard coral, macroalgae, and crustose coralline algae (CCA) cover (%) at Kingman Reef from towed-diver surveys in 2015.

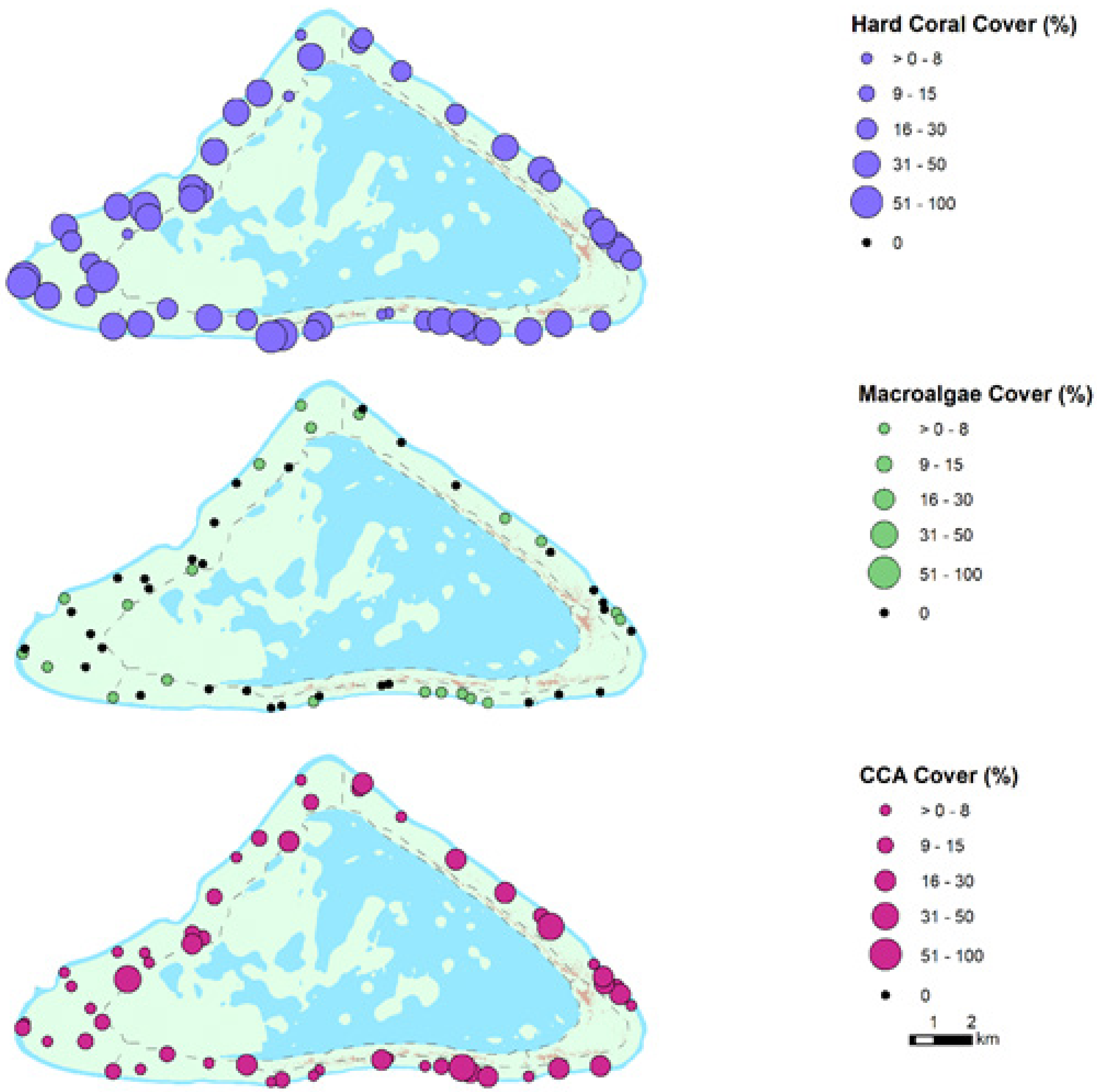


Figure 27. Site level estimates of hard coral, fleshy macroalgae (excluding calcified and encrusting macroalgae), and crustose coralline algae (CCA) cover (%) at Kingman Reef from stratified-random sampling photoquadrat surveys conducted at all forereef depth strata combined (>0–30 m) in 2015.

Hard coral cover was lowest in the shallow strata (mean = 16.7% ± 5.5 SE) and greatest in mid-depth (mean = 37.4% ± 2.2 SE) and deep strata (mean = 30.2% ± 4.8 SE). This pattern is likely driven by differences in the habitat between the West georegion, where no shallow stratum exists, and the South and East georegions, where shallow and mid-depth sites were predominantly surveyed. The West georegion is a favorable environment to support large coral colonies due to its deeper depth that limits physical disturbance from waves and mild benthic slope that provides a stable and relatively flat substrate to allow for greater colony exposure to light needed at deeper depths. CCA cover was highest at the shallow strata (mean = 27.3% ± 4.7 SE) and exceeded hard coral cover in this strata; CCA cover decreased sharply with depth. Macroalgae cover remained notably low (<1%) on all strata.

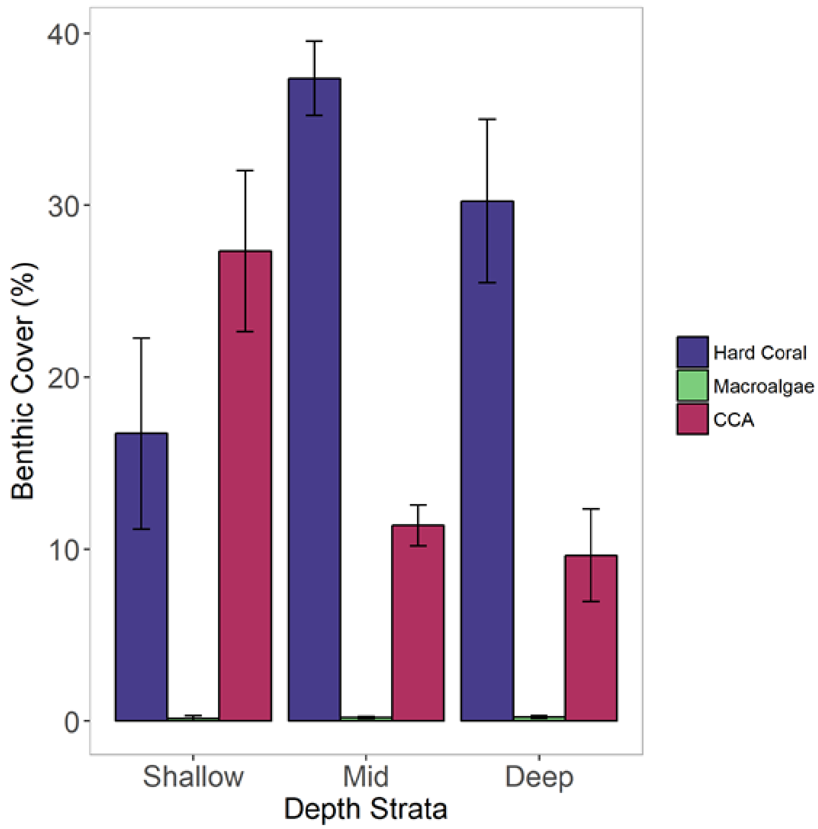


Figure 28. Strata-level mean benthic cover (± 1 SE) at Kingman Reef by benthic functional groups of hard coral, fleshy macroalgae (excluding calcified and encrusting macroalgae), and crustose coralline algae (CCA) for shallow (>0–6 m), mid (>6–18 m), and deep (>18–30 m) depth strata from stratified-random sampling photoquadrat surveys conducted in 2015.

Time Series of Benthic Cover

Based on both REA and TDS methods, mean hard coral cover consistently remained relatively high over the period from 2001 through 2015, except for a reduction in cover observed during 2006 surveys (Figure 29). Coral cover did not meaningfully differ between towed-diver and REA survey designs until 2015, when TDS reported higher cover (mean = 46.9% ± 2.1 SE) than StRS photoquadrats (mean = 37.4% ± 2.2 SE). While coral cover averaged over all survey years appeared to be similar among georegions, variability was observed within georegions (Figure 30a). When looking at changes in cover over the same time period (2001–2015), areas in the South georegion appeared to be the most variable from one another, with some areas increasing in coral cover while others declined, while the East georegion displayed a slight decline in cover over time (Figure 30b and Figure 30c). Macroalgae cover was consistently low through time, remaining ≤10%, apart from a peak in 2004 (TDS: mean = 27.3% ± 4.2 SE). TDS estimates of mean island-wide macroalgae cover (which include fleshy, calcified, and encrusting macroalgae) tended to be greater than estimates acquired using the REA methods (which exclude fleshy, calcified, and encrusting macroalgae) at Kingman Reef. This pattern is consistent with survey results from other islands in the PRIMNM and likely reflects the broader macroalgal definition used by TDS compared to REA surveys. Patterns in CCA cover were variable over time and between survey methods; however, most recent survey efforts (from both methods) suggest CCA levels have declined in recent years at Kingman.

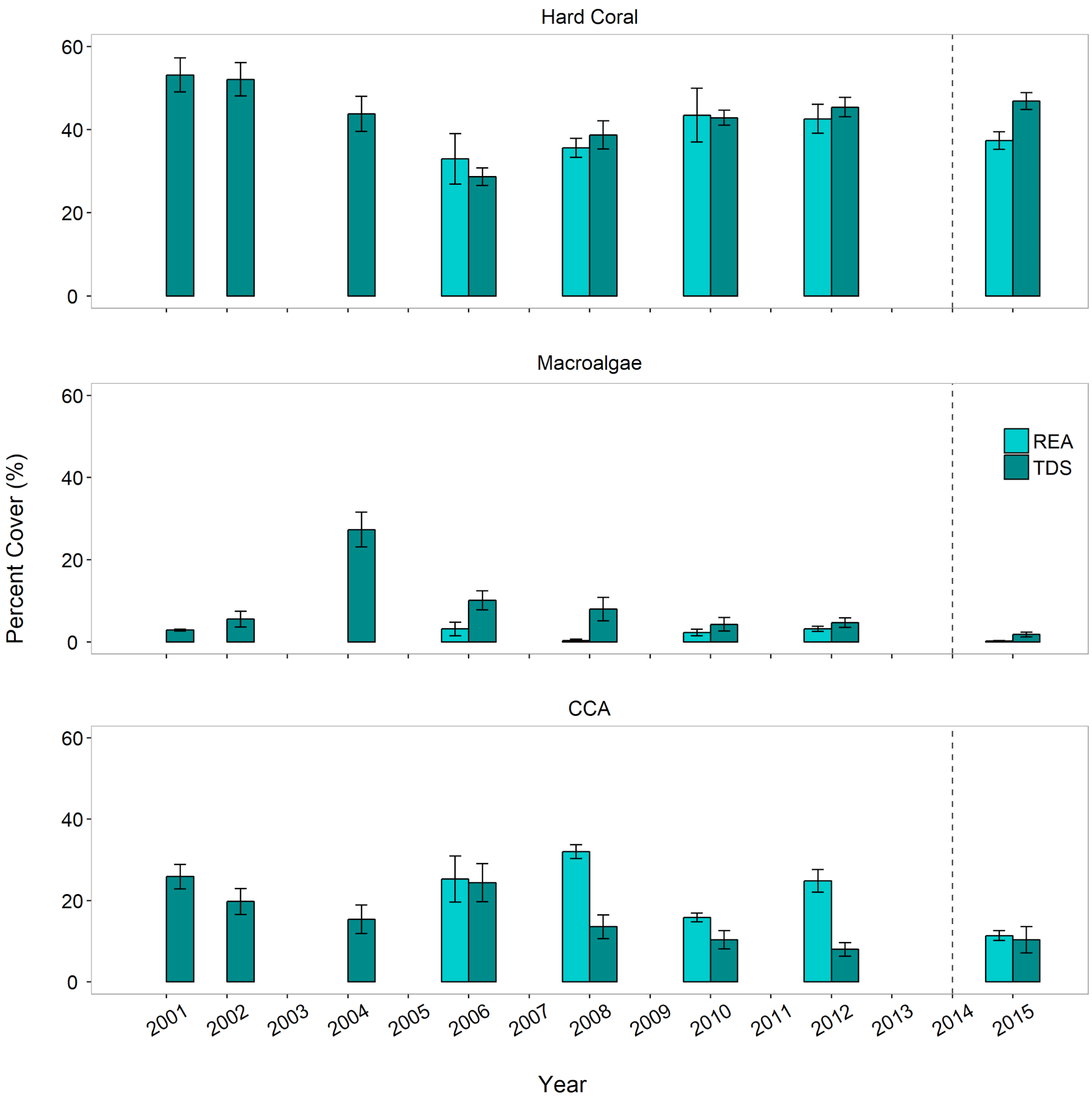


Figure 29. Time series of mean (± 1 SE) hard coral, macroalgae, and crustose coralline algae (CCA) cover (%) at Kingman Reef by survey method (Rapid Ecological Assessments [REA] from 2006 through 2015, and towed-diver surveys [TDS] from 2001 through 2015) conducted at the mid-depth stratum (>6–18 m). In 2014 (dashed line), REA survey methodology changed from line-point-intercept at repeat sites to photoquadrat surveys at stratified-random sites. *Note: TDS macroalgae data include calcified and encrusting macroalgae; the REA macroalgae data exclude it.

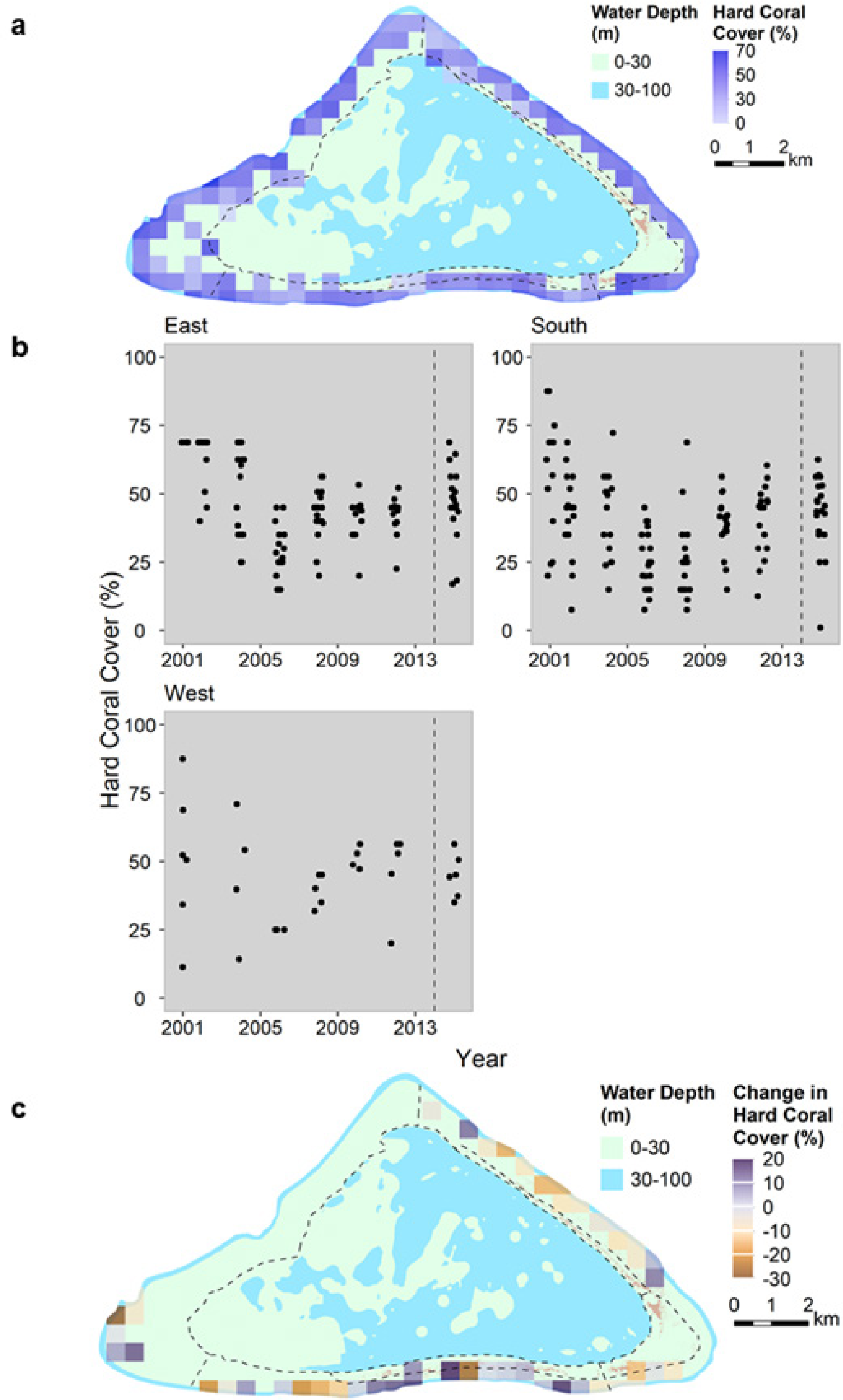


Figure 30. Spatial patterns and temporal trends of gridded (500 m × 500 m) mean coral cover at Kingman Reef across survey years (2001–2015) and methods (towed-diver surveys, line-point-intercept (LPI), and stratified-random sampling (StRS) benthic and fish photoquadrats). (a) Mean hard coral cover per 500 by 500 m grid cell across all survey years; (b) time series of hard coral cover by georegion; and (c) temporal change in hard coral cover per 500 by 500 m grid cell, only including cells with at least a 10-year span of data and at least 3 observation years. 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

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; numbers close to zero indicate low occurrence. There was exceedingly low occurrence of all quantified algal diseases at Kingman Reef throughout the entire period of observations from 2006 through 2015 (Figure 31). The diseases recorded were primarily coralline fungal disease and coralline white band syndrome—both at very low occurrence index values. Observations of CCA disease were exceptionally rare during surveys in 2010 and 2015.

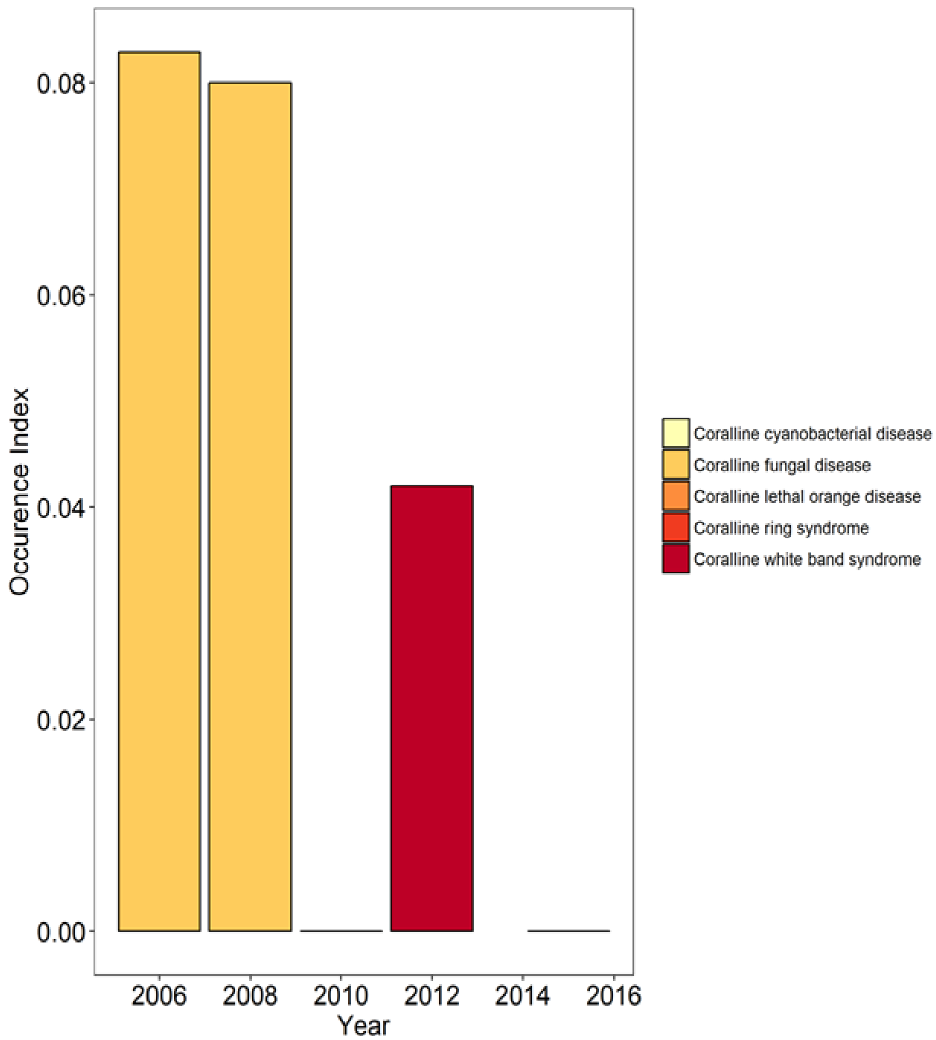


Figure 31. Time series of crustose coralline algae disease occurrences at Kingman Reef for all depth strata combined (>0–30 m) from Rapid Ecological Assessment surveys conducted from 2006 through 2015.

Recent Coral Abundance

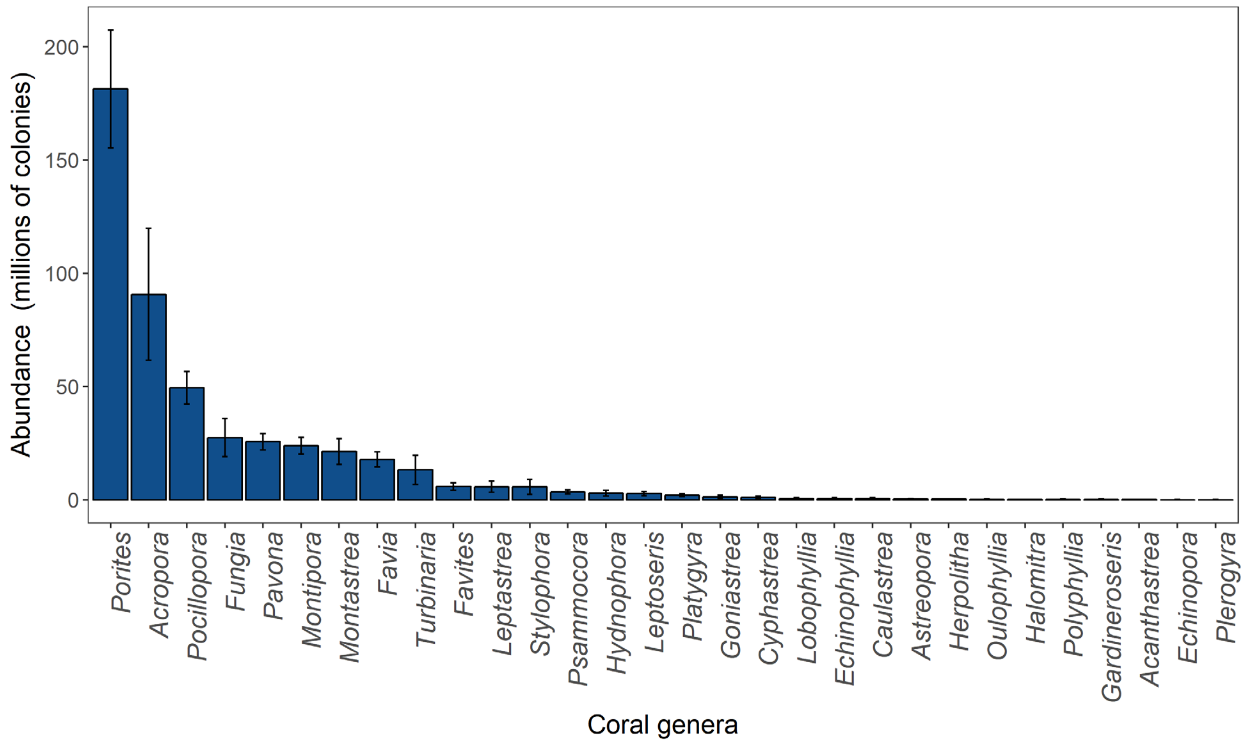


Figure 32. Island-scale abundance (±1 SE) estimates by coral genera for all depth strata combined (>0–30 m) at Kingman Reef from Rapid Ecological Assessment surveys conducted in 2015.

Island-scale colony abundance estimates were generated from the REA transect colony densities extrapolated over the area of hard-bottom habitat found in the survey strata (0–30 m). In 2015, a total of 30 coral genera were enumerated at Kingman Reef. Total abundance estimates indicated that *Porites* was the dominant genus and *Plerogyra* was the least abundant genus (Figure 32).

Based on the 2015 surveys, coral cover was highest at mid-depth strata while coral density was highest in the shallow strata. This suggests larger coral colonies were found in the mid-depths, and smaller, more abundant corals were found in the shallows. As the proportional abundance of genera were similar between these two strata, this difference may reflect a change in species composition (within genera) or a change in colony morphology driven by habitat differences between the shallow and mid-depth strata (Figure 33). Of five abundant coral genera, four decreased in density from shallow to deep strata (*Acropora*, *Montipora*, *Pocillopora*, and *Porites*). *Acropora*, which requires high light availability, had the highest adult density of the abundant genera in the shallow strata (mean = 11.4 colonies/m^2 ± 7.4 SE), though variability was very high. Juvenile corals were relatively abundant across taxa and strata, and consistently comprised around 25% of the total scleractinian density per strata.

In 2015, there were two sightings at Kingman Reef of the coral species *Acropora rudis*, which is listed under the Endangered Species Act. One colony was observed in the shallow depth strata in the East georegion, and the second colony was found in the mid-depth strata in the South georegion. Neither colony displayed signs of old mortality, bleaching, or chronic compromised health conditions. One colony did appear to have a small amount of recent mortality (3%) due to breakage from an unknown source. No photographic records or voucher specimens were collected to verify these sightings. 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.”

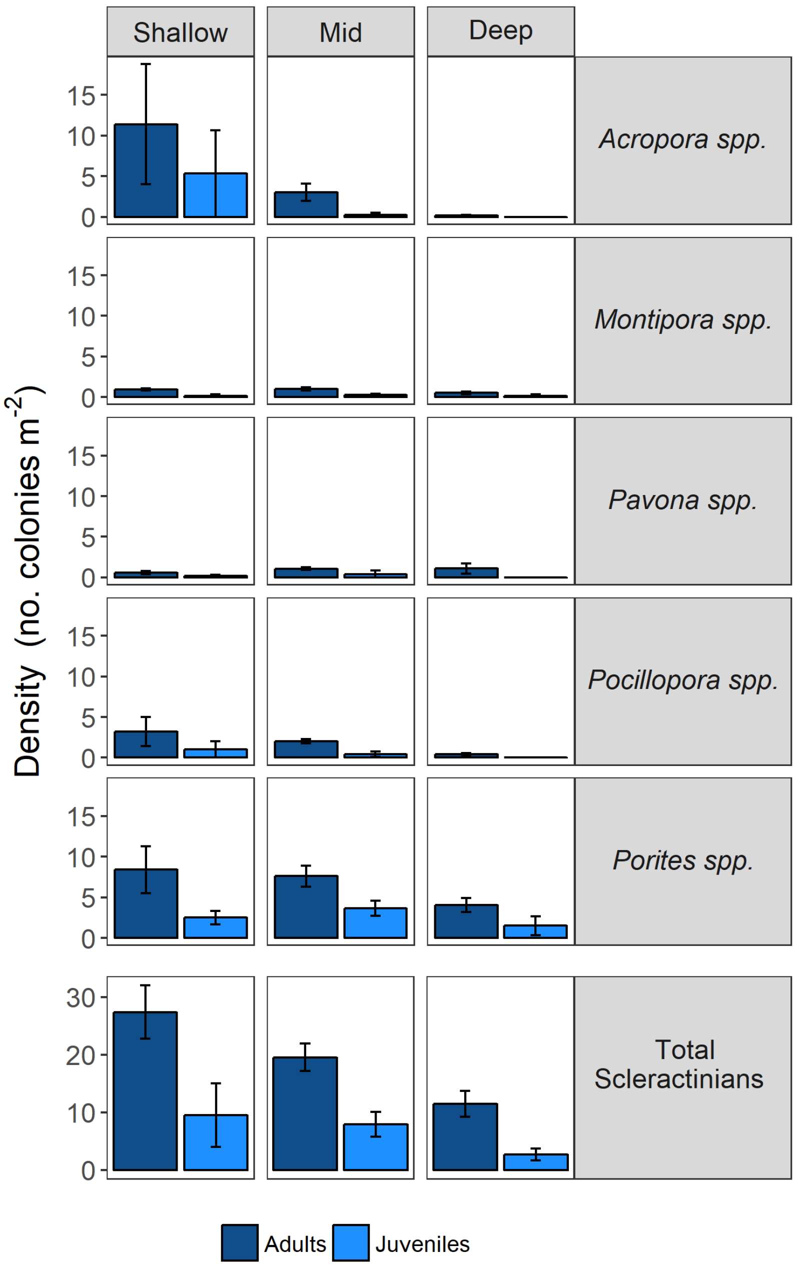


Figure 33. Mean (± 1 SE) adult and juvenile colony density from Rapid Ecological Assessment surveys conducted at Kingman Reef in 2015 at shallow (>0–6 m), mid (>6–18 m), and deep (>18–30 m) depth strata for five coral genera generally abundant in the Pacific Remote Islands Marine National Monument (*Acropora* spp., *Montipora* spp., *Pavona* spp., *Pocillopora* spp., and *Porites* spp.) to facilitate comparison among islands.

Time Series of Coral Abundance and Condition

From 2010 to 2012, mean adult coral colony density at Kingman Reef doubled (Figure 34), largely driven by increases in the density of smaller size classes ranging from 6 to 40 cm (Figure 35). Both the 6–10 cm and 11–20 cm size classes demonstrated an increase in adult coral colony density greater than 130%. Adult coral colony density appeared to decrease from 2012 through 2015 (though the shape of the size structure remained similar); however, the difference in survey design from the use of "repeat sites" in 2012 to the use of StRS sites in 2015 necessitates caution when interpreting differences. In all years, the 6–10 cm size class had the highest density of coral colonies, and density decreased with increasing size class.

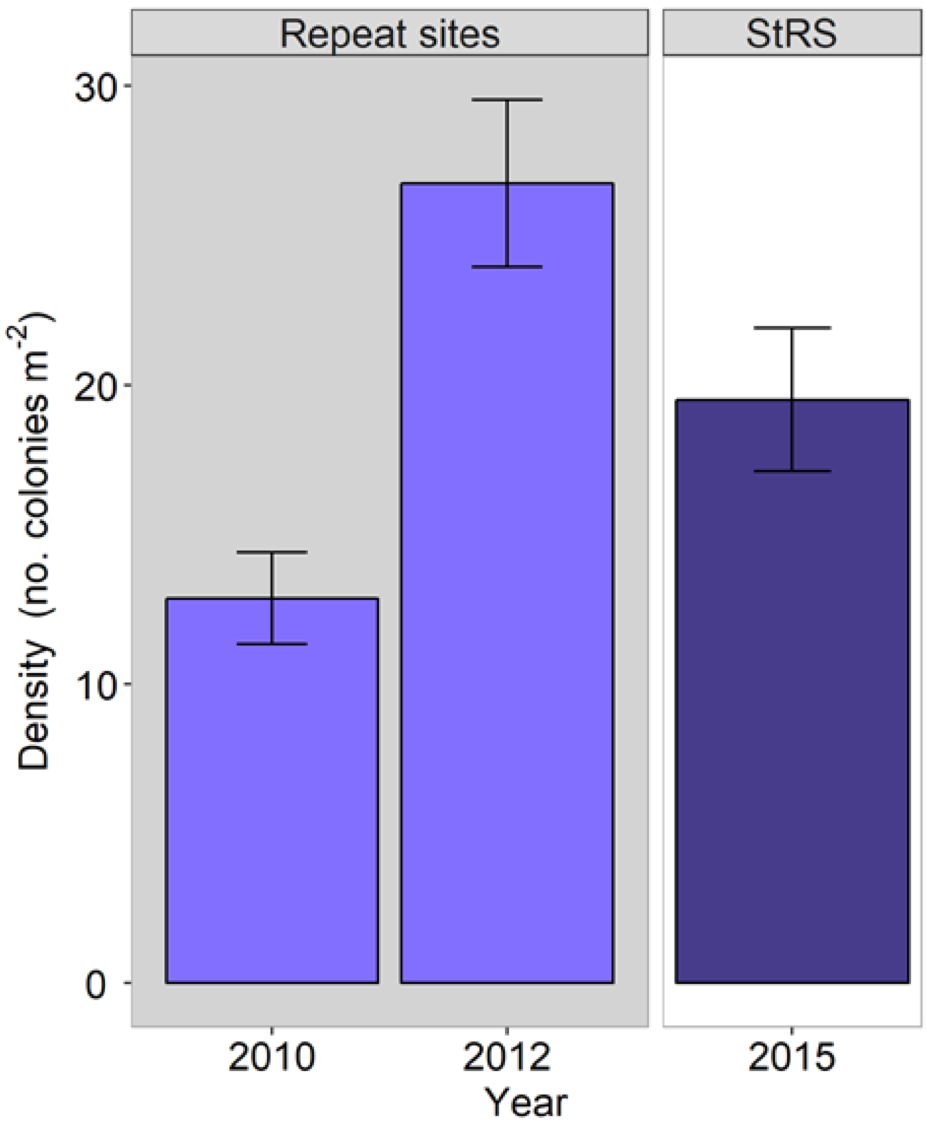


Figure 34. Time series of mean adult colony density (± 1 SE) at Kingman Reef, from mid-depth (>6–18 m) strata Rapid Ecological Assessment surveys by survey design, repeat sites, or stratified-random sampling (StRS), conducted from 2010 through 2015.

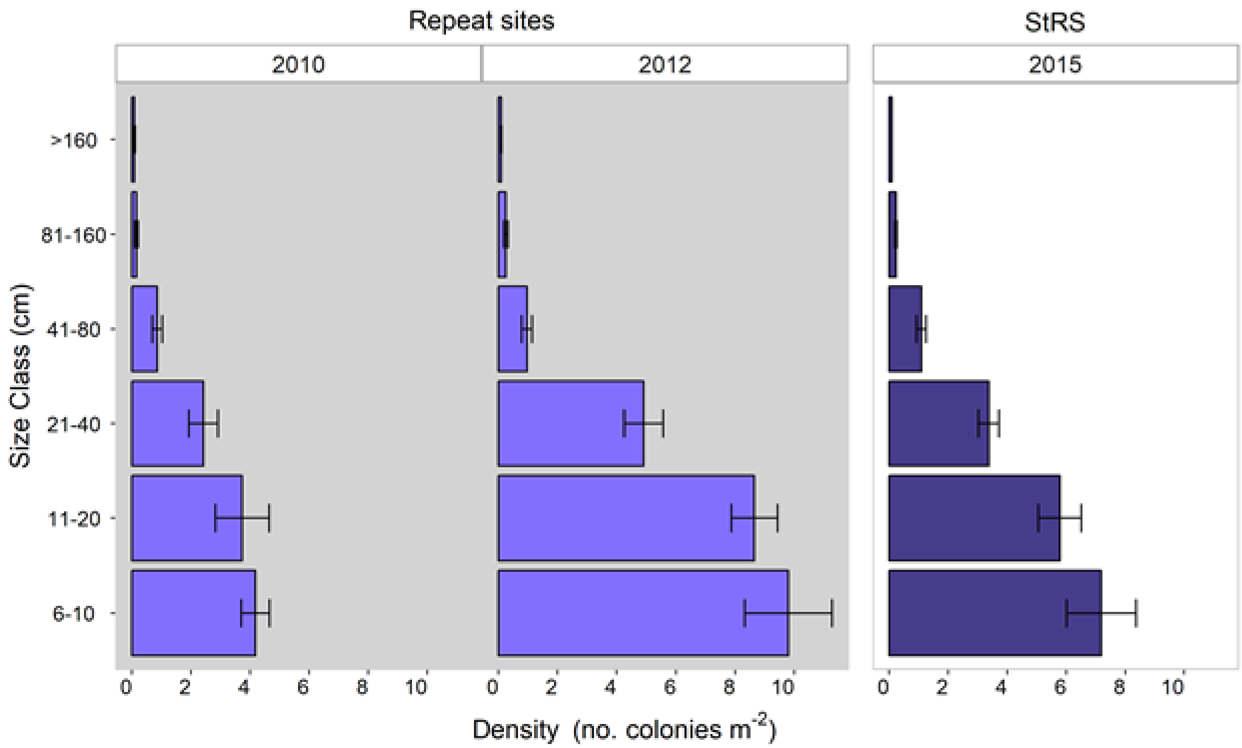


Figure 35. Time series of mean adult colony density (±1 SE) at Kingman Reef by size class from mid-depth (>6–18 m) strata Rapid Ecological Assessment surveys by survey design, repeat sites, or stratified-random sampling (StRS), conducted from 2010 through 2015.

Partial mortality per coral colony was low across the survey years 2010, 2012, and 2015 (Figure 36a). Old mortality on corals was stable during this period (ranging from 4.4% to 6.7% per colony) as recent mortality decreased from 3.7% (±0.5 SE) in 2010 to 0.2% (±0.1 SE) in 2015. Bleaching appeared to be the most common driver of the observed recent mortality; however, prevalence of bleaching, disease, and chronic health condition was at background levels—at or below approximately 2% (Figure 36b). During 2012, bleaching had the highest prevalence (mean = 2.2% ± 0.5 SE) of all survey years, while disease and condition were the lowest (both means < 0.3%). Yet, the prevalence of bleaching remained low at Kingman Reef compared to other islands in the PRIMNM. The variability associated with bleaching and disease (seen by standard error bars in Figure 36b) suggests a pattern of spatial variability amongst sites where some sites exhibited little to no bleaching while others had higher prevalence.

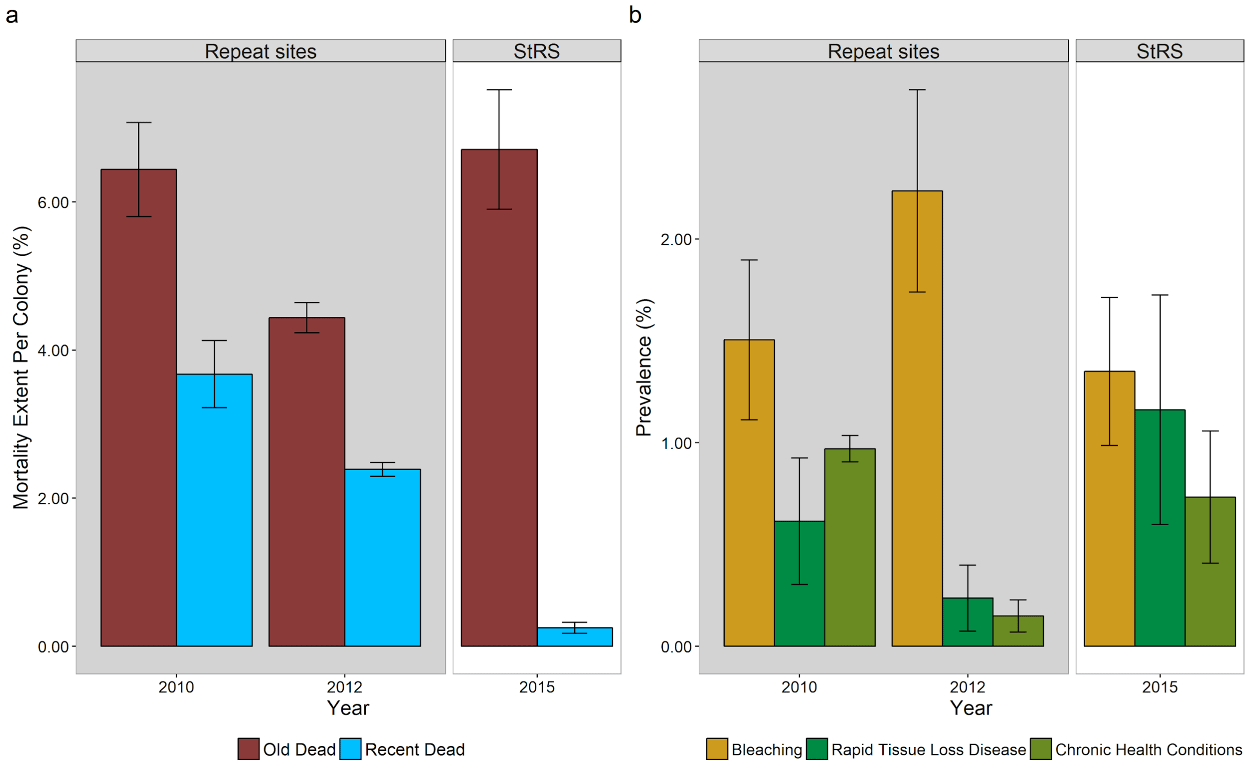


Figure 36. Time series of mean (±1 SE) (a) percent partial coral mortality and (b) prevalence of bleaching, rapid tissue loss diseases, and chronic health conditions at Kingman Reef based on mid-depth (>6–18 m) strata Rapid Ecological Assessment surveys by survey design, repeat sites, or stratified-random sampling (StRS), conducted from 2010 through 2015.

Benthic Macroinvertebrates

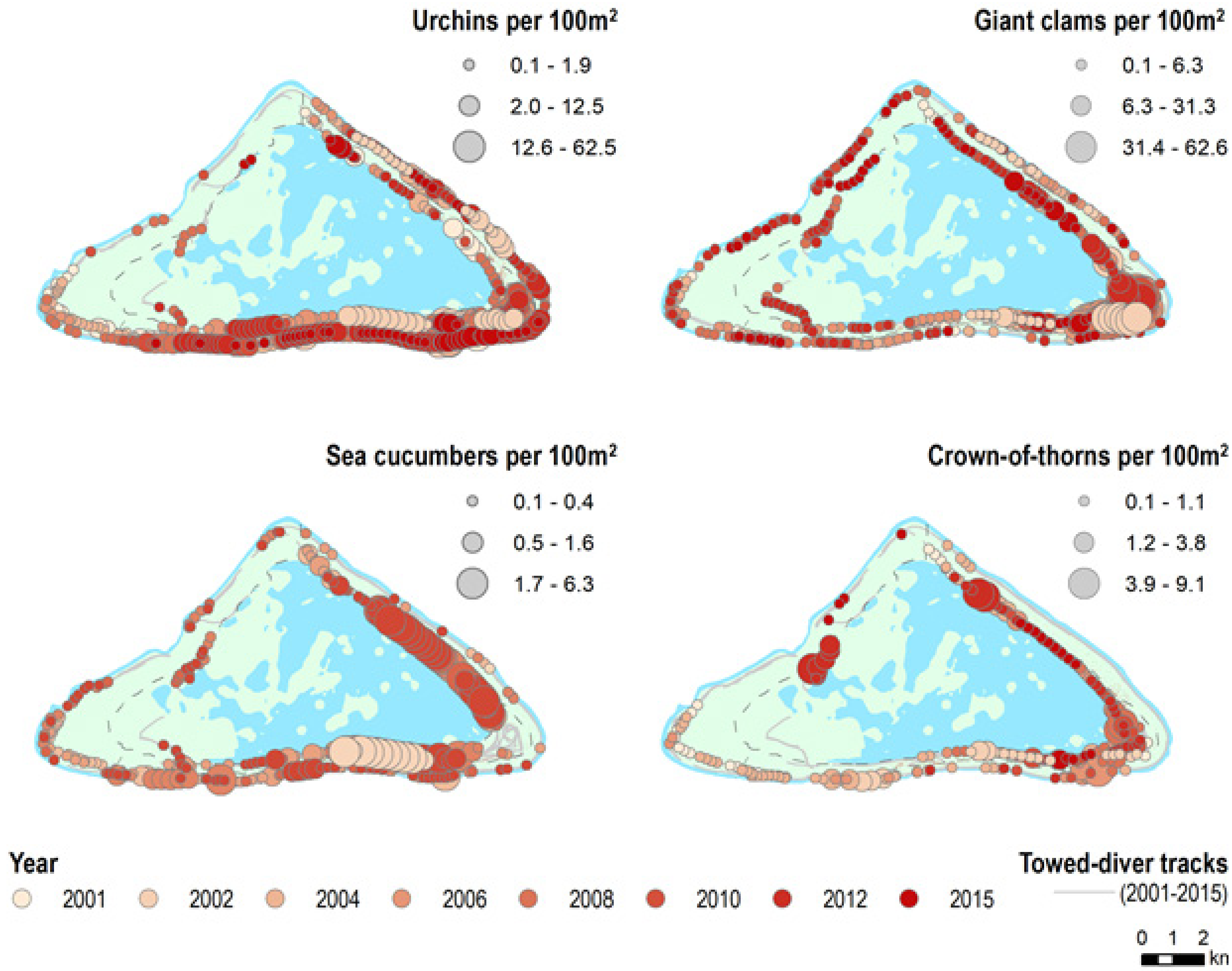


Figure 37. Density of conspicuous ecologically- or economically-important macroinvertebrate (urchins, giant clams, sea cucumbers, and crown-of-thorns sea stars) observed per segment from benthic towed-diver surveys (TDS) conducted throughout all depth strata (>0–30 m) around Kingman Reef from 2001 to 2015. Sea cucumber observations were discontinued from TDS in 2014.

Urchins were observed during each of the eight survey years and were most common in the South, South Backreef, and Eastern Pools georegions. Similar to other macroinvertebrates, urchins were recorded in much lower densities along the West georegion. Overall, tow segments had low but consistent urchin densities over time, with fewer than 10 individuals per 100 m^2 observed in 98% of the segments where urchins were present. The highest densities of urchins per segment were observed in 2004, with a maximum density of 63 individuals per 100 m^2. Compared across all islands surveyed in the PRIMNM, the range of urchin densities observed was widest at Kingman.

Giant clams—currently under status review (Federal Register 2017)—had broad temporal and spatial distributions; they were observed in each survey year and were locally abundant in the southeast, predominantly within the “clam gardens” located in the Eastern Pools georegion, and in the North Backreef georegion. The highest density of giant clams recorded per segment was 63 individuals per 100 m^2, which occurred in 2002, 2008, 2010, and 2012. Compared to other islands in the PRIMNM, Kingman Reef has consistently had the highest densities of giant clams recorded.

Sea cucumbers were observed during each of the survey years from 2001 through 2012, being commonly abundant in the North Backreef and South Backreef georegions and less abundant along the West georegion. Sea cucumber observations were discontinued from TDS in 2014, and therefore not included during the 2015 surveys. Individual segment densities peaked at 6 individuals per 100 m^2 in 2002.

Crown-of-thorns sea stars (COTS) were observed at Kingman Reef during each of the eight survey years, consistently exhibiting the highest COTS densities among the PRIMNM over time. Localized densities commonly reaching outbreak or near-outbreak levels (Moran et al. 1992) were often observed to be accompanied by localized coral devastation as these corallivores consumed many of the corals in their paths. The highest density of COTS recorded per segment was 9 individuals per 100 m^2 in 2012. Despite localized COTS outbreaks at Kingman, the island-wide mean density of COTS over all survey years is still less than 0.1 individuals per 100 m^2, and the forereef habitats have maintained consistently high and stable coral cover, as discussed previously (Figure 29 and Figure 30).

A juvenile orangefin Dascyllus damselfish (Dascyllus auripinnis) swimming by a giant anemone at Kingman Reef.
Photo: Rebecca Weible, NOAA Fisheries.

3.5 Microbiota

A towed-diver maneuvering through the reefs of Kingman reef.
Photo: Kaylyn McCoy, NOAA Fisheries.

The reef microbiota facilitates the cycling of essential nutrients by breaking down organic materials released by photosynthetic picoplankton (e.g., cyanobacteria) and benthic macroorganisms (corals and macroalgae). Habitats dominated by reef-building organisms (i.e., stony corals and calcified algae), such as Kingman Reef, illustrate a functional role that suppresses the energetic losses through microbial catabolism and promotes trophic transfer of energetic resources, carbon and inorganic nutrients, into metazoan food webs. This function is observed through the low microbial standing stocks in the water column and high turnover rates of microbial populations on reefs compared to the surrounding oceanic waters. Reef water samples were collected from all RAMP sites across the U.S. Pacific Islands beginning in 2008, with the first PRIMNM samples measured in 2009 (i.e., Wake and Johnston Atolls) and 2010 (i.e., Jarvis, Howland, and Baker Islands, Palmyra Atoll, and Kingman Reef). The assessment and monitoring of the reef microbiota paired with data collected on benthic and pelagic macrobiota across the entire U.S. Pacific allows for characterization of coral reef ecosystems from a molecular to an ecosystem scale.

Microbial Composition and Diversity

Microbial communities in reef waters were collected from RAMP sites across all U.S. Pacific Islands from 2012 to 2014. Reef water samples were processed for molecular identification of microbial populations using metagenomic sequencing. Microbial community composition at Kingman Reef is characterized by higher community diversity (measured using the Shannon Index, a metric of both species richness and evenness) on average compared to other U.S. islands across the Pacific (Figure 38). The community structure of the microbes at Kingman reflects the complex and nutrient-rich organic material released by coral-dominated systems and the enhanced niche space characteristic of intact reef habitats that promotes biodiversity across macro- and microbiota.

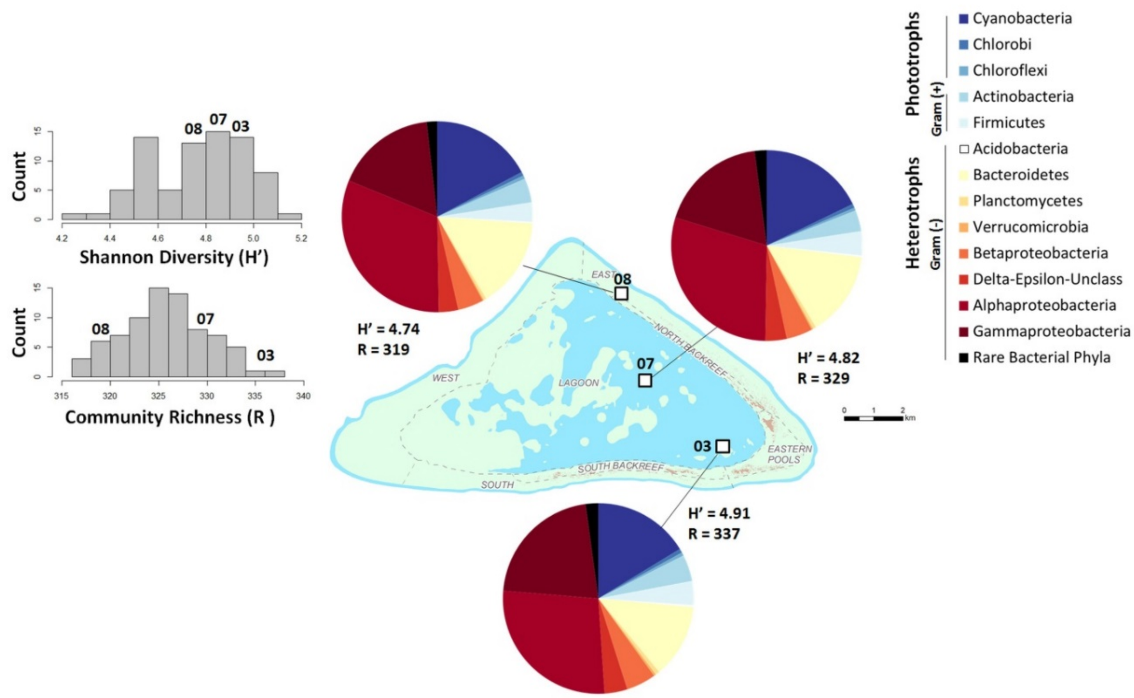


Figure 38. Microbial composition and diversity at Kingman Reef. The microbial taxonomic groups are shown at Phylum Level. Delta-Epsilon-Unclass, Deltaproteobacteria, Epsilonproteobacteria and Unclassified Proteobacteria are all combined. Community Richness and Diversity were calculated at the Genus Level. H', Shannon Index. R, Rarified Richness. Comparison of microbial diversity at three Kingman reefs collected in 2012 (Sites 03, 07, and 08) overlaid on a histogram of all Richness and Diversity observations across the U.S. Pacific islands collected between 2012 and 2014 (n = 77 sites).

Microbial Biomass on Reefs

Microbial biomass at Kingman Reef, similar to other remote atolls (e.g., Rose and Palmyra) is lower than remote equatorial islands that experience equatorial and topographic upwelling (Jarvis, Howland, and Baker) (Figure 39). Habitats dominated by reef building organisms (i.e., stony corals and calcified algae), such as Kingman, illustrate a functional role that suppresses the flow of energy through the microbial pathways and promotes movement through particulate pathways channeling energy and nutrients towards metazoan food webs. Reef degradation towards algae-dominated states promotes greater cell biomass and higher proportions of fast growing heterotrophic taxa (as observed on the main Hawaiian Islands), which exhibit up to an order of magnitude more microbial biomass in the overlying reef waters (i.e., Kingman in 2010 = 18 mg m^{-3} and Oahu in 2008 = 153 mg m^{-3}, respectively). 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.

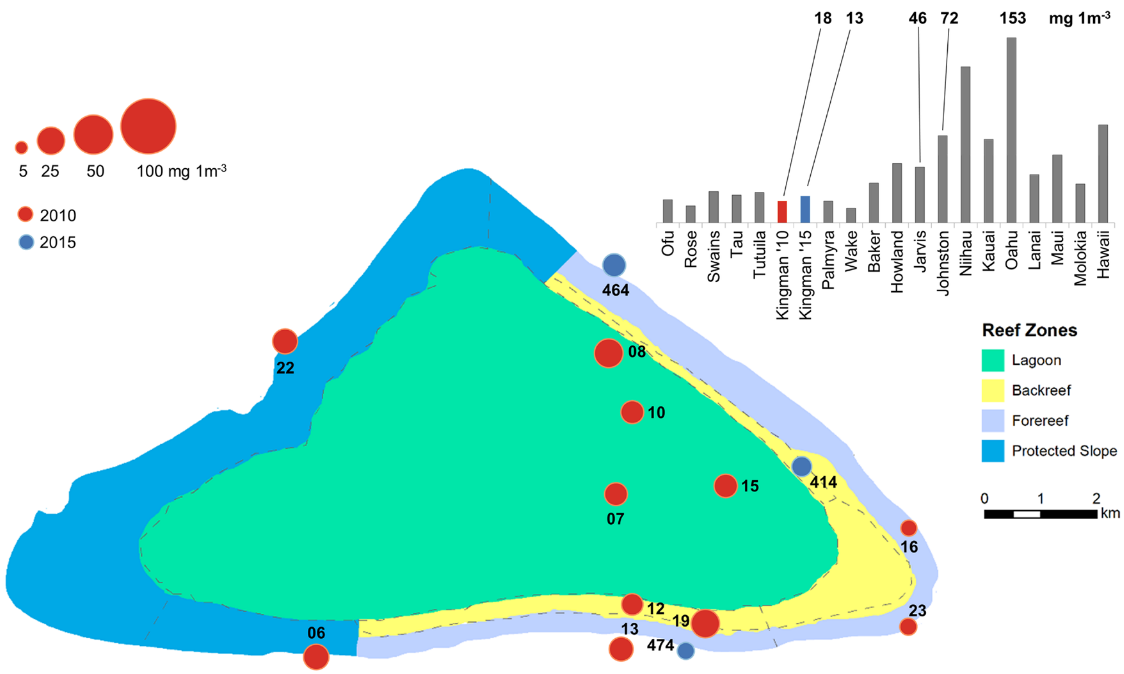
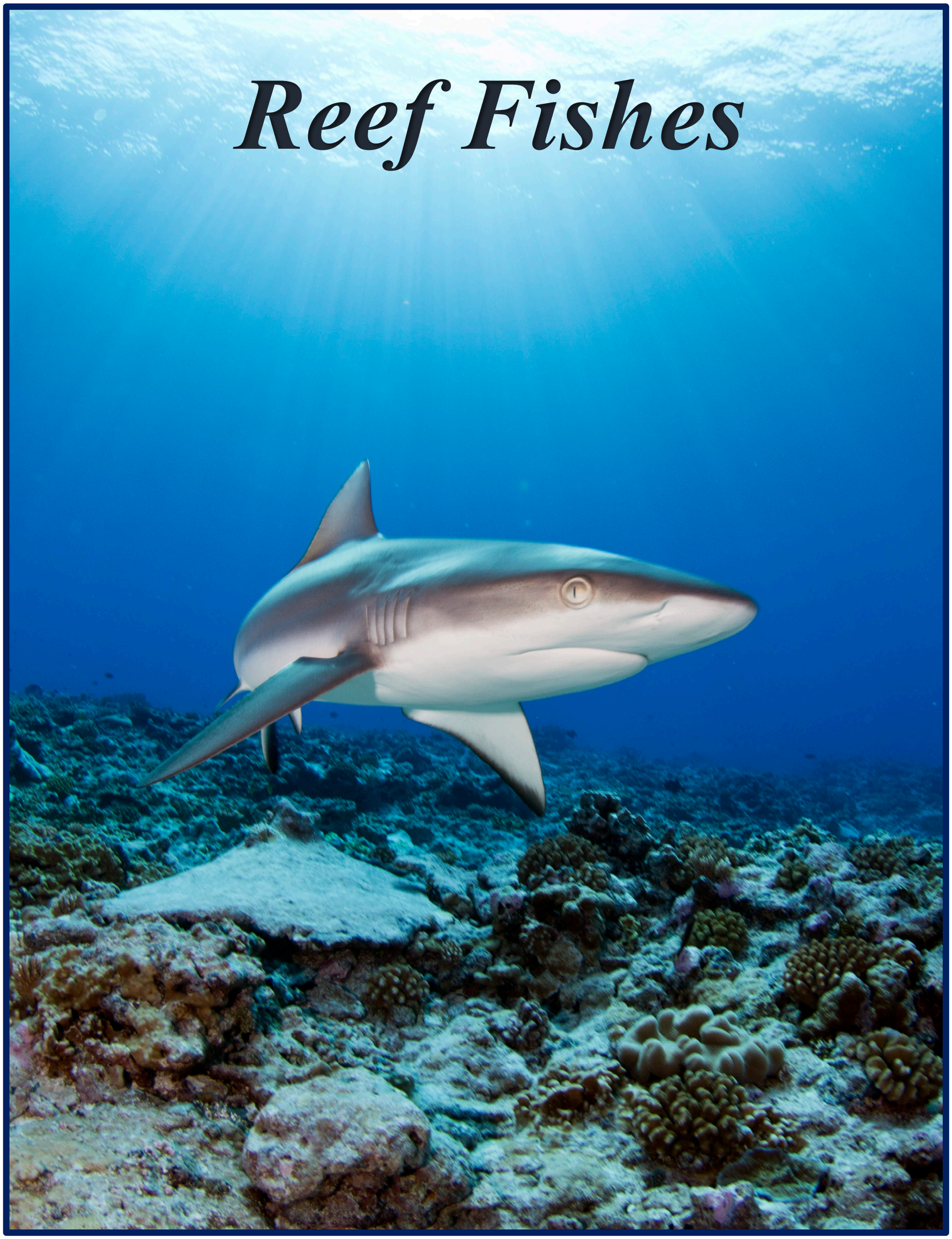


Figure 39. Microbial biomass collected at Kingman Reef in 2010 and 2015 (n= 17). Cell volume is estimated based on measurements of cell length and width and cell abundances enumerated using epi-fluorescent microscopy. Biomass is reported as milligrams per cubic meter (mg m^{-3}). The 2010 data were published in (McDole et al. 2012).



Carcharhinus amblyrhynchos at Kingman Reef.
Photo: Jeff Milisen, NOAA Fisheries.

3.6 Reef Fishes

Epinephelus polyphekadion at Kingman Reef.
Photo: Kevin Lino, NOAA Fisheries.

Survey Effort and Site Information

Reef fishes were surveyed at Kingman Reef on eight occasions during the period from 2001 through 2015 (

Table 4). In each case, surveys were a mix of comprehensive small-area surveys of all reef fishes (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 have been conducted primarily around forereef and backreef habitats of the atoll's perimeter, where large fishes tend to be most abundant (Figure 43). BLT surveys, which were utilized during the period from 2001 through 2008, were mostly conducted at haphazardlylocated mostly mid-depth (~10–15 m) sites, nearly all of which were on the eastern half of the atoll (Figure 40). 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 that encompasses all hard-bottom habitats less than 30 m deep (Figure 40). Since that time, there has also been a concerted effort to increase the number of survey sites per visit, with 33 or more sites surveyed each visit starting in 2010, compared to 14 or fewer sites prior to 2008 (

Table 4). One consequence of the shift in survey design is that stratified-random SPC sites have been much more widely distributed around the island than were BLT surveys—including encompassing reef habitats in the West georegion that had only been surveyed previously during TDS (Figure 40). Because of some inconsistencies in the application of the BLT survey methodology in the program's earliest years, data prior to 2004 were not used here to generate quantitative estimates, such as density. Similarly, BLT data gathered at the time Pacific RAMP shifted to the stratified-random survey design in 2008, cannot be meaningfully comparable with earlier BLT data gathered at repeat site locations. Thus, time series were primarily built from data collected during TDS, which have been relatively consistent across all survey years, and from the stratified-random SPC surveys conducted since 2008.

Table 4. Reef fish survey effort at Kingman Reef. Data are number of surveys by year and method. Towed-diver surveys (TDS) ~2 km long by 10 m wide transects (~20,000 m^2), typically in mid-depth forereef habitats in which divers count only 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).

	All Fishes		Large Fish (>50 cm TL)
Year	BLT	SPC	TDS
2001	9	–	2
2002	9	–	6
2004	9	–	8
2006	14	–	13
2008	23	23	14
2010	–	33	14
2012	–	49	14
2015	–	49	14

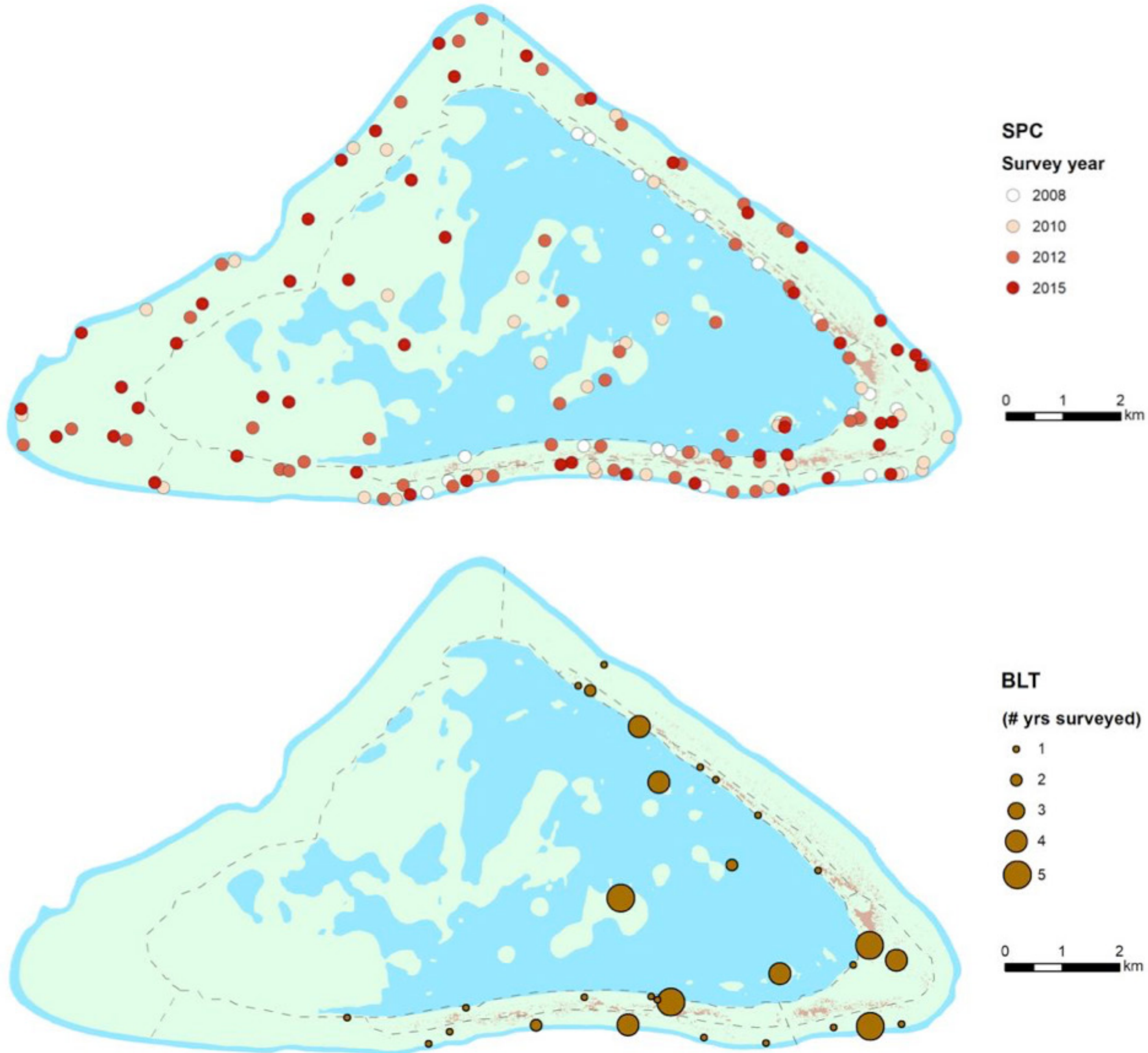


Figure 40. Location of stationary point count (SPC; top) and belt-transect (BLT; bottom) sites at Kingman Reef. SPC sites were not revisited. The survey year for the SPC sites is distinguished by color. BLT survey sites were generally revisited during multiple survey years, and the total number of times each site has been surveyed is indicated by the size of the bubble.

Distribution of Reef Fish Biomass and Abundance

Reef fish biomass from SPC surveys over the period from 2008 through 2015 was generally higher in forereef habitats than in backreef or lagoon habitats, but was particularly high in the South georegion (Figure 41). Higher biomass on forereef areas was largely driven by higher biomass of planktivores and piscivores (Figure 41 and Figure 42).

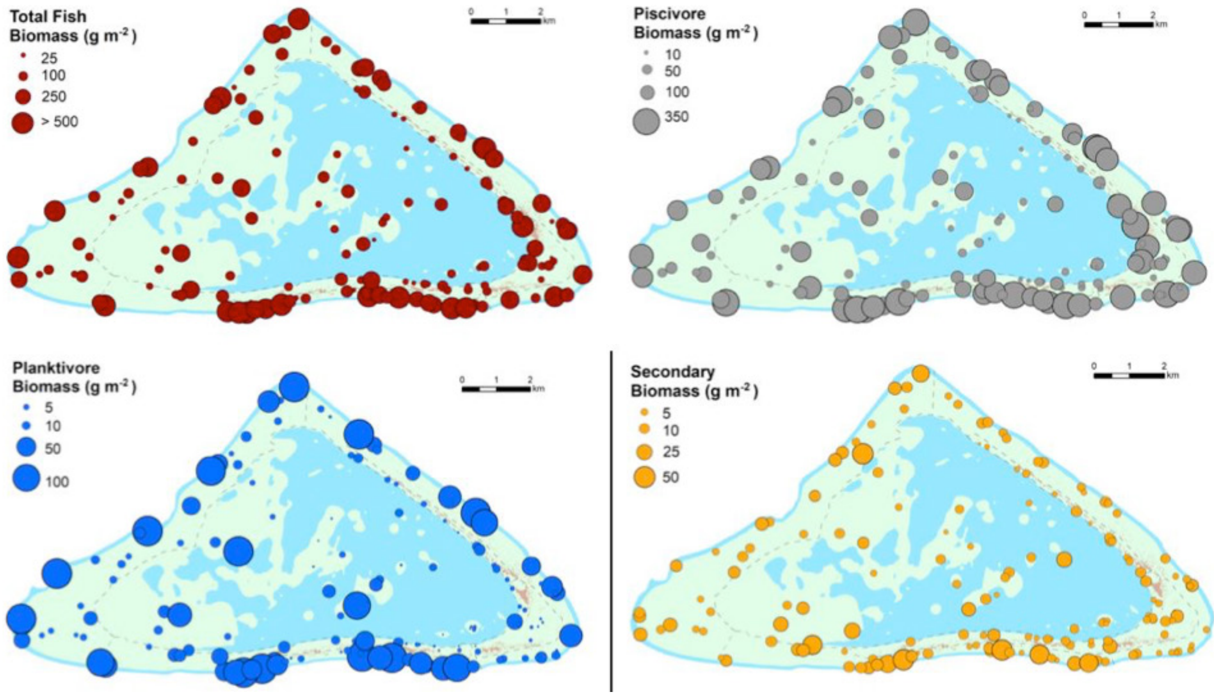


Figure 41. Biomass of Total Fish, Planktivore, Piscivore and Secondary Consumer Groups from stratified-random stationary point count surveys during the period from 2008 through 2015 at Kingman Reef. Secondary consumers include omnivores and invertivores, comprising many abundant and generally small-bodied species.

Planktivore biomass was generally low in backreef sites and at all but a few lagoon sites, but generally high at forereef sites (Figure 41). Highest planktivore biomass was recorded in the South and West georegions, with biomass dominated by the yellow and blueback fusiliers (*Caesio teres*) and the sleek (*Naso hexacanthus*) and bignose (*N. vlamingii*) unicornfishes; however, far more abundant were the small-bodied anthias, particularly Whitley's splitfin (*Luzonichthys whitleyi*) and the olive (*Pseudanthias olivaceus*) anthias.

Herbivore biomass was highest in the South and South Backreef georegions (Figure 42). The high biomass in the South georegion was partly due to several observations of large-bodied milkfish (*Chanos chanos*). The dominant herbivorous surgeonfish was the whitecheek surgeonfish (*Acanthurus nigricans*) and three species of bristletooth surgeonfishes: the striated (*Ctenochaetus striatus*) and striped-fin (*C. marginatus*) surgeonfishes and the bluelip bristletooth (*C. cyanocheilus*). Parrotfish biomass was low at sites in the Eastern Pools georegion, but was otherwise evenly distributed with slightly higher biomass in the South Backreef georegion, where the steephead parrotfish (*Chlorurus microrhinos*) was particularly abundant. Other parrotfishes which contributed substantially to biomass included bridled parrotfish (*Scarus frenatus*), which was particularly abundant in the South Backreef and North Backreef georegions, and the redlip parrotfish (*Scarus rubroviolaceus*) which was widely distributed, but most abundant in the Lagoon georegion.

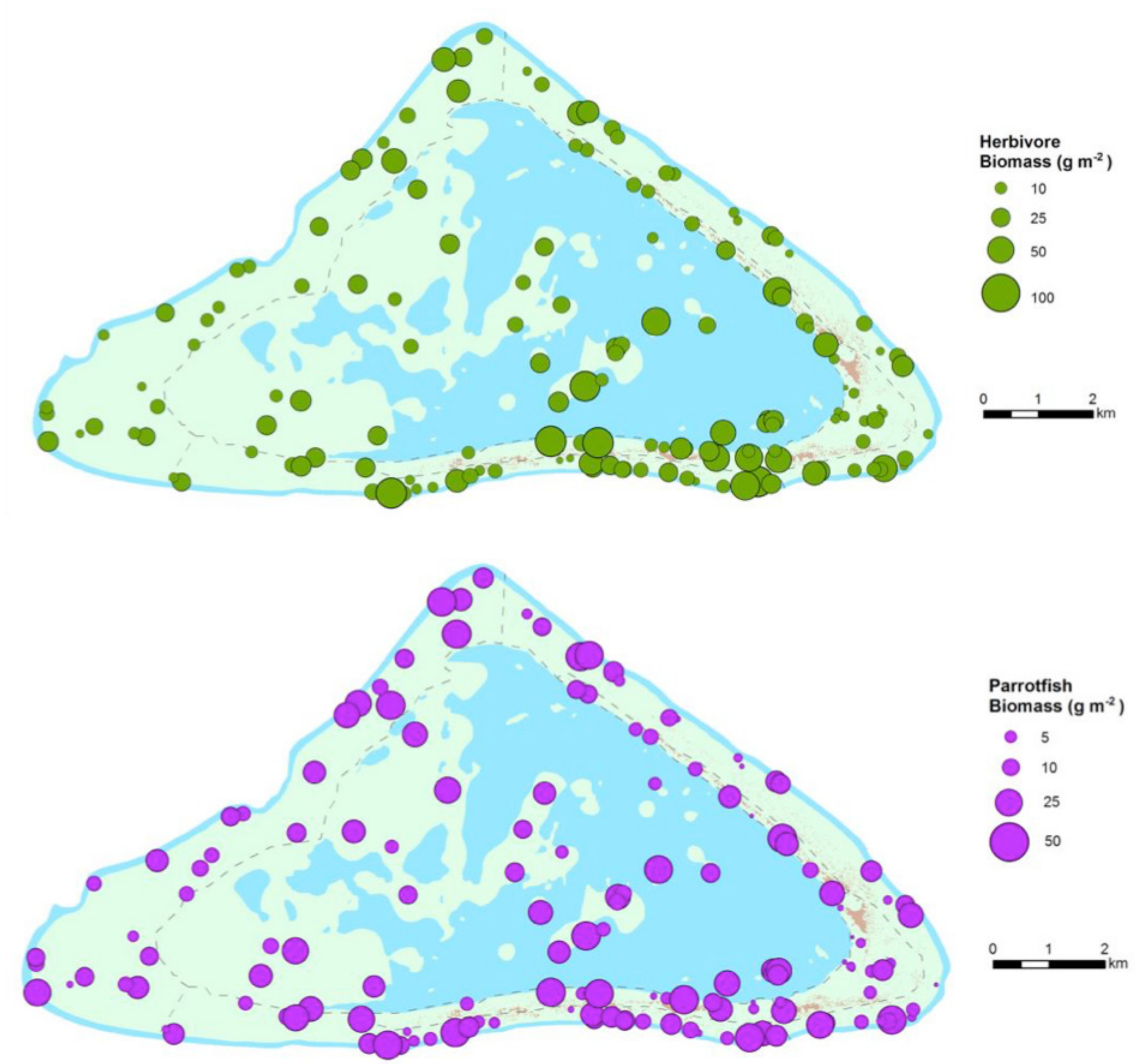


Figure 42. Total herbivore and parrotfish biomass at Kingman Reef from stratified-random stationary point count surveys conducted during the period 2008–2015.

Sharks were observed during more than 60% of all towed-diver segments (~220 m long sub-units of the survey) in both the South and East georegions, but at only 45% of tow segments in the West georegion and approximately 25% of tow segments in the Lagoon and Eastern Pools georegions (Figure 43). Gray reef sharks (*Carcharhinus amblyrhynchos*) were the most commonly observed sharks in all georegions, but were particularly abundant in the South and East georegions. Whitetip reef sharks (*Triaenodon obesus*), although considerably less common, were also frequently observed. Biomass of other predatory species was more evenly distributed around the island, but tended to be low in the North Backreef georegion (Figure 41). The scalloped hammerhead shark, *Sphyrna lewini*, which is listed as endangered under the ESA, has occasionally been observed by survey divers at Kingman. The other major component of piscivore biomass was of the two-spotted red snapper (*Lutjanus bohar*), which was encountered during nearly every SPC survey conducted at Kingman Reef during the 2008–2015 period.

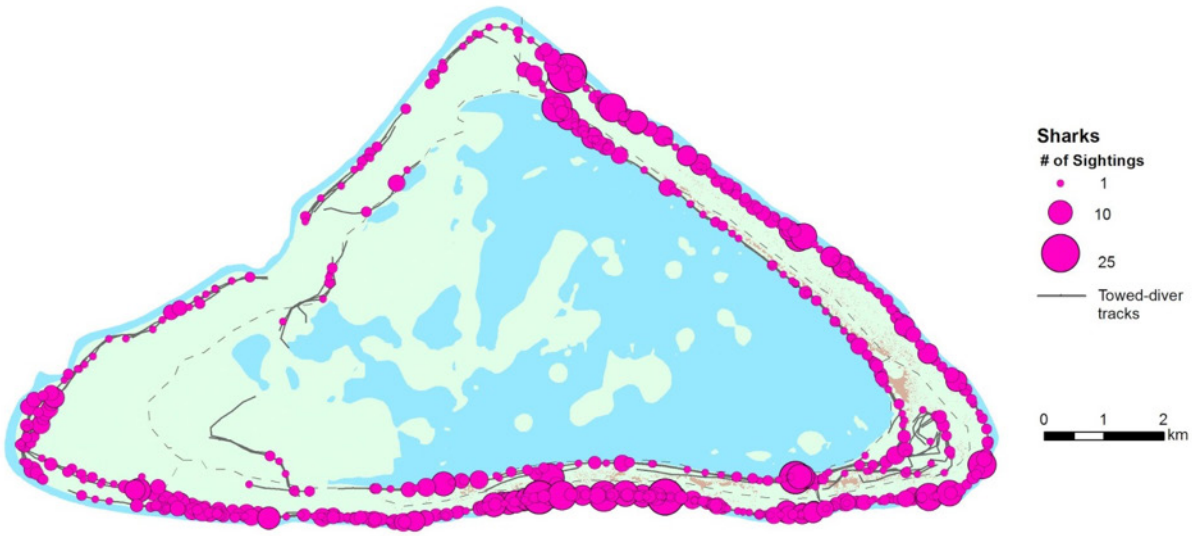


Figure 43. Towed-diver survey sightings of reef sharks at Kingman Reef during the period from 2001 through 2015.

Distribution of Other Species of Interest

Although it is not possible for survey divers to reliably distinguish between the giant manta (*Mobula birostris*), which are listed as threatened under the ESA, and the reef manta (*Mobula alfredi*), which is not listed, were sighted during 2% of all TDS segments at Kingman Reef, with most observations around the eastern tip of the reef or at the northern edge of the East and North Backreef georegions (Figure 44). The large majority of those observations have been in forereef areas (i.e., the East and South georegions).

Green turtles (*Chelonia mydas*), listed as threatened under the ESA, and hawksbill turtles (*Eretmochelys imbricata*), listed as endangered under the ESA, were each recorded during approximately 1% of all TDS segments. All green turtle observations were made in the eastern half of Kingman Reef in both forereef and backreef habitats (Figure 44). Hawksbill turtles were broadly distributed around Kingman.

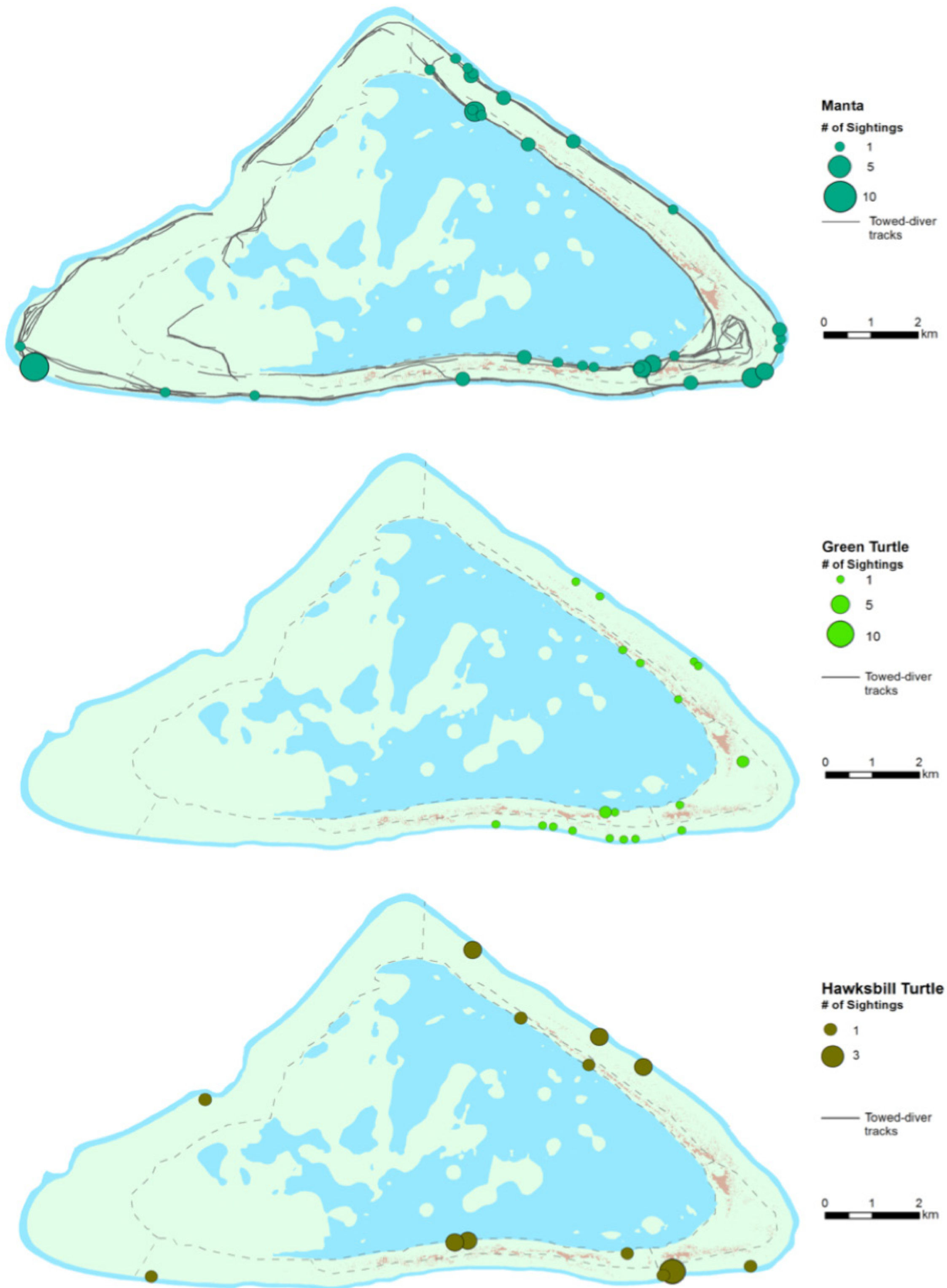


Figure 44. Towed-diver sightings of manta rays and sea turtles during towed-diver surveys at Kingman Reef during the period from 2001 through 2015.

Reef Fish Time Series

Incorporating data from both BLT and SPC surveys, Figure 45 shows time series of biomass of reef fishes over the period from 2004 through 2015. As is evident from the size of the confidence intervals in 2004 and 2006, there were an insufficient number of surveys during those earlier years to identify clear patterns—but certainly there are no clear indications of changes during that time period (Figure 45). Based on the SPC data that were collected during the period from 2008 through 2015, fish biomass tended to be higher in 2010 and 2012 for secondary consumers and perhaps also parrotfishes, but there are no clear overall trends during the period from 2008 through 2015 (Figure 45).

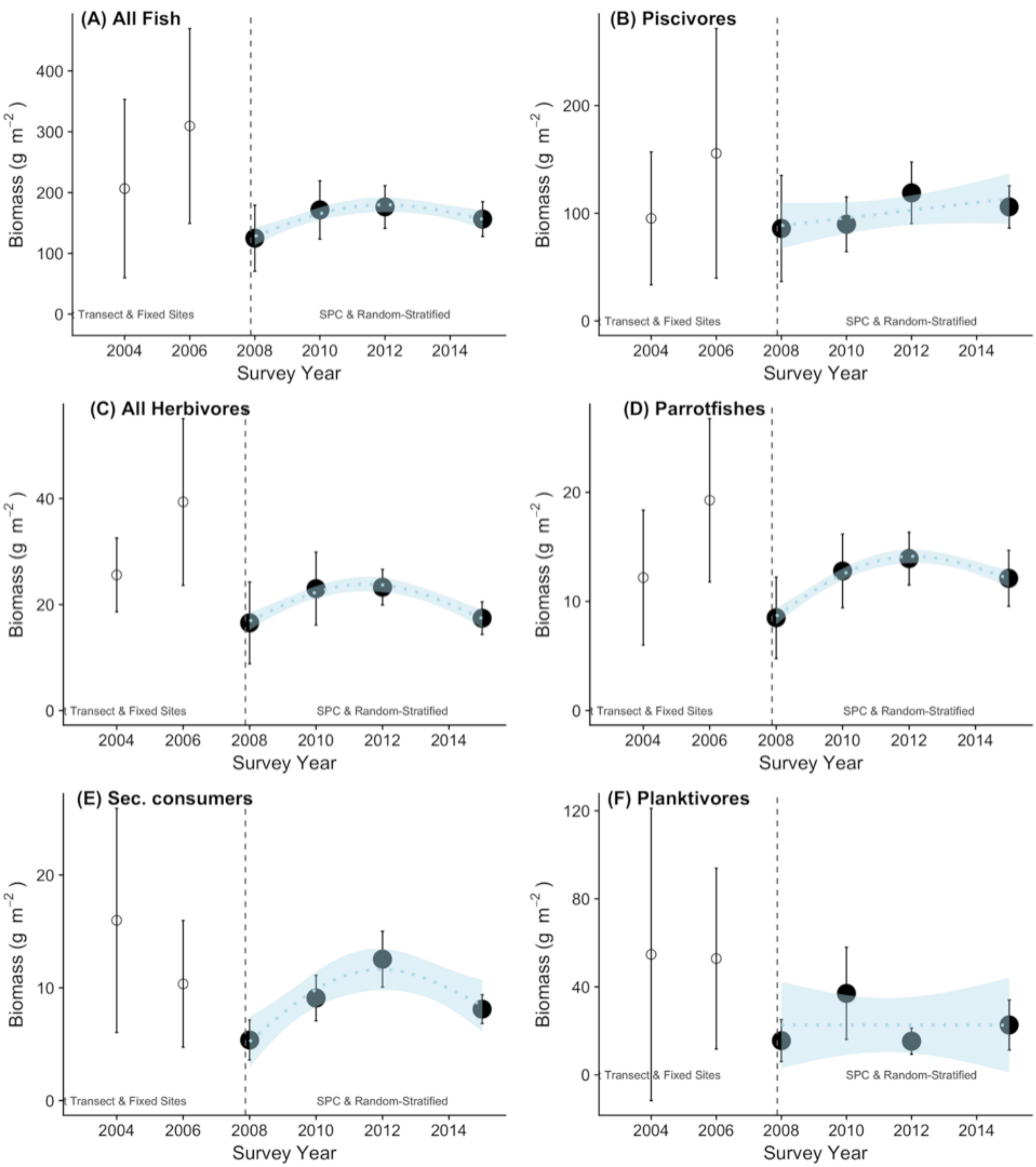


Figure 45. Time series of reef fish biomass at Kingman Reef. Data are shown for belt-transect surveys conducted at a limited number of mid-depth forereef sites in 2004 and 2006, and stationary point count surveys conducted at randomly located sites encompassing all hard-bottom forereef in depths ≤30 m, during the period from 2008 through 2015. Open and black circles indicate mean values, and vertical error bars represent 95% confidence intervals per time period. The light blue dotted trend line and confidence intervals were 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 trends in overall abundance of sharks, jacks, or large (>50 cm total length) snappers or parrotfishes at Kingman Reef, though there were notable increases or decreases in specific years (Figure 46). The peak of reef shark abundance in 2010 occurred as a result of several encounters with large groups of gray reef sharks (*Carcharhinus amblyrhynchos*) during TDS within the East and South georegions. Compared with the other large-fish groupings shown, counts of jacks were the most variable among years, with peaks in 2008 and 2010 caused by encounters with a single large school of bigeye trevally (*Caranx sexfasciatus*) in each year, and a school of rainbow runner (*Elagatis bipinnulata*) in 2010. Those species were also observed in other years, but not recorded in such large numbers. However, such patchily-distributed and wide-ranging species are inherently difficult to count reliably, and a high degree of variability in their counts is common.

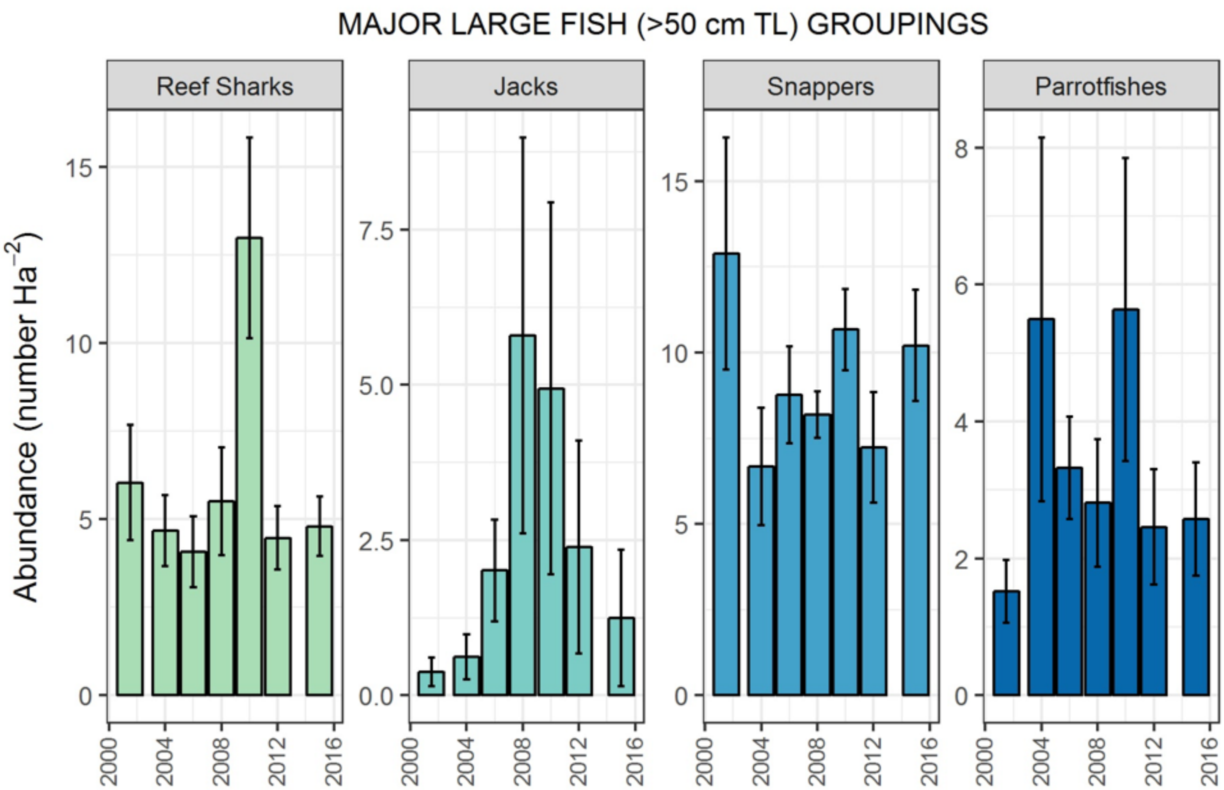


Figure 46. Bar plots by year for reef sharks, jacks, snappers, and parrotfishes from towed-diver surveys (TDS) at Kingman Reef during the period from 2001 through 2015. Note that 2001 and 2002 data were pooled due to low sample sizes in those years. In order to increase consistency among years, trends were derived only from TDS >500 m long, which were conducted in forereef habitats between 10 and 20 m deep. Errors bars represent standard error of the mean.

Species Lists, Encounter Rates, and Diversity

Mean reef fish species richness values at Kingman Reef ranged between around 28 and 40 species per SPC survey, averaging around 34 species per survey (Figure 47). Kingman evenness was at the high end of values from the PRIMNM, ranging between 0.54 and 0.67 (Figure 47). Overall, Kingman had among the highest and most evenly distributed reef fish diversity of any of the PRIMNM islands. Despite some variability among years, including higher richness in 2012 and lower richness in 2008, there are no clear indications of a trend in reef fish assemblage diversity at Kingman over the 2008–2015 period (Figure 47).

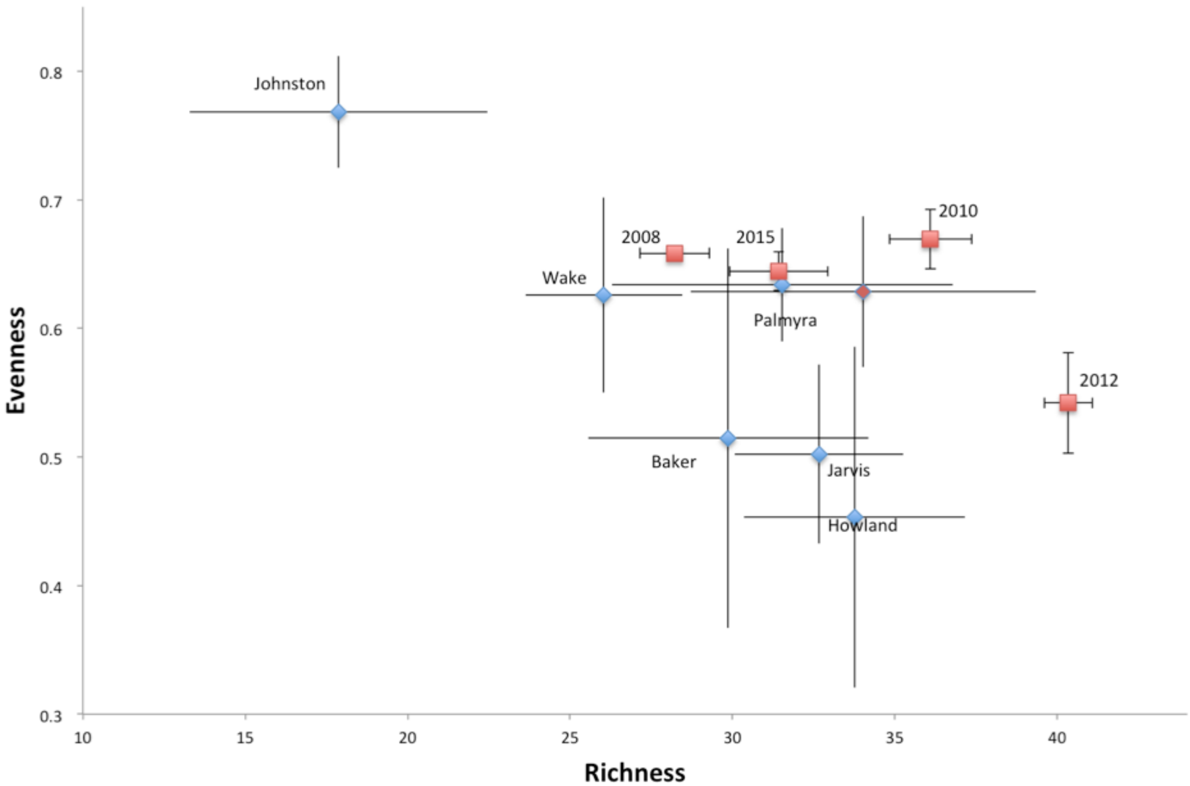


Figure 47. Reef fish richness vs. evenness at Kingman Reef. Red squares are richness and evenness values (+/- SE) by year, blue circles represent mean (+/- SD) of richness and evenness values for other islands in the Pacific Remote Islands Marine National Monument across all years. The single red dot represents the mean at Kingman across all years. For consistency among islands, only outer-reef sites are included for each island.

Ten species of reef fishes recorded during surveys at Kingman Reef 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). Three of those were regularly encountered by survey divers (i.e., recorded on ~20% or more of SPC surveys): the gray reef shark, *Carcharhinus amblyrhynchos;* the chevron butterflyfish, *Chaetodon trifascialis;* and the camouflage grouper, *Epinephelus polyphekadion*. Two species were recorded on around 2% of SPC surveys: manta rays, *Mobula* sp., and the yellowfin tuna, *Thunnus albacares.* Five other IUCN red-listed species have been observed by survey divers at Kingman: the spotted eagle ray, *Aetobatus narinari*; the blacktip reef shark, *Carcharhinus melanopterus*; the scalloped hammerhead, *Sphyrna lewini*; the giant grouper, *Epinephelus lanceolatus*; and the humphead wrasse, *Cheilinus undulatus*. The last of those was a single small individual recorded during a survey in 2002. Given the relative inexperience of divers at that time and the fact that the species has not been recorded since, it is possible that this record is a misidentification. Interestingly, no bumphead parrotfish have been observed by divers at Kingman during any survey visit. Four ESA-listed species have been observed at Kingman: green and hawksbill sea-turtles (*Chelonia mydas* & *Eretmochelys imbricata*), scalloped hammerhead (*Sphyrna lewini*), and *Mobula* sp.—

although as noted above, it is not possible for divers to reliably distinguish between the two species: *M. birostris* and *M. alfredi*, and only the former is listed. A complete list of fish species observed each year is given in the PRIMNM in Appendix B of "Chapter 9: Pacific Remote Islands Marine National Monument in the Pacific-wide Context."

Marine Debris

3.7 Marine Debris

Marine debris was noted during TDS conducted around Kingman Reef between 2001 and 2015 (Figure 48). In total, 16 instances of marine debris were recorded. This does not encompass all debris at Kingman, as the surveys did not cover all reef habitats in each year. In addition, it is possible that the same debris was noted in different survey years. Fishing line made up the majority of the sightings. Line, net, anchors, metal, wrecks, and miscellaneous (other) debris have been recorded.

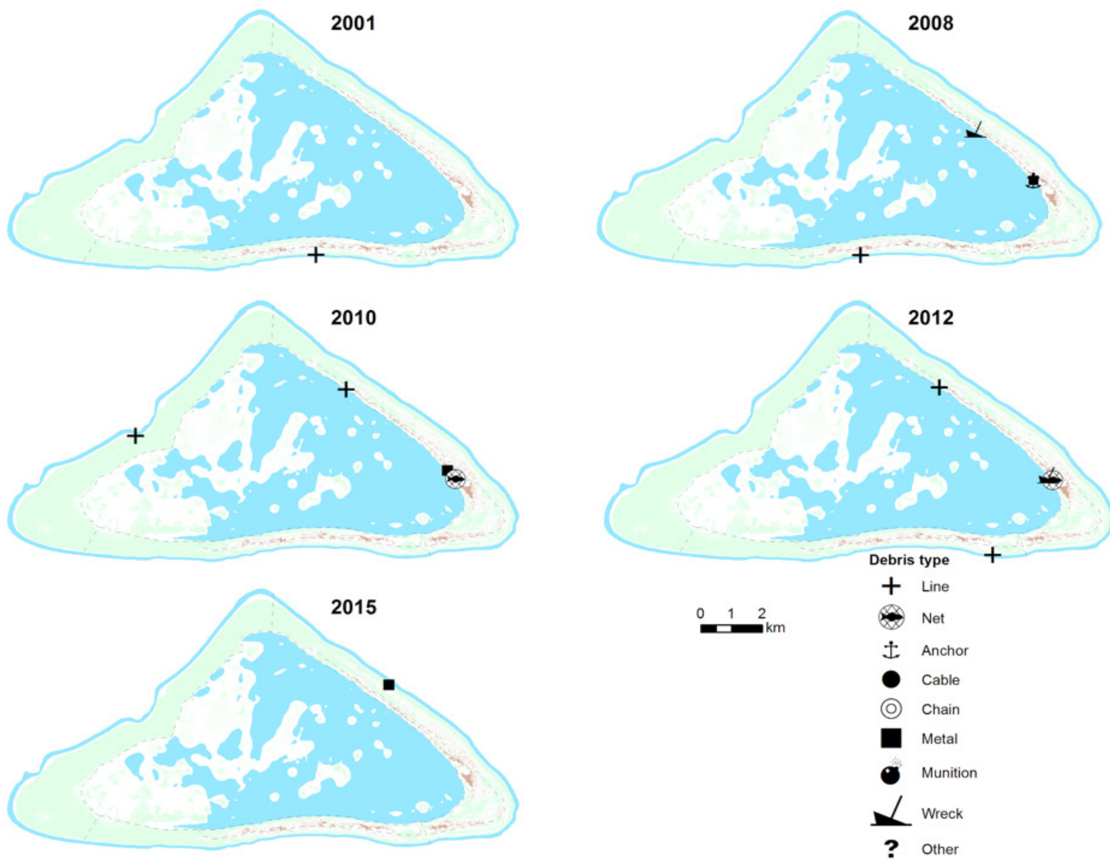
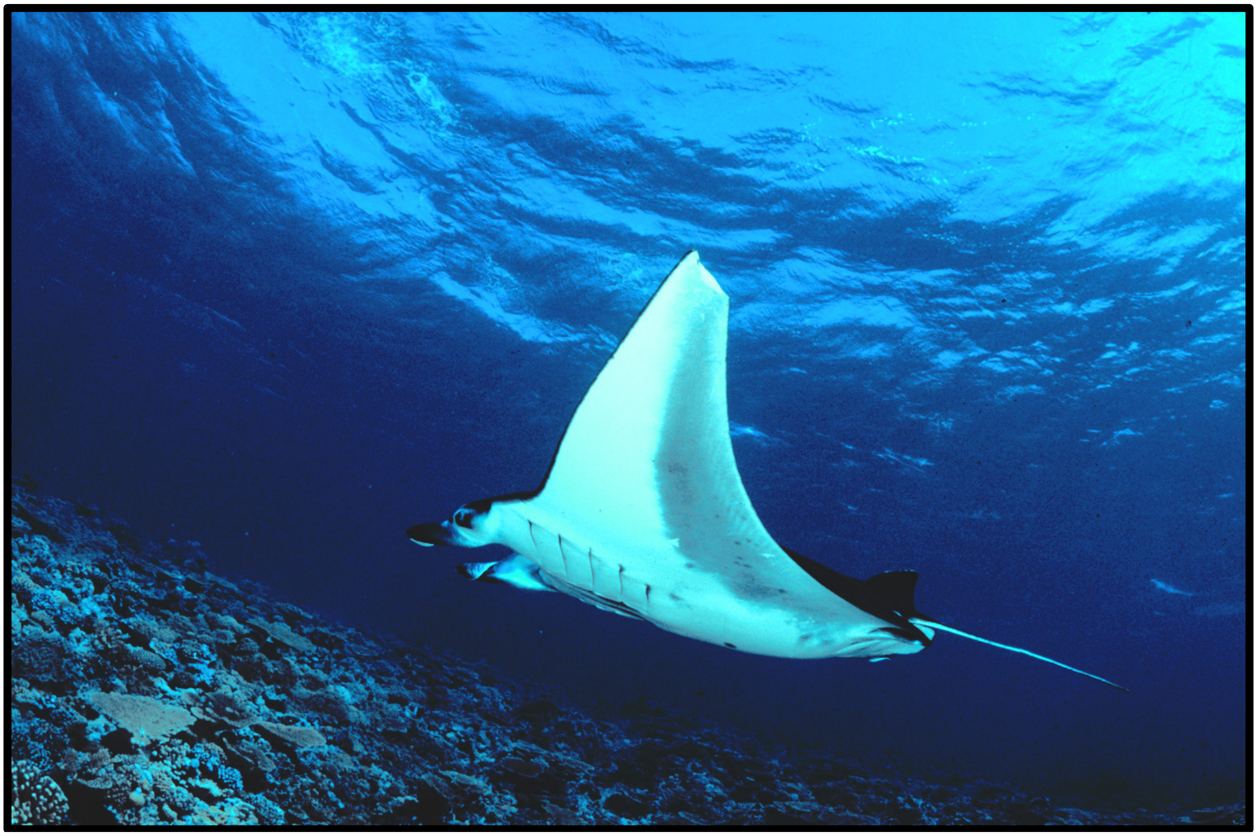


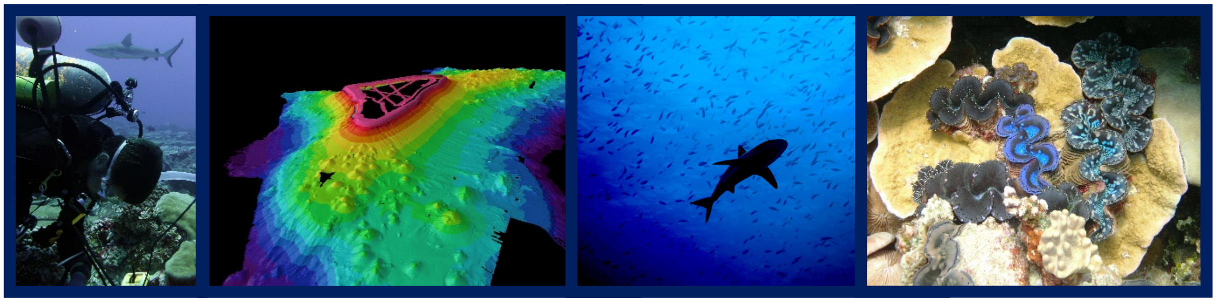
Figure 48. Marine debris sightings during towed-diver surveys at Kingman Reef between 2001 and 2015.



Manta ray (Manta alfredi) in Kingman Reef.
Photo: James Maragos, USFWS, courtesy NOAA Fisheries.

Ecosystem Integration

3.8 Ecosystem Integration



Photos left to right at Kingman Reef: Grey reef shark (Carcharhinus amblyrhynchos) cruises above as NOAA diver installs a subsurface temperature recorder on deep forereef, Photo—Ari Halperin, NOAA Fisheries; 3D multibeam bathymetry of Kingman Reef, Image—Pacific Islands Benthic Habitat Mapping Center; Carcharhinus amblyrhynchos, Photo—Andrew E. Gray, NOAA Fisheries; Colorful coral-Tridacna assemblage on backreef, Photo—Bernardo Vargas-Angel, NOAA Fisheries.

Oceanic Drivers of Benthic and Fish Populations

Located directly in the latitudinal path of the North Equatorial Countercurrent (NECC), Kingman Reef is supplied warm water from the Western Pacific by this eastward-flowing current that typically strengthens in the summer and weakens in the winter during the monsoon season. The reefs at Kingman, which encircle a lagoon, maintain a high diversity of corals (30 genera total) perhaps in part due to the NECC transporting water sourced from more biologically-diverse reefs further west (Kenyon et al. 2010). Interannual variability in oceanographic conditions at Kingman Reef is largely driven by the El Niño-Southern Oscillation, 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 likely supported stable to increasing trends in fish biomass across all functional groups, with only a slight decrease in fish biomass during the most recent surveys conducted in 2015. This productivity also likely supported a diverse community of reef-associated microbes with an abundance similar to other sampled remote U.S. Pacific islands, yet lower compared to abundances observed at PRIMNM islands closer to the equator.

During El Niño events when warmer water temperatures are typically expected, Kingman's reefs experienced fairly mild increases in temperature (no greater than a change of ~3 °C to date) and have accrued a relatively mild amount of thermal stress of only three Degree Heating Weeks during the extreme 2015–2016 El Niño that drove severe coral bleaching and mortality at Jarvis Island located a mere 800 km to the southeast. Given these relatively stable water conditions and milder thermal impacts during El Niño events, perhaps it is not surprising that surveys throughout the forereef at Kingman Reef have revealed attributes indicative of healthy coral communities, whereby across survey years reefs have maintained uniformly high coral cover and low macroalgal cover, an ideal size structure of corals with large abundances of both recruits and juveniles, consistently low rates of partial coral mortality, and very few signs of coral disease or bleaching. In contrast, CCA appears to have declined slightly over time. Furthermore, coral communities at Kingman have persisted despite repeated observations of high densities of the corallivorous crown-of-thorns sea star (*Acanthaster planci*, COTS) that have periodically reached outbreak levels (highest density observed during TDS was 9 individuals per 100 m^2), which may suggest that outbreaks remain localized within a given time period, and/or corals at Kingman are able to recover relatively quickly following disturbances such as thermal events and COTS outbreaks.

Spatial Variation within the Island

Habitat characteristics and oceanic conditions strikingly differ between the eastern and western sides of Kingman Reef. Steep-sloping forereef located along the eastern side of Kingman experiences the greatest wave power driven by the easterly trade winds. The corals in the shallow strata throughout the South and East georegions were characterized by high densities of smaller-sized colonies composed mostly of shallow-water species (i.e., *Acropora* and *Pocillopora*). In contrast, the western side of Kingman consists of only mid- and deep-depth strata, where gradual-sloping reefs are influenced by the eastward-flowing NECC and breaking waves are less likely to form in the deeper water. Coral colonies at Kingman's deeper forereef were typically larger, resulting in high coral cover, but lower densities of individuals overall. The large coral colonies observed along the western side likely persist due to the relative lack of hydrodynamic stress from wave power, enhanced water flow from the NECC, and/or gradual slopes that may provide greater surface area with access to light for corals.

Larger values of herbivorous fish biomass, mostly surgeonfishes and large schools of milkfishes, were often concentrated across the shallower forereef and backreef of the South georegion, which may have contributed to the low cover of macroalgae in addition to the overall stable population of herbivorous sea urchins across Kingman Reef. The shallowest reefs at Kingman are located in the Eastern Pools georegion, where "clam gardens" are also supported and contain the greatest number of sightings of giant clams across all of the surveyed areas of Pacific RAMP. Piscivorous fishes and sharks (mostly grey reef sharks, *Carcharhinus amblyrhynchos*) were mainly sighted in the South and East georegions, as well as ESA-listed green and hawksbill sea turtles (*Chelonia mydas* and *Eretmochelys imbricata*) and the scalloped hammerhead (*Sphyrna lewini*).

Areas with greater water flow, such as channels or habitats with enhanced exposure to currents (e.g., NECC), tended to exhibit higher biomass of planktivorous fishes in the South and West georegions, and seemed somewhat associated with sightings of manta rays (*Mobula* spp., potentially including ESA-listed *M. birostris*) near the northern, eastern, and western points of Kingman Reef. The two-spotted red snapper (*Lutjanus bohar*) was another commonly observed piscivorous fish sighted outside of surveys in groups of thousands of individuals along the northwestern side of Kingman, perhaps as a result of spawning aggregations. One sighting of the giant grouper (*Epinephelus lanceolatus*) also occurred outside of a shallower channel in the South georegion, and the humphead wrasse (*Cheilinus undulatus*) have occasionally been sighted off the southern side of Kingman at deeper depths (20+ m).

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