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CORAL REEF ECOSYSTEMS

of the Pacific Remote Islands Marine National Monument

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

CORAL REEF ECOSYSTEMS

of the Pacific Remote Islands Marine National Monument a 2000–2016 Overview

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Front cover: Giant clams at Kingman Reef, Photo: NOAA Fisheries.

Back cover: Grey reef sharks (Carcharhinus amblyrhynchos) and barracudas at Jarvis Island, Photo: NOAA Fisheries/James Morioka.

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This booklet provides an overview of key findings about spatial patterns and temporal trends of the coral reef ecosystems observed during NOAA's Pacific Reef Assessment and Monitoring Program research surveys conducted in the U.S. Pacific Remote Islands Marine National Monument from 2000 to 2016 by the Coral Reef Ecosystem Program of the NOAA Pacific Islands Fisheries Science Center with financial support from NOAA's Coral Reef Conservation Program. All data sets used in this booklet are documented at NOAA InPort Metadata catalog at https://inport.nmfs.noaa.gov/inport/hierarchy/select/36446 and will soon be archived at the NOAA National Centers for Environmental Information. For more in-depth information, consult the scientific papers referenced throughout this booklet.

Spotband butterflyfish (Chaetodon punctofasciatus) at Wake Atoll, Photo: NOAA Fisheries/Andrew E. Gray.

HISTORY OF CORAL REEF ECOSYSTEM MONITORING BY CREP

National coral reef conservation efforts in the United States were advanced in 1998, with the issuance of Executive Order #13089 by President Clinton to “preserve and protect the biodiversity, health, heritage, and social and economic value of U.S. coral reef ecosystems and the marine environment.” This executive order established the U.S. Coral Reef Task Force and emphasized the need to undertake a comprehensive approach to research, map, and monitor all U.S. coral reef ecosystems. In 2000, the U.S. Coral Reef Task Force developed the National Action Plan to Conserve Coral Reefs (USCRTF, 2000) and the Coral Reef Conservation Act of 2000 laid out a national framework to address the degradation of U.S. coral reef ecosystems and other coral reef conservation issues (16 U.S. Code §6401[2000]). The Coral Reef Conservation Act also led to the creation of the national Coral Reef Conservation Program under the direction of the Secretary of Commerce. This legislation requires NOAA to conduct scientific research, mitigation, and outreach activities that directly contribute to the conservation of coral reef ecosystems. In response to mandates and with the support of NOAA’s Coral Reef Conservation Program, the NOAA Pacific Islands Fisheries Science Center initiated the Pacific Reef Assessment and Monitoring Program (Pacific RAMP) in early 2000, and established the Coral Reef Ecosystem Program (CREP) in 2001. In 2002, NOAA, in cooperation with the U.S. Coral Reef Task Force, released A National Coral Reef Action Strategy to address and reduce threats to coral reefs worldwide.

A primary mission of CREP is to provide high-quality, scientific information about the status and trends of coral reef ecosystems of the U.S. and U.S.-affiliated Pacific Islands to the public, resource managers, policymakers, and scientists to support ecosystem-based management and conservation of coral reefs on local, regional, national, and international levels.

Previous page: Threadfin butterflyfish (Chaetodon auriga) at Kingman Reef, Photo: NOAA Fisheries/Kevin Lino.
Right: Giant blue clams at Kingman Reef, Photo: NOAA Fisheries.

To fulfill this mission, CREP conducts a comprehensive suite of interdisciplinary monitoring and research activities, including habitat mapping, oceanographic and climate studies, and long-term monitoring of multiple components of coral reef ecosystems in the U.S. Pacific islands (Fig. 1). CREP has conducted biennial Pacific RAMP surveys from 2000 to 2012, and triennial surveys from 2012 to 2016, in each of the U.S. Pacific and U.S.-affiliated management jurisdictions. Using consistent survey methodologies across over 40 Pacific island, atoll, and shallow-bank ecosystems enables comparative analyses across diverse gradients of biogeography, environmental conditions, and human uses. Accurate and up-to-date characterizations of coral reef ecosystems are necessary to inform ecosystem-based management and evaluate the effectiveness of management actions for sustainable use and long-term conservation. Pacific RAMP survey results are also used to improve our understanding of ecosystem processes and the cause-and-effect mechanisms that influence the status and resilience of coral reefs.

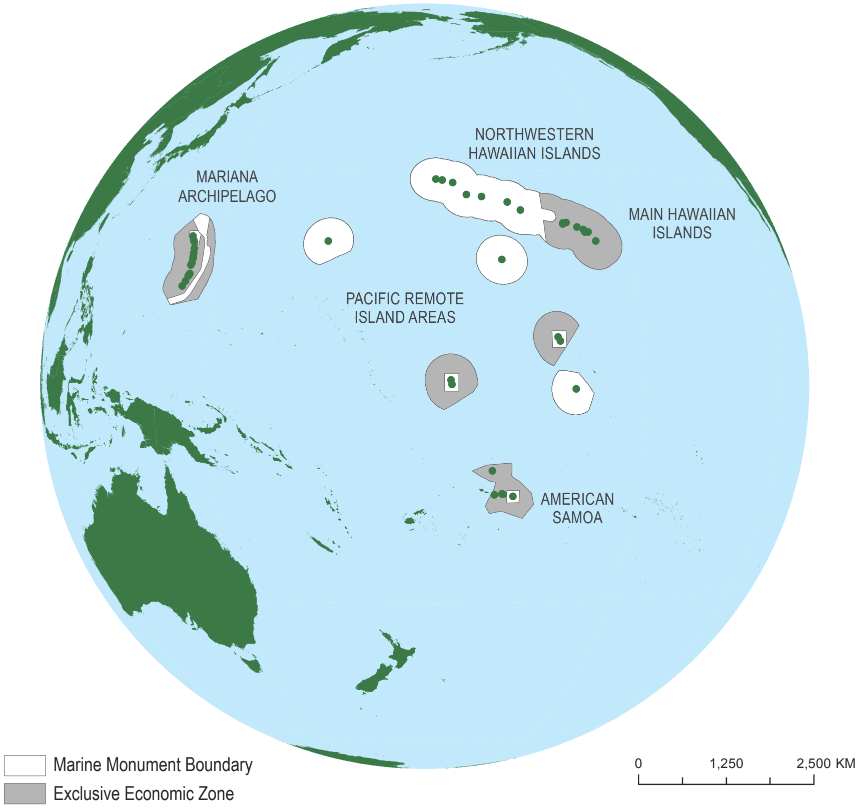


Figure 1. CREP monitors the status and trends of coral reef ecosystems of ~40 islands, atolls, and shallow banks spanning the waters of the Pacific Remote Island Areas, main Hawaiian Islands, Northwestern Hawaiian Islands, Mariana Archipelago, and American Samoa. Gray areas represent the U.S. Exclusive Economic Zones and the white areas represent the Pacific Remote Islands Marine National Monument, Papahānaumokuākea Marine National Monument, Marianas Trench Marine National Monument, and Rose Atoll Marine National Monument.

The initial exploratory surveys of the Pacific RAMP in 2000–2003 provided the first-ever baseline characterizations of the biodiversity, abundance, and distributions of coral reef habitats and associated resources across the U.S. Pacific Islands region. Those early surveys and the inherent logistical and budgetary constraints posed by the vast and remote U.S. Pacific Islands region have shaped many aspects of the long-term Pacific RAMP. By collecting biennial and triennial reef ecosystem 'snapshot' surveys during ship-based research expeditions, the Pacific RAMP was designed to observe the status and detect long-term changes in reef ecosystem conditions over periods of many years to several decades. They provide an improved understanding of island- and region-scale conditions that serve as background context to support more frequent and finer-scale local monitoring in populated island communities and jurisdictions designed to evaluate effectiveness of local management actions.

Over the past few decades, there has been a steadily increasing shift toward ecosystem-based management in the United States and globally. Ecosystem-based management requires efforts to monitor holistic ecosystem indicators, which include information on the status and trends of species, habitats, and environmental conditions in the biophysical and human systems. The goal of these ecosystem-based monitoring programs is to balance ecological scales with management scales so that monitoring meets the needs of management decision-making processes. In 2010, NOAA's Coral Reef Conservation Program unified NOAA's monitoring efforts by establishing the National Coral Reef Monitoring Program (NCRMP) which collects data across biological, climatic, and socio-economic domains. For the U.S. Pacific Islands, NCRMP augmented the ongoing Pacific RAMP surveys with long-term socio-economic surveys aimed at better establishing linkages between the ecological status of coral reefs and the human uses and benefits of coral reef ecosystems. Over the past 16 years, NOAA's Pacific RAMP and NCRMP have been able to continually adapt to evolving management needs and changing political environments without detracting from the overarching goal of long-term coral reef ecosystem status and trends monitoring (Heenan et al., 2016).

As is typical for any long-term monitoring effort, CREP survey protocols have been refined over time to match the priority information needs for management given the resources available for monitoring. For example, ecological survey methods were refined to reduce observer variability and expand the suite of monitored indicators to assess impacts of ocean acidification. To date, CREP has conducted 38 Pacific RAMP survey cruises, including nine to the Pacific Remote Islands Marine National Monument. Information on individual cruises can be found in the cruise reports for these expeditions at www.pifsc.noaa.gov/library/cruise.php. A monitoring report compiling the results of the past Pacific RAMP cruises (2000–2017) is currently in production.

Red pencil and long-spine sea urchins at Kingman Reef, Photo: NOAA Fisheries.

THE PACIFIC REMOTE ISLANDS MARINE NATIONAL MONUMENT

The U.S. Pacific Remote Islands encompass seven islands and atolls scattered across the central Pacific, spanning natural gradients in oceanographic conditions. The islands and reefs can be divided into three groups based on ecological characteristics: (1) the equatorial upwelling islands, Baker, Howland, and Jarvis Islands; (2) the central transition islands, Kingman Reef and Palmyra Atoll; and (3) the northernmost oligotrophic islands, Johnston and Wake Atolls (Fig. 2). The equatorial islands are especially productive as they benefit from the combined effects of regional equatorial upwelling and localized topographic upwelling of the subsurface Equatorial Undercurrent that collectively bring cool, nutrient-rich waters to the sunlit surface where photosynthesis thrives. In contrast, the northernmost islands are situated in the nutrient-poor waters of the central gyre characterized by low biological productivity. The central transition islands, located at the northern edge of the enhanced productivity region, experience a moderate level of biological productivity (Miller et al., 2008).

To protect and preserve the diversity and abundance of ocean life in these waters, all seven islands and atolls were established as the Pacific Remote Islands Marine National Monument (PRIMNM) by Presidential Proclamation #8336 in January 2009. To further care for and manage historic and scientific objects, such as the pelagic ecosystem, deep sea corals, and seamounts, the Monument protection was expanded around Jarvis Island, Johnston Atoll, and Wake Atoll by Presidential Proclamation #9173 in 2014. The Monument area is approximately 370,000 square nautical miles [nm²] (1,269,065 square kilometers [km²]).

Previous page: Grey reef sharks (Carcharhinus amblyrhynchos) and schools of anthias at Jarvis Island, Photo: NOAA Fisheries/Kelvin Gorospe.

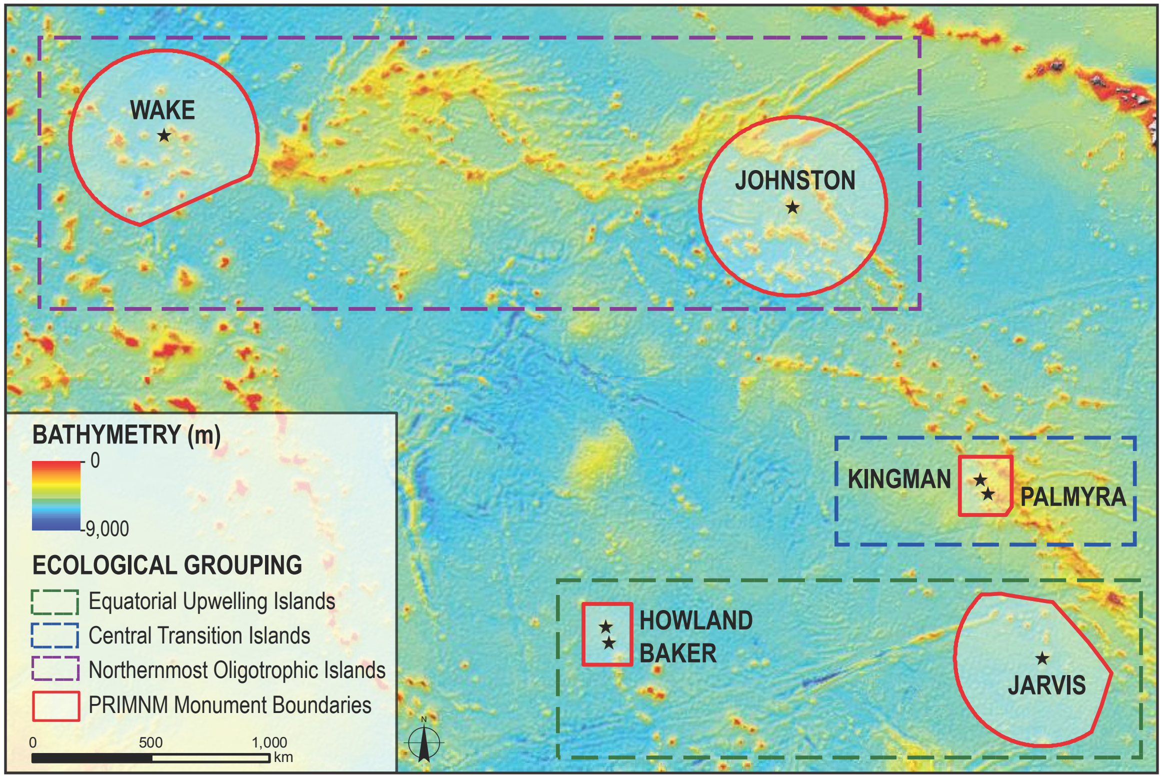


Figure 2. Pacific Remote Islands Marine National Monument boundaries and bathymetry (Becker 2009, Smith and Sandwell 1997) © 2008 The Regents of the University of California.

Each of the Pacific Remote Islands is also unique in terms of size. Wake is the largest of the Pacific Remote Islands with a land area of approximately 7 km². The rest of the Pacific Remote Islands have land areas less than 5 km². While these islands are small in size, reef areas range from approximately 2 km² surrounding Howland to 94 km² surrounding Johnston (Table 1). With the exception of Johnston, Palmyra and Wake, which have small mission-focused human presence, the Pacific Remote Islands are currently uninhabited.

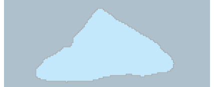
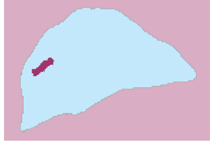
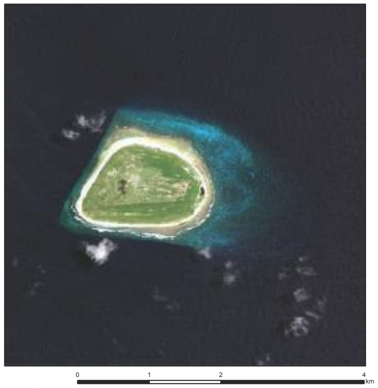
ISLAND	BAKER	HOWLAND	JARVIS	KINGMAN	PALMYRA	JOHNSTON	WAKE
Relative Shape and Size 🟦 30-m contour							
Land Area (km²)	**2**	**2**	**4**	**0**	**2**	**3**	**7**
Seafloor Area 0-30 m (km²)	**4**	**3**	**4**	**48**	**53**	**194**	**19**
Reef Area 0-30 m (km²)	**4**	**2**	**4**	**37**	**42**	**94**	**13**
Seafloor Area 30-150 m (km²)	**2**	**2**	**3**	**37**	**9**	**49**	**3**
Monument Area (km²)	**51,658**		**315,085**	**53,503**		**442,447**	**407,785**
Population	**0**	**0**	**0**	**0**	**4-20**	**4-5**	**94**
Age (million years)	**~124**	**~125**	**~111**	**~112**	**~112**	**~171**	**>160**
Ecological Grouping	Equatorial Upwelling Island	Equatorial Upwelling Island	Equatorial Upwelling Island	Central Transition Island	Central Transition Island	Northernmost Oligotrophic Island	Northernmost Oligotrophic Island
Island Chain	Phoenix Islands	Phoenix Islands	Line Islands	Line Islands	Line Islands	Line Islands	Marshall Islands

Table 1. Summary table of island characteristics across the PRIMNM. Blue area represents the 30-m depth contour around the islands. Colors indicate land area. All areas calculated using geographic information systems techniques. Monument areas were calculated by NOAA's Pacific Island Regional Office. Population estimates were collected from both the Federal Fish and Wildlife Services and Wikipedia. The ages of Baker, Howland, Jarvis, Kingman, and Palmyra were obtained from the Seamount Biogeosciences Network (https://earthref.org/SC/#top). Age of Johnston was determined through Fish and Wildlife Service documentation (http://www.fws.gov/refuge/Johnston_Atoll/about.html), and the age of Wake was obtained from the Pacific Islands Benthic Habitat Mapping Center (http://www.soest.hawaii.edu/pibhmc/pibhmc_pria.htm).

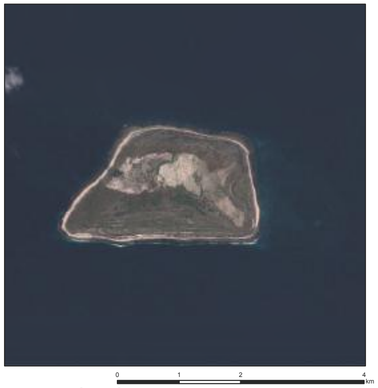
The Pacific Remote Islands have a rich human history that dates back to Polynesian voyages through these waters. In the mid-1800s, some of the islands experienced active whaling and guano mining. Other islands were actively utilized in World War II and the Cold War. Currently on Wake Atoll, there is a U.S. Air Force installation with a resident military population of ~94; on Palmyra Atoll there is a contingent population of ~30 researchers working seasonally with the U.S. Fish and Wildlife Service and The Nature Conservancy as part of the Palmyra Atoll Research Consortium; and on Johnston Atoll there is a small team of volunteers working with the U.S. Fish and Wildlife Service to eradicate invasive ants.

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

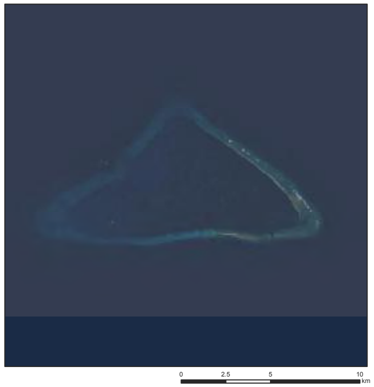


Baker Island

Howland Island



Jarvis Island



Kingman Reef

Satellite images of the seven islands and atolls in the PRIMNM at various scales (© DigitalGlobe Inc. All rights reserved, Johnston Atoll: NASA/U.S. Geological Survey).

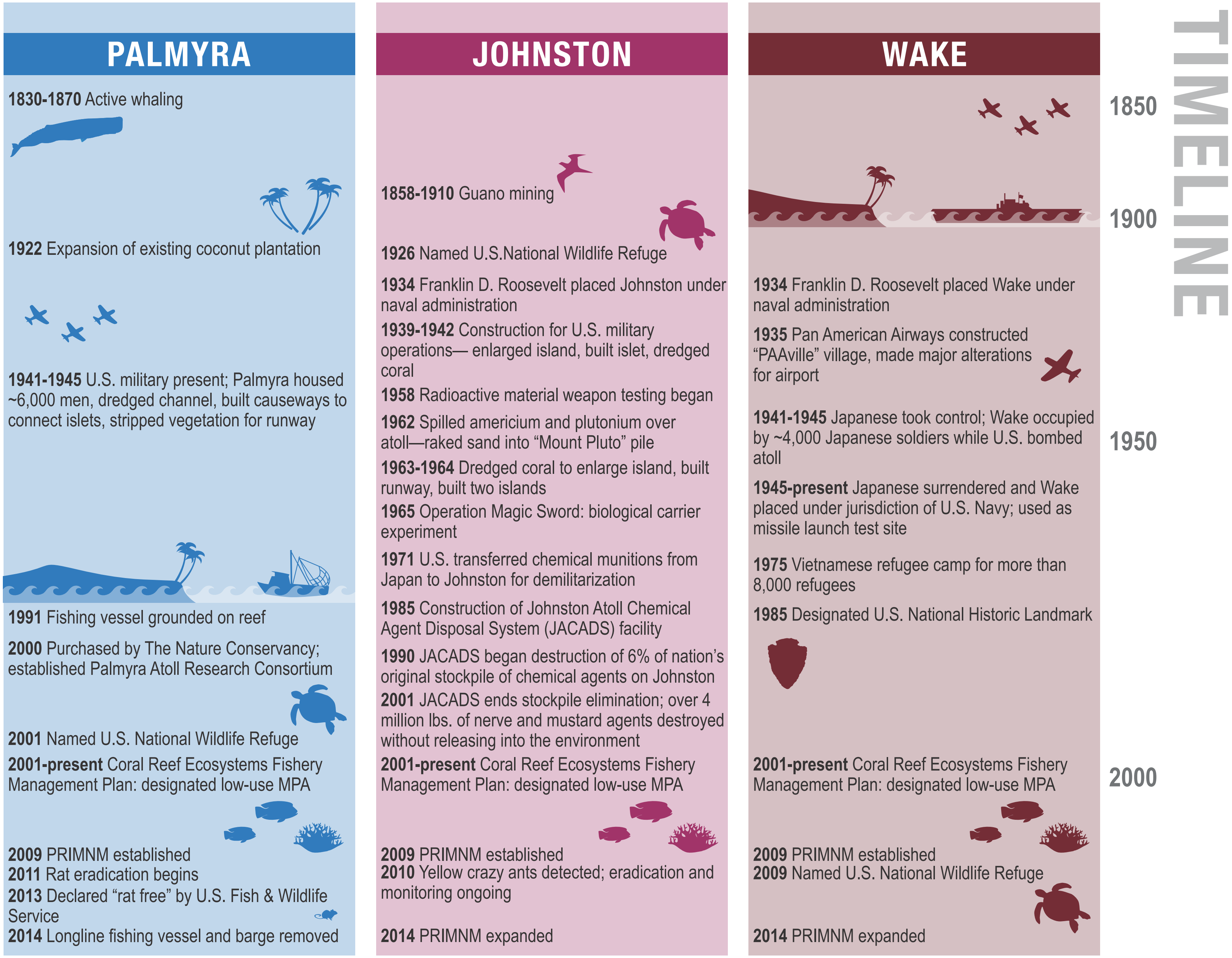
Palmyra Atoll

Johnston Atoll

Wake Atoll

TIMELINE

	BAKER	HOWLAND	JARVIS	KINGMAN
1850	**1830-1870** Active whaling	**1830-1870** Active whaling	**1830-1870** Active whaling	**1830-1870** Active whaling
1900	**1866-1872** Peak guano mining	**1859-1871** Peak guano mining	**1858-1879** Guano mining	
	1935-1942 Hui Panala‘au occupation: students from Kamehameha Schools sent to establish U.S. territories	**1935-1942** Hui Panala‘au occupation: students from Kamehameha Schools sent to establish U.S. territories	**1935-1942** Hui Panala‘au occupation: students from Kamehameha Schools sent to establish U.S. territories	**1934** Franklin D. Roosevelt placed Kingman under naval administration **1935** U.S. Bureau of Air Commerce stationed supply ship in the lagoon as a seaplane base **1938** Seaplane base abandoned **1941** Franklin D. Roosevelt declared Kingman a naval defense sea area
	1943-1946 U.S. military present—more than 15,000 men built and maintained airstrip	**1943-1946** U.S. military present		
1950		**1950’s** Visited by whalers who harvested marine life for ship supplies	**1950’s** Visited by whalers who harvested marine life for ship supplies	
	1965 Operation Magic Sword: biological carrier experiment	**1962** Reef bombed by U.S. Atomic Energy Commission to use land as nuclear site		
	1974 Named U.S. National Wildlife Refuge	**1974** Named U.S. National Wildlife Refuge	**1974** Named U.S. National Wildlife Refuge	
2000	**2001-present** Coral Reef Ecosystems Fishery Management Plan: designated no-take Marine Protected Area (MPA)	**2001-present** Coral Reef Ecosystems Fishery Management Plan: designated no-take MPA	**2001-present** Coral Reef Ecosystems Fishery Management Plan: designated no-take MPA	**2001** Named U.S. National Wildlife Refuge **2001-present** Coral Reef Ecosystems Fishery Management Plan: designated no-take MPA **2007** Fishing vessel grounded on reef
	2009 PRIMNM established	**2009** PRIMNM established	**2009** PRIMNM established	**2009** PRIMNM established
			2014 PRIMNM expanded	**2014** Fishing vessel removed



PALMYRA

1830-1870 Active whaling

1922 Expansion of existing coconut plantation

1941-1945 U.S. military present; Palmyra housed ~6,000 men, dredged channel, built causeways to connect islets, stripped vegetation for runway

1991 Fishing vessel grounded on reef

2000 Purchased by The Nature Conservancy; established Palmyra Atoll Research Consortium

2001 Named U.S. National Wildlife Refuge

2001-present Coral Reef Ecosystems Fishery Management Plan: designated low-use MPA

2009 PRIMNM established
2011 Rat eradication begins
2013 Declared “rat free” by U.S. Fish & Wildlife Service
2014 Longline fishing vessel and barge removed

JOHNSTON

1858-1910 Guano mining

1926 Named U.S.National Wildlife Refuge

1934 Franklin D. Roosevelt placed Johnston under naval administration

1939-1942 Construction for U.S. military operations— enlarged island, built islet, dredged coral

1958 Radioactive material weapon testing began

1962 Spilled americium and plutonium over atoll—raked sand into “Mount Pluto” pile

1963-1964 Dredged coral to enlarge island, built runway, built two islands

1965 Operation Magic Sword: biological carrier experiment

1971 U.S. transferred chemical munitions from Japan to Johnston for demilitarization

1985 Construction of Johnston Atoll Chemical Agent Disposal System (JACADS) facility

1990 JACADS began destruction of 6% of nation’s original stockpile of chemical agents on Johnston

2001 JACADS ends stockpile elimination; over 4 million lbs. of nerve and mustard agents destroyed without releasing into the environment

2001-present Coral Reef Ecosystems Fishery Management Plan: designated low-use MPA

2009 PRIMNM established
2010 Yellow crazy ants detected; eradication and monitoring ongoing

2014 PRIMNM expanded

WAKE

1934 Franklin D. Roosevelt placed Wake under naval administration

1935 Pan American Airways constructed “PAAville” village, made major alterations for airport

1941-1945 Japanese took control; Wake occupied by ~4,000 Japanese soldiers while U.S. bombed atoll

1945-present Japanese surrendered and Wake placed under jurisdiction of U.S. Navy; used as missile launch test site

1975 Vietnamese refugee camp for more than 8,000 refugees

1985 Designated U.S. National Historic Landmark

2001-present Coral Reef Ecosystems Fishery Management Plan: designated low-use MPA

2009 PRIMNM established
2009 Named U.S. National Wildlife Refuge

2014 PRIMNM expanded

Figure 3. Timeline of historical events for each island of the Pacific Remote Islands Marine National Monument (PRIMNM).

METHODS OVERVIEW

Interdisciplinary biological, physical, and chemical surveys were conducted to document the status and trends of the conditions of, and processes influencing, the coral reef ecosystems around each of the Pacific Remote Islands. From 2000 to 2016, CREP conducted 10 Pacific RAMP cruises to Jarvis; 9 cruises to Baker, Howland, Kingman, and Palmyra; 6 cruises to Johnston; and 5 cruises to Wake (Fig. 4).

CREP scientists have collected spatial and temporal observations of key oceanographic parameters to document time-varying oceanographic conditions that influence ecological processes and ecosystem health (Hoeke et al., 2009). The dominant physical drivers influencing coral reefs are temperature, salinity, ocean currents, and waves that are measured using both moored instruments for time series observations and profiling instruments that provide information about conditions at different depths. The dominant chemical parameters influencing coral reefs are carbonate chemistry, dissolved oxygen, and nutrients that are measured with recording instruments and water samples.

PACIFIC RAMP

2000 **BAKER**, **HOWLAND**, **JARVIS**, **KINGMAN**, **PALMYRA**

2001 **BAKER**, **HOWLAND**, **JARVIS**, **KINGMAN**, **PALMYRA**

2002 **BAKER**, **HOWLAND**, **JARVIS**, **KINGMAN**, **PALMYRA**

2003

2004 **BAKER**, **HOWLAND**, **JARVIS**, **KINGMAN**, **PALMYRA**, **JOHNSTON**

2005 **WAKE**

2006 **BAKER**, **HOWLAND**, **JARVIS**, **KINGMAN**, **PALMYRA**, **JOHNSTON**

2007 **WAKE**

2008 **BAKER**, **HOWLAND**, **JARVIS**, **KINGMAN**, **PALMYRA**, **JOHNSTON**

2009 **WAKE**

2010 **BAKER**, **HOWLAND**, **JARVIS**, **KINGMAN**, **PALMYRA**, **JOHNSTON**

2011 **WAKE**

2012 **BAKER**, **HOWLAND**, **JARVIS**, **KINGMAN**, **PALMYRA**, **JOHNSTON**

2013

2014 **WAKE**

2015 **BAKER**, **HOWLAND**, **JARVIS**, **KINGMAN**, **PALMYRA**, **JOHNSTON**

2016 **JARVIS**

Figure 4. Timeline of Pacific RAMP research cruises to the PRIMNM.

Fusilier damselfish (Lepidozygus tapeinosoma) and several species of anthias (Luzonichthys whitleyi and Pseudanthias bartlettorum) at Jarvis Island, Photo: NOAA Fisheries/Kevin Lino. Previous page: Diver takes photoquads above the reef at Baker Island, Photo: NOAA Fisheries/Kelvin Gorospe.

Originally, rapid ecological assessment (REA) surveys were conducted along belt transects at semi-fixed and haphazardly selected sites. In 2008, the sampling design and method for the REA fish surveys were changed to a depth-stratified random approach (with shallow (0–6 m), mid (> 6–18 m), and deep (> 18–30 m) depth strata) using a stationary-point-count (SPC) method to obtain more representative estimates of abundance, size, and diversity of reef fishes on shallow (< 30 m) reefs at island or atoll scales (Ayotte et al., 2015). In SPC surveys, some larger fish, such as sharks and jacks, are sometimes attracted to divers resulting in overestimation of abundance. The biomass of these groups is instead reported more accurately using the towed-diver survey methodology. The REA benthic surveys were changed from semi-fixed and haphazardly selected sites in mid-depths (6–18 m) to a depth-stratified random sampling (StRS) design covering the same depth strata as the REA fish surveys in 2013. The survey methods employed by CREP in the Pacific Remote Islands during the period of 2000–2017 (Fig. 5), are described in greater detail in the Coral Reef Ecosystem Monitoring Report for the Pacific Remote Islands 2000–2017 (in prep).

METHODS

BIOLOGICAL

AUTONOMOUS REEF MONITORING STRUCTURE (ARMS) – biodiversity
BIOEROSION MONITORING UNIT (BMU) – coral reef removal
CALCIFICATION ACCRETION UNIT (CAU) – coral reef growth
RAPID ECOLOGICAL ASSESSMENT (REA) – detailed species-level surveys of benthic and fish community structure
TOWED DIVER – broad surveys of benthic cover, macroinvertebrates, and large fish
TETHERED OPTICAL ASSESSMENT DEVICE (TOAD) – optical validation and habitat characterization

PHYSICAL/ CHEMICAL

MOORED INSTRUMENTS – collection of continuous oceanographic data
CTD CASTS – measurements of conductivity, temperature and depth
WATER SAMPLES – nutrients, chl-*a*, carbonate chemistry

MAPPING

MULTIBEAM SONAR – generates bathymetry, habitat characterization
SATELLITE IMAGERY – estimates bathymetry, habitat characterization

Figure 5. Summary of CREP survey methods.

Since 2009, microbial community data have been collected during all Pacific RAMP cruises in collaboration with San Diego State University to examine relationships between the metabolic energy requirements of microbes and those of reef fishes. For the Pacific Remote Islands, our colleagues collected and filtered large volumes of seawater adjacent to the coral reefs at a subset of our monitoring sites to determine the abundance and diversity of microbes present. Using standard equations (McDole et al., 2012), we converted the abundances of microbes and reef fishes in a 10 m^3 volume of reef water to their metabolic energy requirements, or how much energy fishes and microbes use to live. With these two values, we calculate the microbialization score as the microbial metabolic energy needs of a coral reef divided by the total metabolic energy needs of fish and microbes (McDole et al., 2012). This work has shown that in more human-impacted ecosystems, microbes dominate the food web, or specifically, the metabolic energy that moves between reef organisms as they eat each other.

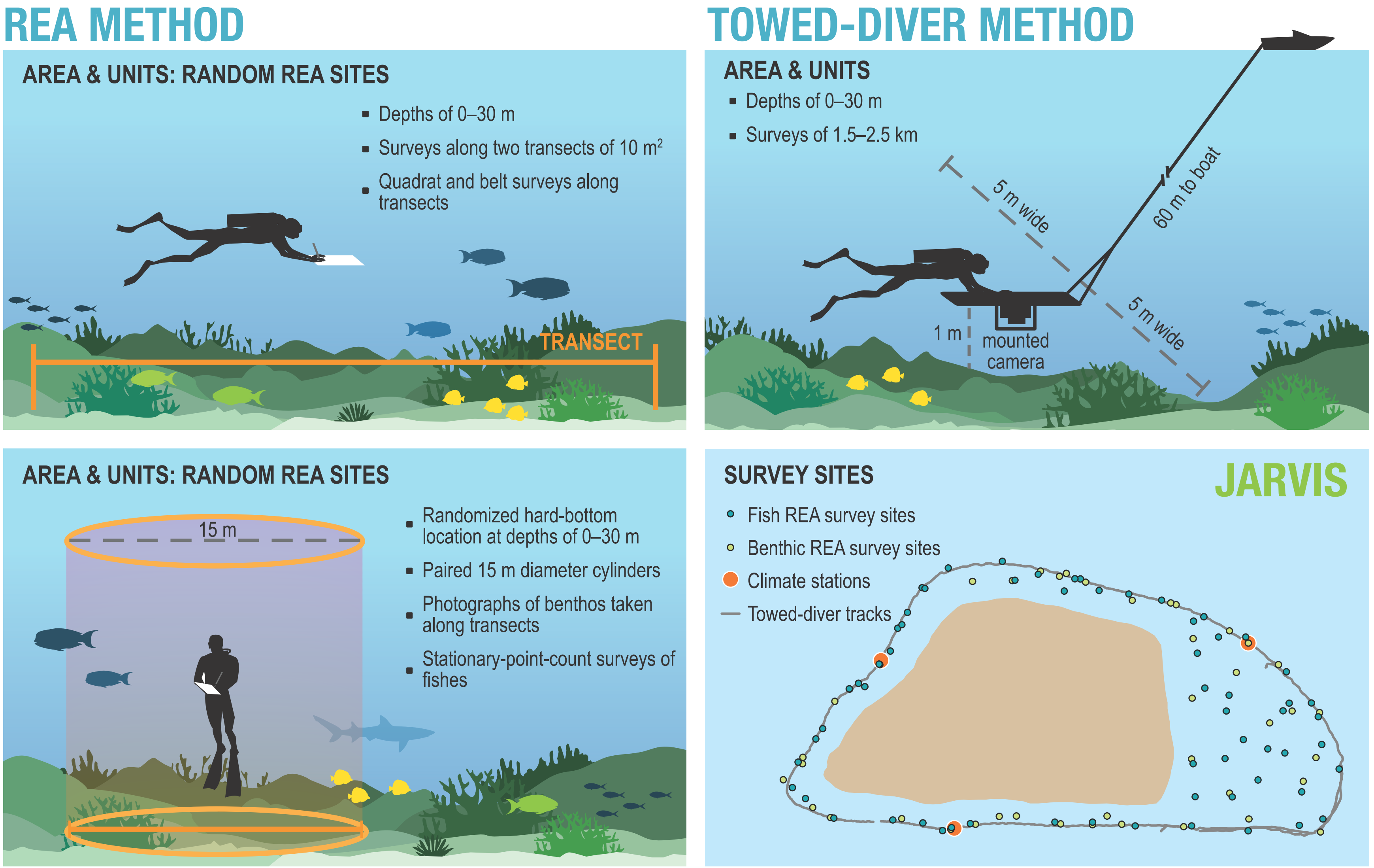


Figure 6. Schematic diagrams of Rapid Ecological Assessment (REA) method and towed-diver method. REA method shows 1. One of two divers conducting a belt-transect survey along a 25-m transect line (top left) and 2. One of two divers conducting a stationary-point-count (SPC) survey at a random REA site (below left). Towed-diver method shows one of two divers conducting a towed-diver survey (top right). An example of survey efforts and site locations at Jarvis Island (below right).

Several methods are deployed by the ocean and climate change team to measure the balance between the production and removal of calcium carbonate, a major reef building material, within the reef ecosystem. If bioerosion, or the removal of calcium carbonate substrate, is excessive, then coral destruction will exceed coral growth, which can lead to a flattening of the reef. Calcification accretion units (CAUs), coral cores, and carbonate chemistry are used to compute net ecosystem calcification and production. Coral cores, bioerosion monitoring units (BMUs), and carbonate chemistry are used to estimate net removal of calcium carbonate through bioerosion and chemical dissolution (Fig. 7). Collectively, these methods are used to determine the balance of calcium carbonate in the system, and indicate whether the reef will be able to persist over time.

In addition to oceanographic characteristics, information on the condition, abundance, diversity, and distribution of biological communities around these islands is collected using towed-diver surveys (Fig. 6), towed optical assessment device (TOAD) surveys, and rapid ecological assessments (REA) (Fig. 6). Towed-diver surveys encompass various habitats along a ~15-m depth contour and provide a broad overview of benthic cover, key macroinvertebrate presence, and abundance and size of large fish (> 50 cm). During each towed-diver survey, underwater video footage and still photographs of the benthos are collected (Kenyon et al., 2006). The TOAD surveys are used for benthic habitat characterization in depths greater than 30 m. REA surveys were adopted beginning in 2001, to gain more detailed site-specific information on the benthic community structure and associated fish assemblages.

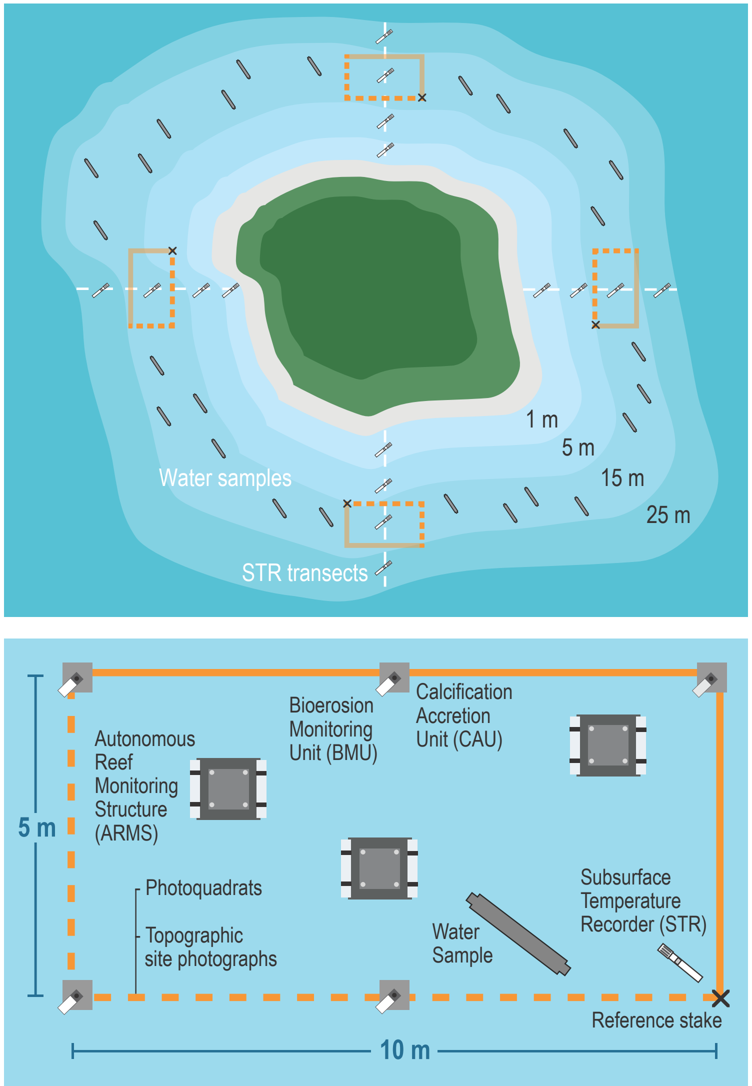


Figure 7. Climate station installation at a sample island location showing depths and instrumentation; additional monitoring efforts include coral cores and reef-area photomosaics.

PACIFIC REMOTE ISLANDS IN A PACIFIC-WIDE CONTEXT

The CREP uses standardized survey methods across all of the U.S. Pacific Islands to enable direct comparison of reef ecosystem metrics across broad biogeographic, geologic, oceanographic, and human-impact gradients. To better understand the status of coral reefs in the PRIMNM on a broader scale, a Pacific-wide comparison was performed for oceanographic conditions, benthic community, fish community and the microbial community.

OCEANOGRAPHY

Coral reef ecosystems are influenced by a diverse suite of oceanographic and meteorological factors, including but not limited to temperature, wind, waves, currents, nutrients, carbonate chemistry, light, and productivity. These factors all vary on daily, seasonal, interannual, and longer time scales. A combination of satellite-derived and in-situ information collected during Pacific RAMP surveys was analyzed to assess the variability of each of these factors across the U.S. Pacific Islands. Satellite observations provide broad spatial coverage and a historical context of surface processes, whereas in-situ observations provide subsurface measurements of the physical and chemical conditions directly influencing coral reef communities. Synthesis and integration of these data sets increase our understanding of the ecological processes that influence the status and trends in the condition of coral reefs in the PRIMNM and how the reefs of the PRIMNM compare to other coral reef ecosystems across the Pacific.

Long-term averages of satellite-derived sea-surface temperature (SST) highlight some of the differences observed in oceanic conditions. Due to the PRIMNM's expansive geographic range, the average SST varies considerably across the monument. Jarvis Island exhibits a noticeably cooler SST than its closest neighbors, Palmyra and Kingman, due to equatorial upwelling and locally intense topographic upwelling of the strong eastward flowing subsurface Equatorial Undercurrent (Gove et al., 2006). The northernmost Pacific island chains, the main Hawaiian Islands and Northwestern Hawaiian Islands, have lower SSTs (23–27˚C) compared to the other Pacific regions, whereas islands of the Mariana Archipelago and American Samoa show higher than Pacific-wide average SSTs, upwards of 28–29˚C (Fig. 8).

Similar to SST, satellite-derived long-term averages of chlorophyll-*a* concentrations (chl-*a*; a proxy for primary productivity) show significant variability across the Pacific, exhibiting highest concentrations in the equatorial region, particularly at Jarvis (0.22 mg m^{-3}), Baker, and Howland Islands due to wind-driven equatorial upwelling. The lower chlorophyll-*a* concentrations seen at Wake and Johnston Atolls are similar to concentrations within the Mariana Archipelago and American Samoa (Fig. 9), which are all located in oligotrophic gyres.

Previous page: Two-spot red snapper (Lutjanus bohar) at Palmyra Atoll, Photo: NOAA Fisheries/Andrew E. Gray.

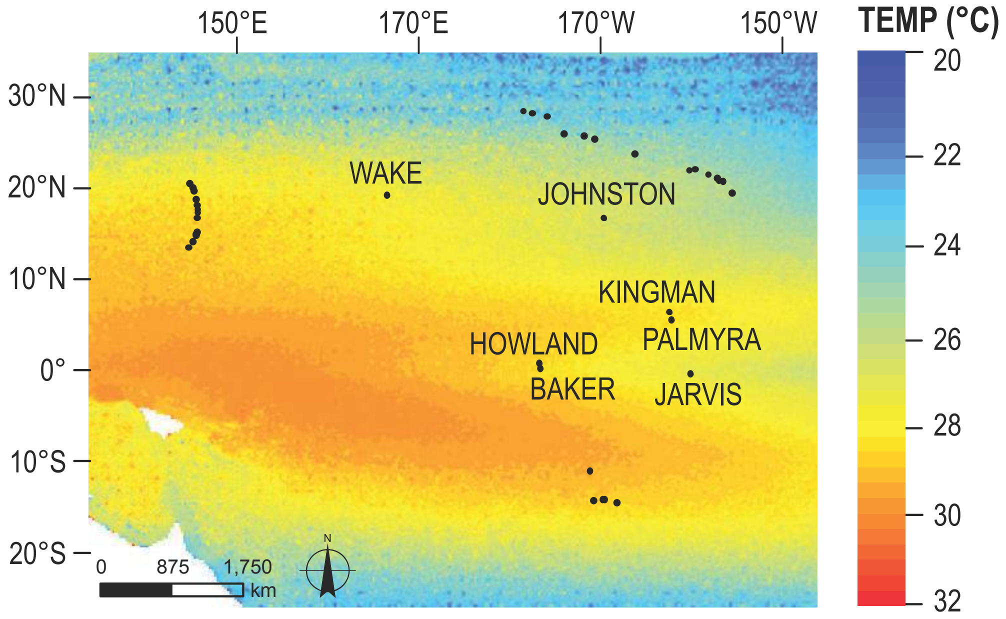


Figure 8. Long-term average sea surface temperature across the Pacific Ocean for 2003–2016, from satellite-derived data (NOAA POES AVHRR) for the geographic area 25°S–35°N, 135°E–145°W. White space indicates areas with no data. Black areas are island midpoints (http://gis.ncdc.noaa.gov/all-records/catalog/search/resource/details.page?id=gov.noaa.ncdc:C00284).

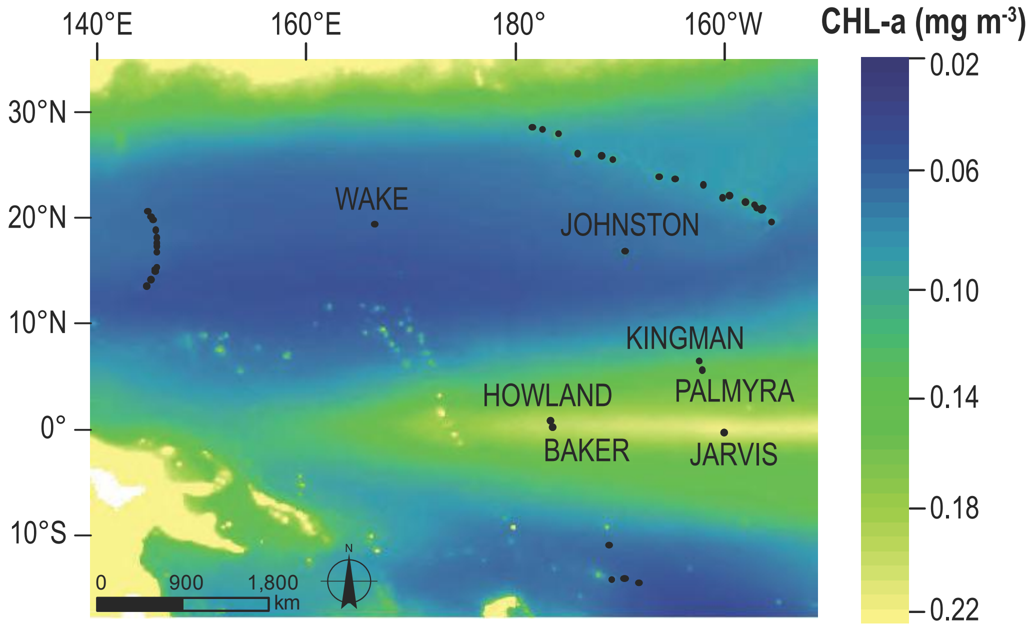


Figure 9. Long-term average chlorophyll-a concentrations across the Pacific for 2003–2016, from satellite-derived data (National Aeronautics and Space Administration Aqua MODIS). White space indicates areas with no data. Black areas are island midpoints (https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/L3SMI).

Coral reefs rely on the ability of reef-building corals and crustose coralline algae to build, or calcify, and maintain the calcium carbonate structures that provide the three-dimensional habitat for the entire reef ecosystem. Corals precipitate mineral carbonate out of seawater and incorporate it into their skeletons. Their ability to calcify depends on the chemical conditions of their seawater environment. A common metric used to describe whether the environment is more or less conducive to calcification is the saturation state relative to the mineral aragonite (Ω_{arag}). When seawater has a higher Ω_{arag}, conditions are more favorable for calcification of reef building corals and crustose coralline algae and vice versa.

During the last few decades, Ω_{arag} and pH have been declining and are expected to continue to decline as the oceans absorb increasing levels of human-induced CO_2, in a process often referred to as ocean acidification. Using multiple methods, CREP scientists are actively monitoring both the changes in carbonate chemistry on coral reefs as well as rates of calcification, accretion, and bioerosion to assess the ability of coral reefs to persist. Across the Pacific Basin there are strong natural Ω_{arag} gradients. Baseline observations of Ω_{arag} ranged from 3.07 at Lisianski Island in the Northwestern Hawaiian Islands to 3.93 at Swains Island in American Samoa (Fig 10). American Samoa and the Mariana Archipelago exhibited the highest regional mean aragonite saturation states of 3.85 and 3.7, respectively. The Pacific Remote Islands, Northwestern Hawaiian Islands, and main Hawaiian Islands all possess average aragonite saturation states within the 3.2–3.6 range.

In the pre-industrial era, similar cross-Pacific gradients in aragonite saturation state were present, but Ω_{arag} levels were likely about 0.5–1 unit higher (~3.5–4.5; Ricke et al., 2013). Reduction of a full unit of saturation state can reduce coral calcification by around 15–20% (Chan and Connolly, 2013) and reduce net accretion of crustose coralline algae by as much as 70–86% (Kuffner et al., 2008, Jokiel et al., 2008, Johnson et al., 2014). Reef ecosystems exposed to Ω_{arag} consistently below 3.0 generally have little or no carbonate reef structure (Manzello et al., 2008).

In relation to aragonite saturation state, carbonate accretion rates were highly variable across the Pacific regions (Fig. 10), ranging from 0.015 g $CaCO_3$ $cm^{-2}yr^{-1}$ at Kure Atoll in the Northwestern Hawaiian Islands to 0.133 g $CaCO_3$ $cm^{-2}yr^{-1}$ at Rose Atoll in American Samoa. American Samoa and the Pacific Remote Islands exhibited the highest carbonate accretion rates of the U.S. Pacific Islands with regional averages of 0.089 g $CaCO_3$ $cm^{-2}yr^{-1}$ and 0.062 g $CaCO_3$ $cm^{-2}yr^{-1}$, respectively. The PRIMNM's northernmost oligotrophic islands, Johnston and Wake, had two of the lowest average carbonate accretion rates, with values of 0.020 g $CaCO_3$ $cm^{-2}yr^{-1}$ and 0.017 g $CaCO_3$ $cm^{-2}yr^{-1}$, respectively. Regional averages for the Mariana Archipelago and the Northwestern Hawaiian Islands were 0.039 g $CaCO_3$ $cm^{-2}yr^{-1}$ and 0.021 g $CaCO_3$ $cm^{-2}yr^{-1}$, respectively. Much of the habitat provided by coral reefs comes from the structural complexity of their calcium carbonate foundations. Net carbonate accretion rates provide an indicator of the reef's growth overall; hence, the low rates observed, especially around the Northwestern Hawaiian Islands, could be cause for concern.

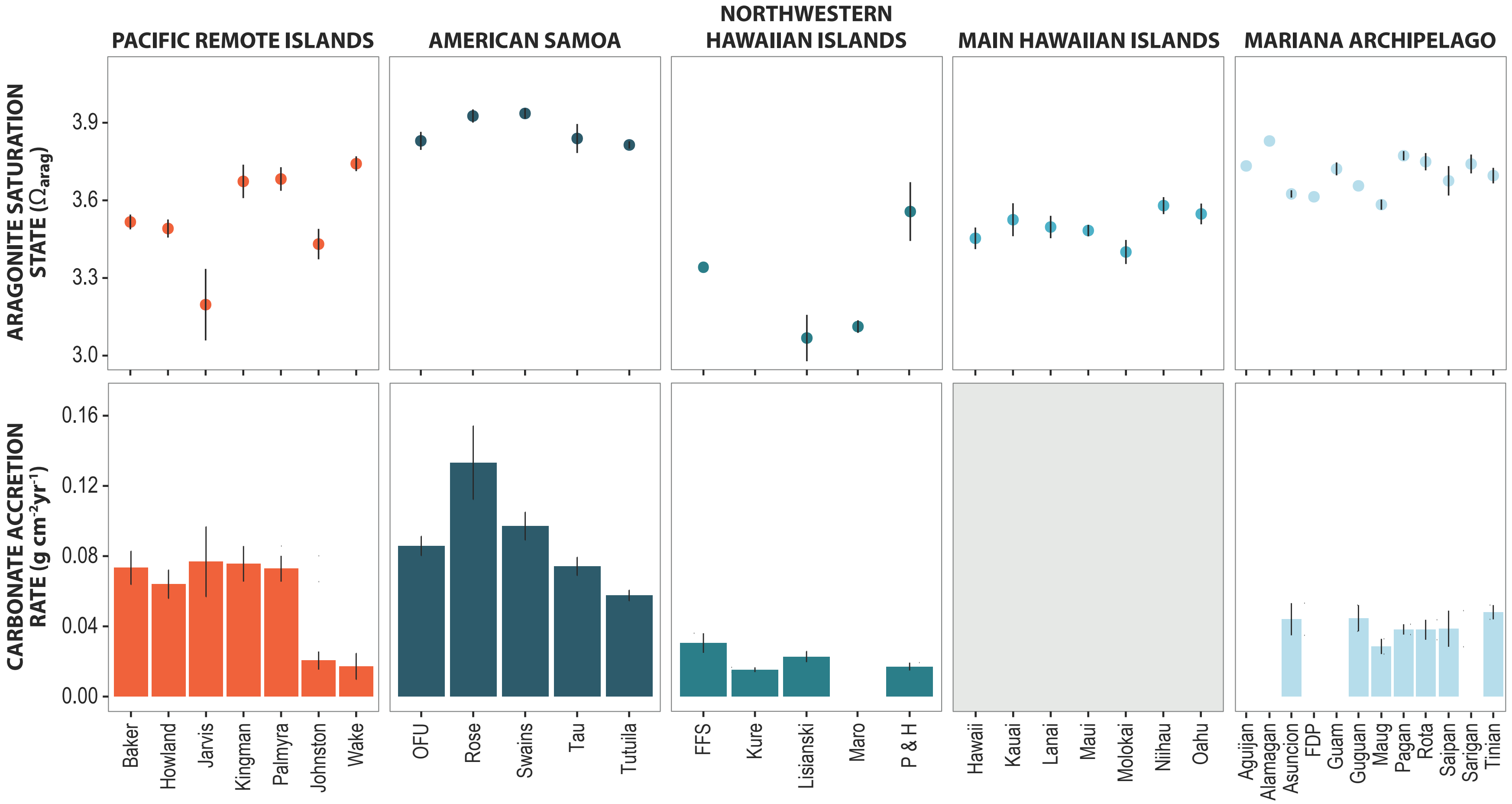


Figure 10. Most recent mean aragonite saturation state per island from 2013 to 2015 (main Hawaiian Islands 2013, Mariana Archipelago and Wake Atoll 2014, American Samoa, Northwestern Hawaiian Islands, and Pacific Remote Islands 2015) (top). Aragonite saturation state values were calculated from dissolved inorganic carbon and total alkalinity values measured from in situ water sampling close to the substrate. Lagoonal sites were removed from the analysis. Error bars indicate standard error (± 1 SE) of the mean. Islands with no error bars only had one water sample. Mean carbonate accretion rate per island from 2012 to 2015. Carbonate accretion rates were measured via CAUs (bottom). Error bars indicate standard error (± 1 SE) of the mean. No CAU samples were recovered from the main Hawaiian Islands until late 2016 and those samples are still being processed and analyzed. CAUs were not deployed at Aguijan, Alamagan, or FDP in the Marianas.

The distinctions seen in patterns of aragonite saturation state and CAU accretion rate (Fig. 10) highlight the importance of tracking both environmental exposures to the seawater carbonate chemistry and ecological responses to that chemistry. For example, you can see that while the equatorial islands are exposed to low aragonite saturation states, largely due to their upwelling environment, they still manage high rates of net accretion (Fig. 11). Conversely, coral reefs at Wake and Johnston show similar in-situ aragonite saturation states, but low rates of accretion. There is strong forcing of net accretion on CAUs by aragonite saturation state (e.g. in American Samoa both aragonite saturation and accretion rates are high), but this distinction is likely modified by the relative high and low productivity of the equatorial islands and northern oligotrophic islands, respectively.

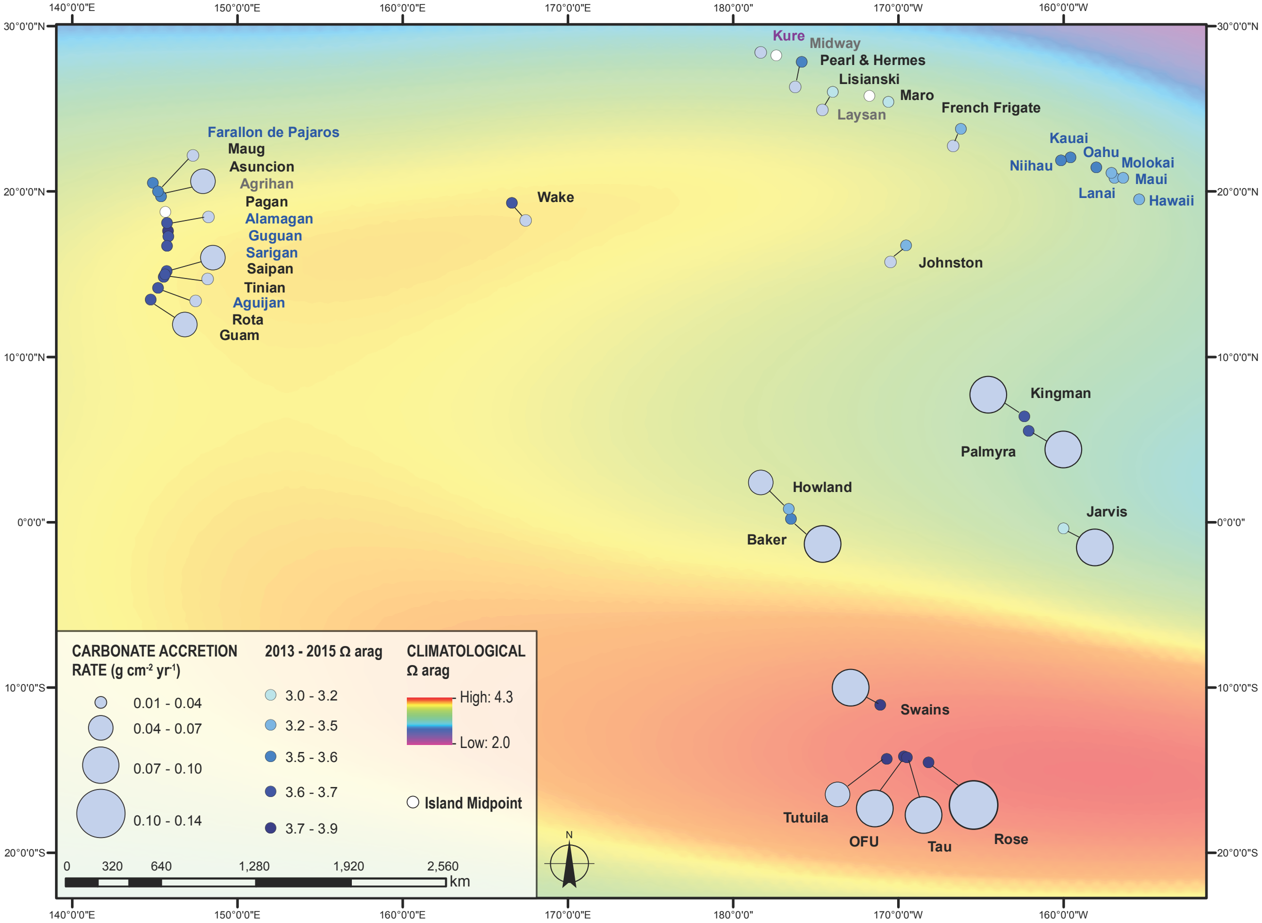


Figure 11. Pacific-wide open ocean climatological distributions of aragonite saturation state (Ω_{arag}) in surface waters (from GLODAP v2), benthic in-situ aragonite saturation state (within island circles), and mean carbonate accretion rate per island from 2012 to 2015. Size of bubble indicates island-level carbonate accretion rate measured via CAUs. Climatological aragonite saturation state source: Jiang et al., 2015; colors show gridded values based on interpolation through Data Interpolating Variational Analysis (DIVA) Software.

BENTHIC COMMUNITY

Percent cover of different benthic substrates is one of the most widely used metrics of reef condition. Live coral cover is the end product of a series of biological and environmental processes; significant changes in percent cover through time are indicative of disturbances. While the balance between algal communities and hard corals can be altered by coral mortality events, the ability of reef ecosystems to return to their natural balance after a disturbance, often termed resilience, is crucial for recovery and survival of coral reefs. This highlights the importance of long-term monitoring for management and conservation of coral reef ecosystems. In general, coral reefs of the PRIMNM have relatively high percent live coral cover and relatively low algal cover compared to the other U.S. Pacific regions. However, natural variability in coral cover occurs across the Pacific as a result of varying oceanic conditions and substrate. For example, the remote reefs of the Northwestern Hawaiian Islands have oceanographic conditions that naturally support predominantly algal-dominated reef communities (Vroom and Braun, 2010).

Across the U.S. Pacific Islands, results from REA surveys conducted from 2013 to 2015, showed island-wide mean estimates of live coral cover ranged between 2% at Midway Atoll and 36.4% at Wake Atoll (Fig. 12). Except for Johnston Island (4.9%), the PRIMNM region exhibited relatively high island-wide live coral cover with an overall mean greater than 26%.

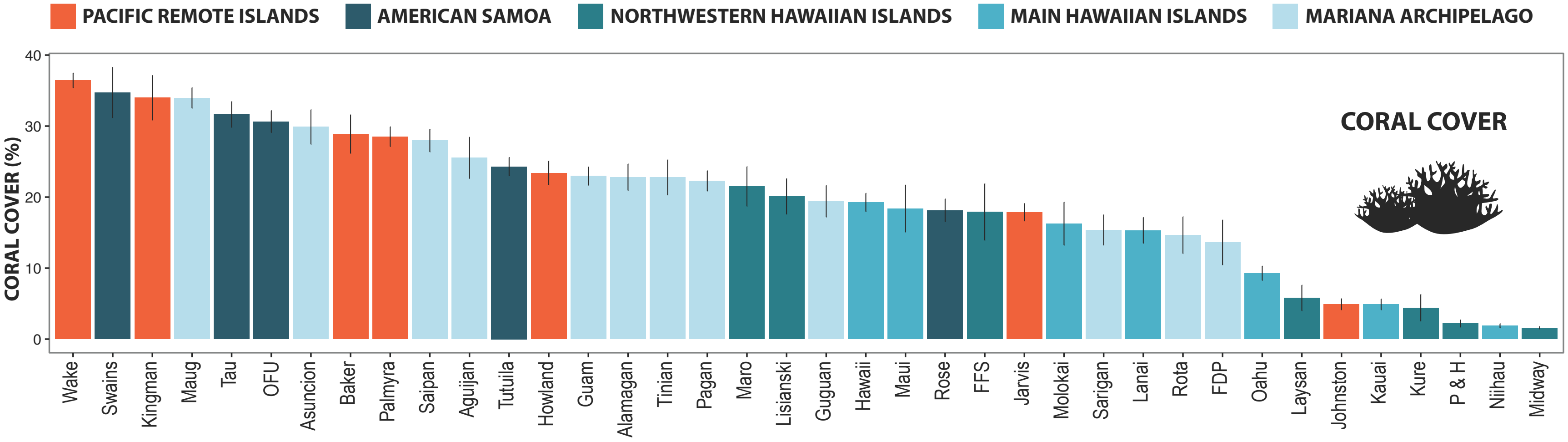


Figure 12. Mean coral cover (%) on forereef habitats from REA StRS surveys and for the Northwestern Hawaiian Islands from benthic visual estimates at SPC fish sites, conducted during the most recent survey years (2013–2015). OFU includes Ofu and Olosega Islands; P & H: Pearl and Hermes Atoll; FFS: French Frigate Shoals; FDP: Farallon de Pajaros. Error bars indicate standard error (± 1 SE) of the mean.

FISH COMMUNITY

Gradients of oceanic productivity as well as other factors, such as sea surface temperature (SST), contribute to large natural variability in fish biomass, particularly for sharks, other piscivores, and planktivores (Nadon et al., 2012, Williams et al., 2015). As such, the highly productive waters of the equatorial upwelling islands tended to have high biomass of large-bodied fishes (sharks and other piscivores), which contributed to high total fish biomass. In addition to natural variability, there are clear negative relationships between human population density and large-fish biomass (Williams et al., 2011, Williams et al., 2015) (Fig.13).

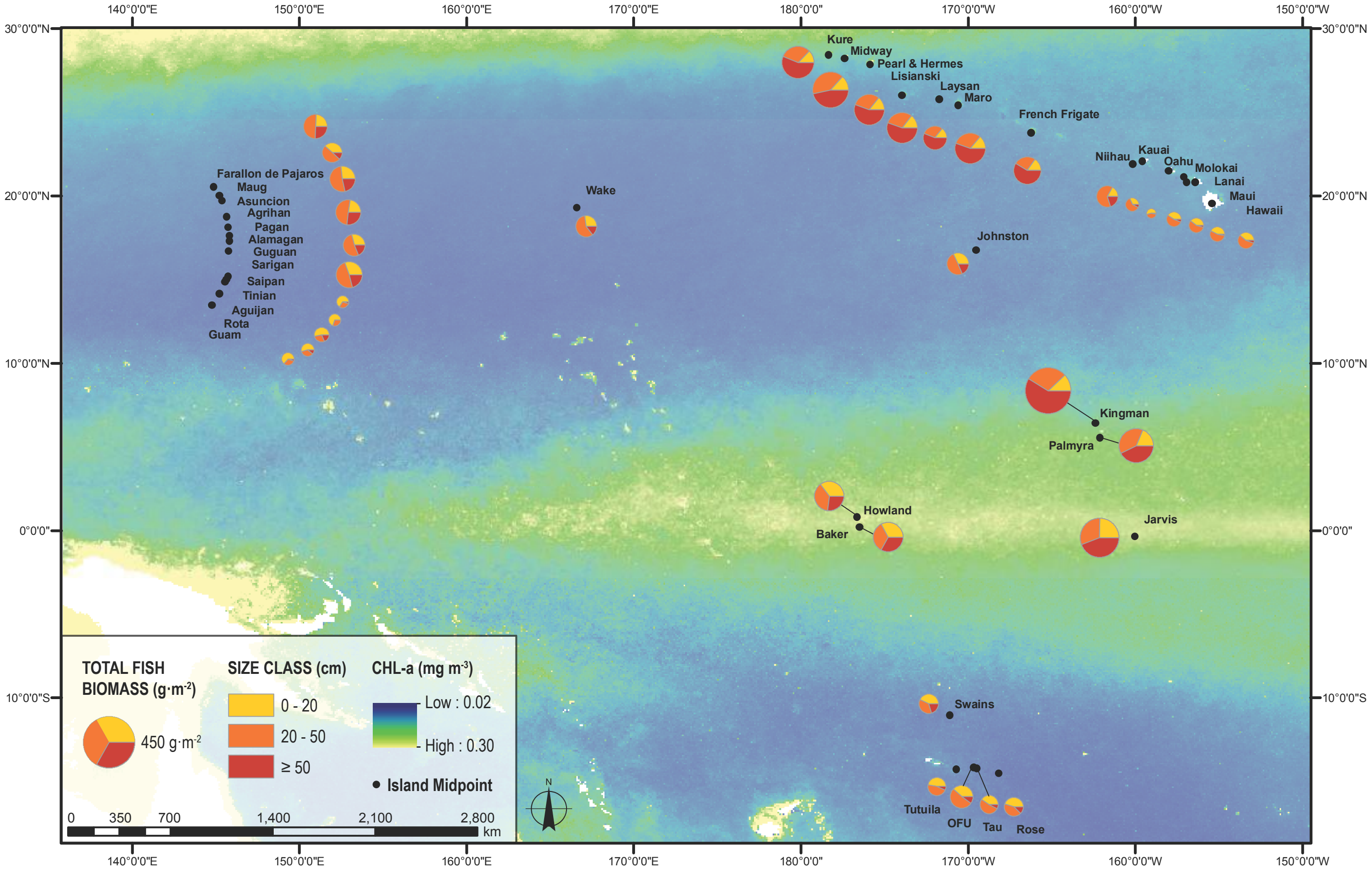


Figure 13. Pacific-wide long-term climatological mean of chlorophyll-a (mg·m⁻³) from 2003 to 2016, and total reef fish biomass (g·m⁻²), from stratified random SPC surveys (depths of 0–30 m, n > 25 per island) conducted during the most recent survey years (2009–2015). Size distribution is shown by pie-chart slices: biomass of small-bodied (0–20 cm in total length; light orange), mid-sized (20–50 cm in total length; medium orange), and large-bodied (≥ 50 cm in total length; dark orange) fishes. Size of pie-chart shows mean total reef fish biomass.

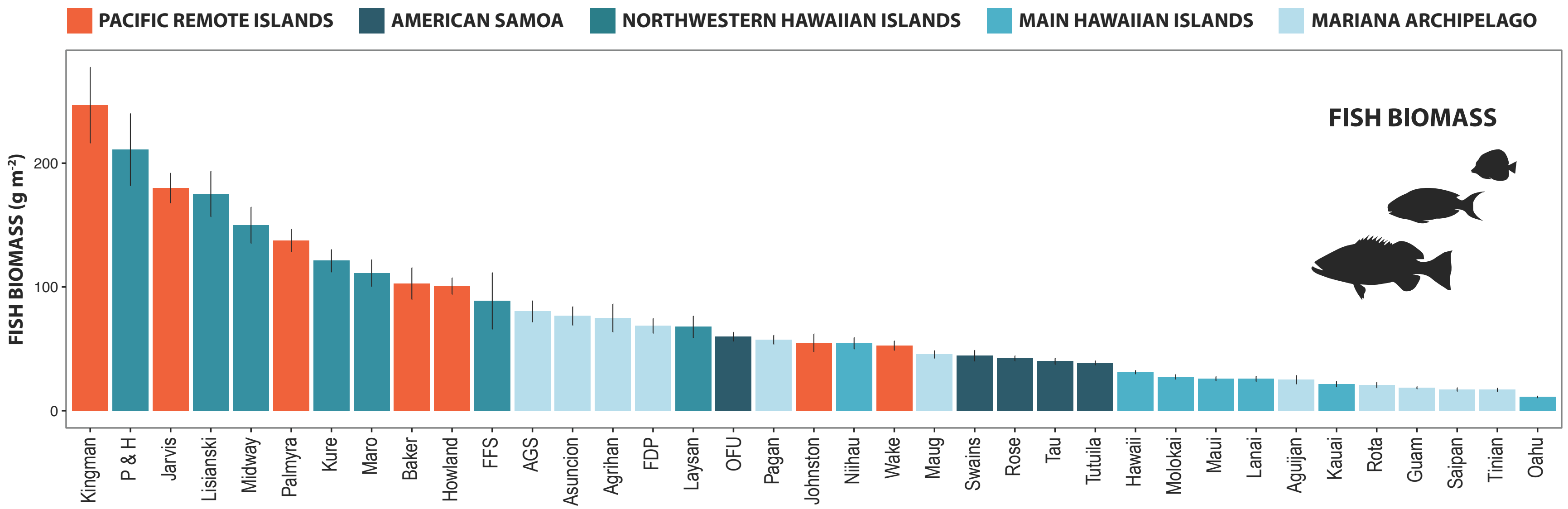


Figure 14. Pacific-wide comparisons of total reef-fish biomass (g·m^{-2}) from stratified random SPC surveys (depths of 0–30 m) conducted during the most recent survey years (2009–2015). P & H is Pearl and Hermes Atoll; FDP is Farallon de Pajaros; FFS is French Frigate Shoals; and OFU includes Ofu and Olosega Islands; AGS is Alamagan, Guguan, and Sarigan. Error bars indicate standard error (± 1 SE) of the mean.

Total reef fish biomass varied from 11.1 g·m^{-2} at Oahu to 246.8 g·m^{-2} at Kingman Reef (Fig. 14). In general, total fish biomass was lower at inhabited, heavily impacted islands, such as the main Hawaiian Islands and the southern Mariana Islands, and higher at remote, uninhabited islands. The PRIMNM and the Northwestern Hawaiian Islands exhibited the highest total reef fish biomass in the U.S. Pacific regions with mean total fish biomass of 125.0 g·m^{-2} and 120.9 g·m^{-2}, respectively. By contrast, average reef fish biomass was 45.6 g·m^{-2} in the Marianas, 45.0 g·m^{-2} in American Samoa, and 28.2 g·m^{-2} in the main Hawaiian Islands.

Whitespot hawkfish (Paracirrhites hemistictus) at Jarvis Island, Photo: NOAA Fisheries/Andrew E. Gray.

These differences in total fish biomass can be largely attributed to the substantial differences in the fish size distribution among islands (Fig. 15). The distribution of small-bodied fishes (0–20 cm in length) was relatively uniform across U.S. Pacific regions, with the exception of the equatorial upwelling islands within the PRIMNM, where biomass of small-bodied fishes was very high due to enhanced productivity. Biomass of mid-sized fishes (20–50 cm in total length) differed across the regions and was substantially lower in the highly populated regions of the main Hawaiian Islands and the southern Mariana Islands compared to less populated areas across the Pacific. The greatest differences of reef fish biomass across the regions can be attributed to the relative lack of large-bodied fishes (≥ 50 cm in total length) at inhabited islands.

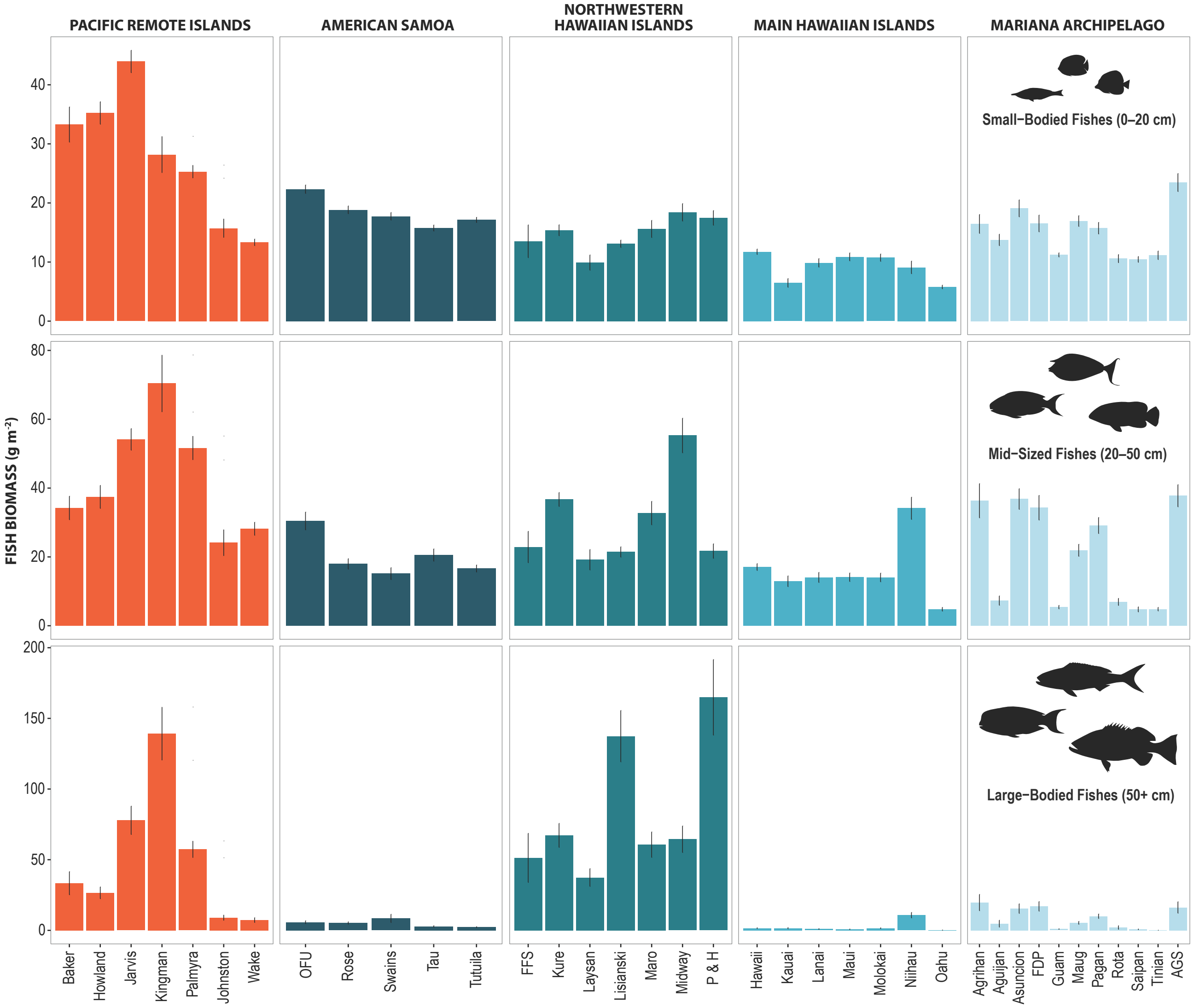


Figure 15. Pacific-wide comparisons of reef-fish biomass ($g{\cdot}m^{-2}$) per size class from stratified random SPC surveys (depths of 0–30 m; n > 25 per island) conducted during the most recent survey years (2009–2015). Note the differences in scale on the y-axes. Biomass of small-bodied (0–20 cm in total length; top row), mid-sized (20–50 cm in total length; middle row), and large-bodied (≥ 50 cm in total length; bottom row) fishes. P & H is Pearl and Hermes Atoll; FDP is Farallon de Pajaros; FFS is French Frigate Shoals; and OFU includes Ofu and Olosega Islands. Error bars indicate standard error (± 1 SE) of the mean.

MICROBIAL COMMUNITY

Nutrient-rich organic material released by coral reefs constitutes an important foundation for the marine trophic food web and the associated biodiversity of coral reef ecosystems. In any coral reef, this organic material forms the base of a microbial and "macrobial" food web of higher consumers. When a reef ecosystem shifts from being dominated by corals to being dominated by macroalgae, the microbial community and recycling mechanisms are disrupted. For example, the organic material released by these non-calcifying organisms (fleshy macroalgae and turf algae) is taken up by fast growing, opportunistic microbial communities; and, hence, shift these energetic materials away from supporting higher consumers, like fish (Fig. 16). This phenomenon is referred to as microbialization (McDole et al., 2012).

One way to look at larger patterns of microbialization is to compare metabolic rates between microbes and fish. Given the mass of an organism, regardless of whether a fish or a bacterium, we can calculate how much energy it needs to survive, i.e., the metabolic needs of that organism. By counting and noting the sizes of fish and microbes, we can calculate the total metabolic needs of each group at a particular reef. We have a strong argument that microbialization is occurring when the microbes' metabolic needs constitute an increasing proportion of the total metabolic needs of the reef ecosystem (i.e., both fish and microbes; Fig. 17).

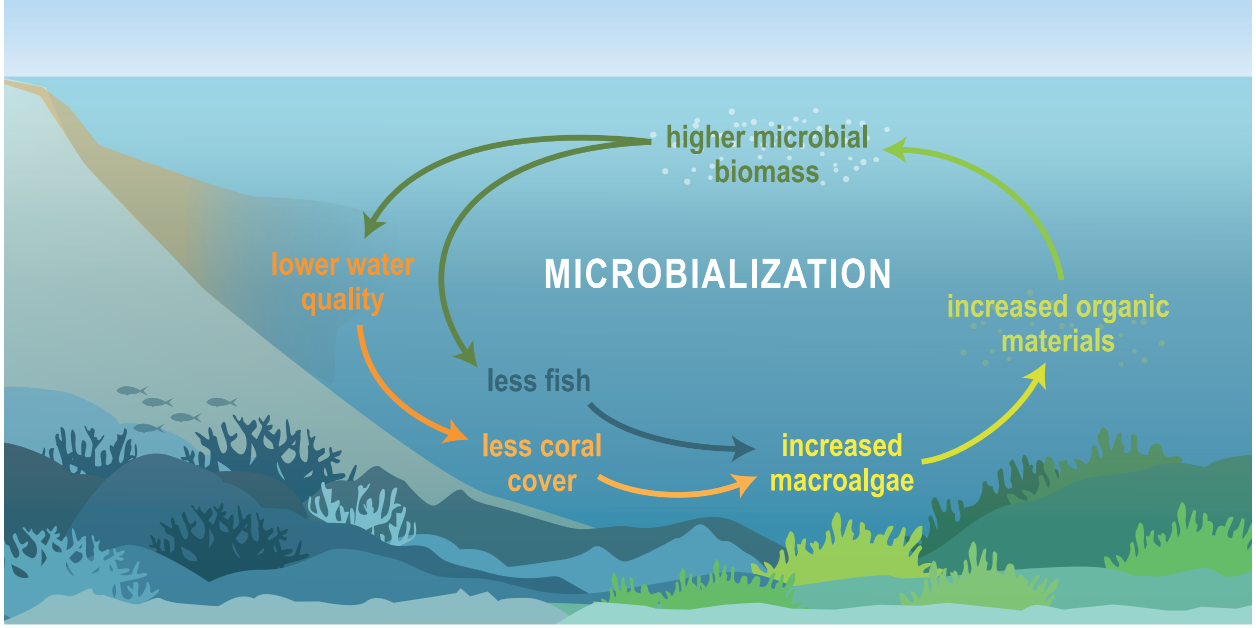


Figure 16. Conceptual depiction of microbialization positive feedback loop. Figure adapted from original diagram by Andreas Haas.

It is also evident that as human impacts on reef ecosystems increases, so does the share of a reef's energy needs going through microbes. In low impacted reef areas, microbial energy needs are about 20% of the total energy used on a reef (e.g., Baker, Jarvis, Palmyra, Kingman), and this increases to about 90% of total energy in highly impacted reefs (Maui, Kauai, Oahu; Fig. 17). A strong significant positive correlation between the microbial share of reef metabolism (i.e., microbialization) and the cumulative human impact scores on reefs from National Center of Ecological Analysis and Synthesis (NCEAS) can be seen on islands from the four archipelagic regions of Pacific RAMP as a result of reef degradation and lower fish biomass (McDole et al., 2012).

The shift towards increased microbial biomass and metabolism at the potential expense of higher trophic levels might create a sustained positive feedback loop (Fig. 16). Consequently, once a regime shift to an algal-dominated state has occurred, the process of microbialization has the potential to make returning to a coral-dominated state more difficult.

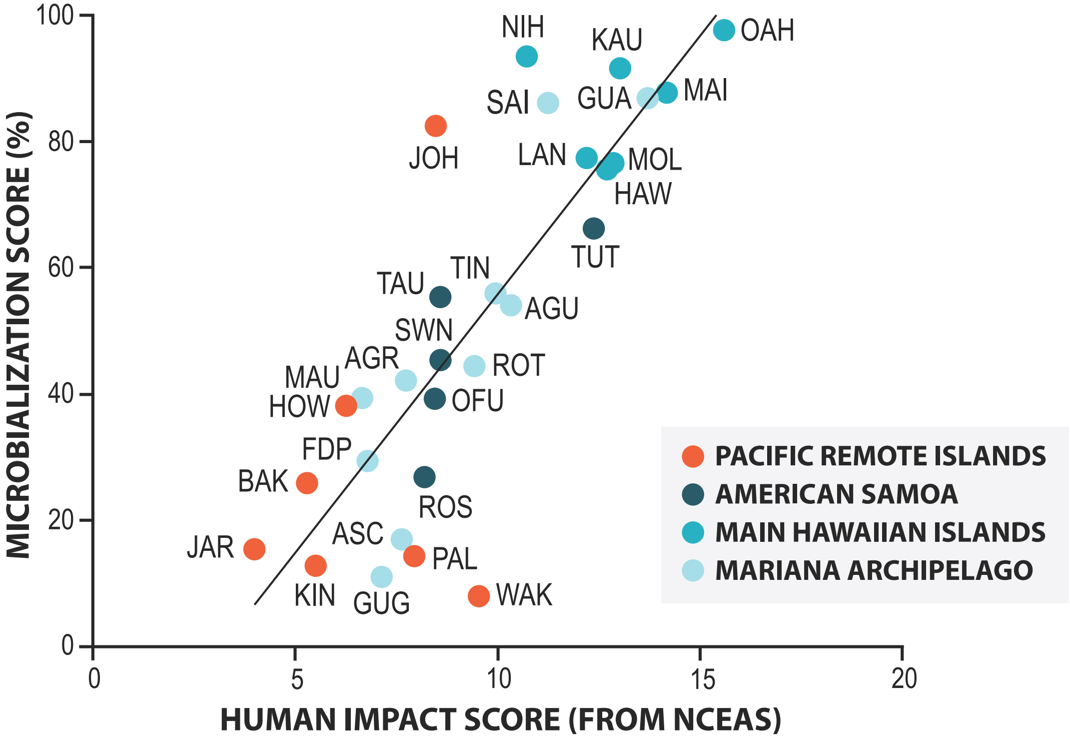


Figure 17. Proportion of Total Reef Metabolic Rate composed of Microbial Metabolic Rate (i.e. "Microbialization Score") against the cumulative human impact scores (NCEAS) on U.S. Pacific coral reefs. Black line is the linear regression line showing the positive relationship between cumulative human impact score and the microbialization score ($y = 8.19x-26.1$, $R^2 = 0.68$, 95% CI = 5.994 to 10.39). Regions are indicated by color and islands are indicated by the first three letters of their name. Higher microbialization scores may indicate a vulnerability of that ecosystem to phase shifts between coral and macroalgal dominated states.

AGR	AGRIHAN	MAU	MAUG
AGU	AGUIJAN	MOL	MOLOKAI
ASC	ASUNCION	NIH	NIIHAU
BAK	BAKER	OAH	OAHU
FDP	FARALLON DE PAJAROS	OFU	OFU & OLOSEGA
GUA	GUAM	PAL	PALMYRA ATOLL
GUG	GUGUAN	ROS	ROSE ATOLL
HAW	HAWAII	ROT	ROTA
HOW	HOWLAND	SAI	SAIPAN
JAR	JARVIS	SWN	SWAINS
JOH	JOHNSTON ATOLL	TAU	TAU
KAU	KAUAI	TIN	TINIAN
KIN	KINGMAN REEF	TUT	TUTUILA
LAN	LANAI	WAK	WAKE ATOLL
MAI	MAUI		

PACIFIC REMOTE ISLANDS IN A MONUMENT CONTEXT

BENTHIC COMMUNITY

Spatial Comparisons of Benthic Cover

Percent cover of benthic functional groups, including coral, crustose coralline algae (CCA), macroalgae, and turf algae, is a widely utilized indicator of coral reef condition. CREP uses both towed-diver and REA surveys to measure percent cover; however, these methods sometimes produce different results, which should be acknowledged when evaluating percent cover estimates. Visual estimates during broad-scale towed-diver surveys sometimes overestimate coral and CCA cover in a given segment (~2,000 m^2). Additionally, the towed-diver surveys do not differentiate between macroalgal cover and turf algal cover. Because turf and macroalgae have different ecological roles in the coral reef ecosystem, REA surveys should be used when evaluating these two functional groups. Generally, high live coral cover and high CCA cover, as commonly observed for reefs in the PRIMNM, are indicative of healthy coral reefs. Based on percent cover observed throughout the U.S. Pacific, reefs exhibiting coral cover above 20% are considered to be in fair condition, reefs exhibiting coral cover above 30% are considered very good, and reefs exceeding 40% coral cover are considered excellent. For CCA cover, reefs exceeding 10% cover are considered to be in good condition and reefs exceeding 20% cover are considered excellent. These reference points were used to score the islands in the reef condition index summarized later in the document.

Above: Crustose coralline algae at Kingman Reef in 2012, Photos: NOAA Fisheries; Previous page: Periclimenes shrimp under a Stichodactyla sea anemone at Palymra Atoll, Photo: NOAA Fisheries/Megan Moews-Asher.

From 2014–2015 REA surveys, live coral cover in the PRIMNM ranged from 4.9% at Johnston Atoll to 36.4% at Wake Atoll, both in the northernmost oligotrophic island group. The central transition islands exhibited live coral cover at 34.0% and 28.5% at Kingman and Palmyra, respectively. The equatorial islands exhibited live coral cover at 28.9%, 23.4%, and 17.8 % at Baker, Howland, and Jarvis respectively. No obvious patterns between islands groups were observed (Fig. 12).

For CCA cover, estimates in the northernmost islands of the PRIMNM were 9.5% at Wake and 13.82% at Johnston. The central transition islands exhibited CCA cover at 9.8% and 18.9% for Kingman and Palmyra, respectively. CCA cover at the equatorial islands was highest at Howland with CCA cover estimated at 26.9%. CCA cover was an estimated 25.6% at Jarvis and 24.2% at Baker.

Generally, reefs with lower percent macroalgal cover are considered healthier. Throughout the U.S. Pacific, reefs exhibiting macroalgal cover less than 10% are considered to be in good health, reefs exhibiting macroalgae cover between 10% and 20% are considered to be in fair health. Johnston exhibited the lowest macroalgal cover at 6.4%, while Wake exhibited macroalgal cover at 16.5%. The central transition islands exhibited macroalgal cover at 7.2% and 12.8% for Kingman and Palmyra, respectively. For all the PRIMNM, Jarvis exhibited the highest macroalgal cover with estimates at 25.4%, likely a result of the high productivity. The other equatorial islands, Howland and Baker, exhibited macroalgal cover at 14.9% and 15.6%, respectively.

Turf algal cover at the PRIMNM was highest at Johnston, which exhibited exceptionally high turf algal cover of 64.0%. With the exception of Johnston, turf algal cover for all of the PRIMNM remained below 29%. Wake exhibited turf algal percent cover at 28.6%. Kingman and Palmyra exhibited turf algal cover at 29.0% and 24.3%, respectively. Turf algal cover at Jarvis, Howland, and Baker was 25.5%, 24.8%, and 22.3%, respectively. Turf algal cover was not included in the reef condition index.

Temporal Comparisons of Benthic Cover

Although there were changes in benthic cover over time, some significant, there were no obvious steadily increasing or decreasing trends from 2006 to 2015 at any of the Pacific Remote Islands. Percent cover has remained relatively stable for all of the functional groups at each of the islands, with the exception of Johnston. Beginning in 2010, there was a significant increase in turf algae and corresponding decrease in CCA cover at Johnston (Fig. 18). In 2010, percent cover of turf algae at Johnston was only 12.5% in 2010, but increased to 64.0% by 2015. Conversely, percent cover of CCA at Johnston was estimated at 57.7% in 2010, but decreased to 13.8% in 2015. The most significant temporal change observed in the PRIMNM occurred during the 2015–2016 El Niño warming event and will be discussed in the island highlights section on Jarvis Island.

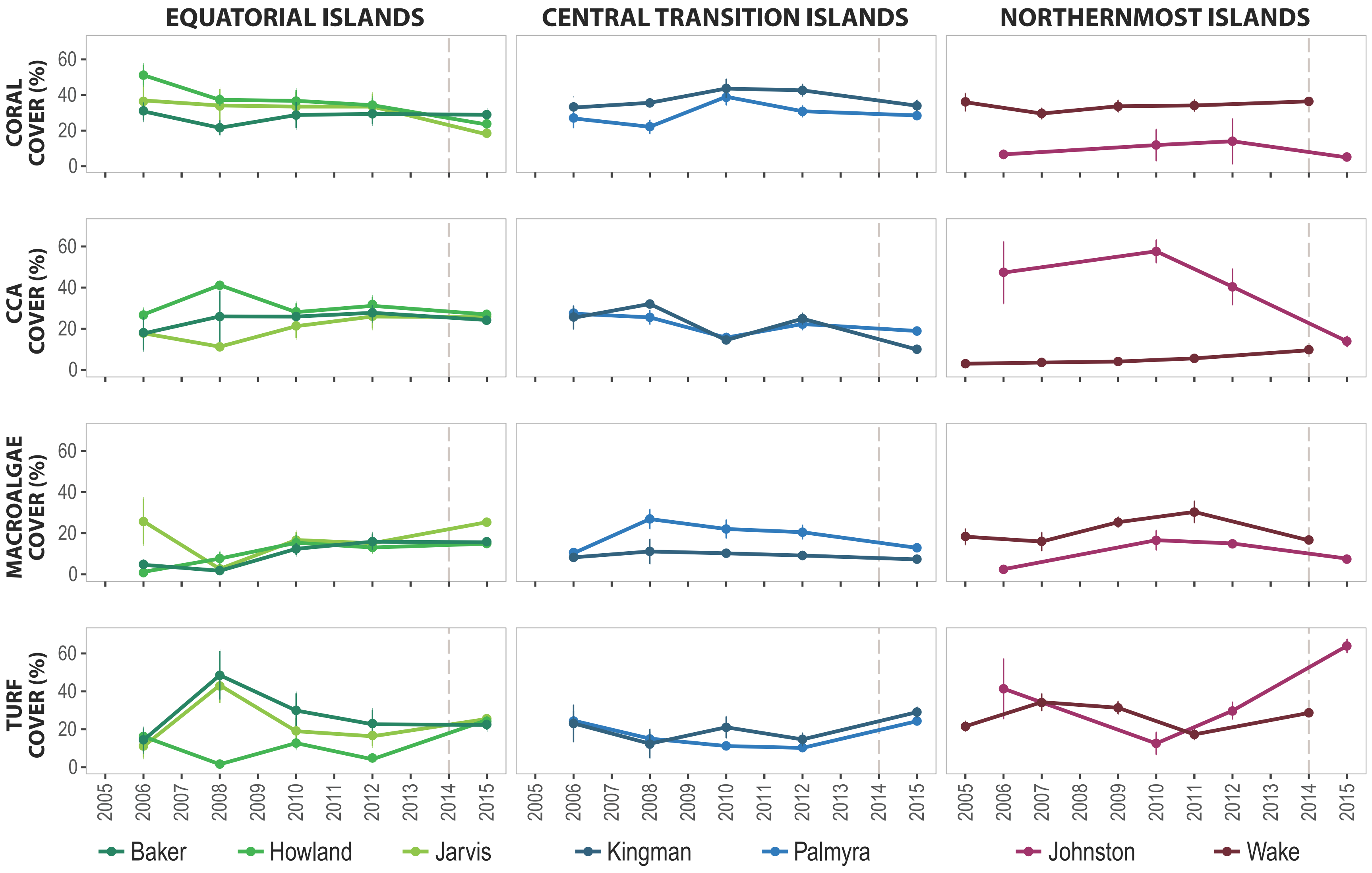


Figure 18. Temporal trends in percent cover for four primary benthic functional groups, including coral, CCA, macroalgae, and turf algae in the forereef habitats from REA surveys conducted in 2005–2015, shown by island group. In 2014, survey design changed from REA sites to stratified random sampling design (StRS), survey design change indicated by dashed vertical line. Error bars indicate standard error (± 1 SE) of the mean.

Coral Diversity

Coral reefs represent the most biologically diverse marine ecosystems in the world, and numerous studies have shown that diverse systems are more resilient to disturbances through time (Folke et al., 2004; Hughes et al., 2005; Worm et al., 2006). Generic richness is the total number of unique genera recorded around each island and, among other measures, is often used as an indicator of coral diversity. Since larger reef ecosystems often support a wider range of habitat types, oceanographic conditions, and taxa, we computed an average generic richness per habitat stratum weighted by stratum area for each island based on our 2014–2015 StRS REA surveys. Kingman and Palmyra had the highest weighted coral generic richness values with mean values of 22.7 and 23.7 species, respectively. Johnston had the lowest generic coral richness with 5.8 species (Fig. 19).

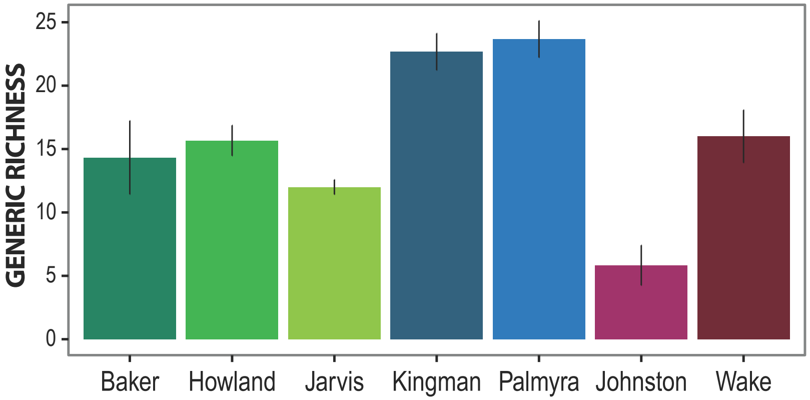


Figure 19. Mean generic richness of adult hard corals for each island estimated from 2014–2015 REA StRS surveys. Generic richness is the total count of unique genera in a sampling area. Error bars indicate standard error (± 1 SE) of the mean.

Disease

Disease occurrence was calculated as the number of diseased colonies divided by the total number of colonies for adult hard scleractinian corals. Disease occurrence estimates are for all diseases except for lesions resulting from barnacle infestation and tubeworm infestation. Disease occurrence on hard corals across the PRIMNM during 2009–2015 sampling years ranged from 0.1% at Baker in 2010 to 3.3% on Palmyra in 2010. Diseases present included, among others: white syndrome, sub-acute tissue loss, skeletal growth anomalies, pigmentation responses, as well as fungal, algal, and cyanobacterial infections. In 2005 and 2006 surveys, Johnston exhibited significantly greater mean overall disease occurrence than other islands in the Pacific (Vargas-Ángel, 2009). This trend is further evaluated in the island highlights section.

Coral diversity observed during benthic survey transect at Kingman Reef, Photo: NOAA Fisheries/Bernardo Vargas-Ángel.

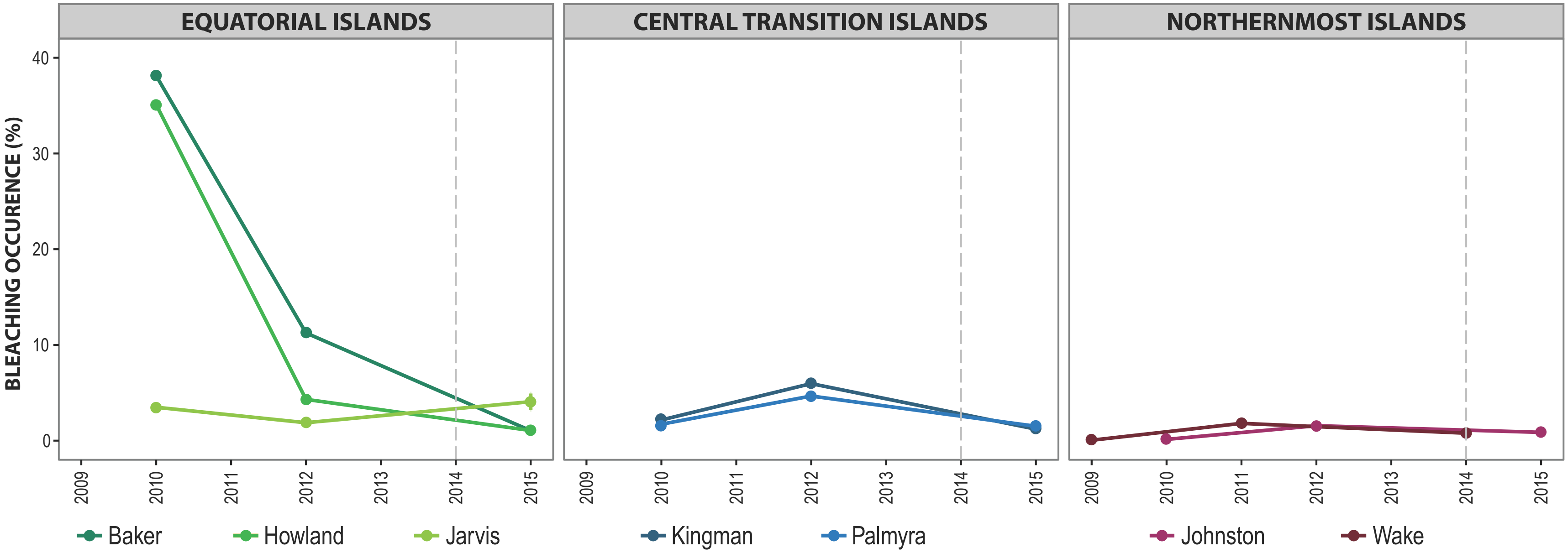


Figure 20. Mean bleaching occurrence—for adult hard corals at all depths and reef zones from 2014 to 2015, estimated from StRS method. The occurrence was calculated as the sum of all infected colonies divided by the total number of colonies. In the permanent site studies (2009–2013), occurrence is the sum of all infected colonies divided by the sum of the total colonies at each island. For StRS surveys (2014–2015), the occurrence is the mean occurrence by island calculated for each StRS sampling site.

Coral Bleaching

REA StRS surveys measure bleaching and disease occurrence on hard scleractinian corals. Bleaching occurrence is presented as prevalence, calculated as the number of colonies exhibiting signs of bleaching (irrespective of severity or extent) divided by the total number of colonies for adult hard scleractinian corals. From 2009 to 2015, bleaching occurrence in the PRIMNM was generally low, below 5% at most islands. (Fig. 20). Spikes in bleaching occurrence occurred at Baker and Howland in 2010 due to a moderate El Niño warm event with mean occurrence reaching 38.1% and 35.1%, respectively (Vargas-Ángel et al., 2011). Noteworthy is the absence of these high bleaching occurrences in neighboring Jarvis Island. The coral bleaching events at Baker and Howland, as well as the massive 2015-2016 coral bleaching event at Jarvis, are evaluated further in the island highlights section.

FISH COMMUNITY

Total Reef-Fish Biomass and Composition

Across the study period, the highest average total reef-fish biomass was observed at Jarvis Island (179.9 $g \cdot m^{-2}$) (Fig. 14 and 21) and Kingman Reef (246.8 $g \cdot m^{-2}$), both located in equatorial, nutrient-rich waters (Fig. 13). By contrast, in the northern oligotrophic waters, average fish biomass was lowest at Wake (52.6 $g \cdot m^{-2}$), followed by Johnston (54.9 $g \cdot m^{-2}$).

Reef fishes play an important role in the function of coral reef ecosystems through the transfer of energy from primary producers at the food web base to top predators and nutrient recycling in microbial and detrital food pathways. It can be useful to consider fishes functionally, as defined by consumer groups, especially as some functional groups can promote ecosystem resilience. The four key functional groups are primary consumers, secondary consumers, planktivores, and piscivores. Primary consumers are fishes that eat algae and detritus (fine organic matters within algal turfs) and are believed to be important contributors to resilience of coral reef ecosystems (Green and Bellwood, 2009). Secondary consumers include omnivores, fishes that consume both algae and other organisms, and benthic invertivores, those that feed on benthic organisms such as crustaceans and other invertebrates. Planktivorous fishes consume both zooplankton and phytoplankton and are generally found feeding in the water column. Lastly, piscivores are fishes that consume other fish. Functional classification of Pacific reef fishes is based largely on diet information taken from FishBase (Froese and Pauly, 2017).

Across the PRIMNM, like total reef-fish biomass, biomass of the four functional groups also varied considerably (Fig. 21). For example, biomass of primary consumers was markedly low at Kingman (19.7 $g \cdot m^{-2}$) relative to total biomass and accounted for less than 8% of total reef-fish biomass, on average, from 2010 to 2015. Estimates of total reef-fish biomass at Kingman were instead driven primarily by extremely high biomass of piscivorous fishes (top predators) (157.6 $g \cdot m^{-2}$), making up over 63% of total reef-fish biomass. By contrast, at Johnston and Wake, primary consumers accounted for a much higher proportion of the total fish community. Primary consumers made up 38% and 43% of total reef-fish biomass at Johnston and Wake, respectively, whereas piscivores were much less abundant at these islands.

Both mean piscivore biomass (8.8 $g \cdot m^{-2}$) and mean planktivore biomass (4.6 $g \cdot m^{-2}$) were lowest at Wake. Similarly, biomass of both piscivores (16.4 $g \cdot m^{-2}$) and planktivores (8.3 $g \cdot m^{-2}$) was also relatively low at Johnston. At both islands, these two functional groups contributed least to overall fish biomass. Both planktivore and piscivore biomass were significantly higher at the equatorial upwelling islands (Kingman, Palmyra, Jarvis) due to the nutrient-rich water and high productivity.

The nutrient-rich water promotes high biomass of large predatory fishes, as well as high biomass of planktivores that feed on the abundant plankton surrounding the islands. The northern oligotrophic islands of Johnston and Wake are located in areas with naturally lower productivity and lower phytoplankton density compared to the other islands in the PRIMNM. Thus, due to the natural variability in oceanographic drivers, it is not unexpected for these islands to have lower biomass for these groups.

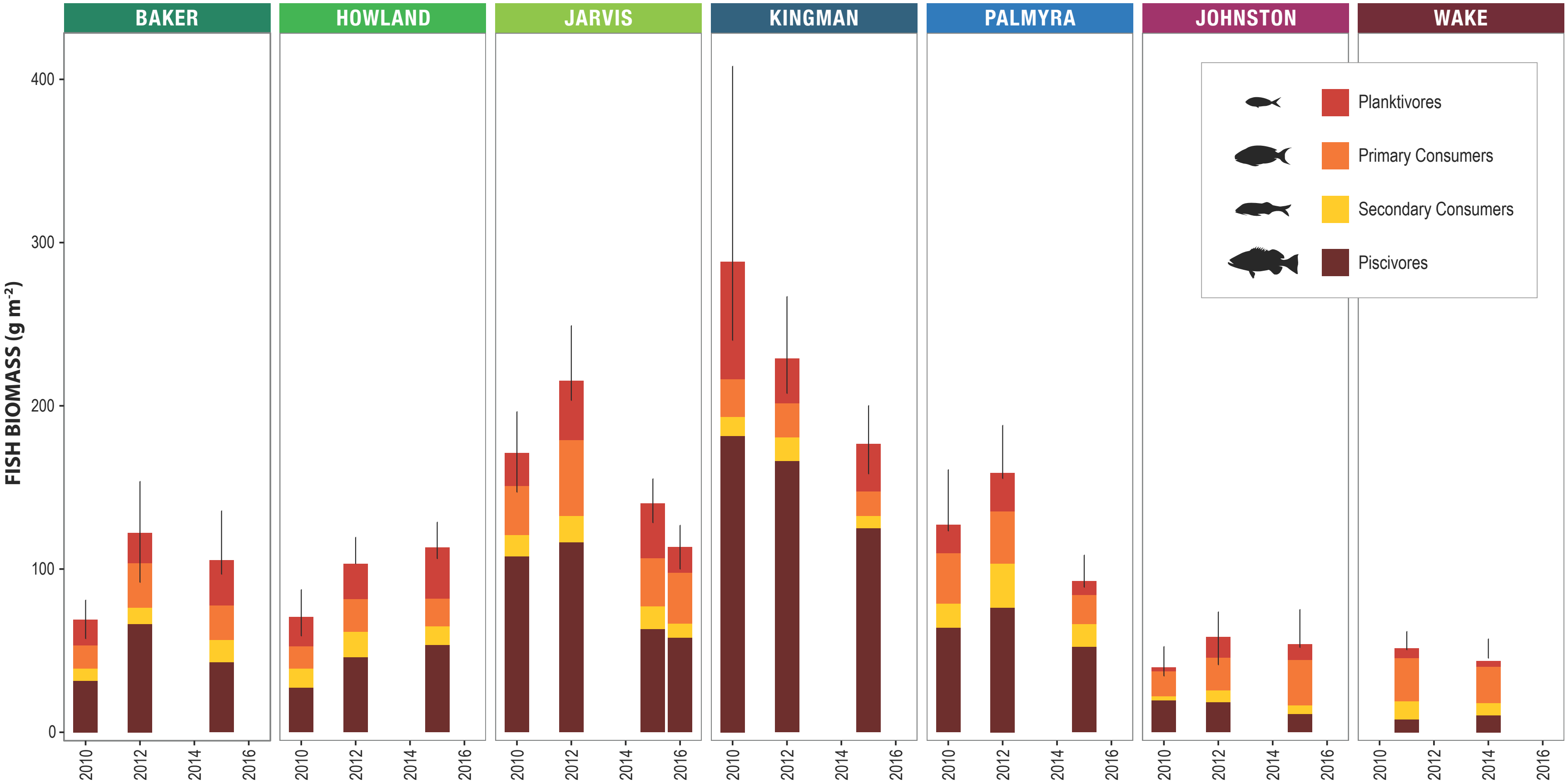


Figure 21. Trends in mean total reef-fish biomass (g·m^{-2}) from fore-reef SPC surveys from 2010 to 2016, ordered by island, from left to right. Stacked bars show biomass per trophic group based on fish diet. Primary consumers include fishes that eat algae and detritus; secondary consumers include fishes with a wide variety in diet (omnivores) and fishes that eat invertebrates (following Williams et al., 2011). Error bars indicate standard error (± 1 SE) of the mean.

Large Fish Biomass

Compared to SPC surveys, towed-diver surveys provide better estimates of large-fish (≥ 50 cm in total length) biomass because the surveys allow divers to cover much larger areas during each survey (~22,000 m^2 per survey compared to 353 m^2); thereby increasing the frequency of encounters with large, rare fishes. Towed-diver surveys across the study period show that there were substantial differences in the biomass of large-bodied fishes across islands in the PRIMNM corresponding to the gradient in productivity (Fig. 22). Biomass of large fishes was highest at Jarvis, averaging 74.2 $g \cdot m^{-2}$ across the 2001–2015 study period. At Johnston, large-fish biomass, was considerably lower, averaging 5.8 $g{\cdot}m^{-2}$ across the 2004–2015 study period.

Likely, the primary reason for the stark differences in large fish biomass across the PRIMNM is the range of oceanic productivity, as mentioned herein. Jarvis is highly productive, and therefore supports a high abundance of both planktivores and piscivores as described above (Williams et al., 2015). For example, these conditions support high biomass of both sharks and rays. Similarly, Baker and Howland Islands also occur in productive waters, which is reflected in the high biomass of these same groups across the study period at these islands. By contrast, Johnston and Wake occur in the oligotrophic region of lowest oceanic productivity and they have substantially lower total large-fish biomass than the productive equatorial islands. Similar to Johnston, average large-fish biomass at Wake across the study period (2005–2014) was low, 19.5 $g{\cdot}m^{-2}$, which was only 26% of the large-fish biomass observed at Jarvis. Notably, large-fish biomass appeared to decline at both Johnston and Wake over the study period. Interestingly, abundance of large parrotfish was highest at Wake, where there have been relatively high numbers of bumphead parrotfish (*Bolbometopon muricatum*).

Reef sharks at Kingman Reef, Photo: NOAA Fisheries.

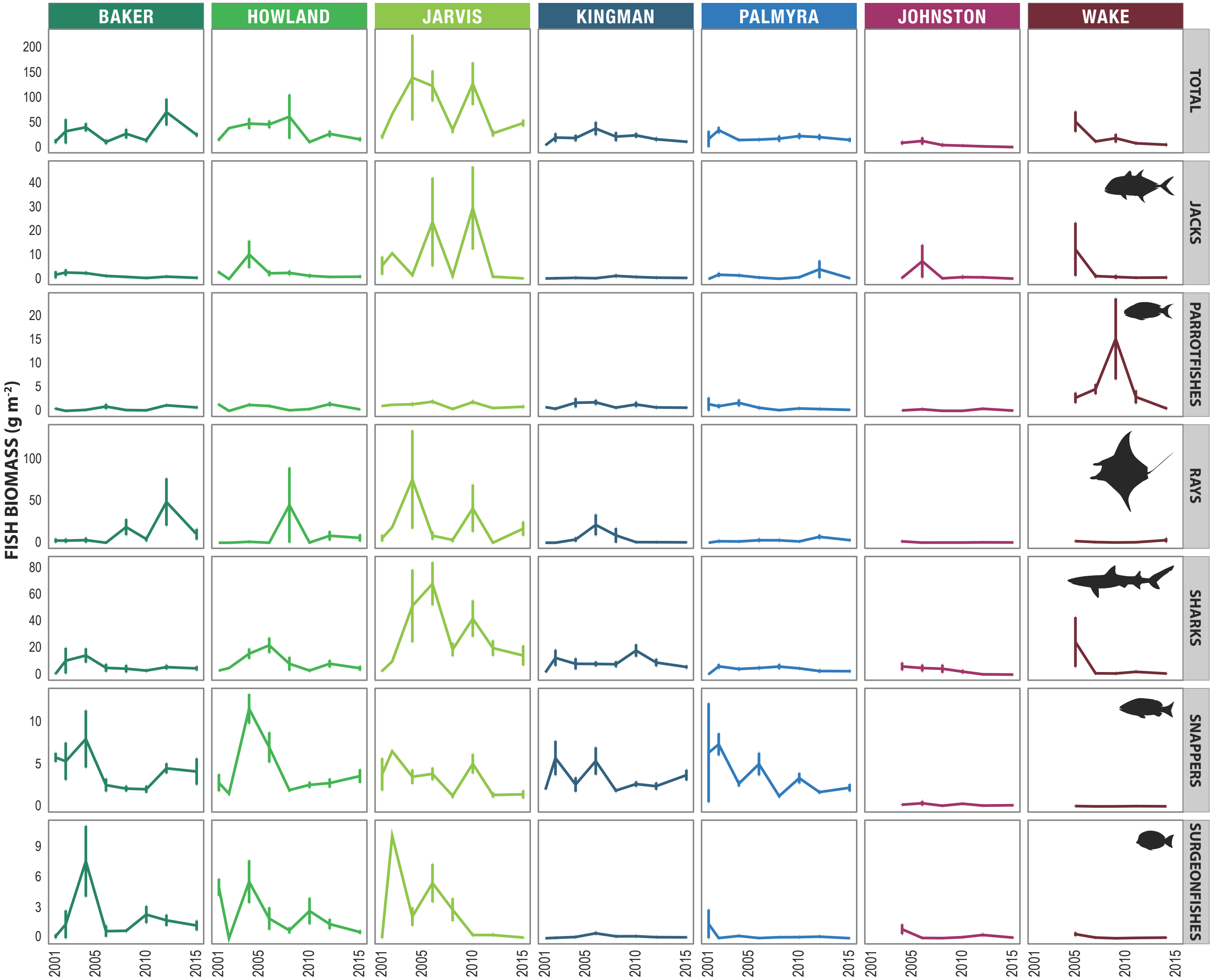


Figure 22. Trends in mean biomass ($g{\cdot}m^{-2}$) of large-bodied fishes (≥ 50 cm total length) from towed-diver surveys across the 2001–2015 study period at Baker, Howland, Jarvis, Kingman, Palmyra, Johnston, and Wake. Total large fish biomass is shown for each island in top row. The following rows show biomass of key families: jacks (Carangidae), parrotfishes (Scaridae), rays (Myliobatidae), sharks (Carcharhinidae), snappers (Lutjanidae), and surgeonfishes (Acanthuridae). Sampling at all islands began in 2001, with the exception of Johnston and Wake, beginning in 2004 and 2005, respectively. Total large fish biomass is scaled to maximum large fish biomass found at each island with each subsequent family scale to maximum biomass found across the PRIMNM (note the differences in scale on the y-axes). Error bars indicate standard error (± 1 SE) of the mean.

INTEGRATING ECOSYSTEM COMPONENTS

With the transition toward ecosystem-based management, it is useful to develop indicators that integrate across ecosystem components to describe the overall condition or status of coral reefs. Following an approach developed for a suite of NCRMP Coral Reef Condition Report Cards, CREP has created a Benthic Condition Index, a Reef Fish Condition Index, and a Climate Condition Index that use various Pacific RAMP data sets collected in recent years. An overall Coral Reef Condition Index is composed of equally-weighted Benthic Condition, Fish Condition, and Climate Condition Indices.

The components of the Benthic Condition Index are benthic cover, including coral, crustose coralline algae, and macroalgae; coral generic richness; adult coral colony densities; juvenile coral colony densities; and partial mortality rates of coral. Colony densities and partial mortality were based on selected coral genera that are ecologically important and abundant at each island. Scores increased with increasing values for all indicators other than macroalgae cover and partial mortality, for which scores decreased with increasing values. The components of the Reef Fish Condition Index are reef fish biomass, mean size of target families, and a combined predator index comprised of shark abundance and total piscivore biomass. The components of the Climate Condition Index are temperature stress, reef material growth, and ocean acidification. Scoring for the components was based on a variety of approaches, all with the goal of generating values on a 0–100 scale, where 90+ represents excellent conditions and less than 60 represents very poor conditions.

The Coral Reef Condition Index provides an interdisciplinary synthesis of the status of the coral reef ecosystems for each of the islands/atolls in the PRIMNM that is comparable with the other U.S. islands and atolls across the Pacific. The Coral Reef Condition Index values calculated for each island in the PRIMNM are displayed as excellent (dark green), good (light green), fair (yellow), poor (orange), or very poor (red) in Figure 23. The overall Coral Reef Condition Index is fair for Johnston (78) and Baker (78) and good for Jarvis (80), Howland (81), Wake (83), Palmyra (84), and Kingman (86). The Reef Fish Condition Index scores were typically the highest of the three indices. All islands scored between good and excellent. In common with other uninhabited (or very lightly populated in the case of Wake) locations, reef-fish communities at each of the PRIMNM islands are relatively intact, with scores ranging from 84 at Baker to 100 at Jarvis. The Benthic Condition Index for all islands in the PRIMNM were fair to good, with scores ranging from 76 at Jarvis to 89 at Kingman. The fair Benthic Condition Index values at Jarvis and Johnston were primarily due to benthic composition and generic richness components of the index. At Jarvis, the low coral cover score (68), the low macroalgae score (65), and the lower generic richness score (70) led to fair benthic condition scores (76). At Johnston, a low coral cover score (43) and low generic richness score (62) decreased Johnston's overall score (79). The Climate Condition Index scores were the lowest of the three indices, ranging from poor scores at Jarvis (65) and Johnston (66) to fair scores at Howland (70), Baker (70), Palmyra (71), Kingman (72), and Wake (73).

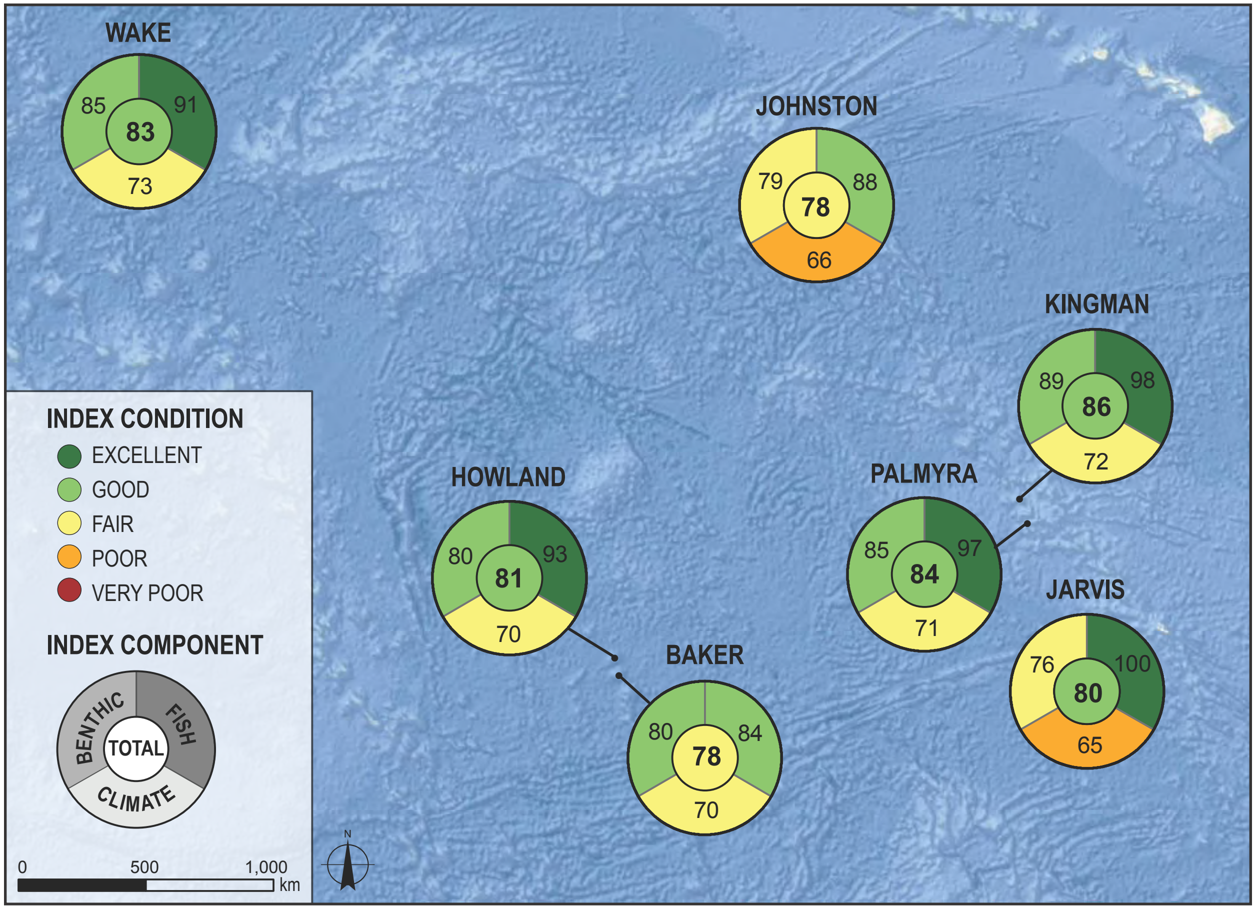


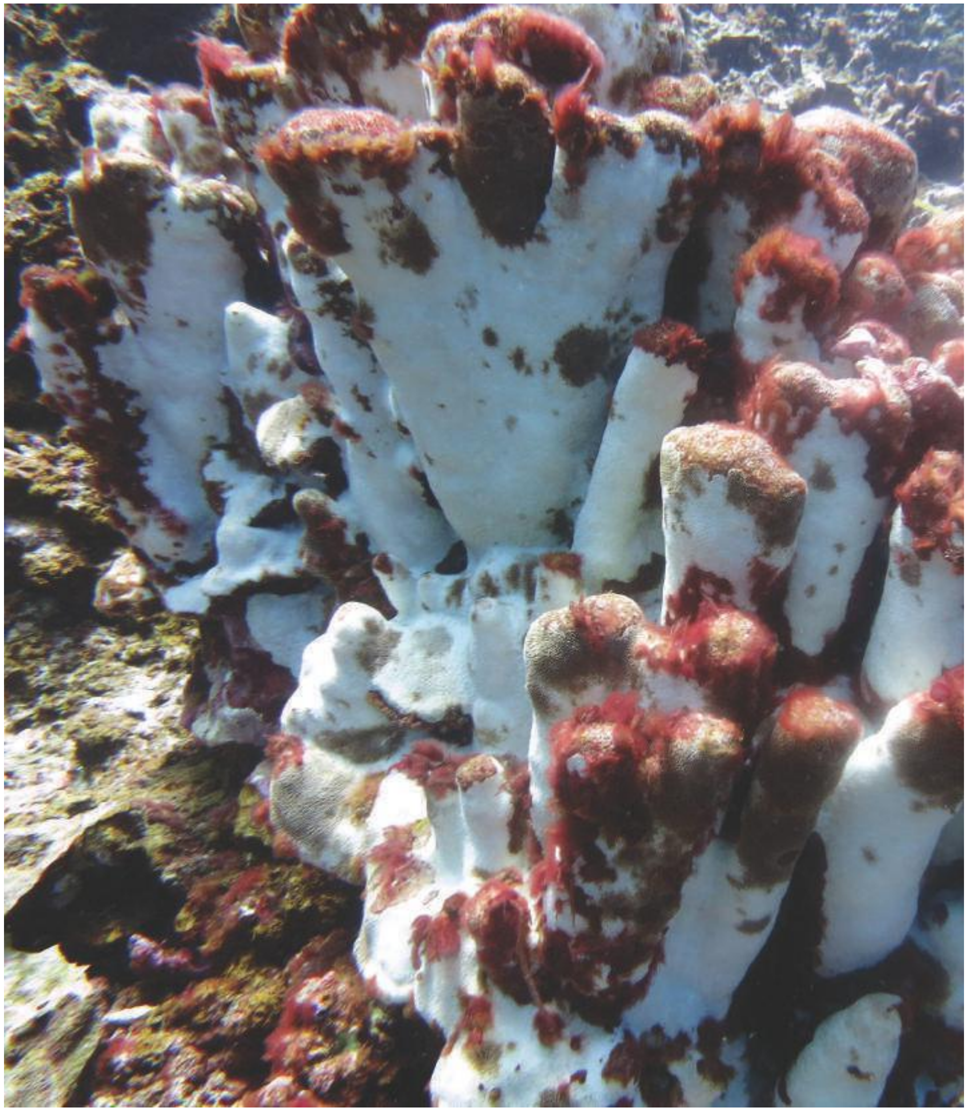
Figure 23. Coral Reef Condition Index across the PRIMNM. Reef Fish Condition, Climate Condition, and Benthic Condition Indices are represented within the pie chart components, with the circle in the middle representing the Coral Reef Condition Index (an equally weighted average of all 3 indices). Index condition ranges from excellent (dark green), good (light green), fair (yellow), poor (orange), to very poor (red).

The Climate Condition Index scores were relatively low due to the extended period of anomalously warm water temperatures associated with the 2015–2016 El Niño and 2014–2016 global coral bleaching event. In addition, ocean acidification scores were based on comparison with pre-industrial levels that were more optimal for growth of coral reefs and are, therefore, relatively low at most or all coral reef locations in the PRIMNM. Despite these relatively low scores for the Climate Condition Index, the overall Coral Reef Condition Indices for all the islands remained fair to good through the end of 2015 (the last year of consistent data). Unfortunately, mass coral bleaching in 2015–2016 at the equatorial upwelling islands of Jarvis (high mortality), Howland, and Baker (low mortality), as discussed in the island highlights section, will likely decrease the Coral Reef Condition Index scores following the next round of Pacific RAMP surveys.

ISLAND HIGHLIGHTS

BAKER, HOWLAND, AND JARVIS ISLANDS: CORAL BLEACHING

Coral bleaching is characterized by the observed whitening of corals that results from the loss of their symbiotic algae, called zooxanthellae, whose pigments provide the colors normally associated with healthy corals. A variety of stressors can induce coral bleaching, including anomalously warm (or cold) water temperatures, increases in solar radiation, reduced salinity, sedimentation and other land-based pollution, or bacteria and other infections (Brown, 1997). Bleaching events often coincide with El Niño episodes characterized by anomalously warm sea surface temperatures. Though bleaching does not mean the coral is dead, it can eventually lead to coral mortality, which can have devastating impacts on coral reef ecosystems.



Above left: One of the few remaining table Acropora corals at Jarvis Island in the foreground with red turf algae growing over damaged corals in 2017, Photo: NOAA Fisheries/Tate Wester; Above: Bleached Pavona corals at Jarvis Island in 2016, Photo: NOAA Fisheries/Bernardo Vargas-Ángel; Previous page: Manta ray at Howland Island, Photo: NOAA Fisheries.

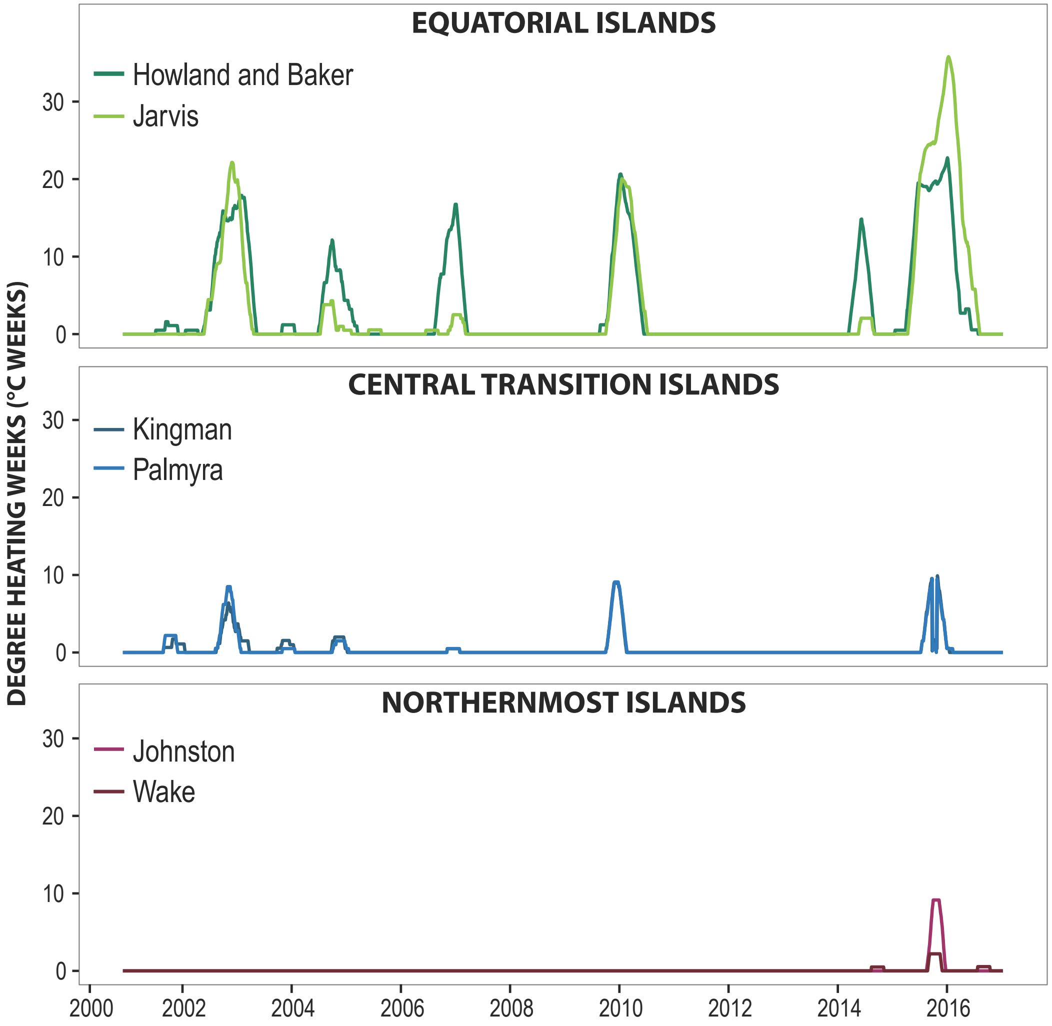


Figure 24. Degree Heating Weeks (DHW; °C weeks) across the PRIMNM from 2000–2016. Data Source: NOAA Coral Reef Watch 50-km Virtual Stations.

The mortality rate is often closely related to the intensity of the bleaching event (Hoegh-Guldberg, 1999), which can be expressed as Degree Heating Weeks (DHW). DHWs indicate how much thermal stress has accumulated in an area within a given period by expressing the duration and magnitude by which temperatures have exceeded a reference coral bleaching threshold, defined as 1°C above the highest summertime mean sea surface temperature (Liu et al., 2006). Climate models project that bleaching events are expected to increase in frequency and intensity in the future. Bleaching-associated coral mortality rates are also expected to increase over the next couple of decades. Baker, Howland, and Jarvis have all been impacted by these ocean warming events, causing disruption to the benthic community structure. Between 2009 and 2010, Baker and Howland experienced 20.65 DHW and Jarvis experienced 20.05 DHW (NOAA Coral Reef Watch 50-km Virtual Stations, 2000). Between 2015 and 2016, Baker and Howland experienced 22.7 DHW and Jarvis experienced 35.8 DHW (Fig. 24). In comparison, the Central Transition Islands experienced approximately 9 DHW between 2009–2010 and 2015–2016, and the Northernmost Islands experienced 0 DHW between 2009 and 2010. During 2015–2016, the Northernmost Islands, Wake and Johnston, experienced 2 DHW and 9 DHW, respectively.

BAKER AND HOWLAND ISLANDS: 2010 BLEACHING EVENT

Baker and Howland Islands have high inter-annual variability in temperature due to their location on the equator and the El Niño-Southern Oscillation. During the 2009–2010 El Niño event, sea surface temperature exceeded the coral bleaching threshold of 29.7°C (1 degree C above the climatological maximum monthly mean; method source: Liu et al., 2006) continuously from October 22, 2009, to January 7, 2010 (Fig. 25). Sea surface temperature continued to fluctuate around the bleaching threshold from mid-January through mid-March, until the temperature progressively decreased after March 15, 2010.

A Pacific RAMP cruise surveyed the coral reefs around Baker and Howland in February 2010, shortly after the El Niño event. The surveys observed bleaching at both islands, with mean bleaching occurrence estimated at 38% for Baker and 35% for Howland. Despite similar degree heating week measurements in 2010, bleaching was not observed during surveys at Jarvis Island in April 2010. By 2012, the following survey year, bleaching occurrence had decreased to 11% for Baker and 4% for Howland (Fig. 20), indicating potential recovery since live coral cover did not decrease from 2009 to 2012. This is evident when comparing the long-term averages of coral cover from 2005 to 2015 (Fig. 18).

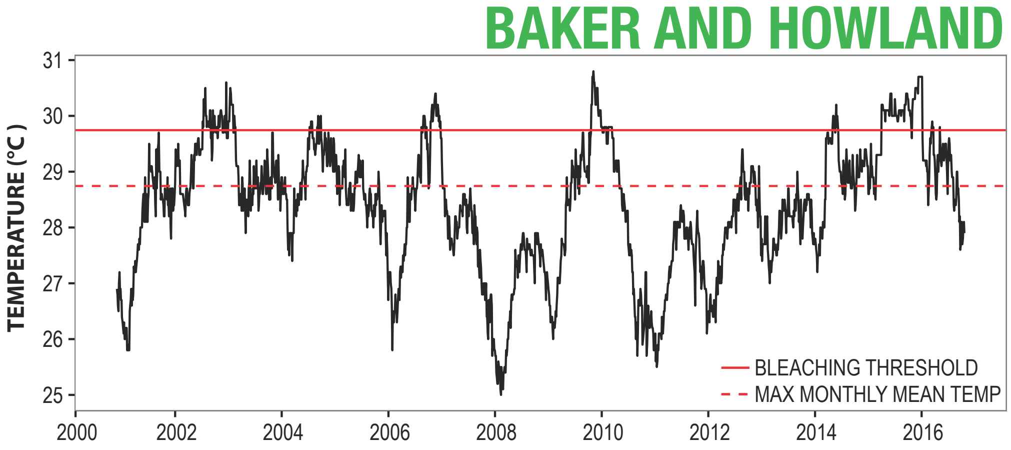


Figure 25. Sea Surface Temperature (SST; °C) at Howland and Baker Islands from 11/28/2000 to 10/13/2016. Data Source: NOAA Coral Reef Watch 50-km Virtual Stations, 2000.

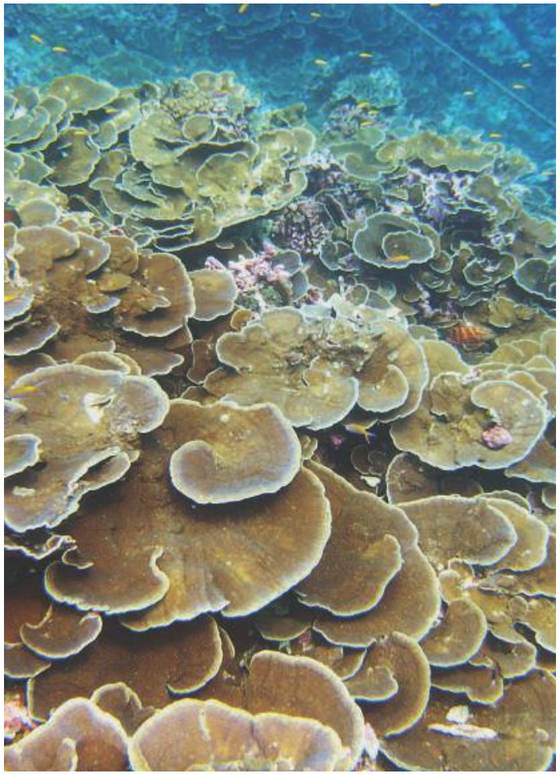
Bleached corals at Howland Island in 2010, Photo: NOAA Fisheries/Bernardo Vargas-Ángel.

Reduction of local and global stressors is essential for sustaining benthic community health and promoting coral resilience after a bleaching (or other disturbance) event. Stressors can be reduced by decreasing land-based pollution and increasing connectivity and gene flow to bolster coral recovery from periodic bleaching events (Hughes et al., 2003, Hughes et al., 2010). Additionally, increasing grazer and detritivore biomass decreases macroalgal and turf algal cover and increases encrusting algae, including reef-building crustose coralline algae. Furthermore, biomass of large parrotfish appears to be positively associated with increased live coral cover. The scraping and excavating of parrotfish open new sites on the reef that facilitate the settlement, survival, and growth of CCA and coral (Heenan and Williams, 2013). A healthy herbivorous fish community may have contributed to Baker and Howland's observed recovery from the 2010 bleaching event and prevented a possible phase shift to an algal-dominated reef (Fig. 18).

Table Acropora at Baker Island in 2017 (Photo: NOAA Fisheries/Tate Wester); Redlip parrotfish (Scarus rubroviolaceus) and crustose coralline algae at Baker Island in 2017, Photo: NOAA Fisheries/Kevin Lino.

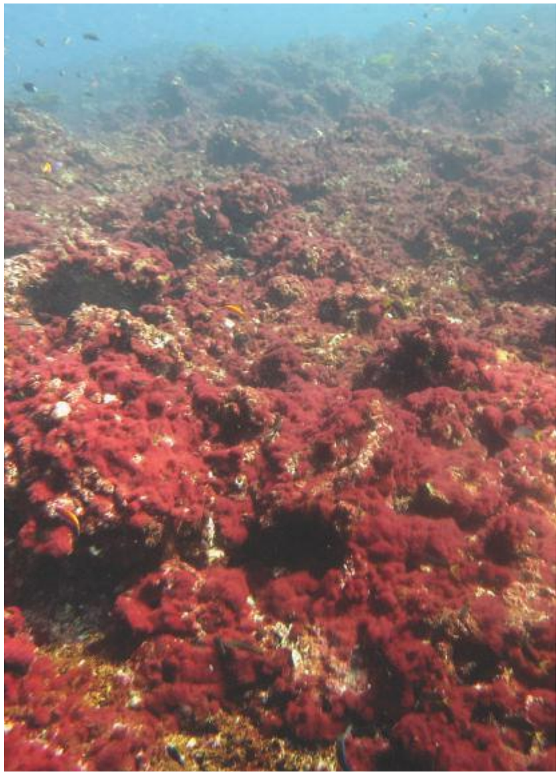
JARVIS ISLAND: 2015-2016 BLEACHING EVENT

Jarvis Island was severely impacted by the strong 2015–2016 El Niño, during which abnormally high sea surface temperatures continuously exceeded the coral bleaching threshold of 28.7 °C from April 16, 2015 to February 29, 2016. SST continued to fluctuate around the bleaching threshold from early March through mid-May of 2016, until the temperature progressively returned to normal conditions after May 19, 2016 (Fig. 26). Conditions at Jarvis surpassed the coral bleaching threshold for 43 consecutive weeks, 3.7 times longer than conditions at Baker and Howland in 2009–2010. Based on REA StRS image analysis, the hard coral cover at Jarvis declined from 17.8% in 2015 (pre-bleaching event), to 0.31% in 2016 (post-bleaching event), representing a decrease of 98% across all depths.



Forereef coral communities at Jarvis Island in 2006 before the bleaching event, Photo: NOAA Fisheries/Bernardo Vargas-Ángel.

Forereef coral communities at Jarvis Island during the 2015–2016 bleaching event, Photo: Woods Hole Oceanographic Institution/Cohen Lab.



Red turf algae growing over dead and damaged coral at Jarvis Island in 2016 after the bleaching event, Photo: NOAA Fisheries/Bernardo Vargas-Ángel.

Time series of percent coral cover (2001–2016) from two complementary data sets, illustrate the catastrophic mortality that occurred in the mid-depth (6–18 m) reef habitats (Fig. 27). The mass mortality of the coral community may have negative impacts elsewhere in the ecosystem. NOAA is currently studying not only how changes in coral cover are affecting the islands, but also how other biological aspects associated with the thermal stress have changed. A more comprehensive publication addressing these changes is forthcoming. Through the continuance of long-term monitoring, NOAA will quantify the impacts of the 2015–2016 El Niño on the coral reef ecosystem at Jarvis and track recovery.

While Jarvis showed severe heating and severe coral mortality due to the 2015–2016 El Niño, Baker and Howland were less exposed to high temperature anomalies and qualitative reports from 2017 surveys show no major in coral cover (quantitative results pending). As the frequency of these high temperature events is projected to increase in coming years, it is important to track how a coral reef ecosystem system with few human impacts, such as Jarvis Island, responds to climate events.

JARVIS

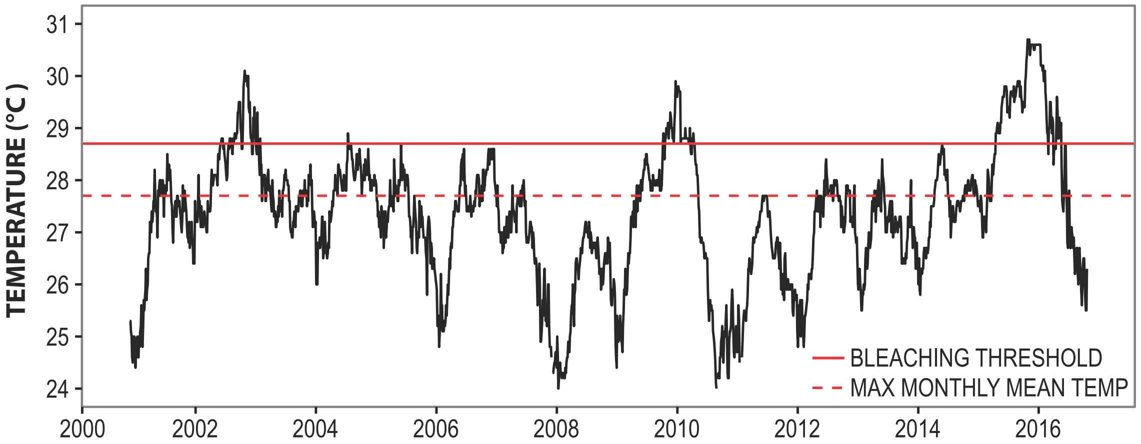


Figure 26. Sea Surface Temperature (SST) at Jarvis Island from 11/28/2000 to 10/13/2016. Data Source: NOAA Coral Reef Watch 50-km Virtual Stations, 2000.

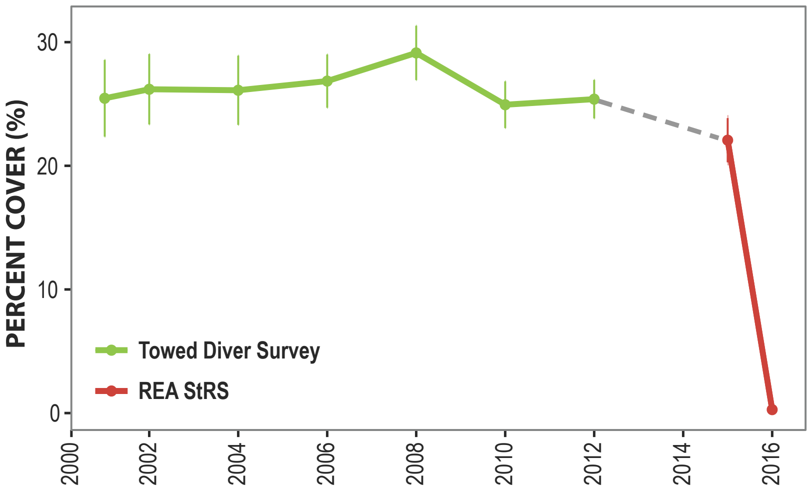


Figure 27. Time series of percent coral cover for forereef strata at mid-depths (6–18 m) at Jarvis Island from 2001 to 2012 benthic towed-diver surveys (green) and from 2015 to 2016 REA StRS surveys (red).

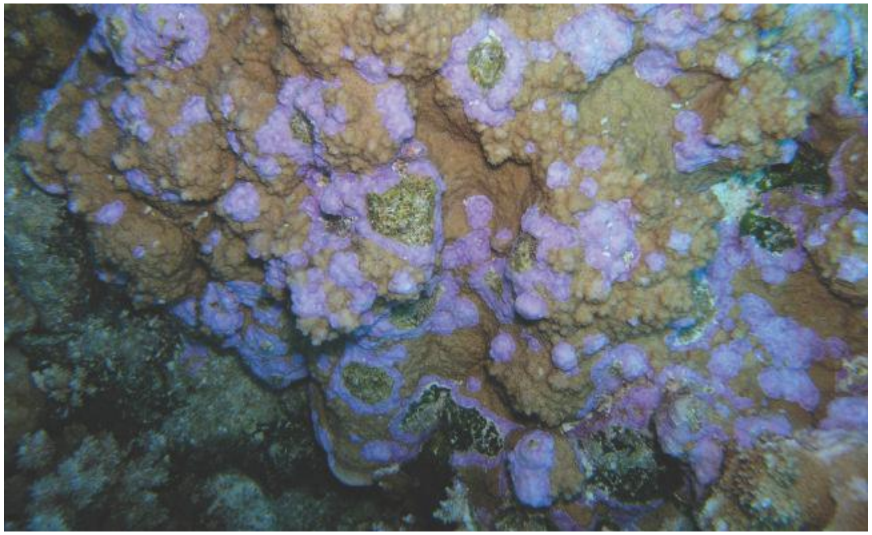
JOHNSTON ATOLL

Johnston Atoll was impacted by human presence more than any other island within the PRIMNM. The U.S. Navy dredged and filled the atoll to expand Johnston, making it an essential fueling depot for military aircraft and submarines (Rauzon, 2016; Coles et al., 2001). Johnston became a busy terminal during World War II (Rauzon, 2016; Magier et al., 2012). In 1958, President Kennedy initiated nuclear weapon testing at Johnston. In 1962, the Bluegill Triple Prime test failed and spilled americium and plutonium across the atoll. The contaminated sand was raked into a pile now referred to as "Mount Pluto." In 1969, the U.S. military removed its chemical weapon stockpile from Johnston after an accidental leakage of VX nerve gas in Okinawa (Rauzon, 2016). The Johnston Atoll Chemical Agent Disposal System (JACADS) was created in 1971, and incinerators and disassembly units were built on the downwind side of the island in 1985 (Rauzon, 2016; Magier et al., 2012; Coles et al., 2001).

By 2000, JACADS had successfully destroyed 4 million pounds of toxic chemicals on Johnston, including 5,600 bombs, 13,300 land mines, 43,600 mortars, 72,300 rockets, and 277,800 projectiles. However, 30,000 gallons of herbicide Agent Orange were reported to have leaked into the soil (Rauzon, 2016). The JACADS facility was dismantled after the mission was completed (Rauzon, 2016; Magier et al., 2012). Johnston Atoll was decommissioned as a military base and most of the buildings were removed by 2004. Although there were multiple ecological disturbances experienced at Johnston Atoll, there is not enough baseline information to quantify the impacts of chemical contaminants on coral reef health (Johannes and Betzer, 1975). The sediments and fish in the northwest region of Johnston Island near the detonation areas and where the Agent Orange was stored exhibited the highest concentration of chemical pollutants. Contaminants in fish tissues were also higher at sites with polluted sediments (Lobel and Lobel, 2008). However, recent studies reveal that the remaining herbicide Agent Orange in the soil no longer poses significant ecological risks to the atoll (Lobel et al., 2003).

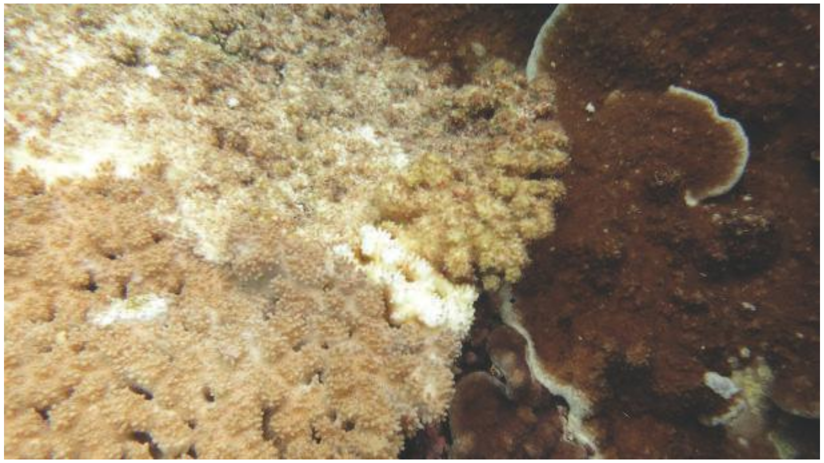
Barrels of Agent Orange in storage at Johnston Atoll circa 1976, Photo: U.S. Government.

Johnston Atoll Chemical Agent Disposal System (JACADS) building, Photo: U.S. Army Chemical Materials Agency.



Disease Occurrence

Pacific RAMP surveys conducted in 2005–2006 revealed that the coral disease occurrence was significantly higher at Johnston than any other island in the PRIMNM (Vargas-Ángel, 2009). While the anthropogenic disturbances at Johnston have not been directly linked to higher coral disease occurrence, the low occurrence of coral disease at other islands within the PRIMNM could suggest that the higher coral disease occurrence at Johnston may be associated with the past environmental disturbances. Notably, sites with closest proximity to environmental stressors (such as Agent Orange storage sites, explosive detonation areas, open burn pits) exhibited the highest levels of coral disease prevalence for all diseases at Johnston. Of the coral diseases present at Johnston, white-syndrome is particularly concerning, as it leads to rapid tissue loss. White-syndrome occurred primarily at Johnston Atoll with one case of white-syndrome at Wake (Vargas-Ángel, 2009).



Above left: Skeletal growth anomalies on a colony of Montipora at Johnston Atoll, Photo: NOAA Fisheries/Bernardo Vargas-Ángel; Above: White-syndrome observed on Acropora cytherea during a benthic survey at Johnston Atoll in 2017, Photos: NOAA Fisheries/Brett Schumacher.

KINGMAN REEF

Kingman Reef is notable for its remarkably high fish biomass and high coral cover, but also for recurrent outbreak level populations of the corallivorous crown-of-thorns (*Acanthaster planci*) sea stars. Kingman Reef is also known for its large population of giant clams (*Tridacna maxima* and *Tridacna squamosa*).

Crown-of-thorns Sea Stars

Crown-of-thorns sea stars (COTS) are coral-eating invertebrates that can inflict devastating impacts to the ecological integrity of coral reefs. COTS outbreaks can alter coral community structure and functioning (Colgan, 1987; Pratchett, 2007), promote macroalgal growth (Moran, 1986; Bradbury et al., 1985), and affect fish population dynamics (Williams 1986, Hart 1996). CREP implements towed-diver surveys to assess the status of COTS populations; densities greater than 1,500 organisms km^{-2} are considered outbreak conditions (Moran, 1992). COTS populations at Kingman have consistently exhibited outbreak levels at multiple locations around the reef since the inception of the surveys in 2002 (Fig. 28). The backreef region of Kingman Reef experienced the highest COTS densities with populations reaching more than 10,000 organisms km^{-2}. Although Kingman Reef is not a high island with terrestrial runoff, high nutrient loadings and specific climatic and ecological conditions are correlated with COTS outbreaks across the Indo-Pacific (Timmers, 2012). Despite persistent COTS outbreaks, Kingman has relatively high coral cover and relatively low macroalgal cover, per 2014–2015 REA and towed-diver surveys (Fig. 18).

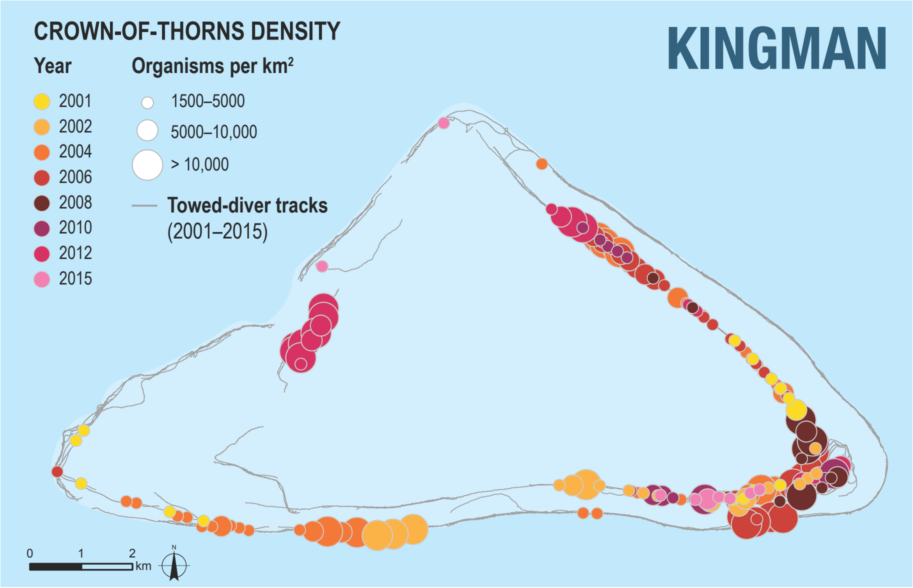
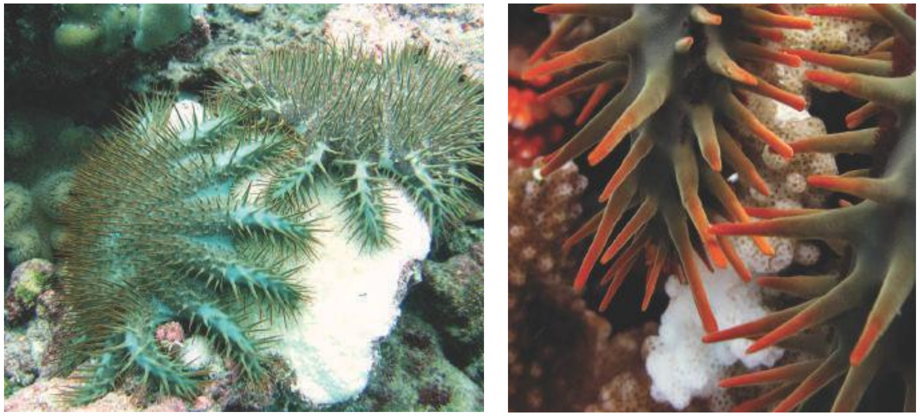


Figure 28. Crown-of-thorns (COTS) sea star outbreaks where densities exceeded 1500 organisms per km^2. Densities were calculated from towed-diver surveys at Kingman Reef conducted from 2001 to 2015. Colors represent different survey years. COTS at Kingman have historically demonstrated higher densities within the backreef reef zone.



Two COTS prey on coral at Kingman Reef, Photo: NOAA Fisheries/Bernardo Vargas-Ángel; Close-up of coral predation, Photo: NOAA Fisheries/James Morioka.

Giant Clams

Giant clams are a valuable food source and exports of clam meat coupled with shell harvesting are linked to their stock depletion. Habitat degradation and decreases in spawning success, as giant clam abundance declines, are also exacerbating population decreases (Teitelbaum and Friedman, 2008). *Tridacna maxima* and *T. squamosa*, both found at Kingman, are listed as species of "least concern" by the International Union for Conservation of Nature (IUCN) (Wells 1996). Their status, however, has not been evaluated by the IUCN since 1996. A petition was submitted to the Secretary of Commerce by the National Marine Fisheries Service to protect giant clams, including *T. maxima* and *T. squamosa* under the Endangered Species Act, and results are still pending (Meadows, 2016).

Extant species of giant clams are only found in the Indo-Pacific region (Newman and Gomez, 2002). These filter feeders form symbiotic relationships with photosynthetic algae, zooxanthellae that transfer carbon to host tissues (Klumpp et al., 1992). The zooxanthellae need sunlight to perform photosynthesis, thus giant clams are found in depths up to 20 meters and prefer clear, oceanic waters where light can penetrate to the bottom (Meadows, 2016). Their growth is limited by nitrogen in the environment, and addition of organic or inorganic nitrogen in the form of ammonium or nitrate can stimulate tissue growth (Hawkins and Klumpp, 1995).

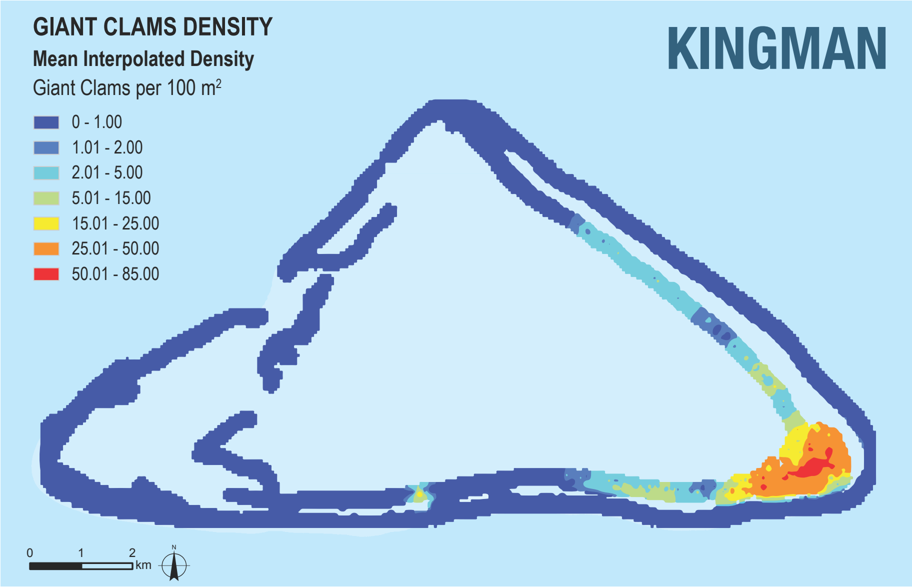


Figure 29. Mean giant clam densities (organisms per 100 m²) from towed-diver surveys at Kingman Reef. Towed-diver surveys indicate highest concentration of these clams in the southeastern clam garden.

Giant clams at Kingman Reef, Photo: NOAA Fisheries/James Morioka.

Giant clams provide numerous ecological services to reefs. Predators, scavengers, and other feeders rely on their tissues, zooxanthellae discharges, and wastes for food. Their shells and mantle cavities allow for the colonization of epibionts, small organisms which live on the surface of their tissues. Furthermore, water filtering allows them to mitigate eutrophication. Giant clams also produce calcium carbonate shell material that is eventually incorporated into the reef framework (Neo et al., 2015). Towed-diver surveys revealed densities as high as 105 organisms 100 m^{-2} located within the southeastern clam garden; this is equivalent to about 1 clam for every square meter of reef habitat. Mean densities within this area for all survey years ranged from 50 to 85 clams 100 m^{-2}, or about 5–8 clams 10 m^{-2} (Fig. 29). These are the highest giant clam densities observed across the Pacific Islands region in Pacific RAMP surveys.

Giant clams at Kingman Reef,
Photo: NOAA Fisheries/Kelvin Gorospe.

PALMYRA ATOLL

In 1991, the longline vessel, *F/V Hui Feng No. 1*, ran aground on the western terrace of Palmyra Atoll (USFWS, n.d.). The shipwreck led to leaching of iron, a limiting ocean nutrient, which fueled the proliferation of the invasive corallimorph *Rhodactis howesii* (Work et al., 2008; Kenyon, 2011). Multiple means of reproduction (sexual, budding, fragmentation, and fission) allow *Rhodactis* to quickly spread, smothering and killing the surrounding corals. At Palmyra, the spread of *Rhodactis* rapidly transformed the shipwreck reef area from a species-rich coral assemblage into a dense, monotypic stand of corallimorphs (Kenyon, 2011). Surveys indicated that in 2005–2006, the corallimorph outbreak extended 50–100 m from the ship and coral cover was estimated at 30% around the shipwreck (Work et al., 2008). By 2007, the corallimorph population had spread out to about 1100 m from the ship, and the surrounding coral cover surrounding had decreased to 1%. At the height of the invasion, prior to the shipwreck removal in 2013, the corallimorph invasion carpeted over 3 km^2 (741 acres) of reef once dominated by reef-building corals (Work et al., 2008).

Due to the devastation of the reef on this remote and relatively pristine atoll, the U.S. Fish and Wildlife Service removed the shipwreck as the first step in restoring the reef by cutting off the nutrient supply, a necessary resource for *Rhodactis*. The *Hui Feng No. 1* wreck site was declared clean and free of debris on December 31, 2013 (USFWS, n.d.). Along with the shipwreck removal, the U.S. Fish and Wildlife Service performed restoration efforts with the goal to remove 70% of the corallimorph by 2016 (Kenyon, 2011). Only partial removal occurred, and monitoring is ongoing to track the recovery process. Despite this invasion, island-wide mean coral cover and fish biomass were comparable to the other islands in the PRIMNM, and the Coral Reef Condition Index had a similar score (84) as neighboring Kingman Reef (86).

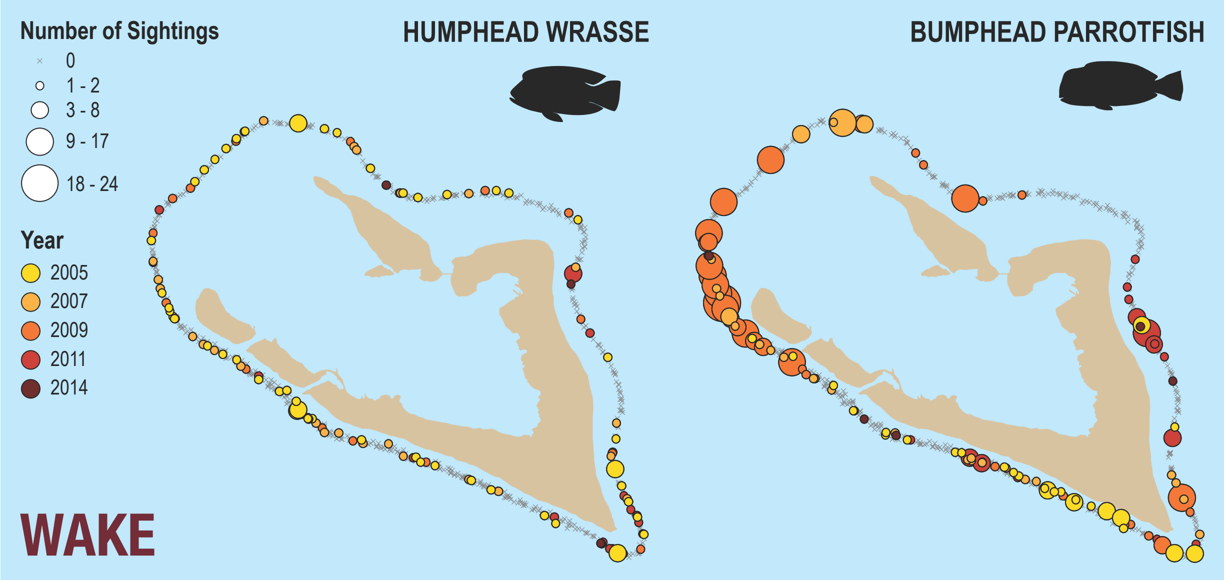
Monoculture of Rhodactis howesii at Palmyra Atoll in 2008, Photo: NOAA Fisheries.

Vibrant Acropora community not affected by corallimorph infestation in Palmyra Atoll in 2015, Photo: NOAA Fisheries.

WAKE ATOLL

Two large fish species of interest in the Indo-Pacific are the humphead wrasse (*Cheilinus undulatus*) and bumphead parrotfish (*Bolbometopon muricatum*). The humphead wrasse is the largest member of the wrasse family and can reach a maximum length of 2 m and weight of 190 kg (Sadovy et al., 2003). The bumphead parrotfish is the largest herbivorous and corallivorous fish on coral reefs, and can reach 1.5 m in length and weigh over 75 kg (Muñoz et al., 2014). Populations of both of these ecologically important species have declined in parts of their range over the last several decades (Kobayashi, et al., 2011; Sadovy et al., 2003). The bumphead parrotfish is a highly-prized fishery target and cultural resource, and the humphead wrasse is among the most prized in the live reef-fish trade and has considerable cultural value (Muñoz et al., 2014; Sadovy et al., 2003). Both fish species are particularly sensitive to fishing pressure, and due to their population decline, humphead wrasse and bumphead parrotfish are IUCN Red Listed as Endangered and Vulnerable, respectively. They are also species of concern for the National Marine Fisheries Service.

Bumphead parrotfish (Bolbometopon muricatum) at Wake Atoll, Photo: NOAA Fisheries/Kevin Lino.



Humphead wrasse and bumphead parrotfish at Wake Atoll, Photo: NOAA Fisheries/Kevin Lino.

Figure 30. Number of individual humphead wrasse and bumphead parrotfish observed per fore-reef towed-diver transect segment from 2005 to 2014 at Wake Atoll. Bubble sizes represent the number of sightings and are colored by the representative year.

Among the PRIMNM, Wake is notable for having a relatively low large fish biomass; however, the sightings of these two large species of concern are more common at Wake. The total number of sightings of humphead wrasse recorded on transect per year was 67 (2005), 34 (2007), 18 (2009), 24 (2011), and 3 (2014) (Fig. 30 left). The total number of sightings of bumphead parrotfish sighted on transect per year was 51 (2005), 62 (2007), 221 (2009), 40 (2011), and 5 (2014) (Fig. 30 right). Both humphead and bumphead abundance were lower in 2014 than in other years, but it is not clear whether those represent real population declines or are instead caused by some short-term phenomena at the time of the 2014 surveys. Any decline of bumpheads at Wake would be substantial, as Wake densities have been higher than at other U.S. Pacific Islands. Specifically, mean abundance of bumphead parrotfish at Wake over the five survey years was 2.8 individuals per hectare, whereas their abundance at the other 5 U.S. Pacific islands recorded by NRCMP surveys averaged less than 0.1 individuals per hectare over the same time period.

In addition to possible temporal trends, there are also spatial patterns in bumphead parrotfish abundance. Over several years of surveys, the CREP team has observed bumphead parrotfish concentrated around the northwest corner of the atoll, which is thought to be the spawning aggregation area for this species (Muñoz et al., 2014). These spatial observations helped identify an area with high bumphead abundance, which allowed researchers to study mating and spawning aggregation behaviors and develop crucial baselines of population density, sex ratio composition, and productivity of a spawning aggregation in a place where bumphead parrotfish are not exploited.

CONCLUSIONS

Standardized ecological and climatological monitoring surveys conducted by CREP are focused on long-term trends of ecosystem health and status across the entire Pacific. Overall, the Pacific Remote Islands Marine National Monument fare well when compared to other islands in the U.S. Pacific, often having both higher coral cover and higher fish biomass. The reef ecosystems are largely intact due to their remote location and relative absence of human presence. While these islands are not subjected to direct human pressures such as land-based sedimentation or fishing, they are significantly affected by climate change and recurring climate patterns such as El Niño-Southern Oscillation. Climate change, especially rising ocean temperatures, remains a major threat to the Monument and may impact the health of the reef ecosystems. To track possible changes in the future, it is necessary for CREP to continue their Pacific-wide monitoring program. Additionally, marine debris and invasive species are a growing threat to these areas, despite their remote location. Thus, monitoring these risks may help to inform management in the future.

School of sea chubs at Wake Atoll, Photo: NOAA Fisheries/Paula Ayotte.

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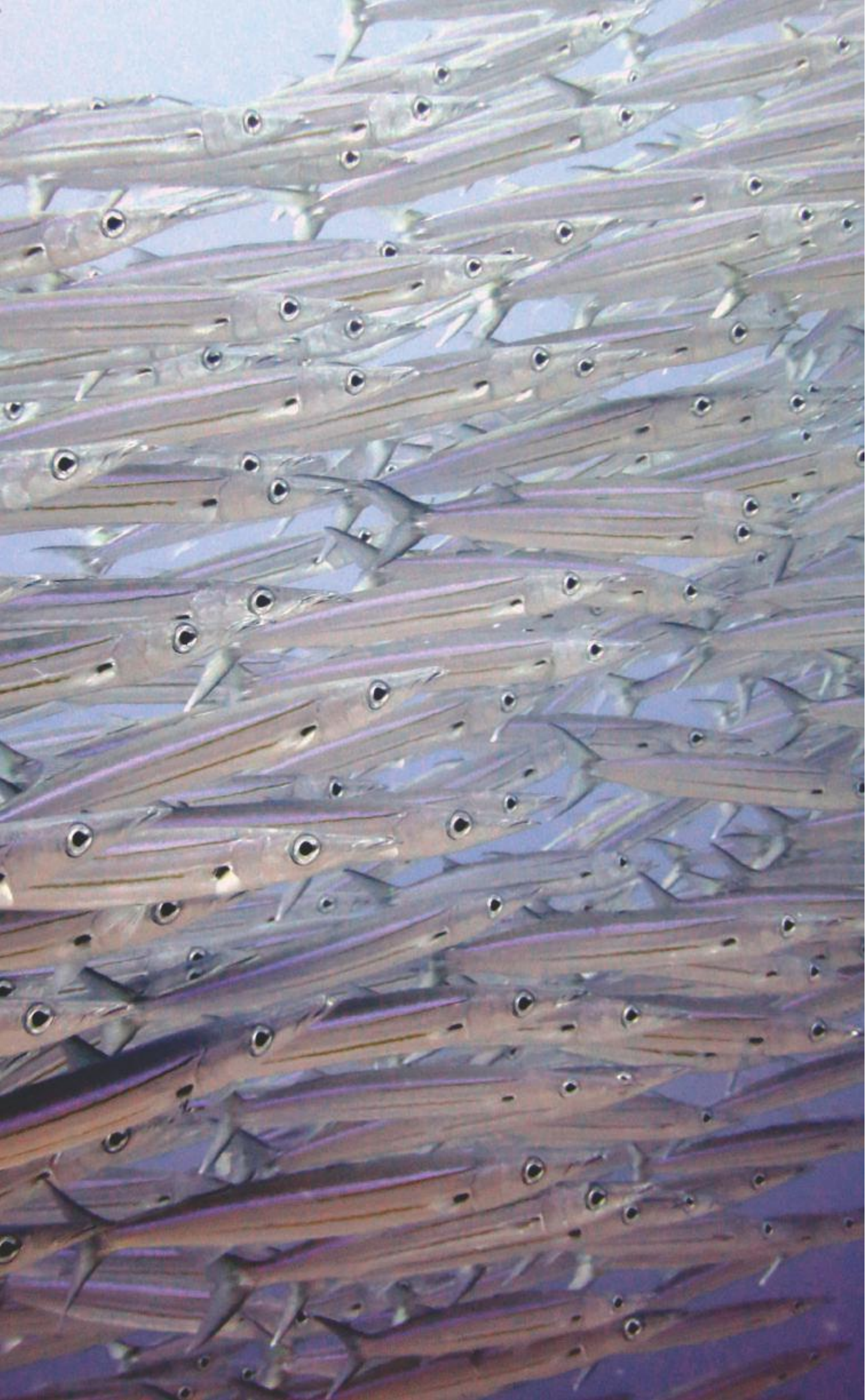
Pencil urchin at Kingman Reef, Photo: NOAA Fisheries/Charles Young.



ACRONYMS

ARMS	Autonomous Reef Monitoring Structure
AVHRR	Advanced Very High Resolution Radiometer
BMU	Bioerosion Monitoring Unit
CAU	Calcification Accretion Unit
CCA	crustose coralline algae
CREP	Coral Reef Ecosystem Program
CTD	conductivity, temperature and depth
DHW	degree heating weeks
IUCN	International Union for Conservation of Nature
JACADS	Johnston Atoll Chemical Agent Disposal System
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	marine protected area
NCEAS	National Center of Ecological Analysis and Synthesis
NCRMP	National Coral Reef Monitoring Program
NOAA	National Oceanic and Atmospheric Administration
Pacific RAMP	Pacific Reef Assessment and Monitoring Program
PIFSC	Pacific Islands Fisheries Science Center
POES	Polar Operational Environmental Satellites
PRIMNM	Pacific Remote Islands Marine National Monument
REA	Rapid Ecological Assessment
SPC	stationary-point-count method
SST	sea surface temperature
StRS	depth-stratified random sampling
TOAD	Tethered Optical Assessment Device
USCRTF	U.S. Coral Reef Task Force

Heller's barracuda (Sphyraena helleri) at Jarvis Island,
Photo: NOAA Fisheries/Kevin Lino.

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