FEDERATED STATES OF MICRONESIA

Nearshore marine resources across the remote FSM atolls

Scientific report from the National Geographic Pristine Seas & Blue Prosperity Micronesia Expedition

MAY 2024

NATIONAL GEOGRAPHIC
PRISTINE SEAS

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INTRODUCTION

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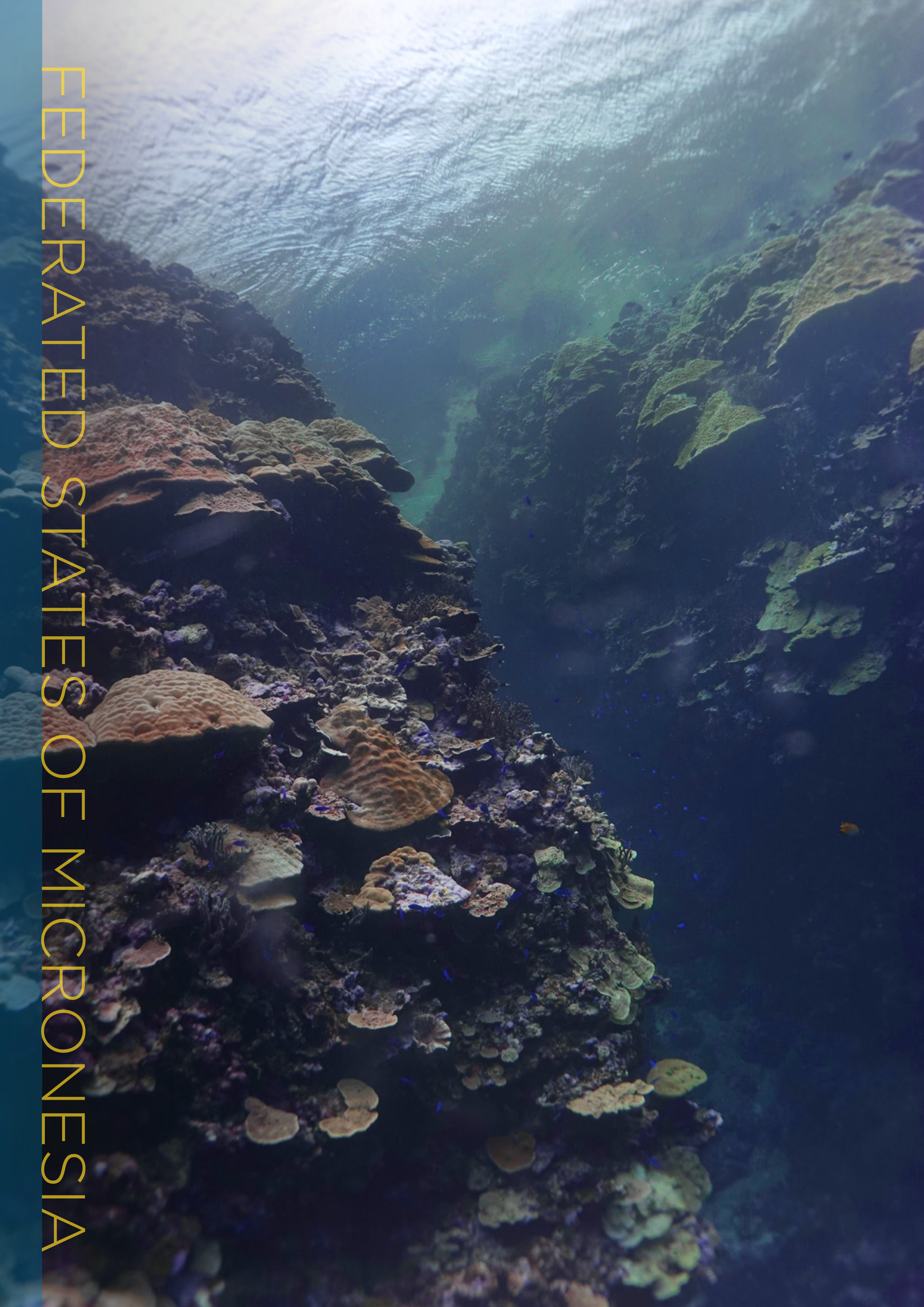
The Federated States of Micronesia (FSM) exclusive economic zone accounts for nearly 3 million km^2 of the western Pacific Ocean despite having only 701 km^2 of land. These extensive ocean resources are a consequence of 607 FSM islands spread across a huge portion of the tropical Pacific (1° to 10° N, 138° to 162° E). FSM sells the rights for foreign fleets to fish in their EEZ and the associated income represents a large portion of their economy, estimated at 72 million USD in 2018. These funds support numerous governmental infrastructure projects including transportation across the sparsely inhabited outer atolls. Despite the significant offshore resources, it is the nearshore resources associated with the 607 FSM islands that support a significant proportion of daily subsistence needs and growing artisanal fisheries sectors across the country. Nearshore resources also form a strong basis for the FSM culture, including traditional forms of navigation across the region that have attracted global attention. Thus, while offshore resources may provide more income to the FSM economy, nearshore resources that are the subject of this report have a greater influence on daily FSM livelihoods.

Extensive programs have evolved to document the status and trends of nearshore coral reef and fisheries resources across the main populated FSM islands over the past two decades (timeline graphic, page 14). In general, declines in marine resources have been documented due to growing fisheries exploitation, climate change, and watershed pollution associated with the few urban centers. In response, an evolving portfolio of management strategies that blends traditional and modern approaches has emerged and continues to gain success on the main islands. In contrast, little is known about the status of marine resources in the remote outer atolls. The limited knowledge in the face of growing exploitation and climate change formed the basis for the Blue Prosperity Micronesia and National Geographic Pristine Seas expedition. This collaboration provided a unique opportunity to examine the status of nearshore marine resources across the remote FSM atolls and build a foundation for management to evolve.

SOME CRITICAL QUESTIONS ADDRESSED INCLUDE:

- What is the status of marine resources across the FSM outer atolls in comparison to main FSM islands and other Micronesian atolls?
- What are the primary stressors influencing the status of fisheries resources across the remote FSM atolls?
- What level(s) of government and types of policies can best address the identified marine resource management needs?
- Does the remote nature of the FSM outer atolls provide protection from climate change disturbance events?
- Are there any unique resources that have not previously been documented that deserve greater attention and protection?


PRISTINE SEAS
APEX


FEDERATED STATES OF MICRONESIA

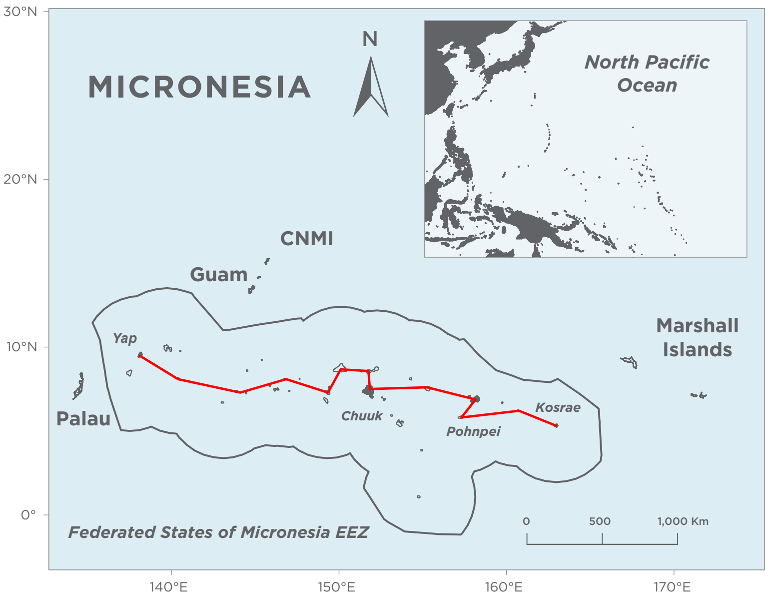
FEDERATED STATES **OF MICRONESIA**

HISTORY

Ancestors of modern Micronesians settled the islands of the Federated States of Micronesia (FSM) an estimated 2,000 to 4,000 years ago.[1] Chief-based systems of governance that included land-and-reef tenure evolved along with traditional forms of navigation that connected the islands of FSM and broader Micronesia.[2,3] European explorers first reached the FSM in the sixteenth century when Spain and Portugal colonized the region and increased religious and economic centers.[4] In the late 1800s, Germany purchased the islands from Spain following the Spanish-American War and colonized FSM for a brief period. Copra, or coconut oils, were one main resource exploited during the German period, but accounts of trade for whale oils, turtle shells, sea cucumbers, and rope made from coconut fibers were noted by influential explorers such as David O'Keefe.[5] Japan conquered the islands during World War I and focused trade on copra, sugarcane, and trochus shells that were seeded to the reefs. Japanese occupancy lasted until World War II when many notorious battles were fought with the Americans in places like Truk (Chuuk) Lagoon.[6] Finally, following WWII, the Americans administered the FSM as part of the Trust Territory of the Pacific Islands until 1979 when the FSM became an independent nation with a formalized constitution.[7] Despite this extensive history of foreign occupancy, FSM has maintained a strong cultural identity that is tied with traditional knowledge and reef tenure systems that are being blended with modern forms of government and resource management.

FIGURE 1.

Map of the north Pacific Ocean and the FSM. The FSM exclusive economic zone is overlaid on the map. The red line depicts the path of the recent expedition surveying the outer FSM atolls starting in Kosrae and ending in Yap.



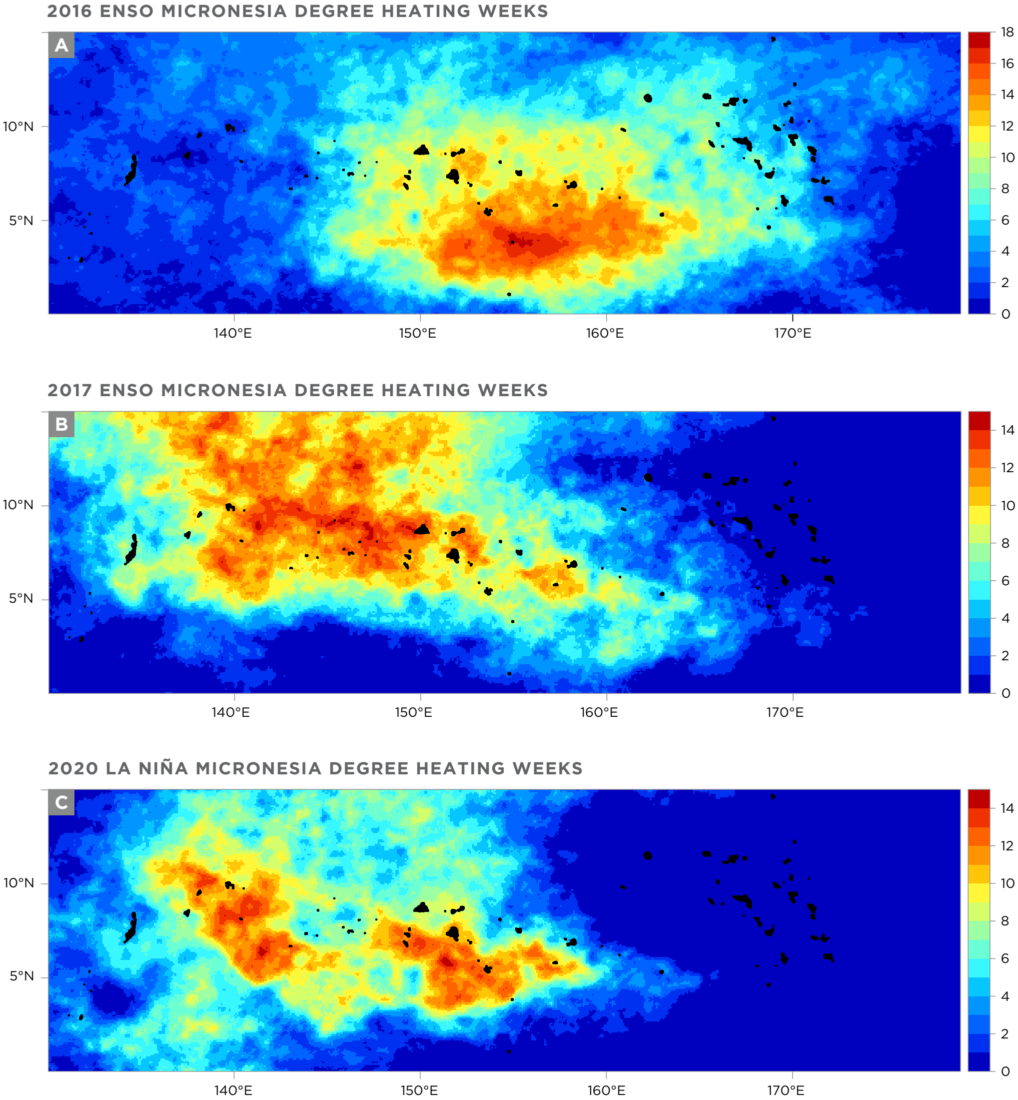
ENVIRONMENTAL SETTING

The four states that comprise the FSM account for a large part of tropical western Pacific ocean (1 to 10 degrees N, 138 to 162 degrees E). This represents over 2,700 kilometers (km) in linear distance crossing the states of Kosrae, Pohnpei, Chuuk, and Yap (east to west, respectively) (Figure 1). In terms of area, the FSM exclusive economic zone accounts for nearly 3 million km^2 of the western Pacific Ocean, representing the 14th largest in the world, despite having only 701 km^2 of land. While there are 607 islands across the FSM, only 65 are inhabited. Human populations are centered on the four main islands of each state which have volcanic origins, significant agriculture, extensive freshwater resources, and diverse coral-reef habitats exist. In contrast, the outer atolls have limited amounts of land and often limited freshwater resources, however, extensive reef structures exist.
An estimated 113,000 people live in FSM spread across the main islands of Yap (7,300), Chuuk (36,000), Pohnpei (36,000), Kosrae (6,700), and the sparse but significant populations on the numerous outer atolls (27,000).

Northeast trade winds prevail from December through April, with periods of weaker winds and doldrums from May to November. High amounts of rainfall have been recorded on the main FSM islands, especially in Kosrae and Pohnpei that average 500 cm of rainfall per year.[8] Chuuk and Yap are also wet and average approximately 350 cm and 300 cm of rainfall per year, respectively. The main oceanographic currents in FSM are the North Equatorial Current that runs from the Americas to Asia across the tropics between 5 to 15 N, and the North Equatorial Counter Current that runs in the opposite direction and below at 3 to 10 N. Thus, the FSM EEZ resides within a productive upwelling zone associated with these contrasting oceanographic currents that provide for extensive offshore fisheries.[9]

FIGURE 2.

Map of Micronesia highlighting the heat stress that occurred in 2016 (A), 2017 (B), and 2020 (C) in association with a large El Niño Southern Oscillation event (ENSO) and the subsequent corrections of the ocean. Map colors show degree heating weeks (DHW) that represent how many weeks temperatures have exceeded historical maximum monthly mean values. DHW above 4 provide a warning that coral bleaching is likely to occur, DHW above 8 are usually associated with bleaching. FSM experienced three heat stress events recently in 2016, 2017, and again in 2020 that were focused on different parts of the country. There is currently a large ENSO event that started in late 2023 and expected to bring heat stress to Micronesia again in the summer or fall of 2024.



CLIMATE CHANGE

As climate change increases its fingerprint across the tropical Pacific and FSM, many negative consequences have emerged.[10] Rising sea levels and storm surges erode the shorelines and saltwater intrusion threatens crops such as taro along with freshwater resources. Periods of heavy rainfall and drought are now more pronounced. Together these changes threaten agriculture throughout the FSM, but especially on the low-lying outer atolls. Perhaps most important to FSM is the heating of the oceans with climate change (Figure 2A–C). The growing frequency and magnitude of El Niño Southern Oscillation events (ENSO) disrupt offshore fisheries yields as currents modulate, cause nearshore coral bleaching as temperatures rise, and lead to higher abundances of Crown-of-Thorn starfish (COTS) that prey on corals as oceanic productivity becomes more variable. FSM is directly exposed to ENSO events because the warm water that builds up in the eastern Pacific Ocean spreads westward across the equatorial North Pacific as the global climate cycle tries to correct itself. Past studies have confirmed that the initial El Niño phase of ENSO events bring cooler nutrient-rich waters to the FSM while the eastern Pacific heats up, which in turn leads to higher than expected abundances of COTS that impact reefs.[11] Subsequently, the La Niña phase of ENSO brings unusually warm ocean waters across the FSM as evidenced by extensive coral bleaching and mortality in 2016 and 2017 (up to 90% in many locations). While these are the general patterns associated with climate change in the FSM, not all islands and atolls are impacted equally by climate-change-related disturbance events.

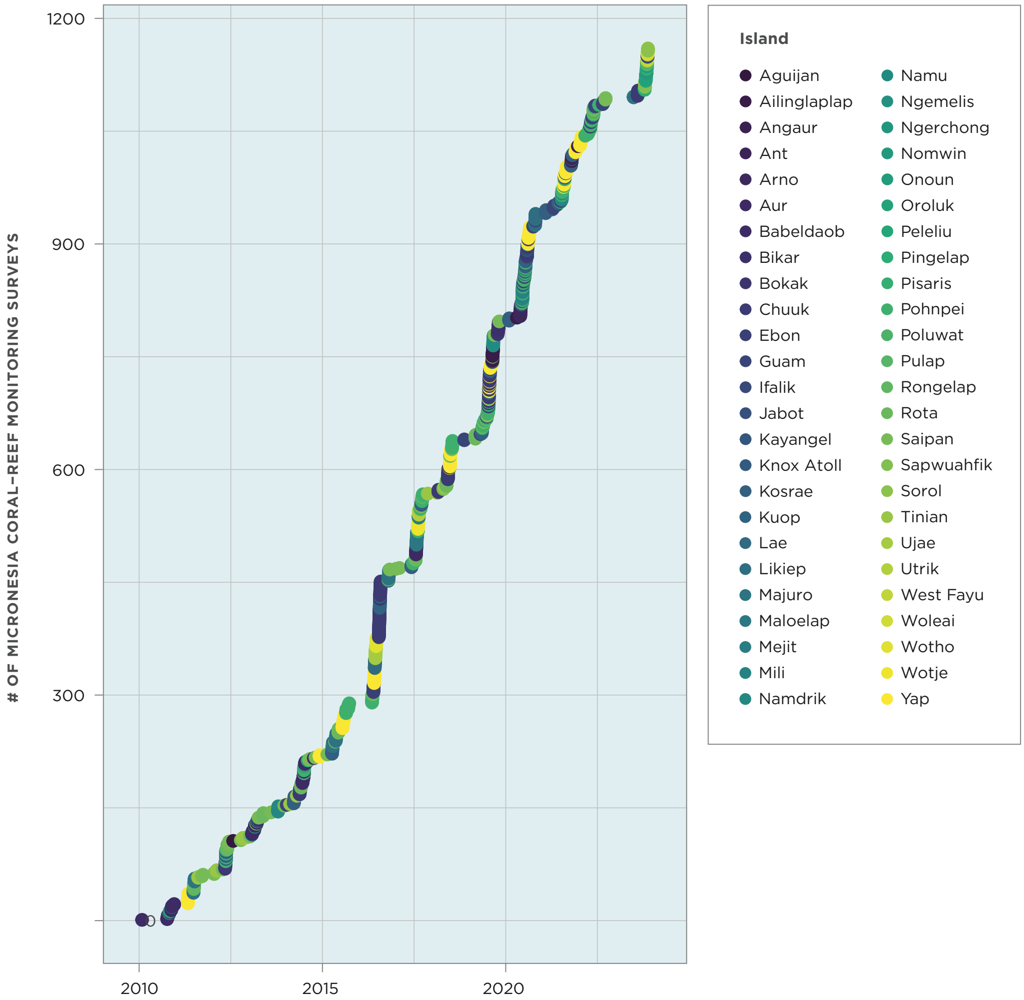
Within FSM, there have been significant spatial differences in the frequency and magnitude of heat stress to the oceans. The recent 2015 to 2017 ENSO event caused heat stress to the FSM ocean, however, many remote atolls near Chuuk experienced up to three times the amount of heat stress compared to remote Yap atolls (Figure 2A–C). In turn, the heat stress leads to coral mortality that we documented in our surveys and also creates unstable fish biomass as the reef cycles through death and recovery. Unfortunately, the frequency and magnitude of climate disturbances continues to rise, and FSM will soon be exposed to the next ENSO event that began in late 2023.

MICRONESIA CORAL-REEF MONITORING

The Micronesia Coral-Reef Monitoring (MCRM) program was established in 2010 to provide standardized datasets that track the status of marine resources across the region in the face of growing exploitation, watershed development, and climate change (https://micronesiareefmonitoring.com/). Scientists from many nations and organizations joined together to define a minimum set of MCRM survey protocols used to collect data. Over the past decade, the MCRM has provided numerous scientific assessments describing the trends in marine resources with respect to localized stressors and climate change. The results include formal published reports and consumable outreach that have guided the development and assessment of numerous management policies. Through the fortunate collaboration between the MCRM, National Geographic Pristine Seas (NGPS) and Blue Prosperity Micronesia (BPM), efforts were expanded across remote atolls that have been previously inaccessible. Cumulatively, the MCRM has now completed over 1,000 surveys across Micronesia that include over 500,000 fish measurements, nearly 1 million benthic data points assessed, over 10,000 sea cucumbers and trochus recorded, and over 300,000 coral colonies identified and measured (Figure 3). This data-rich foundation for the MCRM provides desirable regional benchmarks to interpret the outcomes of recent work conducted in the remote FSM atolls.

FIGURE 3.

Graph showing growth of the regional Micronesia Coral-Reef Monitoring program. Between 2010 and present, over 1,000 surveys have been conducted across over 50 islands and atolls by more than 20 collaborating organizations. These data represent an essential component of marine resources management and evaluation.



FSM TIMELINE

2006

Political leaders of FSM, Palau, Marshall Islands, Guam, and the Commonwealth of the Northern Mariana Islands established the Micronesia Challenge to effectively conserve 30% of nearshore marine resources and 20% terrestrial resources by 2020.

2006-09

Rapid ecological assessments conducted across the main islands and nearby remote atolls to document marine resources, identify potential marine protected areas, and set the stage for long-term monitoring.

2009-10

Micronesia Coral-Reef Monitoring (MCRM) program and regional protocols established for consistent monitoring, databases, and analytics.

2010-15

Extensive Crown-of-Thorn Starfish (COTS) outbreaks across many reefs in Micronesia. COTS control efforts evolve and include both governmental and non-governmental led efforts.

2012-14

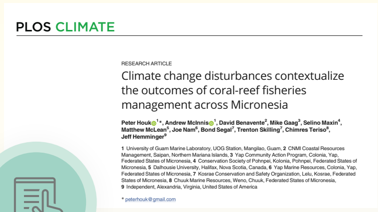
First no-take Marine Protected Areas (MPA) established across FSM main islands. Grouper spawning protection was established in Pohnpei first, then Chuuk a few years later. Regulations established for key target species in Pohnpei with extensive fishing histories.

2015

First Micronesia Challenge (MC) assessment revealed that no FSM state is above the desired 30% effective conservation threshold and nearshore fishing pressure and land-based pollution are the primary and secondary sources of stress, respectively.

2016–17

First major El Niño Southern Oscillation (ENSO) event documented by MCRM surveys on the main FSM islands. ENSO caused significant coral mortality on many reefs (30% to 90%), however, impacts varied spatially across FSM.



PLOS CLIMATE

RESEARCH ARTICLE

Climate change disturbances contextualize the outcomes of coral-reef fisheries management across Micronesia

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2019

MCRM revealed the importance of nearshore fisheries management policies for coral-reef recovery following ENSO disturbances. Enforced MPA and grouper spawning protection as well as species-based regulations all enhanced fish populations for extended periods of time following bleaching, facilitating reef recovery.

2020

Political leaders agreed to strengthen and extend the MC. Leaders set new conservation goals that require effective management of 50% of marine resources and 30% of terrestrial resources by 2030.

2022–23

Blue Prosperity Micronesia and National Geographic Pristine Seas partner with FSM governments and MCRM to conduct extensive nearshore marine assessments of both main islands and remote atolls never surveyed before.

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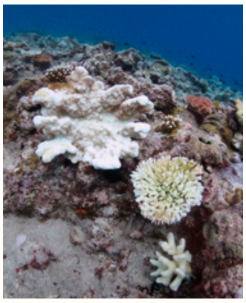
Blue Prosperity Micronesia



2023–

New ENSO event emerges that will likely impact FSM reefs in 2024.

2024

METHODS

METHODS

FSM SURVEY ATOLLS AND LOCATIONS

FSM atolls were selected as potential survey locations based upon a range of factors, including: 1) atoll size in terms of reef and land area, 2) human population, 3) distance to main FSM island population center, and 4) known management status resource use. Proposed atolls were presented to the FSM governmental leadership and refined based upon local needs to include Pingelap, Sapwuahfik, Oroluk, Nomwin, Pisaris, Onoun, Pulap, Poluwat, West Fayu, Ifalik, Woleai, and Sorol (Figure 4). Survey sites were then established to provide a representation of each atoll based upon: 1) reef area and major habitats, 2) wave exposure, and 3) presence/absence of site-based management, typically no-take MPA (Figure 5A–L). Trained observers from the MCRM collected data describing the abundances and sizes of fish, corals, benthic substrates, and macroinvertebrates such as sea cucumbers described below (Figure 6).

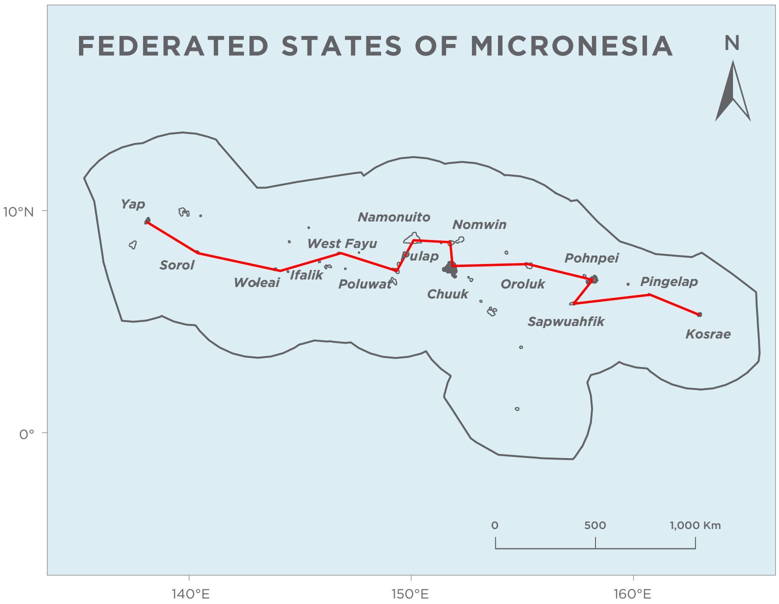
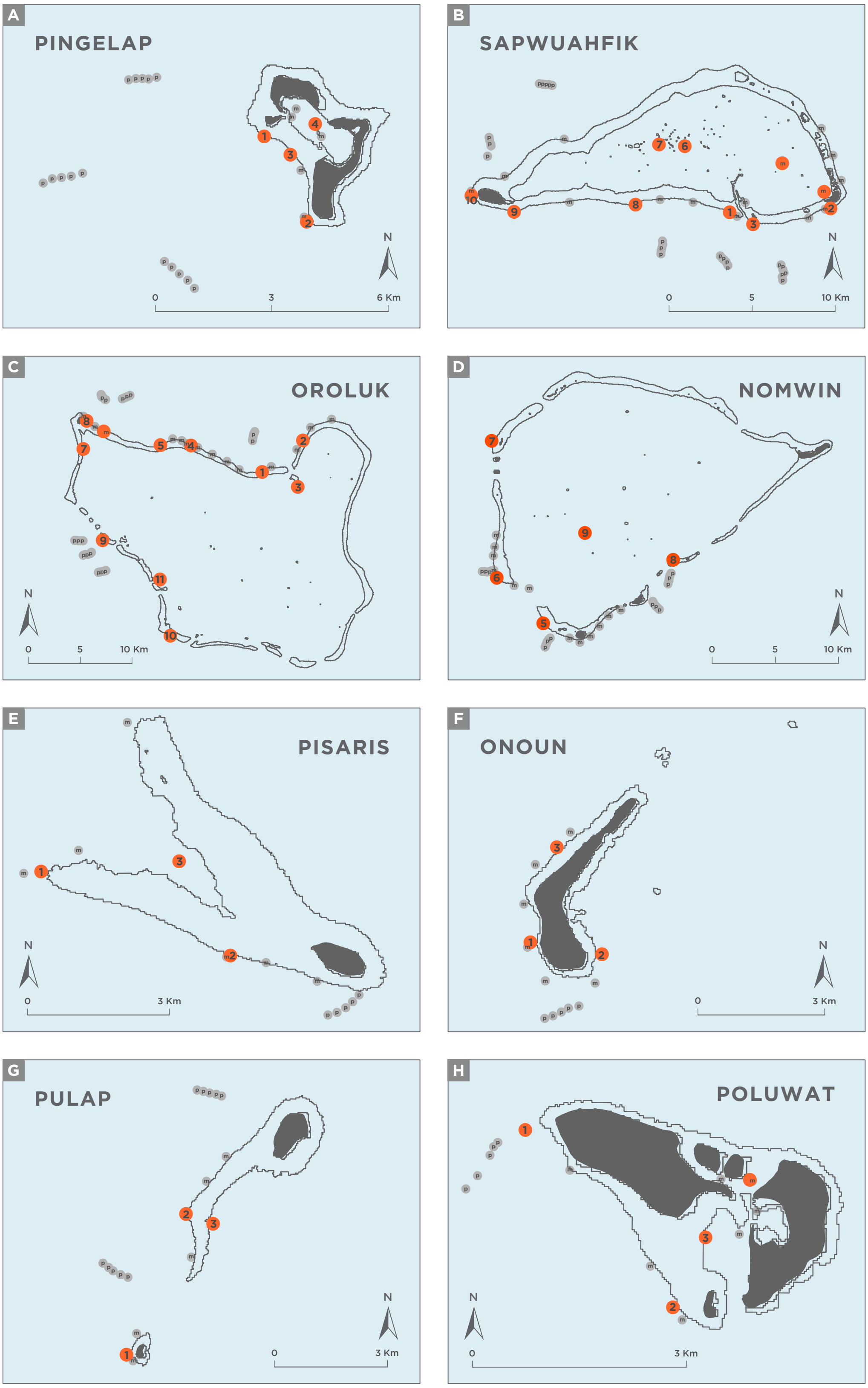


FIGURE 4.

Map showing the FSM and the expedition route.

FIGURE 5.

Maps (A–L) of individual FSM atolls and survey locations. Red dots with numbers show the locations of MCRM surveys, grey dots indicate where baited remote underwater cameras were used to observe reef associated fishes (m) and pelagic fish (p).



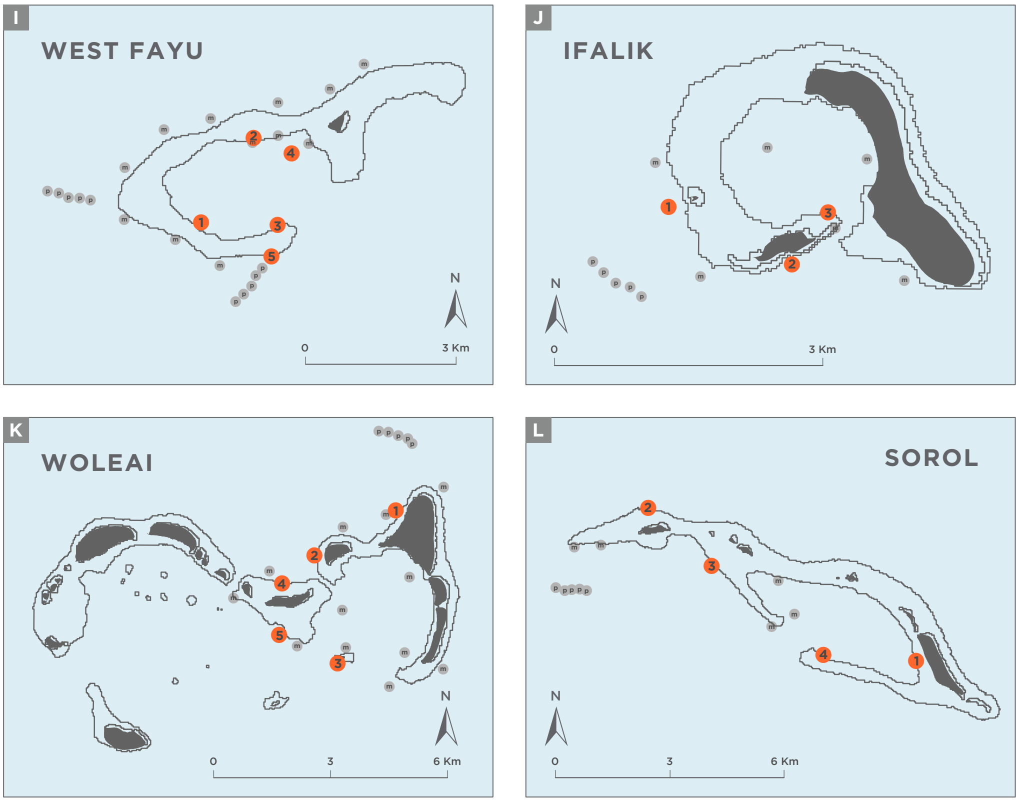
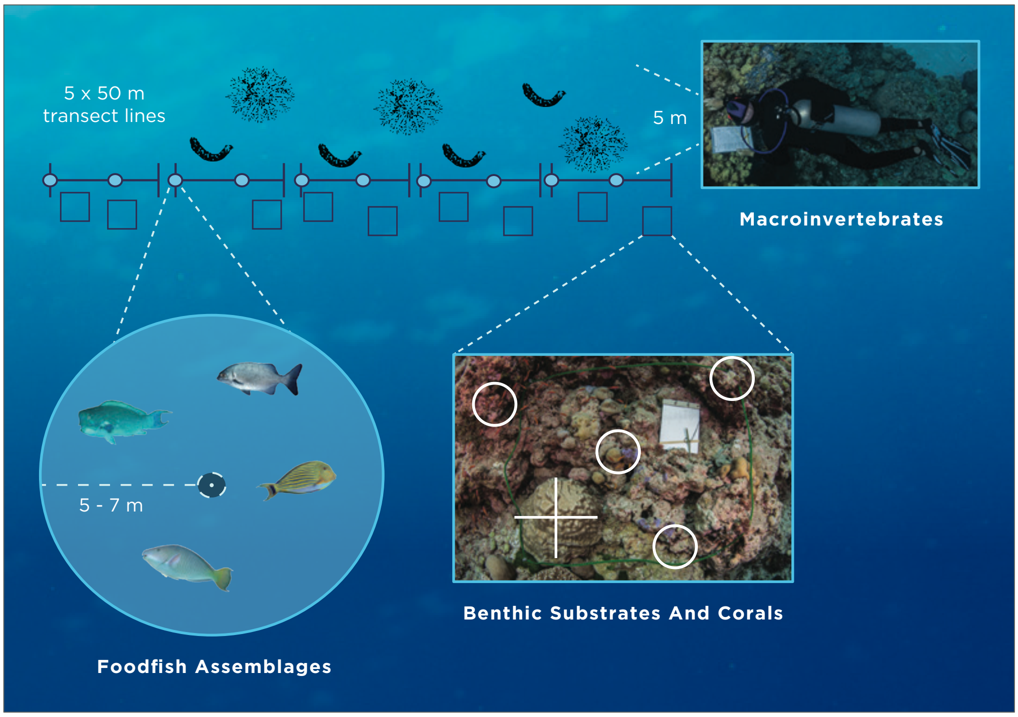


FIGURE 6.

Standardized methods used by the MCRM to collect data on the shallow reefs across Micronesia.



MCRM PROTOCOLS

Survey protocols were selected to provide high statistical power capable of detecting change at both the site and island level, inside and outside of any management regimes.[12] Survey events were initiated by laying out 5 x 50 m transect lines at a common depth contour of 8 m for outer reefs and 5 m for inner reefs.

Fish

Fish observers recorded all fish within a 5 to 6 m radius for a 3 minute period at each of 12 stations equally spaced along the 5 x 50 m transect lines. A second observer recorded the species names and abundances of all food fish that were larger than 40 cm, including sharks during the same SPC timeframes. Observations of larger fish were not restricted to the 5 to 6 m radius but extended as far as the observer could see. No sizes of fish are estimated for larger fish. Foodfish included the acanthurids, scarids, serranids, carangids, labrids, lethrinids, lutjanids, balistids, kyphosids, mullids, holocentrids, and sharks.

Benthic Substrates

Benthic substrates were examined using an underwater camera mounted to a stick or photoquadrat apparatus. The height of the camera was standardized so that 0.5 m^2 of reef was covered by each photograph. Photos were taken at every 1 m interval (50 photographs per transect). Photographs were then loaded into CoralNet for analysis of percent cover for corals (genus or higher), macroalgae (genus or higher, 2 cm or larger), turf algae, and other forms of calcifying and non-calcifying substrates.

Corals

Coral assemblages were examined using ten 1 m^2 quadrats placed at equal intervals along the transect lines. Within each quadrat, all coral colonies with their center points inside the quadrat boundary were identified to the species level and measured for the maximum diameter (x) and the diameter perpendicular to the maximum (y).

Macroinvertebrates

The abundance of edible and functional macroinvertebrates were monitoring using belt transects that extend 2.5 m wide from each side of the transect line. These macroinvertebrates included edible and collectable shells, sea cucumbers, sea urchins, clams, Crown-of-Thorns starfish, other conspicuous starfish, and any other locally-important reef invertebrates of interest to local communities. Surveyors recorded all macroinvertebrates observed within each transect.

NGPS PROTOCOLS

In addition to the coral-reef surveys conducted by MCRM, collaboration with NGPS provided additional data derived from baited remote underwater visual assessments (BRUVS) that were used to assess the deeper bottom fish and offshore pelagic fish. BRUVS provide metrics on the identity and sizes of fishes and other marine wildlife. Bird observations were recorded while deploying the BRUVS and from opportunistic land-based transects.

PELAGIC BRUVS

We collected video footage using mid-water stereo-Baited Remote Underwater Video Systems (BRUVS). BRUVS were used as they provide standardised metrics on pelagic wildlife assemblages (Bouchet et al., 2018). The individual rig configuration consists of a carbon fibre basebar with two GoPro Hero 9 cameras positioned 80 cm apart, directed at a convergent angle of 8 degrees towards a bait canister, an upright bar with 2.5 kg weight on the base, and a 10 m line with inbuilt elastic and buoy for stabilisation and a surface float. Each rig was baited with 1 kg of crushed oily baitfish per deployment. Rigs were deployed during daylight hours at a depth of 10 m for a minimum of 120 minutes and set in a longline formation of five rigs (hereon referred to as a "set") with each rig on a set separated by 200 m of line. A flag with a VHF transmitter was used to assist in the retrieval of the rigs. Rigs were deployed in the epipelagic zone to sample the wide range of taxa present in this environment and allow adequate natural light for identification of animals. Our sampling consisted of 135 deployments at 27 sites at 11 atolls across three states of the FSM. We sampled Ngatik, Pingelap, and Oroluk in PohnPei State; Nomwin, Namonuito, Pulap, and Pulowat in Chuuk state; and West Fayu, Ifalik, Woleai, and Sorol in Yap State.

We processed the video footage to generate taxonomic identifications, relative abundance, and size estimates. All video was processed using standard procedures with the software Event Measure (www.seaGIS.com.au; Cappo et al., 2006).We identified each individual animal to the lowest possible taxonomic resolution, recorded the maximum number of each taxa in a single video frame (MaxN) as our relative abundance measure, and made length estimates based on photogrammetric measurements of fork length (Harvey & Shortis, 1995). We calculated the weight of measured fishes using length-weight relationships on FishBase. We calculated biomass of fish on each deployment by multiplying the MaxN of each species by the mean weight. We used the software package PRIMER 7 with PERMANOVA+ add-on for multivariate analyses.

SEABIRD AND LAND SURVEYS

All birds and mammals observed within a 100 m radius of the boat/observer during each survey transect were recorded. The distance and duration of each transect were recorded to estimate abundances and care was taken not to double count individuals following or circling the vessel. A daily log of additional species observed off transect was also kept. From these raw data, the mean number of each species per hour of sampling effort was examined across the FSM atolls.

DEEP SEA CAMERA SYSTEMS

To explore the deep sea environment of the Federated States of Micronesia, we used baited remote deep sea camera systems. The National Geographic deep sea camera systems are autonomous benthic landers with high definition cameras

(Sony Handycam FDR-AX33 4K Ultra-High Definition video with a 20.6 megapixel still image capability) in a 33 cm diameter borosilicate glass sphere that is rated to ~6,000 m depth. Lighting at depth is achieved through a high-intensity LED array. Viewing area per frame for the cameras is ca. 17 m2, depending on the steepness of the slope where the camera lands. Cameras are baited with 1 kg of oily fish, in this case mackerel. The systems are positively buoyant, and are weighted with a 10 kg anchor system. At the programmed mission end, the camera system is released from the anchor system by burn wire, activated using onboard battery voltage, and the camera system returns to the surface. The system is then located for recovery by communication of an onboard VHF transmitter and locating antennae, with backup location via satellite communication system and an Iridium GPS beacon.

At the first three and last islands (Pingelap, Sapwuahfik, Oroluk, Sorol), cameras were programmed for deployments of 14 hrs, with lights and camera cycling on and off over the duration of the mission, for 1 minute on and 2.5 mins off for a total recording time of 4 hours for each deployment. At the other four islands (Nomwin, Pulap, West Fayu, Woleai), cameras were programmed for deployments of 6 hrs, for operational logistics purposes, with lights and camera cycling on and off over the duration of the mission, for 1 minute on and 1 minute off for a total recording time of 3 hours for each deployment. Locations were selected based on target depth using available bathymetry, with a minimum of 1000 m horizontal distance between deployment locations.

DATA ANALYSES AND MC SCORECARD

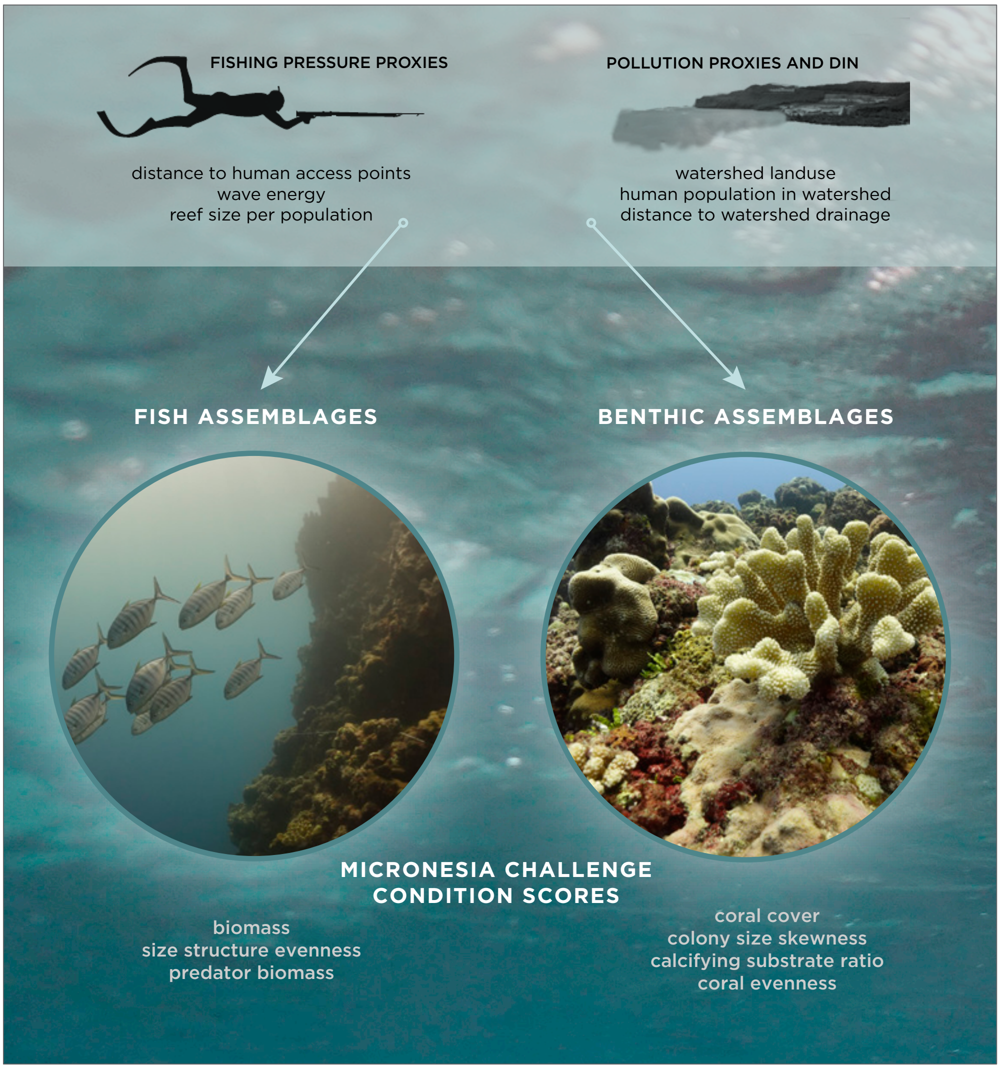
Data were analyzed to produce a series of graphs presented below. Fish data were converted from length to weight using coefficients derived from fish market surveys across Micronesia.[13-15] The biomass and size structure of fish assemblages were presented for the FSM outer atolls, FSM main islands, and other remote atolls in the Marshall Islands that have limited human presence. These locations were selected to provide a useful perspective for understanding the status of fisheries resources in the remote FSM atolls. Coral and benthic substrate percent cover was estimated by overlaying 5 random points on each photograph and assigning each point to predefined categories noted above. Percent cover data were used to understand the overall status of benthic and coral substrates. In addition, coral colony data were used to better understand the distribution of species richness and coral colony sizes. Last, macroinvertebrate data were used to evaluate the abundances of valuable sea cucumber and clam resources across the region.

We next evaluated the condition of the marine resource using the MC scorecard that was previously developed to depict the overall condition of fish and coral resources beyond percent cover or biomass alone.[16] Briefly, the MC scorecard process selected a series of weakly correlated metrics that together depict condition

(Figure 7). Past studies highlight the nature and utility of this condition metric.[16-18] MC condition scores were examined with respect to several environmental factors. Environmental factors included: human population, reef area, distances from humans, and site-based wave energy derived from 10 year wind speed and direction data.

FIGURE 7.

Infographic showing how the condition of fish and benthic assemblages were calculated. The individual metrics on the bottom were standardized and combined to calculate the condition scores. These metrics were selected by a regional team of scientists among a list of over 30 candidate metrics. Environmental factors noted on the top represent drivers of condition scores that were used to understand the spatial patterns of reef condition across the FSM and support management discussions.



RESULTS

RESULTS

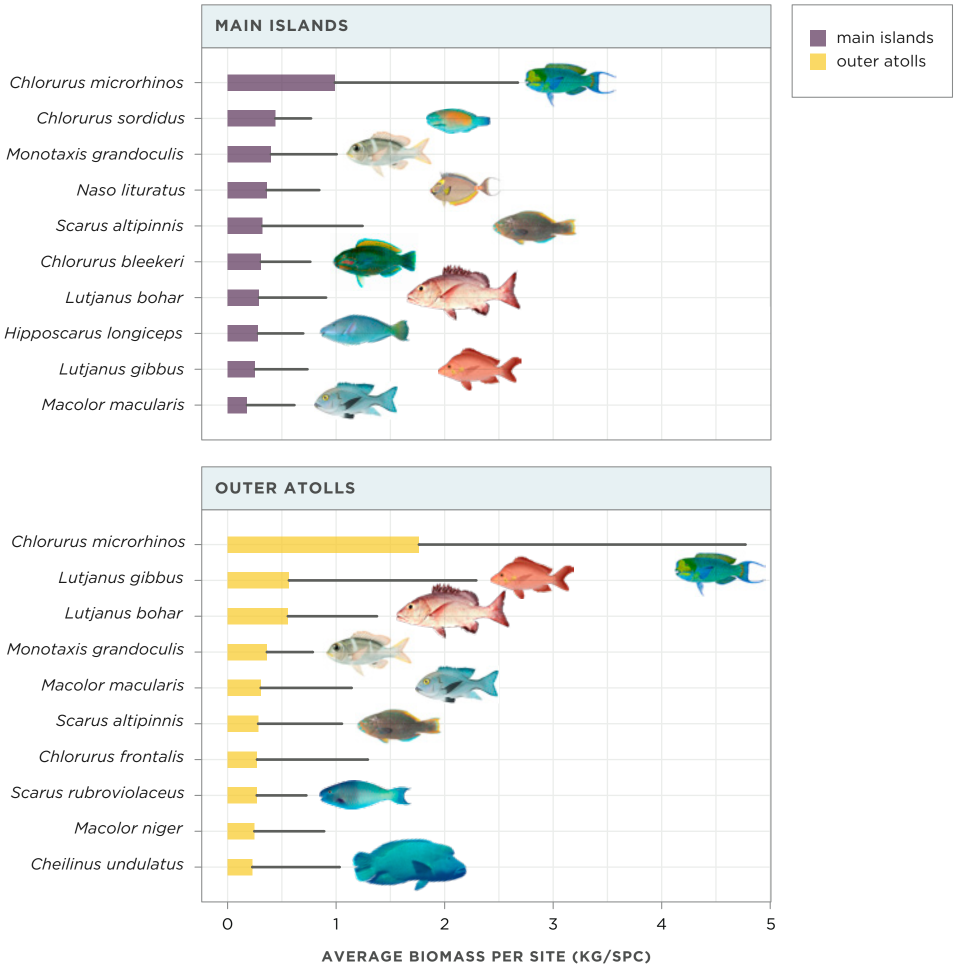
FISH ASSEMBLAGES

While over 100 species of foodfish were observed while conducting surveys in the FSM outer atolls, the top 10 species accounted for 50% of the biomass recorded across the FSM main islands and 65% of the biomass recorded across the FSM atolls (Figure 8). The top species was the iconic blue Pacific steephead parrotfish (*Chlorurus microrhinos*). However, other top species included a suite of large and small parrotfishes, snappers and the dominant big-eye emperor fish (*Monotaxis grandoculis*). These top species represented a mixture of body sizes and trophic levels, and notably for outer atolls, the Napolean wrasse was included among the top species encountered (*Cheilinus undulatus*). Together, these species of foodfish have influential ecological roles in the coral-reef ecosystem.

Overall fish biomass across the FSM atolls was similar to FSM main islands and lower than the remote atolls in the Republic of the Marshall Islands (RMI) that were used as a reference given very limited human presence (Figure 9). FSM trends were similar for both inner lagoon and outer reefs. Uninhabited FSM atolls, including Oroluk, Sorol, and West Fayu, had greatest fish biomass with an even distribution across major herbivores, secondary consumers, and predators. These atolls have less human access due to their remoteness from both main islands and other atolls. Further, only subsistence fishing has been allowed on Oroluk since the mid 1990's when it became a conservation area designated by law (State Law 2L-12-80). Thus, while fish biomass was highest among these FSM outer atolls, the data suggest that intermittent fishing

FIGURE 8.

Top 10 species observed in MCRM surveys for the main FSM islands and outer atolls. While species were similar, there was a greater abundance of smaller-bodied species on the main islands compared to the outer atolls. These 10 species accounted for over 50% of the total fish biomass observed on the main islands and over 60% of the biomass observed on the outer atolls.

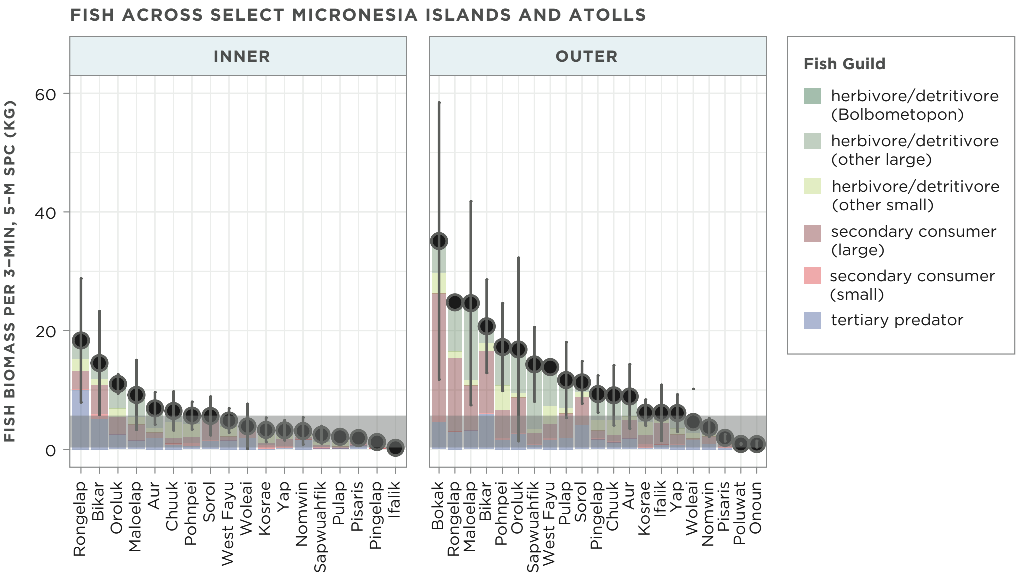


occurs. Meanwhile, several atolls had notably low fish biomass including Onoun, Poluwat, Pisaris, Nomwin, and non-protected reefs around Woleai. All of these atolls had average site-based fish biomass below the 5–6 kg/SPC threshold that was previously associated with reef recovery following climate-induced disturbance events (grey shaded region, Figure 9). Further, inner reefs consistently had lower biomass compared to outer reefs. Low biomass found on some outer atolls was a cause for concern. In contrast, two atolls had much higher fish biomass than expected given their human population and limited reef size. Pulap and Pingelap were interesting outliers, especially among outer reefs discussed.

While fish biomass was similar between FSM main islands and outer atolls, the size structures were different. FSM main islands consistently had smaller fish compared to the atolls; and had a greater abundance of herbivorous fish at lower trophic levels (Figure 10). Thus, while biomass was similar, the size-and-trophic structure of fish assemblages was improved on the outer FSM atolls. These attributes are desirable from an ecosystem perspective.[19,20] Fish assemblages with larger sizes and greater diversity are known to mitigate the effects of climate disturbances while also

FIGURE 9.

Fish biomass across selected islands and atolls associated with the MCRM. Remote atolls in the Republic of the Marshall Islands (RMI) represent reference points with little human influence (Rongelap, Bikar, Bokak). FSM main islands and atolls had lower fish biomass compare to RMI, with several FSM atolls below the 5–7 kg per survey threshold (grey shaded rectangle) that represents a threshold previously observed for reef recovery following disturbance events. Black dots represent mean values per survey for each atoll, colors indicate differing types of fish groups, or guilds.

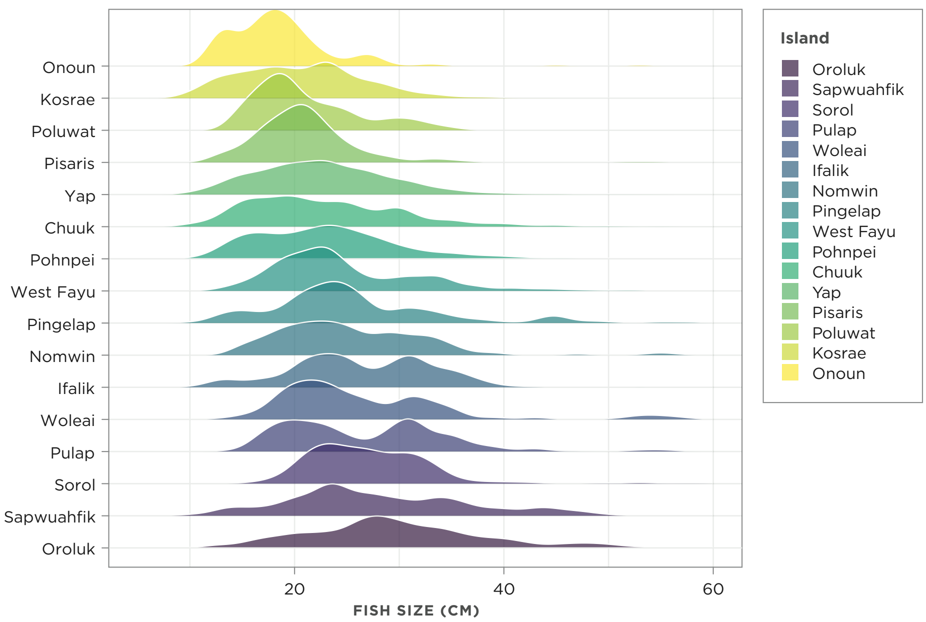


providing an essential food source. These trends may be due to the influence of fish markets on the main islands compared to more subsistence fishing on the atolls. Past studies have shown that fish markets attract larger fish while subsistence fishing often prefers a diversity of species of smaller sizes.[13,14,21]

MC scores for fish assemblage revealed that Oroluk, Sorol, and West Fayu had the highest condition due to the high biomass, large size structure, and notable presence of predators (Figure 11). Pohnpei was the only main FSM island with similarly high MC condition score attributed to successful fisheries management policies including

FIGURE 10.

Size structure of fish observed across FSM main islands and atolls.



MPA, grouper spawning protection, and species-based policies. Pohnpei scores were driven most by diversity and least by biomass and size. Meanwhile, Pulap and Pingelap had unexpectedly high MC scores across all metrics that were anecdotally related to management at the local level based upon conversations with mayors and fishermen. The lowest MC scores existed for other atolls to the north and northwest of Chuuk. While understanding the distribution of fish condition scores provided novel information for our FSM stakeholders, it's essential to understand what was driving the high and low scores that existed.

FIGURE 11.

Fish assemblages condition scores across FSM main islands and atolls. The overall score (left graph) represents the mean values of biomass, size, predator biomass, and evenness (right graphs). Evenness depicts whether fish biomass was spread across many species (high evenness) or just a few (low).

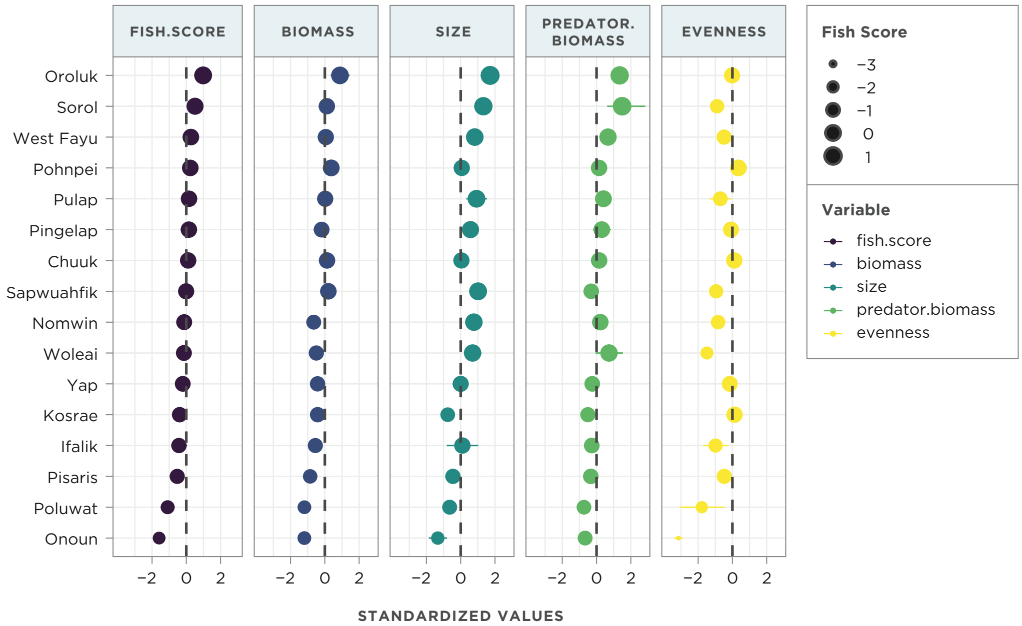


FIGURE 12.

Significant regression between human populations per-reef-area, distances to main human populations, wave energies and the observed condition of the fish assemblages. Fish condition scores increased with lower humans per-reef-area, with greater distances from human populations, and with intermediate wave exposure. Data points below the black regression line indicate reefs that had higher-than-expected fish condition scores, those on top had lower. Colors indicate each FSM atoll and dotted lines show the relationship within each atoll.

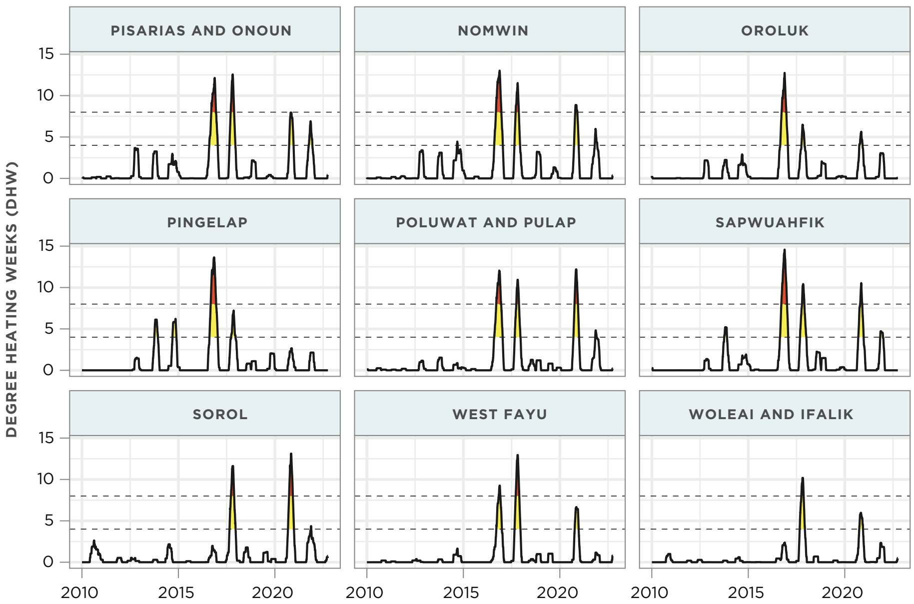
There was a highly significant regression, or prediction, between environmental factors and MC fish scores. Three environmental and anthropogenic factors explained why each reef had a high versus low MC score: human population per-reef-area, distance from the main human population on each atoll, and wave energy (Figure 12). Atolls with higher humans per-reef-area generally had lower scores. Reefs further away from human settlements had higher scores due to limited access and high gas costs for boats. Meanwhile, wave energy results were more interesting and complex. Reefs with low wave energy had the lowest scores due to the high accessibility, reefs with intermediate wave energy had the highest scores, and reefs with high wave energy had intermediate scores due to limited coral growth from high wave exposure that provided less habitat. Interestingly, these patterns were consistent across sites for each atoll, including Oroluk where fishing was limited by legislation (Figure 12). Outlier sites within each atoll were also visualized through this analysis. For instance, on Woleai where fish assemblages had moderate-to-low overall condition scores, we can see the two local MPAs had much higher condition than predicted suggesting localized management success (WOLA-1 and WOLA-3, were on the right of the prediction line, Figure 12). Similarly, a new local MPA on Nomwin had a higher than expected condition score (NOMW-8), and most outer reef sites on Pingelap also had relatively high scores. From these analyses we can estimate the fish condition scores for any reef in the FSM atolls, whether surveyed or not, and discuss forms of management that can account for the environmental drivers of foodfish resources that were revealed.

BENTHIC AND CORAL ASSEMBLAGES

Benthic and coral assemblages were clearly impacted by past heat stress events associated with climate change that have continued to increase over the past decade (Figure 2). However, the frequency and intensity of heat-stress events differed greatly across the FSM atolls (Figure 13). For instance, atolls in central FSM have experienced 2–3 heat stress events in the past decade that have exceeded the 8 degree-heating-week (DHW) threshold known to result in significant coral bleaching and mortality. Meanwhile, atolls in eastern FSM have experienced only 1 major heat stress event in 2016 (i.e., Pingelap), while atolls in western FSM have experienced only 1 in 2020 (i.e., Sorol). Not surprisingly, both the frequency and intensity of heat stress was one clear predictor of the benthic and coral assemblages. Yet, once accounting for heat stress, there was also clear evidence for the role of human stress and natural factors that are disentangled below.

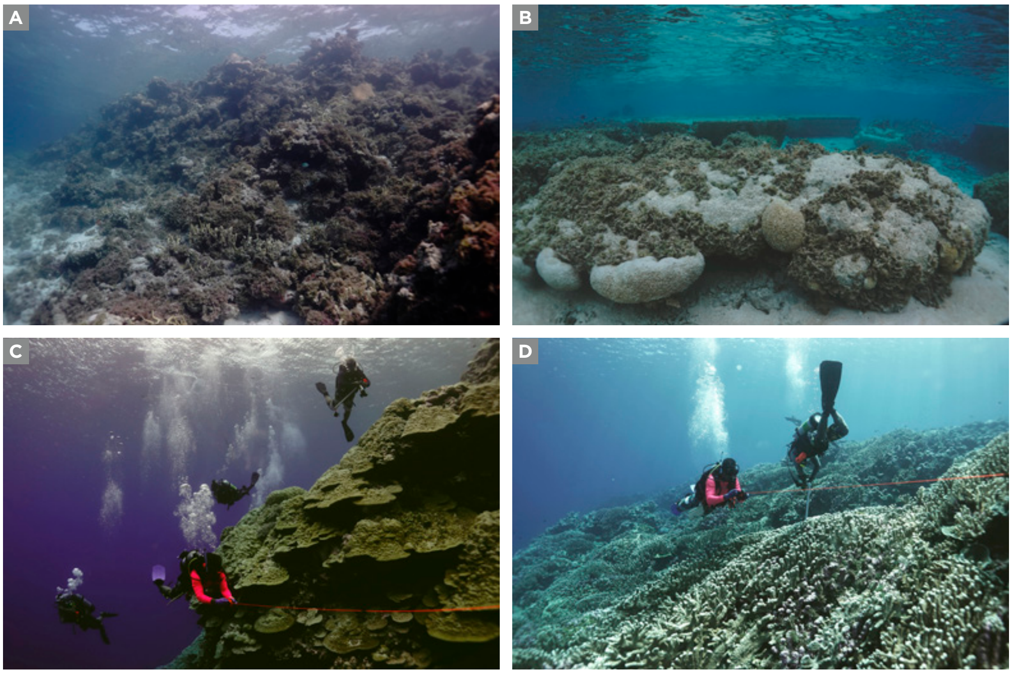
FIGURE 13.

Summaries of heat stress events experienced across FSM atolls based upon degree heating weeks, or DHW. DHW above 4 provided a warning that some bleaching may have occurred, while DHW above 8 suggest that significant coral bleaching likely occurred. See Figure 2 for spatial views of DHW.



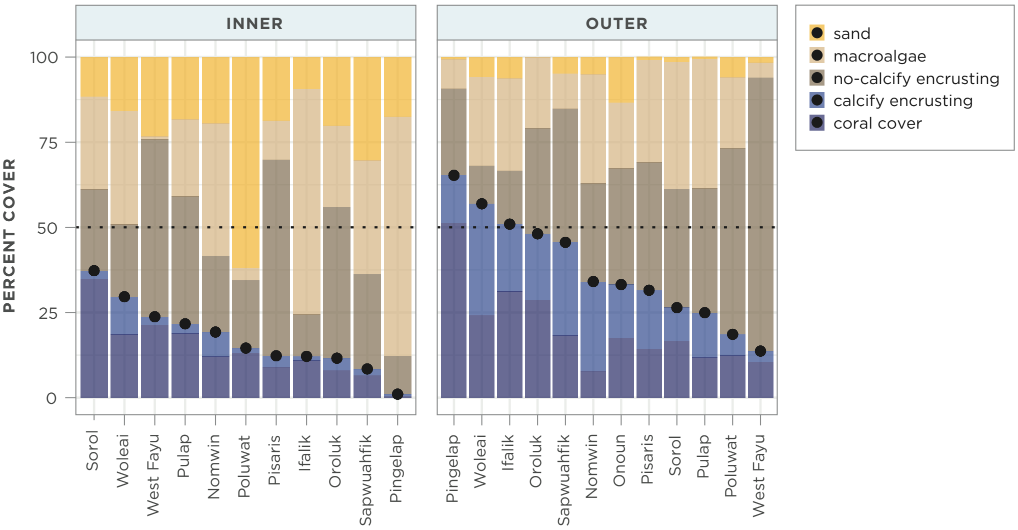
Benthic composition was strikingly different on inner reefs compared to outer (Figure 14 compare plates A–B to C–D). Beyond different coral species and more sand-and-loose substrate, inner reefs had less coral and calcifying coralline algae to facilitate net reef growth through time (Figure 15). In contrast, outer reefs associated with five atolls that were in eastern and western FSM with less heat stress exposure had corals and calcifying substrates near-or-above 50% indicating net-reef growth (Pingelap, Woleai, Ifalik, Oroluk, and Sapwuahfik) (Figure 16). Meanwhile, most central FSM atolls in Chuuk state, where heat stress has been highest and most frequent, had greater abundances of non-calcifying encrusting and macroalgae compared to calcifying substrates. The exception to these trends was

FIGURE 14.



Representative pictures of inner (A–B) versus outer (C–D) reefs. Lower coral cover and greater macroalgae cover were common on inner reefs. Many outer reefs were dominated by stress tolerant corals such as Porites (C), however, there were rare instances of *Acropora palifera* reefs as seen on the north coast of Oroluk.

FIGURE 15.

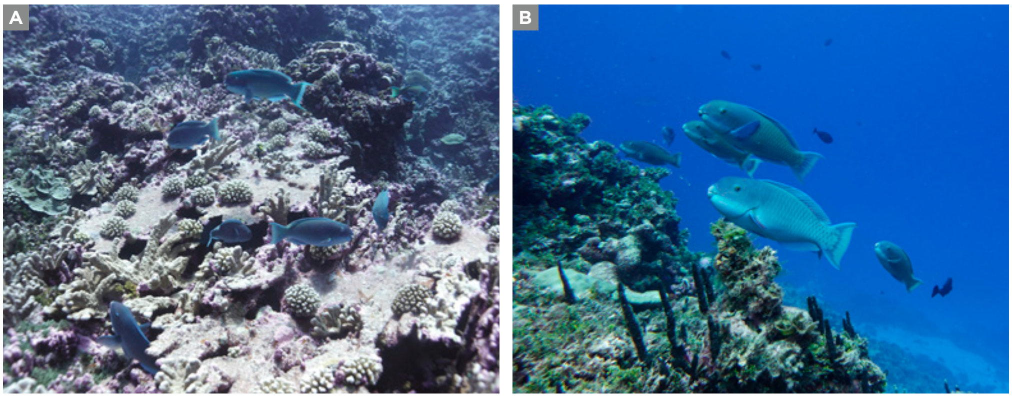


Benthic composition across FSM atolls as summarized by 5 general categories colored by their calcification potential. Blue colors indicate calcifying substrates (corals and crustose coralline algae) while brown colors indicate limited or no calcification potential (encrusting fleshy or erect macroalgae).

the uninhabited Sorol atoll in westernmost FSM that was exposed to two significant heat stress events, most recently and significantly in 2020, resulting in low calcifying substrates on the outer reefs similar to Chuuk (Figure 16). In sum, trends across outer reefs generally followed the history of heat-stress exposure. However, the lower condition of inner reefs compared to outer suggested they may have been in a compromised state prior to bleaching events. This idea was supported by the trends in benthic assemblages across inner atoll reefs that were best predicted by distance proxies to fishing pressure, furthered below.

FIGURE 16.

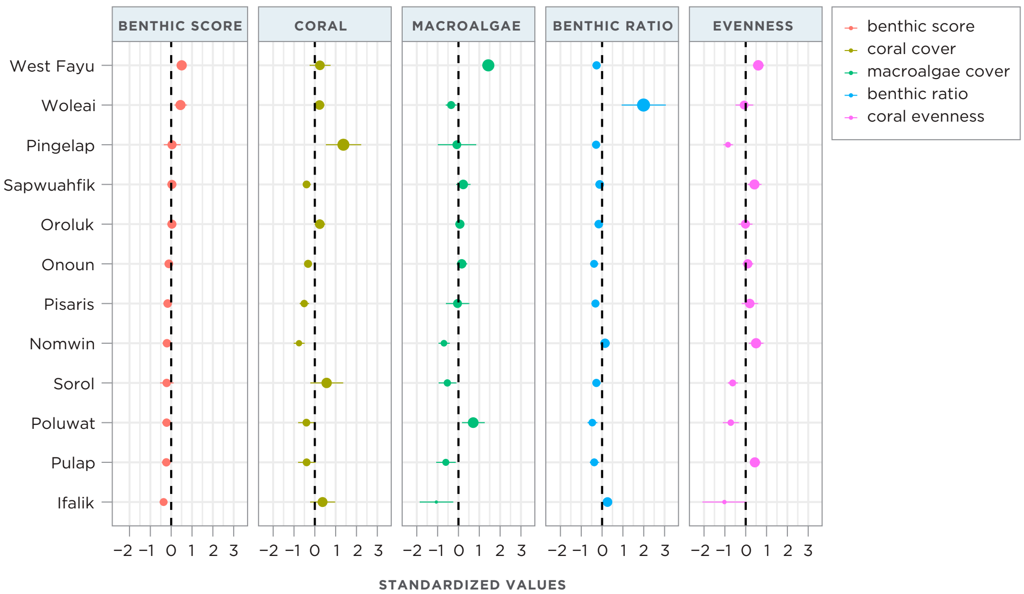
Representative photos of the large Pacific steephead parrotfish that were a strong predictor of whether calcifying (A) versus non-calcifying (B) benthic substrates were most abundant. This large-bodied parrotfish may be a keystone species that deserves protection from commercial sales or export from the atolls based upon its disproportional abundance and function.



Overall MC scores for the benthic assemblages were highest for eastern and western FSM atolls that avoided repeat heat stress events, but also high for uninhabited atolls of West Fayu and Oroluk that were exposed to past heat stress events in 2016 and 2017 only (Figure 18). Benthic substrates, described above, were one component of the overall MC score that aims to depict reef "condition" or "health". However, MC scores also took coral and macroalgae cover into consideration, as well as coral diversity (Figure 7). The highest MC score recorded at the uninhabited atoll of West Fayu despite repeat heat stress was encouraging and due mainly to high coral diversity and low macroalgae cover (Figure 17). While heat stress likely caused low coral cover, the number of coral species present remained relatively high, potentially facilitated by low macroalgal abundance and high fish biomass. In support of this idea, regression analysis revealed that MC benthic scores for outer reefs were (i) modulated by wave energy but (ii) diminished by heat stress and (iii) the number of, and distance to, humans on each atoll (Figure 18A).

FIGURE 17.

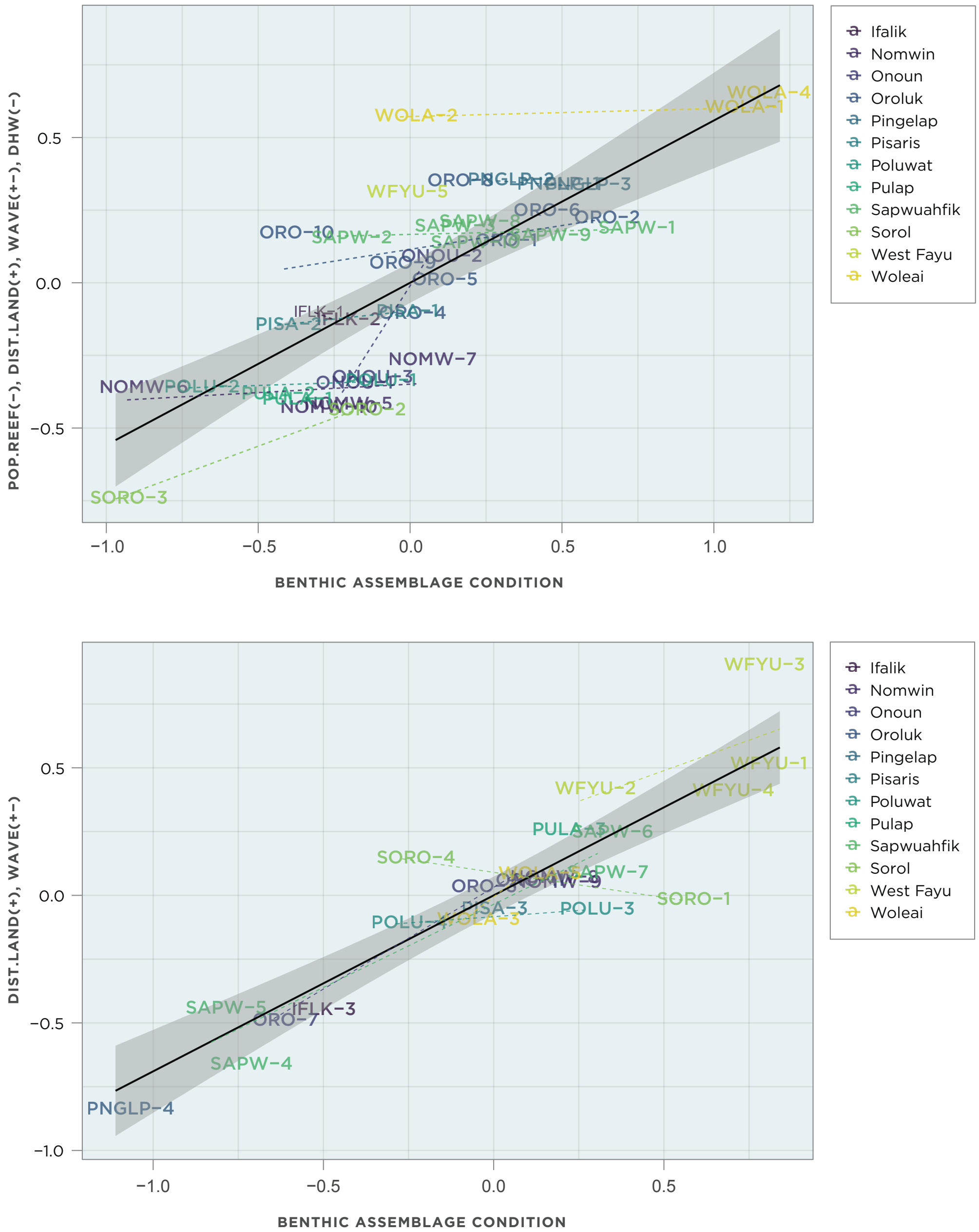
Benthic assemblage condition scores across FSM atolls. The overall score (left graph) represents the mean values of coral cover, macroalgae cover, ratio of calcifying-to-non-calcifying substrates, and coral evenness (right graphs). Evenness depicts whether coral cover was spread across many species (high evenness) or just a few (low).



Interestingly, heat stress did not predict the MC benthic scores for inner reefs where proximity to humans was the primary driver (Figure 18B). Inner reefs may have been compromised by human stressors prior to heat stress with less capacity for decline when heat stress occurred.

FIGURE 18.

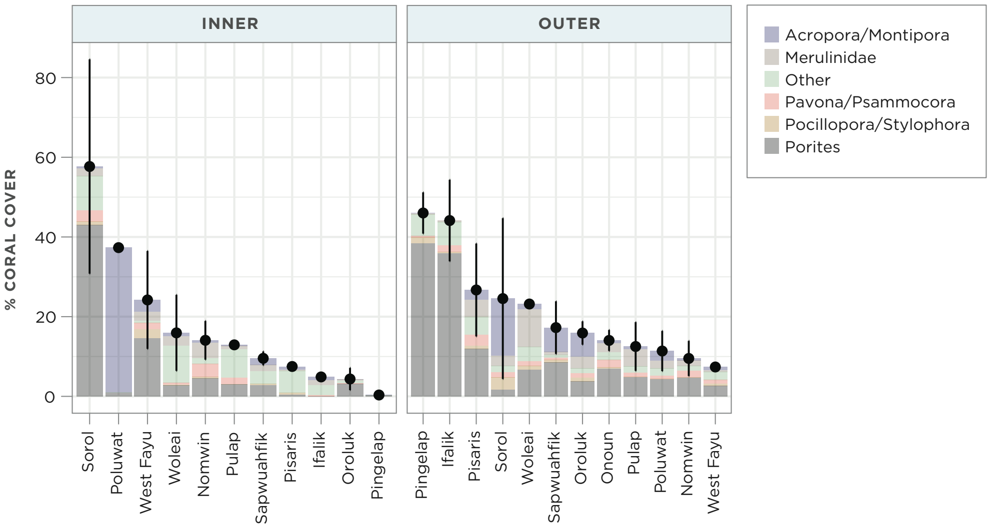
Significant regressions between human population per-reef-area, distances to main human population, wave energies, degree heating weeks (DHW), and the observed condition of the benthic assemblages. Benthic condition scores were influenced by the same set of predictors as fish condition scores (A–B), but with the addition of heat-stress for outer reefs where coral bleaching was most prevalent (B). Inner reefs had limited coral cover of species tolerant to heat stress and abundant macroalgae that were best predicted by human access to fishing. Colors indicate each FSM atoll and dotted lines show the relationship within each atoll.



Beyond the benthic substrates, the impact of cumulative heat stress was also pronounced in the coral assemblages. Framework-building *Acropora* and merulinid corals that used to dominate FSM reefs prior to the 2015–2017 ENSO comprised less than 10% of coral cover across most atolls (Figure 19). However, all atolls similarly had small *Acropora* populations that appeared to be resistant or resilient to heat stress based upon their colony sizes, known growth rates of 5–10 cm per year, and time since the last heat stress event (Figure 20). Identifying environmental characteristics that facilitate heat stress resistance remains a priority for research and management, as reducing local human stressors in these areas has been recommended to mitigate the long-term impacts of climate change. Coral assemblages were instead dominated by slower growing *Porites*, encrusting agariciids, and large stands of *Turbinaria* plate corals less frequently observed (Figure 21). These trends were especially true on the leeward reefs where *Porites* covered more than 40% of some reefs (Figure 19). Because of their tolerance to heat stress, the abundance of these corals is expected to rise across FSM and globally. Yet, maintaining coral diversity in the face of climate change is essential.

FIGURE 19.

Coral composition across the FSM atoll inner and outer reefs. Colors indicate coral genus or families that have differing functions on the reef. Blue colors indicate mainly *Acropora* corals that have rapid growth rates and provide complex habitat for fish. These corals are most susceptible to bleaching, and were expected in much greater abundance. Meanwhile, dark color bars represent Porites corals that are heat-stress tolerant and expected to rise in dominance with climate change. Others provide intermediate growth and complexity.



Beyond coral coverage, maintaining coral diversity is a high priority because of the variety of ecosystem services that diverse coral assemblages offer. Notable ecosystem services include fish habitat provisioning, wave energy dissipation and the protection of shorelines from erosion, and buffering responses to human and heat stress. Our surveys were used to document both the species richness observed and the total species richness that might be expected on each reef. Sampling only 10 m^2 of reef per site, the surveys revealed between 6 and 33 species on inner reefs, and between 12 and 45 species on outer reefs (Figure 22, dotted line).

FIGURE 20.

Representative photos of iconic *Acropora* table corals that facilitate fish habitat and reef complexity but are also very susceptible to heat stress. Across FSM atolls we saw table corals that survived recent heat stress events (A), table corals that died from recent heat stress but have rapid recruitment and recovery ongoing (B), and table corals that died from heat stress with limited signs of recovery. Understanding and managing resistant and fast recovering table corals is key for science and management to help mitigate climate change.

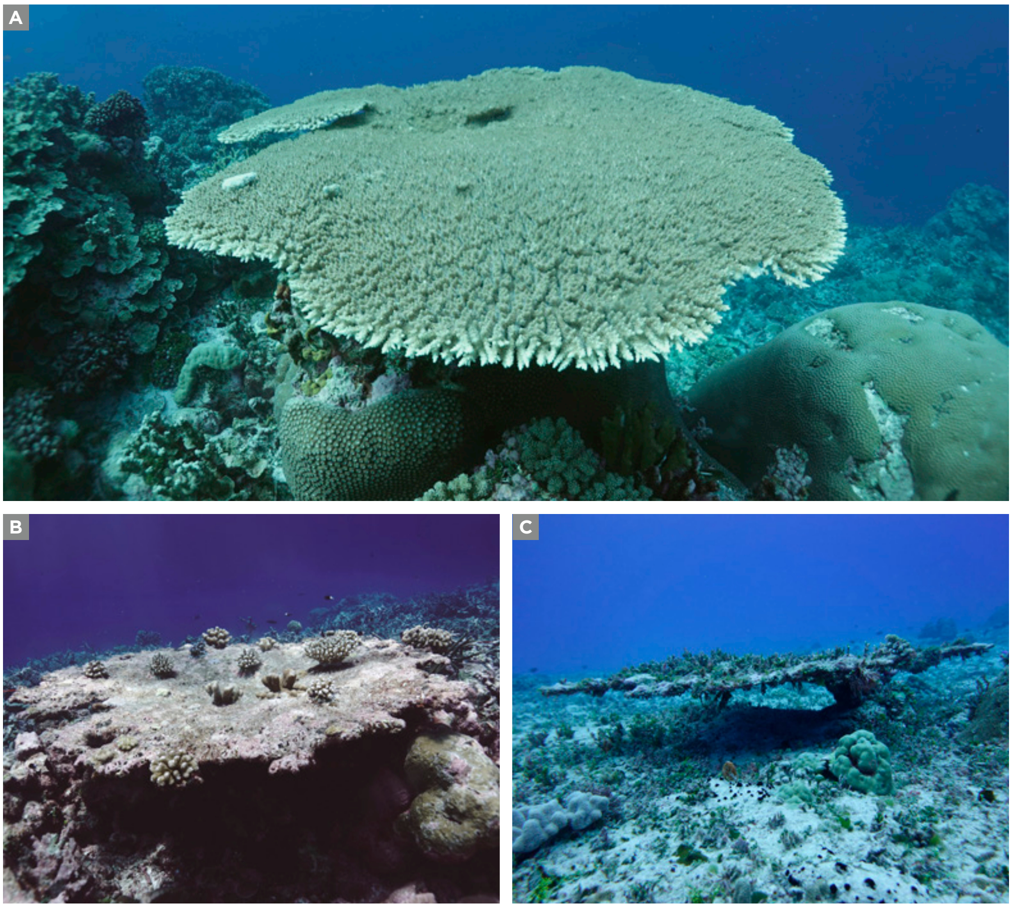
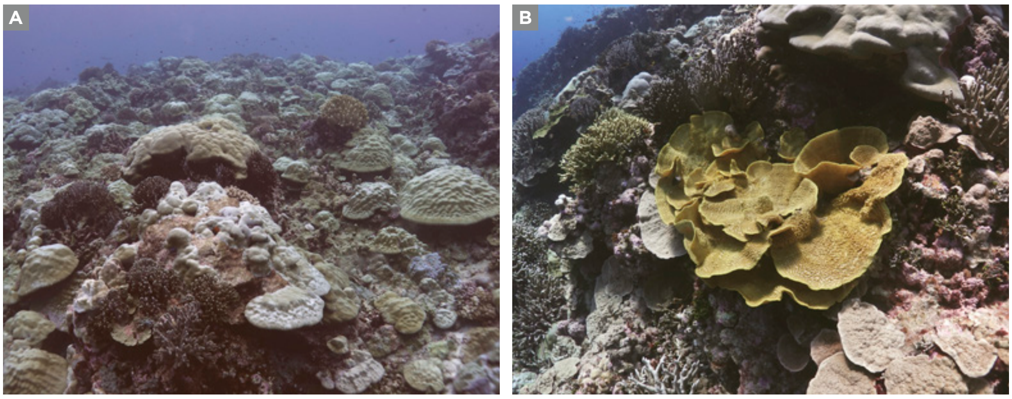


FIGURE 21.

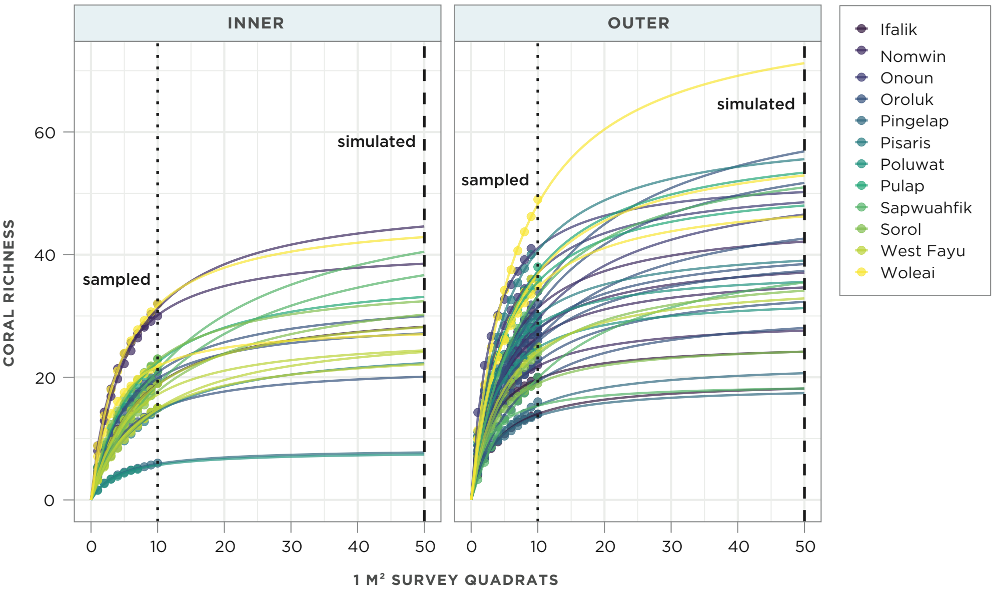
Representative photos of *Porites* dominant reefs found on the leeward sides of many islands (A). Notable but infrequent large stands of *Turbinaria* plate corals (B) were observed mainly on the leeward sides of islands as well. In many instances, the heat stress events have left these corals intact while removing many branching and massive corals leading to a loss of observed coral species diversity.



Species were defined very conservatively with uncertain species groups being lumped together (e.g., *Dipsastraea matthaii/pallida/speciosa*); thus, the actual number of species is higher. Interestingly, extended simulations estimated that a more complete sampling of each reef (50 m^2) would document between 7 and 42 species on inner reefs, and between 17 and 73 species on outer reefs, or a 30–60% increase per site (Figure 22, dashed line). For FSM reefs to remain as close as possible to their coral richness capacity, it is necessary to understand what factors might be managed. We found four influential factors that promoted the highest predicted coral richness. The first two were natural factors that can't be managed: 1) longitude or proximity to highest diversity reefs globally in the Indo-West Pacific, closest to western FSM, 2) moderate wave energy, not too high or low. Yet, the second two were relevant for management: 3) proximity to nearby atolls, and 4) proximity to human presence on each atoll (Figure 23). Meanwhile, exposure to significant heat stress created a larger gap between the highest predicted coral diversity at each site versus the acutal richness observed, whereby we observed between 5 and 11 fewer species on islands exposed to 8 DHW or more in the past 5 years.

FIGURE 22.

Coral species accumulation curves observed (dotted lines) and simulated (dashed lines) for inner and outer reefs. Coral species observed in our study quadrats are represented by circles associated with 1 to 10 quadrats, simulations beyond that were generated by a mathematical fitting procedure. Colors indicate FSM atolls, each line represents one site.



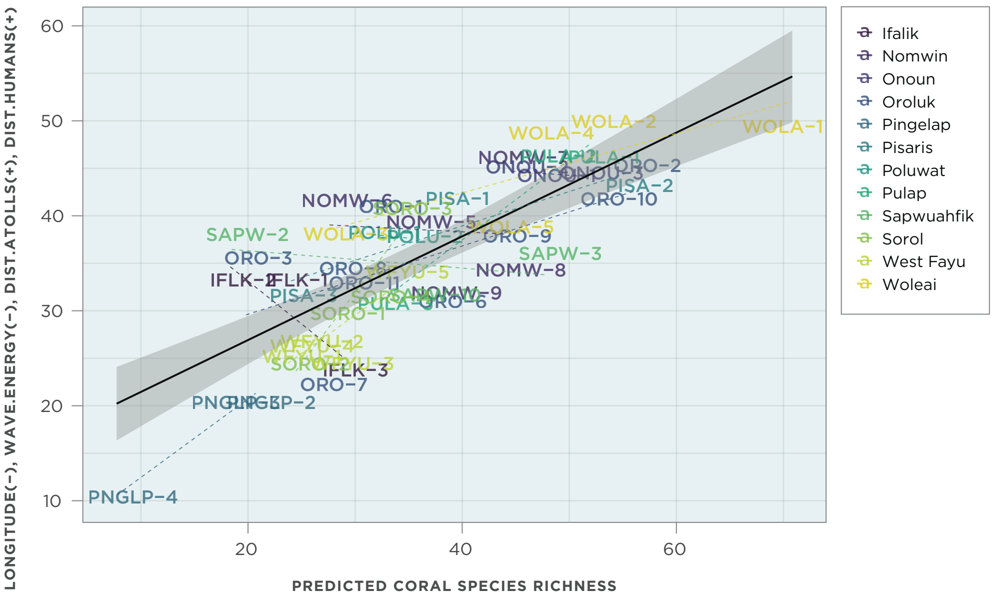


FIGURE 23.

Significant regressions between distances to main human populations, wave energies, distances to nearest atolls, longitude, and the predicted, maximum number of species that could occur on each reefs (dashed lines, Figure 22). The difference between the maximum possible number of species and the observed number of species was predicted by heat stress and local proxies to fishing pressure, similar to benthic substrates, suggesting both local and global stress contribute to diversity loss. Colors indicate each FSM atoll and dotted lines show the relationship within each atoll.

MACROINVERTEBRATES

Belt-transect surveys that covered 250 m^2 for each transect and a total of 1,250 m^2 for each site revealed low abundances of conspicuous macroinvertebrates. Sea cucumbers and clams were most notable, but very low in abundance across the FSM atolls, especially sea cucumbers which were more abundant in the FSM main islands and remote Marshall Island atolls (Figure 24). Two atolls in Micronesia serve as reference points to understand low sea cucumber abundances observed in the FSM atolls. The very remote Bikar and Namdrik atolls in the Marshall Islands where either no humans or limited human presence with subsistence livelihoods existed had between 25 to 80 individuals per transect. In contrast, the highest sea cucumber abundances across FSM atolls were observed on Sapwuahfik, averaging ~14 individuals per transect. However, most FSM atolls had below 5 individuals per transect, including atolls with limited human presence (Sorol, West Fayu, and Oroluk), and many transects on inner atoll reefs had no observed sea cucumbers.

Sea cucumber densities indicated small-bodied individuals were most abundant, especially *Holothuria edulis* (pinkfish), *H. atra* (lollyfish), and *Stichopus chloronotus* (greenfish) (Figure 25). Yet, several large-bodied sea cucumbers typically found on reef slopes were recorded in very low abundances and observed only a few times during the entire expedition on West Fayu and Oroluk (i.e., *Holothuria fuscopunctata* or elephant trunkfish, and *Thelenota anax* or amberfish).

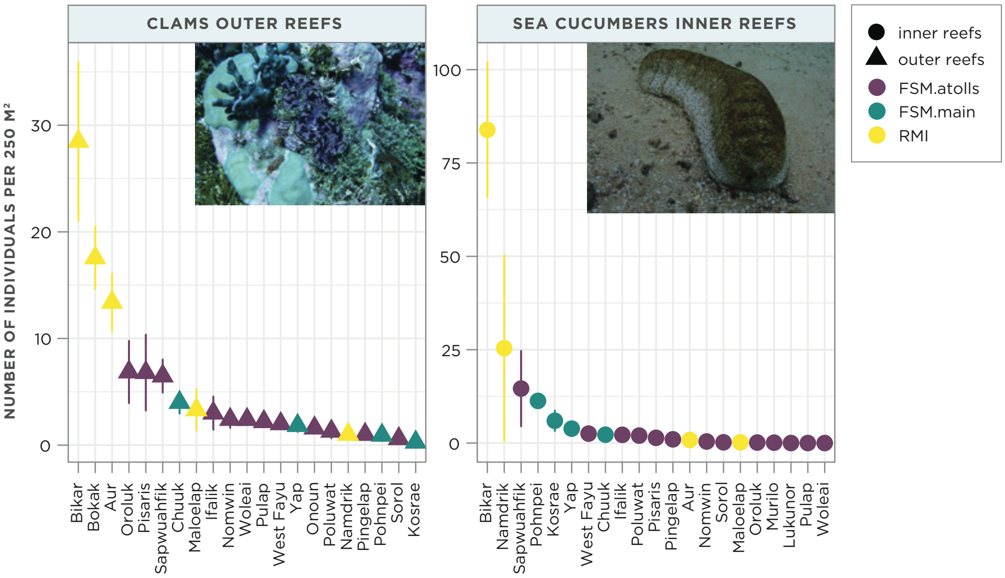


FIGURE 24.

Abundances of clams on outer reefs (A) and sea cucumbers on inner reefs (B) where they were respectively most abundant. References from elsewhere in Micronesia were provided to understand potential baselines. Across FSM atolls, sea cucumbers were in low abundances consistently suggesting their enduring sensitivity to past harvesting. However, clam abundances were better related to local gradient of human access suggesting their ongoing use as a popular food source (Figure 25).

The reef habitats and depths surveyed were less ideal for estimating the abundances of sea cucumber that prefer shallow waters on both protected and exposed reef crest environments. Therefore, targeted surveys within reef flat and reef crest habitats are recommended for more formal stock assessments of sea cucumbers. However, the consistency of our monitoring program provides comparable estimates across a broad spatial scale.

In contrast to inner reefs, sea cucumbers were rarely found on the outer reef slopes averaging less than 1 individual per 250 m^2 transect. Instead, clams were the most notable macroinvertebrates across the FSM atoll outer reefs, with the conspicuous *Tridacna maxima* being most abundant, while the larger *T. squamosa* was represented but less common. Clam abundances ranged between 2 and 8 per 250 m^2 transect, which was about 50% lower than abundances observed across remote RMI atolls (Figure 24). In contrast to *T. maxima* and *T. squamosa* that were mainly associated with outer reefs, clams were rarely encountered on inner atoll reefs. Only 8 large *Hippopus hippopus* clams were observed across the inner reefs, mainly in sandy habitats between reef structures.

While sea cucumber abundances were too low to generate predictive models, clam abundances were well predicted by distance to nearest land on each atoll, confirming their desirability as a subsistence food source. These findings were further supported by a unique project being conducted on Pingelap atoll. We observed a clam farm containing several hundred, if not over a thousand, desirable *Hippopus hippopus* clams in the northeast corner of Pingelap atoll (Figure 26). Discussed below, this represented one of several ongoing projects on Pingelap to provide food security and economic gains from the clam meat and shells.

FIGURE 25.

Only eight species of sea cucumbers were seen across FSM atoll inner reefs with small bodied *Holothuria* species most abundant.

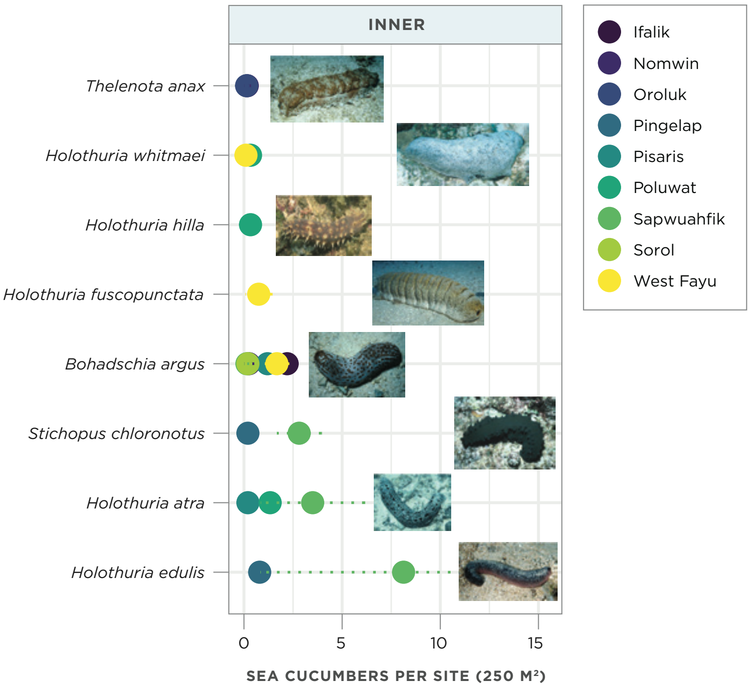


FIGURE 26.

Photos of a unique clam farm observed inside Pingelap atoll that is being maintained for food and sales of shells. The impressive abundance of clams was the only (1) means for residents of Pingelap to maintain food security and diversify opportunities for small-scale economic growth. Findings like these suggest the need for an improved inter-atoll communication network to share the science, traditional and modern management approaches.

PELAGIC BRUVS

We deployed 135 mid-water baited remote underwater video systems (BRUVS) in sets of five at 27 locations across 11 atolls throughout our survey in FSM. We sampled Ngatik, Pingelap, and Oroluk in PohnPei State; Nomwin, Namonuito, Pulap, and Pulowat in Chuuk state; and West Fayu, Ifalik, Woleai, and Sorol in Yap State.

We recorded a total of 1,061 vertebrate animals of 20 unique taxa and 14 families (Figure 27; Table 1), ranging from small forage fishes and juveniles such as driftfish (*Psenes* sp.) and scads (*Decatperus* sp.) to large predatory teleosts such as common dolphinfish (*Coryphaena hippurus*), wahoo (*Acanthocybium solandri*) and black marlin (*Istiompax indica*), and three species of shark. Length of animals ranged from a 1 cm driftfish (*Psenes* sp.) to a 158 cm silvertip shark (*Carcharhinus albimarginatus*). Mean taxonomic richness did not vary significantly among states (p=0.597).

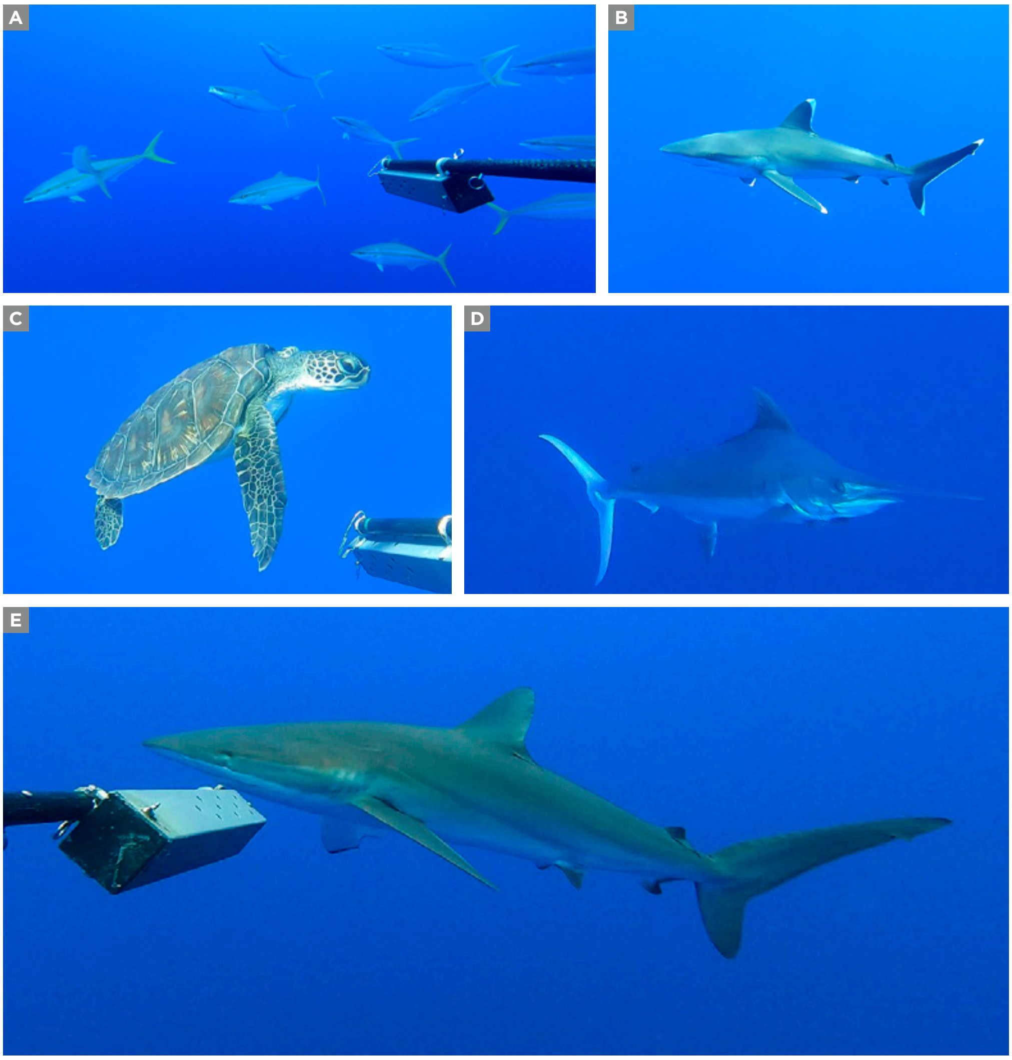


FIGURE 27.

Examples of taxa recorded on mid-water BRUVS surveys in FSM: (A) rainbow runner (*Elagatis bipinnulata*), (B) silvertip shark (*Carcharhinus albimarginatus*), (C) green sea turtle (*Chelonia mydas*), (D) black marlin (*Istiompax indica*), and (E) silky shark (*Carcharhinus falciformis*).

We recorded several species listed on the IUCN Red List of Threatened Species, namely the Endangered green sea turtle (*Chelonia mydas*) and grey reef shark (*Carcharhinus amblyrhynchos*), and Vulnerable silky (*Carcharhinus falciformis*) and silvertip (*Carcharhinus albimarginatus*) sharks and Indo-pacific sailfish (*Istiophorus platypterus*).

Sharks were relatively scarce, noted only at Pingelap in Pohnpei state; Nomwin, Pulap, and Pulowat in Chuuk; and Sorol in Yap. Sailfish and yellowfin tuna (*Thunnus albacares*) were also only noted at Sorol.

TABLE 1.

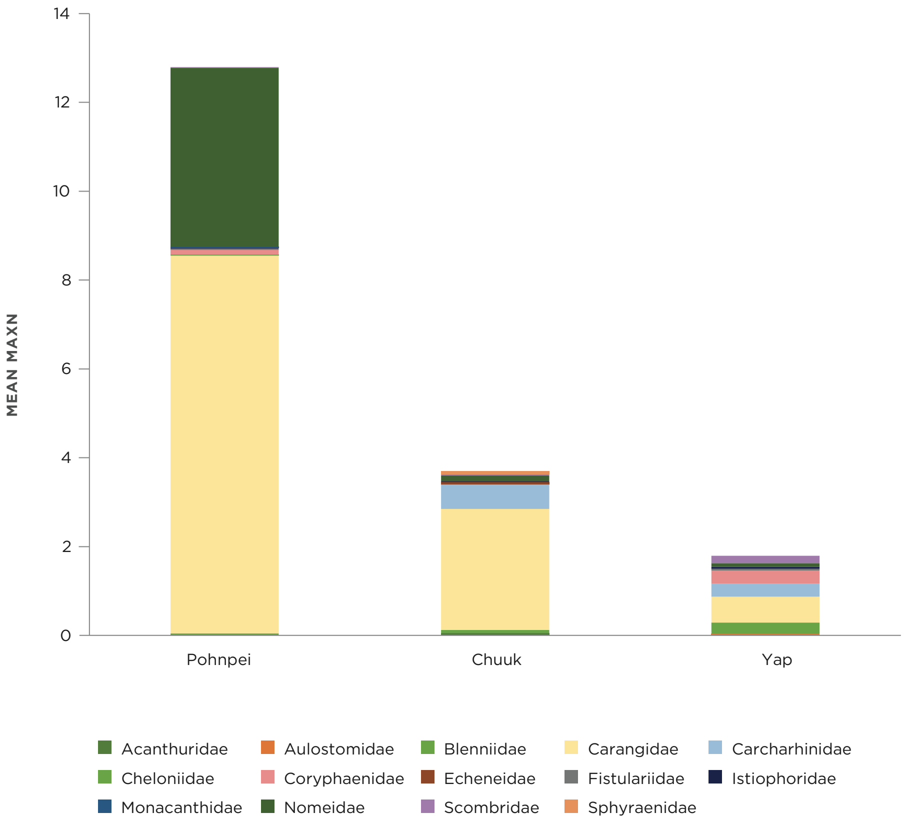
Taxa observed on mid-water BRUVS deployments across FSM survey locations.

Family	Binomial	Common name	Mean MaxN	Mean Biomass (g)	Mean Length (cm)
Acanthuridae	*Naso hexacanthus*	sleek unicornfish	0.015	52.13	-
Aulostomidae	*Aulostomus chinensis*	chinese trumpetfish	0.008	3.445	-
Blenniidae	*Aspidontus taeniatus*	false cleanerfish	0.091	0.088	5.2
Carangidae	Carangidae sp.	jacks	0.045	0.274	7.8
	Caranx sp.	Caranx trevally	0.250	0.310	3.8
	Decapterus macarellus	mackerel scad	0.045	0.115	5.8
	Decapterus sp.	Decapterus scad	4.917	12.10	5.6
	Elagatis bipinnulata	rainbow runner	0.053	94.99	41.8
Carcharhinidae	*Carcharhinus albimarginatus*	silvertip shark	0.045	1089	139.4
	Carcharhinus amblyrhynchos	blacktail reef shark	0.121	1533	100.5
	Carcharhinus falciformis	silky shark	0.053	943.1	122.4
	Carcharhinus sp	requiem shark	0.008	119.0	92.1
Cheloniidae	*Chelonia mydas*	green sea turtle	0.008	213.9	-
Coryphaenidae	*Coryphaena hippurus*	common dolphinfish	0.106	266.8	66.4
Echeneidae	*Echeneis naucrates*	live sharksucker	0.015	0.533	20.3
Fistulariidae	*Fistularia* sp.	cornetfish	0.023	0.098	16.0
Istiophoridae	*Istiompax indica*	black marlin	0.015	451.1	152.5
	Istiophorus platypterus	Indo-Pacific sailfish	0.008	755.2	-
Monacanthidae	*Aluterus scriptus*	scribbled leatherjacket filefish	0.008	0.085	-
	Monacanthidae sp	leatherjackets	0.008	0.025	5.8
Nomeidae	*Psenes* sp.	driftfish	2.129	1.040	2.7
Scombridae	*Acanthocybium solandri*	wahoo	0.015	32.68	72.8
	Scombridae sp	mackerels	0.008	0.019	6.4
	Thunnus albacares	yellowfin tuna	0.023	185.2	-
Sphyraenidae	*Sphyraena barracuda*	great barracuda	0.023	88.19	86.0

Overall, abundance of pelagic vertebrates was dominated by carangids (66.1%), followed by nomeids (26.5%) and carcharhinids (2.8%)(Figure 28). The most abundant taxa were all small pelagic fishes and juveniles, with scads (*Decapterus* sp.) accounting for 61.2% of records (649 records) followed by driftfishes (*Psenes* sp.) 26.5% (281) and juvenile trevallies (*Caranx* sp.) 3.1%.

FIGURE 28.

Composition of mean pelagic vertebrate abundance per deployment by family group as recorded on midwater BRUVS deployed across each of the states sampled.



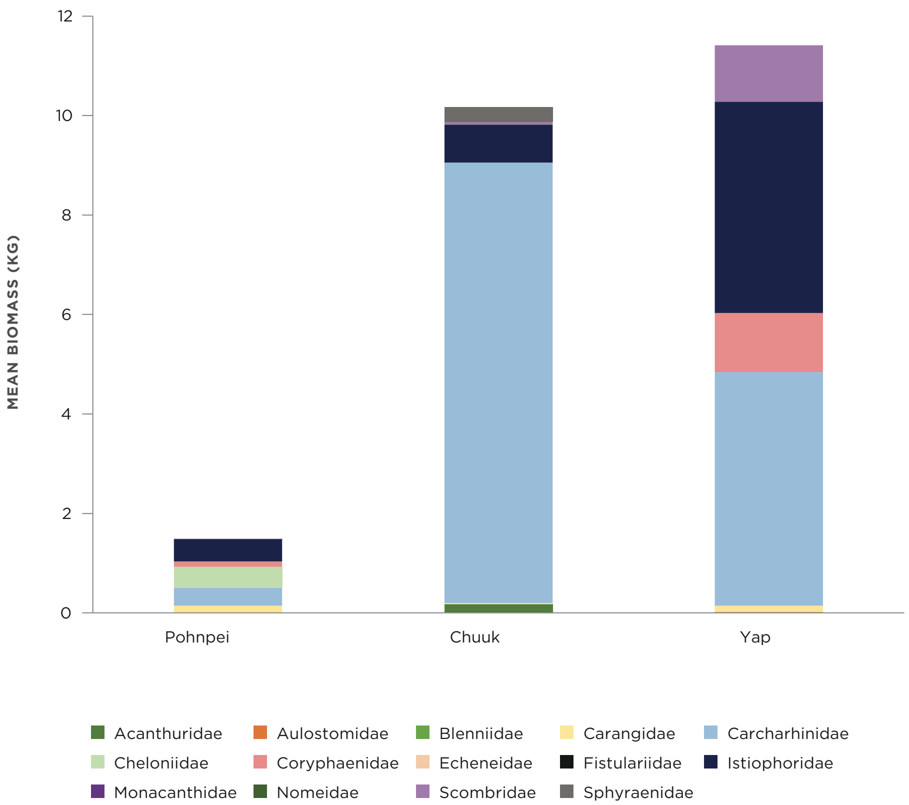
Mean total abundance of pelagic vertebrates differed significantly among states (p=0.020), with sample sites in Pohnpei state having significantly higher total abundance than those in Chuuk (p=0.023) and Yap (p=0.047). Composition of abundance also varied significantly among states (p=0.0001). With composition at sites in Pohnpei state differing significantly from that in Chuuk (p=0.0004) and Yap (p=0.003). Sites in Pohnpei state were associated with higher abundances of driftfishes and scads while sites in Chuuk and yap had a lower overall abundance but a more varied assemblage.

Conversely, biomass was dominated by much less abundant but large bodied pelagics with carcharhinids dominating the assemblage, accounting for 62.8% of total biomass followed by istiophorids (20.8%), coryphaenids (4.6%), and scombrids (3.8%) (Figure 29). The taxa contributing the greatest proportions of overall biomass were silky shark (20.8%) and grey reef shark (20.7%), followed by indo-pacific sailfish (18.4%), silvertip shark (15.9%), and yellowfin tuna (4.5%).

Total biomass did not vary significantly among states (p=0.578) although means were much higher in Chuuk and Yap. This lack of a significant difference is likely due to the patchiness of pelagic assemblages with some sites with very few fish and some sites with large schools of very large fish. Assemblage composition of biomass varied significantly among states (p=0.029). This difference was significant between Pohnpei and Chuuk (p=0.016). Biomass at sample sites in Chuuk was dominated by requiem sharks while those in Pohnpei were more varied.

FIGURE 29.

Composition of mean pelagic biomass per deployment by family group as recorded on midwater BRUVS deployed across each of the states sampled.



DEEP SEA CAMERA SYSTEMS

We conducted a total of 19 deployments of deep sea cameras in the Federated States of Micronesia, across eight different island locations (Table 2). Deployment depths ranged from 338 to 2625 m depth (mean = 1116 m ± 611).

TABLE 2.

Deployments of deep sea cameras, by island, and depth range.

Island	# Deployments	Depth range (m)
Pingelap	1	2625
Sapwuahfik	3	785–1760
Oroluk	2	1593–2213
Nomwin	2	714–925
Pulap	3	559–1621
West Fayu	3	1013–1241
Woleai	3	338–504
Sorol	2	898–963
TOTAL	**19**	**338–2625**

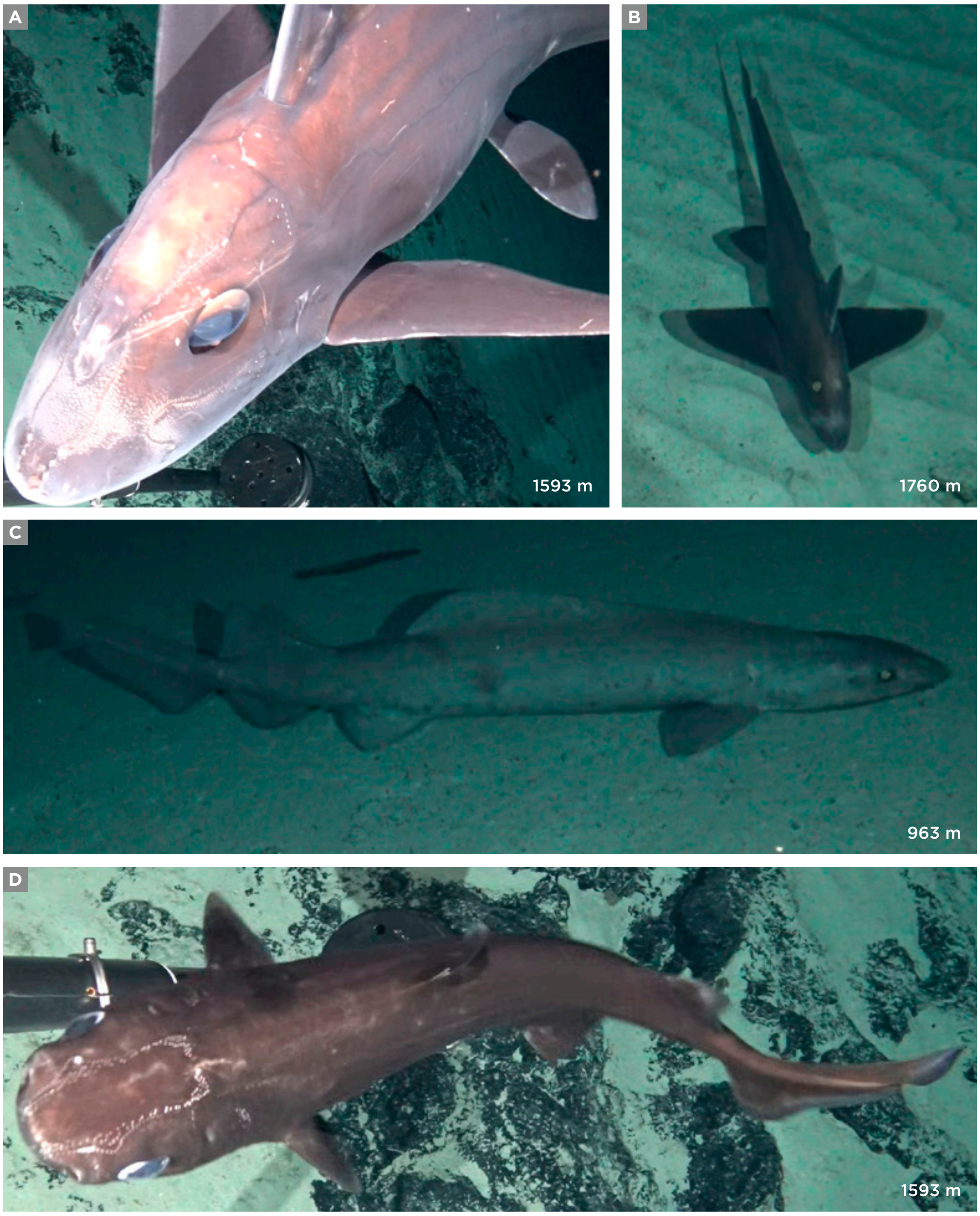
We identified 19 fish taxa, including 6 taxa of deep sea sharks (Appendix Table 1). Shark taxa observed were the bluntnose six-gill (*Hexanchus griseus*), false catsharks (*Pseudotriakis microdon*), dogfish sharks (*Squalus* sp.), lanternsharks (Etmopteridae), and sleeper sharks (*Somniosus* sp.) (Figure 30). False catsharks were the most frequently-occurring sharks, observed on 42% of deployments. Also observed were chimaeras (*Hydrolagus purpurescens*), which were observed with 3 individuals in a single frame (MaxN), on a deployment at 1593 m.

Other frequently-occurring fish taxa were cutthroat eels (Synaphobranchidae), which were observed on all but two of the deployments. *Synaphobranchus* sp. was the most abundant fish, with a maximum MaxN. Rattails (Macrouridae) were also observed on all but two deployments, and were represented by at least five distinct species (Appendix Table 1), the most abundant of which was *Coryphaenoides* sp., with a MaxN of 6. Halosaurs (Halosauridae) occurred on 63% of deployments, and cusk eels (Ophidiidae) on nearly half.

There were 43 identified invertebrate taxa observed on deep sea cameras, the most frequently-occurring of which were amphipods, observed on 84% of deployments, Penaeoid shrimp (freq. of occ. 63%), long-legged shrimp (*Nematocarcinus* sp.; 63%), and mysid shrimp (Mysida; 47%). Aside from amphipods, which are light-attracted taxa, the most abundant invertebrate taxon was Pandalid shrimp (*Heterocarpus* sp.), which were observed with 35 individuals in a single frame. Most other invertebrates

FIGURE 30.

Deep sea chimaeras and sharks observed on deep sea camera systems: (A–B) chimaera (*Hydrolagus purpurescens*), (C) false catshark (*Pseudotriakis microdon*), (D) lanternshark (Etmopteridae).



were observed with MaxN of only 1 or 2. Other observed invertebrates included two genera of king crabs (*Lithodes* sp., *Neolithodes* sp.), carrier crabs (Homolidae), sea urchin (Echinothuriidae), deep-sea sea cucumber (*Enypniastes eximia*), bamboo coral (Keratoisididae), soft coral (*Paragorgia* sp.), hard coral (Scleractinia), and glass sponges (Hexactinellida, Rossellidae, *Hyalonema* sp.) (Figure 32).

FIGURE 31.

Fish taxa observed on deep sea camera systems: (A) rattail (*Coryphaenoides* sp.), (B) oilfish (*Ruvettus pretiosus*), (C) Bathygadinae, (D) cutthroat eel biting a shrimp (*Synaphobranchus affinis* biting *Heterocarpus* sp.), (E) morid cod (*Lepidion* sp.), (F) batfish (Ogcocephalidae), (G) rattail (*Coryphaenoides* sp.; tent. *C. longicirrhus*), (H) cusk eel (*Bassogigas* sp.).

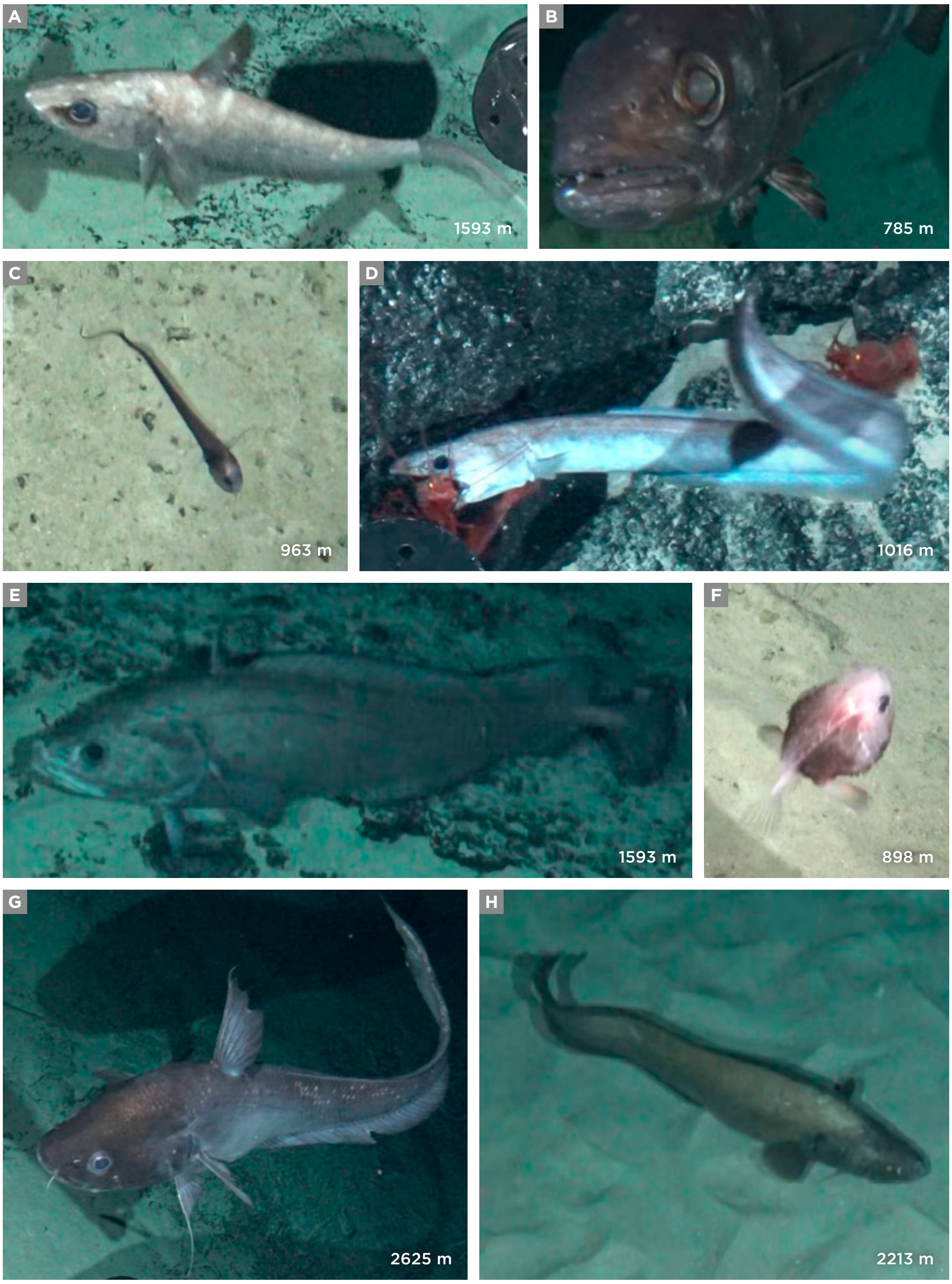
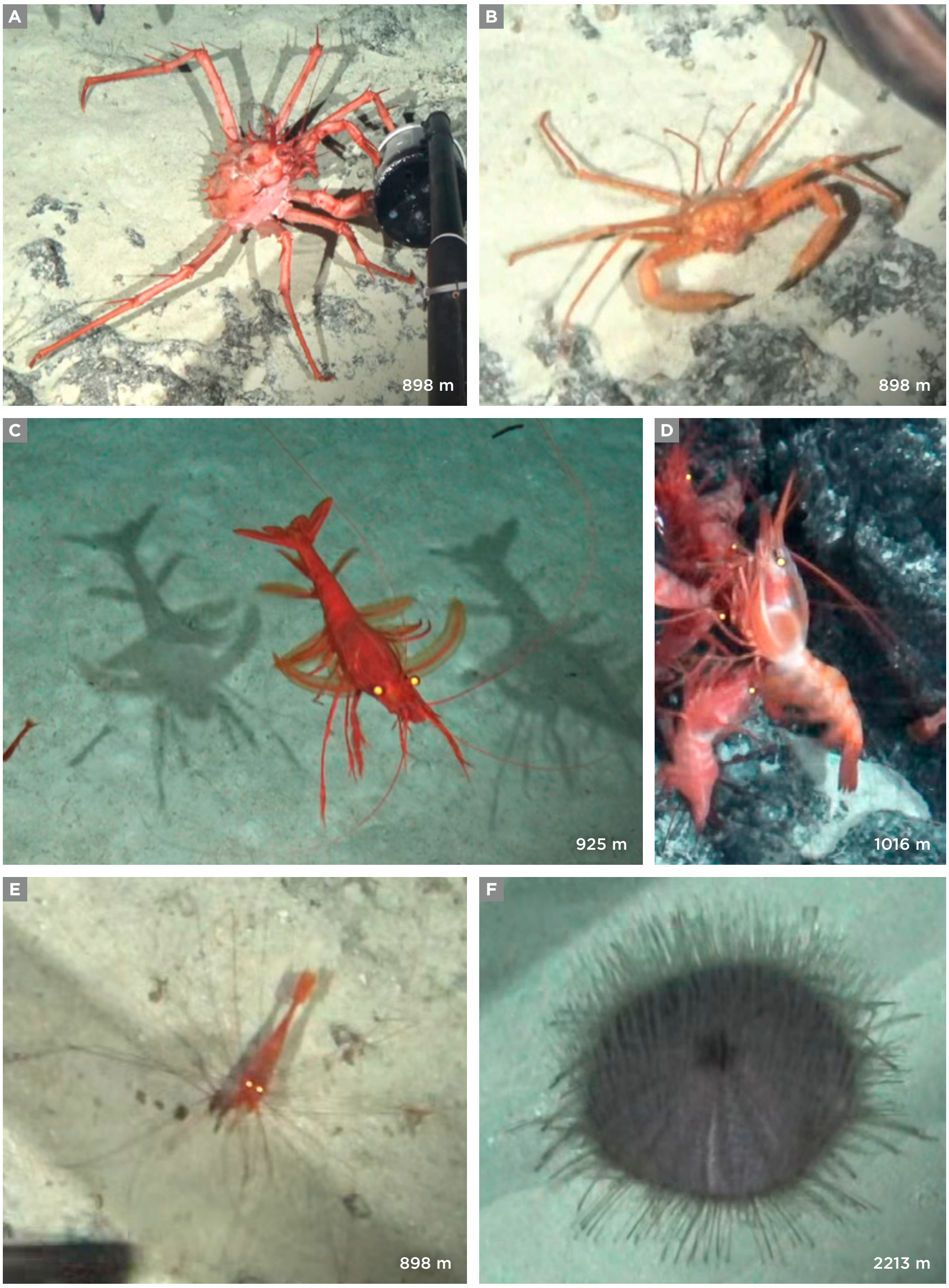


FIGURE 32.

Invertebrate taxa observed on deep sea camera systems: (A) king crab (*Lithodes* sp.), (B) carrier crab (Homolidae), (C) cardinal prawn (*Aristaeopsis edwardsiana*), (D) shrimp (*Heterocarpus* sp.), (E) long-legged shrimp (*Nematocarcinus* sp.), (F) sea urchin (Echinothuriidae).



SEABED BRUVS

We deployed 108 seabed BRUVS across 11 atolls throughout our survey. These deployments were mostly targeted in forereef locations at depths of 15-40 m, however, we also opportunistically sampled shallow lagoon habitats to collect information on different management areas and resident lagoon taxa. Each BRUVS set was left to record for one hour before it was recovered and the footage downloaded. This footage will be processed for taxonomic identifications of all animals present, along with abundance and size estimates using standardised methods for BRUVS analysis.

Initial scans of footage revealed a broad range of taxa, which varied significantly among atolls and habitat types. We recorded a wide array of resource species including snappers, groupers, tunas, jacks, parrotfishes, surgeonfishes, sharks, and goatfishes as well as many small reef species and non-target taxa. Through analysis of this footage across the atolls, we will provide information on the abundance, diversity, and size of fish populations and how management and habitat may be affecting them.

FIGURE 33.

Examples of taxa observed on seabed BRUVS surveys in FSM: (A) bigeye trevally (*Caranx sexfasciatus*), (B) grey reef shark (*Carcharhinus amblyrhynchos*), (C) amethyst anthias (*Mirolabrichthys pascalus*), (D) two-spot red snapper (*Lutjanus bohar*), (E) porcupine whipray (*Urogymnus asperrimus*), and (F) island trevally (*Ferdauia orthogrammus*).

SEABIRDS AND LAND SURVEYS

Throughout our expedition in FSM we logged birds, marine mammals and other locally significant species in each location daily. General notes were made for Pohnpei state and timed transects were completed in Chuuk and Yap states across eight atolls. We conducted 44 timed transects totalling 16.8 hours, recording a total of 11,447 birds. Throughout our surveys and additional off transect observations we recorded 29 unique bird taxa from 12 families (Figure 34, Table 3). The most diverse families were the gulls and terns (Laridae: 8 species), shorebirds (Scolopacidae: 5) and boobies (Sulidae: 3). Larids also dominated abundance contributing 88.4% of all records followed by sulids with 7% and fregatids with 3%. The most abundant taxa were, black noddies (5,836), sooty terns (1,888), brown boobies (417), red-footed boobies (379), and great frigates (343). Overall, mean taxonomic diversity ($p=0.086$), total abundance ($p=0.251$) and taxonomic composition ($p=0.073$) of the avifaunal community did not differ significantly among the states of Chuuk and Yap. However these metrics did vary significantly among atolls ($p=0.008$, $p=0.033$ and $p=0.0002$ respectively; Figure 35). The atolls of West Fayu and Sorol in Yap state which have no permanent population had the highest seabird abundance and the highest diversity with 15 and 19 taxa respectively.

We recorded significant seabird breeding colonies at the atolls of West Fayu and Sorol. At West Fayu we noted large numbers of black noddies breeding (>1,400 nests counted on transects) mostly in tall beach heliotrope (*Tournefortia argentea*), we also noted many old turtle excavations. At Sorol, all islands, except the most southern, had significant breeding colonies present. Across the four northernmost islands we noted high densities of black noddies nesting (>3,700 nests counted on transects) mostly in *Tournefortia argentea*, large colonies of sooty terns with fledging chicks (>2,000 chicks), many nesting brown boobies and chicks of all stages (>400 chicks/nests), many nesting red-footed boobies (>350 chicks/nests), and great frigates (>120 chicks/nests). We also confirmed nesting of red-tailed tropicbirds, masked boobies, and white terns in lower abundances. We noted high abundances of coconut crabs on the northernmost island at Sorol with 52 individuals recorded in a short survey. Land crabs were also abundant on the northern islands and we noted high densities of turtle excavations with several hundred noted on transect. At Oroluk Atoll in Pohnpei State no quantitative surveys were conducted however red-footed boobies, and black noddies were noted in high abundances with nesting confirmed for both species.

The introduced mangrove monitor (*Varanus indicus*) and/or rats may be impacting the bird populations at Sorol Island. We saw three monitors in a 40 minute survey there. The replacement of native vegetation with coconut plantation on this island likely also reduces the quality of this site for breeding birds. The other islands of Sorol Atoll are in much better shape with more intact vegetation and only one monitor seen on the island adjacent to Sorol and none seen on the islands further north. These monitors were also noted in surveys and from conversations with locals at several other atolls (Namonuito, Ifalik, and Woleai). During island surveys at the inhabited atolls of Woleai, Namonuito, and Ifalik we noted very few birds.

Many of the islands surveyed are important for both resident breeders and long-range migrants such as curlews and plovers. With proper management of human use, introduced species and vegetation these important populations could continue to thrive into the future.

FIGURE 34.

Fauna noted on at sea and land based timed surveys: (A) black noddies (*Anous minutus*), (B) great frigate (*Fregata minor*), (C) spinner dolphins (*Stenella longirostris*), (D) brown booby (*Sula leucogaster*), (E) red-tailed tropicbirds (*Phaethon rubricauda*), (F) Pacific golden plover (*Pluvialis fulva*), (G) coconut crab (*Birgus latro*), and (H) mangrove monitor (*Varanus indicus*).

TABLE 3.

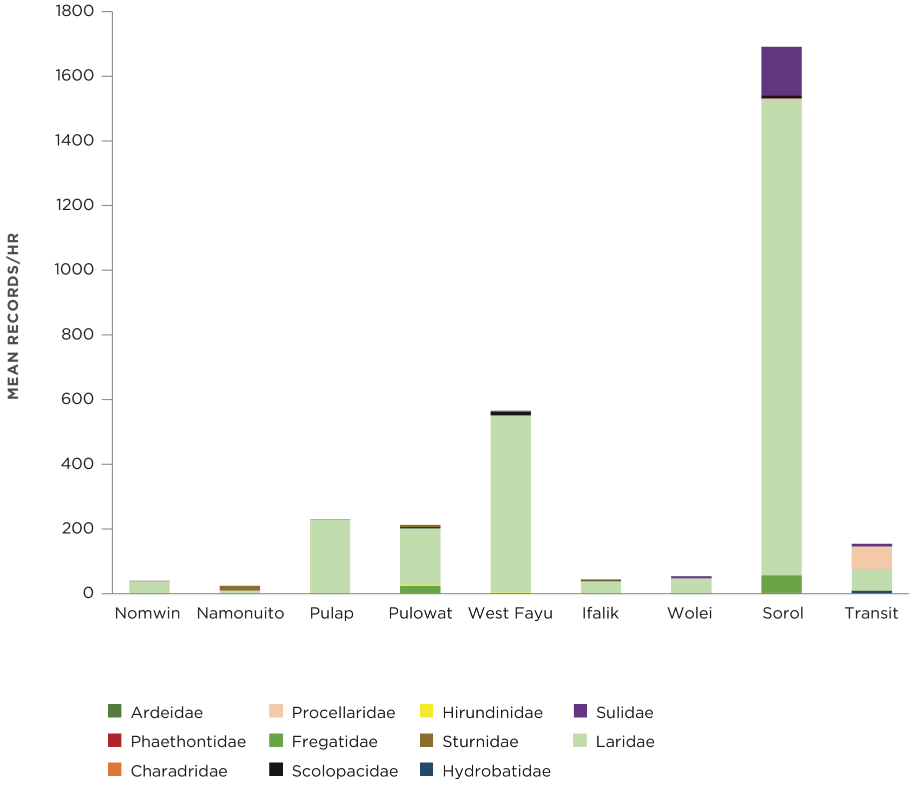
Taxa recorded on timed fauna surveys in Chuuk and Yap states. X's indicate taxa which were present but only observed off transect.

			Chuuk		Yap	
Family	**Binomial**	**Common name**	**Total count**	**Records/hr**	**Total count**	**Records/hr**
Anatidae	*Anas acuta*	northern pintail	0	0	X	X
Ardeidae	*Bubulcus coromandus*	eastern cattle egret	0	0	2	0.20
	Egretta sacra	eastern reef egret	0	0	4	0.40
Charadridae	*Anarhynchus mongolus*	Siberian sand-plover	0	0	1	0.10
	Pluvialis fulva	Pacific golden plover	2	0.29	11	1.10
Fregatidae	*Fregata minor*	great frigate	53	7.76	290	29.05
Hirundinidae	*Hirundo rustica*	barn swallow	9	1.32	6	0.60
Hydrobatidae	Hydrobatidae sp.	storm petrel sp.	0	0	1	0.10
Laridae	*Anous minutus*	black noddy	656	96	7224	723.61
	Anous stolidus	common noddy	79	11.56	173	17.33
	Chlidonias leucopterus	white-winged tern	3	0.44	0	0
	Chlidonias sp.	marsh tern	2	0.29	0	0
	Gelochelidon nilotica	gull-billed tern	2	0.29	0	0
	Gygis alba	white tern	24	3.51	58	5.81
	Onychoprion fuscatus	sooty tern	8	1.17	1880	188.31
	Sterna sumatrana	black-naped tern	2	0.29	9	0.90
	Thalasseus bergii	crested tern	X	X	X	X
Phaethontidae	*Phaethon lepturus*	white-tailed tropicbird	2	0.29	1	0.10
	Phaethon rubricauda	red-tailed tropicbird	0	0	8	0.80
Procellariidae	*Ardenna pacifica*	wedge-tailed shearwater	0	0	8	0.80
	Procellariidae sp.	shearwater sp.	X	X	X	X
Scolopacidae	*Actitis hypoleucos*	common sandpiper	5	0.73	1	0.10
	Arenaria interpres	ruddy turnstone	4	0.59	63	6.31
	Calidris ruficollis	red-necked stint	0	0	1	0.10
	Numenius phaeopus	Eurasian whimbrel	0	0	8	0.80
	Numenius sp.	whimbrel/curlew	X	X	X	X
	Tringa incana	wandering tattler	0	0	6	0.60
Sturnidae	*Aplonis opaca*	Micronesian starling	27	3.95	12	1.20
Sulidae	*Sula dactylatra*	masked booby	0	0	6	0.60
	Sula leucogaster	brown booby	0	0	417	41.77
	Sula sula	red-footed booby	2	0.29	377	37.76

Uninhabited atolls with the highest abundance of seabirds also had the highest fish condition scores. Sorol and West Fayu. Oroluk was noted to be a thriving seabird community but was not surveyed quantitatively.

FIGURE 35.

Relative contribution to abundance of each family of birds recorded on timed transects across the atoll of Chuuk and Yap states. Larids dominated abundance across the board and the atolls of Sorol and West Fayu had the highest abundance of birds.



MANAGEMENT

MANAGEMENT

Marine resources provide essential food sources that are tied deeply with the cultures across the FSM. While a rich traditional knowledge exists that has supported reef tenure and management for centuries, there are modern forces that have quickly changed how resource exploitation can occur.[22] Fire torches that are used mainly during calm nights on reef flats to see fish in the water are being replaced with bright underwater flashlights that extend to the reef slopes. Traditional canoes with limited speed and range are being replaced with fuel-dependent outboard boats. Spears crafted from local wood and shells are being replaced with spears made from metal that are propelled with powerful rubber bands to extend their range. Nets made from plant-based materials are now being replaced with stronger nylon nets that persist for years. One common outcome of these changes is the growing dependence on a western cash-based economy to purchase improved "access" to marine resources, even on the outer FSM atolls that were surveyed. Thus, it was not surprising that human footprints were the primary driver of coral-reef fish assemblages, whereby predictable increases in food-fish biomass existed with distances from land/humans and high wave energy that limits access. While these gradients in fish biomass were common across all atolls, each atoll had a unique baseline, or starting point, which is important when determining the need for, and extent of, management.

In addition to growing fishing technology, climate change represents another major challenge that (traditional) management must cope with. Climate change has begun influencing the FSM atolls in many ways, but especially through the three distinct heat-stress events noted in 2016, 2017, and 2020 (Figure 2). Both the degree of heat stress and the time since heat stress occurred were strong predictors of the abundance and diversity of corals, with predictions and past studies suggesting that ~10 years is needed for recovery for many, but not all, types of coral.[23,24] While the FSM atolls did little to exacerbate climate change, they are among the most influenced by *El Niño* events that are becoming more frequent and intense.

On the global scale, island nations have led global discussions and agreements that aim to mitigate the impacts of climate change. Many studies have discussed how traditional knowledge surrounding reef management might be blended with modern frameworks to help mitigate climate-related impacts.[25-27] Below, management themes are introduced with respect to various levels of government and society.

NATIONAL AND STATE LEVEL

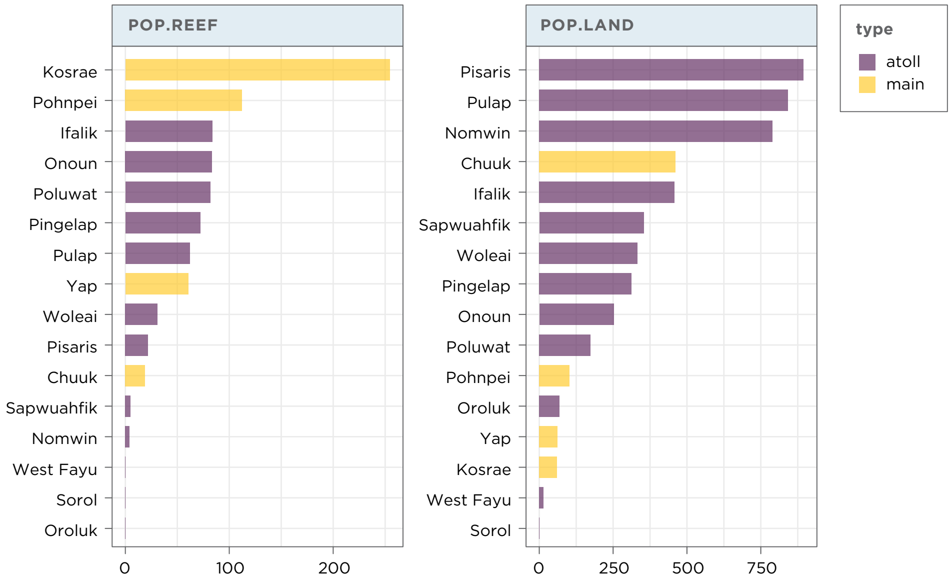
National and state level governments have the potential to address many concerns revealed for the fish resources across uninhabited FSM atolls and for sea cucumber resources across all atolls. Oroluk, West Fayu, and Sorol had relatively high fish biomass that was indicative of sparse human use, representing about 50% of our best estimate of pristine fish biomass found in remote Marshall Islands with no humans. One general rule of thumb used in several published studies is that exploited fish resources should be maintained at 50% of unfished biomass to obtain maximum yields and provide the needed ecosystem functions to recover from major disturbance events.[20,28] Considering that Sorol and West Fayu represent "resource" atolls within Yap State, these results were somewhat expected given intermittent exploitation. However, these results for Oroluk were unexpected considering Pohnpei State law prohibits anything but subsistence fishing for the ~10 people living on the small island, and thus, visits by foreign or even state vessels are the simplest potential explanation. Beyond fish, sea cucumbers were in low abundances across all atolls similarly. Sea cucumbers are known to be susceptible to harvesting and recover slowly following harvesting,[29,30] suggesting that overfishing events can have long-lasting impacts. National and state level management could limit, regulate, and observe foreign and state vessels that have access to these remote locations. This form of management can evolve through two key pathways: 1) improved international cooperation between foreign fleets and the FSM national government that allow better vessel tracking, and 2) improved communication between the local leadership and FSM ships that service the outer islands.

STATE AND ATOLL LEVEL

Among the populated FSM atolls, only three had fish biomass above the 5–7 kg per SPC reference point that strives to balance fisheries productivity and coral-reef resilience in the face of heat-stress events.[31] Sapwuahfik, Pulap, Pingelap had higher than expected fisheries resources on outer reefs (Figure 9). In contrast, none of the atolls had fisheries resources above this benchmark for inner reefs that are more accessible. This was surprising because few of the atolls were actively managing their fisheries resources despite their often-low levels of fisheries resources observed. Unlike FSM main islands, many atolls have high human populations per-reef-area and per-land-area (Figure 36). Therefore, it is unlikely that improving agriculture and terrestrial resources can provide a means for atoll societies to flourish while marine resources decline. This situation sets the stage for improving the management of fisheries resources to promote sustainable livelihoods across the FSM atolls. Because atolls are experiencing similar challenges, improving access to learning networks, discussions of the present science, and sharing of (traditional) forms of management can create a positive learning environment that benefits all.

FIGURE 36.

Human populations per-reef-area and per-land-area across the main FSM islands and outer atolls.



TRADITIONAL AND MODERN FORMS OF MANAGEMENT

No-take MPAs represent an ideal foundation for improving fisheries resources when stocks are at low levels and the risks of overfishing are high in terms of food security. A network of MPAs placed in proximity to each other can allow the fish populations to become connected through migration and larval transport.[32] In turn, connected fish populations can grow faster and provide benefits to the non-MPA reefs around the atoll. In support, MPAs networks were initiated in Pohnpei and Yap about a decade ago and have improved island-scale fisheries resources, especially when combined with other forms of fisheries management.[33] Beyond fisheries, MPA networks can help maintain coral diversity and allow for faster recovery following heat-stress. In fact, one recommended approach to mitigate heat-stress events associated with climate change is to maintain networks of MPAs with distances between them scaled to match both coral and fish larval connectivity. While permanent, rotational, or temporary MPAs have a long history of use across most islands for customary and cultural needs,[34] permanent or long-term fixed MPA networks are recommended based upon present fish abundances observed in combination with growing heat-stress events. In support, the data were unable to detect any benefits from the rotating MPA described at Sapwuahfik atoll, whereby the eastern and western portions of the atoll are open/closed to fishing intermittently. Instead, we simply observed a strong gradient in fish biomass based upon distance to nearest land and humans.

Yet, MPAs are not the total solution for managing fisheries and the depletion of resources close to human settlements found across the atolls requires a greater focus on species-or-gear management as well. This situation was especially true for the inner reefs, and most especially for inner reefs associated with small atolls where fisheries resources were depleted such as Pingelap and Ifalik. In Pingelap, management appeared to be adjusting to this situation, as there was a clam farm project that provided food security and economic benefits from the inner reefs where fisheries were depleted. Without any compensatory management such as clam farms, the depletion of inner atoll resources results in higher costs and greater risks to access reefs further away.

Even if these costs can be overcome, there is a growing need for food security from nearby reefs as storm events also intensify with climate change. Fishing effort might therefore be lowered in many ways that resonate with traditional management. Reef ownership and tenure encourages limited reef use for mainly subsistence purposes throughout several of the atolls visited such as Woleai and Nomwin. Here, reef owners have determined what reefs are fished, what gears are used, and whether or not export beyond the atoll is allowable. The data suggested that no-take MPAs appeared to be improving fish abundance, however, outside of these individual MPAs fish resources were significantly lower. In the interesting case of Pulap atoll, it is currently unclear what leads to the relatively abundant fisheries resources observed despite similar human population densities per-reef-area. However, a greater presence of subsistence livelihoods with less western influence was noted. Similarly, fisheries resources on the outer reefs of Pingelap were better than expected, whereby the community used size-based management to protect larger fish and limited exports through Pohnpei State ships that service the island (i.e., greater focus on subsistence livelihoods). The data collected will contribute to FSM's goals of sustainable resource management, specifically through the Blue Prosperity Micronesia program and Micronesia Challenge. Through Blue Prosperity Micronesia, state governments are developing Marine Spatial Plans – a public, stakeholder-driven and science-based process that involves mapping out different activities and uses in a specific marine area, such as fishing grounds, protected areas and tourism sites, and then determining how they can best coexist and be managed sustainably. This updated baseline data will be used by Blue Prosperity Micronesia in each state to improve resource management and inform marine spatial planning.

CONCLUSIONS

The present report documented the status of marine resources across the remote FSM atolls based upon fieldwork conducted between October and November 2023. The results offer a unique perspective on how remote atoll societies are interacting with their marine resources. Beyond the local use of marine resources, we also revealed how foreign or state ships appear to influence fisheries resources in a disproportional manner. Indeed, proxies to fishing pressure such as distances from humans were the primary drivers of both fish and benthic assemblages. Secondary but growing drivers of benthic substrates and coral assemblages were heat-stress events associated with climate change. By disentangling these factors we hope to facilitate locally-driven management to improve livelihoods in the FSM atolls and their inter-atoll communication networks. The results of the expedition will provide a more comprehensive understanding of the health of FSM's ocean and will help Micronesians make informed decisions about the best way to protect and sustainably manage their marine resources.

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ACKNOWLEDGEMENTS

The Blue Prosperity Micronesia & National Geographic Pristine Seas Marine Science Expedition would not have been possible without the leadership of the national, state and local governments of the Federated States of Micronesia.

The scientific expedition was conducted through a partnership between National Geographic Pristine Seas and the Blue Prosperity Micronesia Program.

Thank you to the following partners who contributed to the planning and execution of this assessment:

- University of Guam Marine Lab
- Micronesia Coral Reef Monitoring Team
- Scripps Institution of Oceanography
- Micronesia Conservation Trust
- Waitt Institute

Research on the main FSM islands has been supported by numerous organizations over the years:

- National Oceanic and Atmospheric Administration Coral Conservation Program (NOAA)
- National Fish and Wildlife Foundation
- The Nature Conservancy Micronesia
- United Nations Development Program for FSM
- Blue Prosperity Coalition
- Waitt Institute

The authors are grateful for the support of the crew on the MV Argo and the logistical team. The expedition team was fortunate to have the support of our expedition leader Paul Rose.

APPENDIX

APPENDIX TABLE 1.

Taxa observed on deep sea camera systems. Frequency of occurrence is measured as the percent (%) of the total 19 deployments on which the taxon was observed. For bait-attracted taxa, MaxN, a metric of relative abundance, represents the maximum number of individuals observed in a single frame at a given time. This metric was derived from only the deployments for which a 14-hour mission time was used, as that mission duration is the standard protocol across other samples from the region; 6-hour deployments were used to derive freq. of occ., but were excluded from MaxN.

Phylum	Class	Order	Family	Taxa	Freq. of occ. (%)	MaxN
Foraminifera				Xenophyophoroidea	5	
Porifera	Hexactinellida	Lyssacinosida	Rossellidae	Rossellidae	5	
		Sceptrulophora	Farreidae	Farreidae	5	
		Amphidiscosida	Hyalonematidae	Hyalonema	5	
			Pheronematidae	Poliopogon	5	
Cnidaria	Anthozoa	Actiniaria		Actiniaria	5	
	Hexacorallia	Antipatharia	Schizopathidae	Schizopathidae	5	
				Telopathes sp.	5	
			Antipathidae	*Antipathes* sp.	5	
		Scleractinia		*Scleractinia* sp.	5	
	Hydrozoa	Trachymedusae		Trachymedusae	11	
			Rhopalonematidae	*Benthocodon* sp.	5	
Cnidaria	Octocorallia	Scleralcyonacea	Chrysogorgiidae	*Chrysogorgia* sp.	11	
			Coralliidae	*Paragorgia* sp.	5	
			Keratoisididae	Keratoisididae	5	
			Kophobelemnidae	*Kophobelemnon* sp.	5	

Cnidaria			Primnoidae	Primnoidae	5	
Ctenophora				Ctenophora	5	
Chaetognatha				Chaetognatha	5	
Arthropoda	Copepoda			Copepoda	42	
	Malacostraca	Amphipoda		Amphipoda	74	75
			Eurytheneidae	*Eurythenes* sp.	21	10
		Decapoda	(Superfamily) Penaeoidea	Penaeoidea	63	2
			Aristeidae	*Aristaeopsis edwardsiana*	42	1
				(tent.) Aristeidae	21	2
			(Infraorder) Caridea	Caridea	37	1
			Acanthephyridae	*Acanthephyra* sp.	32	2
				Acanthephyridae	42	5
			Homolidae	Homolidae	16	1
			Lithodidae	*Lithodes* sp.	5	1
				Neolithodes sp.	5	1
			Nematocarcinidae	*Nematocarcinus* sp.	63	2
			Pandalidae	*Heterocarpus ensifer*	16	
				Heterocarpus sp.	37	35
				Plesionika sp.	11	
			(tent.) Stylodactylidae	(tent.) Stylodactylidae	5	1
			Munididae	*Munida* sp.	11	
				Munididae	26	
			Parapaguridae	*Sympagurus dofleini*	21	
				Sympagurus sp.	5	
				Parapagurus sp.	5	
			Oregoniidae	*Cyrtomaia* sp.	5	
			Leucosiidae	*Tanaoa distinctus*	11	
		Isopoda		Isopoda	5	
			Aegidae	Aegidae	5	
		Mysida		Mysida	26	

Echinodermata	Crinoidea			Crinoidea	11	
	Echinoidea	Echinothurioida	Echinothuriidae	Echinothuriidae	16	1
	Holothuroidea			Holothuroidea	16	
		Elasipodida	Pelagothuriidae	*Enypniastes eximia*	11	
		Synallactida	Synallactidae	*Paelopatides* sp.	5	
	Ophiuroidea			Ophiuroidea	11	1
Mollusca	Cephalopoda			Cephalopoda	5	
Chordata	Holocephali	Chimaeriformes	Chimaeridae	*Hydrolagus purpurescens*	16	3
				Hydrolagus sp.	16	1
	Elasmobranchii	Carcharhiniformes	Pseudotriakidae	*Pseudotriakis microdon*	42	1
		Hexanchiformes	Hexanchidae	*Hexanchus griseus*	5	
		Squaliformes		Squaliformes	21	2
				Squalus sp.	21	
			Etmopteridae	Etmopteridae	21	1
			Somniosidae	Somniosidae	26	1
				Somniosus sp.	5	1
	Teleostei	Anguilliformes	Synaphobranchidae	Synaphobranchidae	37	8
				Synaphobranchus affinis	26	3
				Synaphobranchus sp.	68	10
				Ilyophinae	16	1
			Ophichthidae	Ophichthidae	5	
		Gadiformes	Macrouridae	*Coryphaenoides rudis*	21	1
				Coryphaenoides sp.	42	6
				(tent.) *Coryphaenoides longicirrhus*	16	1
				Coelorinchus doryssus	11	
				Coelorinchus sp.	16	2
				Nezumia sp.	21	1
				Gadomus sp.	5	
				Macrourinae	21	2
				Bathygadinae	5	1

Chordata			Moridae	*Lepidion* sp.	11	1
		Lophiiformes	Ogcocephalidae	(tent.) *Halieutaea* sp.	5	
		Mychtophiformes	Myctophidae	Myctophidae	5	
		Notacanthiformes	Halosauridae	Halosauridae	63	
				(tent.) *Aldrovandia* sp.	5	
		Ophidiiformes	Ophidiidae	Ophidiidae	47	2
				Bassogigas sp.	5	1
		Perciformes	Bembropidae	*Chrionema chryseres*	5	
			Lutjanidae	*Etelis boweni*	5	
		Scombriformes	Gempylidae	*Ruvettus pretiosus*	5	1
		Scorpaeniformes	Peristediidae	*Scalicus* sp.	5	
	(tent.)	Alepocephaliformes	(tent.) Alepocephalidae	(tent.) Alepocephalidae	5	1

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