FEDERATED STATES OF MICRONESIA

Nearshore marine resources across the atolls of the Federated States of Micronesia

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

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NATIONAL GEOGRAPHIC
PRISTINE SEAS

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TABLE OF **CONTENTS**

INTRODUCTION

INTRODUCTION

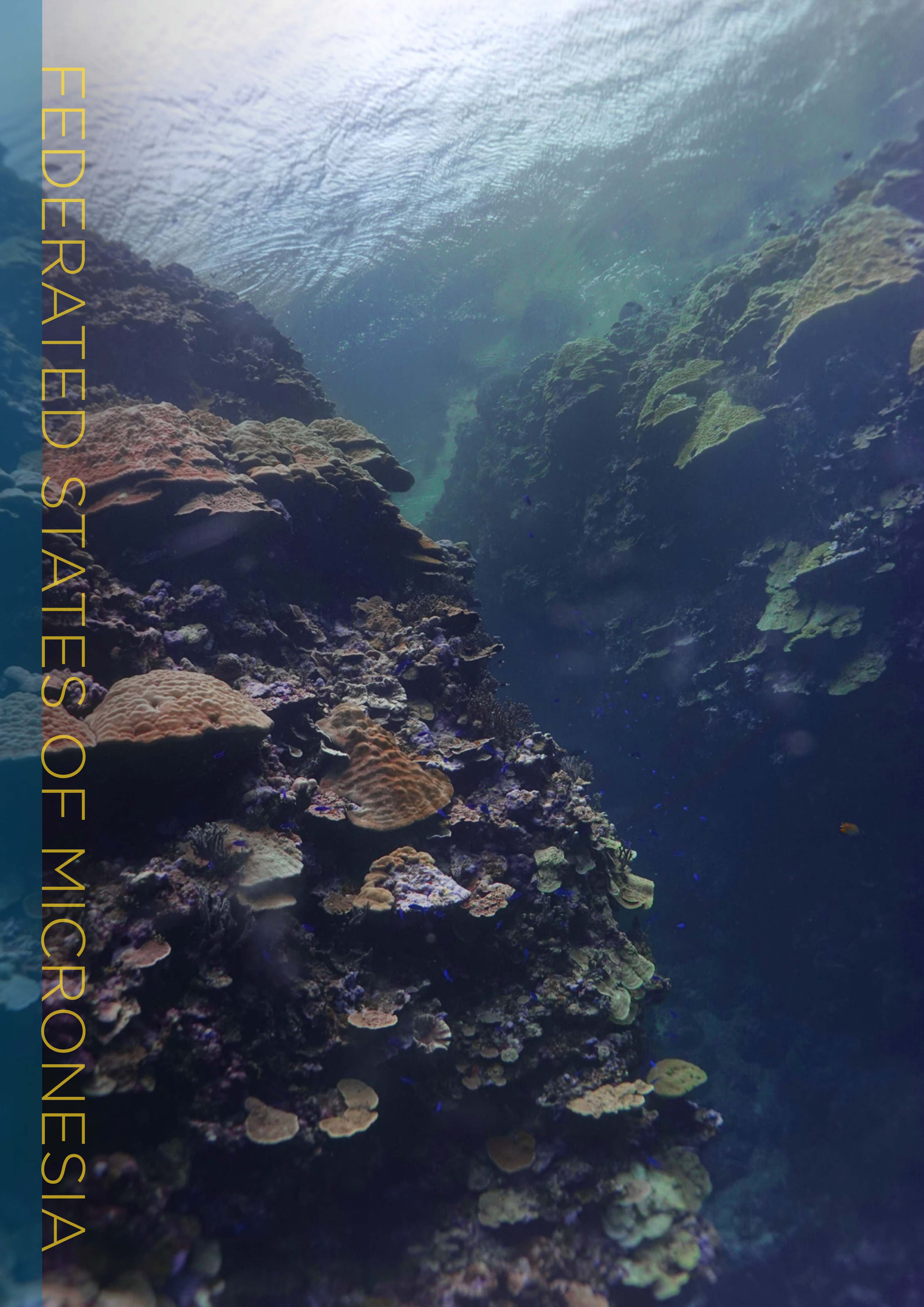
The Federated States of Micronesia (FSM) economic exclusive zone accounts for nearly 3 million km^2 of the western Pacific Ocean despite having only 701 km^2 of land. These extensive ocean resources are a consequence of 607 FSM islands spread across a huge portion of the tropical Pacific (1° to 10° N, 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). In general, 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 a unique collaboration between the National Geographic Pristine Seas, Blue Prosperity Micronesia Coalition, the numerous organizations that together comprise the Micronesia Coral-Reef Monitoring program, and the FSM national, state, and local governments. 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 Micronesia 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

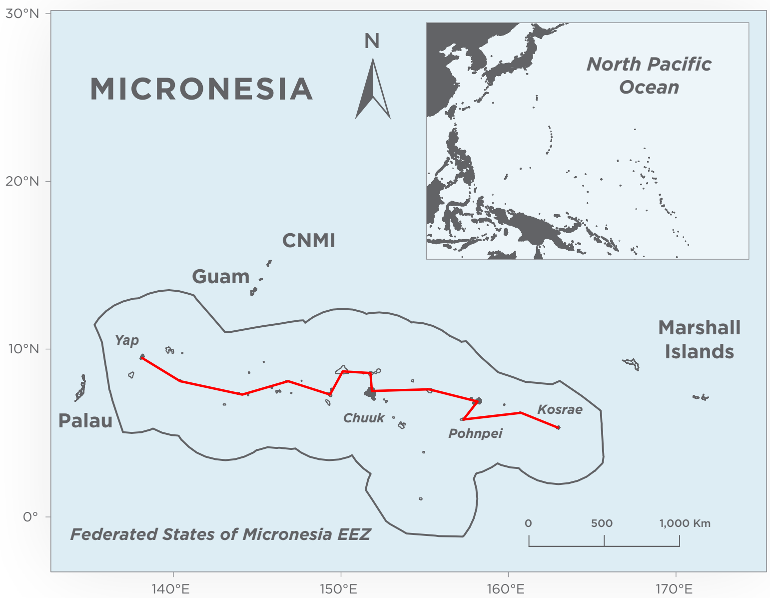
FEDERATED STATES OF MICRONESIA

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 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 increase religious and economic centers.[4] In the late 1800's, 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. Japan 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 economic exclusive 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 economic exclusive zone accounts for nearly 3 million km^2 of the western Pacific Ocean, representing the 14^{th} largest in the world, despite having only 701 km^2 of land. While there are 607 islands across the FSM, 65 are inhabited. Human populations are centered on the main four 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 represent 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]

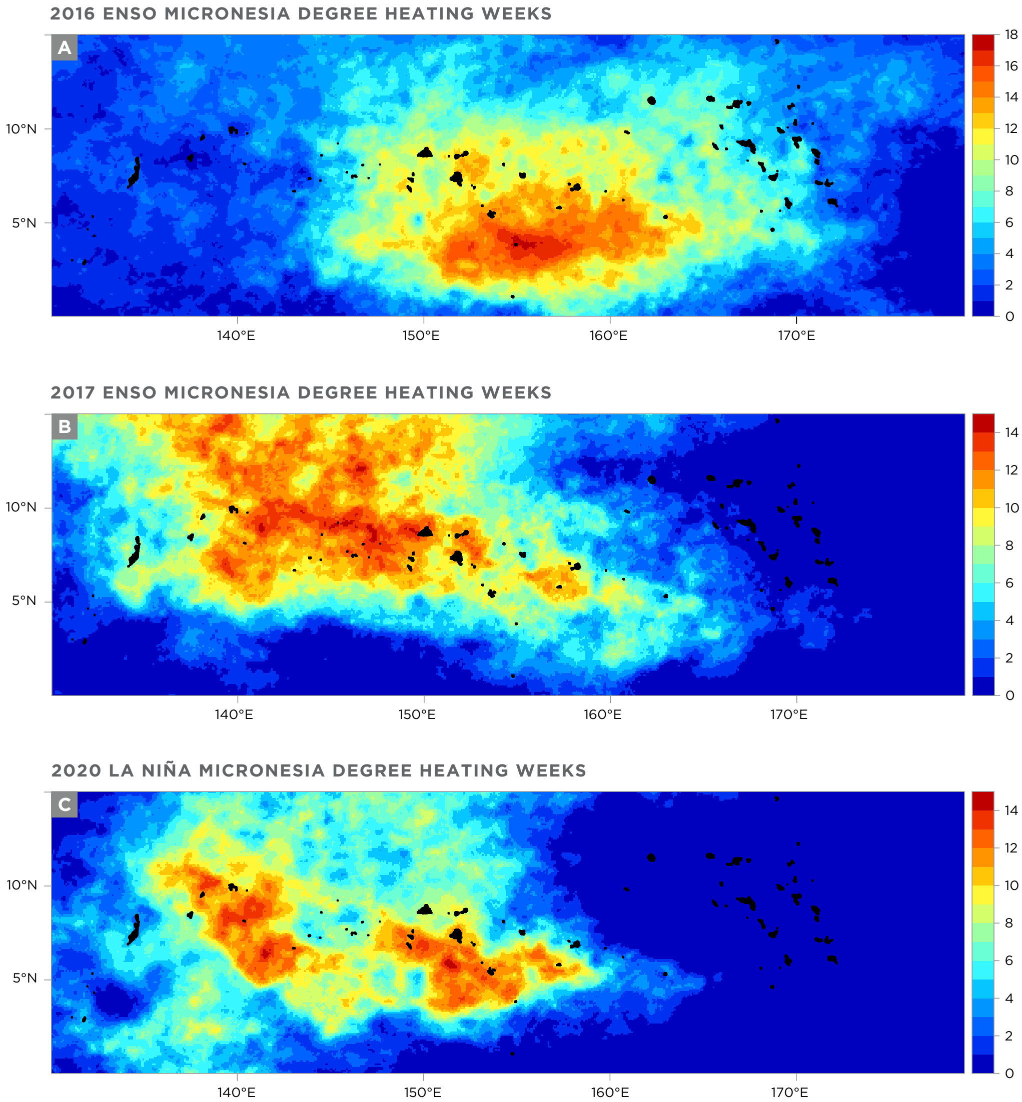


FIGURE 2.

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 predate 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.

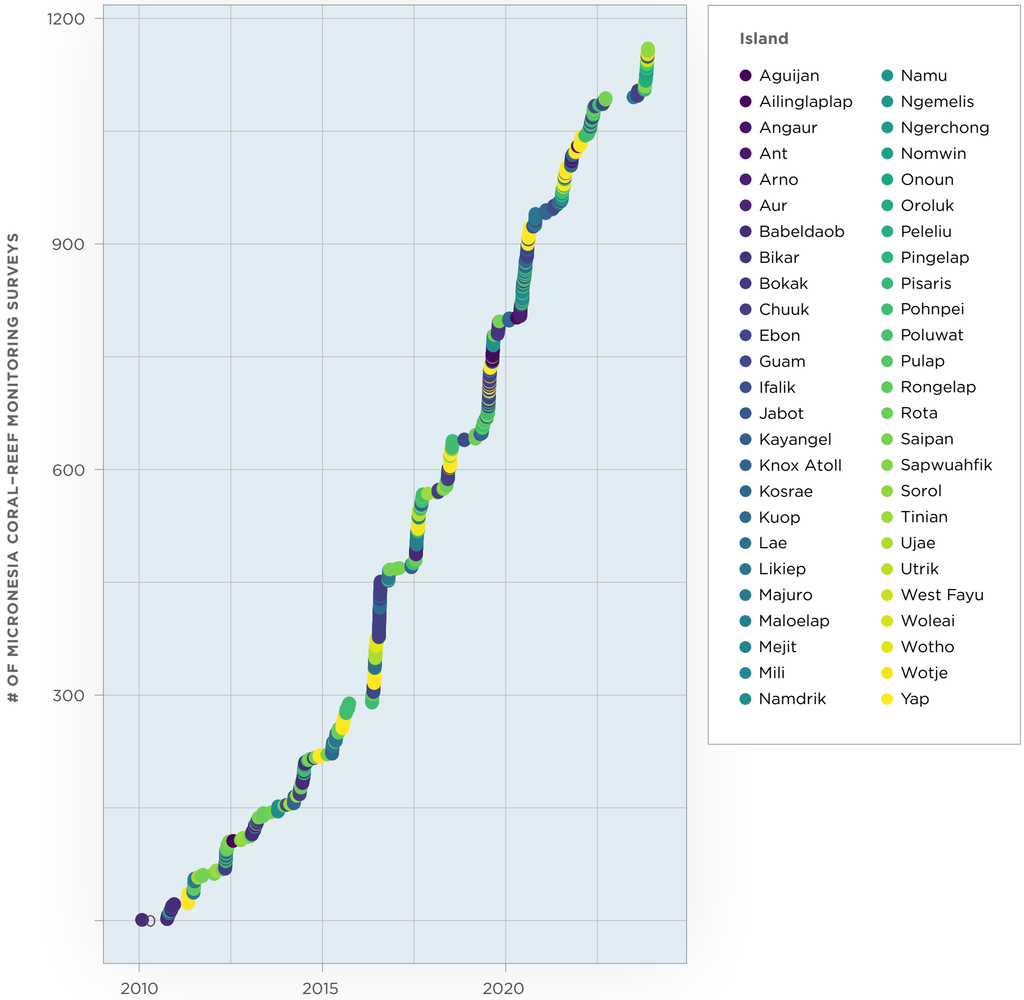
Within FSM, there have been significant spatial differences in the frequency and magnitude of heat stress to the oceans. The recent 2015 to 2017 ENSO event caused heat stress to the FSM ocean, however, many remote atolls near Chuuk experienced up to three times the amount of heat stress compared to remote Yap atolls (Figure 2a-c). In turn, the heat stress lead 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 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.

2009–10

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

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.

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.

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.

2015

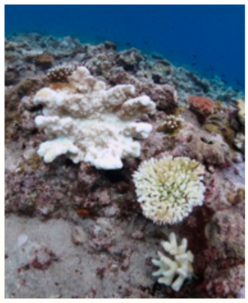
First Micronesia Challenge (MC) assessment revealed that no FSM state is above the desired 30% effective conservation threshold and nearshore fishing pressure and land-based pollution are the primary and secondary sources of stress, respectively.

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.

2020

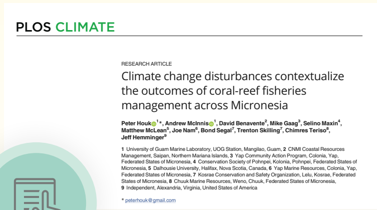
Political leaders agreed to strengthen and extend the MC. Leaders set new conservation goals that require effective management of 50% of marine resources and 30% of terrestrial resources by 2030.



2023–

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

2024



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.

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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METHODS

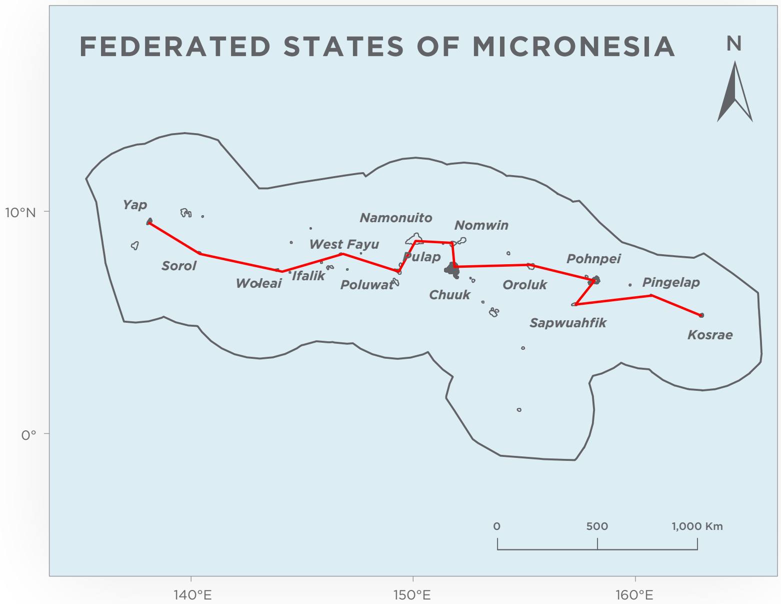
METHODS

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 next 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 then collect data describing the abundances and sizes of fish, corals, benthic substrates, and macroinvertebrates such as sea cucumbers described by MCRM methods (Figure 6).

FIGURE 4.

Map showing the FSM and the expedition route.



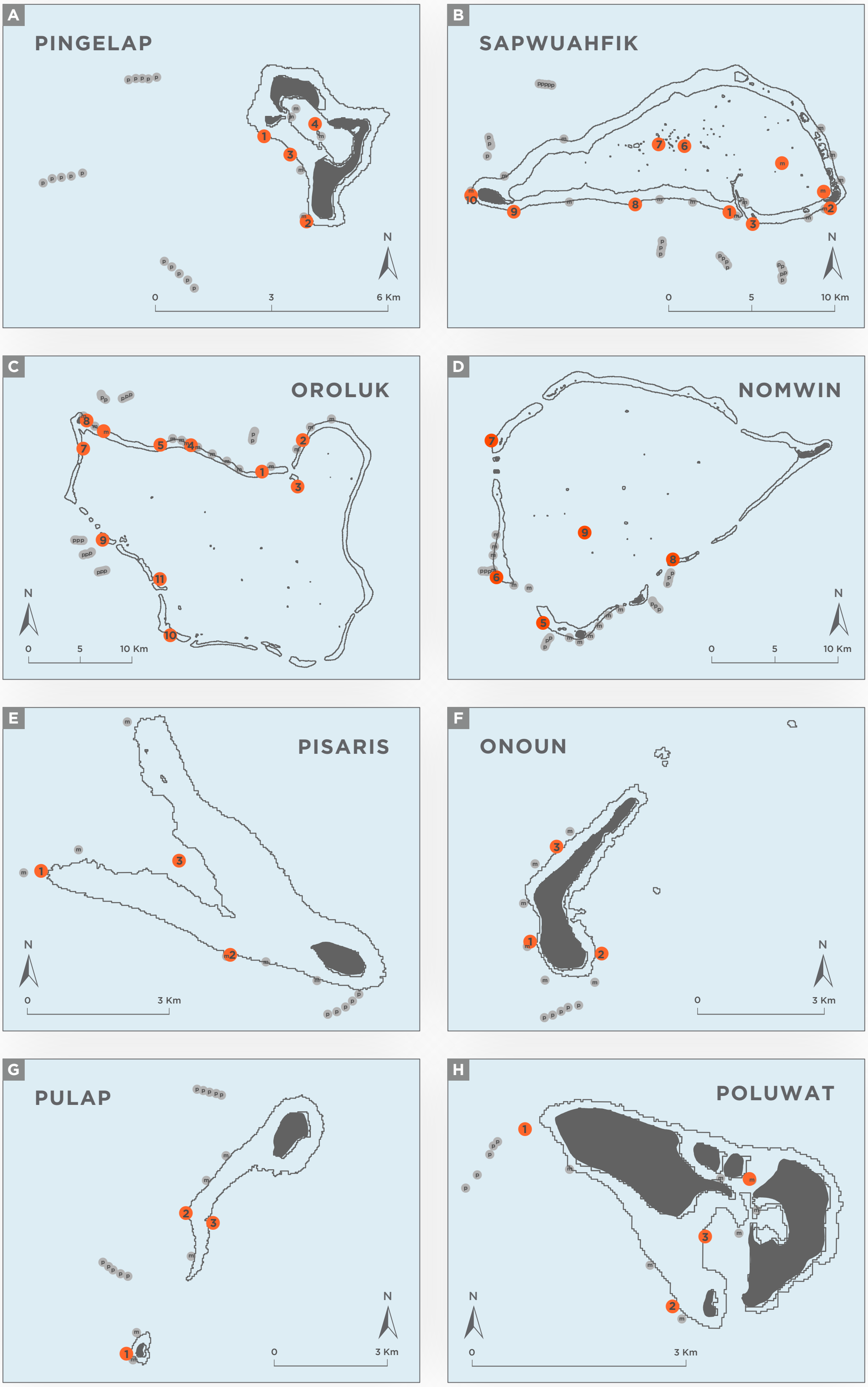


FIGURE 5.

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 mesopelagic bottomfish (m) and pelagic fish (p).

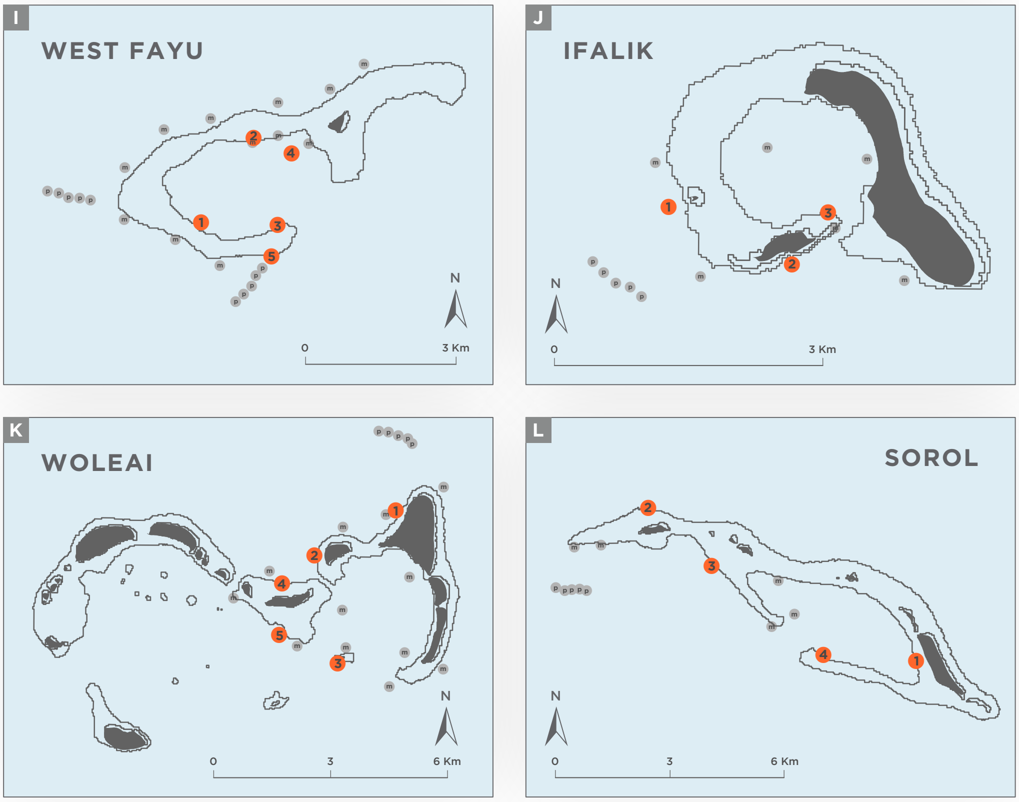
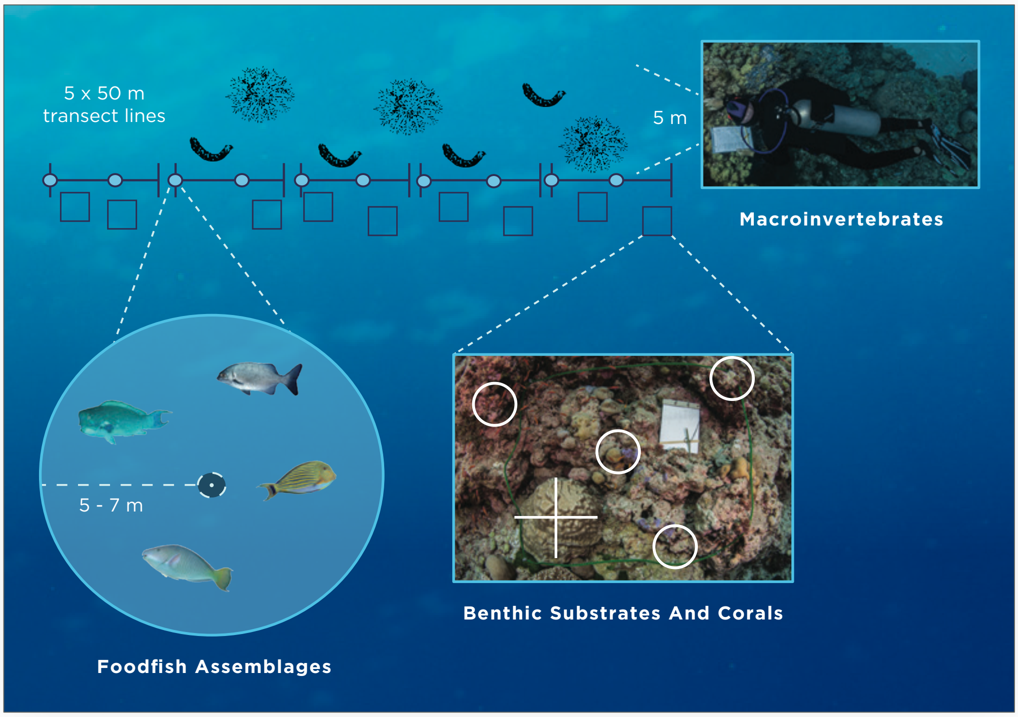


FIGURE 6.

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 observed 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, the fortunate fieldwork collaboration with NGPS provided additional information for the FSM atolls that will be included in the final report. Here, the preliminary report includes site locations for baited remote underwater visual assessments (BRUVS) that were used to assess the deeper bottom fish and offshore pelagic fish. Both resources were assessed using baited camera rigs that record the identity and sizes of passing fish. Last, bird observations were recorded while deploying the BRUVS and also from opportunistic land-based transects.

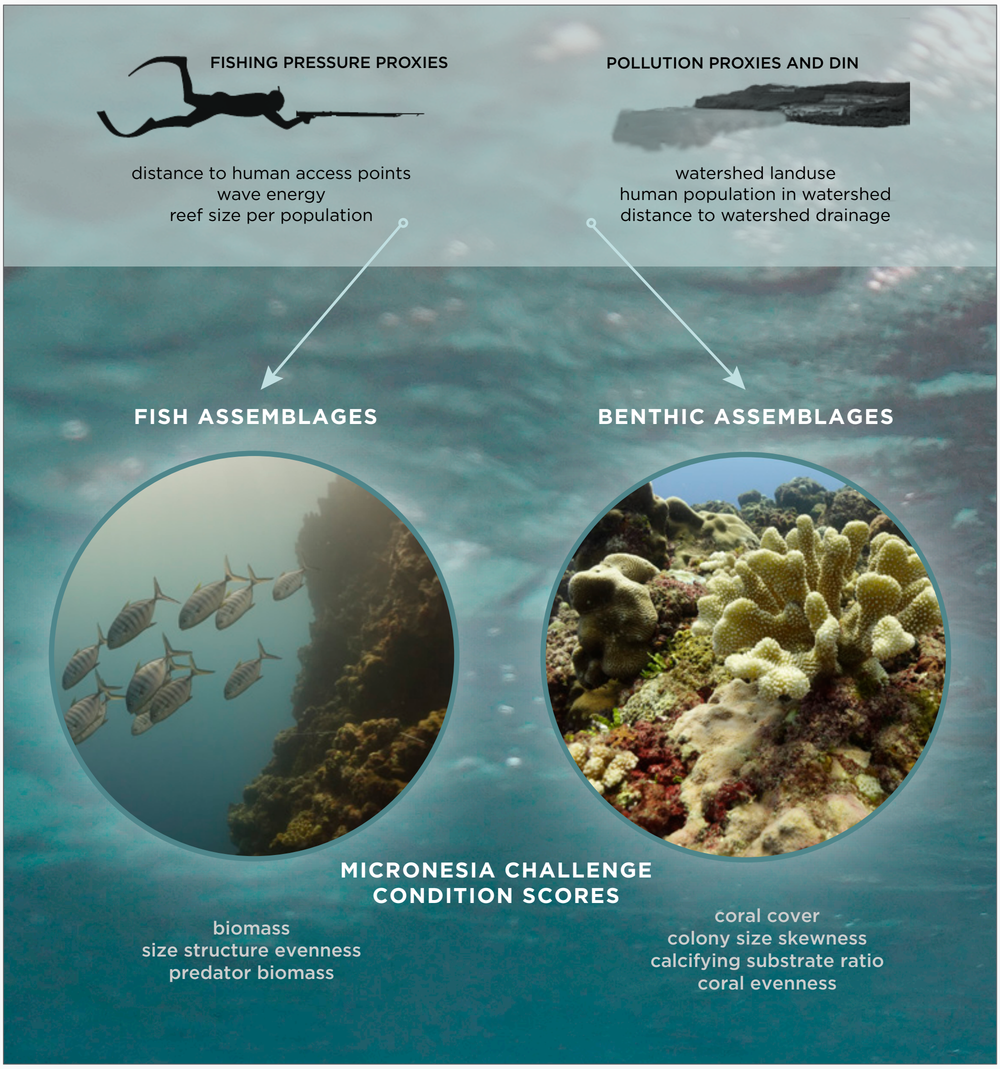
DATA ANALYSES AND MC SCORECARD

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 process, depicting the overall condition or health of fish and corals beyond percent cover or biomass.[16] A regional team of scientists and managers associated with the MC developed a scorecard process by selecting a series of weakly correlated metrics among a large list. These metrics were selected to together depict condition (Figure 7). Many past studies highlight the nature and utility of this condition metric.[16-18] MC condition scores were last examined with respect to several environmental factors. Environmental factors that were used to predict the condition of MC scores in the outer FSM atolls 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

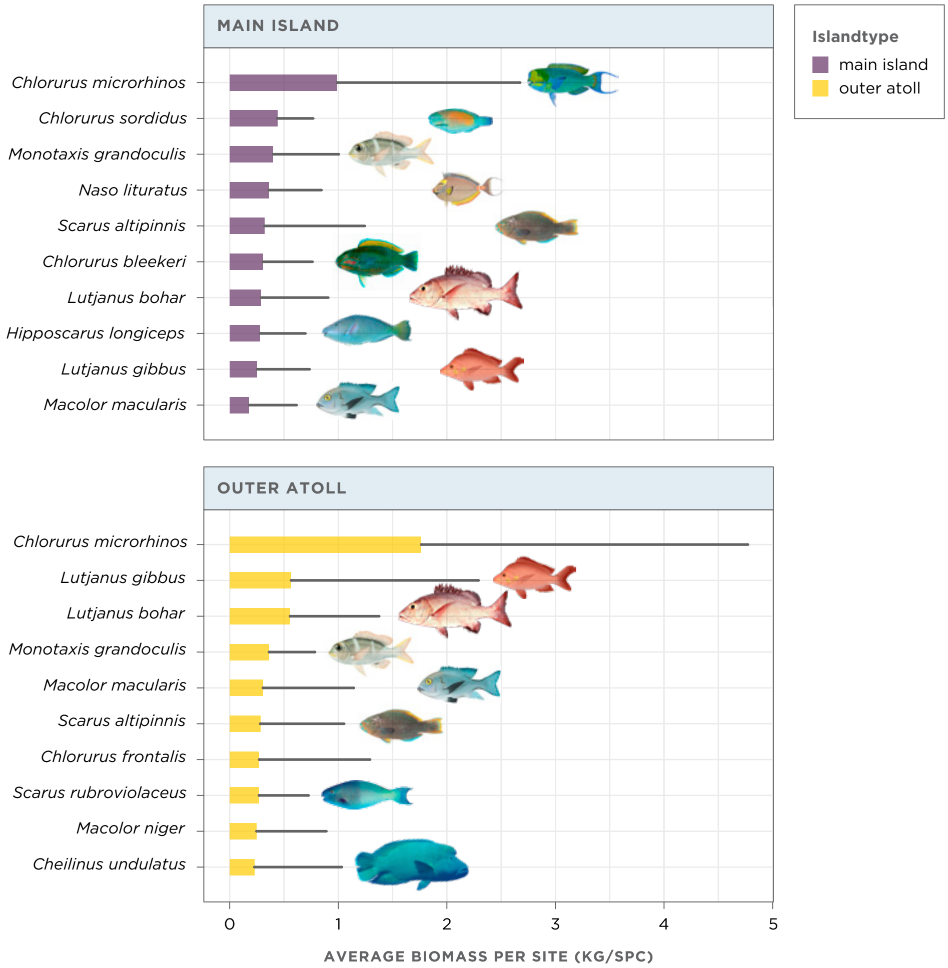
FISH ASSEMBLAGES

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 were a suite of large and small parrotfishes, snappers and the dominant big-eye emperor fish *Monotaxis grandoculis*. Together, these represented popular species of foodfish that have influential ecological roles in the coral-reef ecosystem. Top species were represented by mixed body sizes and trophic levels, and notably for outer atolls, the Napolean wrasse (*Cheilinus undulatus*).

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) with limited human presence (Figure 9). 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 limited 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 occurs.

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.

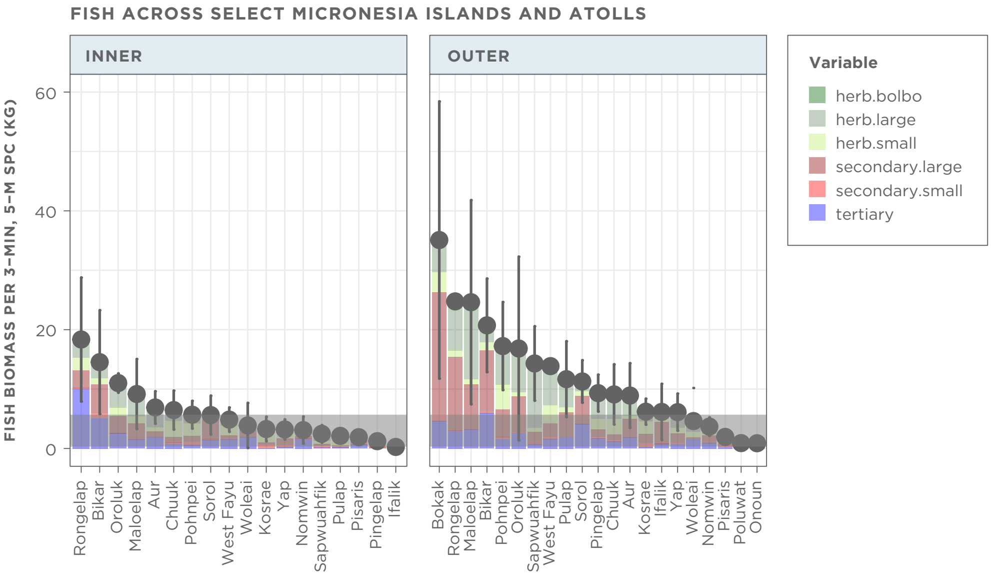


Meanwhile, several atolls had notably low fish biomass including Onoun, Poluwat, Pisaris, Nomwin, and non-protected reefs around Woleai. All of these atolls had average site-based fish biomass below the 5–6 kg/SPC threshold that was previously associated with reef recovery following climate-induced disturbance 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 and furthered in the management section. Notably 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, that are also furthered below.

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

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.

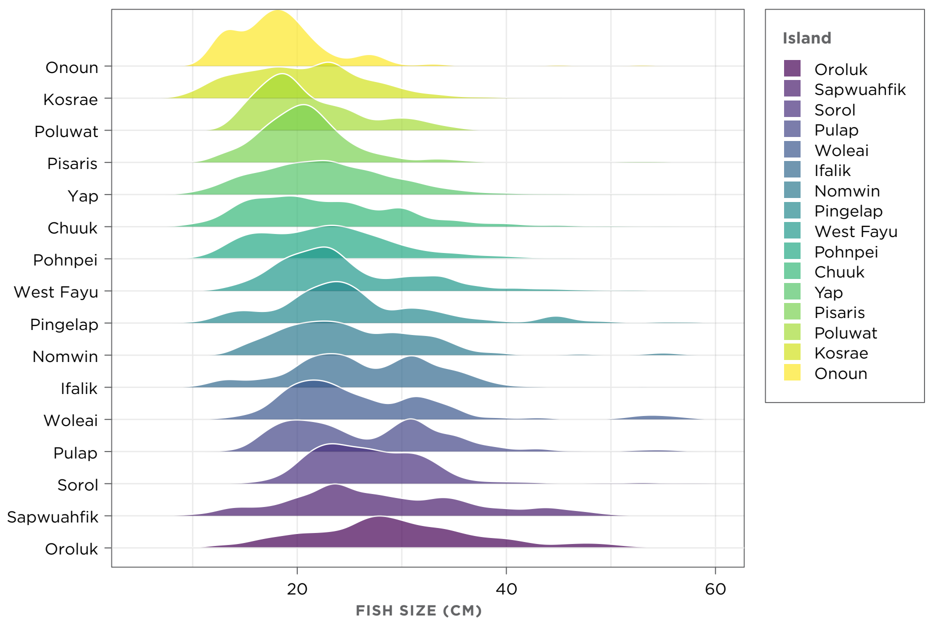


diversity are known to mitigate the effects of climate disturbances while also providing an essential food source. These trends may be due to the influence of fish markets on the main islands compared to more subsistence fishing on the atolls. Past studies have shown that fish markets attract larger 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

FIGURE 10.

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



MC condition score attributed to successful fisheries management policies including 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 that are furthered below. 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).

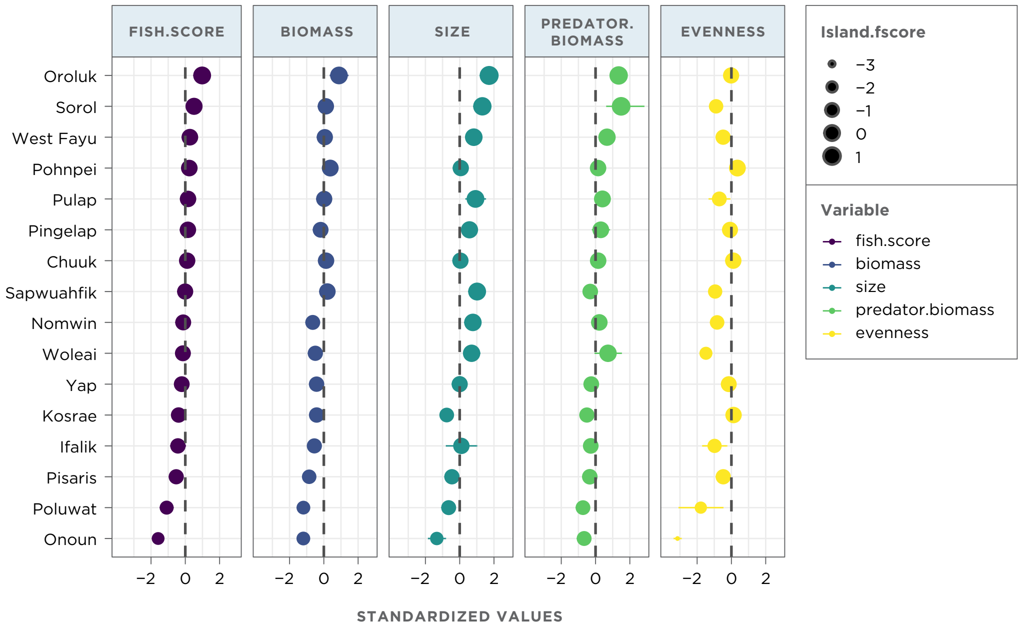


FIGURE 12.

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 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 large waves 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 MPA had much higher condition that 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.

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 have powerful elastic 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. As a result, there have been many studies describing how traditional knowledge can and should be blended with modern management frameworks in order to sustain the diverse Pacific Island cultures.

NATIONAL AND STATE LEVEL

Our results revealed the status of marine resources across the FSM varied widely but predictably. The uninhabited FSM atolls of Oroluk, West Fayu, and Sorol had relatively high fish biomass that was approximately 50% of the most pristine remote Marshall Islands where little human presence exists. 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.[20,23] 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 few people living on the small island.

The main theme of management for these remote atolls is therefore to ensure that no foreign or unauthorized state vessels gain access to fisheries resources. 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 cargo ships that service the outer islands. Anecdotal conversations suggested that these two pathways both lead to undesirable exploitation of fisheries resources, and that localized fishing is small in comparison due to limited access.

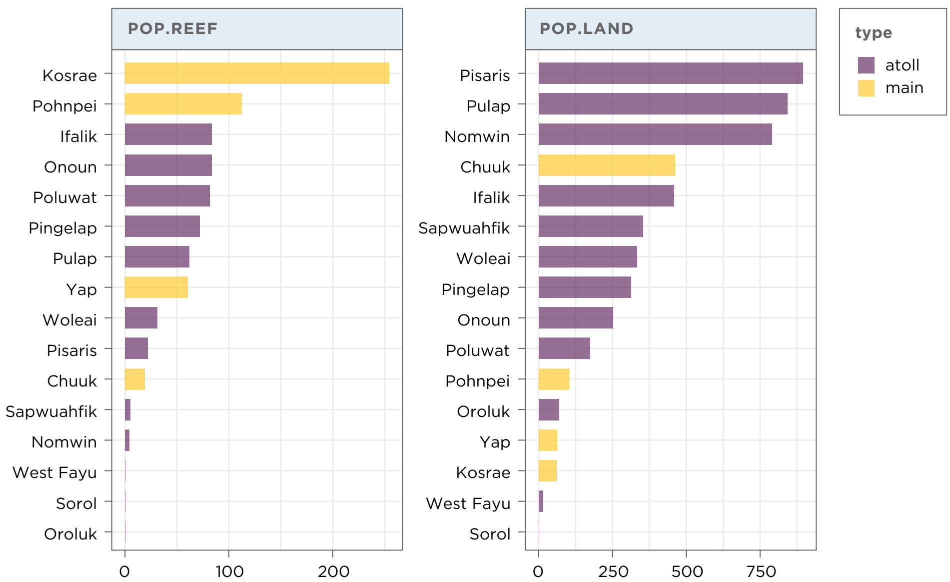
STATE AND ATOLL LEVEL

Elsewhere for the populated FSM atolls, only three had fisheries resources on the outer reefs in excess of the 5–7 kg per SPC reference point previously show to promote both subsistence needs and reef recovery following disturbance events (Sapwuahfik, Pulap, Pingelap—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 and the growing intensity of climate change disturbances observed. Unlike FSM main islands, the atolls have both high human populations per-reef-area and per-land-area (Figure 13). It is less likely that improving agriculture and terrestrial resources can provide a means for atoll societies to deal with marine resources decline. This situation sets the stage for improving the management of fisheries resources.

No-take MPA represent an ideal foundation for improving fishery resources when low levels are observed around an entire atoll, common across several FSM atolls.

FIGURE 13.

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



A network of MPAs placed in proximity to each other can allow the fish populations to become connected through migration and larval transport.[24] In turn, connected fish populations can grow faster and provide benefits to the non-MPA reefs around the atoll. In support, MPAs 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.[25] Permanent, rotational, or temporary MPAs have a long history of use across most islands for customary and cultural needs making them one desirable approach if designed and managed appropriately.[26]

Yet, MPAs are not the panacea for managing fisheries and the depletion of resources close to human settlements found across the atolls (Figure 12). This situation was especially true for the inner reefs associated with small atolls. The distance gradient in fisheries resources was undesirable given the high cost of fuel that is required to access better resources further away, and the growing need for food security nearby as climate change intensifies. Fishing effort can be lowered in many ways that may correspond 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. Meanwhile in Pingelap where fisheries resources on the outer reefs were better than expected, the community uses size-based management to protect spawning stocks and limits fish exports through Pohnpei State cargo ships that service the island. Last, in the interesting case of Pulap atoll, it is currently unclear what leads to the relatively abundant fisheries resources despite high humans per-reef-area. 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 preliminary report covered the fisheries resources documented across the remote FSM atolls. Over the next few months, this report will be updated to include the status of the coral reefs, sea cucumbers and other invertebrates, deeper bottom fisheries, pelagic fisheries, and birds. The goal will be to provide a broad perspective on the status of marine environments across the FSM. This will help disentangle the influences of foreign versus local exploitation, (climate-change) disturbances, and other natural factors that impact FSM marine resources. 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.

REFERENCES

REFERENCES

1 Carson, M. Austronesian migrations and developments in Micronesia. *Journal of Austronesian Studies 4* (2013).

2 Mellon, J. Sacred Vessels: Navigating Tradition and Identity in Micronesia. *The Contemporary Pacific 11*, 501 (1999).

3 Petersen, G. Indigenous island empires: Yap and Tonga considered. *Journal of Pacific History 35*, 5-27 (2000).

4 Cruz Berrocal, M. & Sand, C. A question of impact: Did we underestimate the consequences of the sixteenth and seventeenth centuries period of early European exploration in the Pacific? *Journal of Island 16*, 231-260 (2021).

5 Klingman, L. & Greene, G. J. His Majesty O'Keefe. (1950).

6 Goodman, G. K. & Moos, F. *The United States and Japan in the Western Pacific: Micronesia and Papua New Guinea*. (Routledge, 2019).

7 Burdick, A. The constitution of the Federated States of Micronesia. *University of Hawaii Law Review 8*, 419 (1986).

8 Lander, M. A. & Khosrowpanah, S. *Rainfall Climatology for Pohnpei Island the Federated States of Micronesia*. (Water and Environmental Research Institute of the Western Pacific ..., 2004).

9 D'Arcy, P. The Role of the Tuna Fishery in the Economy of the Federated States of Micronesia. *Pacific Economic Bulletin 21* (2006).

10 Fletcher, C. H. & Richmond, B. M. Climate change in the Federated States of Micronesia. *University of Hawai'i, Hawaii* (2010).

11 Houk, P. *et al.* Predicting coral-reef futures from El Niño and Pacific Decadal Oscillation events. *10*, 7735 (2020).

12 Houk, P. & Van Woesik, R. Progress and perspectives on question-driven coral-reef monitoring. *Bioscience 63*, 297-303 (2013).

13 Cuetos-Bueno, J., Hernandez-Ortiz, D., Graham, C. & Houk, P. Human and environmental gradients predict catch, effort, and species composition in a large Micronesian coral-reef fishery. *PLoSONE 13*, e0198068 (2018).

14 Houk, P. *et al.* An applied framework to assess exploitation and guide management of coral-reef fisheries. *Ecosphere 8*, e01727 (2017).

15 Taylor, B. & Choat, J. Comparative demography of commercially important parrotfish species from Micronesia. *Journal of Fish Biology 84*, 383-402 (2014).

16 Houk, P. *et al.* The Micronesia Challenge: assessing the relative contribution of stressors on coral reefs to facilitate science-to-management feedback. *PLoSONE 10*, e0130823 (2015).

17 Comeros-Raynal, M. T. *et al.* Applying a ridge-to-reef framework to support watershed, water quality, and community-based fisheries management in American Samoa. *Coral Reefs 38*, 505-520 (2019).

18 Houk, P. *et al.* Nutrient thresholds to protect water quality, coral reefs, and nearshore fisheries. *Marine Pollution Bulletin 184*, 114144 (2022).

19 Graham, N. *et al.* Human disruption of coral reef trophic structure. *Current Biology 27*, 231-236 (2017).

20 Houk, P., Cuetos-Bueno, J., Kerr, A. & McCann, K. Linking fishing pressure with ecosystem thresholds and food web stability on coral reefs. *Ecological Monographs 88*, 109-119 (2018).

21 Rhodes, K., Tupper, M. & Wichilmel, C. Characterization and management of the commercial sector of the Pohnpei coral reef fishery, Micronesia. *Coral Reefs 27*, 443-454 (2008).

22 Johannes, R. Traditional marine conservation methods in Oceania and their demise. *Annual Review of Ecology and Systematics 9*, 349-364 (1978).

23 MacNeil, A. *et al.* Recovery potential of the world's coral reef fishes. *Nature 520*, 341-344 (2015).

24 Botsford, L. *et al.* Connectivity and resilience of coral reef metapopulations in marine protected areas: matching empirical efforts to predictive needs. *Coral Reefs 28*, 327-337 (2009).

25 Houk, P. *et al.* Climate change disturbances contextualize the outcomes of coral-reef fisheries management across Micronesia. *PLosClimate 1*, e0000040 (2022).

26 Johnson, S. M., Reyuw, B. M., Yalon, A., McLean, M. & Houk, P. Contextualizing the social-ecological outcomes of coral reef fisheries management. *Biological Conservation 241*, 108288 (2020).