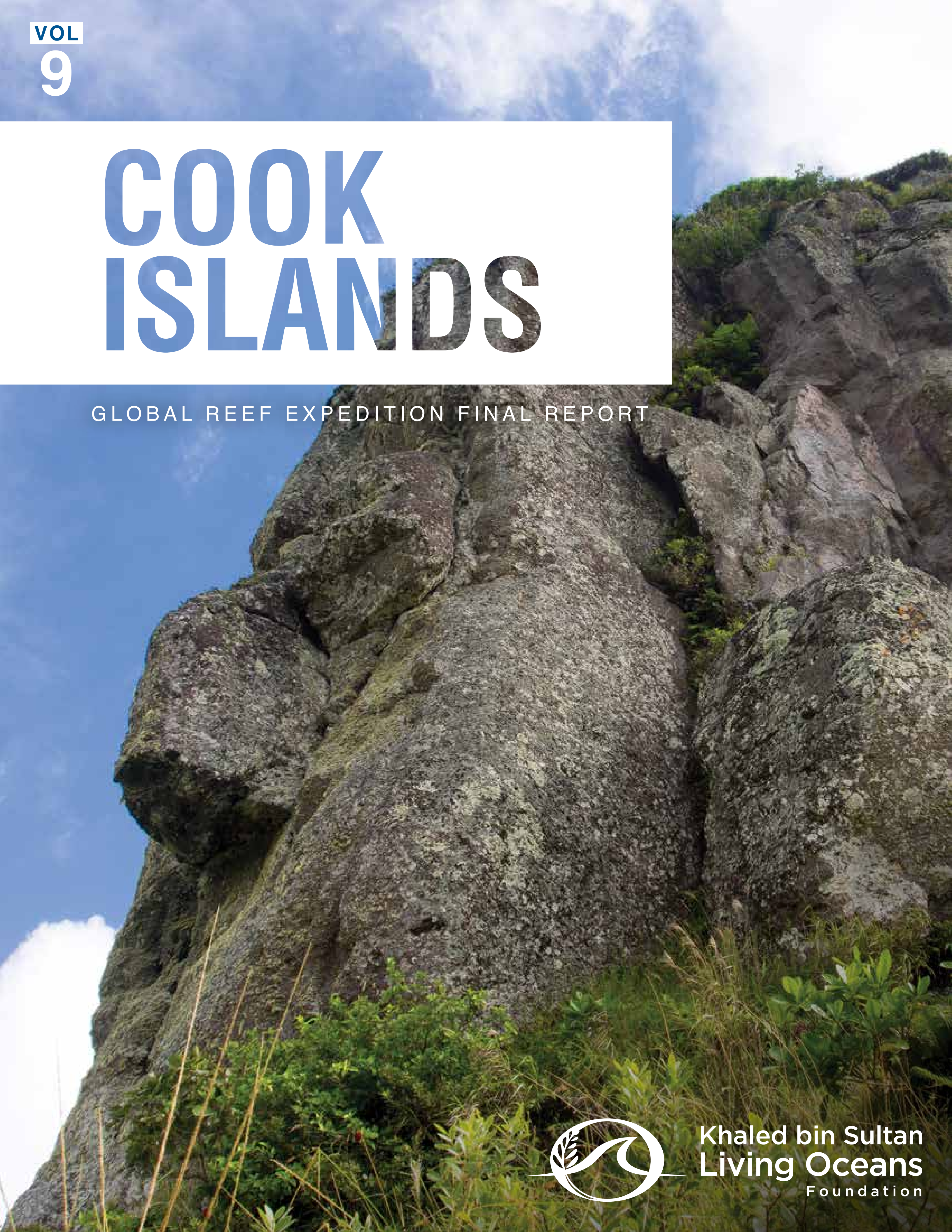
VOL 9

COOK ISLANDS

GLOBAL REEF EXPEDITION FINAL REPORT



Khaled bin Sultan Living Oceans Foundation

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Khaled bin Sultan Living Oceans Foundation

Samuel Purkis, PhD, Alexandra C. Dempsey,
Renée D. Carlton, Katie Lubarsky, Philip P. Renaud

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Science Without Borders®

The findings presented in this report were collected as part of the Global Reef Expedition through the support provided by His Royal Highness Prince Khaled bin Sultan.

This final report is submitted to fulfill the requirements of the Final Report for the Global Reef Expedition: Cook Islands Research Mission. This is in accordance with the research permit under an agreement between KSLOF and the Government of the Cook Islands, Research Committee.

Khaled bin Sultan Living Oceans Foundation (KSLOF) was incorporated in California as a 501 (c)(3), public benefit, Private Operating Foundation in September 2000. The Living Oceans Foundation is dedicated to providing science-based solutions to protect and restore ocean health.

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EXECUTIVE SUMMARY

In April 2011, the Khaled bin Sultan Living Oceans Foundation (KSLOF) embarked on the Global Reef Expedition (GRE)- the largest coral reef survey and mapping expedition in history. The GRE was a rigorous five-year scientific mission to study coral reefs around the world. The expedition was designed to assess the impact of anthropogenic and natural disturbances on reef ecosystems, including runoff, climate change, storm damage, and Crown-of-Thorns Starfish (COTS) outbreaks. The ultimate goal of the Foundation's research is to provide scientists, managers, and stakeholders with recommendations that support the formulation of an effective management strategy for coral reefs and associated habitats. Herein, we report on a study that KSLOF has undertaken to assess the health and resilience of the coral reefs in the Cook Islands. The study took place in April-May 2013 and July 2015. The Foundation quantitatively measured, categorized, and mapped coral reef environments at three islands in the Cook Islands: Rarotonga, Aitutaki (by default the nearby island of Manuae which shares the lagoon with Aitutaki), and Palmerston Atoll.

This scientific mission involved 19 participants from numerous international organizations, who worked alongside scientists representing the government in the Cook Islands and Cook Islands Marine Park Steering Committee, to gather the highest quality data. The mission in the Cook Islands was conducted with the following objectives:

1. **Collect vital data contributing to our global assessment of coral reef health and resilience.**
2. **Document the impacts of broad scale disturbances and patterns of recovery with an emphasis on storm damage and Crown-of-Thorn Starfish (COTS) predation impacts.**
3. **Provide recommendations to help guide Marine Protected Area (MPA) delineation and zoning for protection of the Cook Islands marine resources.**

HABITAT MAPPING

High resolution habitat and bathymetric maps were created for the three islands surveyed in the Cook Islands. These maps have a spatial resolution of 2m x 2m. The habitat classifications (25 in total) clearly describe the substrate and reef habitats found among these locations. The habitat maps were used in conjunction with the bathymetric maps to calculate total area and depth distribution of each habitat type. Such data are of value to marine spatial planning efforts. Scientists and the public can use the maps, but marine managers may find them particularly helpful in understanding areas that might be critical habitat requiring further protection.

BENTHIC COVER ASSESSMENTS

To assess the health of the reefs, KSLOF used a combination of data collected in situ and peer-reviewed scientific literature to classify the reef systems of the Cook Islands as being in either 'good', 'moderate', or 'poor' conditions. These categories are based on overall live coral cover, algae, and invertebrate composition. We found that the health of the sites surveyed around Rarotonga, Aitutaki, and Palmerston varied greatly. The reefs of Aitutaki have been badly compromised by Crown of Thorns Starfish (COTS) and we observed active COTS predation reefs during our surveys that was further degrading the reefs. These COTS outbreaks are the obvious principal reason that Aitutaki's reef condition is classified as poor due to the low live coral cover. We had the opportunity to revisit Aitutaki in 2015, two years after we first discovered the COTS outbreak, and found that although there were still COTS in the lagoon, the fore reefs appeared to be largely unchanged. Continued recovery will be highly dependent on the ability of fish and invertebrates to control the algae population and the space for coral recruits to settle, however. Palmerston had, overall, the healthiest reef system of the three islands visited with nearly all sites classified in good condition. The average live coral cover at Palmerston ranged from 50-62% which is some of the highest coral cover recorded by KSLOF in the South Pacific. Rarotonga had comparable coral cover to that observed in many other South Pacific countries, with sites falling under all three condition categories, averaging in moderate reef health. Rarotonga supports a much higher human population than the other Cook Islands we surveyed and it is a reasonable assumption that human impacts have degraded some of the nearshore reefs.

FISH COMMUNITY ASSESSMENTS

The fish communities were similar across all the islands surveyed in the three Cook Islands, with minor variations in fish density and biomass. Palmerston had the highest mean species richness and biomass, with far more large, predatory fish than Aitutaki or Rarotonga, indicating that the fish community at Palmerston is healthier than at the other two islands. Data suggest, therefore, that fishing pressure on the more populous islands of Aitutaki and Rarotonga has likely decreased the abundance of top predators such as barracuda and sharks which prey on lower trophic levels. Large fish (>40 cm in length) were rarely observed across all sites surveyed on the three islands, which is concerning in the context that large female fish produce significantly more offspring – and sometimes stronger offspring – than younger females do. Researchers have proposed the idea that maintaining old-growth age structure can be important for replenishing depleted fish stocks. Somewhat in jest, it is termed the Big Old Fat Fecund Female Fish (BOFFFF) hypothesis.

RECOMMENDATIONS

The marine conservation progress already made in the Cook Islands is significant and perhaps the most advanced in the South Pacific. For instance, the offshore fishing regulations, MPA establishment, and cooperation with neighboring nations is both commendable and will be crucial for the long-term sustainability of the Cook Islands' marine resources. Despite these regulatory frameworks, however, there is a compelling need for the Cook Islands to establish nearshore fishing regulations and management because reef fish populations in the nearshore are particularly vulnerable to overfishing. A locally managed coastal conservation method, such as ra'ui have the potential to regulate community fishing practices and manage the nearshore fisheries, but without complete participation by the community, this could prove to be futile. KSLOF encourages the government and people of the Cook Islands to establish more rigorous nearshore fishing management practices to preserve fish populations.

Natural disturbances, such as bleaching and COTS outbreaks, are expected to become more frequent in the face of climate change and warming waters. While re-visiting Aitutaki in 2015, KSLOF helped train some of the local islanders in recognizing and establishing removal practices of COTS to try to minimize the impact of this corallivore invertebrate on reef health. We recommend developing a program that can be shared and implemented throughout the Cook Islands so other locations can try to mitigate outbreaks and protect their reefs.

INTRODUCTION

1.0

The Khaled bin Sultan Living Oceans Foundation (KSLOF) mission to the Cook Islands was one of 14 completed on the Global Reef Expedition (GRE). KSLOF visited three of the southern Cook Islands: Rarotonga, Aitutaki (and by default the nearby island of Manuae which shares the lagoon with Aitutaki), and Palmerston. During our time in the Cook Islands in April-May 2013, and again in July 2015 at Aitutaki, we were able to contribute greatly to our overall mission of assessing areas of resilience and recovery of coral reefs globally. The GRE mission to the Cook Islands was conducted with the following objectives:

1. **Collect vital data contributing to our global assessment of coral reef health and resilience.**
2. **Document the impacts of broad scale disturbances and patterns of recovery with an emphasis on storm damage and Crown-of-Thorn Starfish (COTS) predation impacts.**
3. **Provide recommendations to help guide Marine Protected Area (MPA) delineation and zoning for protection of the Cook Islands marine resources.**

The southern Cook Islands visited on the GRE are located to the west of the Austral Archipelago, French Polynesia. These islands are made up of three atolls with varying land mass found at each one. The prevailing ocean currents in this region flows eastward with forcing from the South Equatorial Counter Current (SECC)[1]. The reefs of the southern Cook Islands serve as a source of coral and fish recruits to French Polynesia's southern Austral archipelago[1]. The eddies and currents which flow between the Cook Islands, however, may aid in self-recruitment for corals and fish. However, connectivity has not been well studied and we cannot provide a meaningful description of larval connectivity across the study area.

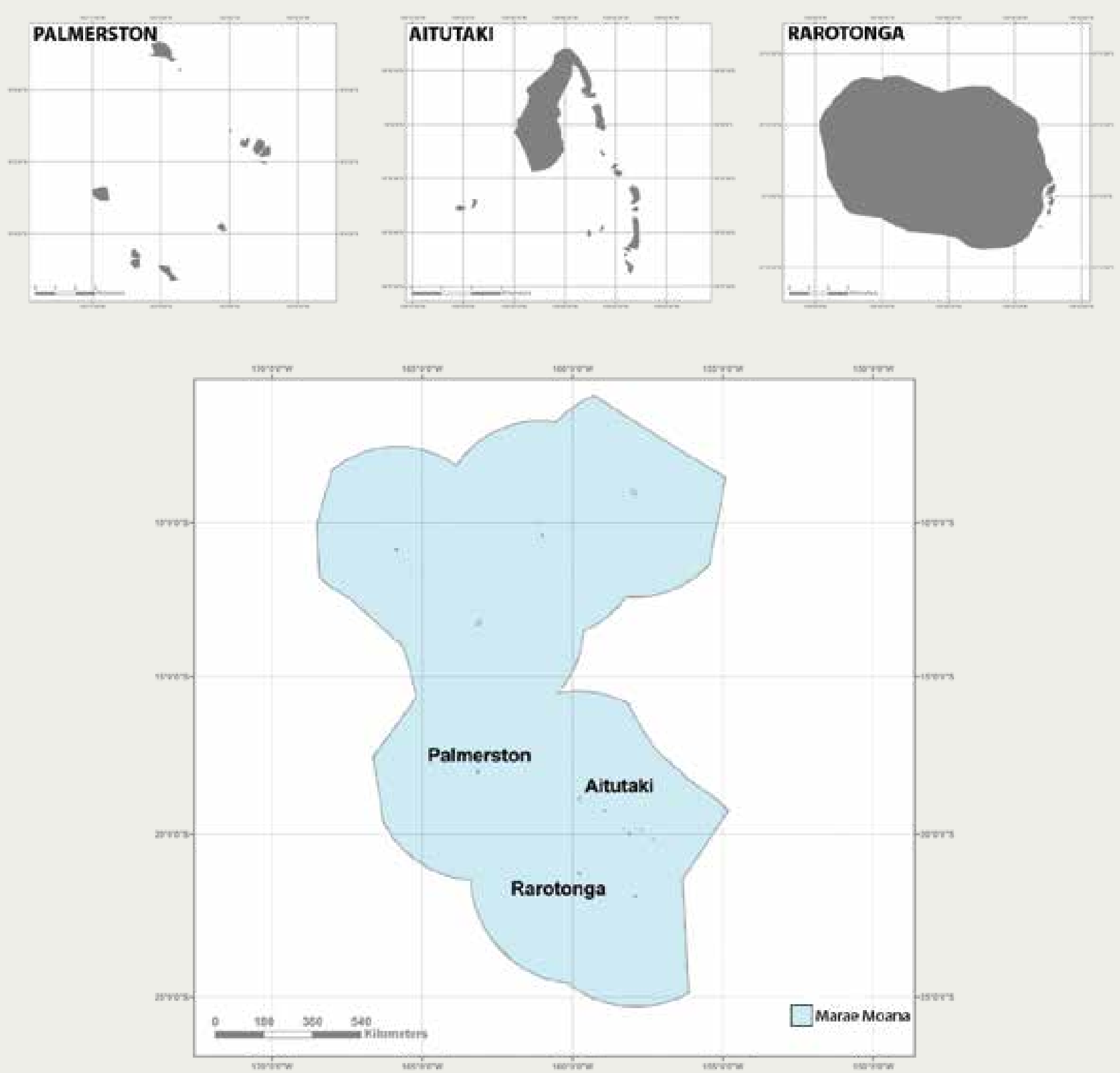
The dedication to protecting natural resources by the people of the Cook Islands was evident during our visit.

The dedication to protecting natural resources by the people of the Cook Islands was evident during our visit. For instance, at the time of our arrival in April 2013, the government of the Cook Islands had already signed an agreement with the government of New Caledonia to establish two sister marine parks which, when combined, established one of the world's largest Marine Protected Areas (MPAs)[2]. This agreement would protect over 1 million square kilometers of ocean and coastal ecosystems in the southern Cook Islands (Figure 1). Besides this internationally recognized MPA, the traditional ra'ui has been used and recognized as a locally managed coastal conservation method that protects coral reef areas to prevent overfishing or destruction of the reefs[3–5]. The ra'ui is a system of traditional laws or "customary prohibitions" that prohibit the collection of resources for a defined period of time, often seasonally. This was traditionally used on land, but more recently has been applied to nearshore marine environments. The ra'ui is typically policed by traditional leadership, the king, and social pressure, with punishment being enforced by the community. This well-preserved tradition has contributed to the health of the reefs surrounding the southern Cook Islands.

Unfortunately, even with this protection, the reefs are susceptible to natural disturbances that cannot always be controlled. For instance, natural disasters such as cyclones, warm water induced coral bleaching, and COTS outbreaks have detrimental effects on the health of coral reefs[6,7]. During our initial trip to the island of Aitutaki, we witnessed first-hand, an outbreak of COTS that caused severe damage to reefs surrounding this island. An outbreak of COTS can consume over 90% of the live coral found on a reef in a matter of weeks[8]. Without proper management, these pests can severely damage local reefs which, compounded with other natural disturbances, can have long-term effects on the benthic and reef fish communities[7,9,10].

In 2010, the Aitutaki and Manuae Bonefish Fishery Regulations were defined by the Ministry of Marine Resources (MMS)[11]. With this new regulation, the MMS set out to implement guidelines on near-shore bonefish fisheries where they established best practice measurements such as licensing, quotas, and restrictions on equipment used for fishing[11]. These management practices will aid in preserving the bonefish fishery and maintaining a healthy stock that may have otherwise been depleted. We were unable to determine if there are similar nearshore regulations in place at any of the other islands besides those imposed through the ra'ui.

Figure 1 MAP OF MARAE MOANA, DESIGNATED COOK ISLANDS MARINE PARK THAT ENCOMPASSES THE ENTIRE EEZ. SUBSET MAPS ARE OF THE THREE ISLANDS VISITED ON THE GRE WHICH ARE INCLUDED WITHIN THE MARAE MOANA.



2.0 METHODS

2.1 SITE DESCRIPTIONS

The GRE mapped and surveyed coral reefs around three of the southern Cook Islands. A total of 30 dive sites were surveyed, among which 175 benthic habitat transects and 238 fish surveys were completed. A list of each dive site visited is found in Appendix 1, including site name, date visited, latitude, longitude, nearest neighboring island, exposure, and reef type (e.g.- fringing reef, reef flat). The dive sites were selected based on accessibility by boat and with the goal of including all reef habitats (as defined in the satellite-derived habitat maps, Figure 2a). Table 1 shows the total number of surveys conducted at each atoll. Unless otherwise specified, the data presented for Aitutaki are from our 2013 mission, although comparisons to some of the sites surveyed in 2015 are made. Fish data were only collected in 2013 in Aitutaki. The methodology used to re-survey Aitutaki sites in 2015 were the same as those used for initial benthic surveying in 2013.

Table 1 TOTAL NUMBER OF DIVE SITES AND TRANSECTS COMPLETED AT EACH ISLAND IN 2013.

REGION	DIVE SITES	NUMBER OF BENTHIC TRANSECTS	NUMBER OF FISH TRANSECTS
RAROTONGA	12	69	89
AITUTAKI	10	56	81
PALMERSTON	8	50	68
Total	30	175	238

A total of 30 dive sites were surveyed, among which **175 benthic habitat transects and 238 fish surveys were completed.**

2.2 HABITAT MAPPING

Using multispectral WorldView-2 satellite imagery obtained from DigitalGlobe Inc., in combination with data obtained from aerial surveys and ground-truthing, high resolution bathymetric maps and thematic habitat maps were created for shallow marine environments found within the lagoon and fore reefs (see examples of map outputs in Figures 2a-c). The remote sensing data and their derivatives will be useful not only for marine spatial planning, but also as a reference for future research on the Cook Islands' coral reefs. The maps extend from the shoreline to approximately 25 m water depth. Prior to the field surveys, an aerial survey of each island's coastline and adjacent shallow marine habitat was undertaken. Ground-truthing, which was used to define habitat classes, and guide interpretation of the remote sensing data, included continuous acquisition of depth soundings, drop-camera deployment, samples of sediment and hard substrates, snorkel and dive assessments, and fine scale photo-transect surveys.

Figure 2a SATELLITE IMAGE, EXAMPLE OF A TRUE-COLOR SATELLITE IMAGE CAPTURED FROM THE WORLDVIEW-2 SENSOR.

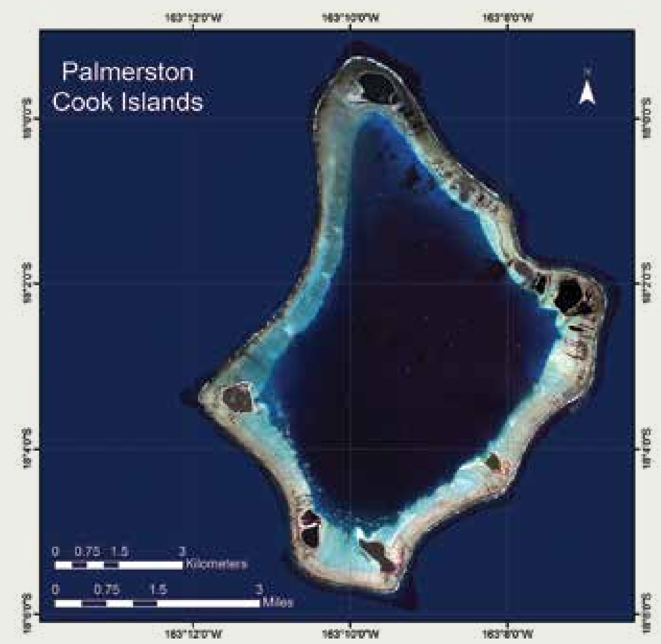


Figure 2b HABITAT MAP WITH CLASSIFICATIONS.

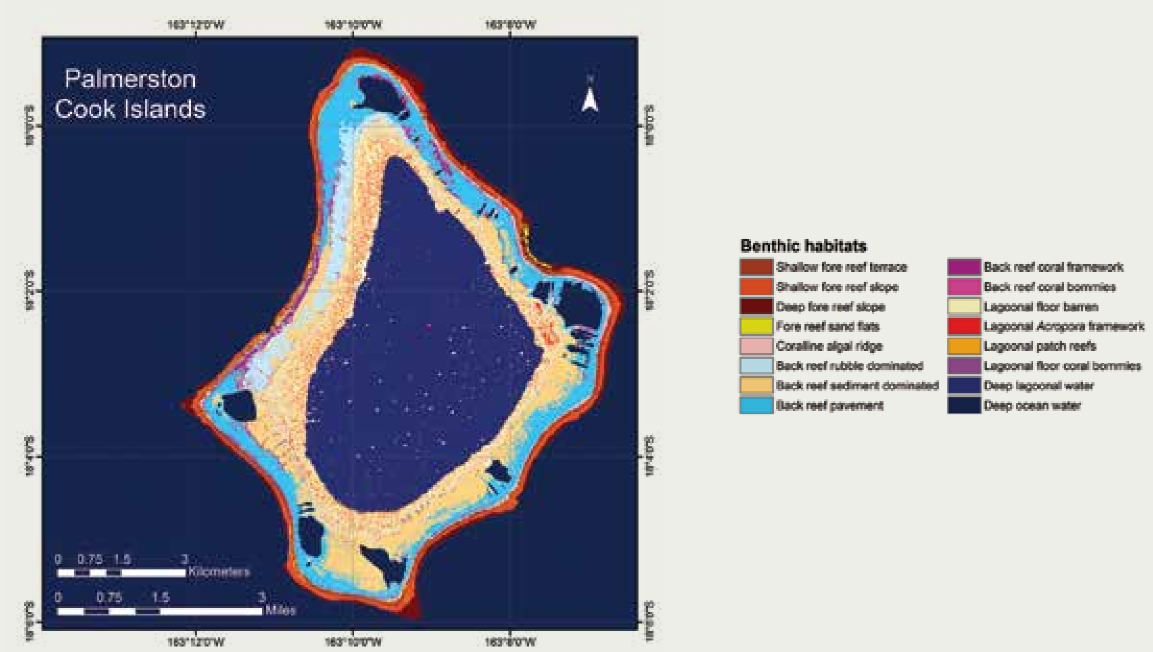
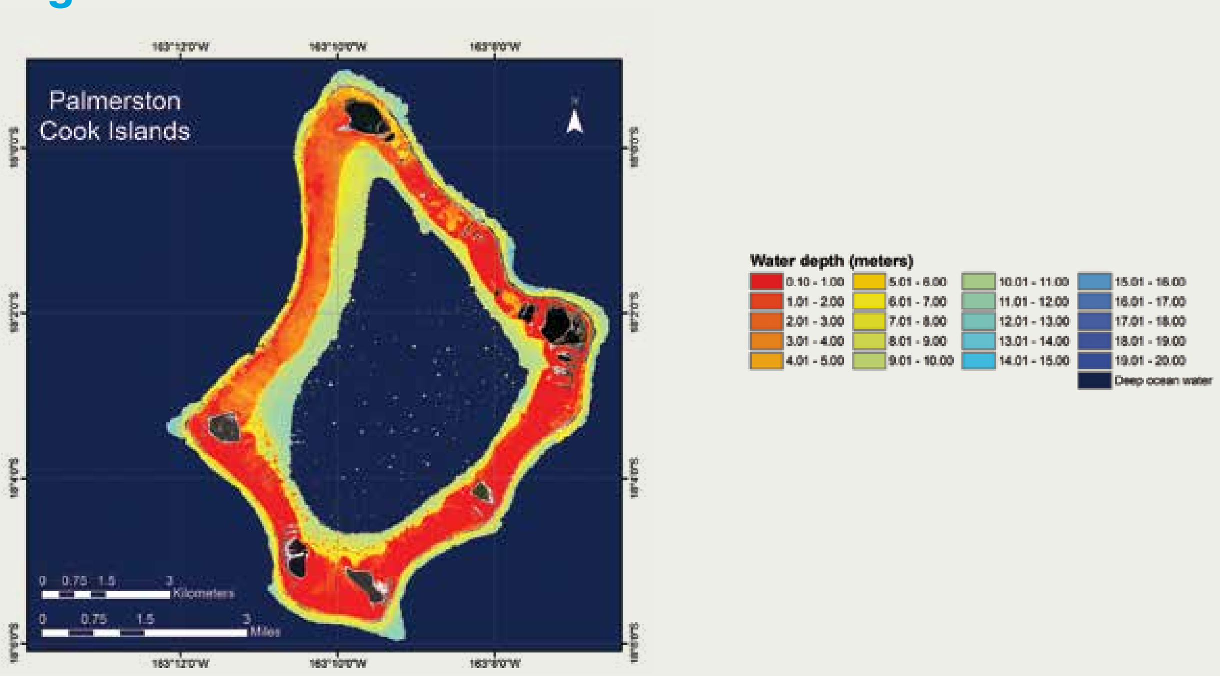


Figure 2c BATHYMETRY MAP WITH DEPTHS.



2.2 a SATELLITE IMAGERY

A total of 406 sq. km of DigitalGlobe Inc. WorldView-2 (8 band) satellite imagery was acquired for the three regions mapped. The satellite images had a spatial resolution of 2×2 m (each pixel covers a 4 m^2 area) enabling real-time navigation in the field to locate features of interest. The team used the scenes in conjunction with a differential GPS device to navigate throughout the islands. Modelers used the imagery, combined with the ground-truthing data, to create bathymetric and benthic habitat maps.

A total of 406 sq. km of DigitalGlobe Inc. WorldView-2 (8 band) satellite imagery was acquired for the three regions mapped.

2.2 b BENTHIC VIDEO

An underwater tethered digital video camera, commonly termed a 'drop-cam', was used to gather video of the benthic composition at each drop-cam location (Figure 3). At each point, the drop-cam was lowered from the survey boat to within 0.5 m of the seafloor and video recorded for up to 60 seconds. During this time, the laptop operator watched the video in real-time and guided the drop-cam operator to raise or lower the camera to avoid any topography. In this manner, any damage to marine life was prevented. The video was recorded on a ruggedized laptop with position, time, date, boat heading, and boat speed digitally etched into the video stream. Drop-cam deployment was limited to depths shallower than 40 m due to the length of the tether cable (50 m).

Figure 3 SEAVIEWER UNDERWATER VIDEO 'DROP-CAM' USED TO RECORD BENTHIC COMPOSITION AROUND EACH ISLAND.

2.2 c HABITAT CLASSIFICATIONS

Habitat classifications of all the marine and terrestrial habitat types were determined using the satellite imagery, ground-truthing, and benthic video surveys. The combination of all data collected was used for development of a habitat classification scheme and training of eCognition software to develop object-based classification models. A total of 25 habitat types were defined. When calculating, and presenting total area coverage of the different habitat classifications, multiple habitat types were sometimes combined (Table 2). For example, for back reef coral, we combined back reef coral bommies and back reef coral framework to represent this broad reef environment.

Habitat classifications of all the marine and terrestrial habitat types were determined using the **satellite imagery, ground-truthing, and benthic video surveys.**

Table 2 TABLE SHOWS CLASSES OF BENTHIC HABITATS USED FOR MAPPING AND AREA CALCULATIONS OF EACH HABITAT. THE MEASUREMENT OF EACH AREA IS PRESENTED IN TABLE 4 FOR EACH OF THE ATOLLS SURVEYED. KSLOF COMBINED SOME HABITATS (RIGHT COLUMN) UNDER A BROADER CLASSIFICATION (LEFT COLUMN) FOR THE PURPOSES OF THIS REPORT."

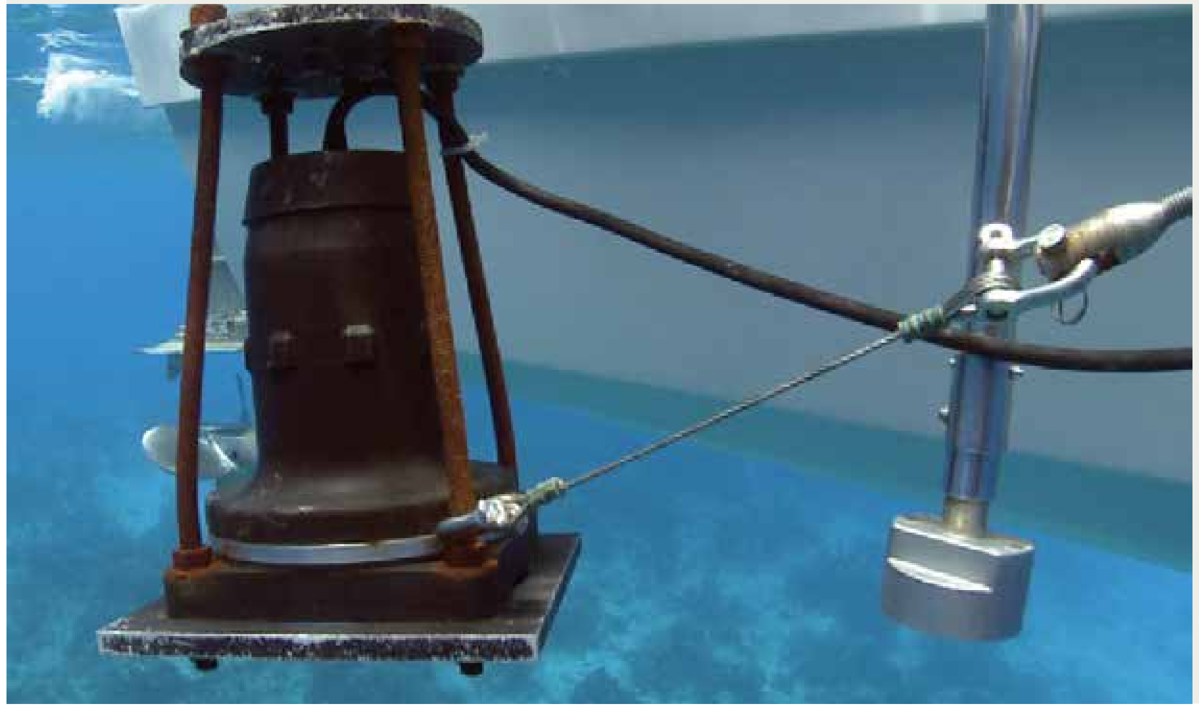
MARINE HABITATS	
Shallow Forereef	Shallow fore reef slope Shallow fore reef terrace
Lagoonal Coral	Lagoonal Acropora framework Lagoonal floor coral bommies Lagoonal patch reefs Lagoonal massive coral framework
Backreef coral	Back reef coral bommies Back reef coral framework
Deep fore reef slope	
Back reef pavement	
Back reef rubble dominated	
Back reef sediment dominated	
Beach sand	
Buried lagoonal coral framework	
Carbonate blocks	
Coral rubble	
Coralline algal ridge	
Deep lagoonal water	
Fore reef sand flats	
Inland waters	
Lagoonal floor barren	
Lagoonal floor macroalgae on sediment	

2.2 d ACOUSTIC WATER DEPTH SOUNDINGS

Sonar soundings were gathered along transects using a Syqwest Inc. Hydrobox, a single-beam acoustic transducer operating at 50 Hz. (Figure 4). Each sounding was positioned using differential GPS and the data were recorded on a ruggedized laptop. The soundings were used to train a satellite water-depth derivation model, which is based on the spectral attenuation of light in the water column. The final topo-bathymetric maps have the same spatial resolution as the satellite imagery from which they were extracted (i.e. 2 x 2 m).

The final topo-bathymetric maps have **the same spatial resolution as the satellite imagery from which they were extracted** (i.e. 2 x 2 m).

Figure 4 ACOUSTIC SONARS USED IN THE SURVEYS. SUB-SEABED PROFILER (LEFT) AND SINGLE-BEAM SONAR (RIGHT).



2.3 CORAL REEF COMMUNITY SURVEYS

The GRE used a combination of quantitative methods, including belt transects, point intercept transects, and quadrats to assess benthic and fish communities of reefs located in the Cook Islands. This standardized collection methodology provides robust data that can be compared regionally and globally. This report provides a broad discussion of trends and patterns as a prelude to more in-depth analysis.

2.3a BENTHIC COVER ASSESSMENT

Cover of major functional groups and substrate type (Table 3) were assessed along 10 m transects using recorded observations and/or photographic assessments. The major functional groups included: corals identified to genus, other sessile invertebrates identified to phylum or class, and six functional groups of algae. At least two surveyors using SCUBA recorded observations using a point intercept method. This technique required the surveyor to lay out a 10 m transect line and record the organism and substrate type at every 10 cm mark (total 100 points per transect). A minimum of four transects among the five depth strata were completed at each dive site (Figure 5), and when possible, surveys were completed at 25, 20, 15, 10, and 5 m water depths.

At some locations, we conducted a photographic assessment to supplement the point intercept surveys. On occasion, we were not able to complete point-intercept surveys at every depth, so we supplemented this data set with photographic assessments. In this sampling technique, a scientific diver used a 1 m × 1 m quadrat, flipping it over a total of 10 times per transect to photograph a full 1 × 10 m photo transect (Figure 6) at each depth. As before, where possible, the diver completed at least one survey at 20, 15, 10, and 5 m depth at each site. In order to determine benthic community composition, coral, and algae cover, the digital photographs were downloaded and analyzed using *Coral Point Count with Excel Extensions* (CPCe), a software developed by Nova Southeastern University's National Coral Reef Institute (NCRI)[12]. The 1 x 1 m images were imported into the software where 50 random points were overlaid on each photograph. A KSLOF scientist then defined the organism and substrate type directly underneath the point (Figure 7). These data were then exported into a Microsoft Excel (2013) spreadsheet, and added to the benthic survey database for further analysis.

Figure 5 A DIVER CONDUCTING A BENTHIC SURVEY. PHOTO BY KEN MARKS. DIVER USES A 10 M TRANSECT LINE AND RECORDS BENTHIC SUBSTRATE TYPE AND COVER EVERY 10 CM.

The benthic substrate cover percentages were calculated for each island as the average percentage of all transects collected at that island, binned first by depth, then by site. The percentage of each substrate type was calculated by dividing the total number of samples observed in each depth on each transect by the total number of points recorded, multiplied by 100. The average percentage of all transects at the island is presented as the measure of each substrate type. To further analyze the coral and algal cover, the sum of the specific algae types or coral genus recorded on each transect was divided by the total number of algae or coral observed per transect. The average of the percentages for each algae type is presented in Figures 11, 13, and 17.

Using existing scientific literature as references, KSLOF established a protocol for classifying the health of the benthic communities of the reef into three categories[13–15]. KSLOF has classified the reefs surveyed as being in "good", "moderate", or "poor" condition based on the overall live coral cover, algae, and invertebrate composition. These parameters are critical in understanding the health of a reef community. The interaction between the type of algae, total coral cover, and invertebrate composition has been shown to be linked to the overall health of a reef system[16]. Areas with high coral cover (>40%), low macro algae, and high crustose coralline algae (CCA) are in "good" condition, shown in green (Figures 10, 12, and 15). Reefs defined as having "moderate" reef conditions, shown in yellow, are considered to have live coral cover between 20-39%, with moderate to low macro algae, and moderate to high CCA. Reefs that are in "poor" condition, shown in red, have overall live coral cover less than 20% with moderate to high macroalgae, and low CCA. Having a healthy assemblage of coral and algae is also directly linked to supporting a healthy fish community[17]. Higher rugosity, or more variable structure, due to a healthy coral community, provides a suitable habitat for fish through better shelter and food availability to support the fish community.

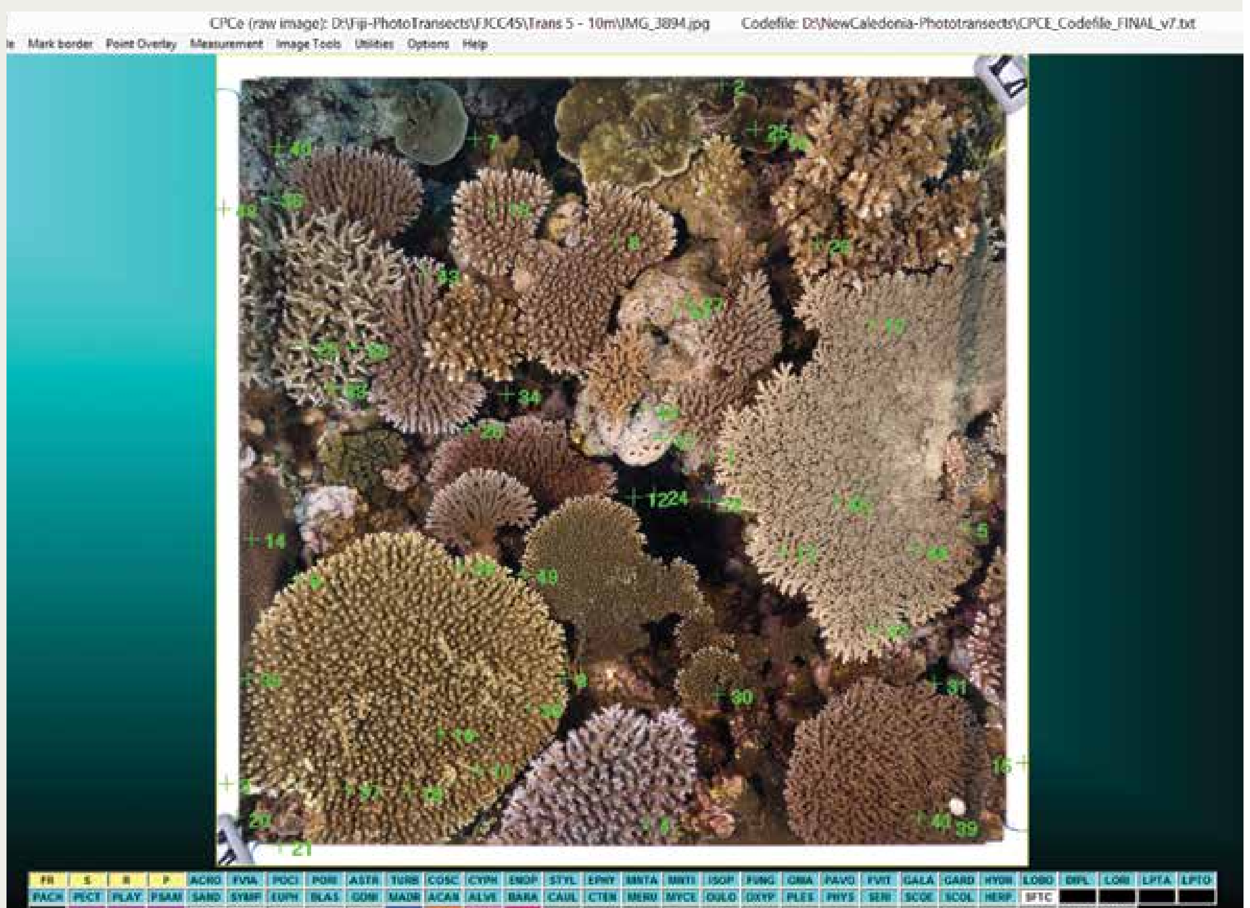
Table 3 CLASSIFICATION OF SUBSTRATE TYPES RECORDED DURING BENTHIC TRANSECT SCUBA SURVEYS.

BENTHIC HABITAT
SUBSTRATE TYPE
Live Coral
Dead Coral
Fused Rubble
Pavement
Rubble
Sand/Sediment
Recently Dead Coral
LIVE COVER
Algae
Macroalgae
Crustose Coralline Algae (CCA)
Erect Coralline Algae
Turf Sediment
Turf
Cyanobacteria
Other Invertebrates
Coral (to Genus)

To measure overall coral diversity (by genus), we used the Simpson Index of Diversity which is commonly used to characterize species diversity in a community[17]. This index uses the total number of individual coral colonies of a specific genus observed per island, and the total number of genera to provide a number to represent the total diversity of the island community. Using this index, the diversity will fall within a range of 0-1 with 0 being low diversity, and 1 being the most diverse.

Figure 6 A DIVER TAKES A PHOTO OF A 1M X 1M SQUARE QUADRAT. TEN PHOTOS FOR EACH TRANSECT ARE COMPLETED AT DIFFERENT DEPTHS AND SUPPLEMENTAL DATA COLLECTED USING TRANSECT LINES AS SHOWN IN FIGURE 5. PHOTO BY PHILIP RENAUD.

Figure 7 EXAMPLE OF A PHOTOGRAPHED QUADRAT IMPORTED INTO CPCE SOFTWARE, WITH RANDOMLY PLACED POINTS FOR IDENTIFICATION. FIFTY RANDOM POINTS ARE OVERLAID ON EACH PHOTO QUADRATE AND SUBSTRATE TYPE AND LIVE COVER CLASSIFICATION ARE IDENTIFIED FOR EACH POINT.



2.3 b FISH ASSESSMENTS

Reef fish surveys were conducted by surveyors at selected locations (atolls, islands and reefs) at each of the island groups. The survey transects covered depths between 1 to 22 m, but the majority of the surveys were between 5 to 20 m depth (Figure 8). Transects were deployed at deep (>12m) and shallow (<10m) sections of the reefs, as allowed by the morphology of the dive site. At least two deep and two shallow transects were conducted by divers. The fish assemblages at each dive site were surveyed following a fish visual census technique modified from the survey principles described by English *et al.* (1994)[18]. The diver identified and counted fish along a 30 × 4 m transect over a period of 10 to 15 minutes.

Figure 8 A SCIENTIFIC SCUBA DIVER RECORDS FISH ALONG A TRANSECT LINE. SCIENTIST RECORDS FISH OBSERVED ALONG A 30 M BY 4 M TRANSECT OVER A 10-15 MINUTE PERIOD. PHOTO BY KEN MARKS.

Fish assemblages were characterized in terms of species richness, abundance, and standing stock biomass. Fish were identified to species level whenever possible with the aid of photographic fish guides and their lengths were estimated to the nearest centimeter. The abundance of each species of a particular size was estimated by actual counts or by cluster in the case of a school of fish. The biomass of each species was then computed using the formula $W=aL^b$ where W is the weight in grams, L is the length of the fish in centimeters, and a and b are the species specific growth constants derived from the length-weight relationships[23–27]. Abundance and biomass data were then converted and represented as density by individuals/100m^2 and biomass by kg/100m^2.

The counted fish were also attributed to trophic level categories based on diet by species[26]. The correspondence between trophic levels and feeding habits is not strictly straightforward or well-defined because of wide overlaps in the food items consumed by different species[28]. Hence, the trophic levels under which a specific species is classified may be considered elastic and representative of the mean of its diet items. Trophic levels were expressed numerically and broadly represented herbivores (2.0 – 2.5), coralivores (2.6 – 3.0), planktivores (3.1 – 3.5), benthic carnivores (3.6 - 4.0), and piscivores (4.1 – 4.5)[29]. By analyzing the fish communities using trophic levels, we strived to understand the community structures and determine how fishing pressures might be affecting the fish communities. Fish in trophic levels 2.0-2.5 and 2.5-3.0 are typically small in size and are not considered important to local fisheries[30]. Fish that are classified in trophic levels 2.0-3.0 are usually important indicator species that contribute to the health of the reef by providing such services as cropping algal growth which otherwise would impede the settlement of juvenile corals[31,32]. These fish include damselfish, tangs, surgeonfish, butterflyfish, and a few small-bodied parrotfish. Fish in trophic level 3.0-3.5 and 3.5-4.0 include larger bodied herbivores, planktivores, omnivores, or carnivores that feed on small benthic invertebrates. Fish classified in these ranges include wrasses, some species of butterflyfish, damselfish, hogfish, goatfish, snappers, and triggerfish. Fish in trophic level 4.0-4.5 are typically considered top predators and prey on finfish of the lower trophic levels. These predatory fish include large wrasse, grouper, hawksfish, snapper, goatfish, and sharks. The majority of the fish important to local fisheries are found in trophic levels 3.5-4.0 and 4.0-4.5[30].

3.0 RESULTS

3.1 HABITAT MAPPING

A total of 25 marine habitats were classified from the satellite data and measured throughout the three locations surveyed in the Cook Islands. Each of the areas surveyed has a distinct geomorphology. Rarotonga is a volcanic island with a surrounding fringing reef. Aitutaki is an atoll which is comprised of a remnant volcanic island within a rim-enclosed lagoon, and Palmerston is an atoll made up of a fringing reef surrounding a large lagoon[33]. Because of these distinct geomorphologies, the islands have varying marine habitats present. The mapped habitats that are important to measure for conservation of coral reef communities of the Cook Islands include the shallow fore reef, deep fore reef slope, back reef coral, and lagoonal coral. These habitats provide vital habitat for maintaining healthy reef and fish communities. The shallow fore reef area can be found shallower than 15 m depth and is defined as a habitat being primarily coral dominated with substantial calcareous, turfing, and macro-algae.

For the purposes of this report, we have combined multiple habitats including shallow fore reef slope and shallow fore reef terrace into a single habitat (Table 2). The atoll with the largest fore reef area was Rarotonga measuring 6.5 km^2, followed by Aitutaki with 5.9 km^2, and Palmerston with 4.7 km^2 (Table 4). The deep fore reef slope is defined as being scleractinian coral dominated and typically ranges from between 15 m and 40 m water depth. Like the shallow fore reef, the deep fore reef slope was largest at Rarotonga measuring 5.8 km^2, followed by Aitutaki at 3.7 km^2, and Palmerston with a total area of 2.2 km^2 (Table 4). The back reef coral habitat combines both the back reef coral bommies and back reef coral framework. These habitats are also dominated by scleractinian coral communities, and the back reef coral bommies are comprised of coral heads (typically massive *Porites*) with plan-form area <200 sq. m growing to near sea level. These habitats foster distinct marine coral and fish communities found on the back reef and are typically found between 1-2 m depth. Back reef coral were observed in all three regions surveyed, but Aitutaki (10.8 km^2) and Rarotonga (6.2 km^2) had the largest areas measured. The lagoonal coral communities were most prevalent in Aitutaki (10.8 km^2) and Palmerston (2.8 km^2), but were absent from Rarotonga, which lacks a lagoon. The lagoonal coral communities include *Acropora* framework, lagoonal floor coral bommies (similar to back reef coral bommies), lagoonal massive framework, and lagoonal patch reefs, all of which typically range between 10-35 m depth.

> The mapped habitats that are important to measure for conservation of coral reef communities of the Cook Islands include the **shallow fore reef, deep fore reef slope, back reef coral, and lagoonal coral.** These habitats provide vital habitat for maintaining healthy reef and fish communities.

Table 4 TOTAL AREA (KM^2) OF HABITAT TYPE, BY ISLAND, CALCULATED FROM HABITAT MAPS.

	TOTAL AREA SQUARE KM		
MARINE HABITAT CLASSIFICATION	Rarotonga	Aitutaki	Palmerston
Shallow Forereef	6.55	5.95	4.77
Lagoonal Coral	0.00	10.79	2.86
Backreef coral	6.19	10.78	2.14
Deep fore reef slope	5.85	3.70	2.25
Back reef pavement	1.67	3.03	9.41
Back reef rubble dominated	0.88	2.38	2.71
Back reef sediment dominated	2.35	20.06	6.94
Beach sand	0.41	0.54	0.43
Buried lagoonal coral framework	--	2.93	--
Carbonate blocks	--	0.29	--
Coral rubble	--	--	0.01
Coralline algal ridge	1.82	1.10	0.82
Deep lagoonal water	--	--	27.23
Fore reef sand flats	0.29	0.66	0.41
Lagoonal floor barren	--	37.01	8.19
Lagoonal floor macroalgae on sediment	--	0.53	--

3.2

BENTHIC COVER ASSESSMENTS

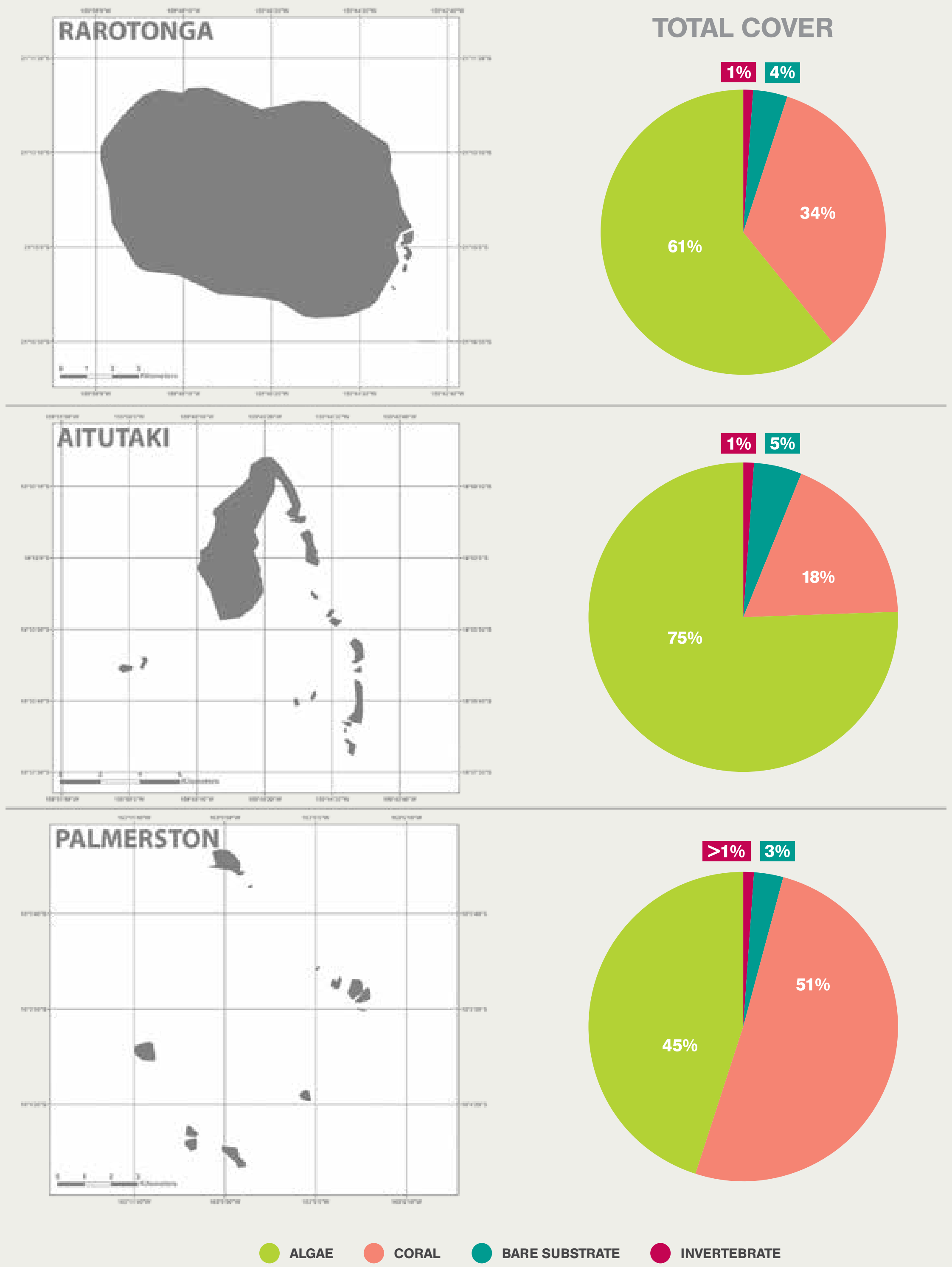
The benthic communities of the Cook Islands appear to be in moderate to good condition, except for Aitutaki, which was experiencing an extensive COTS outbreak at the time of sampling. Data suggest that Palmerston had the healthiest reef system of the three atolls surveyed. Based on the KSLOF ranking system, Palmerston had a good reef system with high coral cover and a healthy assemblage of algae and invertebrates. Rarotonga, meanwhile, had moderate reef health with moderate coral cover and high algae, although the macroalgal cover was low. Aitutaki's reefs were in the poorest health of the three atolls surveyed. We attribute this to the lack of live coral cover due to predation by the COTS outbreak.

Palmerston had an average live coral cover of 51% (±7% S.D., 8 sites) which was some of the highest observed on the Global Reef Expedition, and the highest in the Cook Islands. Rarotonga had an average live coral cover of 34% (±12% S.D., 12 sites) and Aitutaki had the lowest average live coral cover with only 18% (±6% S.D., 10 sites) (Figure 9). Across all the atolls, the dominant coral species included species from the genera *Acropora, Porites, Montipora, Montastrea, Leptoria,* and *Pocillopora.* Each of the atolls exhibited different dominant species, and in many cases, each specific dive site was notably different from others nearby. For instance, at Rarotonga, Site 10 was dominated by *Porites* which accounted for over 70% of the coral measured there, while nearby at Site 5, it only accounted for 19% (±12% S.D.) of the live coral cover. Site 5 had a more even distribution of coral genera.

The average coverage of the seafloor by algae observed at the three atolls ranged between 45-75% of the total substrate cover. Aitutaki had the highest total algae cover present with 75% (±8% S.D., 10 sites) (Figure 9). The algae present was predominantly crustose coralline algae (CCA) which is encouraging for the recovery of these reefs as CCA is a known settlement cue for coral planulae. Rarotonga had the second highest percentage of algae covering the benthos with 61% (±10%S.D., 12 sites). This atoll had the highest percentage of turf algae which accounted for 29% (±12% S.D., 12 sites) of total algal cover. However, there was an even distribution among CCA, turf algae, and turf mixed with sediment, combined accounting for 80% of the total algae recorded at Rarotonga. Palmerston had 45% (±8% S.D., 8 sites) algal cover with the dominant algae being CCA. Palmerston also had the highest average percentage of macroalgae present, accounting for 30% of the total algae.

> Data suggest that
> **Palmerston had the healthiest reef system**
> of the three atolls surveyed.

Figure 9 AVERAGE BENTHIC COVER (%) OF EACH ISLAND SURVEYED IN THE COOK ISLANDS. THE SUBSTRATE TYPES ARE BARE SUBSTRATE, ALGAE, LIVE CORAL, AND INVERTEBRATES. THESE VALUES WERE CALCULATED FROM THE BENTHIC SURVEYS, AVERAGING BY DEPTH, THEN SITE. NUMBER OF TRANSECTS (N) AT EACH ISLAND: RAROTONGA, N=69, AITUTAKI, N=56, PALMERSTON, N=50.



3.2 a RAROTONGA

Rarotonga is the atoll with the greatest land mass, highest elevation, and largest human population[4,33]. Twelve dive sites were surveyed around the island. Based on the benthic cover, we have ranked the sites according to KSLOF's established protocol. While the overall health of the reefs earned a moderate ranking, there was a wide range of coral cover observed. The sites on the northern side of the island, Sites 01, 06, 10, and 12, were all considered to be in good condition (Figure 10). The northern sites had a healthy algal community, being dominated primarily by CCA, turf, turf mixed with sediment, and macroalgae (Figure 11), as well as high live coral cover. These sites ranged in live coral cover from 40-63%, with Site 10 having the highest cover and healthiest algal community. This site was impressive as it had the highest live coral cover observed among all sites surveyed on the GRE mission to the Cook Islands. Sites 02, 03, 04, 05, 08, 09, and 11 had moderate reef health with live coral cover ranging between 22-35%. There was only one site that was in poor condition and that was Site 07 which was located inside the lagoon and had only 19% (±7% S.D., 7 transects) live coral cover. Here, the majority of the benthos was algal-dominated; the algae covered 71% (±9% S.D., 7 transects) of the substrate with the dominant algae being CCA.

The coral diversity at Rarotonga was the lowest of all three islands surveyed, with a diversity index of 0.77. Interestingly, the sites with the highest coral cover at Rarotonga had some of the lowest coral diversity. This result is due to the monospecific coral stands that dominated some of these sites. For example, Site 10 which had the highest overall live coral cover but lowest diversity (0.46) was overwhelmingly dominated by massive *Porites* colonies.

Figure 10

RAROTONGA RANKED DIVE SITES. GREEN INDICATES A REEF WITH GOOD REEF HEALTH, YELLOW HAS MODERATE REEF HEALTH, AND RED INDICATES POOR REEF HEALTH. RANKING IS BASED ON AVERAGE COVER OF LIVE CORAL, ALGAE, AND INVERTEBRATES FOR EACH SITE – SEE TEXT FOR DETAILS. NUMBER OF BENTHIC TRANSECTS *(BN)* AND FISH TRANSECTS *(FN)* MEASURED AT EACH SITE IS LISTED BELOW THE SITE NAME.

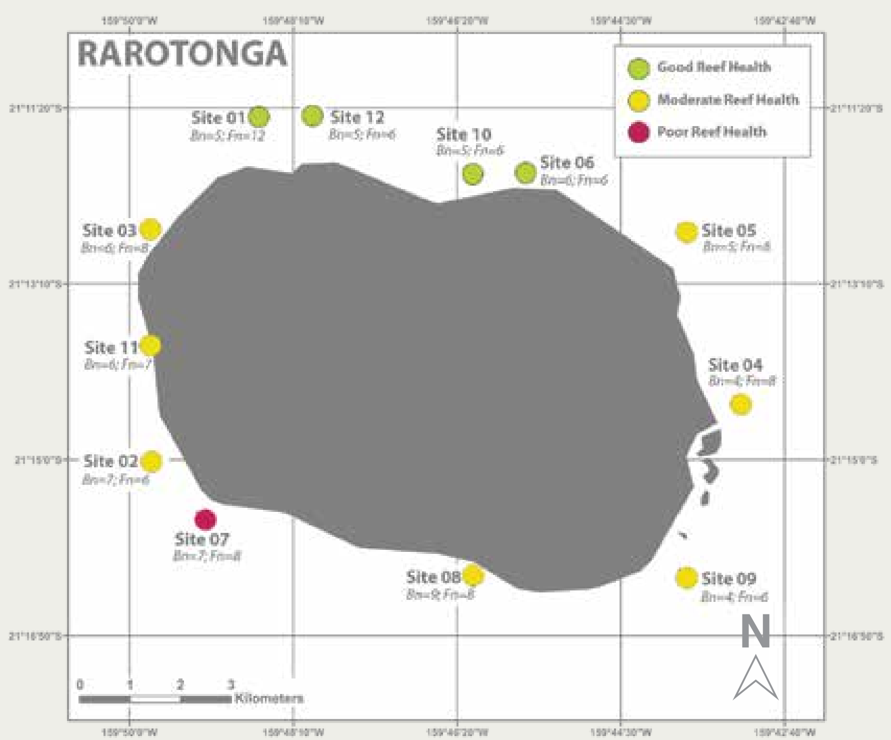
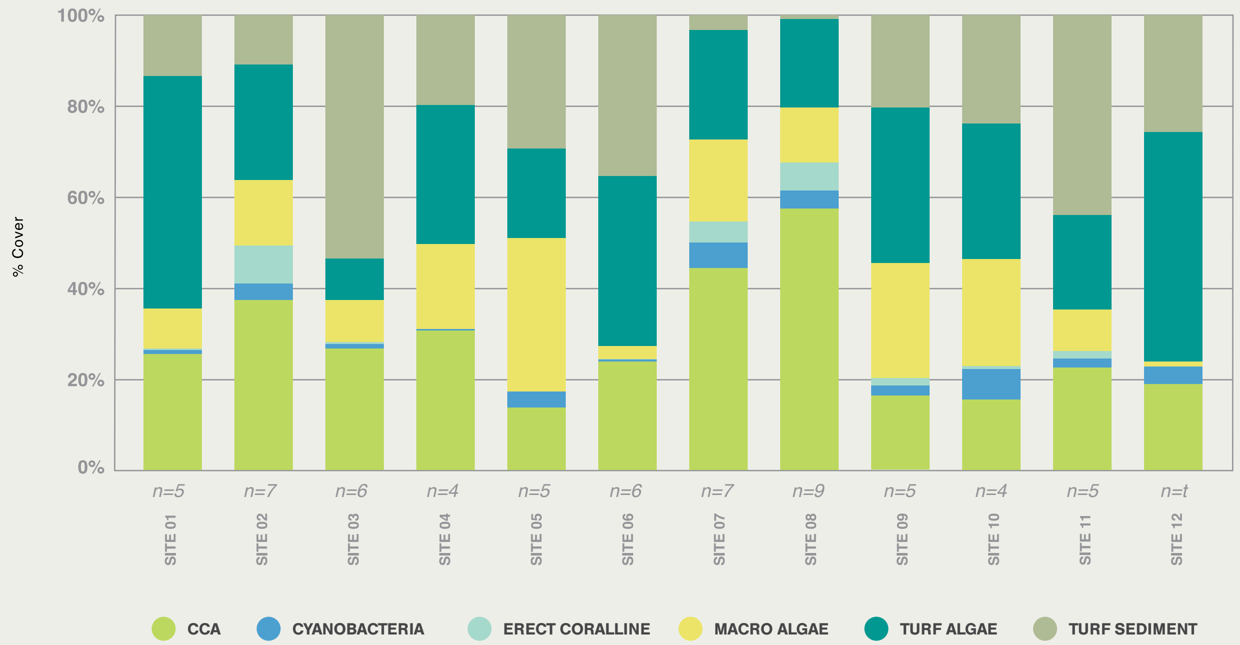


Figure 11

RELATIVE COMPOSITION OF ALGAE (%) AT EACH SITE SURVEYED AT RAROTONGA. THE DATA PRESENTED IS AVERAGED ACROSS DEPTH FROM DATA COLLECTED ON THE BENTHIC TRANSECTS AT EACH SITE. THE NUMBER *(N)* OF TRANSECTS AVERAGED AT EACH SITE IS LISTED WITHIN THE GRAPH FOR EACH SITE.



3.2 b AITUTAKI

At the time of initial sampling in April-May 2013, the reefs surrounding the atoll of Aitutaki were experiencing a COTS outbreak that had a detrimental impact on overall live coral cover. While doing our initial surveys, KSLOF removed 639 COTS from the reefs around the atoll with the hope of preventing further damage. Unfortunately, significant damage had already been sustained, and the majority of sites surveyed in 2013 were found to be in poor condition. The results from our 2013 surveying effort show that there are three sites that can be considered to be in moderate condition (13, 19, and 22). These sites had live coral cover that ranged from 22-31% (Figure 12). Although impacted by COTS, these three were encouragingly dominated by CCA. There was a surprisingly low percentage of macroalgae and turf algae present at nearly all sites in Aitutaki. The remainder of the sites surveyed (14, 15, 16, 17, 18, 20, and 21) were all in poor condition with only 10-19% live coral present. These sites also all had high algal cover ranging from 73-88%, with all except Site 18 having CCA being the dominant algae (Figure 13). Site 18 was evenly covered by macroalgae, turf mixed with sediment, and CCA, combined - accounting for 85% of the algae recorded.

When comparing data collected 2013, Aitutaki had the lowest coral cover, however it did boast the highest coral diversity of 0.88 compared to the other two atolls. This is likely because COTS tend to target specific species to feed on, and therefore increasing the overall diversity of the reefs. Site 16 had the highest diversity of 0.92, while Site 19 had a very low diversity of 0.28. Site 19 was overwhelmingly dominated by Porites, similar to Site 10 in Rarotonga.

Figure 12

AITUTAKI RANKED DIVE SITES FROM SAMPLING EFFORT IN 2013. GREEN INDICATES A REEF WITH GOOD REEF HEALTH (MISSING FROM THIS FIGURE AS THERE WERE NO GOOD SITES AT AITUTAKI), YELLOW HAS MODERATE REEF HEALTH, AND RED INDICATES POOR REEF HEALTH. RANKING IS BASED ON AVERAGE COVER OF LIVE CORAL, ALGAE, AND INVERTEBRATES FOR EACH SITE – TEXT FOR DETAILS. NUMBER OF BENTHIC TRANSECTS (BN) AND FISH TRANSECTS (FN) MEASURED AT EACH SITE IS LISTED BELOW THE SITE NAME.

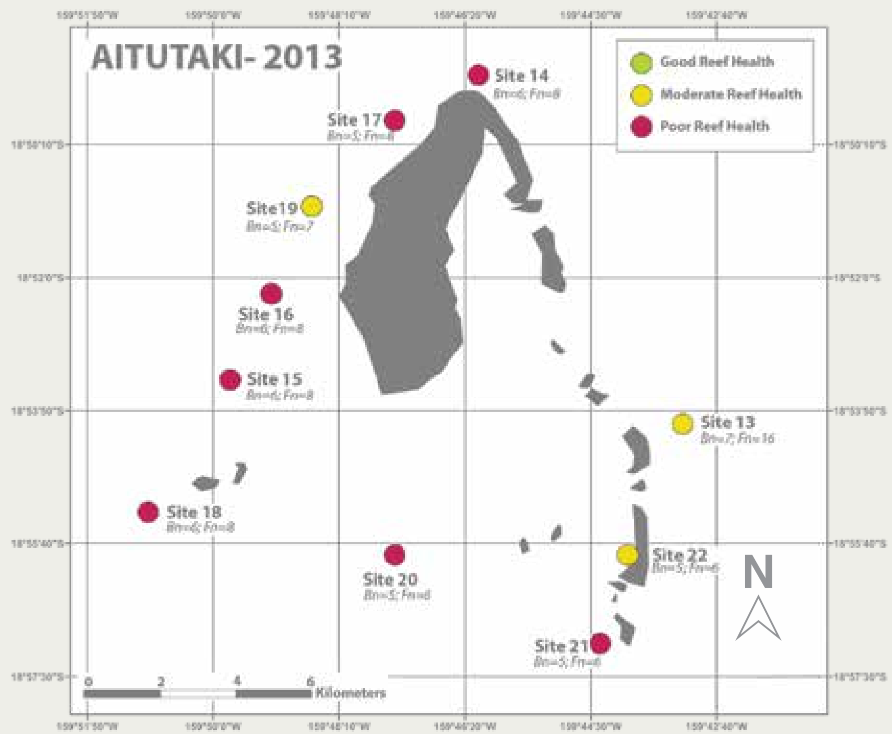


Figure 13

RELATIVE COMPOSITION OF ALGAE (%) AT EACH SITE SURVEYED AT AITUTAKI IN 2013. THE DATA PRESENTED IS AVERAGED ACROSS DEPTH FROM DATA COLLECTED ON THE BENTHIC TRANSECTS AT EACH SITE. THE NUMBER *(N)* OF TRANSECTS AVERAGED AT EACH SITE IS LISTED WITHIN THE GRAPH FOR EACH SITE.

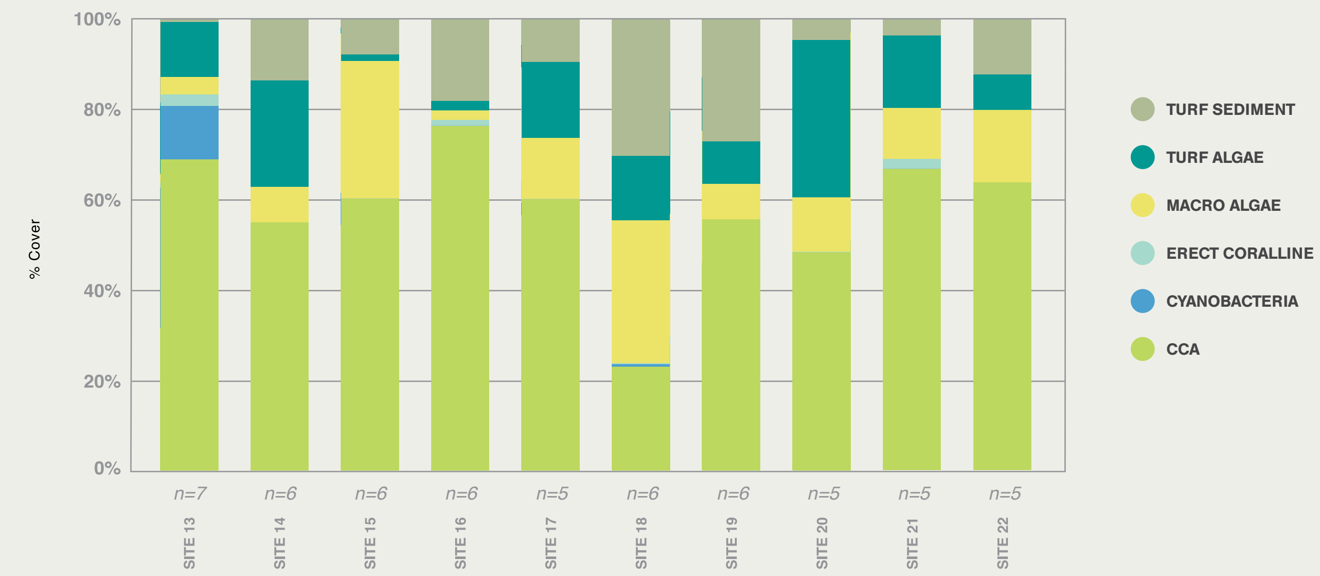
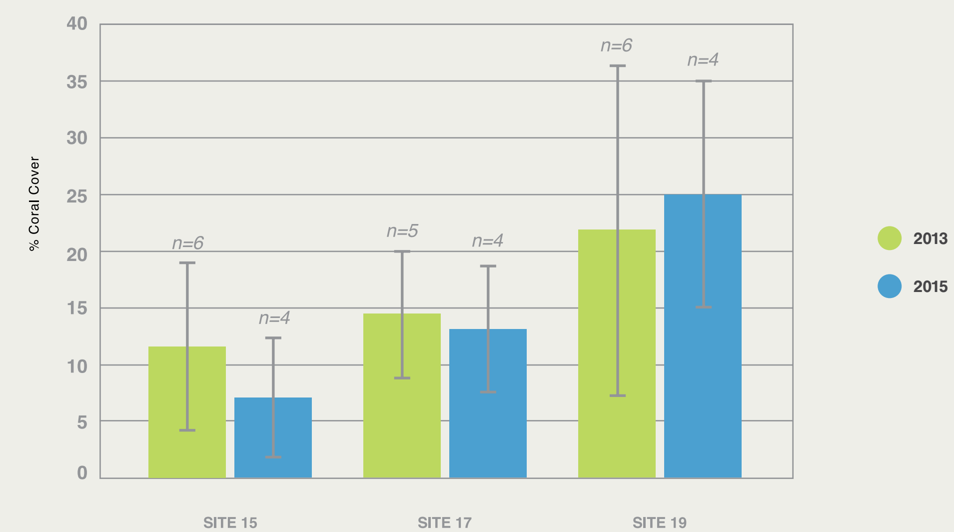


Figure 14

COMPARISON OF LIVE CORAL COVER AT AITUTAKI, BETWEEN 2013 AND 2015, COLLECTED USING BENTHIC SURVEYS AND PHOTO QUADRATES. ERROR BARS INDICATE STANDARD DEVIATION FROM THE MEAN.



In July 2015, KSLOF revisited Aitutaki to examine how the reefs had recovered since the COTS outbreak witnessed two years prior. On this second visit, KSLOF re-surveyed three sites initially surveyed in 2013 (sites 15, 17, and 19), and surveyed five new sites (AI04, AI05, AI07, AI09, and AI10). When comparing the three sites re-surveyed from 2013, we found that there were no substantial changes to the live coral cover (Figure 14). Minor changes were recorded, however.

For example, the average live coral cover increased at Site 19 from 22% (±14% S.D., 5 transects) to 25% (±9% S.D., 4 transects) with a decrease observed at Sites 15 and 17. Site 15 decreased from 12% (±6% S.D., 6 transects) live coral cover to 7% (±5% S.D., 4 transects), and Site 17 had a very minimal change from 14% (±6% S.D., 5 transects) to 13% (±5% S.D., 4 transects) live coral cover. It is worth noting that these changes in the average live cover at all three of these sites could be due to the large spread in the standard deviation seen at each sampling effort. By averaging numerous depths at each site, there will likely be inherent deviation around the mean since corals do not necessarily grow homogenously throughout the depth strata. However, averaging these depths still provides us with a general understanding of the reef health.

The only notable change observed from our 2013-2015 time-separated surveying efforts was that in the algal communities (Figure 15). CCA remained the dominant algae at all three sites. Of the total algae observed at each site, Sites 15 and 19 experienced an overall decrease in macroalgae, while Site 17 experienced an increase. Macroalgal cover decreased at Site 15 by 10% from 26% (±18% S.D., 6 transects) to 16% (±8% S.D., 4 transects) and Site 19 from 8% (±4% S.D., 5 transects) to 6% (±5%S.D., 4 transects). Site 17 saw an increase in macroalgae from 13% (±9% S.D., 5 transects) to 26% (±15% S.D., 4 transects). There was an increase in CCA at all three sites, with the most notable increase being observed at Site 15 where there was a 16% increase in

Figure 15

COMPARISON OF MACROALGAE AT AITUTAKI, BETWEEN 2013 AND 2015, COLLECTED USING BENTHIC SURVEYS AND PHOTO QUADRATES. ERROR BARS INDICATE STANDARD DEVIATION FROM THE MEAN.

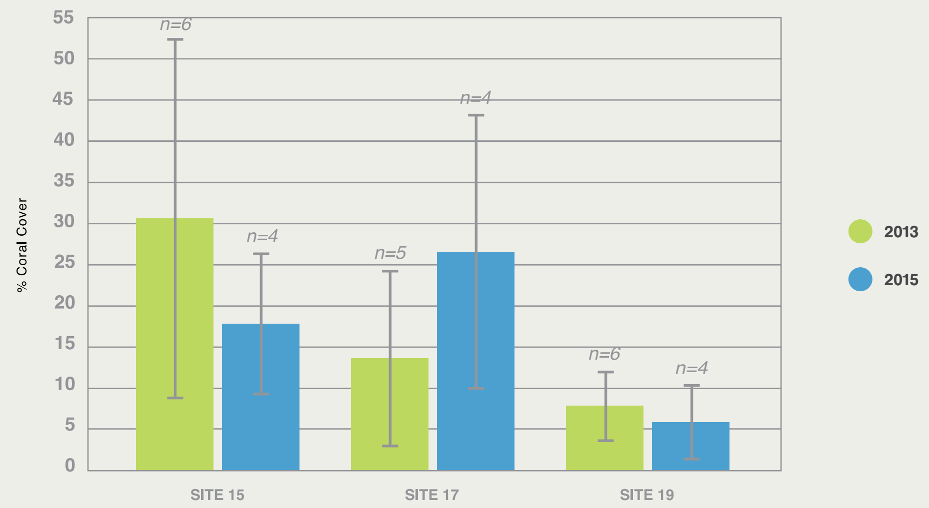
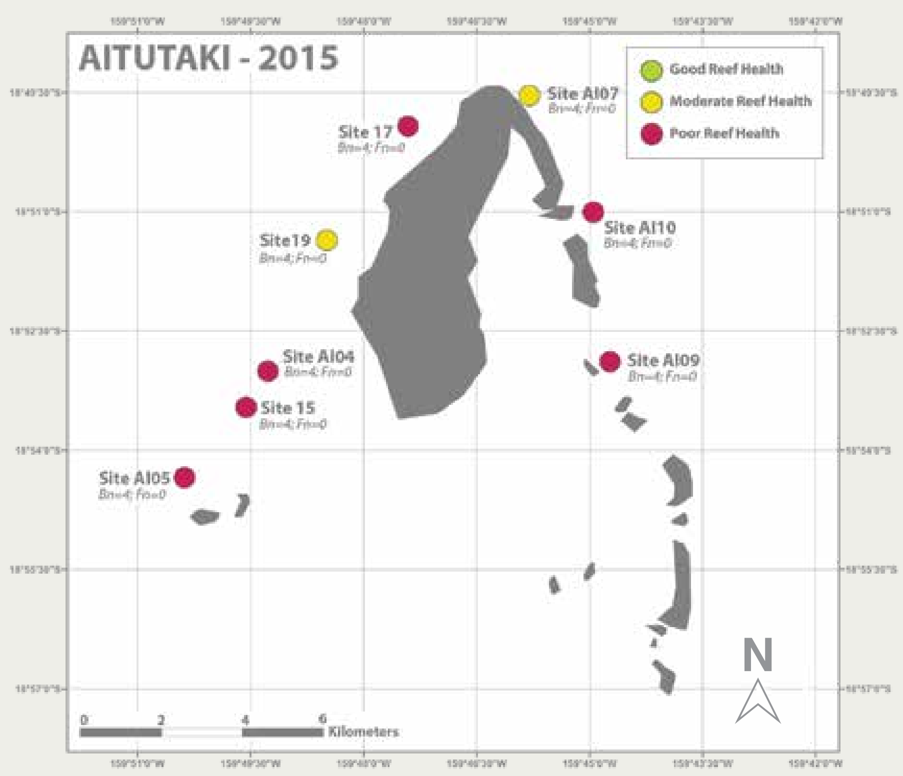


Figure 16

AITUTAKI RANKED DIVE SITES FROM SAMPLING EFFORT IN 2015. GREEN INDICATES A REEF WITH GOOD REEF HEALTH (MISSING FROM THIS FIGURE AS THERE WERE NO GOOD SITES AT AITUTAKI), YELLOW HAS MODERATE REEF HEALTH, AND RED INDICATES POOR REEF HEALTH. RANKING IS BASED ON AVERAGE COVER OF LIVE CORAL, ALGAE, AND INVERTEBRATES FOR EACH SITE – TEXT FOR DETAILS. NUMBER OF BENTHIC TRANSECTS (BN) AND FISH TRANSECTS (FN) MEASURED AT EACH SITE IS LISTED BELOW THE SITE NAME.



CCA from 54% (± 24% S.D., 6 transects) to 70% (±4% S.D., 4 transects). There was a notable decrease in the turf algae observed at both Sites 17 and 19 as there was no turf algae observed at either of these sites during the revisit in 2015. Site 15 experienced no change in turf algae, but there was only 1% present in both years.

The new sites surveyed had lower live coral cover as compared to the island average in 2013. These sites had live coral cover ranging from 7-25% with Site AI07 having the highest live coral cover. Based on the algal community and live coral cover, KSLOF classifies Site AI07 as having moderate reef health, with the rest of the sites having poor reef health (Figure 16). With the remaining presence of COTS in 2015, it is likely the COTS outbreak observed in 2013 continued to impact the reef after our surveying efforts and consumed most of the remaining live coral. This is a common characteristic of a COTS outbreak as these coral predators will often stay at a location until the entire reef is consumed[7]. During our revisit in 2015, we observed that the COTS spread into the lagoon, the location where we collected the majority of the organisms.

> With the remaining presence of COTS in 2015, it is likely the COTS outbreak observed in 2013 **continued to impact the reef** after our surveying efforts and consumed most of the remaining live coral.

3.2 c PALMERSTON

Of the three atolls surveyed, Palmerston was both the most remote and the healthiest reef system, as determined by the KSLOF metrics. In 2013, we surveyed eight sites around the atoll, of which seven were in good condition, and one was in moderate condition (Figure 17). Sites 23, 25, 26, 27, 28, 29, and 30 had high live coral cover that ranged between 50-62% which is some of the highest observed globally on the GRE. Site 24, which was in moderate health, had 34% (±12% S.D., 5 transects) live coral cover and 64% (±13% S.D., 5 transects) algal cover. The algal communities were healthy with the majority of the sites being equally dominated by CCA, macroalgae, turf, and turf with sediment (Figure 18). Interestingly, Palmerston had the highest percentage of cyanobacteria observed, and was most notable at Site 23 where it accounted for 31% (±27% S.D., 8 transects) of the total algae measured at that site.

Like Aitutaki, Palmerston had a fairly high coral diversity of 0.84. Combined with the high overall live coral cover, this is another indicator of a very healthy reef system. Unlike the other two atolls, there were not any sites encountered in Palmerston that were dominated by a single coral species. This shows a diversity in the coral settlement and growth has been successful around the entire island.

Figure 17

PALMERSTON RANKED DIVE SITES. GREEN INDICATES A REEF WITH GOOD REEF HEALTH, YELLOW HAS MODERATE REEF HEALTH, AND RED INDICATES POOR REEF HEALTH. RANKING IS BASED ON AVERAGE COVER OF LIVE CORAL, ALGAE, AND INVERTEBRATES FOR EACH SITE. NUMBER OF TRANSECTS MEASURED AT EACH SITE IS LISTED IN APPENDIX 1.

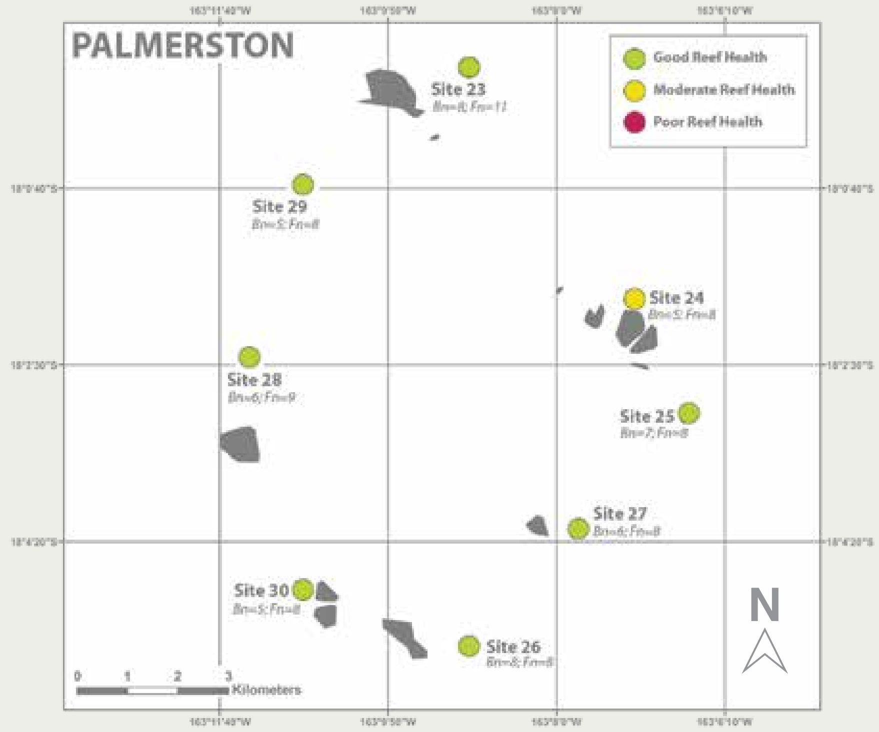
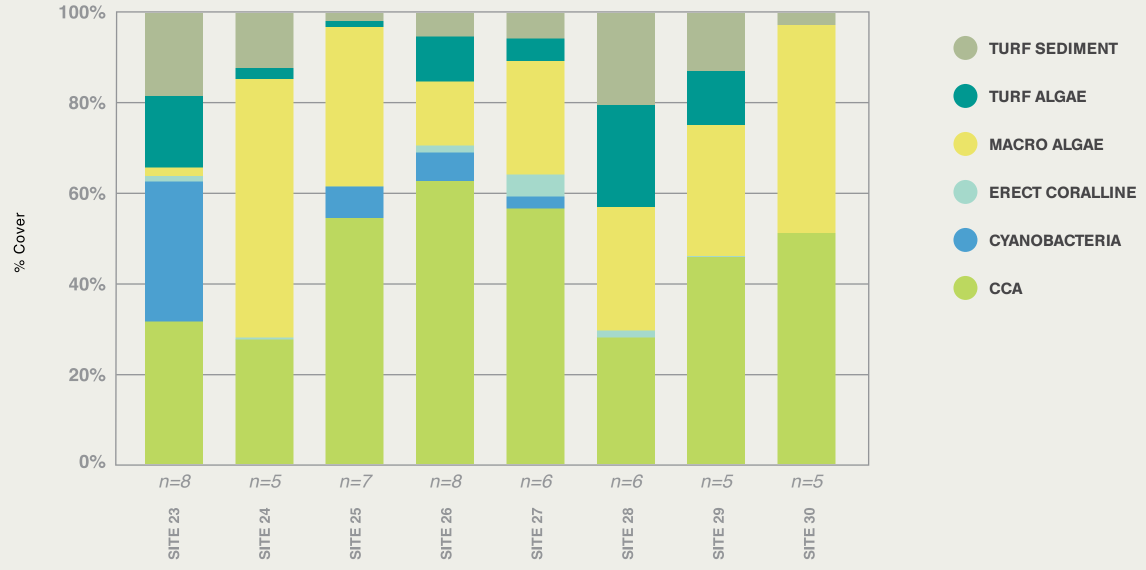


Figure 18

RELATIVE COMPOSITION OF ALGAE (% OF TOTAL ALGAE) AT EACH SITE SURVEYED AT PALMERSTON. THE DATA PRESENTED IS AVERAGED ACROSS DEPTH FROM DATA COLLECTED ON THE BENTHIC TRANSECTS AT EACH SITE. THE NUMBER *(N)* OF TRANSECTS AVERAGED AT EACH SITE IS LISTED WITHIN THE GRAPH FOR EACH SITE.



3.3 FISH COMMUNITY ASSESSMENT

In 2013, the fish communities were similar across all atolls surveyed in the Cook Islands, with only minor variations in fish density and biomass. Palmerston had the highest mean species richness and biomass of the three islands (Table 5), with far more large, predatory fish than Aitutaki or Rarotonga, indicating that the fish community at Palmerston is healthier than at the other two islands.

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3.3 a SPECIES RICHNESS OF FISH ASSEMBLAGE

In total, 242 species from 39 different families were surveyed in the Cook Islands during the research period (Table 5). The total number of species found at each island was similar, with slightly fewer species found at Rarotonga (182 species) than at Aitutaki (190 species), or Palmerston (189 species). Likewise, the mean number of species per 12 m transect (120 m2) was similar between islands, ranging from 32.8 species/120m2 in Aitutaki to 34.4 species/120m2 at Palmerston (Table 5, Figure 19). This indicates fish diversity is similar throughout the three regions sampled in the Cook Islands.

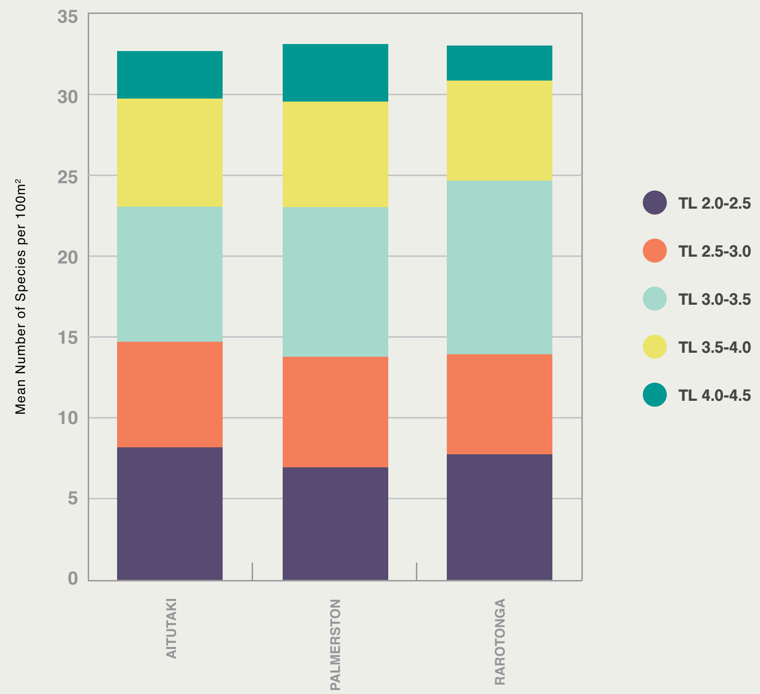
In addition, each island had similar proportions of fish from each trophic level (Figure 19), indicating that the fish communities at each island share a similar trophic structure. Most trophic levels exhibited a fairly uniform number of species across islands, with the smallest differences in trophic level 3.5-4.0, with only a 0.52 species/120m2 difference between the highest (6.70 species/120m2 +/- 1.19 SD at Aitutaki) and lowest (6.18 species/120m2 +/- 1.03 SD at Rarotonga) mean value between islands. The largest difference in mean species richness between trophic levels was only 2.25 species/120m2 in trophic level 3.0-3.5, between Aitutaki (8.56 species/120m2 +/- 1.72 SD) and Rarotonga (10.81 species/120m2 +/- 1.81 SD). Across all islands, trophic level 3.0-3.5 made up the largest proportion of the species richness, while, predictably, trophic level 4.0-4.5 made up the smallest proportion at each island, ranging from 2.20 species/120m2 (+/- 0.57 SD) at Rarotonga to 3.56 species/120m2 (+/- 0.67 SD) at Palmerston.

Table 5 ESTIMATED MEAN SPECIES RICHNESS OF FISH (# OF SPECIES/120M²), MEAN DENSITY (INDIVIDUALS/100M²), AND MEAN BIOMASS (KG/100M²) OF FISH AT 3 ISLANDS IN THE COOK ISLANDS, APRIL-MAY 2013.

LOCATION/ISLAND	# of Survey Stations	# of Replicate Transects	Total Families	Total Species	Mean # of Species	Mean Density	Mean Biomass
Aitutaki	10	81	34	190	32.8	163.6	11.3
Palmerston	8	68	32	189	34.4	154.6	16.8
Rarotonga	12	89	32	182	33.2	133.8	11.2
TOTAL/MEAN	30	238	39	242	33.5	150.7	13.1

Figure 19

ESTIMATED MEAN BIOMASS OF FISH (KG/100M²) BROKEN DOWN BY TROPHIC LEVEL AT 3 ISLANDS IN THE COOK ISLANDS, APRIL-MAY 2013.



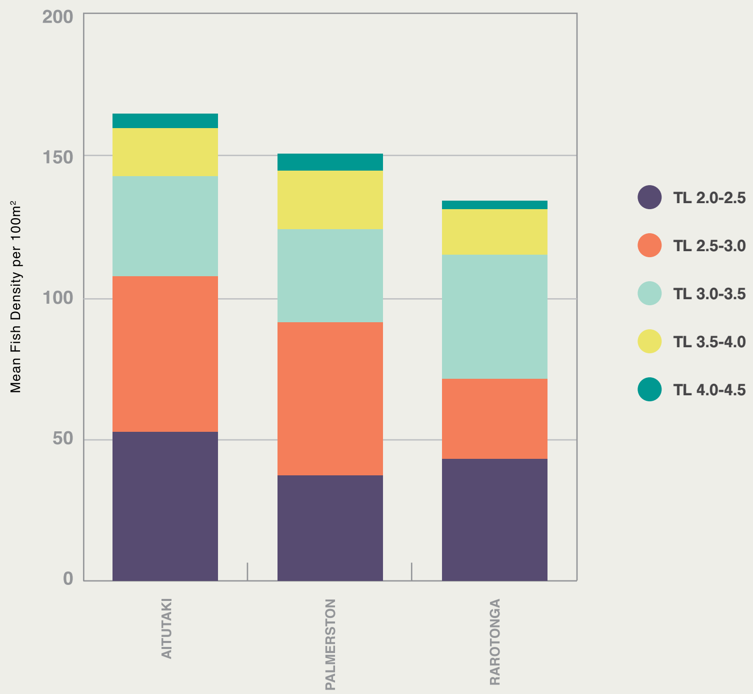
3.3 b FISH DENSITY

The overall mean density of fish in 2013 for all islands surveyed was 150.7 individuals/100m², with the highest mean density found in Aitutaki (163.6 individuals/100m2), followed by Palmerston (154.6 individuals/100m2) and the lowest in Rarotonga (133.8 individuals/100m2; Table 5, Figure 20).

At Aitutaki and Palmerston, trophic level 2.5-3.0 had the highest fish density of the trophic levels, with 53.1 individuals/100m² (+/- 21.0 SD) at Aitutaki and 56.3 individuals/100m² (+/- 21.1 SD) at Palmerston (Figure 20). However, at Rarotonga, trophic level 3.0-3.5 made up the greatest proportion of the fish density, with 43.2 individuals/100m² (+/- 16.0 SD). Across all islands, trophic level 4.0-4.5 had the lowest fish density, ranging from 2.9 individuals/100m² (+/- 1.1 SD) at Rarotonga to 6.0 individuals/100m² (+/- 2.0 SD) at Palmerston.

Figure 20

ESTIMATED MEAN DENSITY OF FISH (INDIVIDUALS/100M²) BROKEN DOWN BY TROPHIC LEVEL AT 3 ISLANDS IN THE COOK ISLANDS, APRIL-MAY 2013.



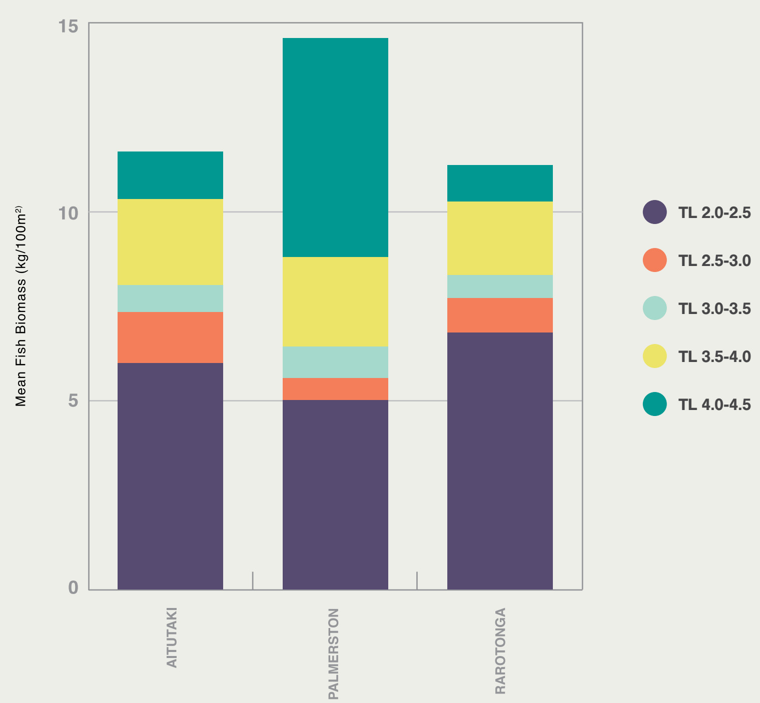
3.3 c FISH BIOMASS

Despite similar values for mean species richness and mean fish density between islands, mean fish biomass in 2013 was markedly higher at Palmerston (16.8 kg/100m2) than at Aitutaki (11.3 kg/100m2) or Rarotonga (11.2 kg/100m2). Interestingly, biomass for trophic levels 2.0-4.0 were comparable between islands; however, biomass in trophic level 4.0-4.5 at Palmerston (5.9 kg/100m2 +/- 2.5 SD) was nearly five times higher than in Aitutaki (1.2 kg/100m2 +/- 0.6 SD), and six times as high as compared to Rarotonga (1.0 kg/100m2 +/- 0.5 SD). This high biomass at Palmerston can be attributed to the presence of large apex predators at this island (Figure 21).

Across all islands, trophic level 2.0-2.5 represented the largest proportion of the total mean biomass, ranging from 5.8 kg/100m2 (+/-2.5 SD) at Aitutaki to 6.8 kg/100m2 at Rarotonga (Figure 21). In fact, at Aitutaki and Rarotonga, this trophic level made up >50% of the total biomass surveyed, due to the large herbivore populations relative to other trophic groups at these sites. Although Acanthuridae (surgeonfish) were the most abundant group, Scaridae (parrotfish) made up the highest proportion of the biomass at both locations. At Aitutaki and Rarotonga, the lowest biomass was found in trophic level 3.0-3.5 (0.7 kg/100m2 +/-0.1 SD at Aitutaki, 0.6 kg/100m2 +/- 0.1 SD at Rarotonga), while at Palmerston, trophic level 2.5-3.0 had the lowest biomass, at 0.6 kg/100m2 (+/- 0.3 SD).

Figure 21

ESTIMATED MEAN BIOMASS OF FISH (KG/100M²) BROKEN DOWN BY TROPHIC LEVEL AT 3 ISLANDS IN THE COOK ISLANDS, APRIL-MAY 2013.

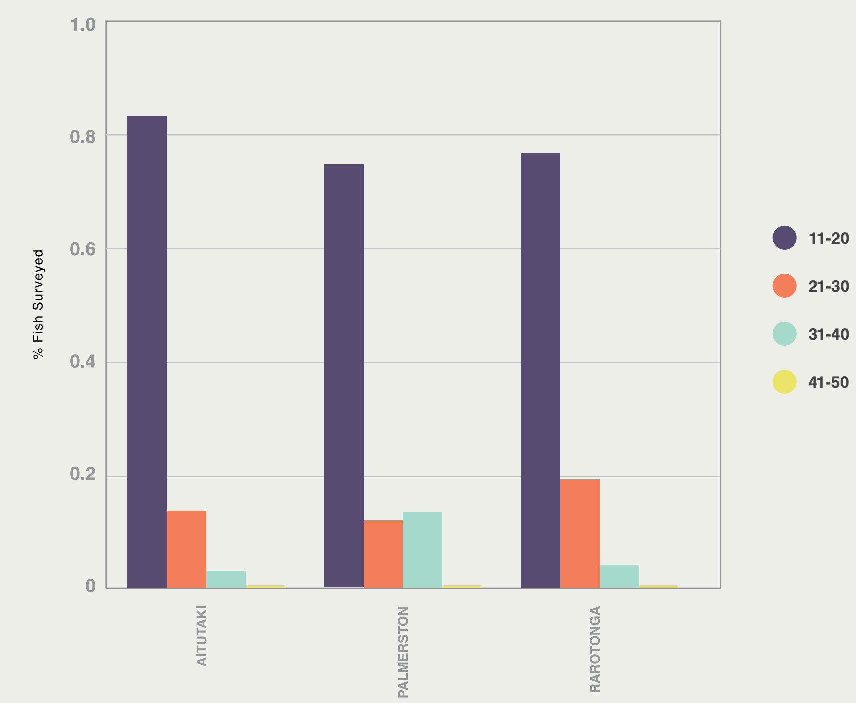


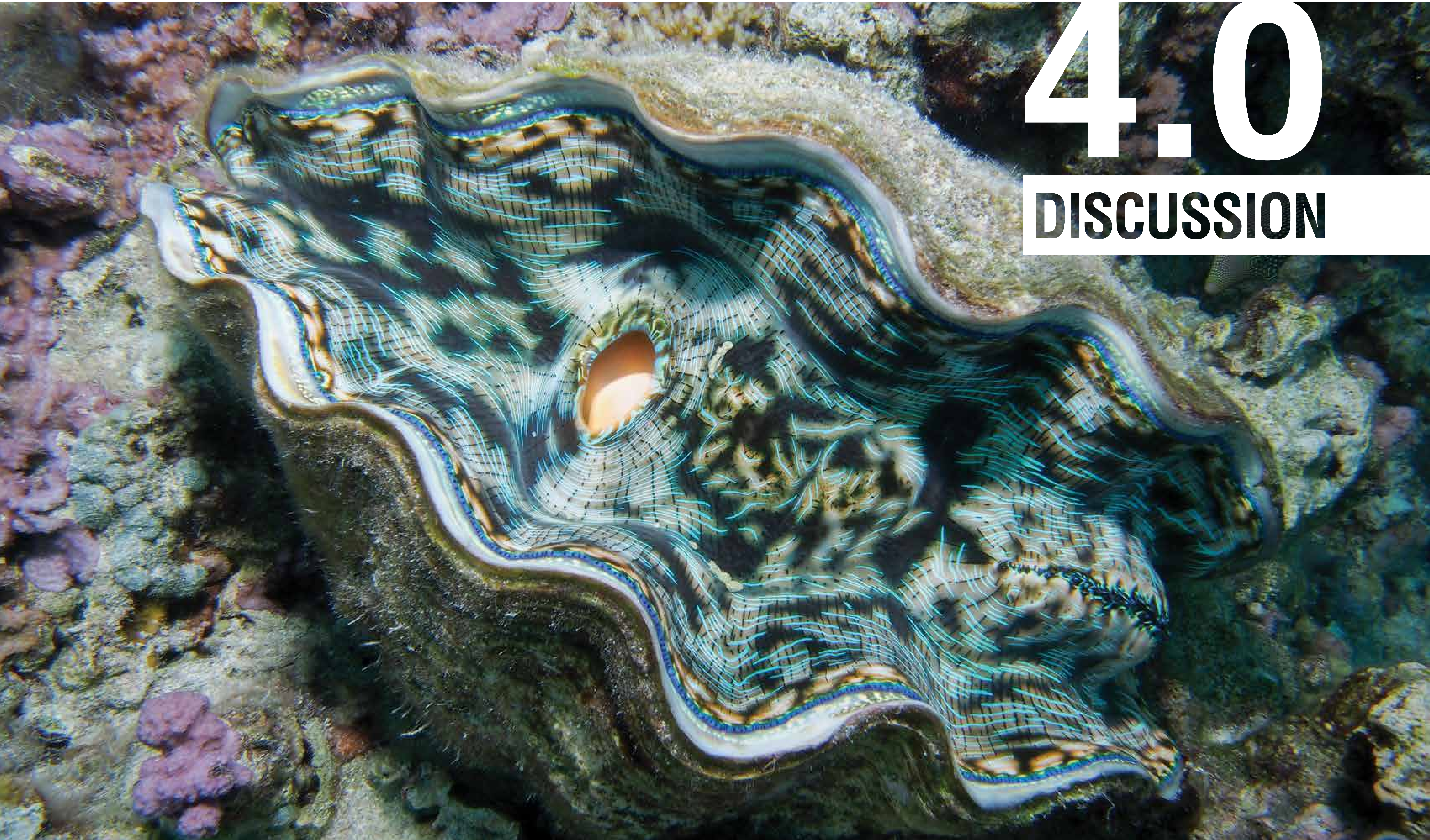
3.3 d FISH SIZE DISTRIBUTION

Small fish (11-20 cm) made up the largest proportion of fish surveyed at all three islands in 2013, making up 83.3% of the fish at Aitutaki, 74.7% of the fish at Palmerston, and 76.8% of the fish in Rarotonga (Figure 22). At Aitutaki and Rarotonga, the percentage of fish in each size category declined with increasing size; however, at Palmerston, the second highest proportion of fish were in the 31-40 cm size category, making up 13.4% of the fish surveyed, compared with 2.9% at Aitutaki and 4.0% at Rarotonga in the same size category. This difference may explain the larger biomass found at Palmerston, particularly in trophic level 4.0-4.5. Large fish (41-50 cm) made up less than 1% of the fish surveyed at all three islands, constituting 0.17% at Aitutaki, 0.05% at Palmerston, and 0% at Rarotonga.

Figure 22

THE RELATIVE SIZE DISTRIBUTION (%) OF SELECTED IMPORTANT FISH FAMILIES BASED ON THE TOTAL DENSITIES FROM 3 ISLANDS IN THE COOK ISLANDS, APRIL-MAY 2013. FAMILIES INCLUDED WERE: ACANTHURIDAE (18 SPECIES), CARANGIDAE (2), HAEMULIDAE (1), LETHRINIDAE (1), LUTJANIDAE (7), NEMIPTERIDAE (1), SCARIDAE (17), SERRANIDAE (9), AND SIGANIDAE (2). FISH WITH TOTAL LENGTHS BELOW 10 CM AND GREATER THAN 50 CM WERE EXCLUDED.





4.0 DISCUSSION

4.0

When compared globally, the Cook Islands benthic and fish communities appear to be in moderate to good health (except for Aitutaki due to the 2013 COTS outbreak). These two communities follow a clear trend where the more populous the island, the more degraded the reef and fish health – i.e. fish community health is inversely correlated with human population (Figure 23). A similar inverse relationship was found in for the benthic communities (Figure 24). Generally, the benthic communities appeared to be healthy with low macroalgae and high CCA cover, but overall live cover tended to decrease at the more populous islands. The minimal changes in the algal community supports our finding that there is a relatively healthy fish and invertebrate population helping to control the macroalgae growth and create space for coral larval recruitment. Perhaps the most encouraging finding is, that after two years, the macroalgae cover did not drastically change at Aitutaki following the COTS disturbance.

A global comparison of the fish density and biomass shows that the fish populations of the Cook Islands are comparable to other nearby countries such as French Polynesia and Fiji (Figures 25-26). Generally, the fish density appears to be unchanging among areas surveyed, whereas the fish biomass is slightly lower indicating a higher proportion of smaller fish. Similarly, the overall live coral cover was like other South Pacific

> With continued efforts to protect and preserve the fish and benthic communities,
> **it is possible for these reefs to become some of the best in the South Pacific.**

Figure 23

FISH BIOMASS (KG/100M²) COMPARED TO ISLAND HUMAN POPULATION, SHOWING THAT AS POPULATION INCREASES, FISH BIOMASS DECREASES. HUMAN POPULATION DATA OBTAINED FROM THE COOK ISLANDS CENSUS AND COOKISLANDS.ORG.

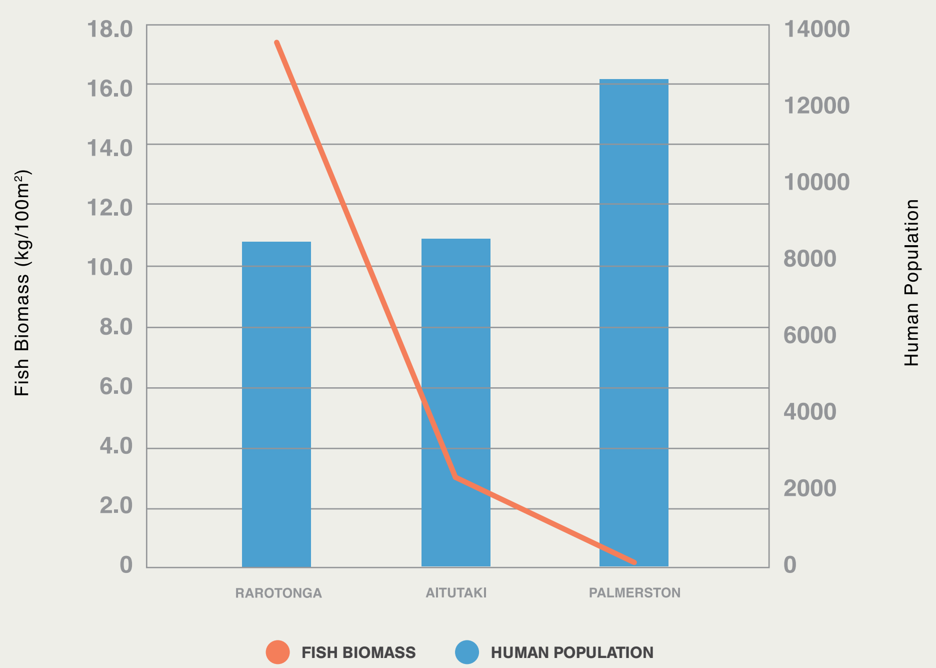
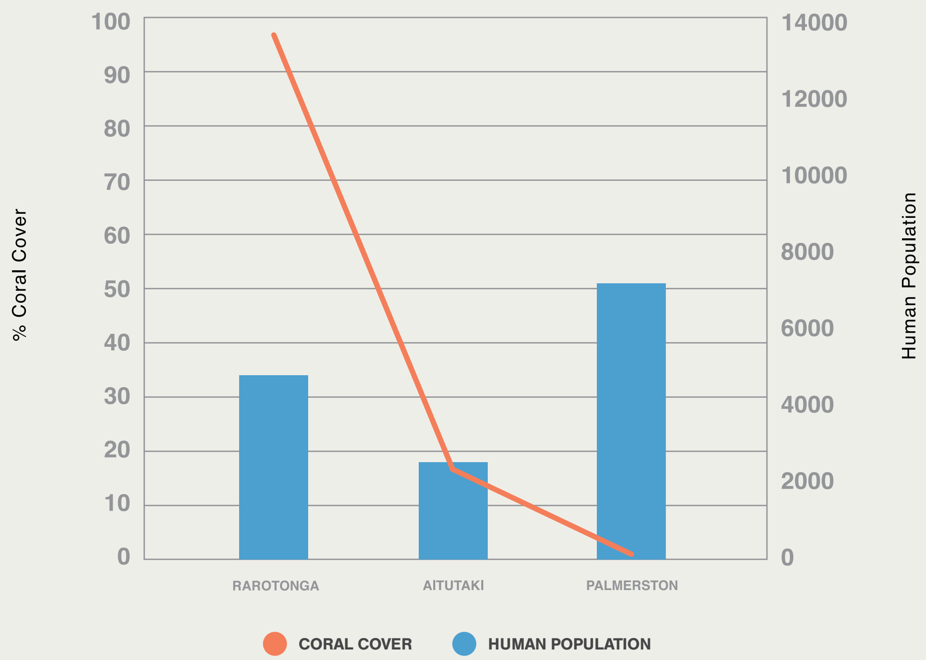


Figure 24

PERCENT LIVE CORAL COVER COMPARED TO ISLAND HUMAN POPULATION SHOWING THAT AS THE HUMAN POPULATION INCREASES, THE LIVE CORAL COVER DECREASES. HUMAN POPULATION DATA OBTAINED FROM THE COOK ISLANDS CENSUS AND COOKISLANDS.ORG.



island nations surveyed on the GRE (Figure 27). With continued efforts to protect and preserve the fish and benthic communities, it is possible for these reefs to become some of the best in the South Pacific.

Palmerston, the most sparsely populated island, had a noticeably higher number of large predatory fish, indicating that fishing pressure on the more populous islands of Aitutaki and Rarotonga has likely decreased the abundance of top predators. Likewise, Palmerston had the highest mean species richness, indicating a greater effect of human pressure on fish diversity at the other two islands. The benthic communities around Palmerston reflected this trend as it had the highest percentage of live coral cover compared to the other two locations. There have been many studies that have shown a healthy reef fish population can directly affect the benthic habitat[17,34].

Conversely Rarotonga, the most populous island in the archipelago, had the lowest mean value for all fish population metrics (species richness, fish density, and biomass), likely due to high fishing pressure. Surprisingly, however, mean values for species richness and fish biomass were almost equal in Aitutaki and Rarotonga, despite the fact that the human population of Rarotonga is approximately five-times that of Aitutaki. This could be due to the higher number of tourist fishing off of Aitutaki's waters, although this should be studied further[4]. Regardless of population, large fish >40cm were nearly absent from all sites surveyed across the archipelago, which is concerning.

DISCUSSION

Figure 25 GLOBAL COMPARISON OF FISH DENSITY OF COUNTRIES VISITED ON THE GRE.

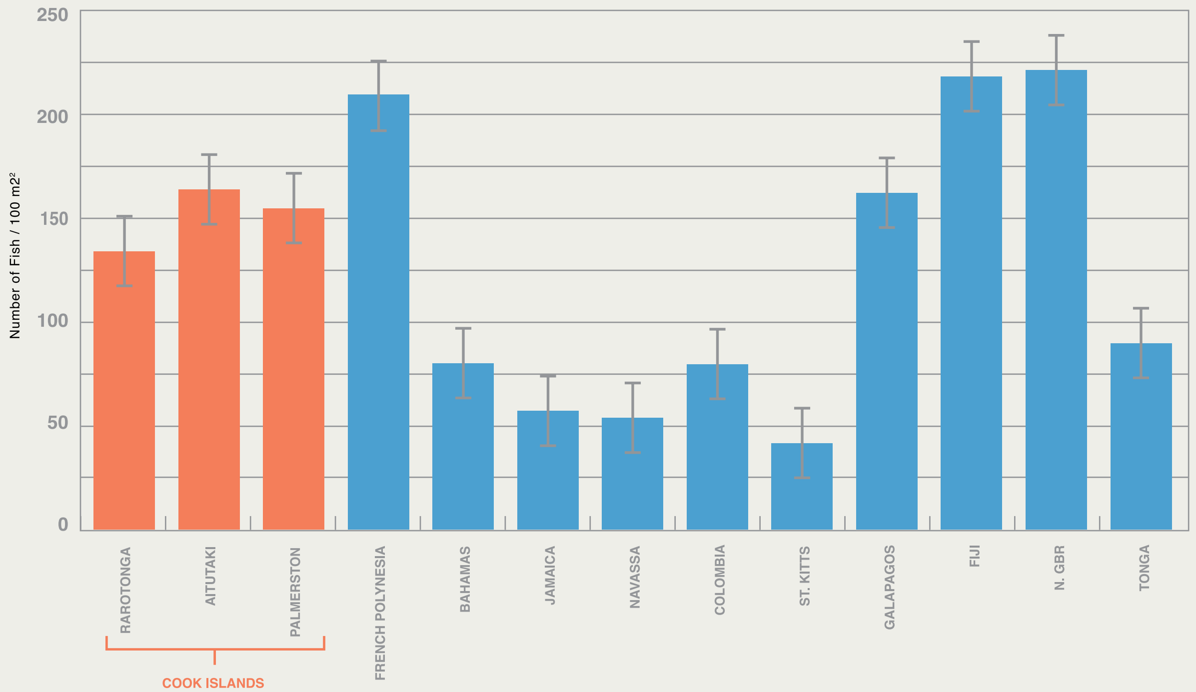


Figure 26 GLOBAL COMPARISON OF FISH BIOMASS OF COUNTRIES VISITED ON THE GRE.

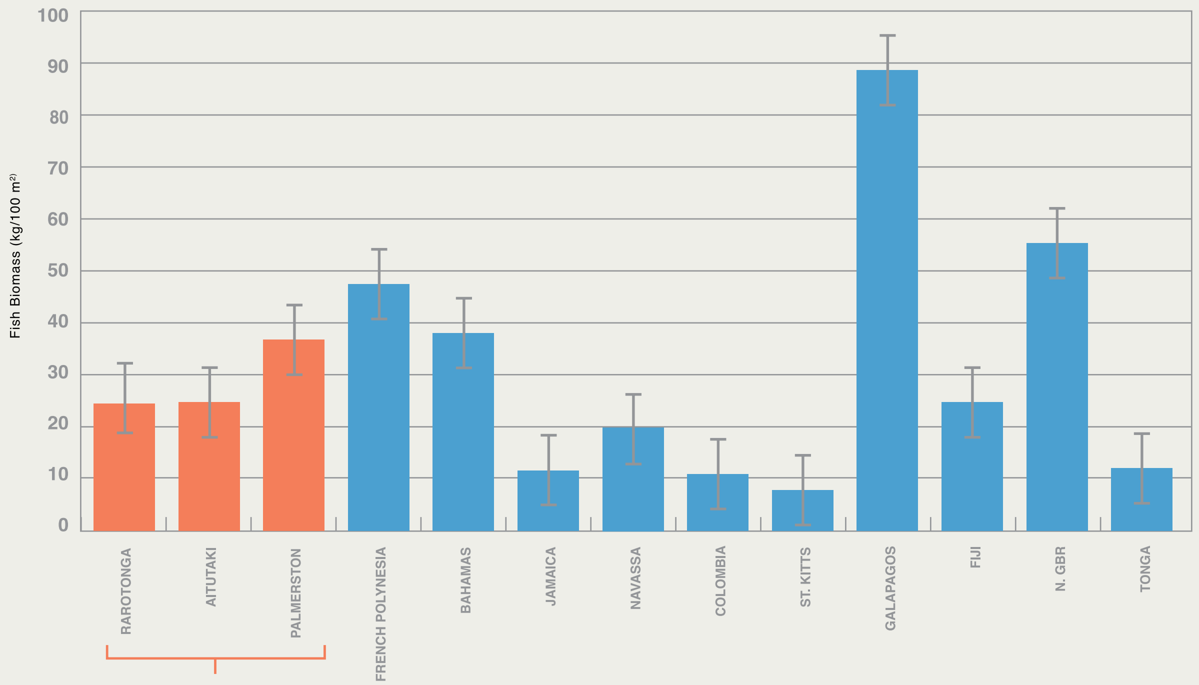
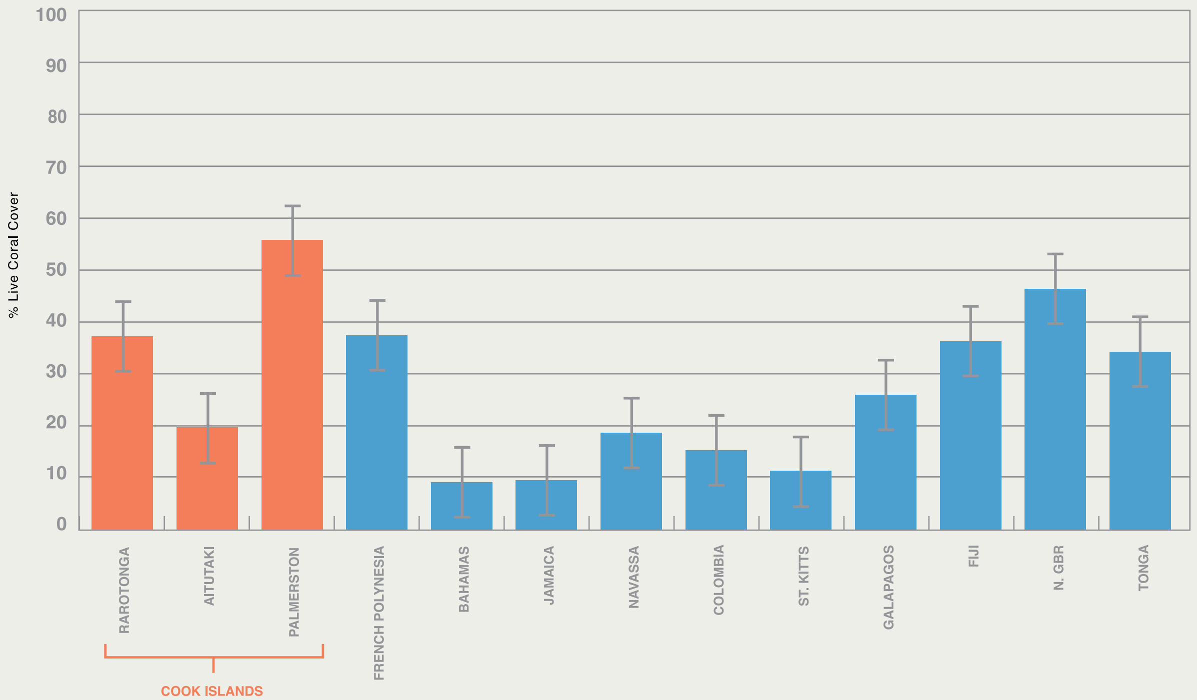


Figure 27 GLOBAL COMPARISON OF PERCENT LIVE CORAL COVER AMONG COUNTRIES VISITED ON THE GRE.



5.0 RECOMMENDATIONS

RECOMMENDATIONS

5.0

The marine conservation progress already made in the Cook Islands is commendable and perhaps some of the most advanced in the South Pacific. The offshore fishing regulations, MPA establishment, and cooperation with neighboring nations is particularly laudable as these actions will be crucial for the long term sustainability of the Cook Islands' marine resources[2].

Despite the general health of the fish and benthic communities being moderately healthy, it is worth noting that there is a lack of large predatory fish around the more populous islands. With lax (or nonexistent) nearshore fishing regulations and management, these fish populations are especially vulnerable to collapse from overfishing. Practices such as ra'ui have the potential to regulate community fishing practices and manage the nearshore fisheries, but without complete participation by the community, this could prove to be futile[3,4]. KSLOF encourages the government and people of the Cook Islands to establish more rigorous nearshore fishing management practices to preserve fish populations. This includes monitoring and recording catch sizes, establishing size and catch limits, and enforcing quotas for important fish species. Participation, cooperation, and enforcement of these fisheries regulations by the people of the Cook Islands will be crucial in protecting and rebuilding reef fish populations. There are a number of resources available, and one in particular that will likely be useful in the Cook Islands is a "fish app" developed by researchers in the Smithsonian's Marine Conservation Program. This app will allow local fishers, managers, and community leaders to easily cooperate and track daily catch. It has been proven useful in managing nearshore fisheries in other countries such as Honduras where their nearshore fisheries were in a similar state as the Cook Islands[35].

> Despite the general health of the fish and benthic communities being moderately healthy, it is worth noting that **there is a lack of large predatory fish around the more populous islands.**

As natural disturbances, such as storms and coral bleaching events, increase in frequency due to climate change, it is important to protect the reefs from other natural and anthropogenic stressors[36–38]. While in Aitutaki, KSLOF helped train Cook Islanders on recognizing COTS and established removal practices to try to minimize the impact of the animals on the benthic habitat. It will be important to educate other islands of the dangers of COTS, how to recognize an outbreak and using safe techniques for handling and removing the organisms from the reef (Figure 28). This will prevent other locations in the Cook Islands from experiencing the detrimental damage that was seen in Aitutaki. COTS outbreaks have been linked to an increase in nutrients in the water[9,39], so monitoring and managing runoff from land will be crucial to avoid further damage and outbreaks in other areas.

KSLOF believes that with improved management and monitoring, the reefs and fish communities of the Cook Islands have the potential to flourish and become some of the best in the South Pacific.

Figure 28 IMAGE OF CROWN OF THORNS STARFISH BEING REMOVED FROM THE REEF BY A KSLOF SCIENTIST IN AITUTAKI IN 2013. PHOTO BY KEN MARKS.

> As natural disturbances, such as storms and coral bleaching events, increase in frequency due to climate change, **it is important to protect the reefs from other natural and anthropogenic stressors[36–38].**

ACKNOWLEDGMENTS

The Khaled bin Sultan Living Oceans Foundation is grateful for the assistance provided by the Cook Islands in obtaining the permits for research, and getting permission to work within the three different atolls visited.

The Foundation would like to express our thanks to the *Cook Islands Research Committee, Office of the Prime Minister* for granting us permission to sample and study the reefs of your country. KSLOF would like to especially thank *Jaqueline Evans, Tou Ariki, Kevin Iro,* and *Ted Nia* of the *Cook Islands Marine Park Steering Committee,* and *Michael Henry of Cruise Cook Islands* for their hard work in assisting with the planning and execution of this research mission. The Foundation is particularly grateful for the dedicated efforts of all scientists, scientific divers, and observers and would like to thank them for their contributions. Several foreign researchers were also invited by KSLOF to participate in the surveys in the frame of local research programs. Their results are not discussed here.

The research mission to the Cook Islands would not have been possible without the leadership, vision, and generosity of His Royal Highness Prince Khaled bin Sultan. The Foundation is deeply appreciative of his financial support and for the generous use of the research vessel, *M/Y Golden Shadow.* His vision of *Science Without Borders®* was materialized in the research mission to the Cook Islands through the involvement and partnerships by scientists from the following countries: Cook Islands, United States of America, Australia, Portugal, the Philippines, and Taiwan.

KSLOF appreciates the skill and dedication of the scientific divers who aided in the collection of vital data for the Foundation, especially our international partners from Nova Southeastern University, University of the Azores, University of Miami, the United States National Oceanic and Atmospheric Administration (NOAA), the Atlantic and Gulf Rapid Reef Assessment, and the National Museum of Marine Biology and Aquarium, Taiwan. The Foundation is particularly grateful for the dedicated efforts of each scientist, and we thank each of you for your contributions, especially the detailed data you gathered.

KSLOF sincerely appreciates the professionalism and hard work of the officers and crew of the *M/Y Golden Shadow.* They were responsible for getting us safely to our research sites and conducting all logistical operations of the dive and research vessels. They ensured that each researcher had access to the study sites and proper working tools and equipment needed to complete the work and had highly capable engineers and electricians that repaired and fabricated gear when we ran into complications.

As deliverables from this research project are completed, we look forward to continuing these partnerships to ensure the information and data from this project are applied toward the conservation needs and goals of the Cook Islands.

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APPENDIX 1 | BENTHIC AND FISH SURVEY SITES FROM 2013 AND 2015 MISSIONS

	Island	Site	Date	Latitude	Longitude	# of Benthic Transects	# of Fish Transects	Exposure	Reef Type
	Raratonga	Site 01	22-Apr-2013	-21.1941	-159.8091	5	12	Leeward	Fringing Reef
	Raratonga	Site 02	23-Apr-2013	-21.2513	-159.8290	7	6	Windward	Fringing Reef
	Raratonga	Site 03	23-Apr-2013	-21.2136	-159.8331	6	8	Windward	Fringing Reef
	Raratonga	Site 04	24-Apr-2013	-21.2417	-159.7225	4	8	Leeward	Fringing Reef
	Raratonga	Site 05	24-Apr-2013	-21.2136	-159.7330	5	8	Windward	Fringing Reef
	Raratonga	Site 06	24-Apr-2013	-21.1993	-159.7569	6	6	Leeward	Fringing Reef
	Raratonga	Site 07	26-Apr-2013	-21.2642	-159.8165	7	8	Windward	Reef Flat
	Raratonga	Site 08	26-Apr-2013	-21.2745	-159.7725	9	8	Windward	Reef Flat
	Raratonga	Site 09	26-Apr-2013	-21.2719	-159.7299	4	6	Windward	Fringing Reef
	Raratonga	Site 10	27-Apr-2013	-21.2007	-159.7714	5	6	Windward	Fringing Reef
	Raratonga	Site 11	27-Apr-2013	-21.2300	-159.8335	6	7	Windward	Reef Flat
	Raratonga	Site 12	27-Apr-2013	-21.1935	-159.7965	5	6	Leeward	Fringing Reef
	Aitutaki	Site 13	28-Apr-2013	-18.9043	-159.7236	7	16	Windward	Fringing Reef
	Aitutaki	Site 14	28-Apr-2013	-18.8184	-159.7735	6	8	Windward	Fringing Reef
2013	Aitutaki	Site 15	29-Apr-2013	-18.8897	-159.8272	6	8	Leeward	Fringing Reef
	Aitutaki	Site 16	29-Apr-2013	-18.8672	-159.8188	6	8	Leeward	Fringing Reef
	Aitutaki	Site 17	30-Apr-2013	-18.8331	-159.7941	5	8	Leeward	Fringing Reef
	Aitutaki	Site 18	30-Apr-2013	-18.9173	-159.8452	6	8	Windward	Fringing Reef
	Aitutaki	Site 19	30-Apr-2013	-18.8517	-159.8054	5	7	Leeward	Fringing Reef
	Aitutaki	Site 20	1-May-2013	-18.9283	-159.7943	5	6	Windward	Fringing Reef
	Aitutaki	Site 21	1-May-2013	-18.9519	-159.7445	5	6	Windward	Reef Flat
	Aitutaki	Site 22	1-May-2013	-18.9271	-159.7250	5	6	Windward	Reef Flat
	Palmerston	Site 23	3-May-2013	-17.9926	-163.1535	8	11	Windward	Fringing Reef
	Palmerston	Site 24	3-May-2013	-18.0291	-163.1178	5	8	Windward	Fringing Reef
	Palmerston	Site 25	3-May-2013	-18.0489	-163.1128	7	8	Windward	Fringing Reef
	Palmerston	Site 26	4-May-2013	-18.0885	-163.1521	8	8	Windward	Fringing Reef
	Palmerston	Site 27	4-May-2013	-18.0697	-163.1293	6	8	Windward	Fringing Reef
	Palmerston	Site 28	5-May-2013	-18.0412	-163.1876	6	9	Leeward	Fringing Reef
	Palmerston	Site 29	5-May-2013	-18.0057	-163.1757	5	8	Leeward	Fringing Reef
	Palmerston	Site 30	5-May-2013	-18.0790	-163.1817	5	8	Leeward	Fringing Reef
	Aitutaki	Site AI04	14-Jul-2015	-18.883	-159.8221	4	0	Leeward	Fringing Reef
	Aitutaki	Site AI05	15-Jul-2015	-18.9052	-159.8403	4	0	Leeward	Fringing Reef
2015	Aitutaki	Site AI07	15-Jul-2015	-18.8255	-159.7641	4	0	Windward	Fringing Reef
	Aitutaki	Site AI09	16-Jul-2015	-18.8812	-159.7462	4	0	Windward	Fringing Reef
	Aitutaki	Site AI10	16-Jul-2015	-18.8498	-159.7498	4	0	Windward	Fringing Reef

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