A report of the *Comprehensive Long-term Coral Reef Monitoring at Permanent Sites on Guam* project

Including the results of an analysis of data collected at high priority reef areas between 2010 and 2018

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with contributions by

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Fishery Biologist, NOAA Pacific Islands Regional Office

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April 2019

NOAA CORAL REEF CONSERVATION PROGRAM

A project funded by NOAA Coral Reef Conservation Program grant NA17NOS4820038, with previous funding provided through grants NA07NOS4260060, NA10NOS4260060, NA11NOS4820007, NA13NOS4820012, and NA15NOS4820039

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Cover: High cover of the plate and pillar coral, *Porites rus*, along the submarine terrace in East Agana Bay in 2015. Coral cover increased at the East Agana Bay monitoring site between 2010 and 2018, and remained stable for the *Porites*-dominated coral communities in the Tumon Bay and Tepungan (Piti) Bay monitoring sites during this period. The stability of the moderate-to-high coral cover at these important, but relatively limited, reef areas is in contrast to the significant declines in live coral observed around much of the island as a result of *crown-of-thorns seastar* outbreaks in the mid-2000s and multiple, severe coral bleaching events between 2013 and 2017.

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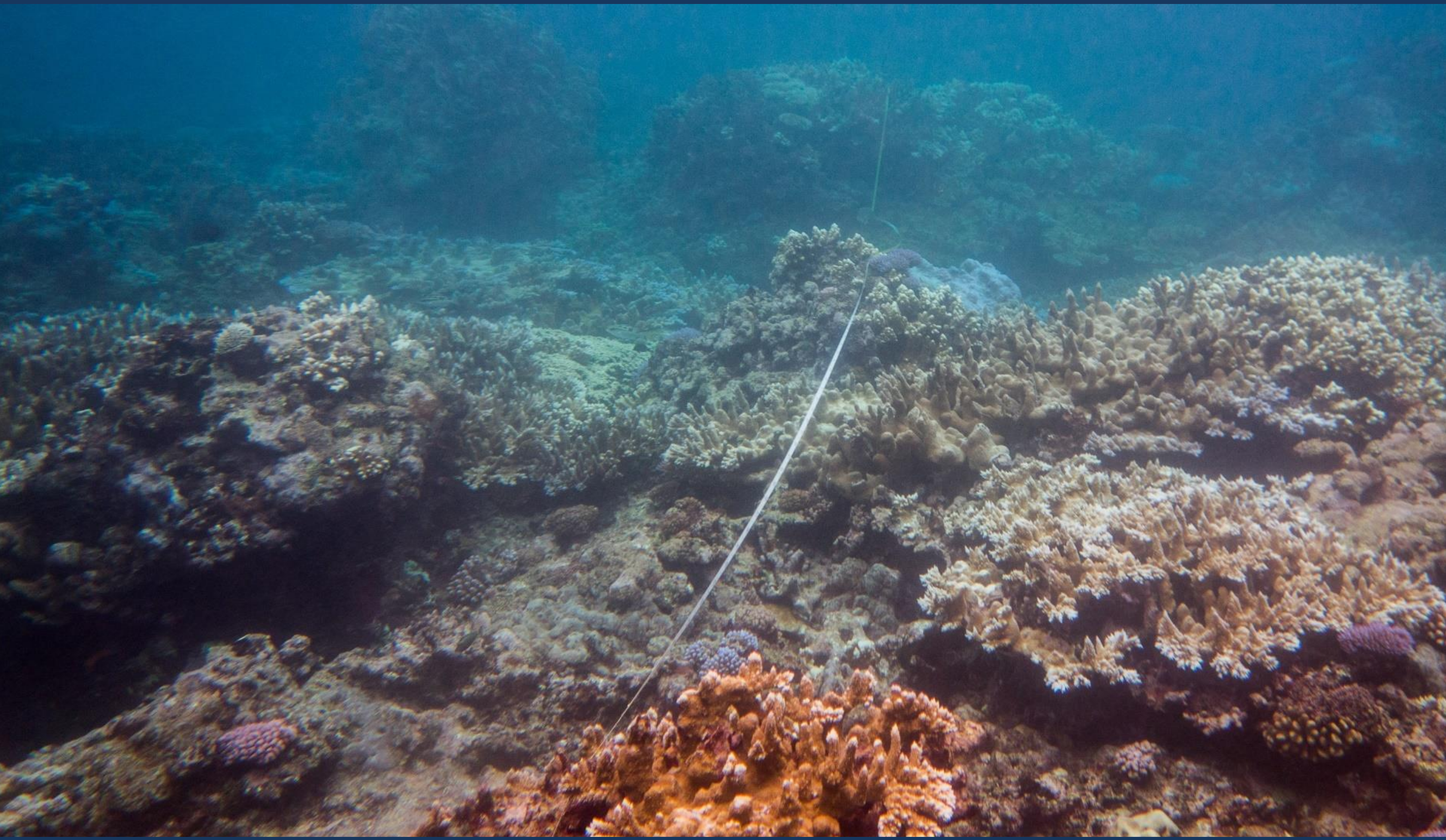
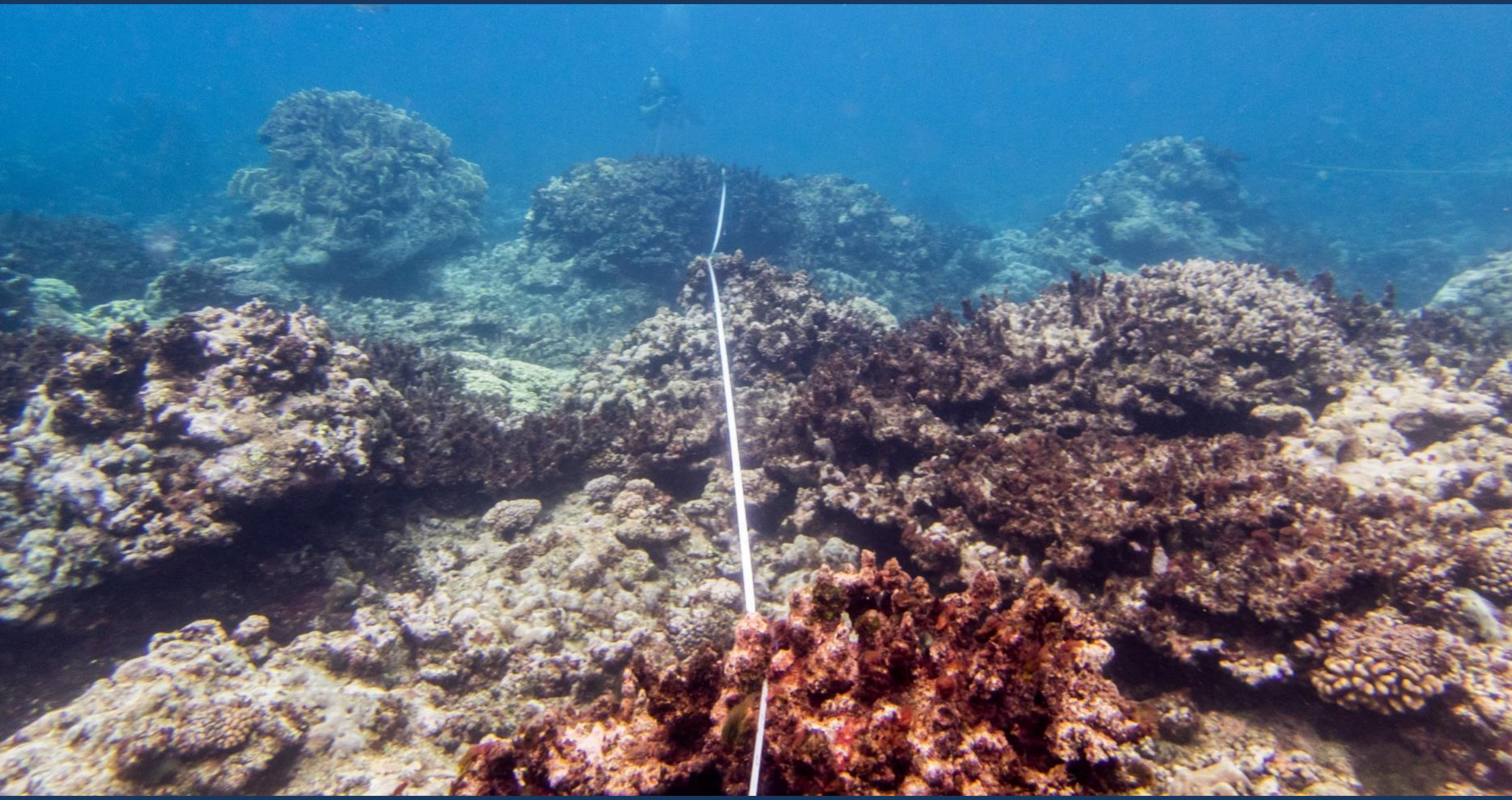
ABOUT THIS REPORT

This report presents the results of an analysis of coral reef monitoring data collected at high priority reef areas since 2010 as part of the *Comprehensive Long-term Monitoring at Permanent sites on Guam project*, also known as the Guam Long-term Coral Reef Monitoring Program (GLTMP). The high priority reef areas targeted for monitoring by the GLTMP include the Tumon Bay Marine Preserve, East Agana Bay, the Piti Bomb Holes Marine Preserve, the Achang Reef Flat Marine Preserve, Cocos-East, Fouha Bay, and Western Shoals, in Apra Harbor. The results presented include the results of an analysis of baseline data collected at the Fouha Bay, Tepungan (Piti) Bay, Achang, and modified Tumon Bay sites, as well as time series data collected at the Tumon Bay (2010-2018), East Agana Bay (2010-2018), and Tepungan (Piti) Bay (2014-2018). Also presented in the report is background information about the project and a summary of data collection activities and other program activities completed to-date.

The results presented here for the high priority reef areas were originally going to be presented in a December 2018 report, however the significant bleaching-associated impacts observed at shallow reef areas in recent years, and the results of preliminary analyses that suggested only minor changes in benthic cover at the high priority reef areas, necessitated the prioritization of the analysis of the copious coral bleaching survey data collected at shallow seaward slope and reef flat survey sites located around the island. The December 2018 report, which is entitled *An interim report of the Comprehensive Long-term Monitoring at Permanent sites on Guam project* was submitted to the Guam Bureau of Statistics and Plans and the NOAA Coral Reef Conservation Program and will be made available through NOAA's Coral Reef Information System (CoRIS) website (http://www.coris.noaa.gov). This interim report includes the results of an initial analysis of coral bleaching survey data collected around Guam between 2013 and 2017, University of Guam Marine Laboratory (UOGML) Reef Flat Monitoring Program survey data collected between 2009 and 2018, and mapping and mortality assessment data collected at all of Guam's major staghorn coral communities between 2009 and 2017. A manuscript that included the results of an initial analysis of coral bleaching survey data as well as UOGML Reef Flat Monitoring Program data was submitted to a peer-review journal and is currently in review. The results of the first of two staghorn mortality assessment efforts were published in *Marine Ecology Progress Series* in 2017.

Photo (previous page): Very low cover of living coral at the monitoring site within the Achang Reef Flat Marine Preserve in 2014. While historical data are limited for this specific area, data collected by NOAA PIFSC around the island show a 60% decline in the amount live coral along windward coast between 2003 and 2017. Only skeletons, such as those evident in this image, remain for most of the corals that are the preferred prey of the crown-of-thorns seastar or which are more susceptible to coral bleaching. **Photo (next page)**: A shallow (2.5 m) wave-exposed reef front community with numerous live *Acropora abrotanoides* colonies in Pago Bay in August 2017, at the beginning of record-breaking coral bleaching event (top), and that same community in April 2018, several months after temperatures returned to normal and after most of the corals had died (bottom). Photo transect images obtained at the site on multiple occasions during and after the 2017 event are currently being analyzed, but the devastating effects of the historic levels of thermal stress in 2017 are clearly evident in the images.





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EXECUTIVE SUMMARY

The *Comprehensive Long-term Monitoring at Permanent Sites in Guam* project, also known as the Guam Long-term Coral Reef Monitoring Program (GLTMP), involves the regular collection of data for a suite of coral reef ecosystem health parameters at high priority reef areas around Guam, as well as critical support for coral bleaching response and other monitoring and assessment activities carried out by the Guam Coral Reef Response Team. This project also includes support for the Reef Flat Monitoring Program (RFMP), an effort led by Dr. Laurie Raymundo of the University of Guam Marine Laboratory (UOGML) to document changes in coral communities on Guam's shallow reef flats.

The high priority reef areas targeted for monitoring include the Tumon Bay Marine Preserve, East Agana Bay, the Piti Bomb Holes Marine Preserve, the Achang Reef Flat Marine Preserve, Cocos-East, and Fouha Bay. Data collection at the high priority reef areas began in 2010, and since then data has been collected at a total of seven priority reef areas, with data collected from six sites on a regular basis. Between 2010 and 2018 GLTMP biologists carried out several hundred dives and collected data for reef fish, benthic, and macroinvertebrate communities at these monitoring sites. Surveys at most sites are carried out along the submarine terrace zone of the seaward slope, at depths between seven and 15 meters.

An analysis of baseline survey data for the benthic communities at the more recently-established Fouha Bay, Achang, Piti, and a modified Tumon Bay site revealed very low cover of living coral in the Achang and Fouha Bay sites, but moderate-to-high coral cover at the Tumon, East Agana, and Piti sites. Total reef fish biomass was low at most sites, ranging from 11–71% of the potential total reef fish biomass estimate for an unimpaired Guam reef by Williams et al. (2015). Baseline benthic cover and reef fish data for the East Agana and Western Shoals sites are provided in a report released in 2012.

An initial time series analysis of benthic cover and macroinvertebrate data was also carried out for the Tumon, East Agana, and Piti sites. Coral cover remained stable or increased at these three sites between 2010/12 and 2018, in contrast to significant losses of coral observed at other reef areas in recent years. An initial analysis of macroinvertebrate survey data revealed significant declines in sea cucumbers at the Tumon Bay and Piti sites between 2012 and 2018, and at the East Agana Bay site between 2010 and 2018. The reasons for these declines are not yet

<6%

Cover of live coral at the Achang and Fouha Bay monitoring sites in 2014/15

0 to +31%

Change in live coral cover at the Tumon, East Agana, and Piti sites between 2010/12 and 2018

>90%

Percentage of total coral cover at Tumon and East Agana sites comprised of stress-tolerant *Porites* corals

11–71%

Proportion of reef fish biomass expected for a healthy Guam reef observed at monitoring sites

60–98%

Decline in sea cucumber density at Tumon, East Agana, and Tepungan Bay monitoring sites between 2010/12 and 2018

clear, but the relative stability of reef habitat at these sites throughout that time period suggest that the declines may be a result of poaching/overharvesting.

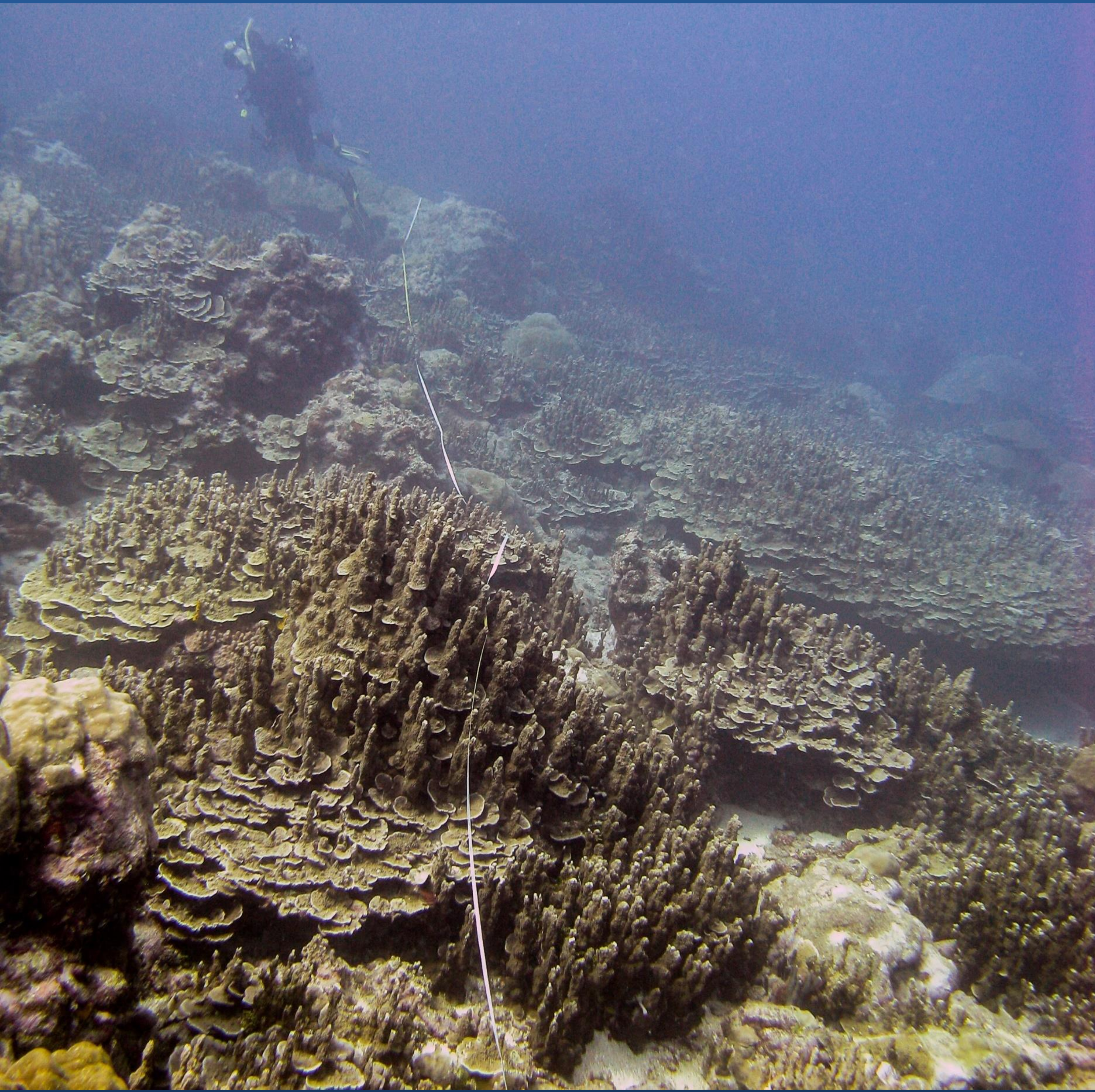
The very low cover of living coral, and the high cover of cyanobacteria and sediment-laden algal turfs, at the Fouha Bay and Achang sites suggest that these sites have been significantly impacted by crown-of-thorns (COTS) outbreaks, degraded water quality, reduced rates of herbivory, and, more recently, by coral bleaching. The low reef fish biomass values for most of the monitoring sites suggest human impacts on these reef fish communities, likely including fishing pressure and poaching of Marine Preserves, as well as impacts to reef fish habitat as a result of degraded water quality and crown of seastar outbreaks. Further analysis of the reef fish data and other data collected at the high priority reef areas will provide an indication of the changes in reef fish and other aspects of the reef ecosystem since monitoring began, and will improve our understanding of the possible causes of these changes.

The relative stability of live coral cover at the Tumon, East Agana, and Tepungan sites is likely a result of the near complete dominance of the coral community at these sites by stress-resistant corals such as *Porites rus* and mounding *Porites* species. These species thrive at these reef areas, which are exposed to relatively low levels of wave energy. These species are also among the least preferred prey of the coral-eating crown-of-thorns seastar, which has devastated coral communities around much of Guam over the last few decades. The high priority reef areas selected for monitoring happened to include these higher coral cover areas, and were not intended to represent the entirety of Guam's coral reef ecosystem. Despite the relatively high cover of living coral at these sites, the very low coral diversity suggests that these reef communities may be vulnerable to rapid losses in coral associated with disease outbreaks, or as a result of heat and light stress once sea surface temperatures exceed the threshold for these few species. Recent declines in the cover of mounding *Porites* species appear to be related to the historically severe 2017 coral bleaching event, and suggest that the resilience of these important corals to human-driven ocean warming may be faltering.

The relative stability of live coral cover at the Tumon, East Agana, and Piti sites is also in stark contrast to island-wide declines observed across the shallow reef flats and shallower (5 m) portions of the seaward slope between 2013 and 2017. As presented in a report released in December 2018, island-wide surveys carried out by GLTMP staff and other members of the Guam Coral Reef Response Team documented a 37% decline in living coral along the shallow (5 m) reef front zone as a result of the record-breaking levels of heat stress and associated coral bleaching. Impacts were most severe for coral communities on the eastern side of the island, which suffered an estimated 59% loss in living coral. The loss of living coral documented at shallow reef flat sites monitored quarterly by the Reef Flat Monitoring Program was similar, with an average loss of 29% between 2009 and 2018. Sites with a greater proportion of the more bleaching-susceptible staghorn corals experienced greater losses, with some sites losing as much as 80% of their living coral. A separate island-wide staghorn coral mortality assessment effort found a 36% decline in the extent of living staghorn coral island-wide between 2013 and 2017, with some sites losing 100% of their staghorn corals.

Photo (next page): A transect tape traversing a high coral cover, *Porites rus*-dominated sampling station in the East Agana Bay site in 2012.

1 PROJECT DESCRIPTION



1.1 PROJECT OVERVIEW

The *Comprehensive Long-term Monitoring at Permanent Sites in Guam* project, also known to as the Guam Long-term Coral Reef Monitoring Program (GLTMP), involves the regular collection of data for a suite of coral reef ecosystem health parameters at high priority reef areas around Guam, as well as support for coral bleaching response and other monitoring and assessment activities carried out by the Guam Coral Reef Response Team. Data are collected and managed by a small team of highly-trained field biologists from the University of Guam Marine Laboratory (UOGML) and NOAA Pacific Islands Regional Office (PIRO) Guam Field Office, with occasional assistance by staff from the Bureau of Statistics and Plans (BSP), the Guam Environmental Protection Agency (GEPA) and the Department of Agriculture's Division of Aquatic and Wildlife Resources (DAWR). The core GLTMP team is currently comprised of five UOGML employees, including a part-time monitoring program coordinator (MPC), a full-time monitoring technician (MT), a part-time monitoring technician (MT), and two UOGML graduate students who serve as part-time monitoring assistants (MA). Valerie Brown, a coral reef ecologist with NOAA PIRO, is also a core member of the monitoring team, providing significant input into project planning as well as leading fish data collection and analysis efforts. All staff are highly skilled scientific divers trained to carry out a variety of coral reef survey methods.

Data collection at the high priority reef areas began in 2010, and since then data has been collected at a total of seven priority reef areas, with data collected from six sites on a regular basis. The high priority reef areas targeted for monitoring by the program include the Tumon Bay Marine Preserve (Tumon), East Agana Bay, the Piti Bomb Holes Marine Preserve (Piti), the Achang Reef Flat Marine Preserve (Achang), Cocos-East, and Fouha Bay (Figure 2.1). Baseline surveys were carried out at Western Shoals, in Apra Harbor, in 2011 but further data collection at this site has been postponed indefinitely. The GLTMP's comprehensive approach to ecological monitoring, combined with the high density of samples within relatively large (0.1–0.2 km^2) reef areas, provide data critical to understanding changes in reef condition at these areas, for the development of management strategies specific to each area, and for evaluating the effectiveness of management actions in improving the condition of these high value marine ecosystems. The data collected at the high priority reef areas are also essential for evaluating the relative resilience of the reef communities to climate change impacts and for tracking changes in resilience over time. GLTMP data collection efforts at three of the five locally-managed Marine Preserves provide the only long-term monitoring data available for evaluating the effectiveness of individual preserves.

The initial focus of the GLTMP was on the high priority reef areas, but a severe mass coral bleaching event in 2013 necessitated a shift to island-wide data collection efforts that targeted the shallow reef communities that were most severely impacted by the event. The limited capacity of the small GLTMP team, and the very limited underwater data collection capacity of Government of Guam agencies, was not sufficient to carry out annual monitoring at the high priority reef areas while also implementing an island-wide, survey-intensive data collection effort aimed at documenting the extent and severity of a historic coral bleaching event. Subsequent bleaching events in 2014 and 2016, and yet another record-breaking event in 2017, required continued focus on the documentation of the extent and severity of these events as they occurred. Additional survey efforts were also carried out between bleaching events, such as the 2015 bleaching recovery assessment, which aimed to document the cumulative impact of the 2013 and 2014 bleaching events and evaluate the potential for recovery. Data collection continued at the

Box 1.1. Components of the NOAA Coral Reef Conservation Program Strategic Plan supported by GLTMP activities

Climate Pillar

Strategy – Support a resilience-based management approach

Objective 2: Support the assessment of coral reef ecosystem vulnerabilities to the impacts of climate change, and use the assessment results to inform and support management actions

Objective 3: Support the collection, sharing, and integration of multiple types of monitoring and modeling to provide a dynamic understanding of the system to inform decisions and allow for adaptive management

Objective 5: Support and encourage management partners *to address potential climate change impacts in resilience-based management planning efforts*

Fisheries Pillar

Strategy – Provide data essential for coral reef fisheries management

Objective 2: Support baseline and performance biological or socioeconomic assessments of key marine protected areas (MPAs) to better understand human perceptions and behaviors and realize ecological benefits

Objective 3: Support and advocate for life history and ecological research, monitoring, and data integration to provide information on population status and ecology of key fisheries taxa and advance our understanding of ecological sustainability

Pollution Pillar

Strategy – Develop, coordinate, and implement watershed management plans

Objective 3: Determine the efficacy of key erosion and sediment control practices and stormwater management practices to reduce sediment and nutrient loads through coordinated baseline and performance monitoring

Restoration Pillar

Strategy – Prevent avoidable losses of corals and their habitat

Objective 2: Support emergency response to and restoration of areas impacted by physical events (e.g., vessel groundings, hurricanes) in high-value areas (e.g., areas of high coral cover)

high priority reef areas during this period, but the limited program capacity meant that not all sites could be visited each year, nor could all survey methods be carried out during each site visit. Recently-proposed changes (described in Section 1.5) will help the program adapt to the shifting management priorities in this period of catastrophic climate change-associated coral reef impacts.

In addition to carrying out the monitoring of high priority reef areas and coral bleaching response surveys members of the GLTMP have also made essential contributions to the mapping, assessment and monitoring of Guam's staghorn communities; the aforementioned island-wide reef resilience assessment in 2016; and a variety of other monitoring, assessment, outreach, and management-related activities (see Section 1.3). The MPC, as well as other members of the monitoring team, have also provided—and continue to provide—key input into the development of management strategies, such as the recently-completed Guam Coral Bleaching Response Plan and Guam Reef Resilience Strategy, and are expected to

Box 1.2. Components of the Guam Coral Reef Resilience Strategy supported by GLTMP activities

Outcome F: Effective fisheries management

Objective 2: Conduct management-driven monitoring and research to assess the status of reef fish communities, habitats, and target marine species; the impacts of climate change on fisheries; and the effectiveness of management

Outcome P: Decreased land-based sources of pollution

Objective 3: Conduct management-driven research and develop new tools for watershed restoration and BMPs for tropical coastal ecosystems

Outcome RR: Increased reef response and restoration

Objective 1: Increase the capacity of the Guam Coral Reef Response Team to rapidly respond to acute impacts affecting Guam's coral reefs (e.g. coral bleaching events; vessel groundings and spills; and outbreaks of disease, COTS, and nuisance and invasive species).

Objective 3: Develop and implement a science-based, community-driven Coral Reef Restoration Strategy to restore viable coral communities on Guam's reefs.

Objective 4: Continue to support Guam's Long-term Coral Reef Monitoring Program and conduct research that quantifies change in Guam's reef communities and informs response and restoration efforts

make significant contributions to the development of a restoration strategy through participation in the new Guam Coral Reef Restoration Group.

The *Comprehensive Long-term Monitoring at Permanent Sites in Guam* project also includes support for the Reef Flat Monitoring Program carried out by Dr. Laurie Raymundo of the UOGML, which has tracked changes in the condition of Guam's reef flat coral communities since 2009. The results of a broad-level analysis of data collected through the Reef Flat Monitoring Program between 2009 and 2018 were presented in the December 2018 Interim report, which will soon be available through the NOAA Coral Reef Information System (CoRIS) at http://www.coris.noaa.gov.

1.2 BACKGROUND

Guam's reefs have been the subject of numerous studies in recent decades, but not until the establishment of the Guam Long-term Coral Reef Monitoring Program had there been a coral reef monitoring program that comprehensively addresses changes in the condition of benthic habitat, water quality, and associated biological communities at high priority reef areas through regular data collection efforts. This lack of baseline information limited managers' ability to evaluate natural and anthropogenic impacts to specific reef areas around Guam and to gauge the effectiveness of management activities at the scale of individual management areas. In order to address this major gap the Government of Guam's natural resource agencies, with the assistance of the UOGML and NOAA PIRO, developed a long-term monitoring strategy aimed at addressing the management needs of local resource agencies and the objectives set by the National Coral Reef Ecosystem Monitoring Program (NCREMP). A program coordinator was hired in January 2007 to further develop and implement the monitoring strategy. A large amount of baseline data for a number of key ecosystem health parameters is now available for seven high priority reef areas that are currently the focus of a number of management actions aimed at improving reef condition. Subsequent data collection, which is on-going at six of these reef areas, provides critical information to managers about the effectiveness of management efforts, and alerts managers to emerging threats that may not otherwise be detected.

1.3 ACTIVITIES CARRIED OUT TO-DATE

1.3.1 Regular monitoring at high priority reef areas

Data collection at the high priority reef areas began in June 2009, with initial surveys targeting the southwestern end of the Tumon Bay Marine Preserve. A more extensive data collection effort was carried out in 2010 along a portion of the Tumon Bay outer reef slope and an equivalent area along the outer reef slope in East Agana Bay. In 2011 surveys were conducted at Western Shoals and in 2012 surveys were carried out at the Piti, Tumon, and East Agana sites. In 2014 baseline surveys were carried out at the Achang site and at portion of the Cocos-East site, and return visits were made to the Tumon, East Agana, and Piti sites. A new site was established in Fouha Bay in 2015, with all surveys carried out at a total of 13 permanent sampling stations in 2015. The team returned to the Tumon and East Agana sites in 2015 (and early 2016). Data collection at other long-term monitoring sites did not occur in 2016 because of the team's focus on a multi-month bleaching response effort, but data collection at the long-term sites resumed in 2017 with visits to the Tumon, East Agana, and Piti sites. Surveys at the Achang, Cocos-East, Tumon, and East Agana sites were completed in 2018. A detailed account of GLTMP data collection activities at the high priority reef areas to-date is provided in Appendix A, and maps showing the locations of all sampling stations surveyed to-date are provided in Appendix B–Appendix I.

1.3.2 Coral bleaching response

Researchers at the UOGML and scientists from local and federal government agencies have documented coral bleaching on Guam's reefs since the phenomenon was first reported in 1994 (Paulay and Benayahu 1999, Burdick et al. 2008). GLTMP staff and other members of the Guam Coral Reef Response Team contributed to these efforts to track the relatively modest impacts of past coral bleaching phenomena on Guam's reefs. In 2013 the coral reefs of Guam and other islands in the Mariana Archipelago experienced a significant bleaching event associated with anomalously high sea surface temperatures and an extended period of calm water conditions. At the time, the 2013 mass coral bleaching event registered as the most severe to have affected Guam's reefs, but within just a few years that major event would itself be overshadowed by an even more devastating event.

A large-scale data collection effort was initiated by UOGML researchers and other members of the Guam Coral Reef Response Team in order to document the extent and severity of the historic 2013 event, and to collect a dataset that would prove critical to understanding the impact of mass coral bleaching on

Guam's reefs and inform predictions about the future of Guam's reefs (Figure 1.1). Members of the GLTMP made significant contributions to the organization and implementation of the UOGML-led, island-wide assessment. Follow-up surveys were carried out with the assistance of the GLTMP staff in 2015 at a subset of the original 48 bleaching response sites in order to assess the full impact of the 2013 event, as well as assess additional mortality that may have resulted from a subsequent bleaching event in 2014. Beginning in July 2016 one of the MT assisted the NOAA Coral Fellow with numerous qualitative and quantitative bleaching response surveys at various reef flat sites around the island, and several GLTMP staff documented bleaching observed along the seaward slope in conjunction with surveys for an island-wide reef resilience assessment[1] (Figure 1.1).

In response to the record-breaking 2017 bleaching event GLTMP team members participated in surveys at 12 previously-surveyed sites located along the northern, western, and southern coasts (Figure 1.1). The team also established three shallow (2 m), shore-accessible, 30 m-long permanent transects at Tanguisson Pt., on the western leeward side of the island, and in Pago Bay, on the eastern windward side of the island, at the beginning of the 2017 bleaching event. In addition, the team re-established four 50-m transects originally established in 2007 along the 10 m depth contour in Pago Bay by Dr. Peter Schuup of the UOGML. Baseline and multiple follow-up benthic photo transect surveys were carried out at the three sites in an effort to document changes in the benthic communities at these sites—all of which hosted a high proportion of bleaching-susceptible species—with greater temporal resolution than what could be achieved with an island-wide effort.

The data collected with the significant support of GLTMP team members during and between the multiple coral bleaching events that have impacted Guam's reefs since 2013 provide the only record of the extent and severity of these historic events. These data are being used to assess the susceptibility of different coral species to bleaching, determine the environmental and human-associated drivers of any differences in bleaching impacts observed across different reef areas, and make predictions about the future composition and function of Guam's reefs under a range of climate change scenarios.

GLTMP staff and collaborators have developed several journal articles based on initial analyses of the data and continue to further analyze the data to better understand the impact of ocean warming on Guam's reef ecosystem. Bleaching survey data collected in 2013 provided the foundation of a UOGML graduate student thesis project completed in 2016, and data collected in 2013 and 2015 were also recently provided to Dr. Jeff Maynard and colleagues for a NOAA-funded study of the human and natural drivers of coral reef resilience to climate-induced coral bleaching in Guam and the identification of potential climate refugia. A manuscript that included the results of an initial analysis of coral bleaching survey data collected between 2013 and 2017 was submitted to a peer-reviewed journal and is currently in review. Coral bleaching survey data were also submitted to NOAA Coral Reef Watch staff for inclusion in an analysis of the 2014–2017 global coral bleaching event, the results of which will be published in a special issue of the journal Coral Reefs. Summaries of the results included in the recently-submitted manuscript that pertain to data collected during the island-wide shallow seaward slope surveys, staghorn coral mortality assessments, and reef flat monitoring surveys were provided in the Interim report submitted to NOAA CRCP in December 2018.

[1] The MPC served as Co-PI with Dr. Jeffrey Maynard on a NOAA Saltonstall-Kennedy grant-funded project aimed at assessing the resilience of reef areas around island. The results of this effort were presented in a report, *Coral reef resilience to climate change on Guam in 2016*, available on the NOAA CoRIS site (http://www.coris.noaa.gov).

Box 1.3. Impacts of recent coral bleaching events

The Guam Long-term Coral Reef Monitoring Program (GLTMP) has played a key role in the response to the multiple coral bleaching events that affected Guam's reefs between 2013 and 2017. As members of the multi-partner Guam Coral Reef Response Team, GLTMP staff carried out surveys at numerous locations around the island during and between the recent bleaching events. The data collected by the GLTMP and other members of the Response Team represent the best available data for understanding the extent and severity of each of these events, and will be critical for predicting the future of Guam's reefs in this era of anthropogenic climate change.

The results of an initial analysis of coral bleaching-related datasets were presented in a report provided to the NOAA Coral Reef Conservation Program in December 2018 (pictured at right) as well as in published journal articles and two articles currently in review.

Shallow seaward slope communities

32% Loss in live coral island-wide

59% Loss in live coral along east coast

An analysis of data collected at shallow (5 m) reef front sites between 2013 and 2017 revealed major losses in live hard coral cover in this wave-exposed reef zone. The stark difference between the significant losses of coral along the shallow reef front compared to deeper reef communities, is likely a result of the greater proportion of bleaching susceptible corals found in the shallow wave-washed areas. GLTMP biologist also report even greater losses of corals at depths shallower than the 5 m depth targeted for surveys.

Reef flat and staghorn coral communities

29% Loss in live coral at reef flat sites

53% Loss in live staghorn coral

An analysis of data collected at reef flat sites by the UOGML Reef Flat Monitoring Program revealed an average loss of nearly a third of live coral cover between 2009 and 2018, with staghorn coral-dominated sites losing up to 65% of live coral. Another GLTMP-supported effort led by Dr. Laurie Raymundo of the UOGML documented an average 53% loss of live coral across all major staghorn coral thickets around Guam as a result of back-to-back bleaching events and an extreme low tide event between 2013 and 2015. Some major staghorn areas experienced losses greater than 70%, while a large thicket in Agat suffered 100% mortality. Additional mortality of reef flat and staghorn coral communities was recorded by survey efforts in 2016 and 2017, although some recovery has been observed at sites visited more recently.

1.3.3 Other rapid response activities

While coral bleaching response has comprised the bulk of the GLTMP's rapid response efforts, monitoring team members have also contributed to other Guam Coral Reef Response Team activities. Examples of GLTMP staff involvement in recent Guam Coral Reef Response Team activities include the following:

- Participation in regular team meetings
- Contributing to the development of response strategies, such as the Guam Coral Bleaching Response Plan and the Crown-of-Thorns Outbreak Response Plan
- Providing technical assistance in the assessment of coral reef damage caused by vessel groundings, including the following incidents:
    - French Navy landing craft, Jade Shoals, Apra Harbor (2017)
    - Daiku Maru, Orote Pt (2014)
    - Min Don Rye, Falcona Beach (2008)
    - Tamara V, West Agana Bay (2008)
    - Mid Summer, Agana Boat Basin (2005)
- Assisting Guam EPA with coral mitigation activities at the site of the French Navy landing craft grounding on Jade Shoals in Apra Harbor
- Carrying out *Acanthaster* removal activities at Gun Beach and Dadi Beach
- Receiving training in the deployment of an ox bile solution injection method to control *Acanthaster* populations and participated in control activity at Hap's reef in May, 2018

1.3.4 Mapping and assessment of staghorn coral communities

Between 2009 and 2013 GLTMP staff opportunistically recorded the presence and species composition of staghorn communities around the island in an effort to generate a comprehensive, geographically-referenced inventory of these communities. The in-water observations and location data recorded using GPS receivers were used to inform the development of a spatial data layer that included all known staghorn coral communities on Guam (Figure 1.2). The staghorn corals spatial data layer and related information provided the foundation for a study led by Dr. Laurie Raymundo of the UOGML to assess the amount of staghorn coral loss associated with the back-to-bleaching events in 2013 and 2014. The results of the study, which were published in Marine Ecology Progress Series in 2017, along with the results of a follow-up staghorn mortality assessment conducted in 2017, were summarized in the December 2018 Interim report.

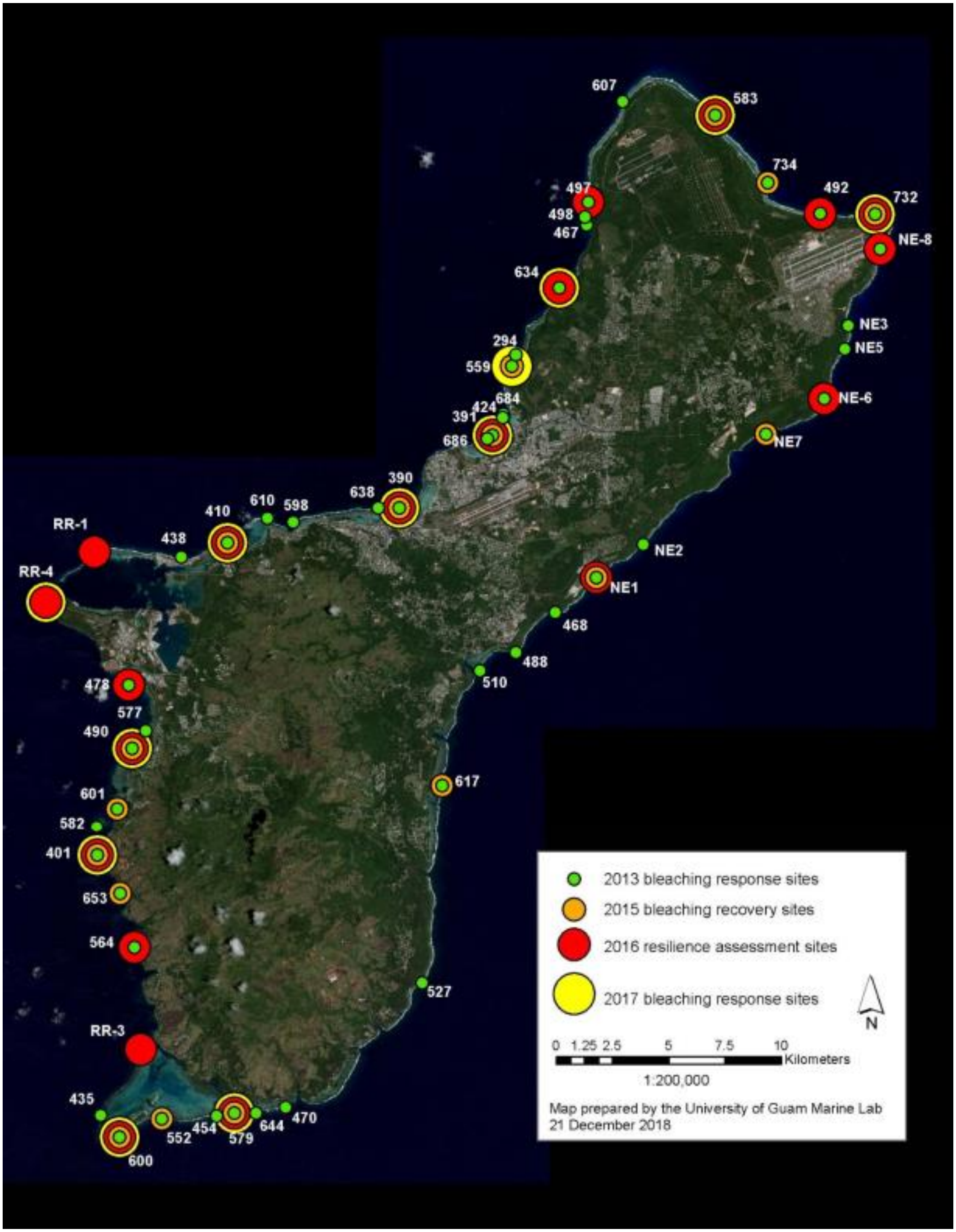


Figure 1.1. Location of coral bleaching response and reef resilience assessment sites surveyed between 2013 and 2017 with the significant support of GLTMP biologists.

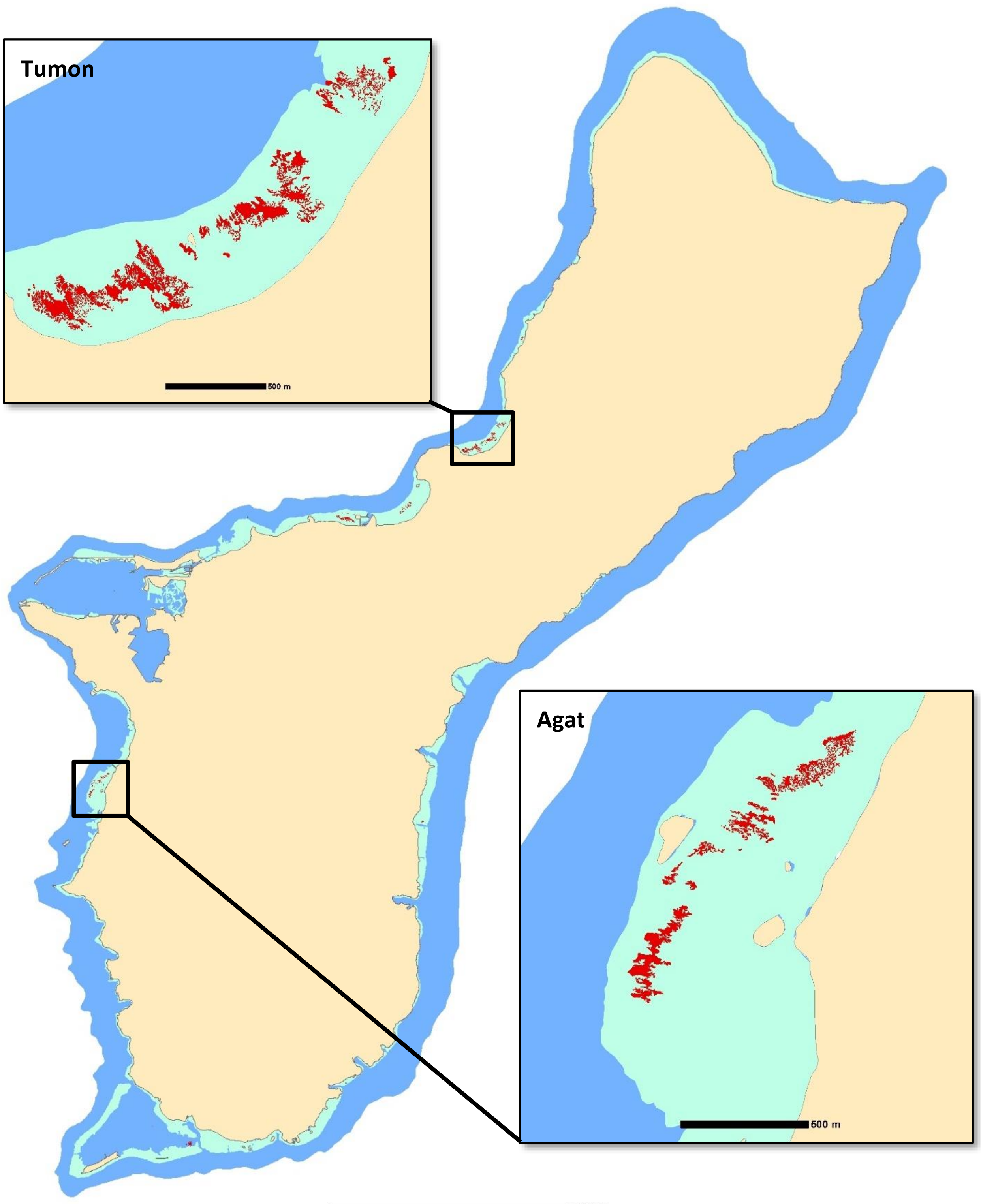


Figure 1.2. Extent of major staghorn *Acropora* stands prior to the 2013 coral bleaching event. These ecologically important, but vulnerable, communities were opportunistically mapped by GLTMP staff between 2009 and 2013.

1.3.5 Beyond long-term monitoring and rapid response

The work of the GLTMP team extends beyond monitoring at the high priority reef areas, reef resilience assessments, coral bleaching assessments and other monitoring and assessment activities. The broad array of activities presented in the abridged list below is illustrative of the critical capacity GLTMP team members provide to reef management efforts on Guam.

- Provided data and expert input via document review, workshops, and other communications regarding the initial listing and subsequent management of ESA-listed coral species
- Participated in the development of the recently-released Guam Coral Reef Status Report (https://www.coris.noaa.gov/monitoring/status_report)
- Assisted with SECORE (SExual COral REproduction) workshops, coral colony out-plantings, coral nursery establishment, and methods testing experiments on Guam (http://www.secore.org/site/our-work/detail/project-guam.20.html)
- Collected coral samples and carried out fish diversity surveys as part of a UOGML/Penn State study of the genetic connectivity of Guam's staghorn populations and the importance of these coral communities as fish habitat
- Carried out coral surveys as part of the 2009, 2011, and 2017 NOAA PIFSC Marianas Reef Assessment and Monitoring Program cruises
- Carried out all field work and contributed to the development of a final report for a 2015 NOAA PIRO Moving Window Analysis of benthic communities in Fouha Bay (manuscript in prep)
- Contributed to the development of measures of success for marine resources under the Micronesia Challenge
- Assisted with a study of sediment impacts in Fouha Bay conducted by a University of Hawai'i Ph.D. candidate
- Participated in a major marine debris cleanup effort at Ga'an Pt. in 2012
- Contributed to a 2015 Coral Health Impacts workshop led by Dr. Laurie Raymundo
- Contributed to a collaborative NSF RAPID-funded study of bleaching susceptibility and resilience in 2014
- Assisted with Guam Community Coral Reef Monitoring Program training activities
- Carried out surveys in support of a RARE Pride project in Tepungan (Piti) Bay in 2012 and 2014
- Assisted the Guam Department of Agriculture's Forestry and Soil Resources Division with the development of a State-wide Assessment and Resource Strategy
- Assisted the Guam Department of Agriculture's Aquatics and Wildlife Division with the planning and implementation of a series of community workshops in which the Limits of Acceptable Change framework was used to solicit public input into the development of regulations for a Marine Preserve Eco-permitting law
- Assisted the Guam Coastal Management Program and its contractor with the development of the North and Central Guam Land Use Plan
- Assisted the Guam Bureau of Statistics and Plans and partners in in the review of National Environmental Policy Act-related documents and other documents pertaining to the proposed military build-up
- Participated in the Natural Resources Subcommittee of the Governor of Guam's Civilian-Military Task Force, including contributing to the development of Guam Natural Resources Strategy
- Contributed technical information and participated in several meetings pertaining to management of the NOAA Habitat Blueprint focus area on Guam

- Provided datasets and input to NOAA Pacific Islands Fisheries Science Center scientists towards the development of the Guam Coral Reef Ecosystem Model developed by NOAA PIFSC
- Assisted a UOGML graduate student with a thesis study comparing fish populations inside and outside four Marine Preserves (manuscript in prep)
- Carried out coral condition surveys in support of the Federated States of Micronesia's Atolls Climate Change Vulnerability and Adaptive Assessment in 2010
- Provided input to NOAA Center for Coastal Monitoring and Assessment scientists towards the development of a Mariana Islands connectivity model
- Carried out coral biodiversity surveys as part of an independent assessment by NOAA-USFWS of coral reef resources within the impact area of a planned nuclear aircraft carrier turning basin and wharf in Apra Harbor
- Assisted Dr. Steve Kolinski with a NOAA Pacific Islands Regional Office-led assessment of an area proposed for a U.S. Navy Underwater Electromagnetic Measuring Range and three potential coral transplantation locations in Apra Harbor

1.3.6 Data management

Several datasets collected at the high priority reef areas currently reside in a relational database accessible by GLTMP members through a web-based data entry portal (Figure 1.3). The database and data entry portal were developed through a collaboration with the NOAA Coral Reef Ecosystem Division (now merged with other sections of NOAA PIFSC) and BSP. The data management system has significantly improved the management of the large amount of coral reef monitoring data generated by the GLTMP. Other datasets generated by the GLTMP, as well as data generated by the NOAA PIRO-supported Guam Community Coral Reef Monitoring Program and the UOGML Reef Flat Monitoring Program may be integrated into the data management system in the future. To facilitate broader awareness of the available data sets, metadata records developed for datasets from high priority reef areas have been posted to CoRIS. In addition, through a collaboration with PIFSC funded by the federal Big Earth Data Initiative, existing metadata records have been updated and re-formatted and additional metadata records have been developed for submission to InPort, a National Marine Fisheries Service data management program, and the National Centers for Environmental Information (NCEI). Metadata for other datasets collected supported by the GLTMP, such as coral bleaching survey data, will be developed and submitted to CoRIS, InPort, and NCEI in 2019. Full datasets are currently being prepared for archival with NCEI. While data collected by the GLTMP are available upon request, archival with NCEI will facilitate the efficient distribution of these data to a broader community of end users.

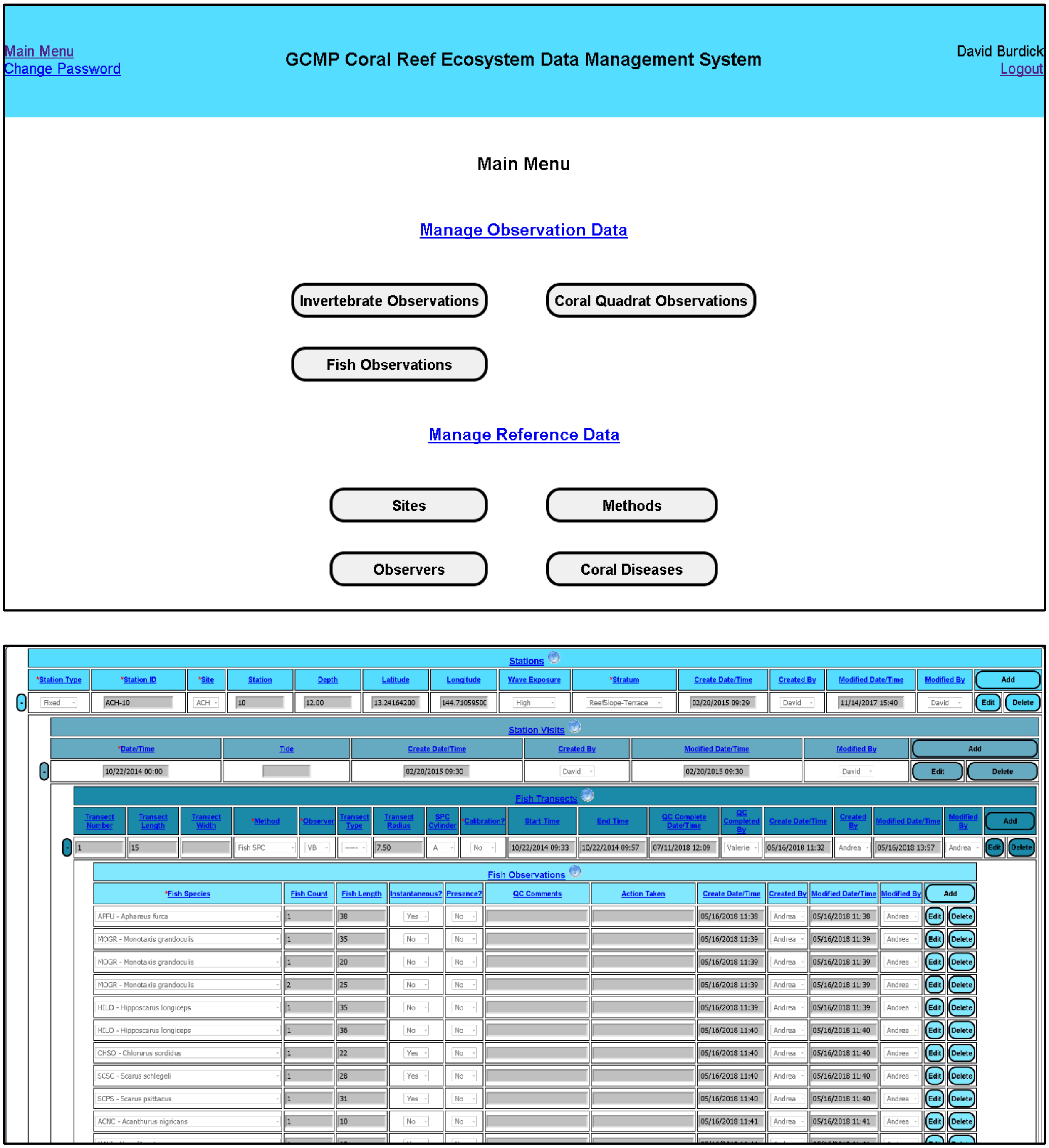


Figure 1.3. The main menu page of the data entry web portal of the GLTMP's data management system (top) and an example of the data entry page for fish survey data (bottom).

1.3.7 Outreach

GLTMP staff have also carried out numerous outreach activities in an effort to raise awareness about the status and trends in the condition of Guam's reefs. These outreach activities include online and printed articles, a website, an informational brochure, reef status reports, and numerous presentations provided to audiences of all ages. Examples of outreach materials generated by monitoring team members and by others who wished to highlight the work of the monitoring team can be found at the following links:

- Article in Governor's PROA newsletter, Issue 29, p. 29 – "Gathering data about Guam's reefs": http://issuu.com/governor_calvo/docs/proa_i29
- Episode VI (Parts 2 and 3) of *Into the Islands* series:
  https://www.youtube.com/watch?v=HNUjCphalOs
  https://www.youtube.com/watch?v=jotqDNwwMoc
- Blog posts at http://www.micronesiachallenge.org/ (Scroll down to "Saving our Micronesia" community blog link in the left-hand navigation bar)
  - "Coral bleaching Guam 2013" (January 2014)
  - "GUAM: 'tis the season for monitoring!" (March 2012)
  - "When you were a kid, what did you want to be when you grew up?" (April 2012)
  - "Monitoring Season: REDUX" (May 2012)
  - "Monitoring, and weather, and presentations…Oh my!" (November 2012)
  - "Adios 2012!" (December 2012)

Other examples of outreach for which active URLs are not available include:

- Articles in Man, Land, and Sea newsletters – "Love Guam, love the Earth!" and "Coral monitoring gears up for field season"
- Article on Governor's PROA newsletter, Issue 39 – "Guam SECORE workshop 2013"
- Brochure "Guam's Long-term Coral Reef Monitoring Program"
- Participated in multiple Island Pride Earth Day festivals
- Presentation to 2013 Indigenous Fellow Institute participants
- Participated in Natural Resource Expo held by Guam Coastal Management to inform the public about the potential impacts of the proposed military build-up
- Presented to high school students about potential impacts of proposed military build-up at 2010 Youth Speak workshop

In addition to the brochure, the online and printed articles, and the presentations mentioned above, the MPC and the 2012 NOAA Technical Support Specialist/2013 NOAA Coral Fellow (now one of the MTs) presented information about the monitoring program and closely related topics to audiences of all ages. Examples of these presentations include talks for high school career days, regular (nearly every semester) talks to a University of Guam Environmental Biology class, presentations to a University of Guam Introduction to Geography class, presentations to a University of Guam Scientific Photography class, presentations for the NOAA PIRO and NPS-supported Friends of Reefs Guam Science Sunday lecture series, presentations for the University of Guam's POETS lecture series, presenting on recent coral reef research for a workshop aimed at Guam educators, as well as several other presentations to school students of various ages.

1.3.8 Conference, workshop, and training participation

GLTMP staff also gave presentations at several local and international conferences and provided presentations or facilitation support, and were actively involved in, numerous workshops and training opportunities. Examples of conference and workshop participation are provided in Box 1.4, and comprehensive lists are provided in Appendix J (conferences) and Appendix K (workshops and training).

Box 1.4. Highlighted GLTMP conference and workshop participation

Conferences

4th Guam Coral Reef Symposium (27 March 2018). *Assessing the resilience of Guam's reefs to climate change impacts*, presented by D. Burdick.

13th International Coral Reef Symposium (19–24 June 2016, Honolulu, HI). *Home is where the waves are: Corals in Guam's exposed reef fronts appear resilient to local stressors but vulnerable to regional warming*, presented by D. Burdick.

13th International Coral Reef Symposium (19–24 June 2016, Honolulu, HI). *Let the reef be your guide: An adaptive approach to monitoring on Guam*, presented by R. Miller.

3rd Asia-Pacific Coral Reef Symposium (23–27 June 2014, Taiwan). *A quantitative description of Guam's reef front coral communities and a preliminary analysis of their robustness to local stressors*, presented by D. Burdick.

2013 Guam Coral Reef Symposium (24 June 2013). *Where are Guam's canaries in the coal mine? Mapping the island's staghorn thickets*, presented by D. Burdick.

Workshops and training

Climate-smart Design Workshop: Incorporating climate-smart design considerations into coral reef management efforts (24–25 September 2018)

SECORE Guam Coral Restoration workshops (15–24 April 2017, 14–24 July 2014, and 25 July–4 Aug 2013)

Guam Coastal Climate Change Resilience workshops I and II: Climate change and coastal ecosystems in Guam—Management, sustainability forecasts and community engagement (30 March 2017 and 2 March 2016)

Recreational Tour Operator workshop (29 September 2016)

Micronesia Challenge Measures Working Group meetings (23–25 August 2016, Guam; 21–23 September 2014, Guam; 6–11 February 2012, Palau; 15–19 February 2010; 2–6 June 2008, Pohnpei

Species identification of ESA-listed Indo-Pacific corals workshop (25–26 June 2016, Honolulu, Hawai'i)

Guam Coral Bleaching Symposium (19 May 2016)

PRIMER multivariate statistics software training (14–18 March 2016, Ponte Vedra Beach, Florida—DB); 4–8 November 2013, Plymouth, UK--RM; 25–29 June 2018, Coffs Harbor--AH)

Coral Health Impacts Workshops (14–18 January 2013, Guam)

Motorboat Operators Certification Course and Open-water Module (March 26–30, 2012, Honolulu, Hawai'i)

1.3.9 Publications

Examples of reports and peer-reviewed publications authored or co-authored by GLTMP staff are provided in Box 1.5, and a comprehensive list of publications is provided in Appendix L.

Box 1.5. Highlighted GLTMP publications and contributions

Raymundo, L., D. Burdick, W. Hoot, R. Miller, V. Brown, T. Reynolds, and J. Gault. In review. Successive bleaching events cause mass coral mortality in Guam, Micronesia.

Burdick, D. and L. Raymundo. 2018. An interim report of the *Comprehensive Long-term Coral Reef Monitoring at Permanent Sites on Guam* project. Report submitted to the NOAA Coral Reef Conservation Program.

Maynard, J., S. Johnson, D. Burdick, A. Jarrett, J. Gault, J. Idechong, R. Miller, G. Williams, S. Heron, and L. Raymundo. 2017. Coral reef resilience to climate change in Guam in 2016. NOAA Coral Reef Conservation Program. NOAA Technical Memorandum CRCP29. Available at https://www.coris.noaa.gov/activities/guam_coral_resilience/

Raymundo, L., D. Burdick, V. Lapacek, R. Miller, V. Brown. 2017. Anomalous temperatures and extreme tides: Guam staghorn *Acropora* succumb to a double threat. Marine Ecology Progress Series 564:47-55. Available at https://www.int-res.com/abstracts/meps/v564/p47-55/ or upon request.

Reynolds, T., D. Burdick, P. Houk, L. Raymundo, S. Johnson. 2014. Unprecedented coral bleaching across the Mariana Archipelago. Coral Reefs 33: 499. Available at https://link.springer.com/article/10.1007/s00338-014-1139-0

Burdick, D., R. Miller. 2012. Comprehensive long-term monitoring at permanent sites on Guam: 2012 status report. Report submitted to the NOAA Coral Reef Conservation Program. Available at https://repository.library.noaa.gov/view/noaa/991

Burdick, D., V. Brown. 2011. Comprehensive long-term monitoring at permanent sites in Guam: Report of program status and presentation of preliminary baseline data and power analyses results for Tumon Bay, East Agana Bay, and Western Shoals sites. Report submitted to the NOAA Coral Reef Conservation Program. Available at https://www.coris.noaa.gov/search/catalog/search/resource/details.page?uuid=%7B9AF65D1F-668E-4D2B-99A0-4B0D2907F1A8%7D

Burdick, D., V. Brown, J. Asher, C. Caballes, M. Gawel, L. Goldman, A. Hall, J. Kenyon, T. Leberer, E. Lundblad, J. McIlwain, J. Miller, D. Minton, M. Nadon, N. Pioppi, L. Raymundo, B. Richards, R. Schroeder, P. Schupp, E. Smith, and B. Zgliczynski. 2008. Status of the Coral Reef Ecosystems of Guam. Bureau of Statistics and Plans, Guam Coastal Management Program. iv + 76 pp. Available at https://www.researchgate.net/publication/236590561_Status_of_the_Coral_Reef_Ecosystems_of_Guam

1.4 REEF FLAT MONITORING PROGRAM

The Reef Flat Monitoring Program (RFMP) currently involves quarterly data collection at five reef flat sites that extend along the western coast of Guam. The RFMP emerged following a study carried out by Dr. Laurie Raymundo and colleagues examining sewage nutrient eutrophication and its impact on coral disease along Guam's northwestern coast (Redding et al. 2013). At the time of the original study seven sites were selected for assessment and monitoring of disease impacts. Two of these sites, Tanguisson and West Agaña, were nearshore to recently-upgraded sewage outfalls. The study examined whether there was any improvement in coral condition over the course of the year following the upgrade. The study concluded that all sites showed indications of sewage-based nitrogen pollution, little overall change in the concentration of nitrogen over the year of monitoring, and a positive correlation between the degree of nitrogen eutrophication and the severity of the coral disease, white syndrome, in resident corals per site. Upon completion of the study local management agencies requested that the monitoring of a subset of these sites be continued as part of the *Comprehensive Long-term Coral Reef Monitoring at Permanent Sites on Guam* project.

The RFMP has provided important, detailed information about trends in coral community health, and places particular attention on coral diseases, predators, bleaching and other coral health concerns and the relationship with water temperature and nutrients. The data generated through the RFMP provides a strong complement to the data collected at the seaward reef slope sites targeted with the GLTMP. The RFMP provides information to managers for a critical, dynamic, yet vulnerable reef zone, and is an essential component of a comprehensive coral reef monitoring strategy.

The results of a preliminary analysis of benthic cover data collected between 2009 and 2014 as part of the RFMP were presented in a 2012 progress report for the *Comprehensive Long-term Coral Reef Monitoring at Permanent Sites on Guam* project, which is available at:

https://data.nodc.noaa.gov/coris/library/NOAA/CRCP/other/grants/NA11NOS4820007/Guam_Reef_Monitoring_FinalRept.pdf).

The results of further analysis of RFMP data collected between 2009 and 2018 are presented in Section 4 of the December 2018 interim report.

1.5 ADAPTING TO A WARMING WORLD

As described in the Interim Report, the frequency and severity of the bleaching events and the associated major changes in benthic communities at sites around the island has necessitated a re-evaluation of GLTMP priorities. By conducting the full suite of benthic surveys at only permanent sampling stations, reducing the frequency of coral quadrat surveys, and using the CoralNet website for the first-pass analysis of images from the seaward slope submarine terrace sites, the GLTMP team can free up the capacity necessary to establish permanent transects in the more dynamic reef front zone of the high priority reef areas, make permanent 16 of the island-wide bleaching response/recovery sites, and monitor benthic cover at these new sites on an annual or biennial basis.

Another emerging goal of the GLTMP is to actively integrate threat-reduction and reef restoration activities into GLTMP efforts when necessary and appropriate. This new goal has been proposed in recognition of the limited funding and capacity available to implement threat-reduction and reef restoration activities on Guam, and in recognition that GLTMP team members possess the technical skills required to carry out many of these activities. These activities include, but are not limited to, opportunistic *Acanthaster* control at monitoring sites; targeted *Acanthaster* control at other reef areas; continued participation in vessel grounding site response and rehabilitation; and assisting with coral nursery, coral out-planting, and other active restoration activities.

The monitoring of water quality parameters is recognized as an important component of the program, but it has become clear that the limited capacity of the GLTMP, especially in consideration of the immense effort that has been dedicated to the collection and analysis of bleaching response/recovery survey data over the last few years, is currently not sufficient for carrying out long-term monitoring of water quality parameters. In recognition of this limitation the MPC has sought out collaborations with researchers interested in collecting water quality data as part of research projects carried out at the high priority reef areas. Through these collaborations the GLTMP would lend use of the instruments, provide training, and assist with data management and analysis. The GLTMP may also be able to assist by allowing the researchers or their students/staff to join the GLTMP team on regular data collection outings using GLTMP-funded boat trips.

1.6 OUTCOMES AND BENEFITS

The results of data analyses are summarized in periodic reports made available to the government agencies and the general public. Datasets collected through GLTMP efforts are provided upon request to resource agencies, research teams, and others, and once archived with NCEI will reach an even larger community of end-users. Anecdotal reports and the results of preliminary analyses of data obtained through GLTMP activities are also regularly presented to resource agency staff at relevant multi-partner meetings and workshops, and communicated via email, telephone conversations, and in-person in an effort to provide up-to-date information on the status of Guam's rapidly-changing reef ecosystem.

The GLTMP continues to contribute to local coral reef monitoring and management capacity through the continued employment of program staff. Thus far, the program has provided part-time employment for a total of 11 graduate students from the University of Guam Marine Laboratory. Participation in the GLTMP has provided these individuals with a wide range of experiences, and a level and quality of participation in sampling design, protocol development, procurement, data collection, and data analysis that most have not previously experienced. As described in more detail in Section 1.3.5, monitoring team members, particularly the MPC and the two MTs, play important roles in reef management efforts on Guam that extend well beyond the collection of data at monitoring sites.

Photo (next page): A GLTMP biologist carrying out a coral quadrat survey at the Tumon Bay monitoring site in 2015.

2 METHODS

2.1. Methods overview

The fundamental sampling design and survey protocols at the seven high priority management sites have been developed and implemented, but they remain subject to change as better methods and equipment become available. Recent bleaching events have also necessitated the implementation of sampling at an island-wide scale, as well as the establishment of permanent transects in the shallow reef front zone, which hosts coral communities that have been most severely impacted by bleaching.

The goals of the Guam Long-term Coral Reef Monitoring Program are to:

- Determine the status and trends in selected coral reef ecosystem indicators to better inform the resource managers' decision-making process and increase the effectiveness of natural resource management on Guam
- Provide managers with early notice of abnormal conditions of selected resources to encourage effective mitigation measures and reduce the costs of management
- Provide data to better understand the dynamic nature and condition of the island's coastal ecosystems
- Allow natural resource agencies to meet certain legal and Congressional mandates related to coastal resource protection
- Measure progress towards performance goals

Primary Objectives
The GLTMP collects data about a number of important parameters related to ecosystem condition. These parameters are grouped into three categories: water quality, benthic habitat, and associated biological communities. The parameters identified for Guam are provided below, with parameters currently being monitored in bold:

Benthic Habitat
- **Benthic % Cover**
- **Coral Colony Size**
- **Coral Colony Density**
- **Coral Condition**
- **Rugosity**
- Macroalgae diversity
- Coral Colony Growth Rates
- Macroalgae biomass

Assoc. Biological Communities
- **Reef Fish Abundance and Biomass**
- **Reef Fish Diversity**
- **Protected Species**
- **Abundance of Ecologically and Commercially Important Macroinvertebrates**
- **Macroinvertebrate diversity**

Water Quality
- **Temperature**
- Turbidity
- Dissolved Oxygen
- pH
- Conductivity
- Chlorophyll
- Nutrients (P, N)
- Bacteria

Water quality parameters and a few biological parameters have not yet been incorporated into field surveys. Refer to Section 1.5 for a discussion of the challenges and potential solutions to obtaining water quality data at the monitoring sites.

Photo (previous page): A GLTMP biologist carrying a coral quadrat survey at Tumon Bay sampling station in 2015.

2.2. Site selection

The high priority reef areas currently targeted for long-term monitoring include the Tumon, East Agana Bay, Western Shoals, Piti, Achang, Cocos-East, and Fouha Bay sites (Figure 2.1 and Appendix B–Appendix I). Sites were selected by the multi-partner Guam Coral Reef Monitoring Group (GCRMG) after consideration of cultural and economic importance, the number of other management activities in the watershed, the amount and quality of available historical data, protected status, accessibility, and other factors. In order to achieve a relatively high level of detection and significant power with a practical number of samples, sampling at most sites (with the exception of Western Shoals and Fouha Bay) is restricted to the submarine terrace, which is an area of relatively gentle slope that is found between the base of the high wave energy reef front and the steeper lower reef slope. A detailed account of the reasoning behind the selection of each site and the targeting of the submarine terrace zone can be found in past grant proposal documents. Monitoring is not likely to be resumed at the Western Shoals site unless Department of Defense efforts to construct a nuclear aircraft carrier wharf and turning basin in Apra Harbor are revived, or another major threat to this important reef emerges. Monitoring will continue within the reef terrace zones of the remaining sites, but because the effects of recent coral bleaching events were most severe at shallower depths additional transects may be established along the wave-exposed reef front zones (~5 m depth) at some or all of the monitoring sites beginning in 2019. As mentioned in sections 1.3.2 and 1.5 above, and described in more detail in the Interim Report, another significant change to the program in response to the rapid and significant loss of coral in the reef front zone is establishment of shore-accessible reef front monitoring sites and the proposed establishment of permanent transects at 16 island-wide sites that have been surveyed one or more times during or between bleaching events beginning in 2013.

2.3. Sampling design

Data collection at the high priority reef areas is carried out using a stratified random sampling approach and the combined use of both fixed and non-fixed sampling stations across reef areas of significant size (0.1 to 0.2 km^2). This general approach is used for most of the original monitoring sites (with the exception of Fouha Bay), but the details of the sampling design may differ between sites. However, sampling strategies and survey methods are made consistent across sites to the fullest extent possible in order to maximize the ability to make between-site comparisons. This split-panel sampling approach was originally selected after consultation with the NPS, which uses this approach at sites comparable in size to the high priority reef areas selected by the GCRMG for long-term monitoring. The approach is intended to provide robust data across relatively large reef areas that could be influenced by management activities carried out within their respective watersheds. These data would be more robust than data collected at a set of three to five closely-spaced transects established in a small area that may not represent the broader benthic community influenced by the watershed. This approach was also selected because there had been a recent move towards site-based, ridge-to-reef reef management on Guam, and because the island-scale data collected during the biennial (now triennial) NOAA PIFSC RAMP cruises were not sufficient (and were not intended) to detect changes in reef condition at individual priority reef areas.

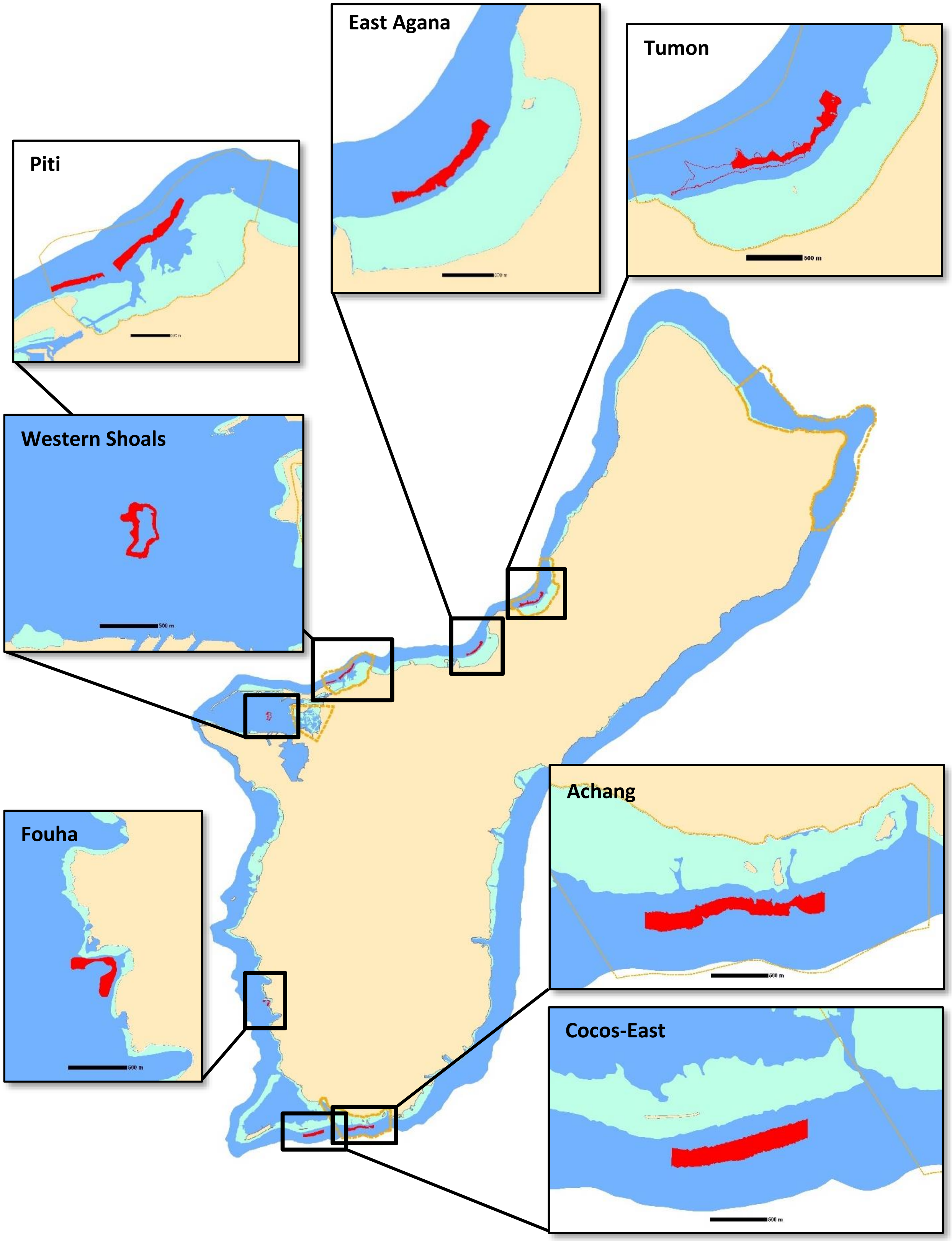


Figure 2.1. Location of the "High priority reef area" long-term monitoring sites around Guam. Detailed site maps that display the location of all sampling stations surveyed between 2010 and 2018 are provided in Appendices B–I.

The locations of sampling stations within the boundaries of the original long-term monitoring sites are generated randomly using Geographic Information System (GIS) software. Even-numbered stations are fixed, while odd-numbered stations are unfixed; a new set of re-randomized, unfixed stations are generated for subsequent visits. Site boundaries were initially defined using LIDAR bathymetry data and benthic habitat data within a GIS, but were subject to revision (as was the case with the Tumon Bay site) if analysis of baseline benthic data indicated that the site included two or more distinct benthic communities, resulting in high variances for key parameters. The delineation of boundaries for more recently-established sites occurred after a series of exploratory/mapping dives were carried out across a large area of interest.

The split-panel approach is currently used only for high-intensity data collection at the high priority reef areas; monitoring at the 16 island-wide sites will involve the establishment of three 30 m-long transects laid end-to-end at each site. The locations of the 16 sites were randomly selected from a larger set of survey sites previously generated by NOAA PIFSC using a random stratified approach.

Data collection for most of the high priority reef areas is currently focused on hardbottom habitat of the outer reef slope terrace, between the depths of seven and 15 m. Baseline monitoring at the Western Shoals site was focused within three strata, including the reef slope on the western half of the shoals, the reef flat margin on the western half of the shoals, and the reef flat margin on the eastern half of the shoals. Baseline data collection in the Fouha Bay site focused on areas towards the inner portion of the bay (three transects) as well as the outer portion of the bay (five on north side and five on south side). Transects established at the 16 island-wide sites will be placed near the lower extent of the reef front (~5 m depth). A second set of three transects will also be placed immediately down-slope at a depth of 12 m if enough capacity is available to carry out this task. Data collection has occurred within the reef front zones of most of the island-wide sites beginning in 2013, while data collection along the 12 m depth contour was initiated at some of the sites as part of the 2016 reef resilience assessment or in 2017 as part of the bleaching response effort.

2.4. Site monitoring

2.4.1. Site monitoring overview

Site monitoring currently involves the regular collection of data for benthic habitat and associated biological community parameters listed above. Data collection efforts at the original high priority reef areas, the new set of 16 island-wide sites, and the shore-accessible sites, will each target a different, but overlapping, set of parameters. Monitoring at the high priority reef areas will continue to include the collection of data for the full suite of parameters, although note that modifications to the coral quadrat survey method may be required in order to improve program efficiency and accommodate the new island-wide sites. Although the approach has not yet been finalized, surveys at the island-wide sites and shore-accessible sites will likely be limited to benthic photo transect surveys and possibly a modified version of the NOAA SPC survey method for reef fish that includes counts and size estimates for only mobile predators, herbivores, and other food fishes (but which still includes all taxa in diversity counts).

The original intent was to visit all of the high priority reef areas annually, but it has become clear that the large number of sampling stations required to attain a reasonably high level of detection and statistical power with relatively limited resources make this target unrealistic. The following schedule of timing and effort will be adopted beginning in 2019; this schedule will continue if it is determined to be feasible:

High-priority reef areas: The Tumon, East Agana, and Piti sites will be visited on an annual basis; the Achang and Cocos-East sites, which are more difficult to access, will be visited on a biennial basis. The full suite of benthic surveys, including photo transect, coral quadrat, macroinvertebrate, and rugosity surveys will be carried out at permanent sampling stations, while only photo transect and rugosity surveys will be carried out at non-permanent sampling stations in conjunction with fish surveys (which will occur at both permanent and non-permanent sampling stations).

Island-wide sites: The 16 island-wide sites will be visited on an annual basis when possible. An effort will be made to carry out surveys at all sites between the September and November, when bleaching is typically observed. Benthic photo transect surveys will likely be the only survey method carried out at these sites, but a modified version of the NOAA SPC fish survey method may be carried out annually or less frequently if capacity is available.

Shore-accessible sites: The two currently-established shore-accessible monitoring sites, and other shore-accessible sites that may be established in the future, will be visited at least semi-annually. More frequent visits will be made immediately before, during, and after severe bleaching events. Benthic photo transect surveys will likely be the only survey method carried out at these sites, but a modified version of the NOAA SPC fish survey method may be carried out annually or less frequently if capacity is available. An effort will also be made to coordinate with other researchers who could collect additional datasets at these shore-accessible sites, and who would benefit from the benthic community data available for those reef areas.

2.4.2. Survey logistics and permanent site establishment

Each sampling station is located using a GPS receiver. Upon reaching a station's location, a small lead fishing weight and line tied to a buoy is dropped. When a buoy cannot be dropped, such as when the site is located in a shallow, high energy reef area, divers are dropped immediately offshore of the site. In optimal situations where at least four divers are available, two divers enter the water first to carry out the reef fish surveys. At non-permanent sampling stations or when a new permanent station is being established the transect is laid out beginning at the weight tied to the buoy. The transect is laid out in a clockwise direction (clockwise from a planar view of Guam), following the depth contour if it is readily determined, or at a previously-determined heading parallel to the reef margin if the area is relatively flat and a depth contour is not readily discernable. For previously established permanent stations, divers locate the rebar marking the beginning of the transect and lay out the tape in line with the existing rebar. The two or more divers conducting the benthic surveys enter the water after the fish surveys are completed. For fixed sampling stations, 24" rebar is installed at the beginning of the transect and 12" rebar is installed at the center and end of the transect; four-inch concrete nails are installed at two or more of the corners of each quadrat. For stations where high cover prevents the installation of rebar, a small PVC float is tied to dead coral at the beginning of the transect and large zip ties are placed at the beginning, middle, and end of the transect. Small zip ties are used to mark two or more corners of each permanent quadrat location in high coral cover areas.

2.4.3. Qualitative surveys

Short qualitative surveys are conducted at each station when possible to establish species lists for key taxa and to characterize the site. These surveys are usually conducted immediately before or after the quantitative surveys, when time is available. In combination with the quantitative data, the qualitative data contribute to a master species list and general site description for each site that can be referenced by monitoring personnel and local agencies. More comprehensive biodiversity surveys, including genetic sampling, may be carried out in the future.

2.4.4. Water quality

Temperature loggers have been deployed at most sites, but, as mentioned above, the deployment of the multi-parameter datasondes and other instrumentation has been repeatedly delayed by the team's focus on bleaching response and other activities. As discussed in Section 1.5, an effort will be made to collaborate with researchers interested in collecting water quality data to support research projects within the monitoring sites. Through these collaborations, the monitoring program would gain water quality data for monitoring sites by lending use of the instruments, providing training, and assisting with data management and analysis.

2.4.5. Benthic community

2.4.5.1. Benthic cover

Benthic cover and coral and algal generic diversity are currently being assessed using digital photo transects. Non-overlapping digital photos are taken along each transect with a digital point and shoot camera mounted on a PVC frame. Initially, photos were taken every 0.5 meters along the transect tape, but in order to minimize overlap (especially at high rugosity reef areas) photos are now taken every 1 m. The percent cover for various benthic cover types is currently estimated from the images using Coral Point Count (CPCe). The CPCe analysis was initially carried out using 25 points per frame, stratified using a five by five grid, and now is carried out using 16 points per frame, stratified using a four by four grid.

After recent testing of the CoralNet website, which provides fully- or semi-automated annotation of benthic images using computer vision algorithms, it has been determined that the service can be used to analyze images from the reef terraces of the high priority reef areas. Testing showed that percent coral cover estimates provided by CoralNet using a fully-automated approach were highly comparable to estimates obtained by human users. The service was also able to accurately discern between *Porites rus* and massive *Porites* species, which are the two coral groups that together comprise the majority of coral cover at most sites. The intent is to use CoralNet to rapidly provide estimates of benthic cover, in combination with follow-up analysis by human observers if the CoralNet results or anecdotal observations call for the additional effort. The use of CoralNet will greatly reduce the amount of time and effort dedicated to image analysis, allowing members of the monitoring team to dedicate more time to data collection at additional sites as well as other high priority activities.

2.4.5.2. Coral community

Shortly after the first diver begins the photo transect, another diver then identifies and measures all coral colonies within 0.5 x 0.5 m quadrats placed at 0 m, 5 m, 10 m, 15 m, 20 m, and 25 m along the right side of the transect. Percent old dead, percent recent dead, and disease type and severity observations are recorded for each colony. The cause of tissue mortality is noted if it can be determined with a reasonable degree of confidence. Measurements of the longest dimension and the width of the colony perpendicular to the longest dimension are made. An effort is made to carefully count all coral recruits/juvenile corals in order to assess the rates of coral recruitment to natural substrate. Care is taken to prevent the count of remnants of larger colonies as coral recruits/juvenile corals. Any tissue isolate suspected of being a remnant of a larger colony will be noted as such and taken into account during analysis, in order to prevent the calculation of erroneous coral recruitment rates. At least two photos are taken of each quadrat in order to maintain a photographic record of all quadrats. These photos may allow for the determination of planar growth rates for various coral species and for investigating benthic organism dynamics that can be appropriately observed at an inter-annual time scale.

As discussed above, the significant time and skill required to carry out the coral quadrat survey may necessitate modification of the method or the frequency of its deployment in order to allow monitoring team members to focus on surveys of benthic cover at a new suite of monitoring sites. Preliminary analysis of coral quadrat data suggests that the use of a relatively small quadrat size, which was selected because of the significant amount of time required to survey the high densities of *Porites rus* colonies and high rates of partial mortality observed at most sites, appears to have resulted in too few samples of non-*Porites rus* colonies for an adequate analysis. This realization, combined with the recognition that the coral quadrat survey demands a high degree of skill and an amount of effort that may not be practical given the program's limited capacity, may lead to significant modifications to the method or conducting the survey less frequently than others.

2.4.5.3. Rugosity

Beginning with the 2012 field season, rugosity is measured at each sampling station using the standard chain-and-tape method. A diver carefully drapes a 15 m light chain over the substrate along a taut transect tape, paying out as much chain as is necessary to conform to the substrate profile along the length of the tape. The diver then records the length of the tape under which the chain was placed. A rugosity index value is calculated as the ratio between the length of chain and the linear distance between the chain endpoints. Using this method, a perfectly flat area would yield a rugosity index value of 1 and an area of more complex terrain would yield rugosity index value greater than 1.

2.4.6. Associated biological communities

2.4.6.1. Reef fishes

Reef fish surveys are one of the key components of the Guam Long-term Coral Reef Monitoring Program. Fish are a culturally and economically valuable resource for the island (van Beukering et al., 2007). Coral reef fish communities play an important role in Guam's coral reef ecosystems and may be an indicator of reef resiliency (Green and Bellwood 2009). The reef fish survey data collected by the LTMP are expected to provide results on fish density, biomass, and diversity as well as allow exploration of community structure by functional group and size structure. The surveys will also be used to detect changes in fish communities over time.

The fish team currently uses a Stationary Point Count Method (SPC) adapted from Ault et al. (2006) and NOAA Fisheries Coral Reef Ecosystem Division (Williams et al., 2011; Heenan et al., 2017) at the high priority reef areas surveyed between 2012 and 2018. To conduct the surveys a pair of fish divers descend and deploy a 30 m transect across the substratum. Divers are positioned at 7.5 m and 22.5 m and count fish within a 7.5 m radius cylinder extending from the substrate to the limits of vertical visibility. Surveys are not carried out if visibility is less than 7.5 m. The simultaneous surveys start once the divers deploy the transect and both divers are ready to proceed. Due to staffing constraints, at times only one fish diver is available to conduct SPCs. In that situation, the fish diver lays the transect and conducts an initial SPC at 22.5 m and then conducts a second SPC at 7.5 m. The diver's buddy remains at the other point.

The SPC surveys are conducted in two parts. During the first five minutes, divers record all species observed within the cylinder, but do not count or size fish. All fish are identified to species level or the next lowest taxonomic level possible (genus or family). If a rare fish (shark, species of concern, large mobile predators, etc.) is observed during the first 5 minutes, it is counted and sized, but the diver notes that it was not an instantaneous count. After the first five minutes divers enumerate fish, one species grouping at a time, using rapid visual sweeps of the plot. The counts are designed to be "instantaneous" to avoid double counting. All fish of the target species within the SPC boundaries are counted and sized to the nearest centimeter; however, divers use size classes for large schools or high densities. This process is continued until all of the listed species are counted. If a rare fish is still present during the counts, it is counted and sized and the original measures are crossed off. If a species is no longer present in the cylinder during the second phase, divers record their best estimate of size and number and note that it is a "non-instantaneous" count. At the end of the survey, divers swim through the 7.5 m radius plot to enumerate small and cryptic species that were not captured from the stationary central position. Species that enter the SPC after the first five minutes are noted, but not used for quantitative analysis. Species entering during the five-ten minute and ten-fifteen minute periods are recorded and the size is noted. Species entering the cylinder after the initial fifteen minutes or that are observed outside the cylinder are noted on the species list for the site. To document species richness at the sites, the fish team conduct roving diver swims throughout the survey station after the SPCs.

2.4.6.2. Macroinvertebrates

Counts of commercially and ecologically important macroinvertebrate species (*Acanthaster*, echinoids, holothurians, *Tridacna*, etc.) are made within a 4 m belt (2 meters on either side of the transect). The size of *Tridacna* are measured to the nearest cm.

2.4.6.3. Rare species

Protected or rare species utilizing the general area around the site are recorded and photographed. These species include marine mammals, sea turtles, *Bolbometopon muricatum*, and *Cheilinus undulatus*. Data include species, number, activity, and size when possible.

2.5. Data analysis

2.5.1. General approach

Similar to the general approach used for the previous analysis of baseline data for the East Agana Bay, Western Shoals, and original Tumon Bay sites, baseline benthic cover data from the Fouha Bay, Tepungan (Piti) Bay, Achang, and modified Tumon Bay sites were first explored in multivariate space and a post-hoc power analysis was carried out for total coral cover. Descriptive statistics were generated and tests of significant differences between data groupings from the baseline sampling year were carried out for broad level parameters (e.g., total coral percent cover, macroinvertebrate density, reef fish density, etc.), as well as for important species/species groups (e.g., percent cover of *Porites rus*, sea cucumber density). Selected pairwise comparisons were made between sampling years for key benthic cover and macroinvertebrate parameters at individual sites.

2.5.2. Multivariate analyses

Multivariate analyses were carried out on baseline benthic cover data for Fouha Bay (2015), Tepungan Bay (2012), Achang (2014), and modified Tumon Bay (2012) sites. Baseline data from these sites were explored in multivariate space using the statistical software package PRIMER-E and the PERMANOVA add-on prior to generating description statistics and carrying out power analyses. Benthic cover values generated by the CPCe application were imported into PRIMER-E, square root transformed and a Bray-Curtis Similarity Matrix was generated. Non-Metric Dimensional Scaling (nMDS) analysis was carried out with benthic cover values from all sampling stations in each site and eigenvector overlays were used to visualize those components of the benthic community that most significantly influenced the similarity/dissimilarity between sampling station groupings. A SIMPER analysis was carried to quantify the contribution of each variable to the average Bray-Curtis dissimilarity and similarity between benthic community groupings. Analysis of Similarity (ANOSIM) was used to test for significant differences between the benthic communities for possible sample groupings. Multivariate analysis has not yet been carried out on reef fish or macroinvertebrate survey data.

2.5.3. Post-hoc power analysis

Square root-transformed coral cover data were tested for normality using a Shapiro-Wilk's test (Shapiro.test) and for equal variances using an F-test (var.test). Univariate power analyses were carried out on the transformed coral cover values using the power.t.test function in R.

2.5.4. Descriptive statistics

Percent cover values of all benthic cover classes were obtained for each sampling station at each sampling period by pooling the CPCe-generated point count data for all photo transect images from each station visit. The percent cover of each class was calculated as (number of points of a given class/total number of points at the sampling station)*100. Mean percent cover values of major benthic cover types (e.g., coral, turf algae, etc.) were calculated for individual sites by averaging the percent cover values from all stations surveyed within a site during a given sampling period. Mean percent cover values of major benthic cover types were also calculated for sample groups within a site for each sampling period by averaging percent cover values from only those stations within each group.

Reef fish density was calculated for each sampling station by combining the number of fish observed in the SPCs at each station and dividing the sum by the total area sampled (i.e. # of SPCs x area of an SPC). This was then converted into an area based measure (# of fish/ 100 m^2).

$$Density = \frac{\#\ of\ fish\ at\ station}{\#\ of\ SPC * (\pi * 7.5\text{^}2)} \times 100$$

Relative reef fish density was calculated by dividing the total number of fish observed in each family across all stations by the total number of fish observed across the site.

$$Relative\ Density = \frac{\sum \#\ of\ fish\ in\ family}{\sum \#\ of\ all\ fish}\ x\ 100$$

Biomass, the estimated mass of the fish, was computed from length-weight regression factors and the observed length of the fish observed, using the following equation:

$$M_i = a\ x\ l^b$$

where *M* is mass in grams (g) per record, *a* and *b* are species specific length-weight coefficients, and *l* is length of the fish observed. Length-weight regression values were obtained from NOAA NMFS ESD to facilitate comparison with regional estimates. For species that were not included in that table, values from Fishbase were used. The values for a similar species or species group were used if a value was not available for that species in either the ESD table or Fishbase.

Biomass values for all fish were aggregated to species or family by station and then converted to an area-based measure, using the following equation:

$$Biomass = \frac{\sum M_i n_i}{\#\ of\ SPC * (\pi * 7.5m^2)}$$

where *M* is mass (g) per record and n is the number of fish of size *l* observed at the station. The sum of the mass is then divided by the area sampled to provide total biomass of the species for the station in g/m^2. Biomass values for all fish were aggregated to species or family by station.

Relative reef fish abundance was calculated by dividing the total biomass (g/m^2) of fish observed in each family across all stations by the total biomass (g/m^2) of all fish observed across the site.

$$Relative\ Abundance = \frac{\sum Biomass\ of\ fish\ in\ family}{\sum Biomass\ of\ all\ fish}\ x\ 100$$

Reef fish species richness was calculated by using a pivot table in Excel to create a table of the stations at which each species was observed. The number of stations at which a species was observed was counted and converted to a percentage of occurrences.

Mean reef fish density, biomass, and species richness were also calculated for each site. For site level density and biomass estimates, the mean of the station values was calculated along with standard deviation and standard error. All species observed at a station were added to the site-level species list to calculate a total species richness. The average species richness for each site was calculated by taking the mean of the species richness at all of the stations at a site. Standard error is reported for these values to provide consistency with regional reef fish reporting statistics.

The total density of macroinvertebrates and densities of broad macroinvertebrate groups (e.g., edible shell, octopus, sea cucumber, sea star, and sea urchin) were calculated as the number of individuals per 100 m^2. As the belt transect survey area outlined in the monitoring protocol for macroinvertebrates was defined as 100 m^2, most density calculations are equivalent to the total number of invertebrates recorded for that station. In subsequent years there were instances in which the total length of the transect was either more or less than outlined in the monitoring protocol, and for those instances the density was calculated as:

$$Density = \left[\frac{\#\ of\ individuals}{total\ area\ surveyed}\right] * 100$$

2.5.5. Within-site comparisons of sample groups from same sampling period

Benthic percent cover data were square root-transformed and macroinvertebrate density data were square root (x +1) transformed, tested for normality using a Shapiro-Wilk's test (Shapiro.test), and for equal variances using an F-test (var.test). Two-sample T-Tests or Wilcoxon Signed Rank Tests were carried out in R to test for significant differences between sample groupings within the same sampling year. Within-site comparisons of sample groups for reef fish and macroinvertebrate data will be carried out in the future and the results presented in another report.

2.5.6. Time series analysis

Tests for significant differences in mean values of selected benthic community and macroinvertebrate community parameters, such as total coral percent cover, *Porites rus* percent cover, and sea cucumber densities, between time periods for individual sites were carried out using the Partover.test function available in the Partiallyoverlapping package for R. The Partiallyoverlapping package was specifically designed to handle a mix of paired and unpaired data, allowing two-sample comparisons for individual parameters. This package appears to offer the best available approach to analyzing data from all sampling stations, including both permanent and non-permanent stations, without violating assumptions about sample independence or having to discard either the permanent or non-permanent station data. The ability of the Partover.test to compare values from only two sample groups limited comparisons to select time ranges, such as between baseline data and most recently available data, or other significant time periods. Data were square root or square root (x+1) transformed, tested for normality using a Shapiro-Wilk's test (Shapiro.test), and tested for equal variances using an F-test (var.test) prior using the Partover.test function. A Paired Wilcoxon Signed Rank Test was used with data from only paired sampling stations when normality was rejected for one or both sample groups.

2.5.7. Future analyses

Due to time constraints the analysis of coral diversity, colony size, and colony condition data generated from the coral quadrat surveys could not be completed for inclusion in this report. The results of the on-going analysis of these data will be included in a future report or other publication. The lack of sufficient benthic cover and macroinvertebrate data for the initial 2014 GLTMP survey of the Cocos-East site prevented the adequate analysis of the baseline data from the site, and the current availability of only CoralNet-generated benthic cover data for the 2018 survey of the Cocos-East prevented an adequate exploration of the data in multivariate space, a power analysis, and comparisons to the limited 2014 data. However, data collected by the GLTMP at the Cocos-East and Achang sites, along with additional reef fish and benthic survey data collected at these sites by the NOAA PIFSC and NOAA PIRO in 2014 and 2017 are currently being analyzed by NOAA PIFSC and NOAA PIRO. The results of this analysis will be presented in a report associated with the Manell-Geus Habitat Focus Area, which contains both the Achang and Cocos-East monitoring sites.

Multivariate analyses and power analyses will be carried out with reef fish and macroinvertebrate survey data in the near future and the results presented in a subsequent report. Time series analysis and comparisons between sites will also be carried out for the reef fish survey data, and for additional benthic community and macroinvertebrate species/species groups. The results of these analyses will also be presented in a future report.

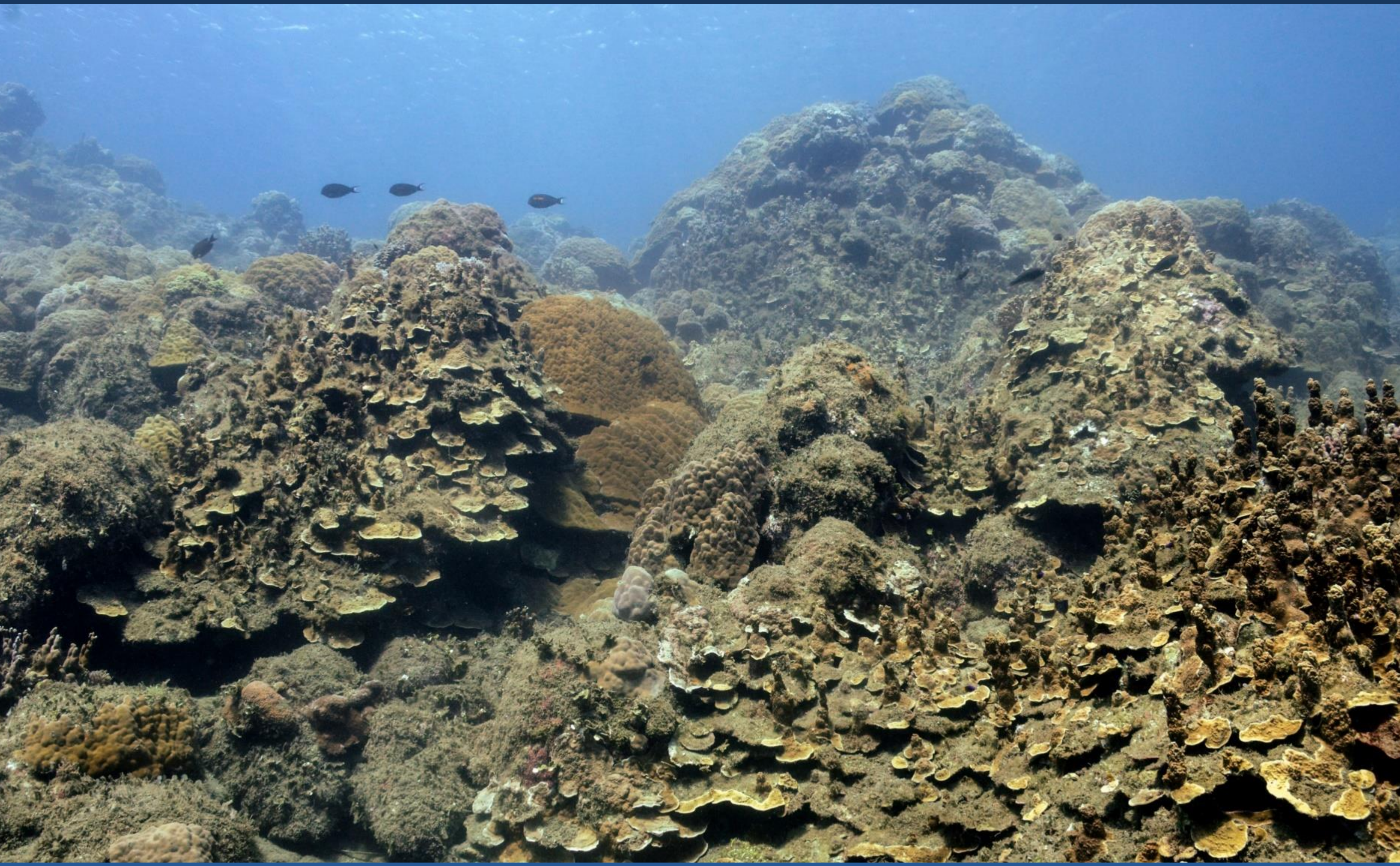
Additional future analyses of data collected at the high priority reef areas may include regression analyses and additional multidimensional statistical tools to test relationships between biological parameters and environmental variables; to quantify, characterize and explain relationships between datasets within a site; and quantify, characterize and explain shifts in the structure of biological communities within a site over time.

An attempt will also be made in the near future, possibly through collaboration with NOAA PIFSC or other potential collaborators, to compare the biological communities of paired Marine Preserve/non-Preserve sites, and possibly between other sites, using a more quantitative analytical approach rather than the more qualitative comparisons presented in this report.

Photo (previous page): A *Porites*-dominated reef along the submarine terrace in the Tumon Bay monitoring site in 2015.

3 RESULTS AND DISCUSSION

3.1 Baseline condition and power analyses for the Fouha, Piti, Achang and modified Tumon Bay sites



3.1.1. FOUHA BAY

3.1.1.1 SITE OVERVIEW

Fouha Bay was the most recent long-term monitoring site to be established, with baseline data collection occurring in 2015. Fouha is a small, semi-enclosed embayment in southwestern Guam that comprises the nearshore extent of the La Sa Fua watershed. A small-scale watershed restoration effort was underway at the time the decision to monitor the Fouha Bay site was made, and although plans for an expansion of those efforts had not yet been formalized, there was an expectation that such an expansion would eventually occur. Fouha Bay was also a site for which some historical data existed, and earlier in 2015 was the site of a NOAA PIRO-funded, GLTMP-supported study to estimate the potential movement of more diverse benthic communities towards the head of the bay with a decrease in sediment load. Due to the extremely low coral cover, the generally poor condition of the benthic community, and the limited active

Photo (above): A *Porites*-dominated reef along the north-central portion of Fouha Bay, near the "Inner" set of sampling stations surveyed in 2015.

management of the watershed it was determined that the Fouha Bay site was to be surveyed every three to five years. Since that determination was made, Dr. Bastian Bentlage of the UOGML has begun investigating the response of different aspects of the coral community to sediment stress in Fouha Bay, and has partnered with the GLTMP in the deployment and maintenance of GLTMP water quality monitoring instrumentation in the bay. This new focus on Fouha Bay may justify the annual collection of biological data within the site. A return visit to the site is currently planned for May 2019.

Data collection within the Fouha Bay site occurs at a total of 13 permanent sampling stations, including a cluster of five along the relatively flat submarine terrace (5–7 m) in the outer portion of the northern side of the bay; a cluster of five along the flat submarine terrace in the outer portion of the southern side of the bay (5–7 m); and a cluster of three stations in a distinct, more structurally-complex, habitat occurring closer to the head of the bay on the bay's north side (~6 m)(Appendix I). The limited extent of reef habitat within the small bay constrained the number of transects that could be placed without resulting in overlapping survey areas. Quantitative visual reef fish survey data was only collected at the sampling stations located in the outer portion of the bay. Low visibility and high reef complexity prevented the execution of quantitative reef fish surveys at stations inside the bay, but qualitative species presence surveys were conducted in the vicinity of these stations.

3.1.1.2 BENTHIC COMMUNITY

Benthic cover

Exploration of data in multivariate space

The benthic communities for the group of three sampling stations inside Fouha Bay (Inside), the five on the north side of the outer portion of the bay (Out-N), and the five on the south side of the outer portion of the bay (Out-S) formed distinct clusters in the nMDS plot (Figure 3.1). The results of a One-way ANOVA Analysis of Similarities indicated that, despite the low level of replication within each group, the differences among the benthic communities were statistically significant ($R = 0.7$, $p = 0.01$). An eigenvector overlay (Pearson Correlation >0.7) and Similarity Percentages (SIMPER) analysis of dominant benthic community variables indicated that the benthic community variables that contributed the most to the differences between the communities of the three sampling stations inside the bay and those in the outer part of the bay included the greater cover of the corals, *Porites rus* (PRUS) and *P. horizontalata* (PHOR), and sediment-laden turf algae (TURS) inside the bay compared to the greater cover of fleshy macroalgae (FMA), *Halimeda* spp. (HALI), cyanobacteria (CYAN) and non-articulated branching coralline algae (BCAN) at the outer sampling stations (Figure 3.1 and Table 3.1). The results also indicated that the differences between the sampling stations in the northern and southern sides of the outer portion of the bay were largely driven by the greater cover of fleshy macroalgae at the southern stations and the greater cover of *Halimeda* spp., cyanobacteria, and non-articulated branching coralline algae at the northern stations.

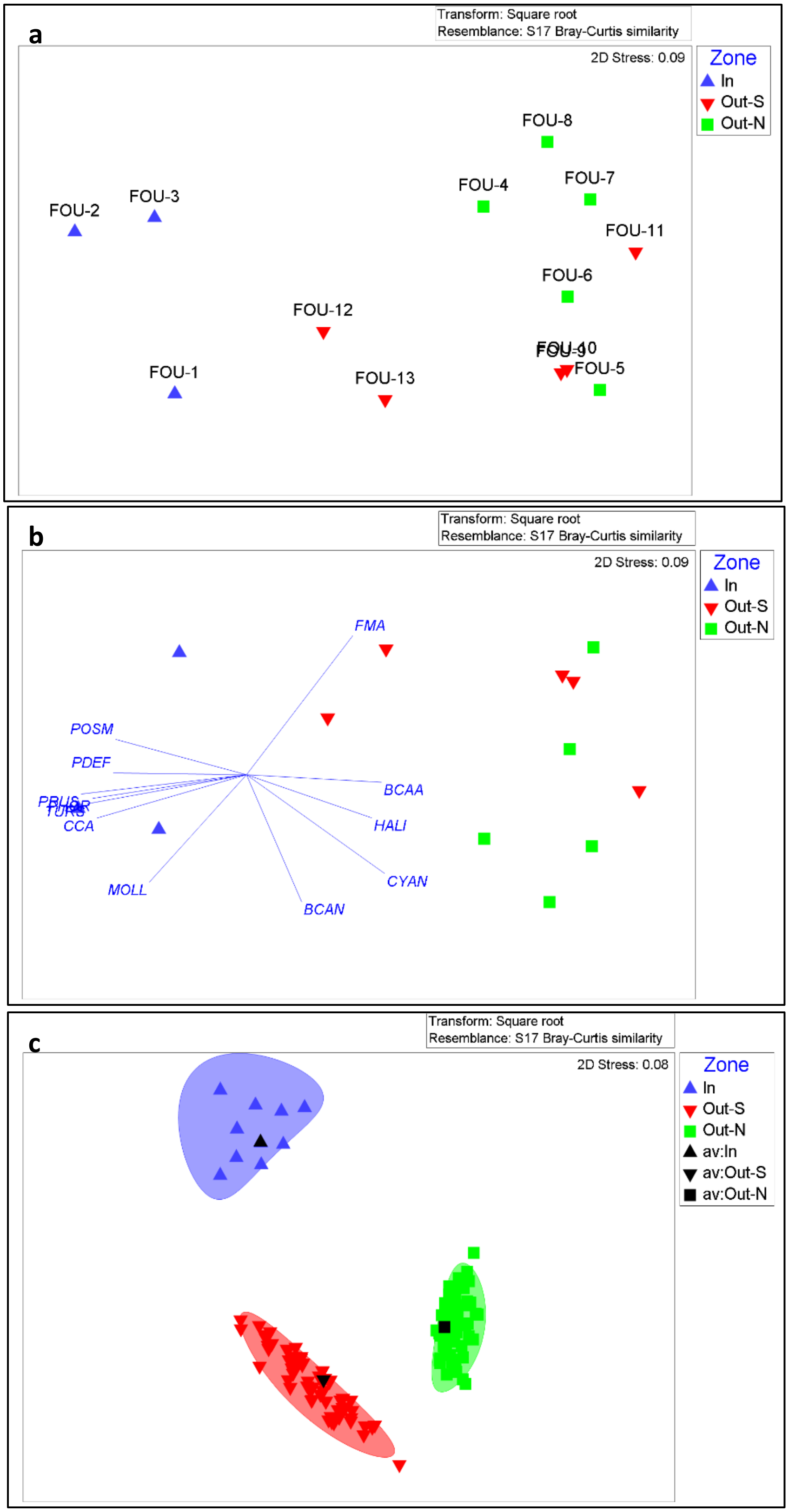


Figure 3.1. Bray-Curtis based nMDS plot of benthic communities at sampling stations in the Fouha Bay monitoring site (**a**), the same nMDS plot with eigenvectors overlay (Pearson coefficient >0.7)(**b**), and nMDS bootstrap averages (95% confidence interval) for the three sampling station groupings (**c**). The results of an ANOSIM indicated that the Inner, Outer-South, and Outer-North groups were more dissimilar than expected by chance (R = 0.7, p = 0.01).

Table 3.1. Results of a Similarity Percentages (SIMPER) analysis of the benthic communities at the Inner (In), Outer-South (Out-S), and Outer-North (Out-N) sampling stations groupings within the Fouha Bay monitoring site. Values are square root-transformed percent cover values from data collected in 2015.

Groups In & Out-S

Average dissimilarity: 40.47

	Group In	Group Out-S				
Species	*Av.Abund*	*Av.Abund*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
PRUS	3.05	0.11	5.12	5.93	12.65	12.65
FMA	5.18	7.31	3.76	1.74	9.28	21.93
CYAN	0.91	2.95	3.53	1.36	8.72	30.65
POSM	2.5	0.82	3.15	1.4	7.79	38.44
TURS	5.45	3.99	3.03	1.54	7.49	45.93
CCA	3.14	1.79	2.6	1.65	6.42	52.35

Groups In & Out-N

Average dissimilarity = 42.38

	Group In	Group Out-N				
Species	*Av.Abund*	*Av.Abund*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
CYAN	0.91	4.4	5.76	2.67	13.6	13.6
PRUS	3.05	0	5.13	7.73	12.1	25.7
TURS	5.45	3.1	4.02	1.9	9.48	35.19
POSM	2.5	0.36	3.59	1.52	8.47	43.66
PAD	0.51	2.08	2.96	1.67	6.99	50.65

Groups Out-S & Out-N

Average dissimilarity = 29.41

	Group Out-S	Group Out-N				
Species	*Av.Abund*	*Av.Abund*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
CYAN	2.95	4.4	3.64	1.71	12.39	12.39
PAD	0.56	2.08	2.93	1.64	9.97	22.36
FMA	7.31	6.41	2.51	1.41	8.55	30.9
TURS	3.99	3.1	2.23	1.31	7.59	38.49
CCA	1.79	1.89	1.33	1.69	4.52	43.02
POSM	0.82	0.36	1.26	1.41	4.27	47.28
FMAD	0.32	0.97	1.16	1.94	3.93	51.22

Power analysis

Univariate power analyses (of a two-sided, paired t-test, $\alpha = 0.05$) were carried out separately with square root-transformed total coral cover values for all 13 sampling stations (All), the three inner stations (Inner), the ten pooled outer sampling stations (Outer), as well as for the five outer-South (Out-S) and five outer-North (Out-N) sampling station groupings (Table 3.2). Power for mean coral cover values was 0.17, 0.18, 0.17, 0.14 and 0.17 for All, Inner, Outer, Out-S, and Out-N sampling stations, respectively. The very low power values for all sampling station groupings is expected, and is likely a result of the low number (n = 3) of stations for the Inner grouping and the very low (<1–3%) mean coral cover values for all other groupings. The detection of a 30% change from those low mean coral cover values equates to the detection of less than 1% absolute coral cover, which is not realistic given the inherent heterogeneity in benthic communities and the limited capacity that prevents the much greater sampling of these heterogeneous communities. For example, in order to detect a 30% change from the current mean of 2% coral cover a total of 61 Outer sampling stations would have to be surveyed. At the current level of sampling effort, which would be difficult to increase given the capacity limitations as well as the limited area of reef in the targeted strata, a 97% change in mean coral cover at the Outer stations could be detected at a power of 0.8. While this value seems high, it equates to detecting an increase from 2% to 5% coral cover, which is biologically meaningful and is detectable at the current level of sampling effort. However, a decline from such a low starting point would likely be undetected.

Table 3.2 Results of a t-test power analysis of percent coral cover values for Fouha Bay sampling stations surveyed in 2015.

	Mean ± SD%	N	Delta = 30% of mean	Power	N required for power = 0.8	Delta at current sampling effort, power = 0.8
All stations	5.6 ± 7.3%	13	1.7%	0.17	150	6.2%
Inner stations	17.6 ± 5.3	3	5.3	0.18	10	17.3
Outer stations	2 ± 1.7	10	0.6	0.17	61	1.7
Outer-North	1 ± 0.5	5	0.29	0.17	26	0.9
Outer-South	3.1 ± 1.8	5	0.9	0.14	32	3

Descriptive statistics

Mean percent cover (± SD) values of major benthic cover types for the Inner and pooled Outer sampling stations are presented in Figure 3.2a and for the Inner, Outer-North, and Outer-South sampling stations in Figure 3.2b. The cumulative cover of major benthic types is provided for the Inner and pooled Outer sampling stations in Figure 3.3a and for the Outer-North and Outer-South stations in Figure 3.3b. Mean coral cover (± SD) across the entire site was 6 ± 7%. The outer stations were characterized by very low coral cover (2 ± 2%) and high fleshy macroalgae cover (48 ± 15%), while coral cover was higher (18 ± 5%), and fleshy macroalgae cover more moderate (26 ± 8%), at the inner sampling stations. Although an analysis of available historic data from the bay has not yet been carried out, the very low coral cover at the Outer sampling stations may be a result of coral mortality associated with past crown-of-thorns seastar (COTS) outbreaks and severe sediment stress from the construction of the coastal highway. Recovery from these past events has likely been inhibited by low coral recruitment rates, chronically impaired water quality, and reduced herbivore populations. The cover of major benthic cover types were similar for the Outer-South and Outer-North stations, although coral cover was slightly higher (3 ± 2% and 1 ± 1% respectively) at the Outer-South stations (t-test, $p = 0.02$). The difference in the cover of cyanobacteria between the Outer-South stations and Outer-North stations was not statistically significant, while the difference in cover of branching coralline algae (5 ± 2% and 8 ± 3%, respectively) was only significant at the $\alpha = 0.1$ level (t-test, $p = 0.059$).

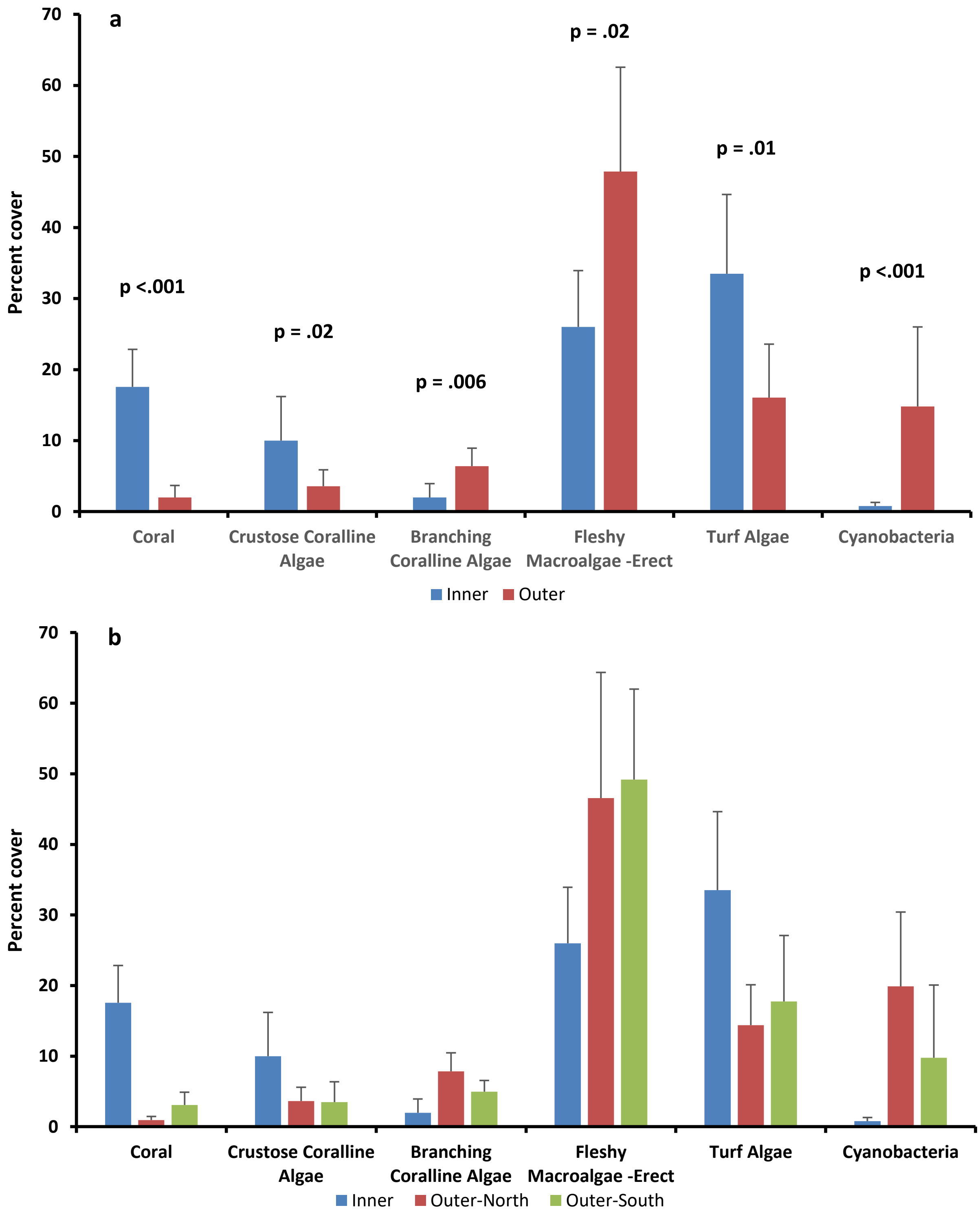


Figure 3.2. Mean percent cover of major benthic cover categories for the Inner (*n* = 3), and pooled Outer (*n* = 10), sampling station groupings (**a**) and for the Inner (*n* = 3), Outer-North (*n* = 5), and Outer-South (*n* = 5) sampling stations groupings (**b**) in the Fouha Bay monitoring site. P values are provided for comparisons (Student t-test or Wilcoxon Signed Rank Test) between square root-transformed mean cover values for Inner and Outer (pooled) sampling station groupings. Error bars represent standard deviation.

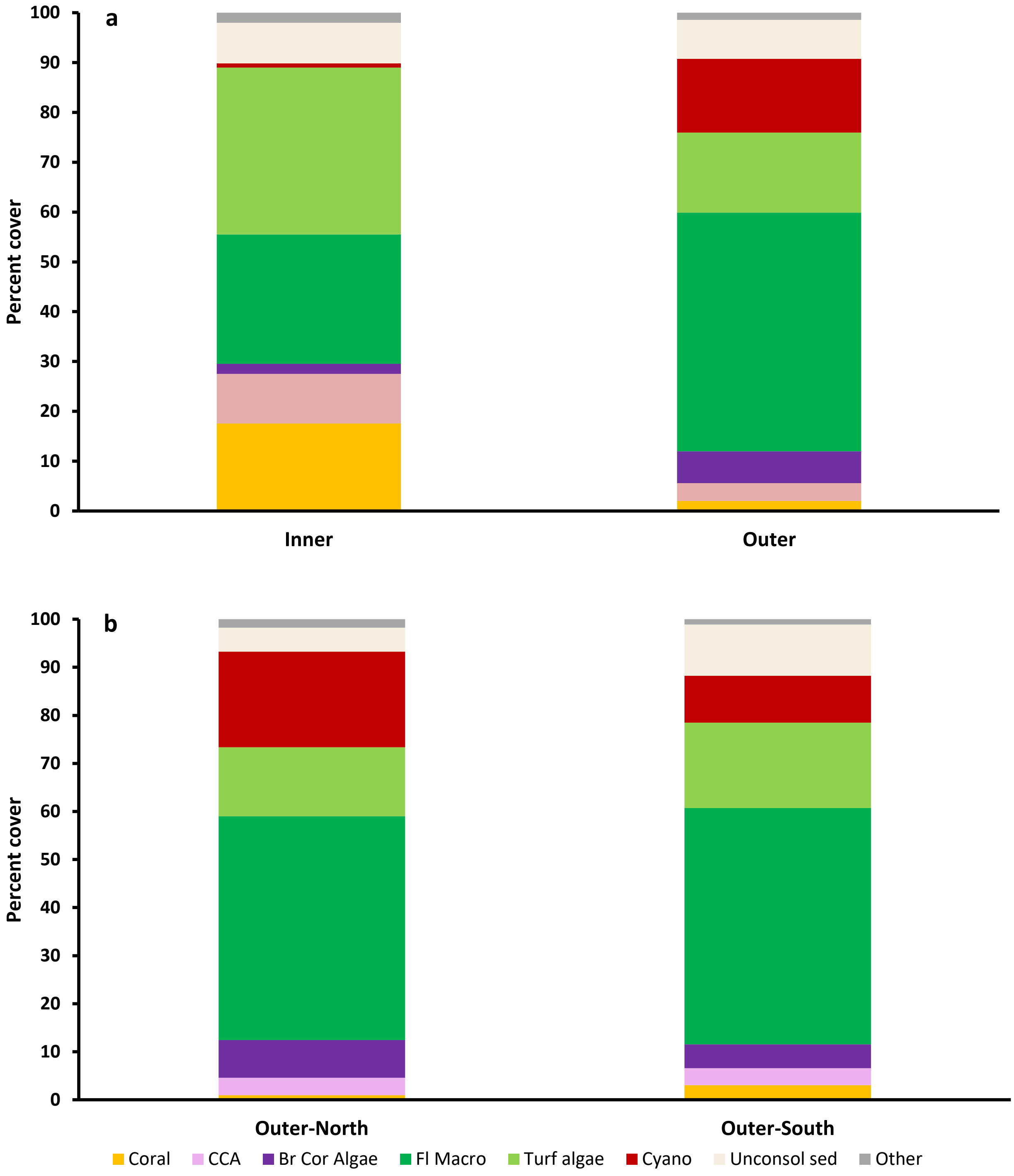


Figure 3.3. Cumulative percent cover of major benthic cover categories for the Inner and Outer sampling stations groupings (**a**) and the Outer-North and Outer-South (**b**) station groupings in the Fouha Bay monitoring site.

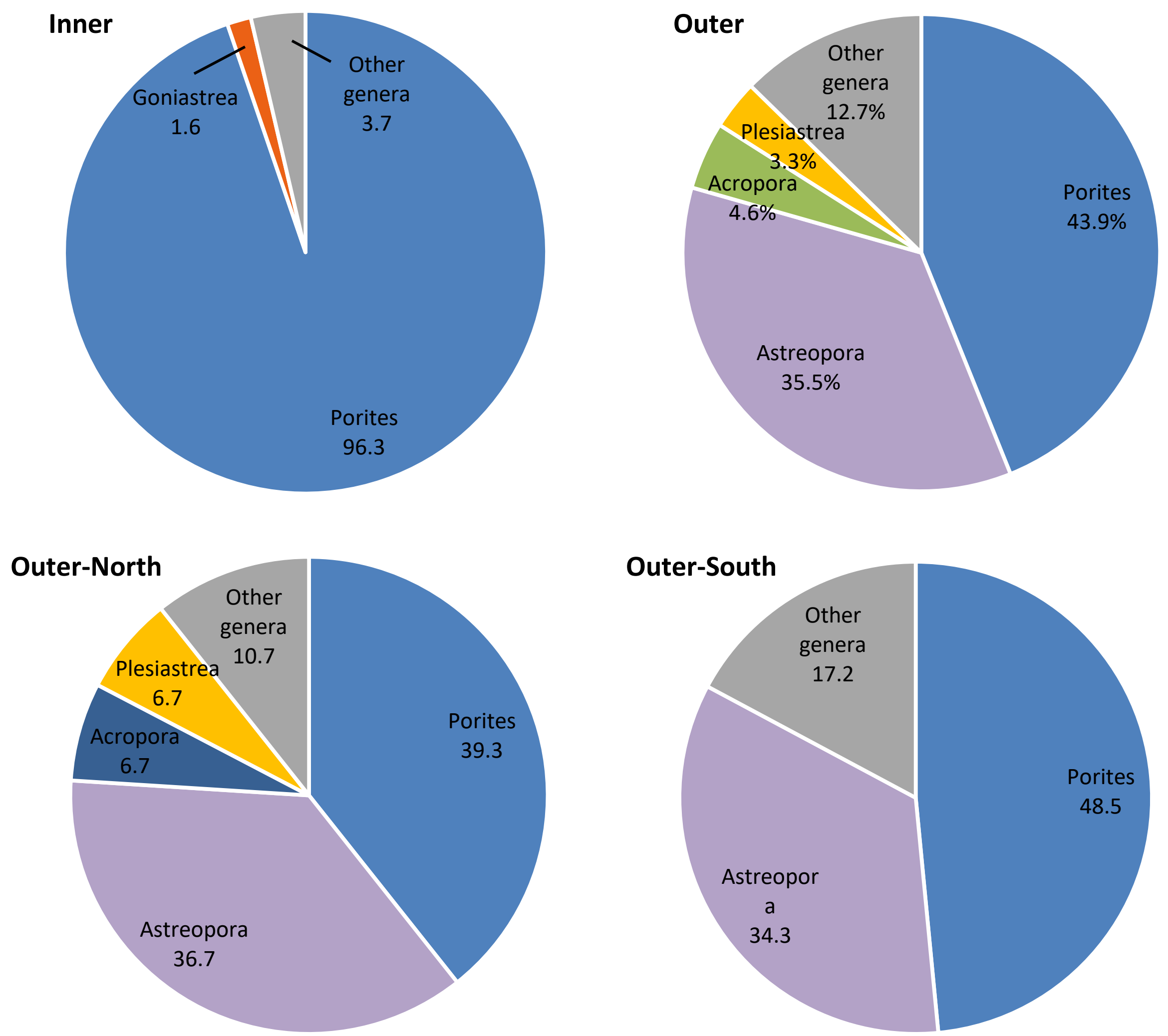


Figure 3.4. Percent contribution of the mean cover of individual coral genera to mean total coral cover for the Inner, Outer (pooled), Outer-North, and Outer-South sampling station groupings in the Fouha Bay monitoring site. Only coral genera comprising ≥5% of total coral cover are presented in the figure; all other coral genera are grouped under the "Other genera" category.

Nearly all of the total coral cover at Inner sampling stations was comprised of *Porites* (mainly *P. rus* and massive *Porites* species), while less than half of total cover at the Outer stations was comprised of *Porites*. Several genera that contributed greater than 5% of total coral cover, such as *Astreopora*, *Acropora*, and *Plesiastrea*, at the Outer stations were either not recorded at all or comprised less than 5% of total cover at the Inner Stations. The proportion of total cover at the Outer-North and Outer-South stations comprised by *Porites* and *Astreopora* were highly similar, but *Acropora* and *Plesiastrea* contributed greater than 5% to total coral cover only at the Outer-North stations. The extremely low total cover at the Outer sampling stations, and even lower absolute cover for individual genera, however, necessitates caution when making these comparisons, as they likely are not statistically significant.

3.1.1.3 ASSOCIATED BIOLOGICAL COMMUNITIES

Reef fishes

Descriptive statistics

Density

Reef fish density at the Fouha site in 2015 ranged from 48 fish/100m^2 at station 12 to 170 fish/100m^2 at station 5 (Figure 3.5). Mean (± SE) fish density was 117 ± 12 fish/100 m^2 and the median was 127 fish/100 m^2. Relative density by family is presented in Figure 3.6. The pomacentrids were the primary contributor to density, accounting for approximately 66% of fish counted, followed by labrids (19%), and acanthurids (4%).

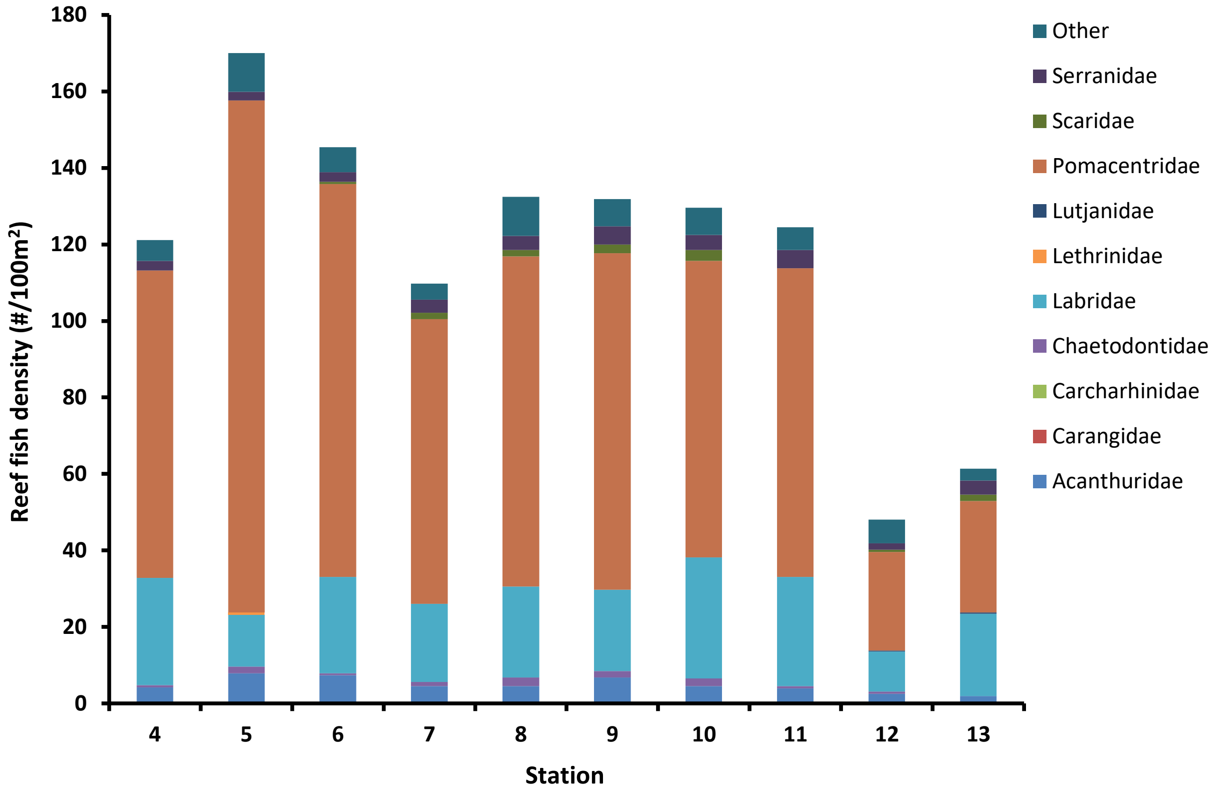


Figure 3.5. Reef fish density (# of fish/100m^2) by family at Fouha Bay sampling stations in 2015.

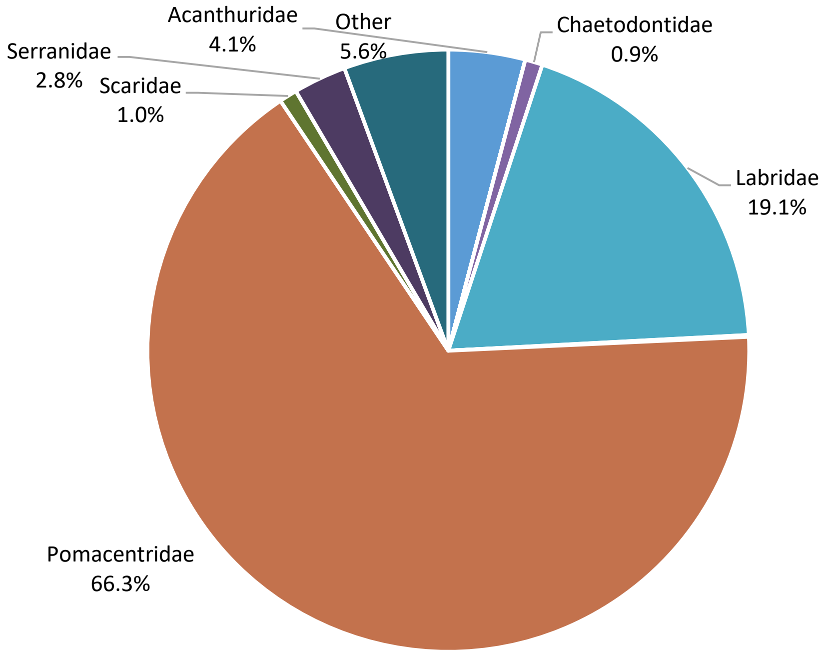


Figure 3.6. Relative density of reef fish by family at the Fouha site in 2015.

Biomass

The minimum total reef fish biomass recorded at the Fouha Bay stations in 2015 was 3 g/m^2 and the maximum biomass was 11 g/m^2. Mean (± SE) biomass across the site was 6 ± 1 g/m^2, and the median was 5 g/m^2 (Figure 3.7). Relative abundance by family is presented in Figure 3.8. Pomacentrids were a major contributor to biomass (23%), followed by balistids (13%), acanthurids (13%), scarids (12%), and labrids (12%). Other contributors included serranids (11%) and holocentrids (6%). The mean total reef fish biomass at the Fouha site in 2015 was the lowest among all of the monitoring sites to-date, and represents only 11% of the potential total reef fish biomass value (53 ±7 g/m^2) estimated for an unimpaired Guam reef community by Williams et al. (2015).

Species Richness

A total of 110 reef fish species was documented across the Fouha Bay site in 2015. Species richness varied from 25 species at station 4 to 52 species at station 9 (Figure 3.9). The average (± SE) number of species observed was 39 ± 3 and the median was 40. Of the species recorded, 10 species were found at all ten sites and 41 were recorded at only one of the stations. The majority of species (78) were found at less than half of the stations.

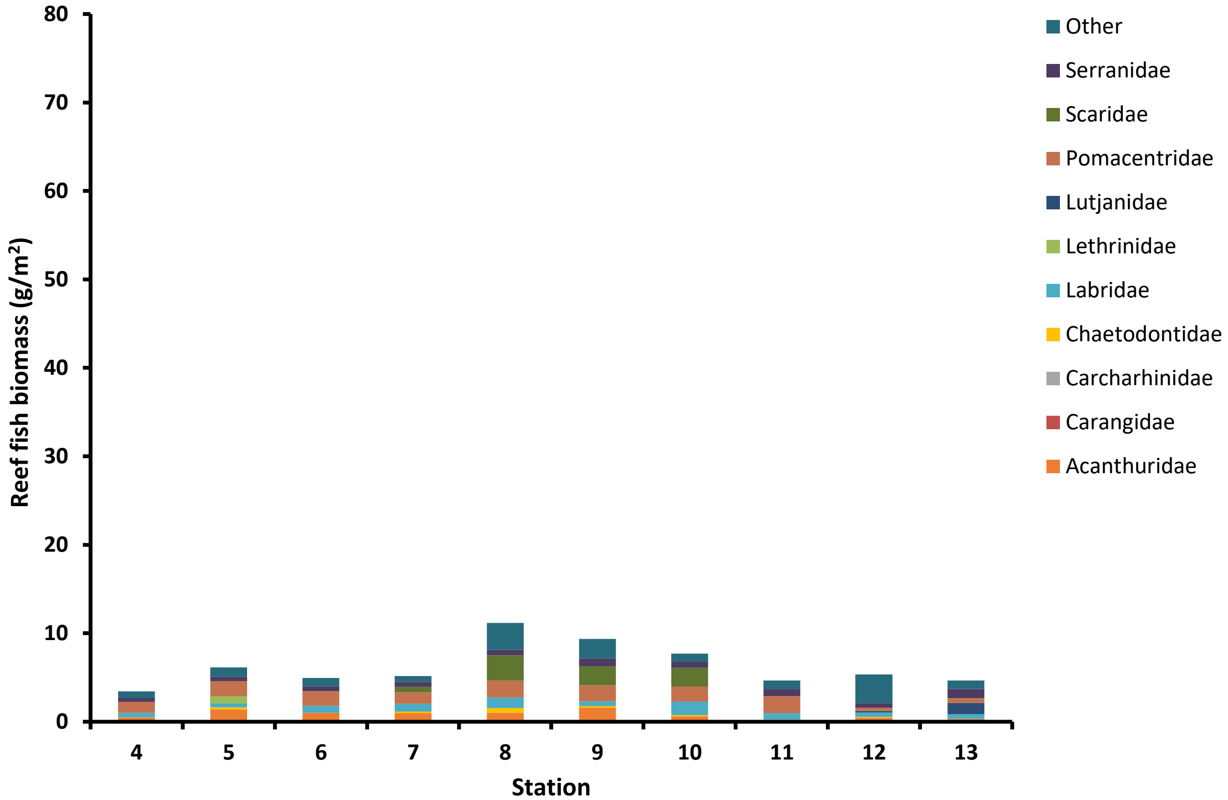


Figure 3.7. Reef fish biomass (g/m^2) by family at the Fouha Bay sampling stations in 2015.

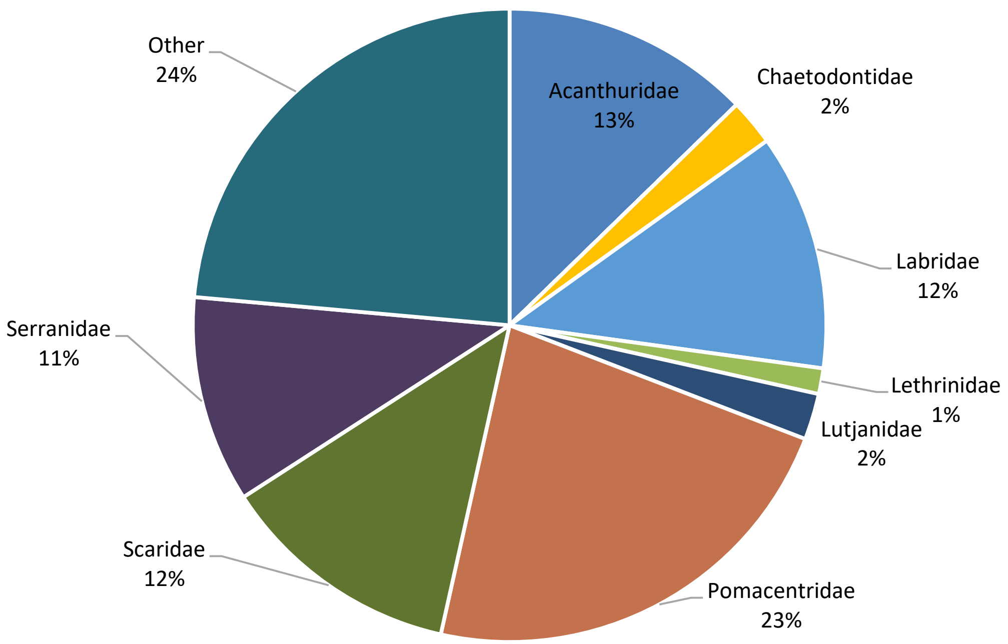


Figure 3.8. Relative abundance of reef fish by family at the Fouha Bay sampling stations in 2015.

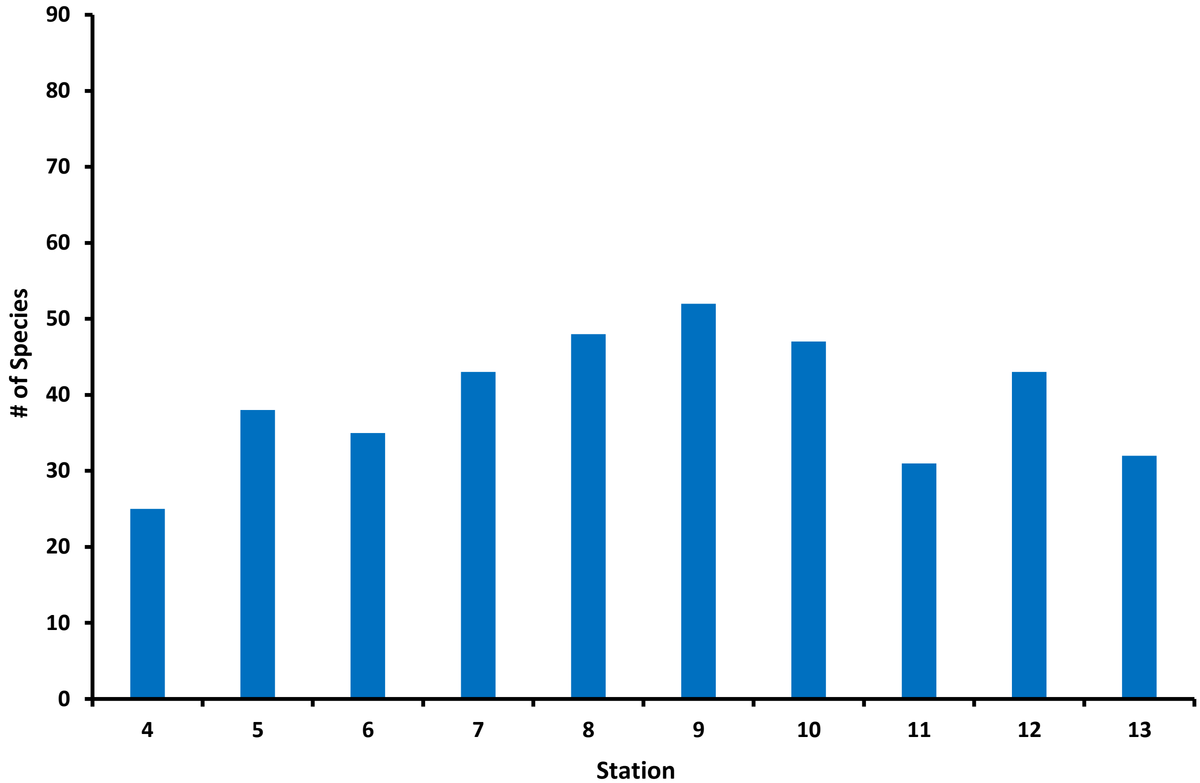


Figure 3.9. Reef fish species richness for sampling stations within the Fouha monitoring site in 2015.

Macroinvertebrates

Descriptive statistics

Mean density (ind/100m^2 ± SD) for each broad macroinvertebrate taxonomic group is presented in Figure 3.10. Relative abundance for individual taxa is presented in Figure 3.11. The small, rock-boring urchin *Echinostrephus aciculatus* represented 57.3% of total abundance, with *Linckia multiflora* comprising 33.9%. The "other" category was comprised of *Tectus* spp., *Tridacna* spp., *Linckia laevigata*, *Diadema savignyi*, *Echinometra mathaei*, and *Echinometra* sp. A. A total of 8 species was recorded in Fouha Bay in 2015.

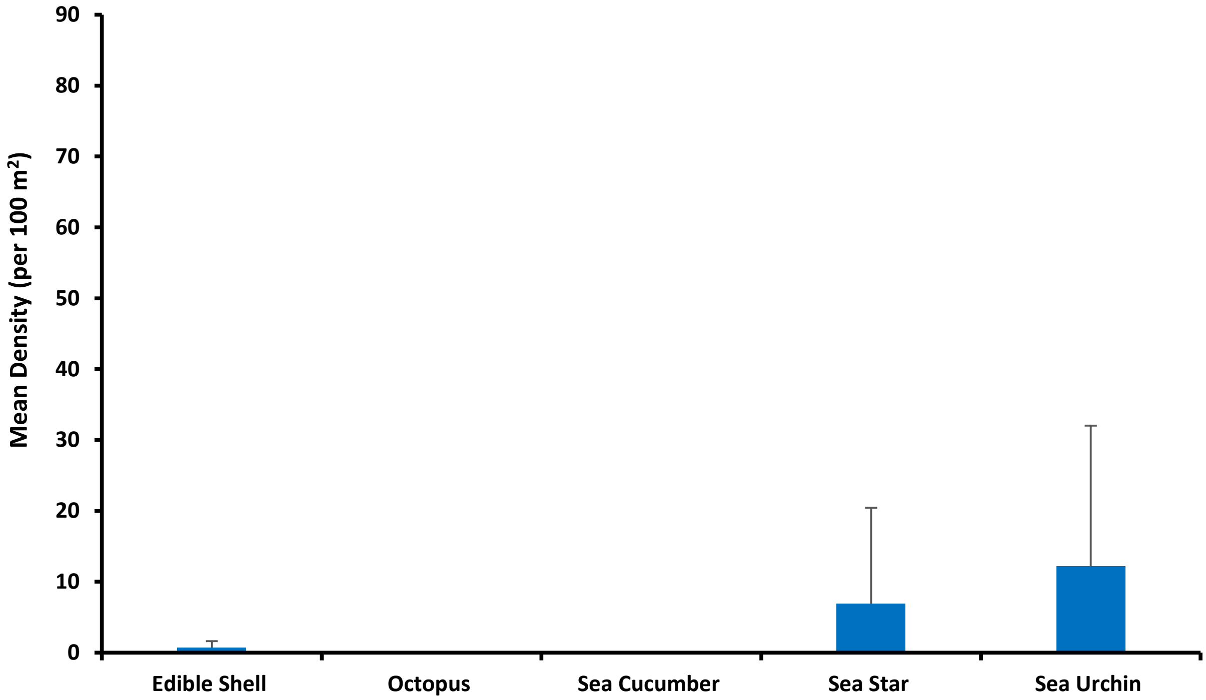


Figure 3.10. Mean density (ind/100 m^2) for broad macroinvertebrate taxonomic groups within the Fouha Bay monitoring site in 2015. Error bars represent standard deviation.

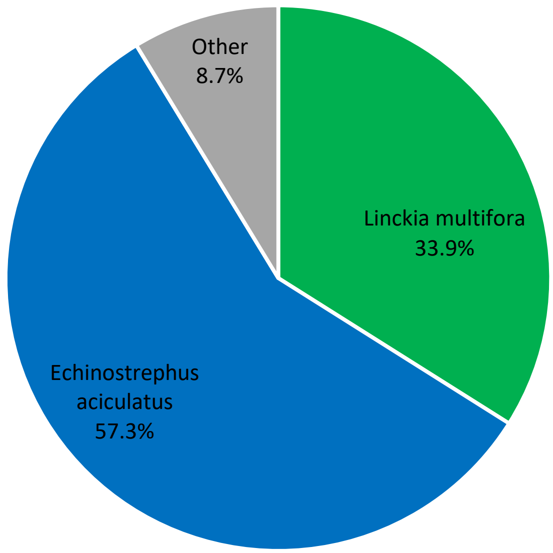
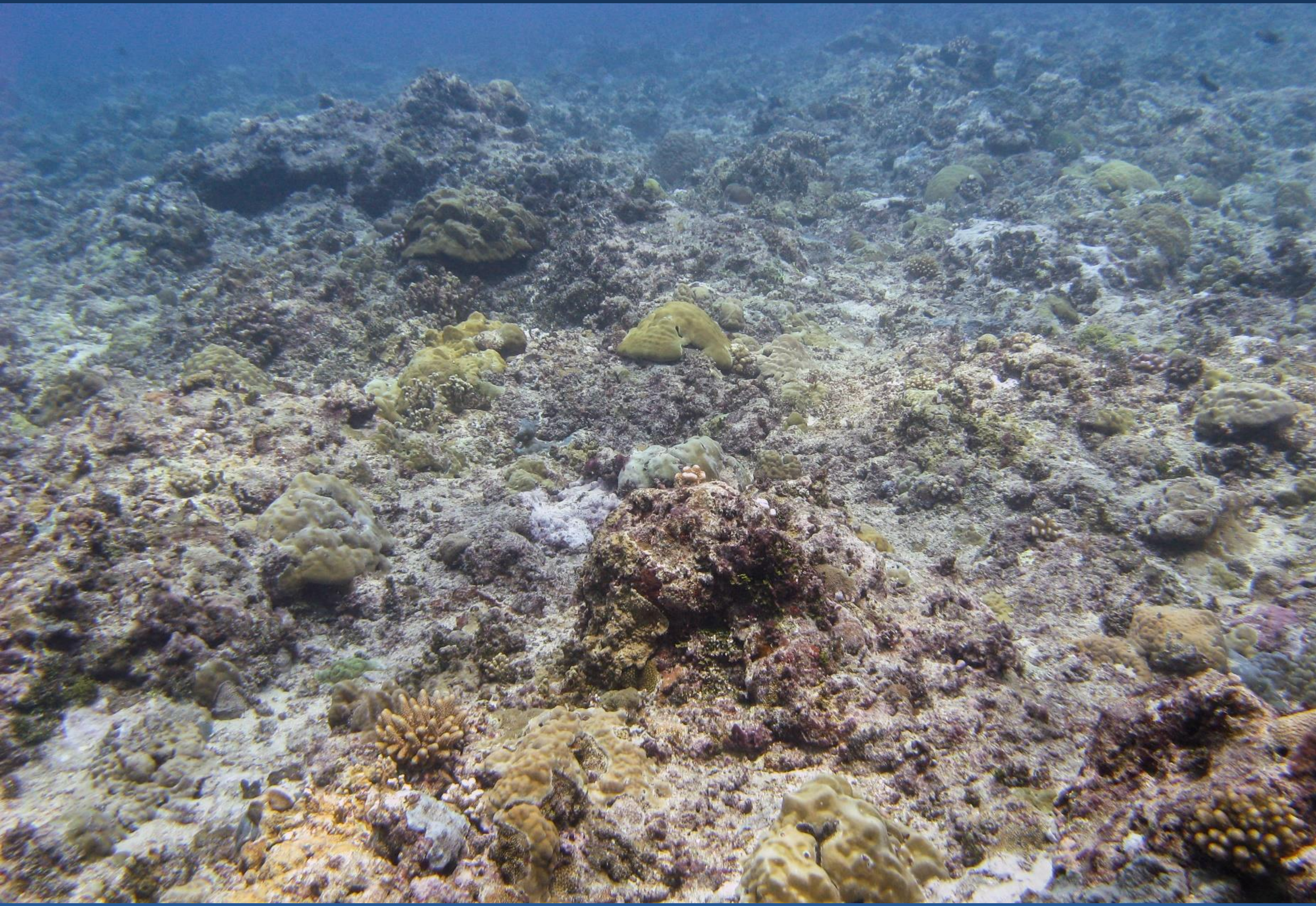


Figure 3.11. Relative abundance of individual macroinvertebrate taxa at the Fouha Bay site in 2015. Colors represent broad taxonomic groupings.

Sea turtles

No sea turtles were recorded during reef fish surveys at the Fouha Bay sampling stations, although they were ocassionally observed from the surface during surface intervals.



3.1.2 PITI BOMB HOLES MARINE PRESERVE

3.1.2.1 SITE OVERVIEW

The Piti Bomb Holes Marine Preserve was selected for long-term monitoring upon completion of baseline monitoring at Western Shoals in 2011, with baseline data collection occurring in 2012 (Appendix F). Piti, or Tepungan, Bay is considered a high priority reef area on account of its designation as a locally-managed Marine Preserve, its location downstream from watershed restoration activities, its heavy use by

Photo: A reef community to the west of Tepungan Channel in the Piti monitoring site in 2014. While stress-tolerant corals, such as *Porites* spp., still comprise the majority of the coral community to the west of Tepungan Channel, this area supports a greater proportion of more stress-susceptible coral genera than the reef area occurring to the east of the channel.

commercial tourism operators and resident recreational users, and its location adjacent to a non-preserve site (Asan) monitored on a regular basis by the National Park Service. Since its establishment as a long-term monitoring site, a coral nursery, coral mitigation sites, and a community-based coral reef monitoring program site have been established in Piti Bay. In order to maintain consistency with the East Agana and Tumon Bay monitoring sites, monitoring in Piti Bay occurs within the same reef zone and depth range. However, in order to contribute to an understanding of the impacts of land-based sources of pollution on coral reef ecosystems within the bay, and to assist in the evaluation of the effectiveness of watershed restoration activities in improving water quality and coral reef health, the monitoring site includes two separate sections of reef slope: one extending to the west of Tepungan Channel and one extending to the east of the channel.

3.1.2.2 BENTHIC COMMUNITY

Benthic cover

Exploration of data in multivariate space

The benthic communities for the group of sampling stations to the west and east of Tepungan Channel that were surveyed in 2012 formed distinct clusters in the Bray-Curtis based nMDS plot (Figure 3.12). The results of a One-way ANOVA Analysis of Similarities indicate that despite the low level of replication within each group the differences between the benthic communities to the west and east of Tepungan Channel were significant enough to detect ($R = 0.37$, $p = 0.01$). The overlay of eigenvectors (Pearson Correlation > 0.6) on the nMDS plot and the results of a SIMPER analysis indicate that the factors contributing most to the differences between the benthic communities to the west and east of Tepungan Channel include the greater cover of sediment-laden turf algae (TURS) and fleshy macroalgae (FMA and DICT) at the East stations and the greater cover of multiple coral genera, including genera considered more stress-susceptible, at the West stations (Figures 3.12 and Table 3.3). The significantly different coral cover values and the distinct benthic communities at the East and West sampling stations suggest that these sampling station groupings be considered separately for time series analysis.

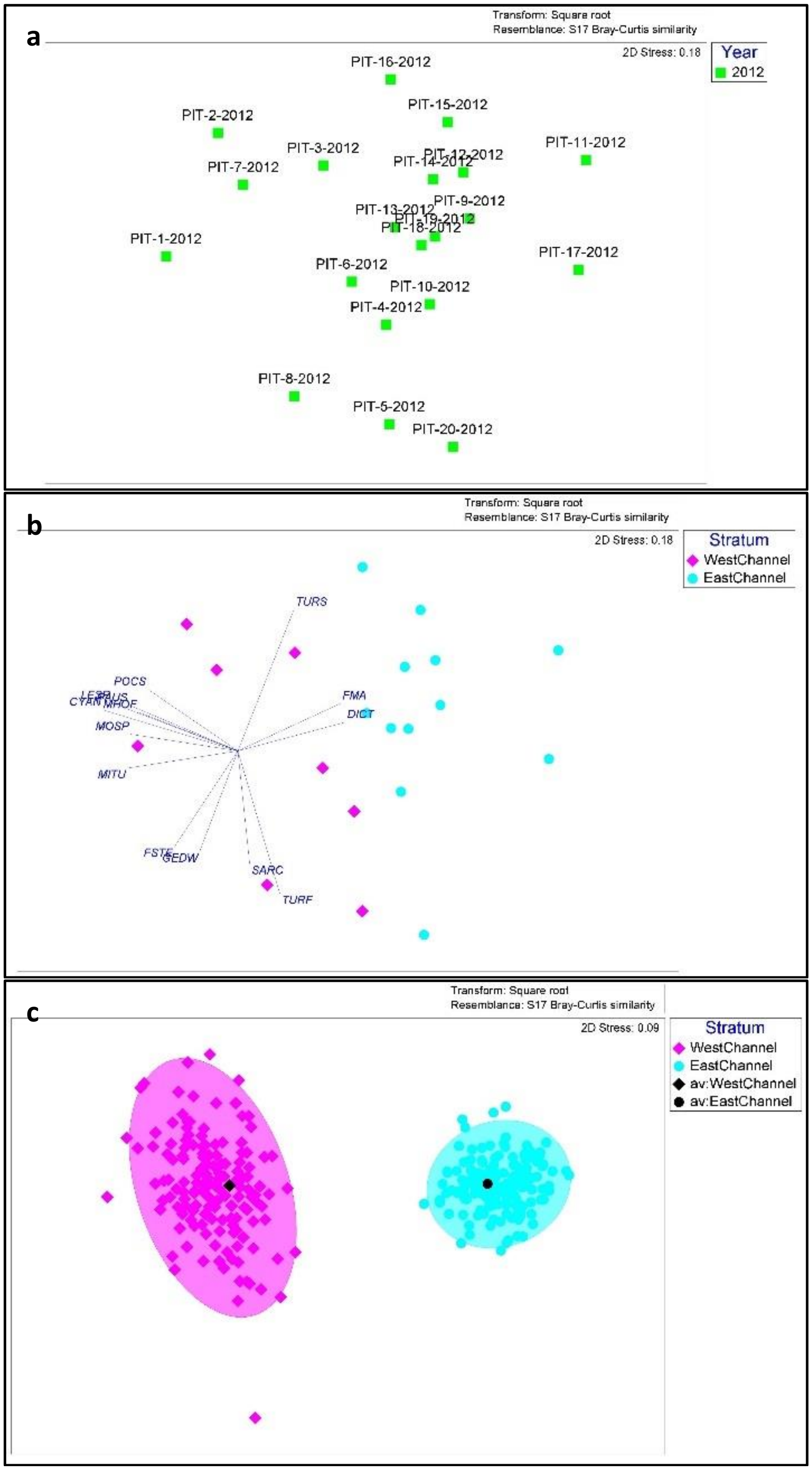


Figure 3.12. Bray-Curtis based nMDS plot of benthic communities at sampling stations in the Piti monitoring site (**a**), the same nMDS plot with eigenvectors overlay (Pearson coefficient >0.6) and with different symbols for stations to the west and east of Tepungan Channel (**b**), and nMDS bootstrap averages (95% confidence interval) for west of channel and east of channel sampling station groupings (**c**). The results of an ANOSIM indicated that the west of channel and east of channel station groups were more dissimilar than expected by chance (R = 0.37, p = 0.01).

Table 3.3. Results of a Similarity Percentages (SIMPER) analysis of benthic communities at the sampling stations occurring to the west (West) and east (East) of Tepungan Channel within the Piti monitoring site. Values are square root-transformed percent cover values from data collected in 2012.

Groups West & East
Average dissimilarity = 37.28

Species	Group West *Av.Abund*	Group East *Av.Abund*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
TURS	3.37	5.12	3.14	1.63	8.43	8.43
CYAN	4.5	3.29	2.31	1.42	6.2	14.63
TURF	4.13	4.24	2.16	1.42	5.79	20.42
CCA	3.91	3.97	1.7	1.32	4.55	24.97
HALI	2.32	2.56	1.41	1.41	3.79	28.76
POSM	2.93	2.56	1.34	1.71	3.59	32.35
PRUS	1.03	0.5	1.26	1.05	3.37	35.72
LESP	1.34	0.62	1.2	1.57	3.22	38.95
LPHR	0.51	0.76	1.12	1.09	3	41.94
PLUT	0.69	0.2	1.02	0.94	2.75	44.69
POSB	0.8	0.6	0.98	1.48	2.62	47.31
FMA	0.29	0.8	0.86	1.51	2.3	49.61
MOSP	0.77	0.28	0.83	1.11	2.22	51.83

Power analysis

Univariate power analyses (of a two-sided, unpaired t-test, $\alpha = 0.05$) were carried out separately with mean total coral cover values for all 20 sampling stations (All), the eight stations to the west of Tepungan Channel (West), and the 12 stations to the east of Tepungan Channel (East). A separate power analysis (two-sided, paired t-test) was carried out using only permanent sampling stations in order to assess statistical power when data are only available for permanent stations. It is not yet clear how to carry out a power analysis that accounts for the combination of permanent and non-permanent sampling stations; as such, the results of the power analyses presented here do not directly inform the comparisons of sampling stations from different sampling periods that include both permanent and non-permanent sampling stations. Still, the results can approximate statistical power and thus can inform any necessary modifications to the sampling design.

Power (of a two-sided, unpaired t-test, α=0.05, delta = 30% of mean) for mean coral cover values was 0.47, 0.33, and 0.3 for All, West, and East sampling stations, respectively (Table 3.4). The low power is a result of the significant variability in coral cover across the entirety of the site, and the limited number of samples for the areas to the west and east of Tepungan Channel. An increase in statistical power can be achieved if the permanent sampling station PIT-8, which has considerably higher coral cover (37%) than any other station within the monitoring site, is eliminated. According to the power analyses results, more than 40 sampling stations must be surveyed across the site in order to detect a change of 30% of the mean at a power of 0.8; this number is reduced to 29 if station PIT-8 is eliminated. The power analysis results indicate that the level of sampling effort used for 2012 (10 permanent sampling stations and 10 non-permanent sampling stations) would allow the detection of 45% change in coral cover relative to the mean

(= a change of 7% absolute coral cover from the 2012 mean of 16%). The elimination of station PIT-8 would allow the detection of a 35% change relative to the mean, or a change in absolute coral cover of 6%.

Power (of a two-sided, paired t-test, α = 0.05, delta = 30% of mean for mean coral cover was 0.32, 0.14, and 0.28 for All, West, and East permanent sampling stations, respectively (Table 3.4). As above, the very low statistical power is a result of high variability in coral cover and the low number of permanent sampling stations across the site and for the areas to the east and west of Tepungan Channel when examined individually. A significant increase in statistical power (to 0.52) can be achieved for the entire site and for the West stations (to 0.23) if station PIT-8 is eliminated. The power analysis results indicate that 30 sampling stations must be surveyed across the site in order to detect a change of 30% of the mean at a power of 0.8; this number is reduced to 16 if station PIT-8 is eliminated. The power analysis results indicate that continued monitoring of the 10 permanent sampling stations established in 2012 would allow the detection of 57% change in coral cover relative to the mean (= a change of 9% absolute coral cover from the 2012 mean of 16%). The elimination of station PIT-8 would allow the detection of a 42% change relative to the mean, or a change in absolute coral cover of 6%.

Table 3.4. Results of a t-test power analysis of percent coral cover values for Piti sampling stations surveyed in 2012.

	Mean ± SD%	N	Delta (mean*0.3)	Power	N required for power = 0.8	Delta at current sampling effort, power = 0.8
All stations	15.7 ± 7.7%	20	4.7%	0.47	43	7%
All stations, excl. PIT-8	14.6 ± 5.9	19	4.4	0.61	29	5.5
West of channel	20.5 ± 7.6	8	6.2	0.33	25	11.5
West of channel, excl. PIT-8	16.1 ± 5.2	7	4.8	0.75	9	5.7
East of channel	12.5 ± 6.1	12	3.7	0.3	44	7.3
Permanent stations only						
All stations	16.1 ± 9.1	10	4.8	0.32	30	9.1
All stations, excl. PIT-8	13.7 ± 5.4	9	4.1	0.52	16	5.8
West of channel	22.4 ± 10.7	4	6.7	0.14	22	22.8
West of channel, excl. PIT-8	17.3 ± 4.4	3	5.2	0.23	8	14.4
East of channel	11.9 ± 5.2	6	3.6	0.28	18	7.5

Descriptive statistics

Mean percent cover (± SD) values of major benthic cover categories for the East and West sampling stations are presented in Figure 3.13. Coral cover was low-to-moderate across the site, and the difference between mean coral cover at the sampling stations to the west and east of Tepungan Channel (21 ± 8% and 13 ± 6%, respectively) was statistically significant (t-test, p = 0.01). The cover of turf algae, which was comprised mainly of micro-turfing algae, was higher (42 ± 8% vs. 29 ± 9%; t-test, p = 0.003) and the cover of cyanobacteria was lower (10 ± 5% vs. 20 ± 12%; t-test, p = 0.02) at the East sampling stations in comparison the West sampling stations. The proportion of total coral cover comprised by the generally stress-tolerant genus *Porites* was highly similar between the East and West sampling stations, but the proportion of the generally more stress-susceptible genus, *Montipora*, appeared to be greater at the West stations. Further analysis is required to determine if the differences in the cover of individual coral genera or other taxonomic groupings at the East and West stations were statistically significant. The higher coral cover, lower cyanobacteria cover, and greater relative abundance of *Montipora* at the West stations suggests that the area to the west of Tepungan Channel may be less impacted by the river discharge (e.g., if the general flow of the river discharge tends to move towards northeast).

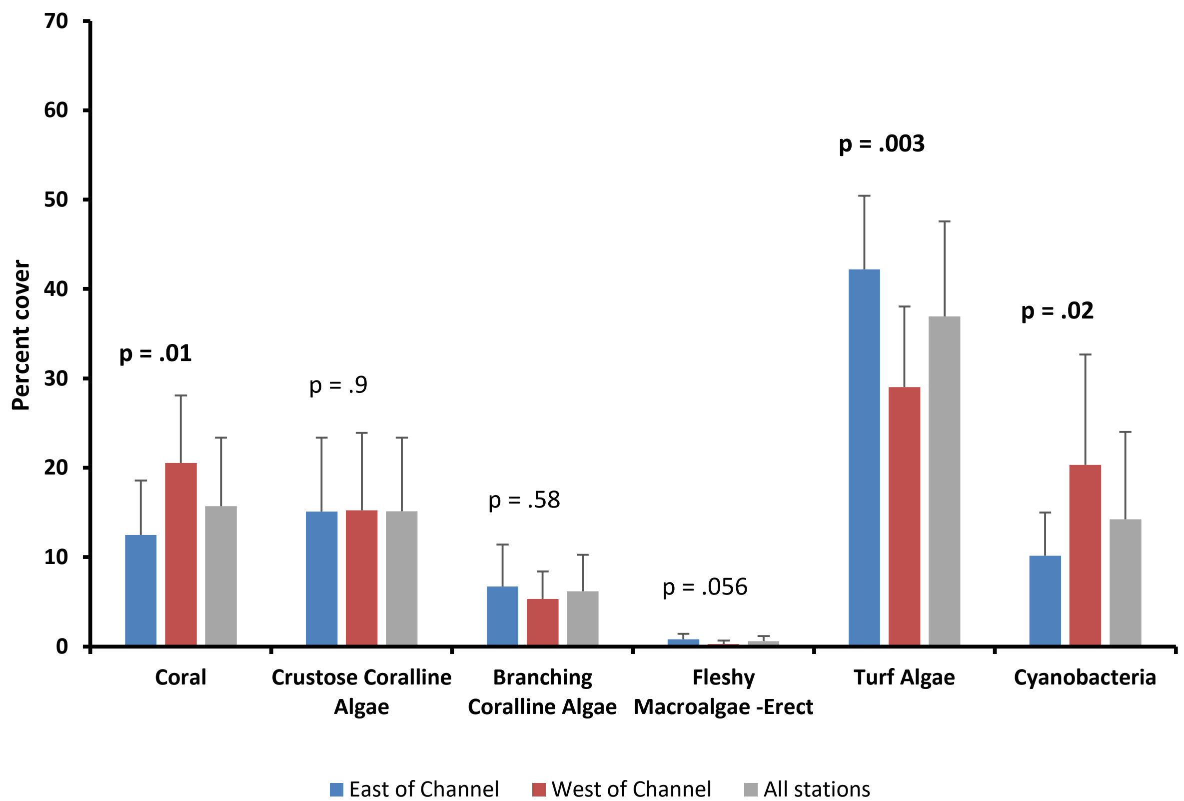


Figure 3.13. Percent cover of major benthic cover categories for the sampling stations to the east (n = 12) and west (n= 8) of Tepungan Channel, as well as for all sampling stations in the Piti monitoring site in 2012. P values are provided for comparisons (Student t-test or Wilcoxon signed rank test) between square root-transformed mean cover values for sampling stations to the east and west of Tepungan Channel. Error bars represent standard deviation.

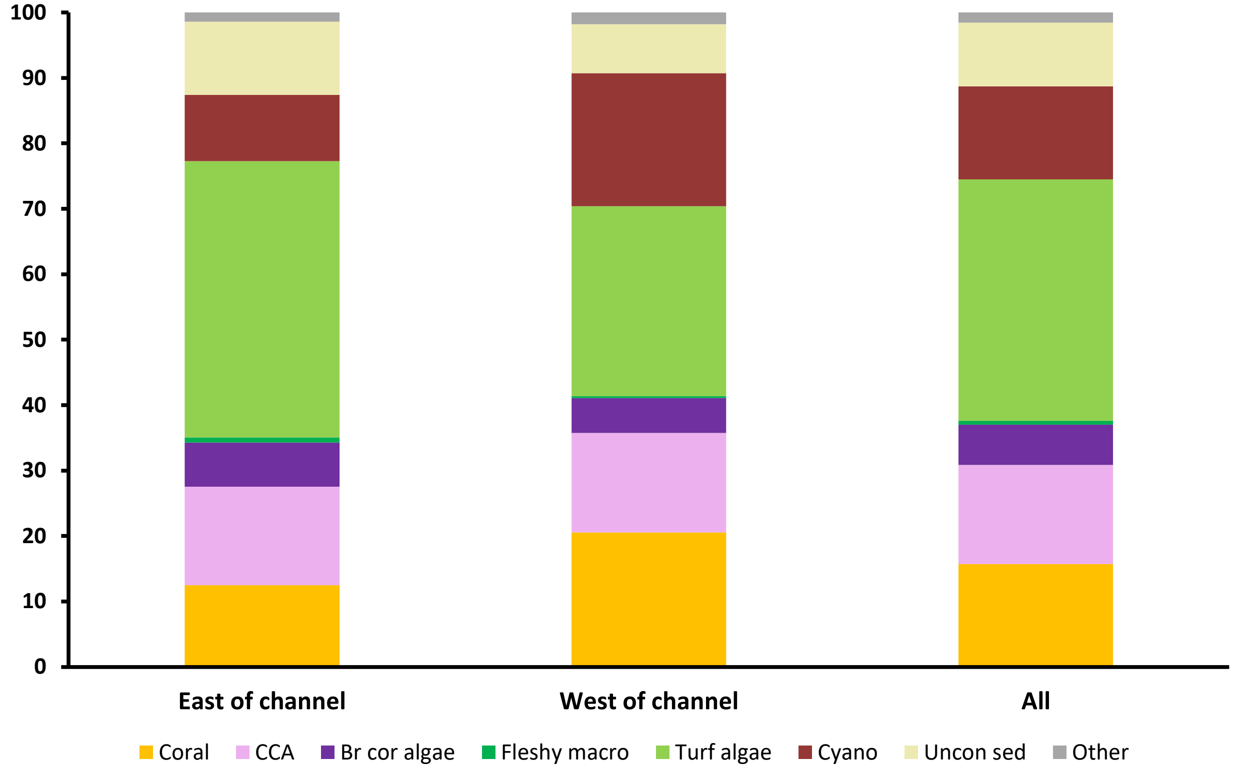


Figure 3.14. Cumulative percent cover of major benthic cover categories for sampling stations to the east and west of Tepungan Channel, as well as all stations surveyed in the Piti monitoring site in 2012.

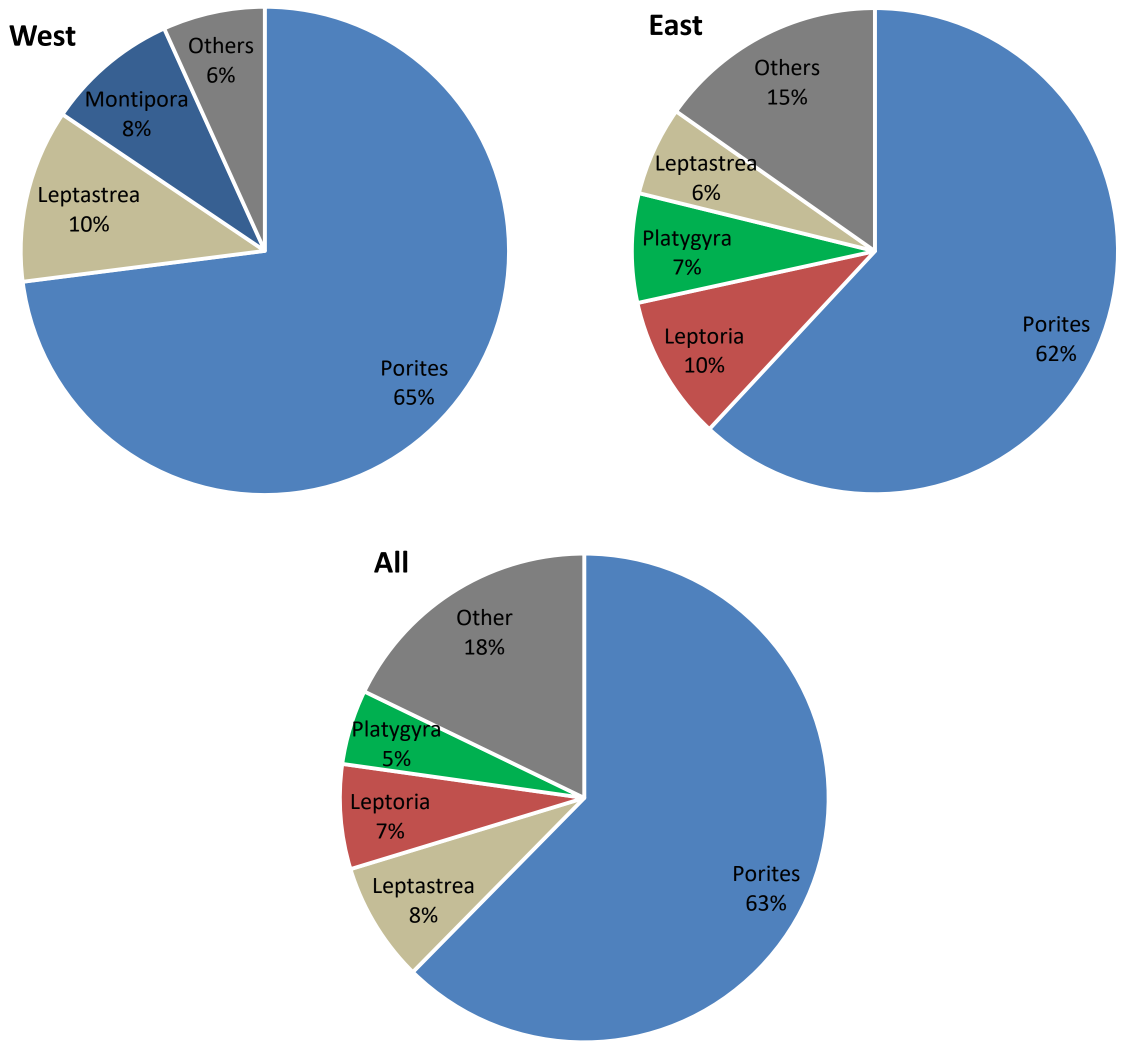


Figure 3.15. Percent contribution of individual coral genera to mean total coral cover for the sampling station groupings to the west (n = 8) and east (n = 12) of Tepungan Channel, as well as for all sampling stations, in the Piti monitoring site in 2012. Only coral genera comprising ≥5% of total coral cover are presented in the figure individually; all other coral genera are grouped under the "Other" category.

3.1.2.3 ASSOCIATED BIOLOGICAL COMMUNITIES

Reef fishes

Descriptive statistics

Density

Reef fish density at Piti site in 2012 ranged from 44 fish/100m^2 at station 14 to 127 fish/100m^2 at station 2 (Figure 3.16). Mean (± SE) fish density was 83 fish/100 m^2 ± 3 and the median was 87 fish/100 m^2. Relative density by family is presented in Figure 3.17. The pomacentrids were a major contributor to density, accounting for approximately 45% of fish counted, followed by labrids (19%), acanthurids (11%), and scarids (7%).

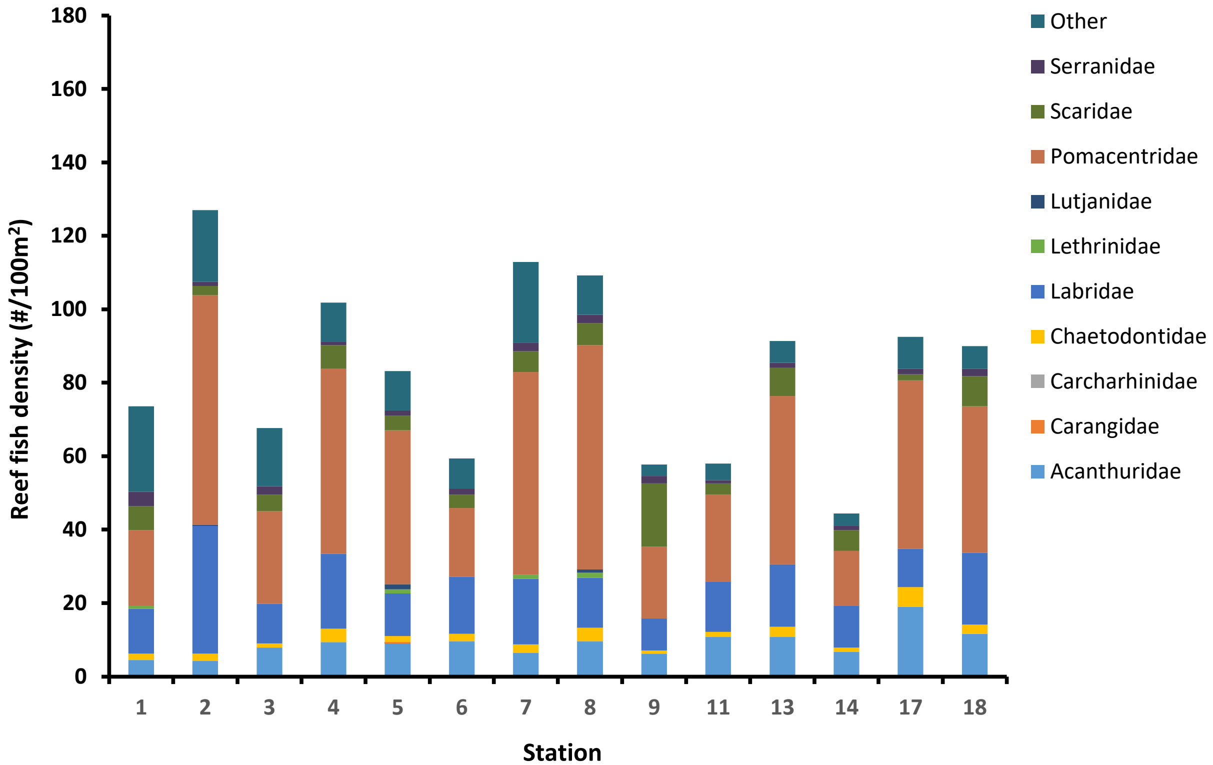


Figure 3.16. Reef fish density (# of fish/100m^2) by family at Piti sampling stations in 2012.

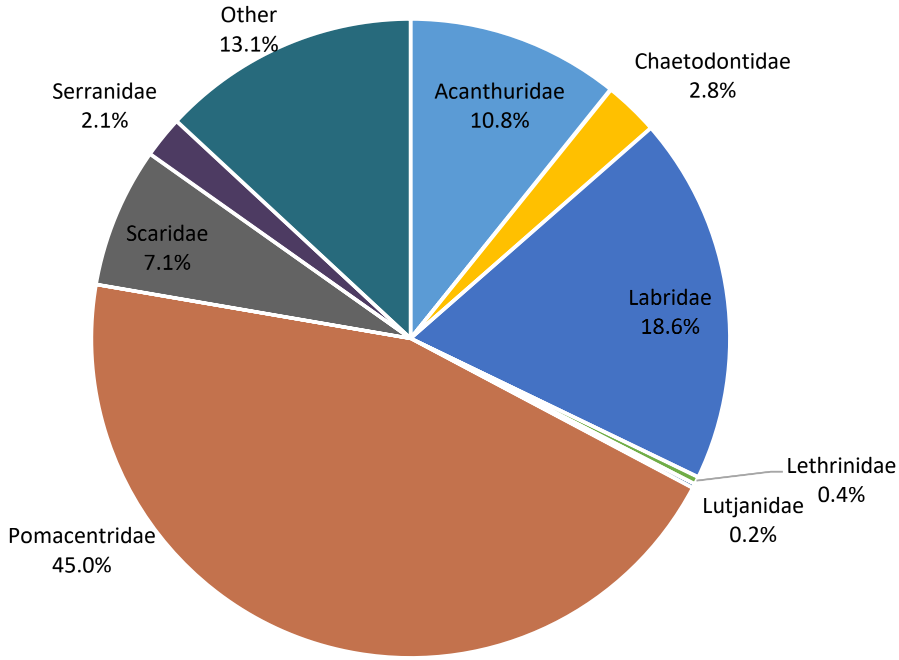


Figure 3.17. Relative density of reef fish by family at the Piti site in 2012.

Biomass

The minimum total reef fish biomass recorded at the Piti sampling stations in 2012 was 12 g/m^2 and the maximum biomass was 77 g/m^2. Mean (± SE) biomass across the site was 28 ± 4 g/m^2 and the median was 24 g/m^2 (Figure 3.18). Relative biomass by family is presented in Figure 3.19. Scarids were the primary contributor to biomass (26%), followed by acanthurids (17%). Other contributors included labrids (12%), and pomacentrids (8%). The mean total reef fish biomass at the Piti site in 2012 was just over half (53%) of the potential total reef fish biomass value (53 ±7 g/m^2) estimated for an unimpaired Guam reef community by Williams et al. (2015).

Species Richness

A total of 170 species was documented across the Piti site in 2012. Species richness varied from 31 species at station 14 to 84 species at station 8 (Figure 3.20). The average (± SE) number of species observed was 60 ± 3 and the median was 59. Of the species recorded, 8 species were found at all 14 of the surveyed stations and 41 were recorded at only one of the stations. The majority of species (146) were found at less than half of the stations.

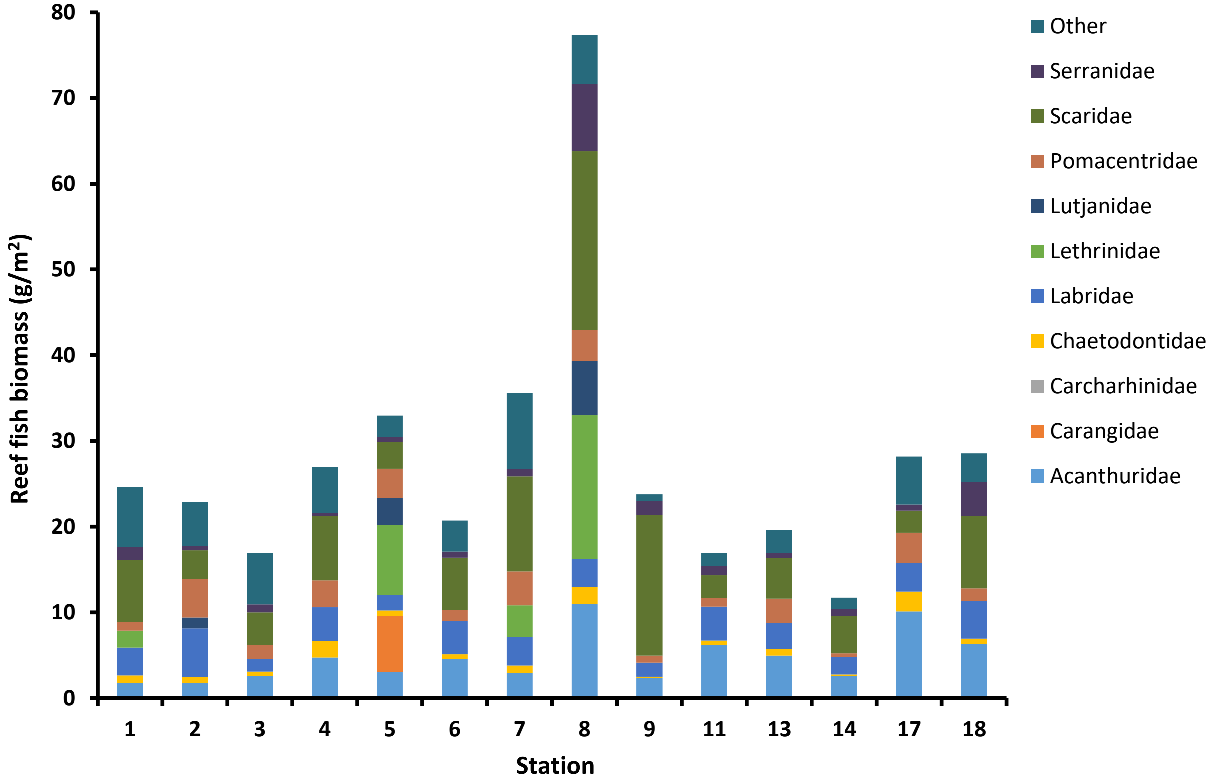


Figure 3.18. Reef fish biomass (g/m^2) by family at the Piti sampling stations in 2012.

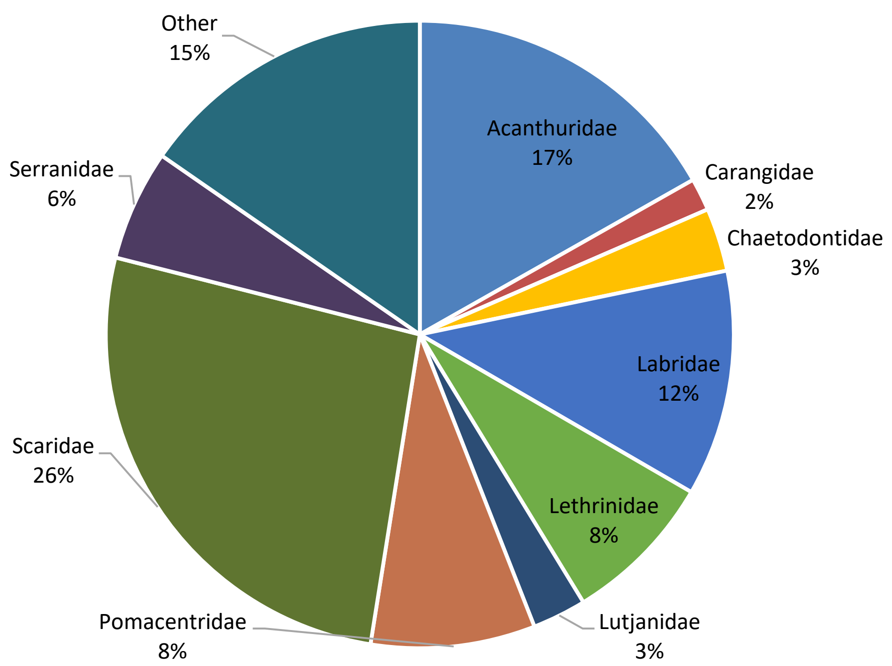


Figure 3.19. Relative abundance of reef fish by family at the Piti site in 2012.

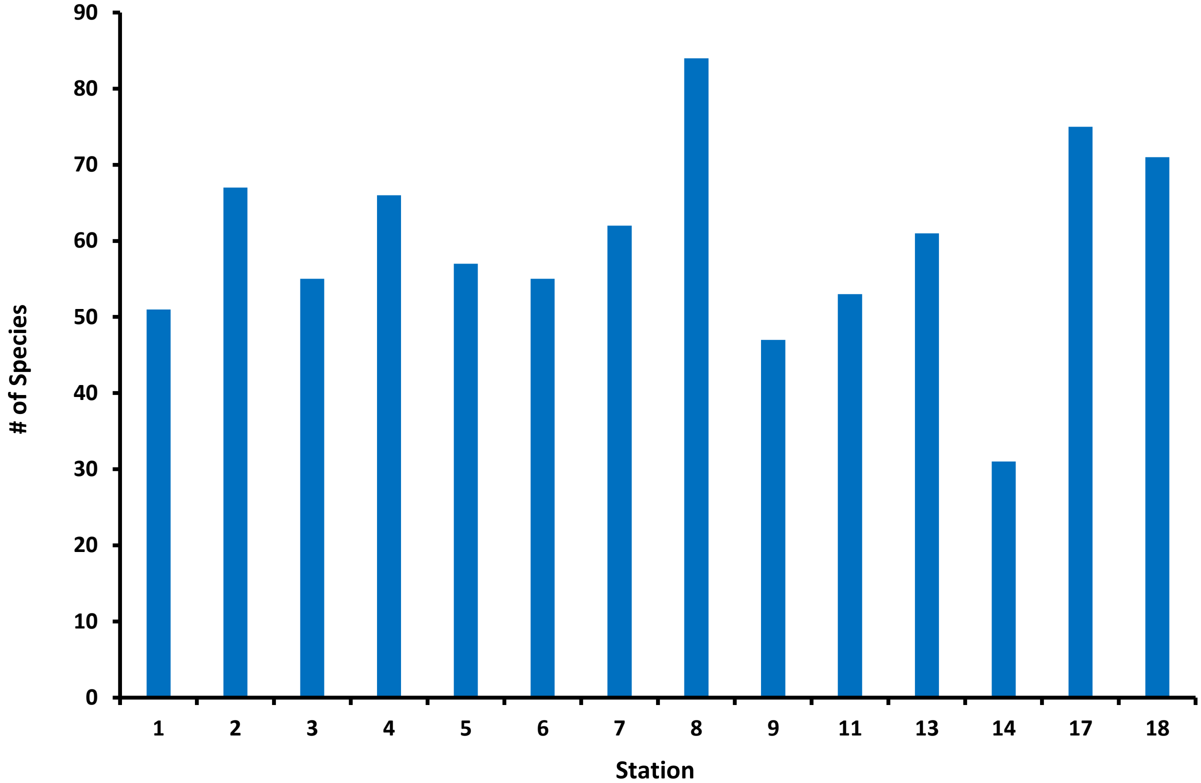


Figure 3.20. Reef fish species richness for sampling stations within the Piti monitoring site in 2012.

Macroinvertebrates

Descriptive statistics

Mean density (ind/100m^2 ± SD) for each broad macroinvertebrate taxonomic group is presented in Figure 3.21. Relative abundance of individual macroinvertebrate taxa is presented in Figure 3.22. The small, rock-boring urchin, *Echinostrephus aciculatus*, represented 67% of the total abundance, with trochus (*Tectus* spp.), the sea cucumber, *Stichopus chloronotus*, and, another rock-boring urchin, *Echinometra mathaei,* comprising a combined 16%. The "other" category was comprised of the following species: *Heteractis malu*, *Lambis* spp., *Tectus niloticus*, *Tridacna* spp., *Octopus* spp., *Actinopyga echinites*, *Actinopyga mauritiana*, *Bohadschia argus*, *Holothuria (Halodeima) atra*, *Holothuria (Microthele) whitmaei*, *Pearsonothuria graeffei*, *Thelenota ananas*, *Acanthaster planci, Culcita novaeguineae, Fromia milleporella*, *Gomophia egyptiaca, Linckia guildingi*, *Linckia laevigata, Linckia multifora*, *Echinothrix calamaris*, *Echinothrix diadema*, *Eucidaris metularia*, and *Tripneustes gratilla*. A total of 27 species was recorded in Tepungan Bay in 2012.

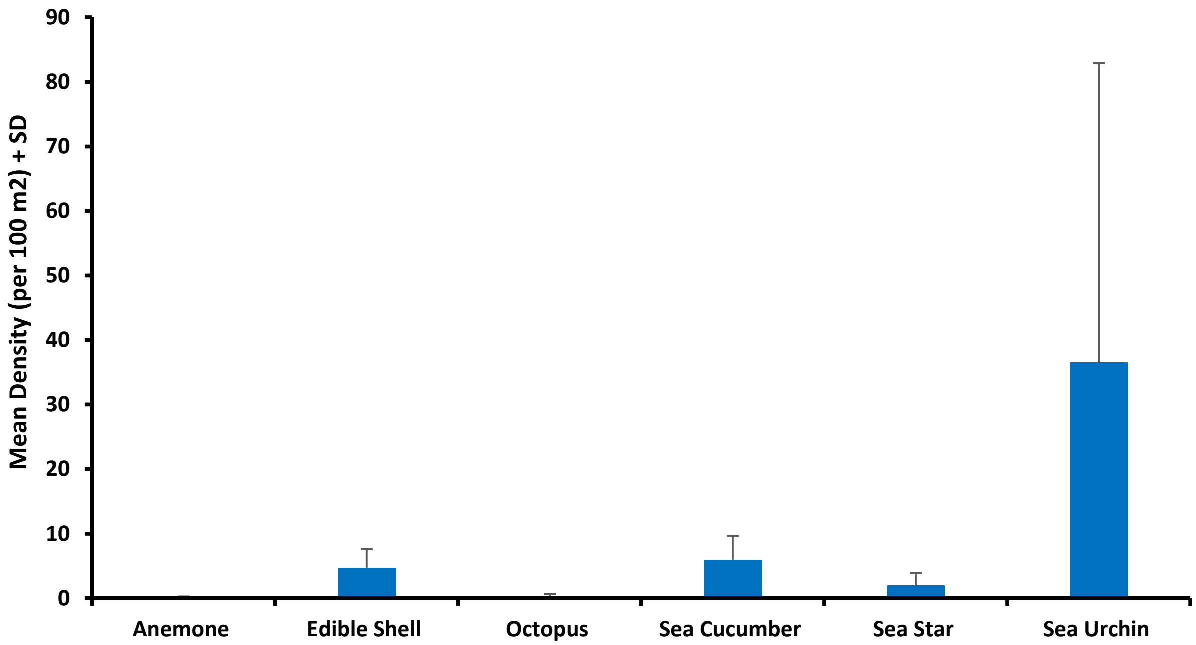


Figure 3.21. Mean density (ind/100 m^2) for broad macroinvertebrate taxonomic groups at the Piti site in 2012. Error bars represent standard deviation.

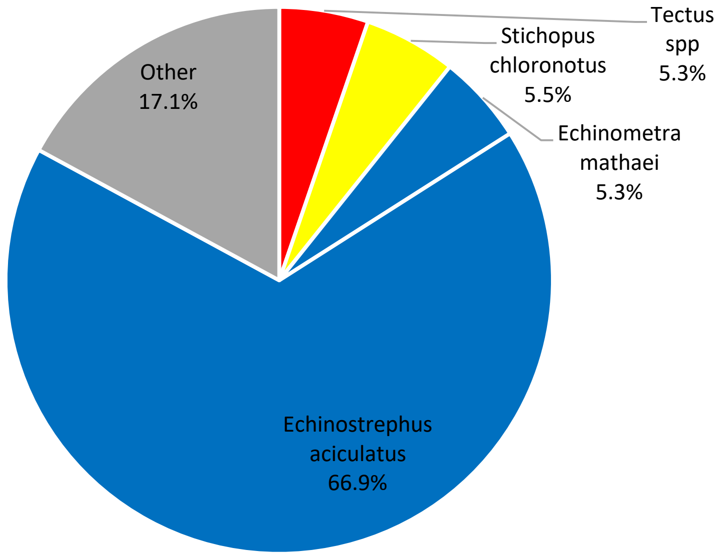
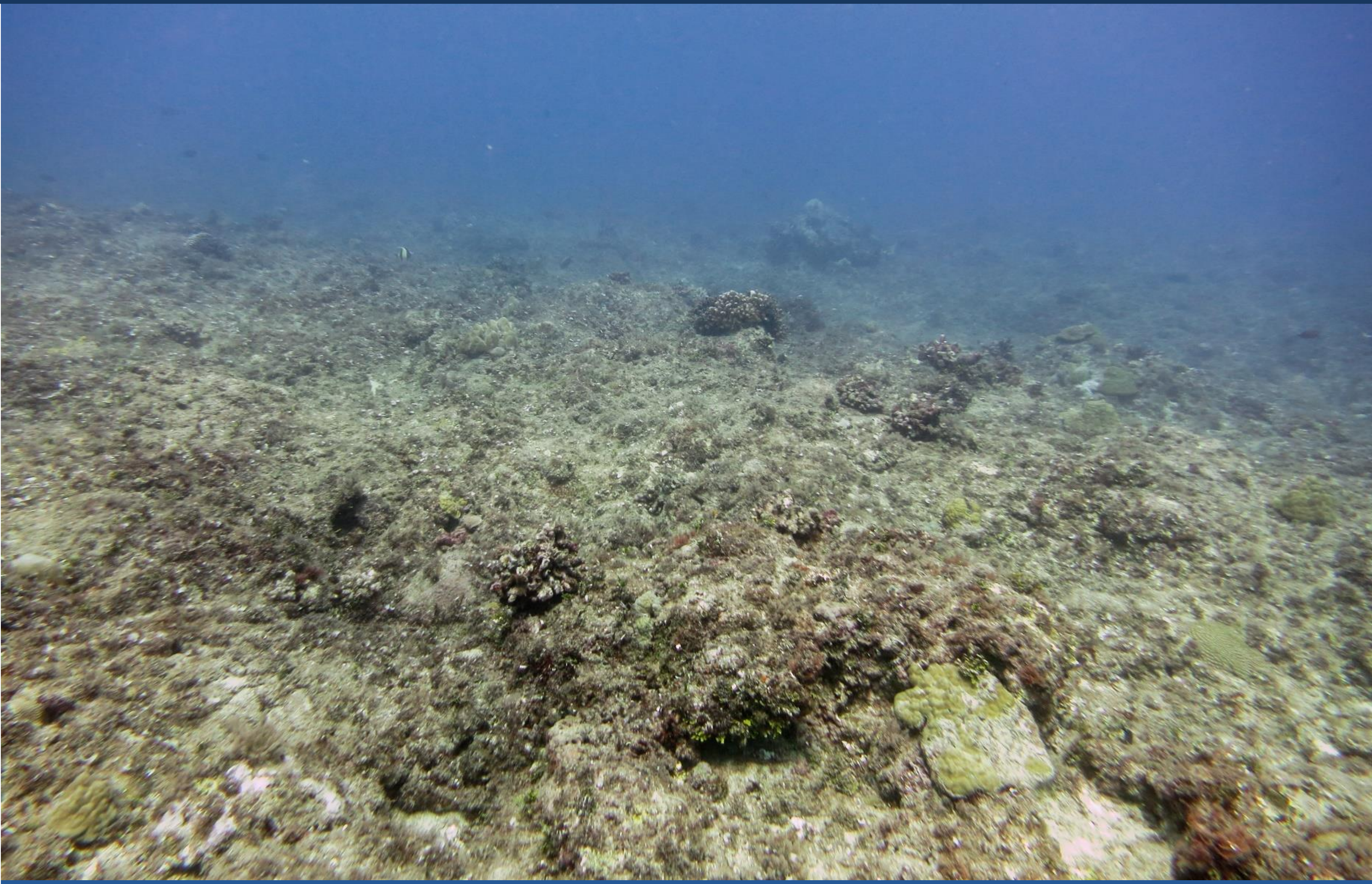


Figure 3.22. Total species relative abundance for the Piti site in 2012. Color represents broad taxonomic groupings.

Sea turtles

No sea turtles were recorded during reef fish surveys at the Piti sampling stations, although they were regularly observed from the surface during surface intervals.



3.1.3 ACHANG REEF FLAT MARINE PRESERVE

3.1.3.1 SITE OVERVIEW

The Achang Reef Flat Marine Preserve, and a potential comparison non-preserve site along the seaward slope to the southwest of Manell Channel (Cocos-East), were established in 2014 (Appendix G and Appendix H). These sites were selected primarily to serve as another potential preserve/non-preserve pair, but also because these two sites are influenced by poor water quality associated with the Manell River and smaller rivers in the Manell-Geus watershed unit. The Manell-Geus watershed unit was designated as a high priority watershed management area just prior to selection as monitoring sites. It

Photo: A reef community along the submarine terrace of the Achang Reef Flat Marine Preserve in 2014. Coral cover across the Achang monitoring site was very low and the cover of cyanobacteria and sediment-laden algae high, indicating that the benthic community at the site has been highly impacted by local stressors, such as crown-of-thorns outbreaks, poor water quality, and possible illegal fishing activity.

has since been designated as a NOAA Habitat Blueprint site, and is currently the location of several pilot watershed restoration and community outreach projects.

3.1.3.2 BENTHIC COMMUNITY

Benthic cover

Exploration of data in multivariate space

No distinct sampling station clusters could be discerned from the nMDS plot, although stations ACH-22, ACH-26, and ACH-30 did appear to be somewhat separated from the other stations. Examination of the nMDS plot did not reveal a consistent influence of depth and water quality (using the distance to the Manell Channel as a proxy for water quality) on benthic assemblages (Figure 3.23). Stations ACH-22, ACH-26, and ACH-30 do occur at the shallower end of the depth range targeted at the site, with ACH-30 occurring at the shallowest surveyed depth (8 m). In addition, coral taxa that might be expected to be more common at shallower depths on Guam's reefs, such as *Leptoria phyrygia* (LPHR) and *Montipora* spp. (MOSP), are among the members of the benthic community that met the 0.63 Pearson correlation threshold for display as eigenvectors on the nMDS plot, indicating that the greater abundances of these corals at the ACH-22, ACH-26, and ACH-30 stations are important contributors to the dissimilarity of these stations compared to other Achang sampling stations. However, the distribution within the nMDS plot of other stations with similar, relatively shallow depth values, such as ACH-6 (10 m), ACH-2 (10 m), ACH-14 (9 m) and several stations that occurred at depths of 11 m, closer to stations with greater depths, weakens the argument that sampling station depth is a strong factor in driving differences in benthic assemblages across the site.

It should be noted that the influence of water quality on benthic communities across the site is complicated by the influence of small, seasonal streams the discharge sediment-laden water through two channels located near the center of the monitoring site, in addition to the influence of the much larger Manell Channel. The possible influence of multiple sources of degraded water quality may significantly limit the effectiveness of a simple distance-to-channel proxy for water quality. A major effort to collect water quality data across the site would likely be required in order to properly evaluate the impact of the current water quality regime on benthic assemblages across the site and to detect the influence of modest improvements in water quality (e.g., improvements associated with near-term watershed restoration activities) on benthic communities within the site. Further analysis will be undertaken in order to better understand the possible drivers of spatial differences in benthic assemblages across the site.

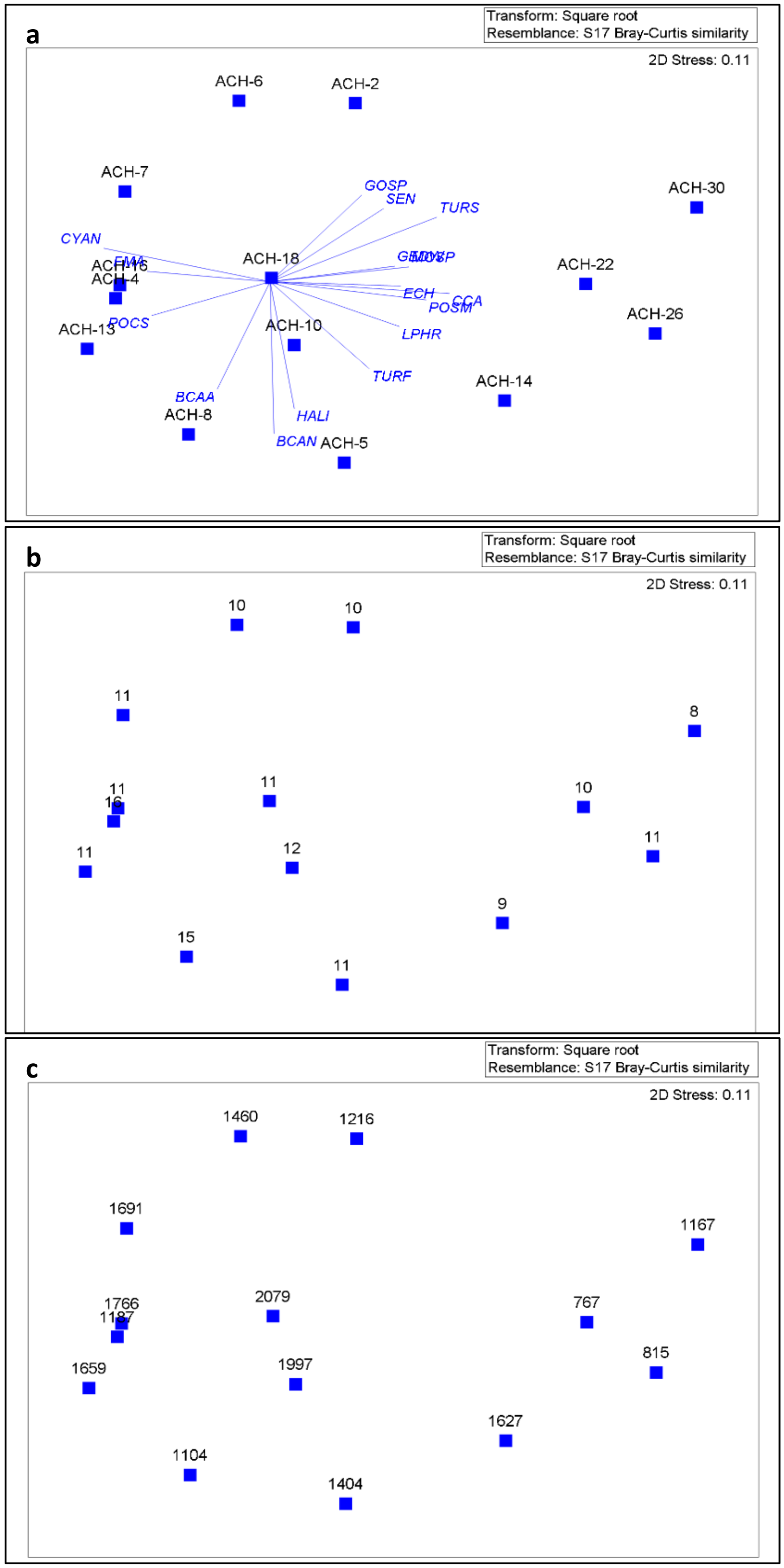


Figure 3.23. Bray-Curtis based nMDS plot of benthic communities at sampling stations in the Achang monitoring site with an eigenvectors overlay (Pearson coefficient >0.7) (**a**), the same nMDS plot with stations labeled with depth (m) values (**b**), and the distance (m) to Manell Channel (**c**).

Power analysis

A univariate power analysis (two-sided, unpaired t-test, α = 0.05) was carried out with total coral cover values for all 20 sampling stations surveyed in 2014. A separate power analysis (two-sided, paired t-test) was carried out using only permanent sampling stations in order to assess statistical power when data are only available for permanent stations. As mentioned above, it is not yet clear how to carry out a power analysis that accounts for the combination of permanent and non-permanent sampling stations; as such, the results of the power analyses presented here do not directly inform the comparisons of sampling stations from different sampling periods that include both permanent and non-permanent sampling stations. Still, the results can approximate statistical power and inform any necessary modifications to the sampling design.

Power (of a two-sided, unpaired t-test, α = 0.05, delta = 30% of mean) for mean coral cover values at all 14 sampling stations surveyed in 2014 was 0.18 (Table 3.5). The very low power is likely a result of the significant variability in coral cover across the entirety of the site as well as the very low (5 ± 4%) mean coral cover value for the site. Similar to what was discussed in the Fouha section above, the detection of a 30% change from the low mean coral cover value equates to the detection of 1.5% absolute coral cover, which is not a realistic goal given the inherent heterogeneity in benthic communities and the limited capacity that prevents a significant increase in the sampling of these communities. In order to detect a 30% change from the current mean of 5% coral cover a total of 96 sampling stations would have to be surveyed. At the current level of sampling effort, from which it would be difficult to increase given the capacity limitations as well as the limited area of reef in the targeted stratum, an 80% change in mean coral cover could be detected at a power of 0.8. While this value seems high, it equates to detecting an increase from 5% to 9% coral cover. However, a decline from such a low starting point may not be detected. An increase in statistical power can be achieved (from 0.18 to 0.42) if the permanent sampling stations ACH-22 and ACH-26, which had considerably higher coral cover (15% and 11%, respectively) than any other station within the site, are excluded. The exclusion of these stations, and the resulting decrease in variance and an increase in power, would allow the detection of a 50% change relative to the mean, or a change in absolute coral cover of 2% from the 2014 mean of 4%.

Power (of a two-sided, paired t-test, α=0.05, delta = 30% of mean) for mean coral cover values at only the 11 sampling stations surveyed in 2014 was 0.24 (Table 3.5). In order to detect a 30% change from the mean of 6% coral cover at the surveyed permanent sampling stations a total of 48 sampling stations would have to be surveyed. At the current level of sampling effort a 68% change in mean coral cover, or a change of 4% in absolute coral cover, could be detected at a power of 0.8. The elimination of stations ACH-22 and ACH-26 results in an increase in statistical power (from 0.24 to 0.39) and would allow the detection of a 50% change relative to the mean, or a change in absolute coral cover of 2% from the 2014 mean of 4%.

Table 3.5. Results of a t-test power analysis of mean percent coral cover values for Achang sampling stations surveyed in 2014.

	Mean ± SD%	N	Delta (30% of mean)	Power	N required for power = 0.8	Delta at power = 0.8, current sampling effort
All stations	5.1 ± 3.7%	14	1.5%	0.18	96	4.1%
All stations, excl. ACH-22 and ACH-26	3.8 ± 1.6	12	1.2	0.42	29	1.9
Permanent stations only						
All stations	5.6 ± 4.1	11	1.7	0.24	48	3.8
All stations, excl. ACH-22 and ACH-26	4 ± 1.9	9	1.2	0.39	22	2

Descriptive statistics

Mean percent cover (± SD) values of major benthic cover categories for the Achang sampling stations surveyed in 2014 are presented in Figure 3.24. Mean coral cover was very low (5 ± 4%) across the site, as was the cover of crustose coralline algae (5 ± 4%) and branching coralline algae (3 ± 2%), while the cover of cyanobacteria was very high (49 ± 13%).

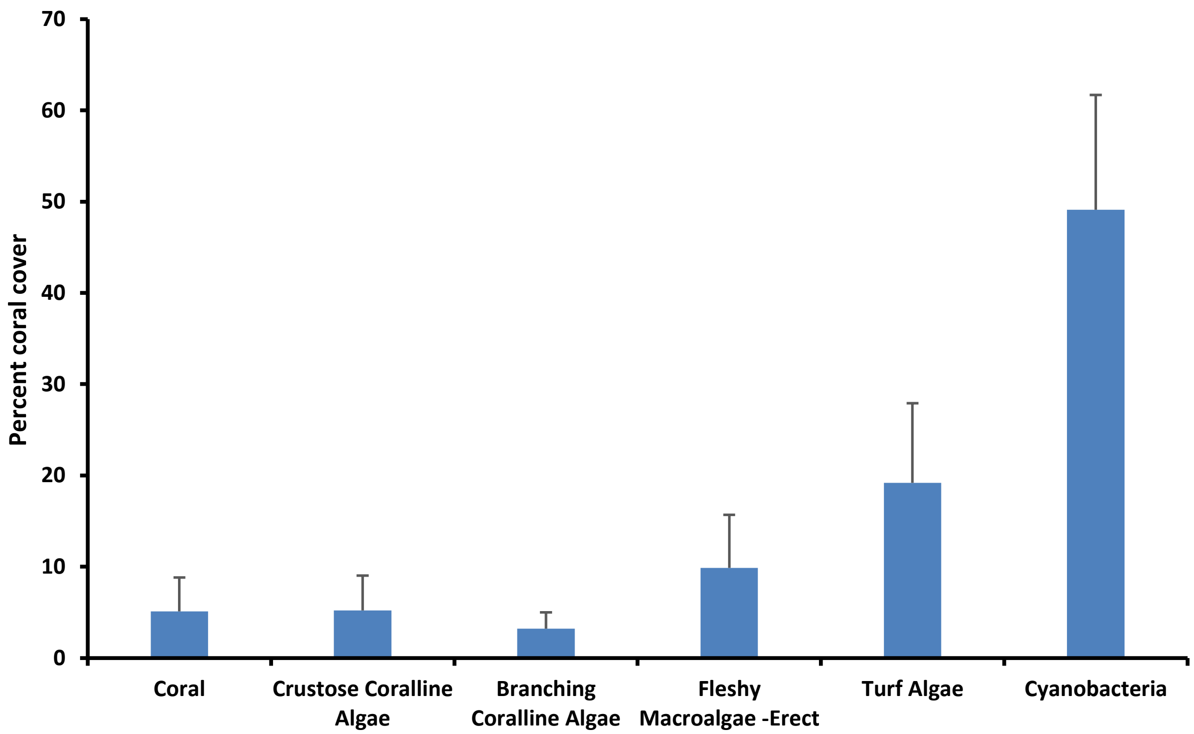


Figure 3.24. Percent cover of major benthic cover categories for the sampling stations surveyed in the Achang monitoring site in 2014.

About half of the total coral cover at the Achang stations was comprised by the more stress-tolerant coral genera, *Porites*. *Leptastrea*, *Astreopora*, and *Pocillopora* together comprised about a quarter of total coral cover, and other genera comprising another quarter of total coral cover. The extremely low total cover across the site, however, necessitates caution in the interpretation of the relative cover of coral taxa, as differences between them may not be statistically significant.

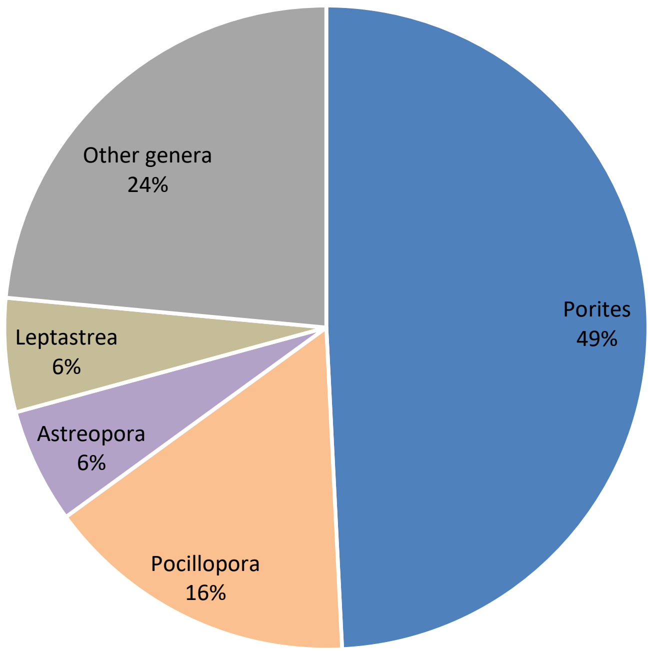


Figure 3.25. Percent contribution of individual coral genera to mean total coral cover for the sampling stations surveyed in the Achang monitoring site in 2014. Only coral genera comprising ≥5% of total coral cover are presented in the figure individually; all other coral genera are grouped under the “Other genera” category.

3.1.3.3 ASSOCIATED BIOLOGICAL COMMUNITIES

Reef fishes

Descriptive statistics

Density

Reef fish density at the Achang site in 2014 ranged from 55 fish/100m^2 at station 16 to 107 fish/100m^2 at station 7 (Figure 3.26). Mean (± SE) fish density was 73 ± 5 fish/100 m^2 and the median was 66 fish/100 m^2. Relative density by family is presented in Figure 3.27. The acanthurids (28%) and pomacentrids (28%) were major contributors to density, accounting for approximately 56% of fish counted, followed by labrids (22%) and cirrhitids (6%).

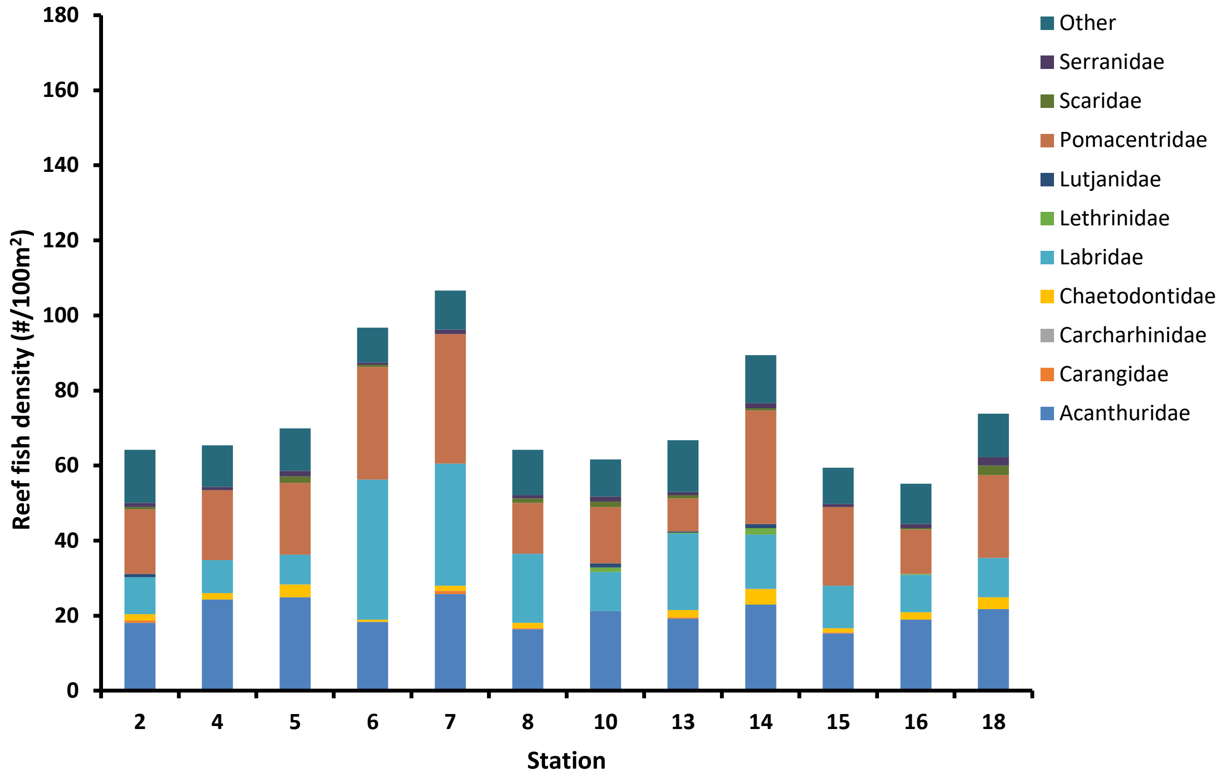


Figure 3.26. Reef fish density (# of fish/100m^2) by family at the Achang sampling stations in 2014.

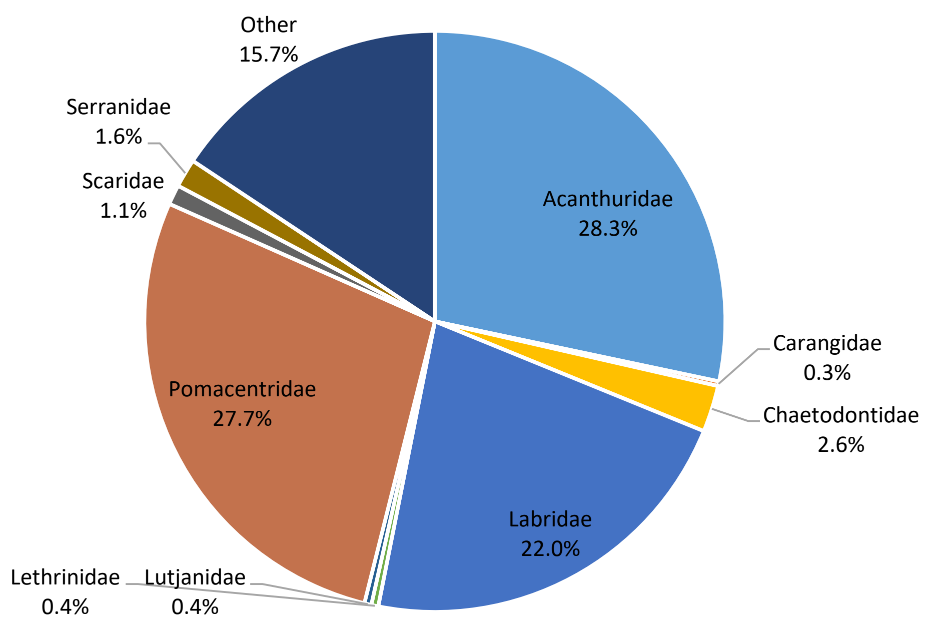


Figure 3.27. Relative density of reef fish by family at the Achang site in 2014.

Biomass

The minimum total reef fish biomass recorded at the Achang stations in 2014 was 5 g/m^2 and the maximum biomass was 49 g/m^2. Mean (± SE) fish biomass across the site was 18 ± 4 g/m^2 and the median was 14 g/m^2 (Figure 3.28). Relative biomass by family is presented in Figure 3.29. Scarids (18%), acanthurids (17%), and lutjanids (17%) were the primary contributors to biomass, followed by labrids (10%). The mean total reef fish biomass at the Achang site in 2014 was only about a third (34%) of the potential total reef fish biomass value (53 ±7 g/m^2) estimated for an unimpaired Guam reef community by Williams et al. (2015).

Species Richness

A total of 157 species was documented across the Achang site in 2014. Species richness varied from 35 species at station 15 to 70 species at station 14 (Figure 3.30). The average (± SE) number of species observed was 53 ± 3 and the median was also 53. Of the species recorded, 12 species were found at all twelve stations and 50 were recorded at only one of the stations. The majority of species (122) were found at less than half of the stations.

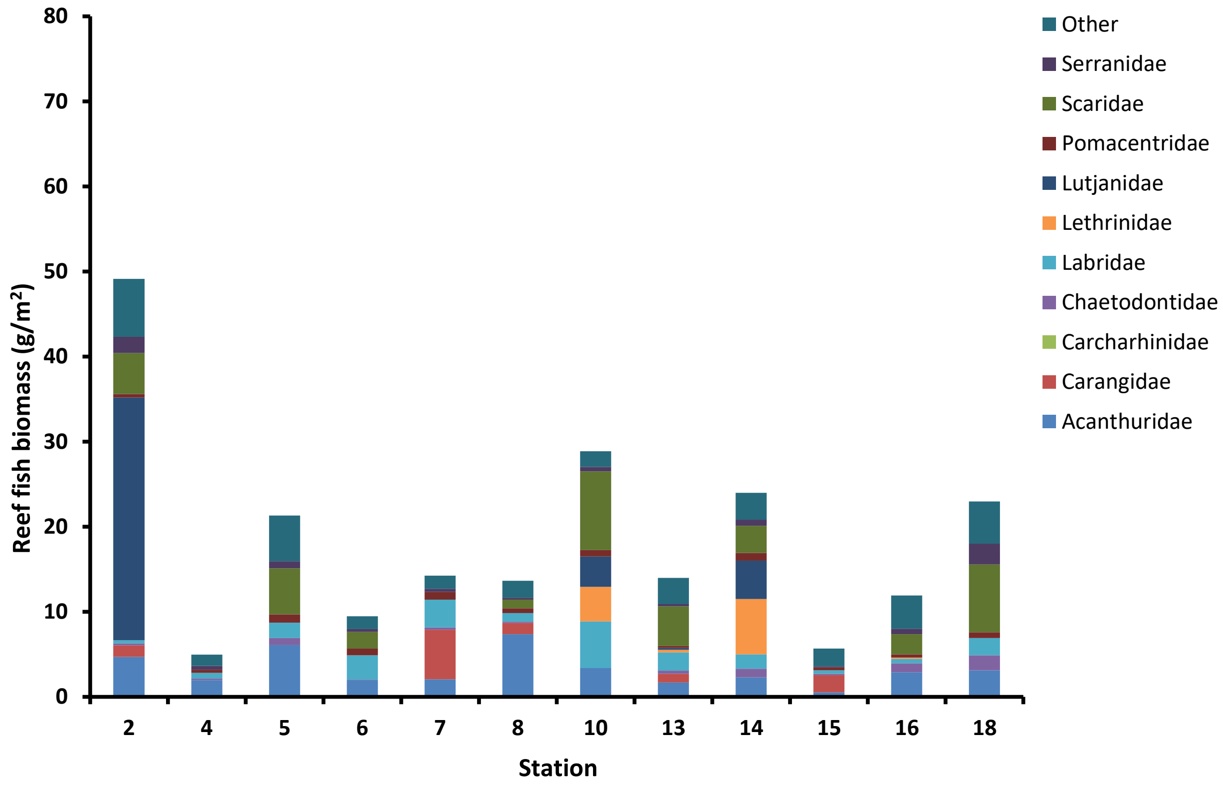


Figure 3.28. Reef fish biomass (g/m^2) by family at the Achang sampling stations in 2014.

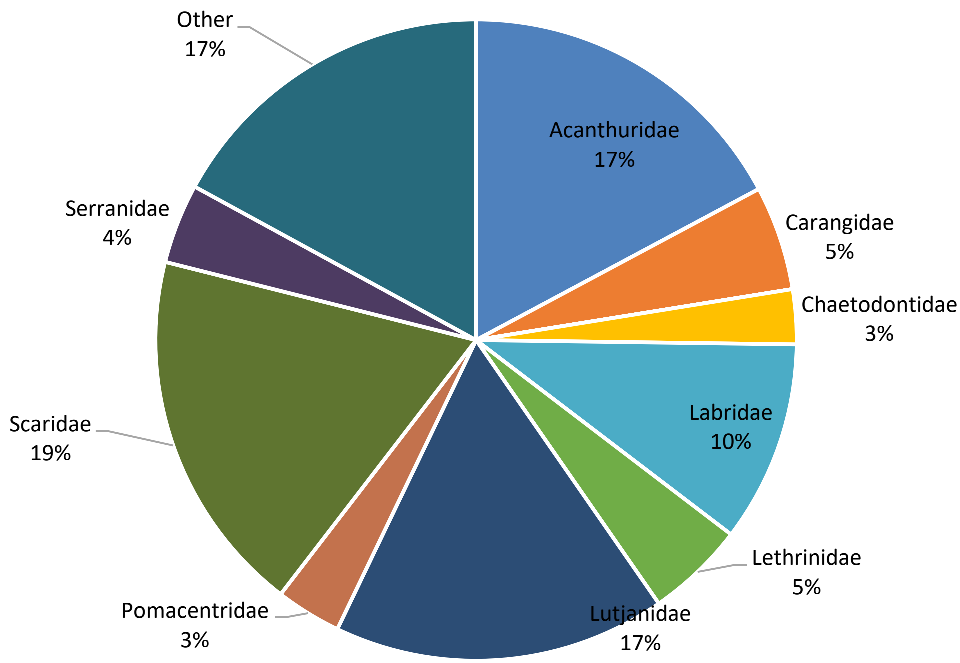


Figure 3.29. Relative abundance of reef fish by family at the Achang site in 2014.

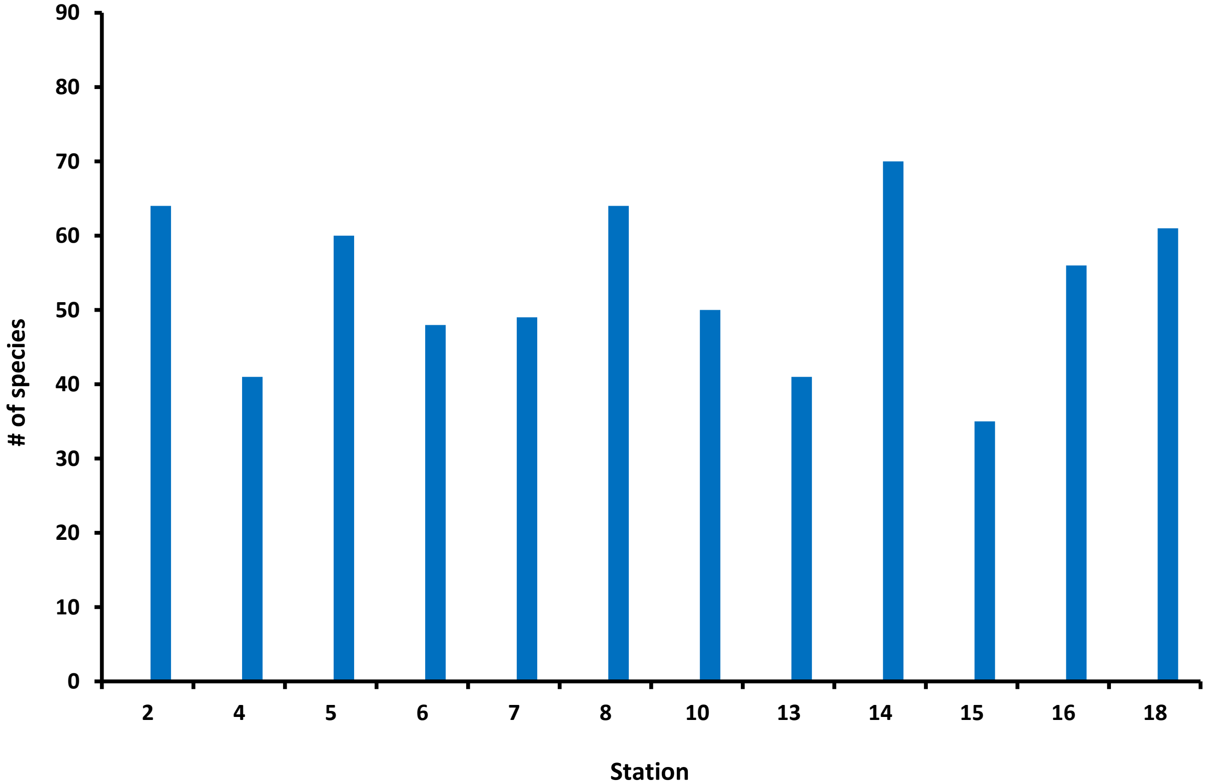


Figure 3.30. Reef fish species richness for sampling stations within the Achang monitoring site in 2014.

Macroinvertebrates

Descriptive statistics

Mean density (ind/100m^2 ± SD) for each broad macroinvertebrate taxonomic group is presented in Figure 3.31 and relative abundance for individual taxa is presented in Figure 3.32. The small rock-boring urchin, *Echinostrephus aciculatus,* accounted for 93% of the total number of macroinvertebrates observed at the Achang site in 2014. The "other" category was comprised of the following species: *Lambis* spp., *Tectus niolticus*, *Tridacna* spp., *Octopus* spp., *Holothuria (Halodeima) edulis*, *Holothuria (Microthele) whitmaei*, *Stichopus chloronotus*, *Linckia multifora*, *Echinometra mathaei*, and *Echinothrix diadema*. A total of 11 species was recorded at the Achang site in 2014.

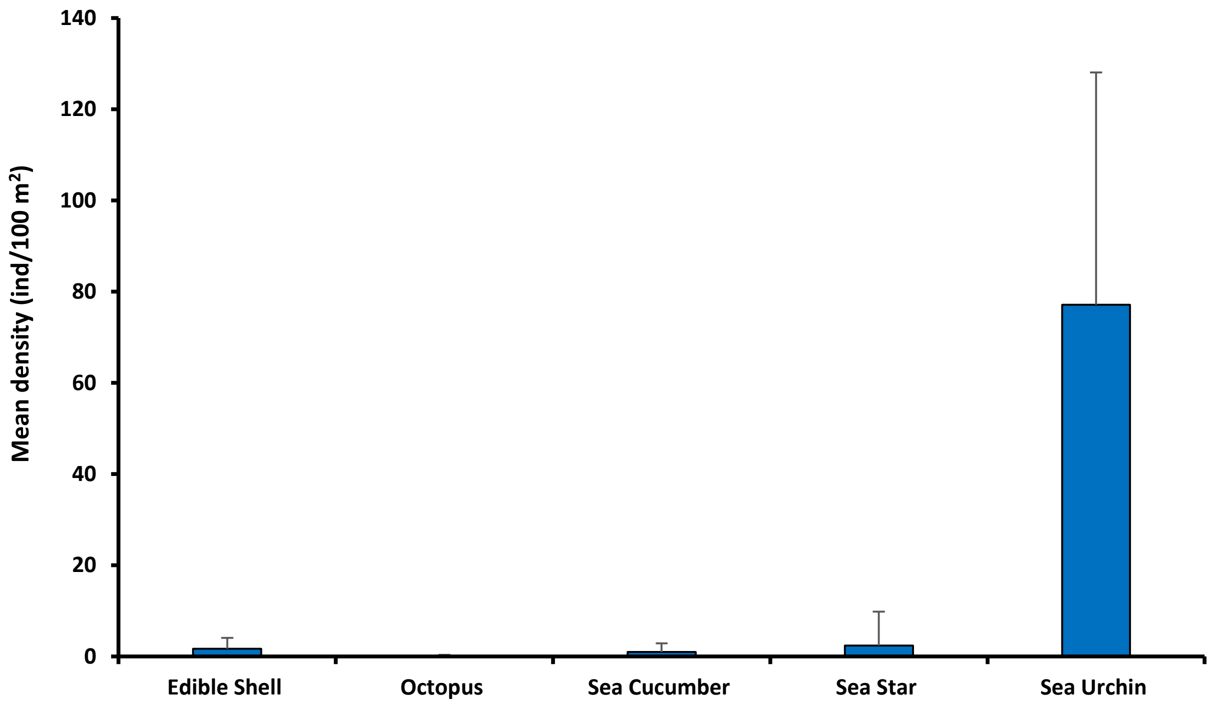


Figure 3.31. Mean density (ind/100 m^2) for broad macroinvertebrate taxonomic groups within the Achang site in 2014. Error bars represent standard deviation.

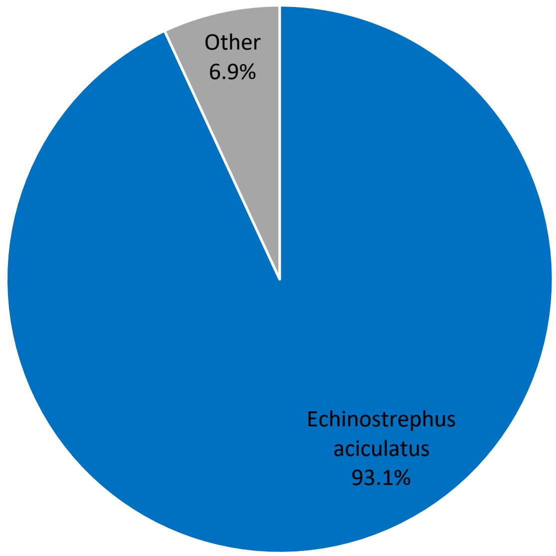


Figure 3.32. Total relative abundance for individual macroinvertebrate taxa within the Achang site in 2014. Color represents broad taxonomic groupings.

Sea turtles

One green sea turtle (*Chelonia mydas*) was observed during reef fish surveys at the Achang sampling stations; sea turtles were also frequently observed from the surface during surface intervals.

3.1.4 TUMON BAY MARINE PRESERVE

3.1.4.1 SITE OVERVIEW

Tumon Bay hosts the Tumon Bay Marine Preserve and is a hub for tourism, recreational, and cultural activities on Guam. While the numerous potential impacts to the bay's reef ecosystem, such as from coastal development and recreational and commercial use, make discerning individual impacts difficult, the intensive, comprehensive monitoring of a carefully selected reef stratum will increase the likelihood that even relatively small changes in key ecosystem health parameters can be detected, and that reasonable indications of probable causes can be provided. Tumon Bay was selected as the first high priority reef area targeted for long-term monitoring, with partial monitoring within the bay having occurred in June 2009 and a full data collection having occurred in 2010 (Appendix B). The boundaries of

Photo: A school of bigeye jacks, *Caranx sexfasciatus*, in the Tumon Bay Marine Preserve monitoring site in 2010.

the monitoring site were shifted northwestward after analysis of data collected in 2010 showed that the original boundaries included two distinct benthic communities and that the large variance in the data limited the ability to detect change in these communities[2]. Data collection occurred within the new site boundaries in 2012, 2014, 2015, 2017, and 2018, although the re-prioritization of resources required to respond to the multiple bleaching events between 2013 and 2017 prevented the collection of all datasets at all permanent and non-permanent sampling stations for each of these visits (Appendix C). A time series analysis of benthic cover and macroinvertebrate data collected within the new Tumon site boundaries between 2012 and 2018 is presented in Section 3.2.1. Baseline fish survey data for the modified Tumon Bay site were not collected until 2015, as surveys could not be completed at the newly modified Tumon Bay site in 2012 or 2014 because of poor weather conditions and staffing limitations. The results of an initial analysis of the 2015 data are presented below, but note that these data were collected three years after the benthic cover and macroinvertebrate data presented in this section.

3.1.4.2 BENTHIC COMMUNITY

Benthic cover

Exploration of data in multivariate space

A loose cluster comprised of the four northernmost sampling stations in the new Tumon Bay site boundaries (TUM-60, TUM-48, TUM-46, and TUM-63) can be discerned in the nMDS plot (Figures 3.33 and 3.34 . The results of a One-way ANOVA Analysis of Similarities, which should be interpreted cautiously given the small sample size of the northern sampling stations, indicate that the difference between the benthic communities in the north and south of the modified Tumon Bay site was statistically significant ($R = 0.62$, $p = 0.003$). The eigenvectors overlay (Pearson correlation > 0.6) and a Similarity of Percentages (SIMPER) analysis indicate that the greater cover of sediment-laden turf algae, cyanobacteria, and massive *Porites* spp. at these northern stations, and the greater cover of *Porites rus*, “clean” turf algae, and cyanobacteria at the stations to the south are important contributors to the dissimilarity of the northern and southern station groupings (Figure 3.33, Table 3.6). The more northwest-ward location of these four stations places them closer to a channel that bisects the reef margin and which delivers warm, more turbid water rich with organic matter and nutrients from the reef flat to the seaward slope. However, these northwestern-most stations are also associated with the lowest wave exposure values (using an east-to-west measurement as a proxy) among the Tumon sampling stations, which was a factor that was strongly associated with the two distinct benthic communities detected within the original site boundaries using data collected in 2010. However, confounding the effort to discern the factors that might be contributing to differences in the northern and southern stations is the fact that the two stations that occur most distant from other stations in the nMDS plot, and which are members of the “North” grouping, are also the two deepest stations.

[2] The results of this analysis were presented in the report, Comprehensive long-term monitoring at permanent sites in Guam: Report of program status and presentation of preliminary baseline data and power analyses results for Tumon Bay, East Agana Bay, and Western Shoals sites. The report is available on the NOAA CoRIS website at https://data.nodc.noaa.gov/coris/library/NOAA/CRCP/other/grants/MonitoringGrants_FY10_Products/NA10NOS4260046_GuamLTMP_ProgressReport_3-8-12.pdf

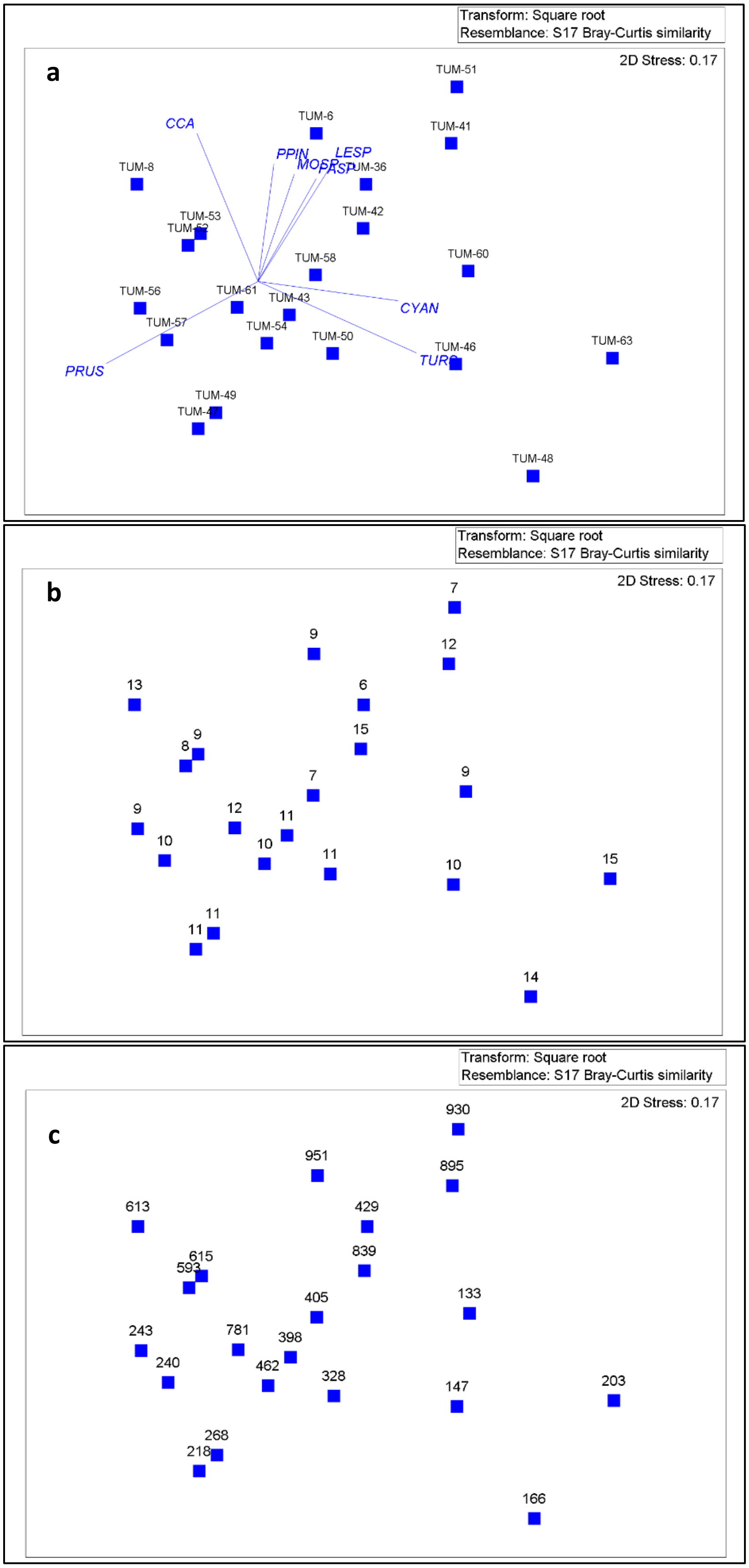


Figure 3.33. Bray-Curtis based nMDS plot of benthic communities at sampling stations in the modified Tumon Bay site with an eigenvectors overlay (Pearson coefficient >0.7) (**a**), the same nMDS plot with stations labeled with depth (m) values (**b**), and distance perpendicular to the easternmost point of the site (as a proxy for wave exposure)(**c**).

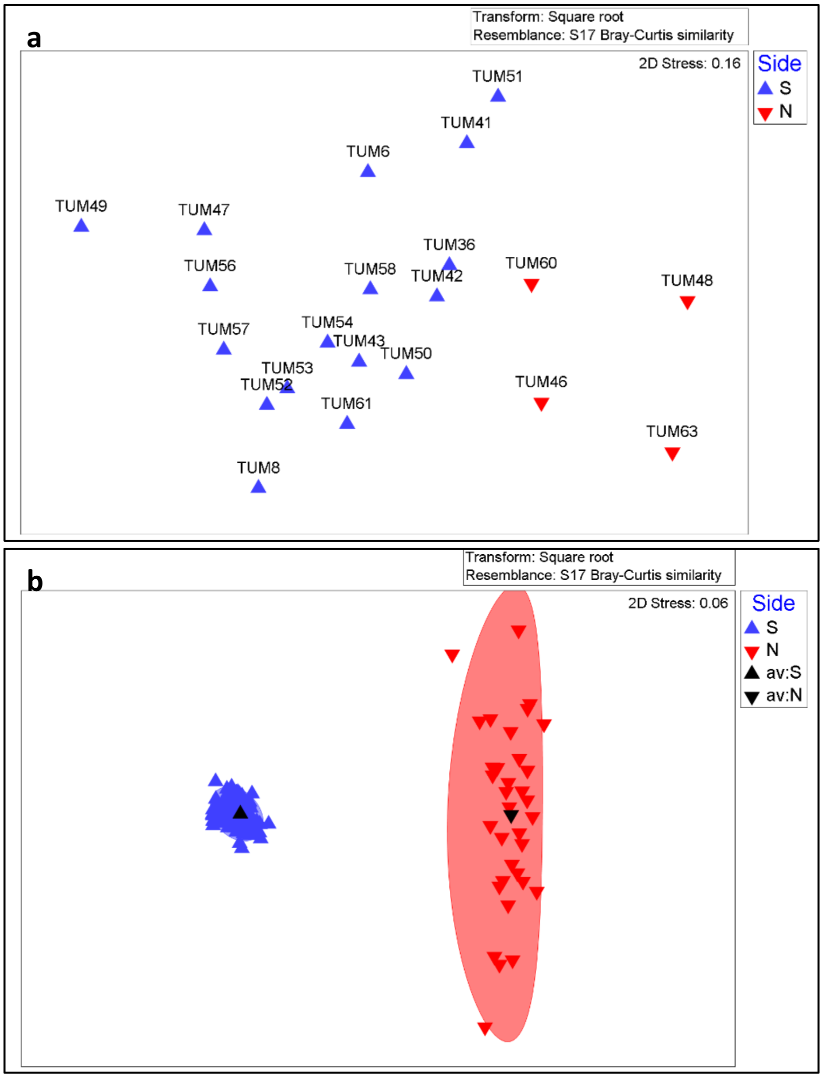


Figure 3.34. Bray-Curtis based nMDS plot of benthic communities at sampling stations in the modified Tumon Bay monitoring site with different symbols for the North and South sampling station groupings (**a**), and nMDS bootstrap averages (95% confidence interval) for the North and South sampling station groupings (**b**). The results of an ANOSIM indicated that the North and South station groups were more dissimilar than expected by chance (R = 0.62, p = 0.003).

Depth, like exposure, was identified as an important factor influencing benthic community structure in the 2010 dataset, and was used to eliminate several of the original sampling stations that occurred at the deepest and shallowest ends of the depth range and which hosted distinct benthic communities. Further analysis is required to better understand the drivers behind the apparent difference in the northern and southern sampling stations, and if these northern stations should be abandoned for more stations located in the southern three-fourths of the site.

Table 3.6. Results of a Similarity Percentages (SIMPER) analysis of the benthic communities at sampling stations occurring in the northern (Group N) and southern (Group S) portions of the modified Tumon Bay monitoring site. Values are square root-transformed percent cover values from data collected in 2012.

Groups S & N

Average dissimilarity = 33.41

Species	Group S Av.Abund	Group N Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Turf -with Sediment	2.2	4.7	4	2.57	11.97	11.97
Porites rus	4.58	2.95	3.05	1.65	9.12	21.08
Crustose Coralline Algae	4.14	2.45	2.68	2.13	8.04	29.12
Cyanobacteria	2.91	4.31	2.46	1.5	7.38	36.5
Turf -Clean	4.95	3.87	2.41	2.24	7.22	43.72
Porites deformis	0.51	0.98	1.57	1.29	4.69	48.41
Porites sp.-massive	2.51	2.94	1.28	1.26	3.83	52.24

Power analysis

Univariate power analyses (two-sided, unpaired t-test, α = 0.05) were carried out separately with total coral cover values for all 21 sampling stations (All), the four northernmost stations (North), and the 17 southernmost stations (South). A separate power analysis (two-sided, paired t-test) was carried out using only permanent sampling stations in order to assess statistical power when data are only available for permanent stations. As mentioned above, it is not yet clear how to carry out a power analysis that accounts for the combination of permanent and non-permanent sampling stations; as such, the results of the power analyses presented here do not directly inform the comparisons of sampling stations from different sampling periods that include both permanent and non-permanent sampling stations. Still, the results can approximate statistical power and inform any necessary modifications to the sampling design.

Power (of a two-sided, unpaired t-test, α=0.05, delta = 30% of mean) for mean coral cover values was 0.78, 0.25, and 0.72 for All, North, and South sampling stations, respectively (Table 3.7). While still below the target power of 0.8, power values of 0.78 and 0.72 for All and South sampling stations were relatively high. The low power for the North sampling stations is a result of the limited number of samples and the significant variability in coral cover across the four stations. The power analysis results indicate that the 12 permanent and 10 non-permanent sampling stations currently targeted across the site are sufficient to detect a change of 30% of the mean at a power of 0.8 (= a change of 10% absolute coral cover). However, if the northern and southern portions of the site are to be surveyed separately an estimated that 15 stations would need to be surveyed in the northern portion and 20 in the southern portion in order to detect a change in coral cover of 30% from the mean at a power of 0.8.

Power (of a two-sided, paired t-test, α=0.05, delta = 30% of mean) for mean coral cover was 0.81, 0.17, and 0.69 for All, North, and South permanent sampling stations, respectively (Table 3.7). As above, power was relatively high for All and South permanent sampling stations, with power for All stations exceeding the target power of 0.8. Also as above, the low statistical power for the North stations is a result of the limited number of stations and the significant variability in coral cover across those three permanent stations. An increase in statistical power (to 0.9) can be achieved for the entire site and for the South stations (to 0.89) if station TUM-6, which had significantly lower coral cover (12%) than the other stations, is eliminated. The power analysis results indicate that the twelve permanent sampling stations currently targeted across the site are sufficient to detect a change of 30% of the mean at a power of 0.8 (= a change of 9% absolute coral cover). However, if the northern and southern portions of the site are to be surveyed separately an estimated that 17 permanent stations would need to be surveyed in the northern portion and 7 in the southern portion in order to detect a change in coral cover of 30% from mean at a power of 0.8. The elimination of station TUM-6 would allow the detection of a 26% change relative to the mean, or a change in absolute coral cover of 8%. The modest increase in statistical power achieved with the elimination of station TUM-6, for which data is also available from 2010, likely does not justify abandoning the station for future sampling efforts. The high level of statistical power to detect a 30% change in coral cover relative to the mean that was achieved using only the 12 permanent sampling stations suggests that it is not necessary to survey the additional 10 non-permanent stations. However, power analyses for other important major benthic classes may yield different results. The additional data provided by the non-permanent stations may also provide enough statistical power for more detailed benthic classes, such as coral functional groups (e.g., massive, branching, encrusting), other coral groupings (e.g., massive *Porites* spp.), or individual, but relatively abundant, taxa (*Halimeda* spp., *Porites rus*, *Terpios hoshinota*).

Table 3.7. Results of a t-test power analysis of mean percent coral cover values for the modified Tumon Bay sampling stations surveyed in 2012.

	Mean ± SD%	N	Delta (30% of mean)	Power	N required for power = 0.8	Delta at power = 0.8, current sampling effort
All stations	30.8 ± 10.8%	21	9.3%	0.78	22	9.6%
All stations, excl.TUM-8	31.8 ± 10.2	20	9.5	0.82	19	9.3
North stations	23.1 ± 6.4	4	6.9	0.25	15	15.2
South stations	32.7 ± 10.9	17	9.8	0.72	20	10.8
South stations, excl. TUM-8	33.9 ± 9.9	16	10.2	0.81	16	10.1
<u>Permanent stations only</u>						
All stations	29.7 ± 9.9	12	8.9	0.81	12	8.8
All stations, excl. TUM-8	31.2 ± 8.7	11	9.4	0.9	90	8.2
North stations	23.9 ± 7.6	3	9.5	0.17	17	25
South stations	31.6 ± 10.2	9	9.5	0.69	11	10.9
South stations, excl. TUM-8	34 ± 7.7	8	10.2	0.89	7	8.9

Descriptive statistics

Mean percent cover (± SD) values of major benthic cover categories for sampling stations in the northern and southern portions of the modified Tumon Bay site, as well as for all sampling stations across the site, are presented in Figure 3.35. Coral cover was moderate across the site (31 ± 11%), as was the cover of turf algae (32 ± 8%), which was primarily comprised of micro-turfing algae. The cover of erect macroalgae was very low (1 ± 1%). The difference between mean coral cover at the sampling stations in the northern and southern portion of the bay was not statistically significant (Wilcoxon signed rank test, $p = 0.14$). The cover of crustose coralline algae was lower (t-test, $p < 0.001$) and the cover of cyanobacteria higher (t-test, $p < 0.01$) at the northern stations; there were no significant differences in the cover of branching coralline algae, erect fleshy macroalgae or algae between the northern and southern stations.

The stress-tolerant genus *Porites* comprised nearly all of the total coral cover for the modified Tumon Bay site in 2012 (Figure 3.36). The proportion of total coral cover comprised by *Porites* at the north and south sampling stations was approximately the same.

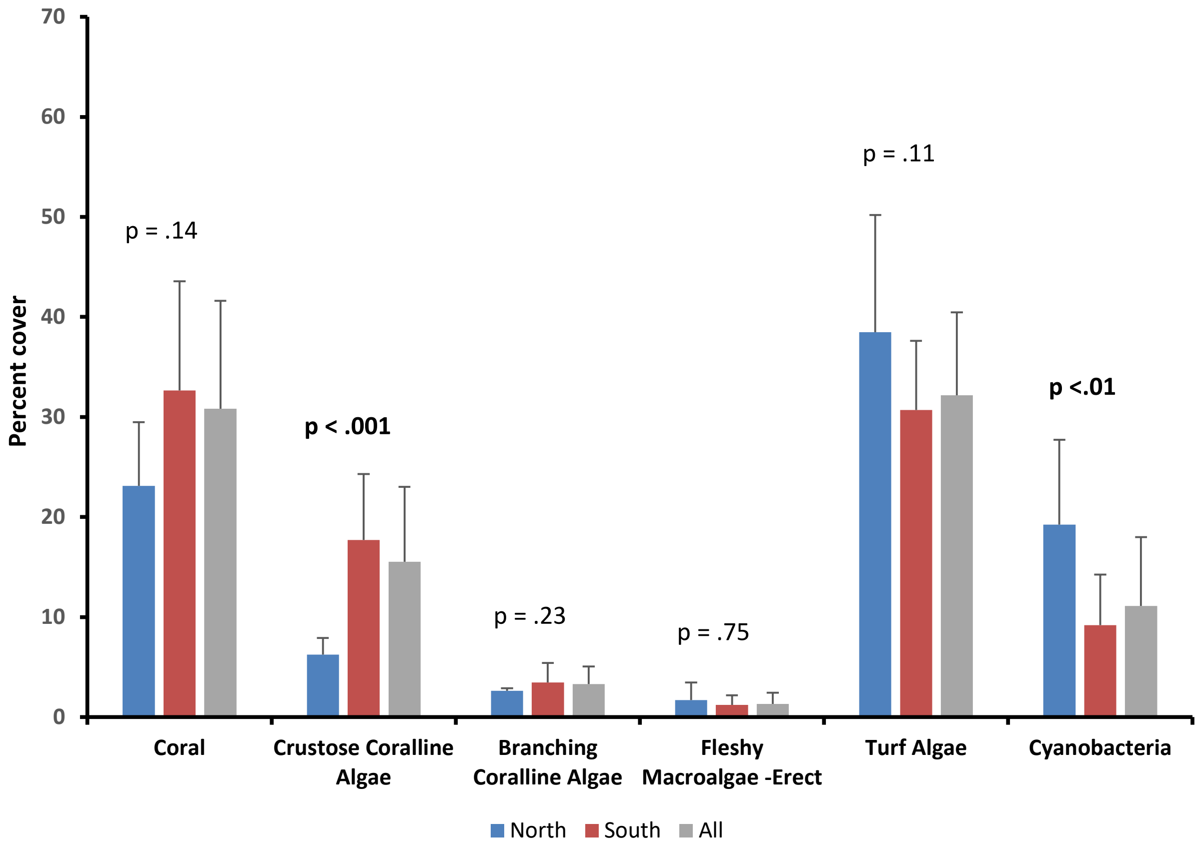


Figure 3.35. Percent cover of major benthic cover categories for sampling stations in the north and south groupings, as well as all sampling stations, surveyed in the modified Tumon Bay monitoring site in 2012. P values (two sided t-test or Wilcoxon rank sum test) are provided for comparisons of between square root-transformed mean cover values for North and South sampling station groupings. Error bars represent standard deviation.

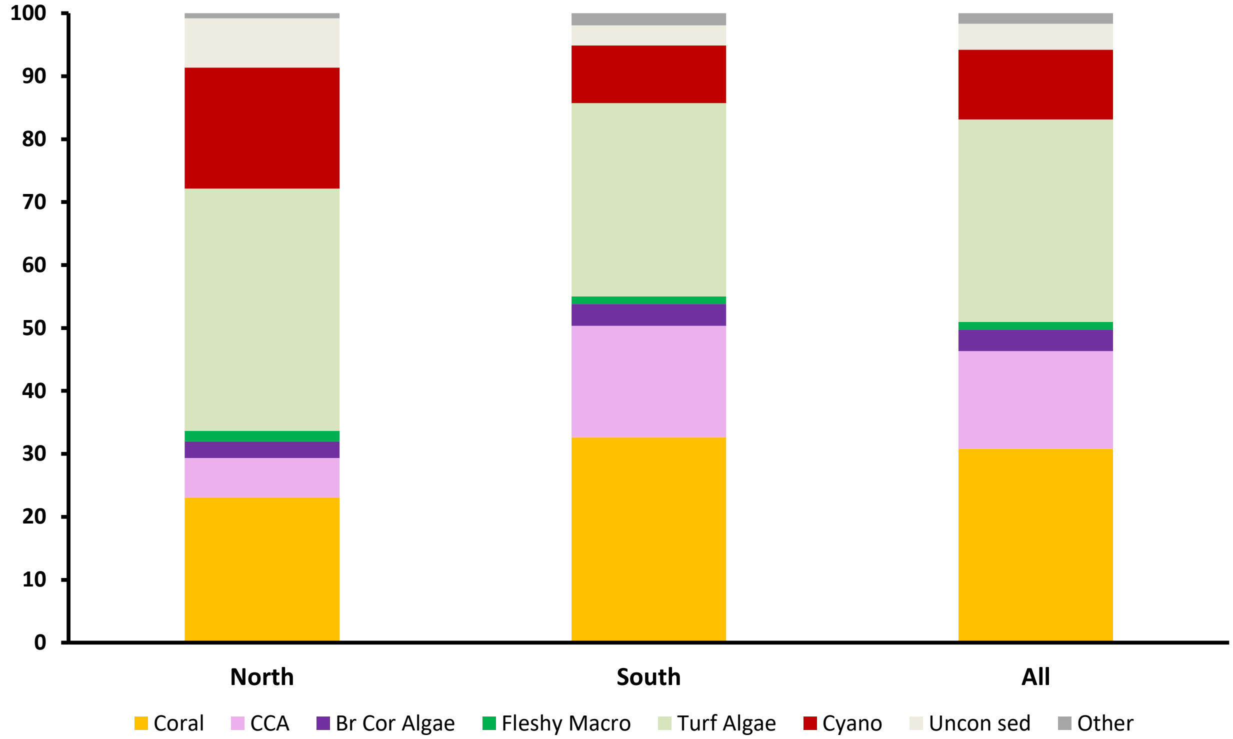


Figure 3.36. Cumulative percent cover of major benthic cover categories for the north and south sampling station groupings, as well as for all sampling stations, surveyed in the modified Tumon Bay monitoring site in 2012.

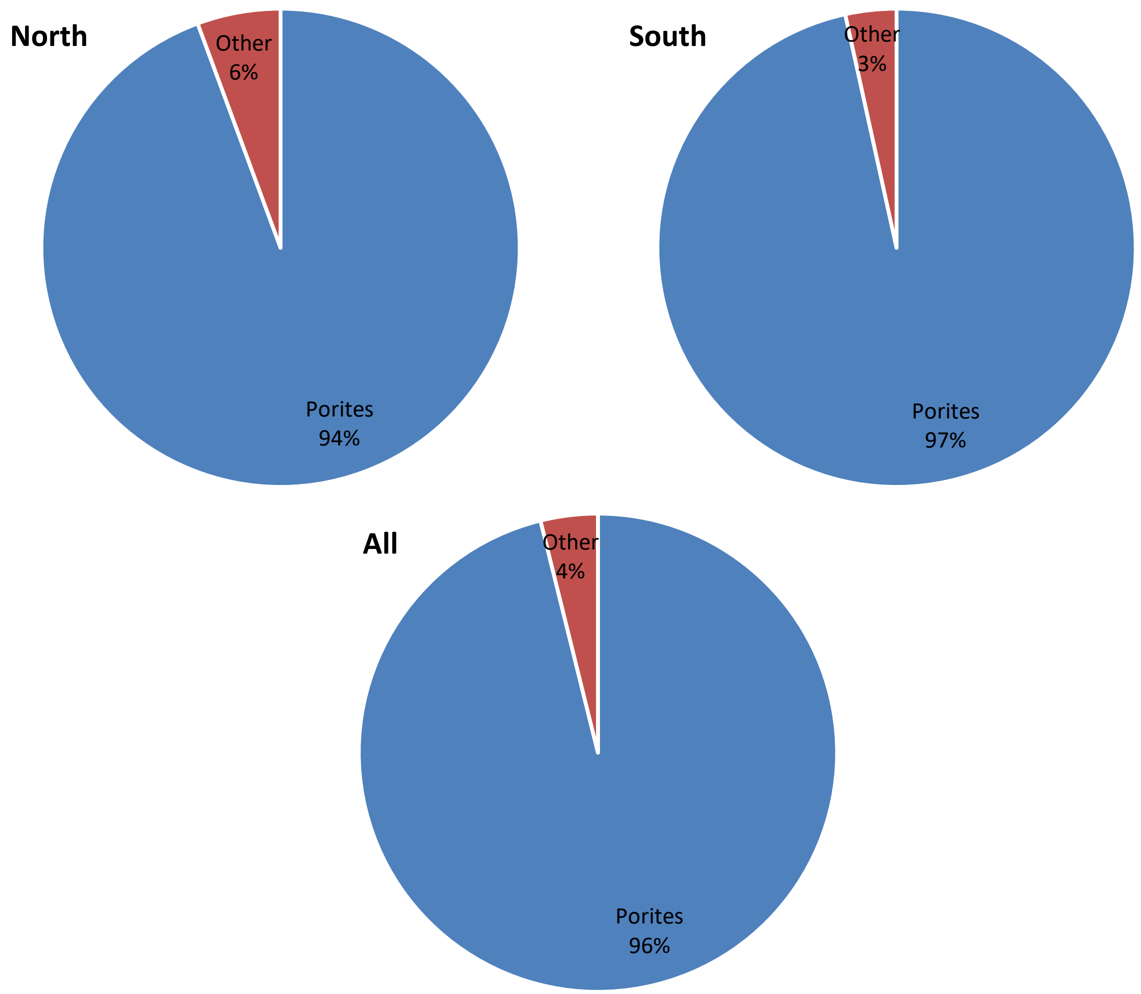


Figure 3.37. Percent contribution of individual coral genera to mean total coral cover for the sampling station groupings in the north (n = 4) and south (n = 18) portions of the modified Tumon Bay monitoring site, as well as for all stations within the site, in 2012.

3.1.4.3 ASSOCIATED BIOLOGICAL COMMUNITIES

Reef fishes

Descriptive statistics

As mentioned in Section 3.1.4.1, baseline fish survey data for the modified Tumon Bay site were not collected until 2015, as surveys could not be completed at the newly modified Tumon Bay site in 2012 or 2014 because of poor weather conditions and staffing limitations. The results of an initial analysis of the 2015 data are presented below, but note that these data were collected three years after the benthic cover and macroinvertebrate data presented elsewhere in this section.

Density

Reef fish density at the modified Tumon Bay site in 2015 ranged from 68 fish/100m^2 at station 95 to 203 fish/100m^2 at station 87 (Figure 3.38). Mean (± SE) fish density was 116 ± 7 fish/100 m^2 and the median was 110 fish/100 m^2. Relative density by family is presented in Figure 3.39. The pomacentrids were a major contributor to density, accounting for approximately 47% of fish counted, followed by acanthurids (18%) and labrids (12%).

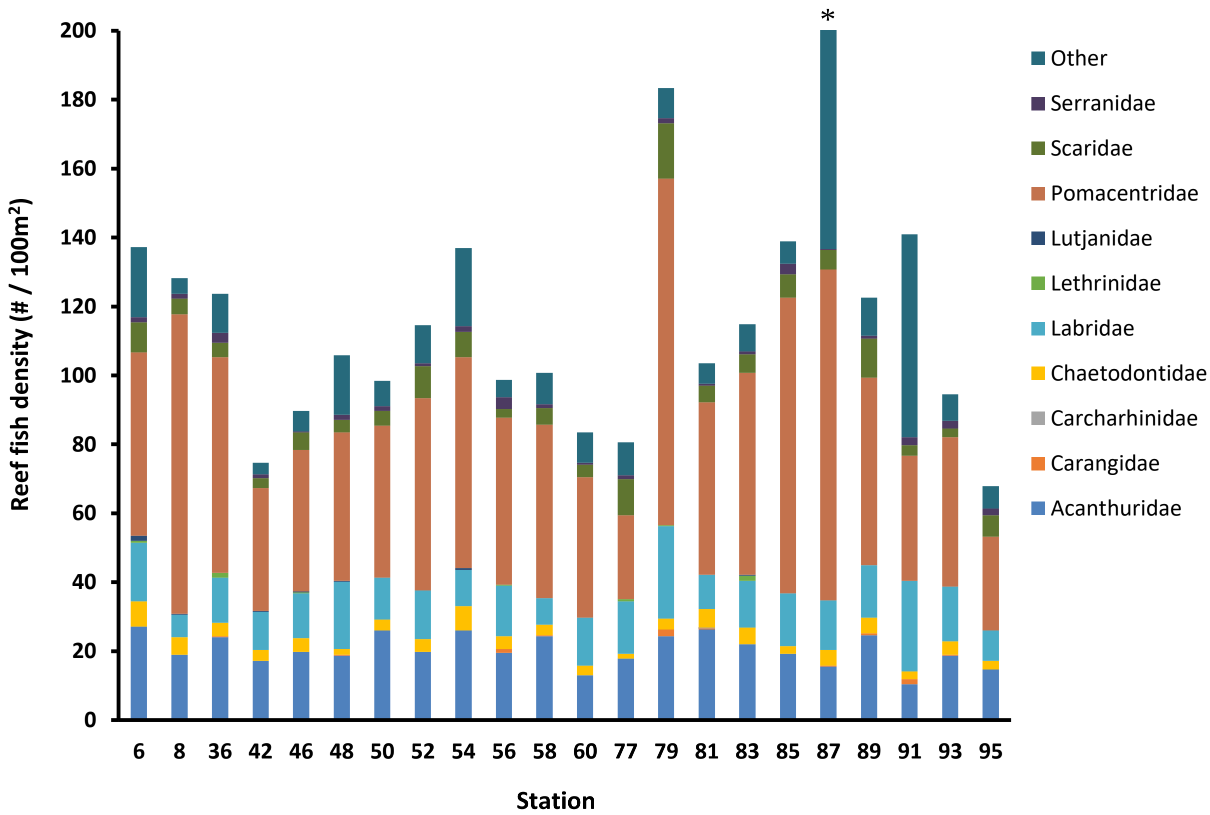


Figure 3.38. Reef fish density (# of fish/100m^2) by family at the Tumon sampling stations in 2015.Note that reef fish density at station 87 was 203 fish/100m^2, and thus slightly exceeded the maximum value of the vertical axis.

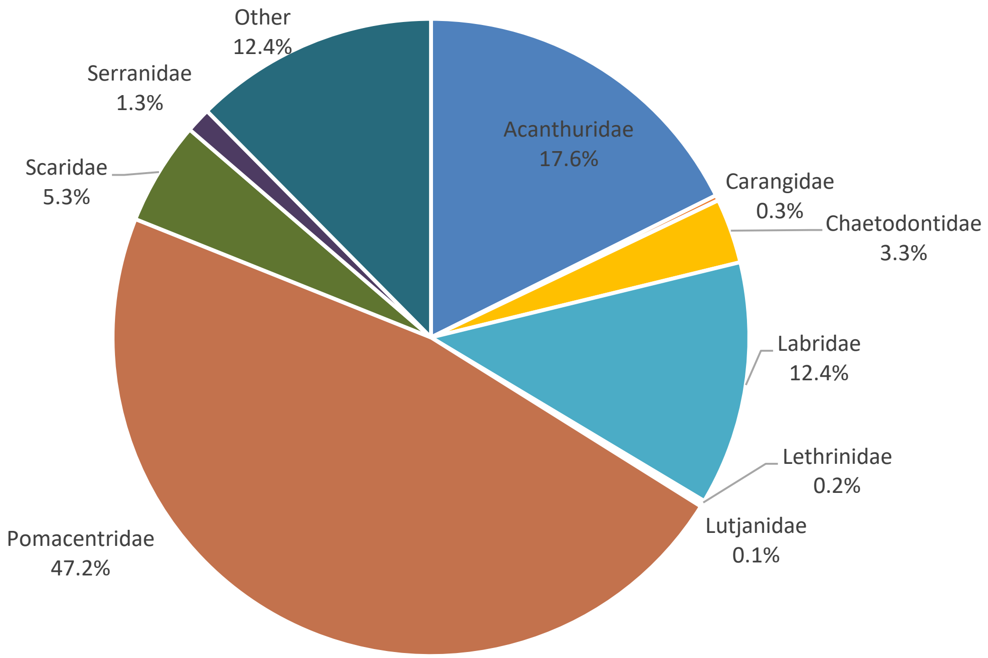


Figure 3.39. Relative density of reef fish by family at the Tumon Bay site in 2015.

Biomass

The minimum total reef fish biomass recorded at the modified Tumon Bay stations in 2015 was 17 g/m^2 and the maximum biomass was 791 g/m^2 at station 87. Mean (± SE) biomass across the site was 79 ± 35 g/m^2 and the median was 32 g/m^2 (Figure 3.40). Relative abundance by family is presented in Figure 3.41. A school of sphyraenids at station 87 were the primary contributor to biomass (42%), followed by scarids (11%) and a single large *Nebrius ferrugineus* (11%) at station 36. If the sphyraenids and *N. ferrugineus* are removed from the calculations, scarids are the primary contributor to biomass (23%) followed by acanthurids (19%) and labrids (12%). If the sphyraenids at station 87 and *N. ferrugineus* are excluded from the calculations the maximum biomass in Tumon Bay dropped to 83 g/m^2 and the average (± SE) biomass was 38 ± 3.7 g/m^2. If the sphyraenids and *N. ferrugineus* are included in the calculation, the mean total reef fish biomass at the modified Tumon Bay site in 2015 was 150% of the potential total reef fish biomass value (53 ±7 g/m^2) estimated for an unimpaired Guam reef community by Williams et al. (2015). However, if these large, infrequently encountered species are excluded from the calculation, mean total reef fish biomass represents 71% of the Williams et al. (2015) estimate for an unimpaired reef community on Guam.

Species Richness

A total of 206 species was documented across the modified Tumon Bay site in 2015. The species richness varied from 52 species at station 95 to 87 species at station 6 (Figure 3.42). The average (± SE) number of species observed was 64 ± 2 and the median was 61. Of the species recorded, 10 species were found at all 22 stations and 54 were recorded at only one of the stations. The majority of species (106) were found at less than half of the stations.

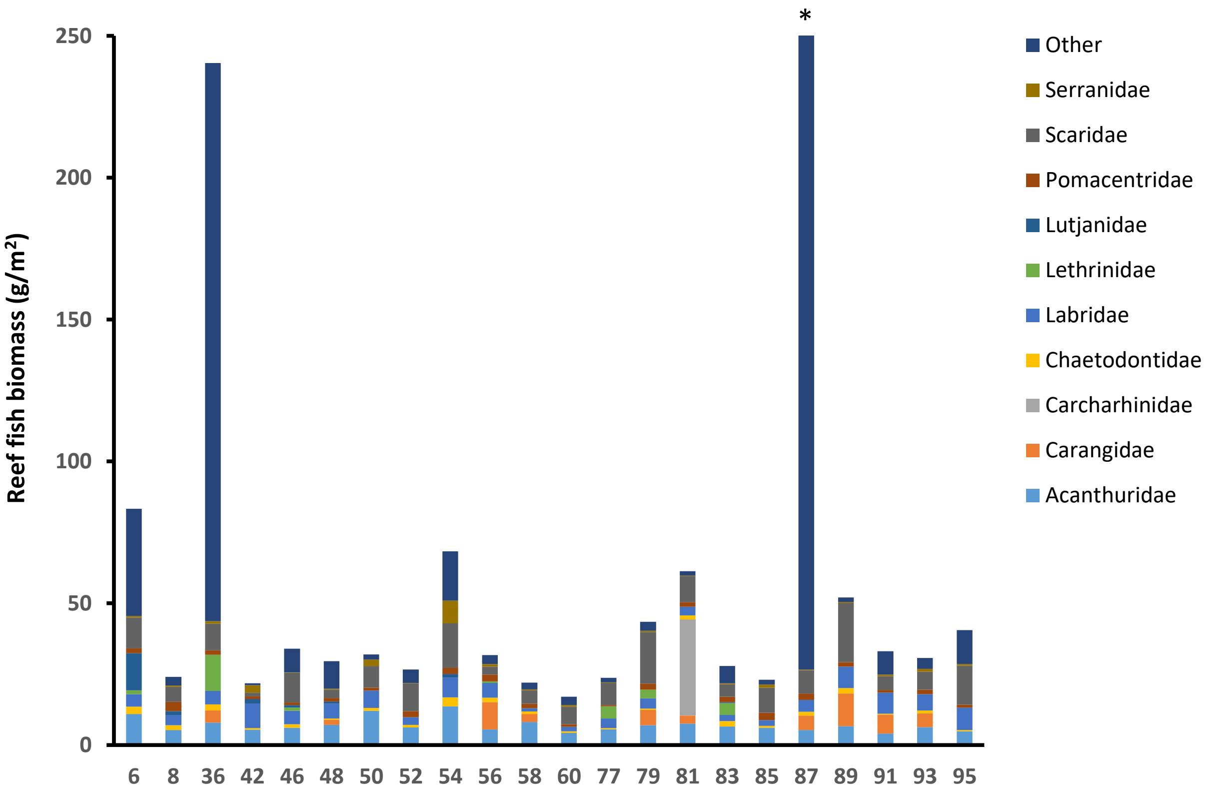


Figure 3.40. Reef fish biomass (g/m^2) by family at the Tumon Bay sampling stations in 2015. Reef fish biomass at station 87 was 791 g/m^2 due to a school of barracuda, and thus extends beyond the maximum value in the vertical axis. Note that the scale of the vertical axis differs from other reef fish biomass graphs presented in this report.

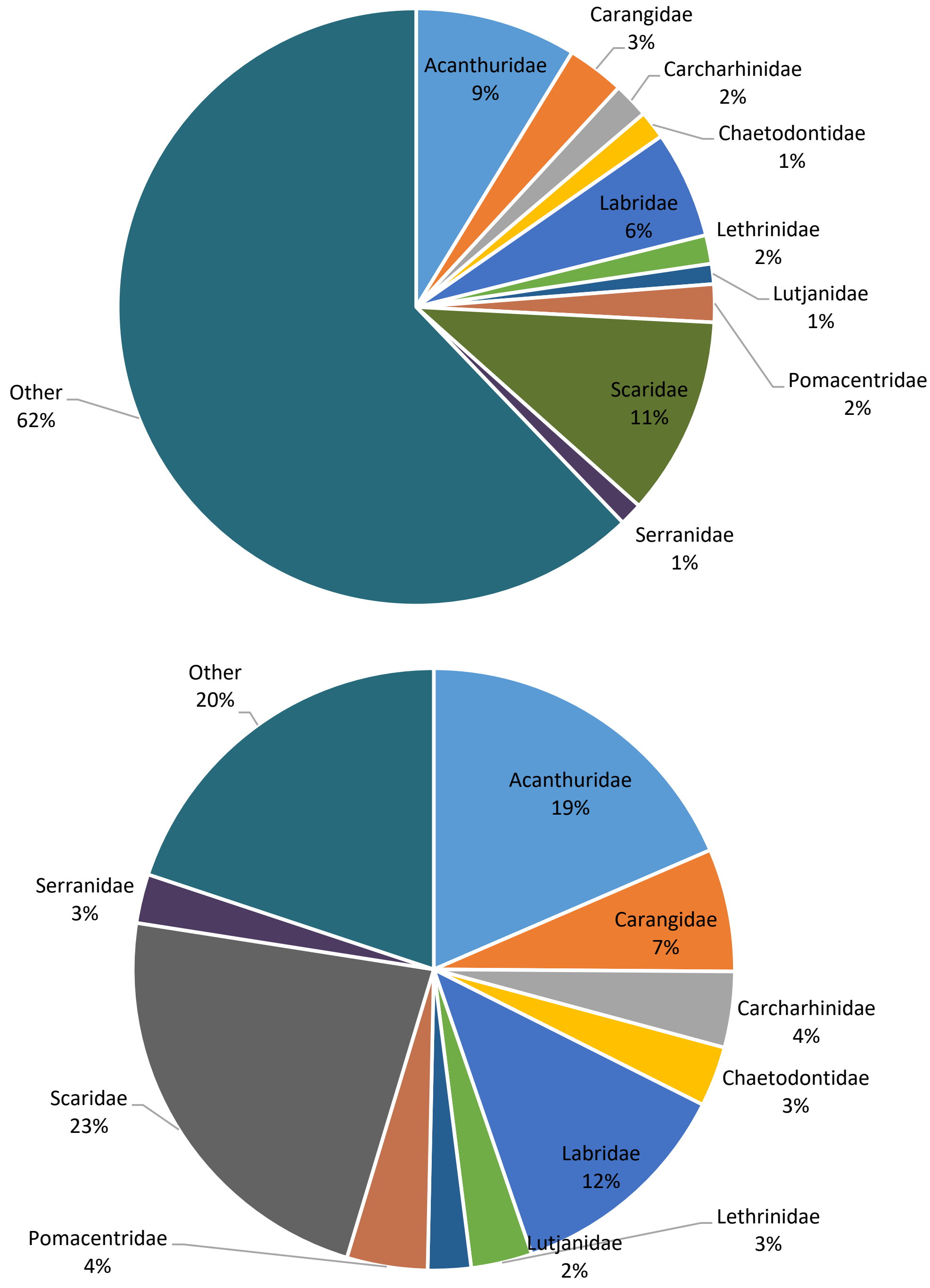


Figure 3.41. Relative abundance of reef fish by family at the Tumon Bay site in 2015 (top), and in the same year but with biomass associated with a school of sphyraenids and a single *Nebrius ferrugineus* removed (bottom).

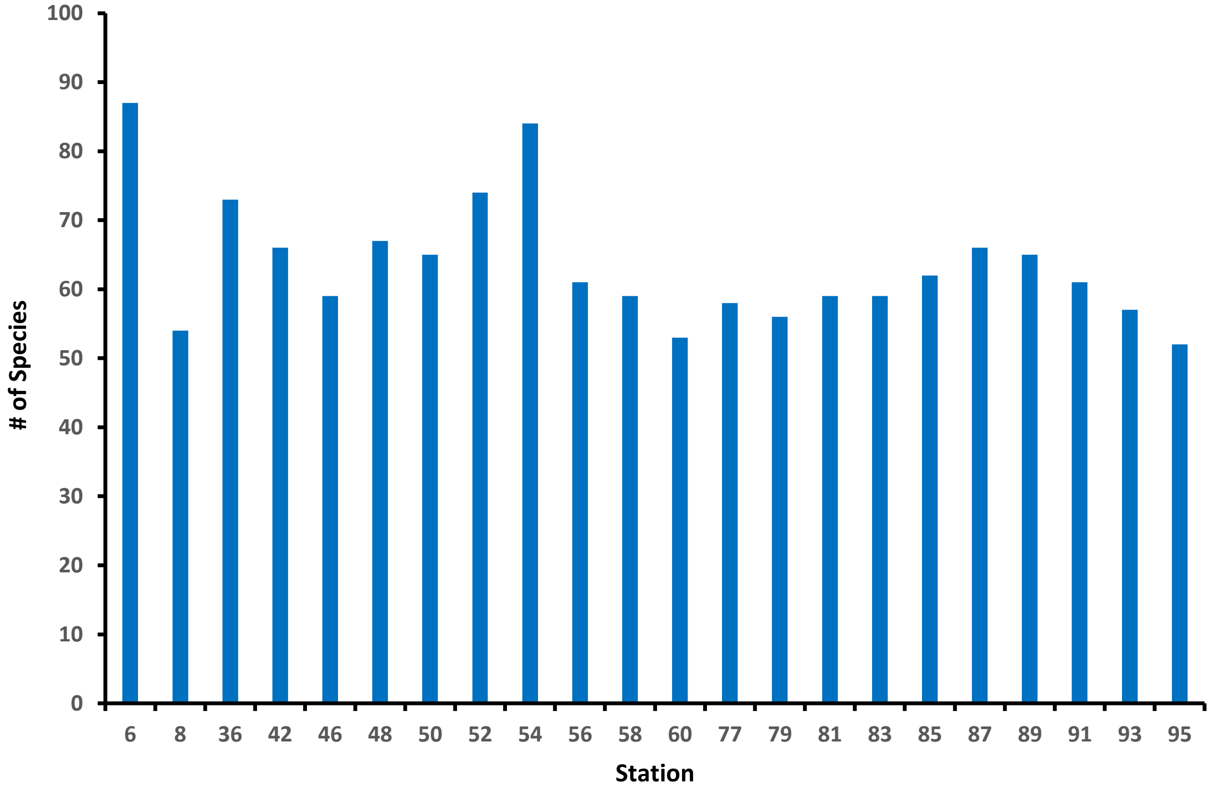


Figure 3.42. Reef fish species richness for sampling stations within the Tumon Bay site in 2015.

Macroinvertebrates

Descriptive statistics

Mean density (ind/100m^2 ± SD) for each broad macroinvertebrate taxonomic group is presented in Figure 3.43. Relative abundance for individual macroinvertebrate taxa is presented in Figure 3.44. The sea cucumber, *Stichopus chloronotus,* and the small rock-boring urchin, *Echinostrephus aciculatus,* represented 36.3% and 27.3% of total abundance, respectively, with trochus (*Tectus* spp.), *Linckia multiflora*, and *Echinaster luzonicus* together comprising only another 20%. The "other" category was comprised of the following species: *Lambis* spp., *Tectus pyramis*, *Tridacna* spp., *Octopus* spp., *Actinopyga mauritiana, Actinopyga palauensis*, *Bohadschia argus*, *Holothuria (Halodeima) atra*, *Holothuria (Microthele) whitmaei*, *Pearsonothuria graeffei*, *Thelenota ananas*, *Acanthaster planci, Culcita novaeguineae, Fromia milleporella*, *Gomophia egyptiaca, Linckia guildingi*, *Linckia laevigata*, *Echinometra mathaei*, *Echinometra* sp. A, and *Echinothrix diadema*. A total of 25 species was recorded in the modified Tumon Bay site in 2012.

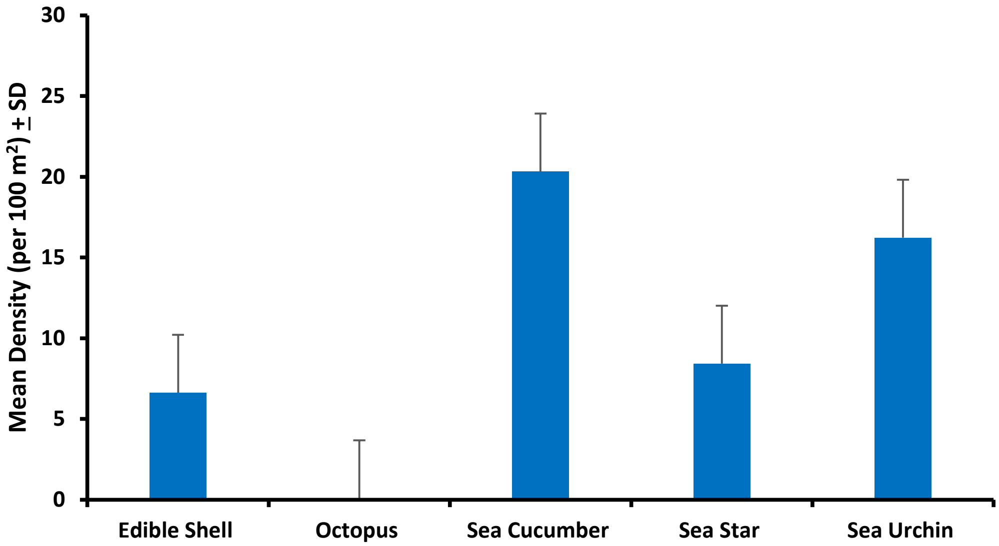


Figure 3.43. Mean density (ind/100 m^2) for broad macroinvertebrate taxonomic groups within the modified Tumon Bay site in 2012. Error bars represent standard deviation.

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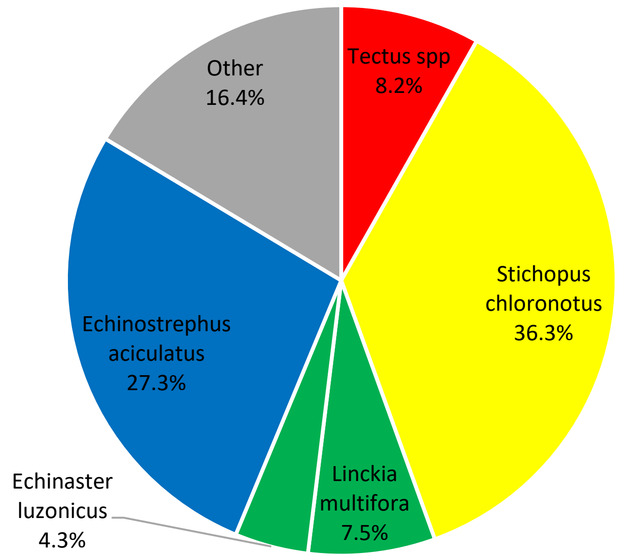
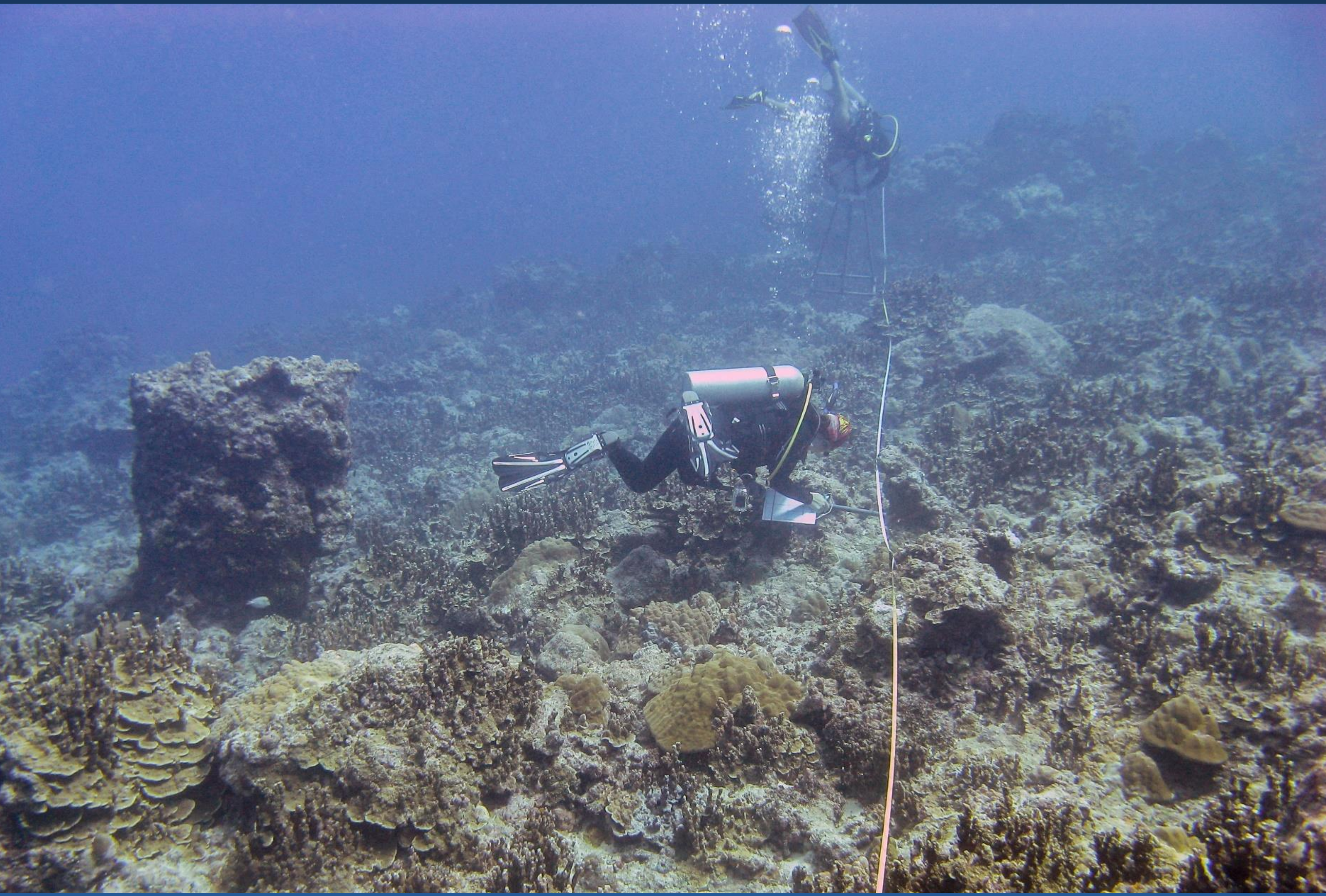


Figure 3.44. Total relative abundance of individual macroinvertebrate taxa for the modified Tumon Bay site in 2012.Color represents broad taxonomic groupings.

Sea turtles

In 2015, a total of four green sea turtles (*Chelonia mydas*) were observed during surveys at three stations (36, 6, and 81) and one was within the SPC cylinder during a count at station 6. Sea turtles were also often observed from the surface during surface intervals in 2012 and 2015.

3.2. Change in reef condition at the Tumon, East Agana, and Piti sites



3.2.1 TUMON BAY MARINE PRESERVE

3.2.1.1 SITE OVERVIEW

As described in Section 3.1.4.1 above, Tumon Bay hosts the Tumon Bay Marine Preserve and is a hub for tourism, recreational, and cultural activities on Guam. The boundaries of the monitoring site were shifted northwestward after analysis of data collected in 2010 showed that the original boundaries included two distinct benthic communities and that the large variance in the data limited the ability to detect change in these communities.

Photo (previous page): The reef community at a sampling station to the west of Tepungan Channel in 2018. While analysis of the 2018 data for the Piti site are on-going, diver observations of numerous dead corals in 2018 (such as the small branching coral skeletons visible in this image) are consistent with coral mortality rates recorded around the island during the 2017 bleaching event. **Photo (above)**: GLTMP biologists carrying out surveys in the modified Tumon Bay monitoring site in 2012.

The regular data collection carried out within the Tumon Bay site by GLTMP staff is focused on the seaward slope terrace, an area of relatively gentle slope that extends from the base of the reef front (7 m) to the edge of a steep lower slope (15 m). The benthic community prevalent within this seaward slope zone is distinct from that observed in the shallower, more wave exposed reef margin and reef front zones, and is dramatically different from the various benthic communities that occur across the shallow reef flat within the bay.

Data collection occurred within the modified Tumon Bay site in 2012, 2014, 2015, 2017, and 2018, although the re-prioritization of resources required to respond to the multiple bleaching events between 2013 and 2017 prevented the collection of all datasets at all permanent and non-permanent sampling stations for each of these visits. Unfortunately, reef fish surveys could not be completed at the modified Tumon Bay site in 2012, 2014, or 2018 as a result of staffing limitations. Descriptive statistics for the 2015 reef fish survey data are presented in Section 3.1.4.3 above, but the time series analysis of the 2015 and 2017 data was not completed prior to the release of this report. The results of further analysis of reef fish survey data collected at the Tumon Bay site and other monitoring sites will be presented in a future report.

In addition to data collected during regular visits to the monitoring site, data was also collected at four shallow (5 m) sites along the reef front in Tumon Bay, including two within the monitoring site boundaries, in 2013 as part of a UOGML-led bleaching response effort to which GLTMP staff made significant contributions. One of these reef front sites was re-visited in 2015 as part of an island-wide bleaching recovery assessment, in 2016 as part of an island-wide reef resilience assessment, and in 2017 as part of the response to another major bleaching event. In addition, the UOGML Reef Flat Monitoring Program led by Dr. Raymundo, has collected data at a reef flat site in Tumon Bay since 2009.

It should again be noted that photo transect-derived benthic cover data collected in 2017 and 2018 were generated by the CoralNet algorithm. Comparisons of results generated by the CoralNet algorithm and human observers for the same set of images indicate the CoralNet algorithm achieved a high degree of accuracy for measures of percent coral cover (no greater than ±1.5% absolute coral cover or ±7% of human observer-generated values) but was less accurate for other major benthic cover classes. Thus, any apparent changes in the cover of non-coral classes after 2015 should be considered highly tentative until verified through an analysis of these image sets by human observers.

3.2.1.2 BENTHIC COMMUNITY

Benthic cover

There was no detectable change in mean coral cover across the modified Tumon Bay monitoring site between 2012 and 2018 (Figure 3.45). While the values for sampling stations in the North and South portions of the modified site are not presented in the figures referenced here, no statistically significant difference in coral cover was detected for either of these groupings between 2012 and 2018 when examined separately. A change in total coral cover was not detected between 2012 and 2018, but coral cover appeared to increase between 2015 and 2017, before decreasing to levels similar to the starting point in 2012. The increase from 30% to 39% coral cover between 2015 and 2017 represents a 30% increase in coral cover (Partover.test, $p = 0.001$), with the change in the cover of *Porites rus* from 15% to 28% (Partover.test, $p < 0.001$) comprising the majority of the change in total coral cover (Figure 3.46). *Porites rus* can extend horizontally at a relatively rapid rate, but this large increase in cover in just a two-year period would be quite notable, if not remarkable, and should be re-examined when benthic cover data generated by a human observer becomes available.

Changes in mean percent cover estimates for other major benthic classes between 2012 and 2018 were not tested because of the limited accuracy of cover estimates for these classes generated by the CoralNet algorithm, which was used to generate cover values for 2017 and 2018. The apparent increase in crustose coralline algae and the decline in the cover of turf algae and cyanobacteria visible in Figure 3.45 may not reflect a change in the actual cover of these benthic classes within the site, and are more likely artifacts of making comparisons between human observer-generated benthic cover estimates to those generated by the CoralNet algorithm; the turf algae, cyanobacteria, and crustose coralline algae classes are particularly difficult to discern even for a human observer. An empirical examination of possible changes in the cover of non-coral benthic classes will be carried out upon the completion of the analysis of the 2017 and 2018 photo transect images by a human observer.

A comparison of mean coral cover from 2010 and 2018 was made using only those sampling stations that occurred within the area of overlap shared by the original and modified site boundaries, which represents the southwestern half of the modified site. The results of this comparison indicate that coral cover increased from 27% to 37% (a 37% increase) within this shared area, although this change was only significant at the 0.1 level ($p = 0.06$).

The results of an analysis of CoralNet algorithm-generated cover data indicate a decline in total cover from 39% to 33% between 2017 and 2018 (a 15% change relative to the 2017 mean) although this change was only significant at the 0.1 level (Partover.test, $p = 0.08$). Interestingly, the cover of *P. rus* did not appear to change between 2017 and 2018 as it did between 2015 and 2017, but the cover of massive *Porites* spp. appeared to decline (Partover.test, $p < 0.001$)(Figure 3.46). The decrease in the cover of massive *Porites* spp. from 10% to 7% between 2017 and 2018 (a 30% change relative to the 2017 mean), if real, may be related to observations of tissue mortality associated with the 2017 coral bleaching event. This tissue mortality, which occurred as irregularly-distributed, diffuse patches, appeared to be indirectly related to thermal/light stress, and may have been directly caused by one or more pathogens. Observers who participated in coral bleaching response efforts in both 2013 and 2017 recall seeing many more massive *Porites* species colonies exhibiting significant tissue mortality in 2017. The results of an on-going, detailed analysis of photo transects images obtained in 2013 and 2017 will provide information regarding the possible differential impacts of the 2013 and 2017 events on individual coral taxa. The results of these further analyses will be critical in understanding the response of massive *Porites* species to thermal/light stress. The record-breaking level of heat stress (13 Degree Heating Weeks) at the peak of the 2017 coral bleaching event may have exceeded a tolerance threshold for one or more of the more abundant massive *Porites* species, or may be the result of cumulative stress from multiple previous stress events. Massive *Porites* species represent a significant proportion of the remaining living coral on Guam's reefs, and understanding the response of this species group to thermal and light stress is critical to predicting the future composition and function of Guam's reef ecosystem.

The apparent stability of total coral cover along the seaward slope terrace within the Tumon Bay site, despite the impact of multiple thermal/light stress events during the study period, suggests that the coral community within the site is relatively robust to the levels of stress experienced during these events. This is in stark contrast to the coral communities occurring on the bay's shallow reef flat platform, which are comprised of different sets of dominant coral species that overlap little with the set of species that dominate the submarine terrace zone within the monitoring site. A staghorn coral mortality assessment in 2015 estimated mortality rates at 40–70% for major staghorn *Acropora* thickets in the bay as a cumulative result of thermal stress evens in 2013 and 2014 (Raymundo et al. 2017). The results of an analysis of data collected at an *Acropora pulchra*- and *A. intermedia*-dominated reef flat coral community surveyed on a quarterly basis by the Reef Flat Monitoring Program indicated a 36% decline in live coral cover at the site between 2009 and 2018. However, a remarkable 88% increase (from 17% to 32%) in coral cover was observed at the site between 2016 and 2018, after reaching a low of 17% in 2016 as a result of mortality associated with multiple thermal stress events between 2013 and 2016 and subaerial exposure during extreme low tide events in 2015. If this change is statistically significant it suggests that recovery can be rapid at this and similar reef flat coral communities when conditions are favorable, and even when these communities experience significant thermal stress levels during the study period.

The stability of coral cover on the submarine terrace targeted within the Tumon Bay monitoring site is also in contrast to major losses of live coral cover at shallow (5 m) reef front sites since 2013, which were estimated at 34% island-wide and 59% for the eastern windward reef front sites, and which were comprised of a larger proportion of stress-susceptible coral taxa than the western leeward communities (GLTMP 2018). Interestingly, no significant change in the cover of live coral at the western leeward reef front sites was detected, likely because of the much lower proportion of stress-susceptible coral taxa along the leeward coast. Coral cover at a bleaching response site located in the reef front adjacent to the submarine terrace zone targeted within the Tumon Bay monitoring site between 2013 and 2017 remained stable, although data collected in 2017 would not have captured the full impact of the 2017 bleaching event. This is consistent with the stability of mean coral cover observed across western reef front sites, and of coral cover in the submarine terrace zone of Tumon Bay, in recent years. However, too much emphasis should not be placed on cover values for this single reef front site, which includes a small proportion of the reef front zone across the bay, and which is only quasi-permanent (i.e., surveys occurred at the same coordinates but rebar were not installed). Individual reef front sites surveyed during and between recent coral bleaching events were also not originally intended to be considered in isolation, and instead were meant to serve as samples for detecting change in reef front benthic communities at the island scale and at the scale of island sides or quadrants.

The relatively high resilience of the coral community at the Tumon Bay site to recent levels of thermal/light stress is likely a result of the dominance of the generally stress-tolerant *Porites* corals. The cover of other coral taxa, especially stress-susceptible taxa, such as *Acropora* spp. and *Montipora* spp., was already very low prior to onset of the 2013 bleaching event. Historical data is limited for Tumon Bay and nearby areas, but data collected as part of a 1971 study by a UOG graduate student indicate that the cover of stress-susceptible taxa was higher prior to the first recorded COTS outbreak in late 1960s. Subsequent COTS outbreaks and chronically-elevated COTS densities have likely suppressed populations of corals that are the preferred prey species of COTS, and limited recruitment, water quality impacts and reduced levels of herbivory may have further inhibited recovery.

The stability of coral cover and the resilience of the coral community may not persist as sea surface temperatures continue to increase, and the frequency and severity of coral bleaching events increases in response. The almost total dominance of the coral community along the submarine terrace in Tumon Bay by *Porites rus* and a small number of massive *Porites* species may make it more vulnerable to devastation by diseases, the virulence of which may be enhanced by warming ocean temperatures. The apparent decline in the cover of massive *Porites* species, which may be a direct or indirect result of the record-breaking thermal stress levels in 2017, may indicate that the resistance to bleaching may be faltering in this important coral group on Guam.

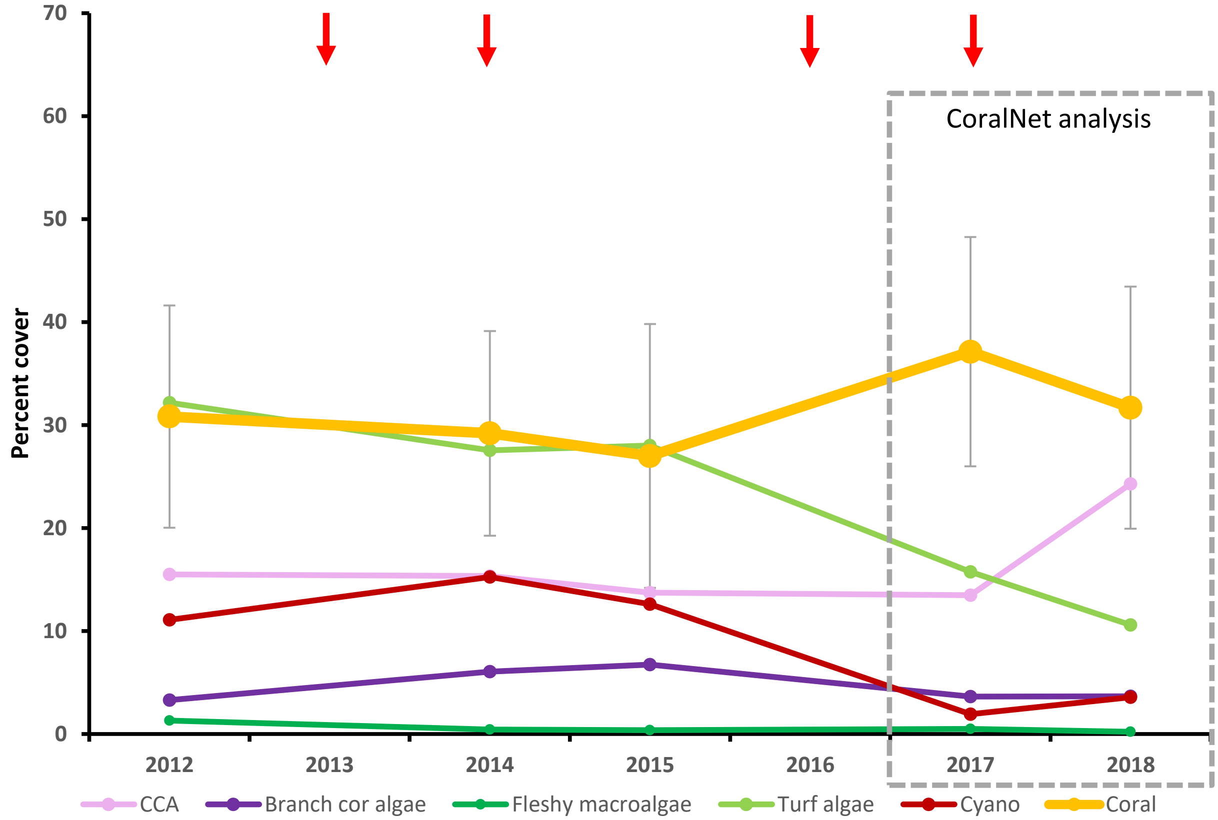


Figure 3.45. Percent cover of major benthic cover classes for the Tumon Bay monitoring site between 2012 and 2018. Photo transect images from 2012, 2014 and 2015 were analyzed by human observers, while images from 2017 and 2018 have thus far only been analyzed using the CoralNet algorithm (fully automated annotation). Comparisons of results generated by the CoralNet algorithm and human observers for the same set of images indicate the CoralNet algorithm achieved a high degree of accuracy for measures of percent coral cover (no greater than ±1.5% absolute coral cover or ±7% of human observer-generated values) but was less accurate for other major benthic cover classes. Thus, the apparent changes in the cover of non-coral classes after 2015 should be considered highly tentative until verified through an analysis of these image sets by human observers. Red arrows indicate the timing of significant coral bleaching events, including the historically severe 2013 and 2017 events. Note that survey years are not presented in regular annual increments, and thus the elapsed period of time between each pair of neighboring data varies from one to two years.

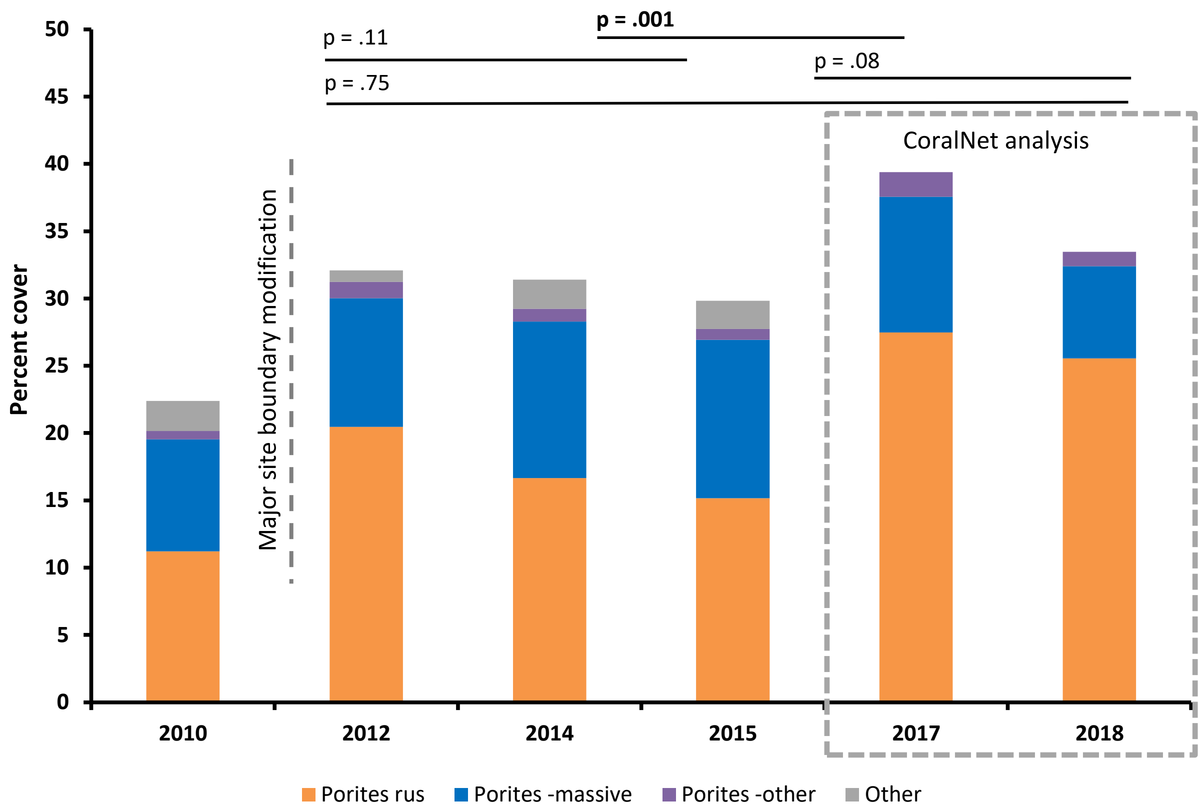


Figure 3.46. Percent cover of coral taxa for the Tumon Bay monitoring site between 2010 and 2018. As described in the caption for Figure 3.45, photo transect images from 2012, 2014 and 2015 were analyzed by human observers, while images from 2017 and 2018 have thus far only been analyzed using the CoralNet algorithm. Comparisons of results generated by the CoralNet algorithm and human observers for the same set of images indicate the CoralNet algorithm achieved a moderate degree of accuracy for measures of percent cover for *Porites rus* and massive *Porites* spp. (no greater than ±2.3% absolute cover or ±23% of human observer-generated values). The accuracy of the CoralNet algorithm estimates for the cover of other taxa has not yet been determined, but the low cover of other taxa and thus the limited number of data points available to train the CoralNet algorithm suggests that these estimates should be considered highly tentative until verified through an analysis of these image sets by human observers. P values are provided for two-sample comparisons (Partover.test) of square root-transformed mean coral cover values for selected survey years. Note that survey years are not presented in regular annual increments, and thus the elapsed period of time between each pair of neighboring data varies from one to two years.

3.2.1.3 ASSOCIATED BIOLOGICAL COMMUNITIES

Macroinvertebrates

An in-depth analysis of changes in macroinvertebrate communities at the modified Tumon Bay site between 2012 and 2018 has not yet been carried out, but a preliminary analysis indicates that the density of sea cucumbers declined by 90% during this period (Paired Wilcoxon signed ranks test, paired stations only, $p < 0.001$). Further analysis is required to determine which sea cucumber species/species groups declined during this period and to understand the possible driver(s) of this significant decline. Changes in other macroinvertebrate groups between 2012 and 2018 will also be examined.

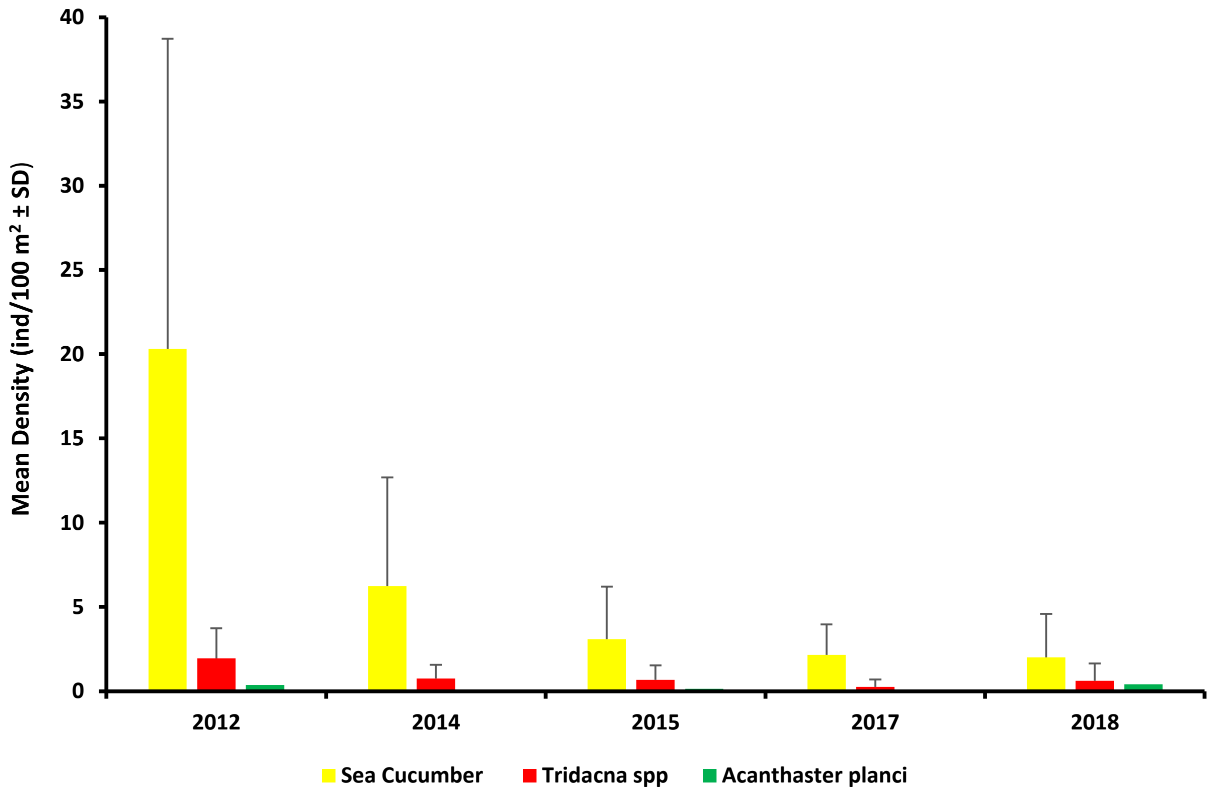


Figure 3.47. Mean density (ind/100 m^2) for macroinvertebrate species/groups of interest for the modified Tumon Bay site between 2012 and 2018. Error bars represent standard deviation. Note that scale used for the vertical axis in this figure is different than the scale used for showing change in the density of macroinvertebrate groups in the East Agana and Piti sites (Figures 3.50 and 3.53).

3.2.2 EAST AGANA BAY

3.2.2.1 SITE OVERVIEW

East Agana Bay was the second high priority reef area to be established for long-term monitoring, with the completion of baseline data collection in 2010 (Appendix D). East Agana Bay was chosen as a comparison site to Tumon Bay, thus monitoring in East Agana occurs along the reef slope terrace within the same depth range as that targeted within the Tumon Bay site. The reef structure in the bays is generally similar and the bays are both impacted by non-point source pollution, so it is hoped that the pairing of the bays will allow an examination of the relative effects of protection status on the reef

Photo (above): High coral cover at a *Porites*-dominated reef along the submarine terrace in the East Agana Bay monitoring site in 2010. Bleaching-susceptible corals like the branching coral (*Stylophora mordax*) in the bottom right were uncommon in 2010, but are now rarely encountered after the recent coral bleaching events.

communities in the bays. While a direct comparison of reef ecosystem condition between the sites will not be addressed here, as further analysis is required before such comparisons can be made, comparisons of significant trends in key ecosystem health parameters are made when appropriate.

3.2.2.2 BENTHIC COMMUNITY

Benthic cover

The mean cover of living hard coral increased from 45% to 58% (an increase of 31% relative to the 2010 mean) within the East Agana Bay monitoring site between 2012 and 2018 (Partover.test, p = 0.007)(Figure 3.48). However, because the 2018 cover estimates were generated through the fully automated annotation of photo transect images by the CoralNet algorithm this value should be considered highly tentative until verified by the analysis of the 2018 images by a human observer. Mean coral cover remained stable between 2010 and 2016, the years for which human observer-generated estimates are available. Mean coral cover was similar between 2016 (human observer-generated) and 2017 (CoralNet algorithm-generated), but cover increased significantly (from 44% to 58%, a change of 32% relative to the 2017 mean) between 2017 and 2018 (Partover.test, p = 0.004), despite the impact of the historically severe bleaching event in 2017. As with the 2010 to 2018 comparison, the comparison between 2017 and 2018 values should be considered tentative until verified by the analysis of the 2018 images by a human observer.

The increase in coral cover between 2010 and 2018 and between 2017 and 2018 within the East Agana Bay site appear to be comprised primarily by increases in the cover of *Porites rus* during these time periods (Figure 3.49). Mean cover of *Porites rus* increased from 37% to 53% between 2010 and 2018, representing a 42% increase relative to the 2010 mean, but it should be noted that this change was significant only at the 0.1 level (Paired Wilcoxon signed rank test, p = 0.07). The apparent increase in the cover of *P. rus* from 41% to 53% between 2017 and 2018 was not statistically significant (Paired Wilcoxon signed rank test, p = 0.76). The cover of massive *Porites* spp., which represents a smaller proportion of total cover than the proportion of these taxa in the Tumon Bay site, remained stable throughout the study period, in contrast to the apparent decline observed at the Tumon Bay site between 2017 and 2018. The reason for this discrepancy is not clear, but may be related to the relatively low cover of massive *Porites* species in the East Agana Bay site and the limits of the current sampling effort to detect changes from these low values. However, as mentioned above for the change in total coral cover, the possible increase in the cover of *P. rus* and stability in the cover of massive *Porites* species between 2010 and 2018 within the East Agana Bay site should be verified with benthic cover data generated by a human observer.

Changes in mean percent cover estimates for other major benthic classes between 2010 and 2018 were not tested because of the limited accuracy of cover estimates for these classes generated by the CoralNet algorithm, which was used to generate cover values for 2017 and 2018. The cover of crustose coralline algae, branching corralling algae, fleshy macroalgae, and cyanobacteria appeared to remain stable, but this apparent stability of cover values across time, and the apparent decrease in turf algae algae visible in Figure 3.48 may not reflect stability/change in the actual cover of these benthic classes within the site. As described above, it is possible that this apparently stability or change may be an artifact of making comparisons between human observer-generated benthic cover estimates to those generated by the CoralNet algorithm, especially for these benthic classes, which are particularly difficult to discern even for a human observer. An empirical examination of possible changes in the cover of non-coral benthic classes will be carried out upon the completion of the analysis of the 2017 and 2018 photo transect images by a human observer.

The apparent increase in total coral cover along the submarine terrace within the East Agana Bay site suggests that, like the coral community within the Tumon Bay site, the coral community is relatively robust to the levels of stress experienced during recent coral bleaching events. Although a reef flat site within East Agana Bay has not been surveyed as part of the Reef Flat Monitoring Program, staghorn coral communities within the bay assessed during the 2015 staghorn coral mortality assessment were estimated to have experienced an estimated 20% mortality rate as a cumulative result of thermal stress evens in 2013 and 2014. While this mortality rate was the lowest among all major staghorn thickets assessed in that study, the decline in staghorn coral on the reef flat in East Agana Bay between 2013 and 2015 is still significant, and is in contrast to the stable coral cover values within the submarine terrace zone during this period.

The increase in coral cover on the submarine terrace targeted within the East Agana Bay monitoring site is also in contrast to major losses of live coral cover at shallow (5 m) reef front sites discussed previously, and to the loss of coral cover observed at a shallow (5 m) reef front site within the bay. Total coral cover at the reef front site, which occurs adjacent to the submarine terrace zone targeted within the East Agana Bay monitoring site, declined from 35% to 18% between 2013 and 2017. The represents a 49% decline relative to the 2013 mean (two-sided t-test, $p = 0.01$). Caution is urged in placing too much emphasis on this apparent change in cover at this single reef front site, however, as it comprises a small proportion of the reef front zone across the bay, is only quasi-permanent, and was originally intended to serve as a sample for detecting change in reef front benthic communities at the island scale and at the scale of island sides or quadrants.

As discussed for the coral community of the Tumon Bay site, the relatively high resilience of the coral community in the East Agana Bay site to recent levels of thermal/light stress is likely a result of the dominance of the generally stress-tolerant *Porites* corals at the site and the very low abundance of stress-susceptible taxa. The already-low cover of stress-susceptible taxa present at the site prior to the onset of severe coral bleaching events in 2013 may have declined further as a result of these events, but this question can only be properly investigated once human observer-generated benthic cover values are generated.

Like the similar coral community in the Tumon Bay site, the apparent resilience of the coral community along the submarine terrace in East Agana Bay monitoring site may not persist as sea surface temperatures continue to increase, and the frequency and severity of bleaching events increases in response. The dominance of the coral community by a single coral species (*Porites rus*) may make it more vulnerable to devastation by diseases, the virulence of which may be enhanced by warming ocean temperatures.

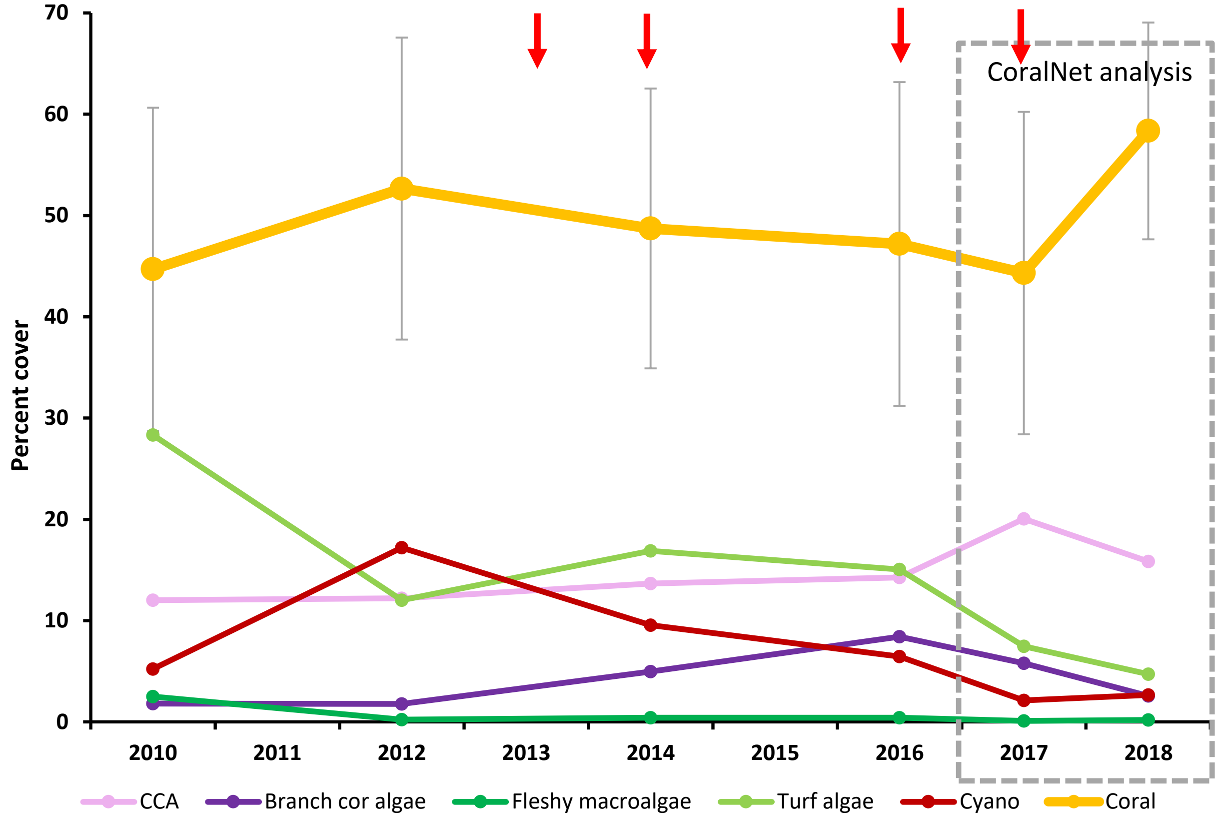


Figure 3.48. Percent cover of major benthic cover classes for the East Agana Bay monitoring site between 2010 and 2018. Photo transect images obtained between 2010 and 2015 were analyzed by human observers, while images from 2017 and 2018 have thus far only been analyzed using the CoralNet algorithm (fully automated annotation). As described above, comparisons of results generated by the CoralNet algorithm and human observers for the same set of images indicate the CoralNet algorithm achieved a high degree of accuracy for measures of percent coral cover (no greater than ±1.5% absolute coral cover or ±7% of human observer-generated values) but was less accurate for other major benthic cover classes. Thus, the apparent changes in the cover of non-coral classes after 2015 should be considered highly tentative until verified through an analysis of these image sets by human observers. Red arrows indicate the timing of significant coral bleaching events, including the historically severe 2013 and 2017 events. Note that survey years are not presented in regular annual increments, and thus the elapsed period of time between each pair of neighboring data varies from one to two years.

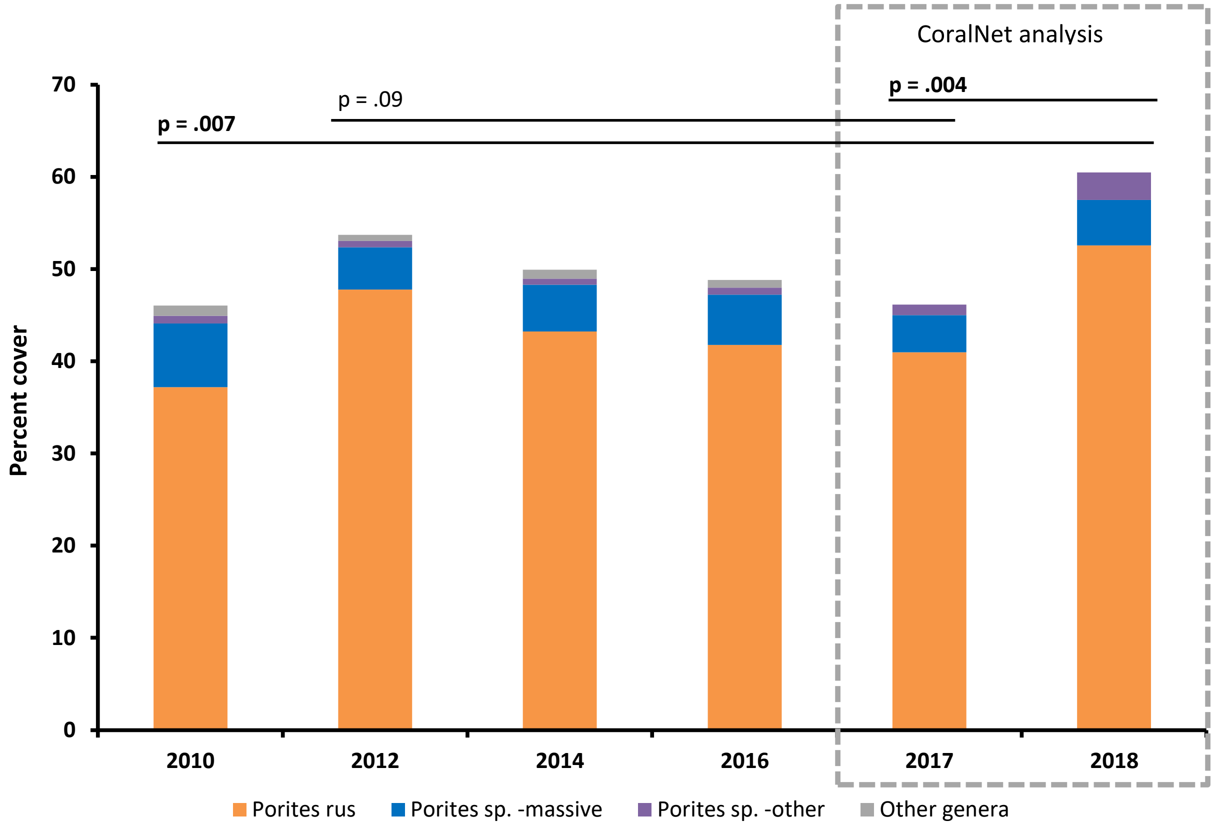


Figure 3.49. Percent cover of coral taxa for the East Agana Bay monitoring site between 2010 and 2018. Photo transect images obtained between 2010 and 2016 were analyzed by human observers, while images from 2017 and 2018 have thus far only been analyzed using the CoralNet algorithm (full automation). Comparisons of results generated by the CoralNet algorithm and human observers for the same set of images indicate the CoralNet algorithm achieved a moderate degree of accuracy for measures of percent cover for *Porites rus* and massive *Porites* spp. (no greater than ±2.3% absolute cover or ±23% of human observer-generated values). The accuracy of the CoralNet algorithm estimates for the cover of other taxa has not yet been determined, but the low cover of other taxa and thus the limited number of data points available to train the CoralNet algorithm suggests that these estimates should be considered highly tentative until verified through an analysis of these image sets by human observers. Note that survey years are not presented in regular annual increments, and thus the elapsed period of time between each pair of neighboring data varies from one to two years.

3.2.2.3 ASSOCIATED BIOLOGICAL COMMUNITIES

Macroinvertebrates

An in-depth analysis of changes in macroinvertebrate communities at the East Agana Bay site between 2010 and 2018 has not yet been carried out, but, as was observed for the modified Tumon Bay site during a similar period, a preliminary analysis indicates that the density of sea cucumbers declined by 98% during this period (Paired Wilcoxon signed ranks test, paired stations only, $p = 0.048$). Further analysis is required to determine which sea cucumber species/species groups declined during this period. The decline in the mean density of *Tridacna* spp. between 2012 and 2018 was statistically significant (Paired Wilcoxon signed ranks test, paired stations only, $p = 0.01$), but the apparent spike in *Tridacna* densities in 2012 is curious and the data need to be analyzed further to determine if this spike, and the change between 2012 and 2018, actually occurred. Further analysis is required to understand the possible driver(s) of these significant declines. Changes in other macroinvertebrate groups at the East Agana Bay site between 2010 and 2018 will also be examined.

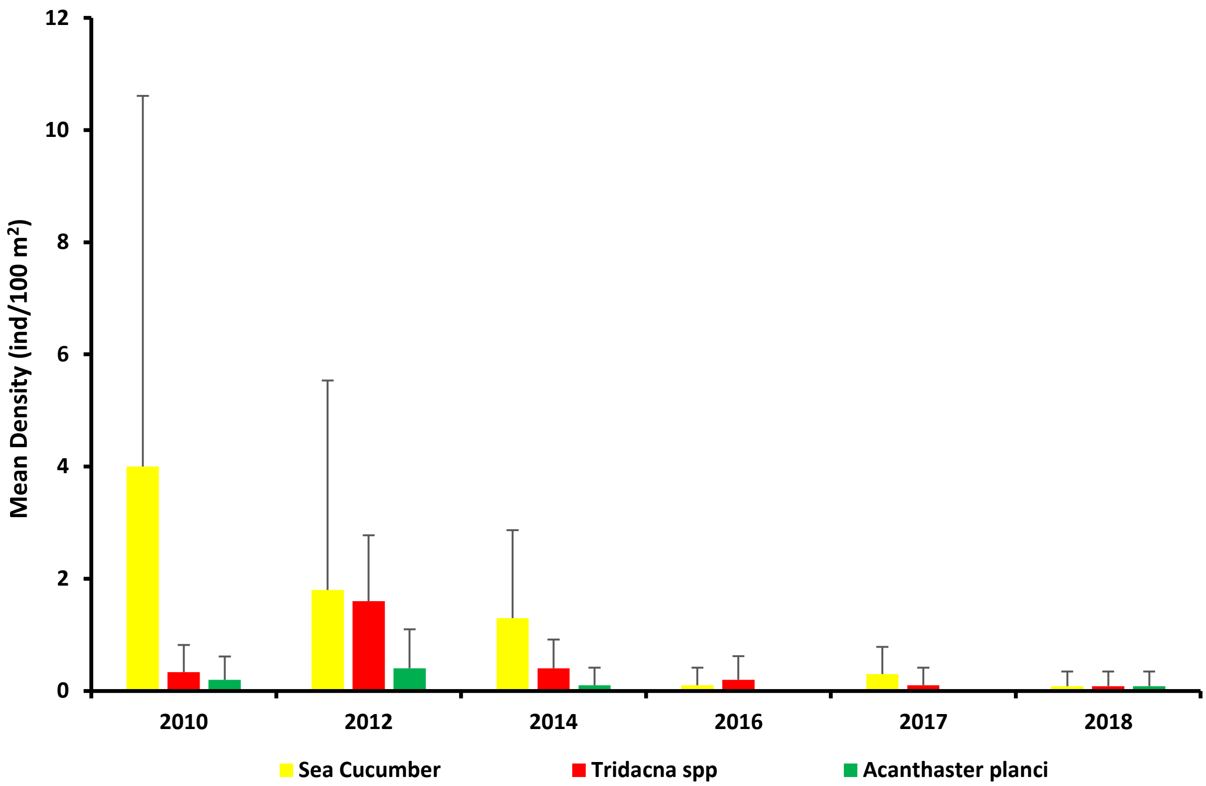


Figure 3.50. Mean density (ind/100 m^2) for macroinvertebrate species/groups of interest for the East Agana Bay site between 2010 and 2018. Error bars represent standard deviation.

Photo (next page): A reef community along the submarine terrace to the east of Tepungan Channel in the Tepungan (Piti) Bay monitoring site in 2018. Stress-tolerant corals, such as the mounding *Porites* spp. visible in this image, comprised the majority of the coral community at the site. Despite the lack of preferred coral prey species, crown-of-thorns seastars (one visible in lower right of image) are still regularly observed feeding on non-preferred prey species in Tepungan Bay and other reef areas along the west coast.

3.2.3 PITI BOMB HOLES MARINE PRESERVE

3.2.3.1 SITE OVERVIEW

As described in Section 3.1.2.1, Piti, or Tepungan, Bay was selected for long-term monitoring on account of its designation as a locally-managed Marine Preserve, the upland restoration activities occurring in the watershed, and its importance to tourism and recreation. As with the Tumon Bay, East Agana Bay, Achang, and Cocos-East sites, data collection within the Piti site occurs along the submarine terrace zone between a depth of 7 and 15 m (Appendix F). In order to enhance our understanding of the impacts of land-based sources of pollution on coral reef ecosystems within Piti Bay, and to assist in the evaluation of the effectiveness of watershed restoration activities in improving water quality and coral reef health, sampling stations occur both to the west and east of Tepungan Channel. Baseline data collection occurred at the site in 2012, with subsequent data collection efforts occurring in 2014 and 2018. The re-prioritization of resources required to respond to the multiple bleaching events between 2013 and 2017 prevented the collection of data the Piti site every year between 2012 and 2018 and prevented the collection of all datasets at all permanent and non-permanent sampling stations for the 2012, 2014, and 2018 sampling years.

3.2.3.2 BENTHIC COMMUNITY

Benthic cover

There was no detectable change in mean total coral cover across the Piti monitoring site between 2012 and 2018, with cover hovering at 16% (Partover.test, p = 0.41)(Figure 3.51). However, because the 2018 cover estimates were generated through the fully automated annotation of photo transect images by the CoralNet algorithm this value should be considered tentative until verified by the analysis of the 2018 images by a human observer.

Changes in mean percent cover estimates for other major benthic classes between 2012 and 2018 were not tested because of the limited accuracy of cover estimates for these classes generated by the CoralNet algorithm, which was used to generate cover values for 2018. The apparent slight increase in the cover of crustose coralline algae and the decline in the cover of cyanobacteria visible in Figure 3.51 may not reflect an actual change in the cover of these benthic classes within the site, and is more likely an artifact of making comparisons between human observer-generated benthic cover estimates to those generated by the CoralNet algorithm. An empirical examination of possible changes in the cover of non-coral benthic classes will be carried out upon the completion of the analysis of the 2018 photo transect images by a human observer.

While a change in mean total coral cover was not detected across the site between 2012 and 2018, coral cover appeared to increase between 2012 and 2014, before decreasing to levels similar to those observed in 2012. The increase from 16% to 20% coral cover between 2012 and 2014 represents a 25% increase in coral cover relative to the 2012 mean (Paired t-test[3], p = 0.01), with the change in the cover of massive *Porites* species from 9% to 12% (Partover.test, p = 0.046) comprising the majority of the change in total coral cover during this two-year period (Figure 3.52). This increase in total coral cover and the cover of massive *Porites* species observed between 2012 and 2014 occurred despite the impact of the 2013 coral bleaching event. Mean coral cover across the site then returned to 16% by 2018, representing a 20% decline from the 2014 mean (Paired t-test[2], p = 0.015). The decline in total coral cover between 2014 and 2018, if real, was comprised primarily by a decline in the cover of massive *Porites* species from 12 to 8% (Partover.test, p = 0.02). In contrast, the mean cover of *Porites rus* remained stable at 1–2% through 2014 but appears to have increased significantly (from 2% to 9%) between 2014 and 2018 (Paired Wilcoxon signed rank test, p = 0.01). Changes in the cover of specific coral taxa or taxonomic groupings, such as *P.*

[3] The transformed coral cover values for the 2014 sampling stations were not normally distributed and thus the full dataset from 2014 could not be compared to the full 2012 or 2018 datasets using Partover.test. The coral cover values for only permanent sampling stations surveyed 2014 were normally distributed, allowing a comparison between 2012 and 2014 and between 2014 and 2018 using a two-sample, paired student t-test for data collected only at those permanent stations visited both years being compared. Mean coral cover values for 2012, 2014, and 2018 calculated using all sampling stations and only paired permanent sampling stations were highly similar.

rus or massive *Porites* species, using the CoralNet-generated cover estimates for 2018 should be considered even more tentative than changes in total coral cover; however, the apparent decline in the cover of massive *Porites* species may be related to tissue mortality observed in massive *Porites* species during the 2017 bleaching event (discussed in Section 3.2.1.2 above). The increase in *P. rus* cover in the Piti site, if real, is consistent with apparent increase or stability in the cover of this species in the Tumon Bay and East Agana Bay sites, suggesting that *P. rus* colonies occurring along the submarine terrace of portions of Guam's western coast were not significantly impacted by recent thermal stress events and may actually have benefitted from the availability of substrate provided by corals killed during the bleaching events.

The apparent disappearance of merulinids (mainly *Favia* spp.) between 2014 and 2018 visible in Figure 3.52 very likely does not reflect an actual disappearance of this group from the monitoring site, and is more likely a result of the limited ability of the CoralNet algorithm, as currently configured and trained, to detect non-*Porites* corals. An actual decline in the cover of merulinds and other non-*Porites* coral taxa may be expected, however, as a result of the severe 2017 bleaching event. A re-examination of possible changes in the cover of *P. rus*, massive *Porites* species, and other corals in the Piti site will be carried out upon the completion of the analysis of the 2018 photo transect images by a human observer.

The apparent stability of total coral cover along the submarine terrace within the Piti site, despite the impact of multiple thermal/light stress events during the study period, suggests that the coral community within the site is relatively robust to the levels of stress experienced during these events. Stability in total coral cover was also observed at a *Porites*-dominated reef flat site surveyed quarterly as part of the Reef Flat Monitoring Program. Total cover at the reef flat monitoring site was identical (33%) at the start of monitoring (2009) and at the last year for which data is available (2018). A decline in total coral cover was observed at the reef flat site from a peak of 43% in 2011 to a low point of 23% in 2013, however, but by 2018 coral cover had rebounded to 2012 levels.

The stability of coral cover for the *Porites*-dominated communities of the submarine terrace and reef flat is in marked contrast to the trajectory of the small staghorn coral thickets that occur on the bay's shallow reef flat platform, which experienced mortality rates of between 80% and 95% as a cumulative result of thermal stress events in 2013 and 2014[4] (Raymundo et al. 2017). Staghorn corals and other bleaching-susceptible corals comprise a small proportion of the coral communities that occur across the bay's reef flat, however, with stress-tolerant taxa such as *Porites cylindrica*, *Porites rus,* and *Pocillopora damicornis* comprising the majority of hard coral communities across much of the reef flat platform.

The maintenance of coral cover on the submarine terrace targeted within the Piti monitoring site is also in contrast with the a possible increase in coral cover detected at a shallow (5 m) reef front site within the bay. Total coral cover at the reef front site, which occurs adjacent to the submarine terrace zone targeted within the Piti monitoring site, appeared to increase from 21 ± 4% in 2013 to 33 ± 5% in 2017, representing an increase of 57% relative to the 2013 mean (Unpaired t test, $p = 0.03$). As mentioned above, caution is urged in placing too much emphasis on this apparent change in cover at this single reef front site, which includes a small proportion of the reef front zone across the bay, is only quasi-permanent,

[4] Data collected in 2015 for the staghorn coral mortality assessment did not include data for numerous small *Acropora pulchra* thickets that occur at the bottom of Tepungan Channel. These thickets, which appear to have been unaffected by the multiple recent bleaching events, were not discovered until after the study was completed. Staghorn coral species that suffered significant losses, and which may no longer occur in the Tepungan Bay, include *Acropora intermedia*, *A. teres*, and *A. muricata.*

and was originally intended to serve as a sample for detecting change in reef front benthic communities at the island scale and at the scale of island sides or quadrants.

However, it is important to note that while the stability of coral cover along the submarine terrace and the significant increase at the single reef front survey site in Piti Bay in recent years are consistent with the lack of detection of change along the western leeward coast in response to recent bleaching events, they are in contrast to major losses of live coral cover at shallow reef front sites island-wide discussed previously. While historical data for Piti Bay is limited, the dominance of stress-tolerant corals and observations of skeletons of long-dead *Acropora* and other stress-susceptible taxa, suggest that the current benthic assemblages in the bay are the result of selection pressure from decades of local stressors, and that the proportion of stress-susceptible coral taxa—many of which contribute substantially to reef growth and complexity—likely disappeared before they could be devastated by the historically severe bleaching events of recent years.

As discussed in relation to the coral communities of the Tumon and East Agana sites, the relatively high resilience of the coral community in the Piti site to recent levels of thermal/light stress is likely a result of the dominance of the generally stress-tolerant *Porites* corals at the site and the low abundance of stress-susceptible taxa. The relatively low cover of stress-susceptible taxa at the site prior to the onset of severe coral bleaching events in 2013 may have declined to even lower levels as a result of these events, but this question can only be answered with confidence after human observer-generated benthic cover estimates are generated for 2018. The apparent resilience of the *Porites*-dominated coral community along the submarine terrace in the Piti monitoring site, like the similar communities in the Tumon and East Agana sites, may not persist as sea surface temperatures continue to increase, and the frequency and severity of bleaching events increases in response. The dominance of the coral community by a small number of *Porites* species may make it more vulnerable to devastation by diseases, the virulence of which may be enhanced by warming ocean temperatures.

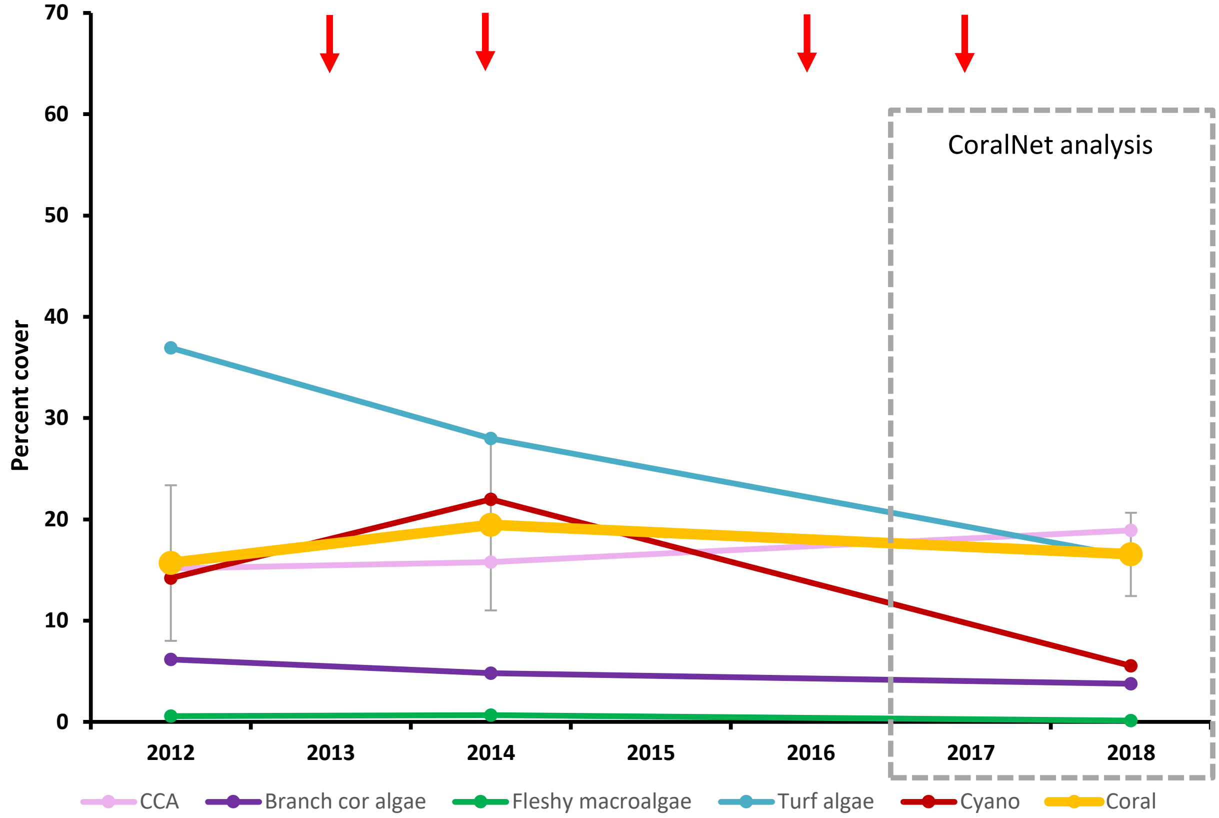


Figure 3.51. Percent cover of major benthic cover classes for the Piti monitoring site between 2012 and 2018. Photo transect images obtained in 2012 and 2014 were analyzed by human observers, while images from 2018 have thus far only been analyzed using the CoralNet algorithm (full automation). As described above, comparisons of results generated by the CoralNet algorithm and human observers for the same set of images indicate the CoralNet algorithm achieved a high degree of accuracy for measures of percent coral cover (no greater than ±1.5% absolute coral cover or ±7% of human observer-generated values) but was less accurate for other major benthic cover classes. Thus, the apparent changes in the cover of non-coral classes after 2014 should be considered highly tentative until verified through an analysis of the 2018 images by human observers. Red arrows indicate the timing of significant coral bleaching events, including the historically severe 2013 and 2017 events. Note that survey years are not presented in regular annual increments, and thus the elapsed period of time between each pair of neighboring data varies from two to four years.

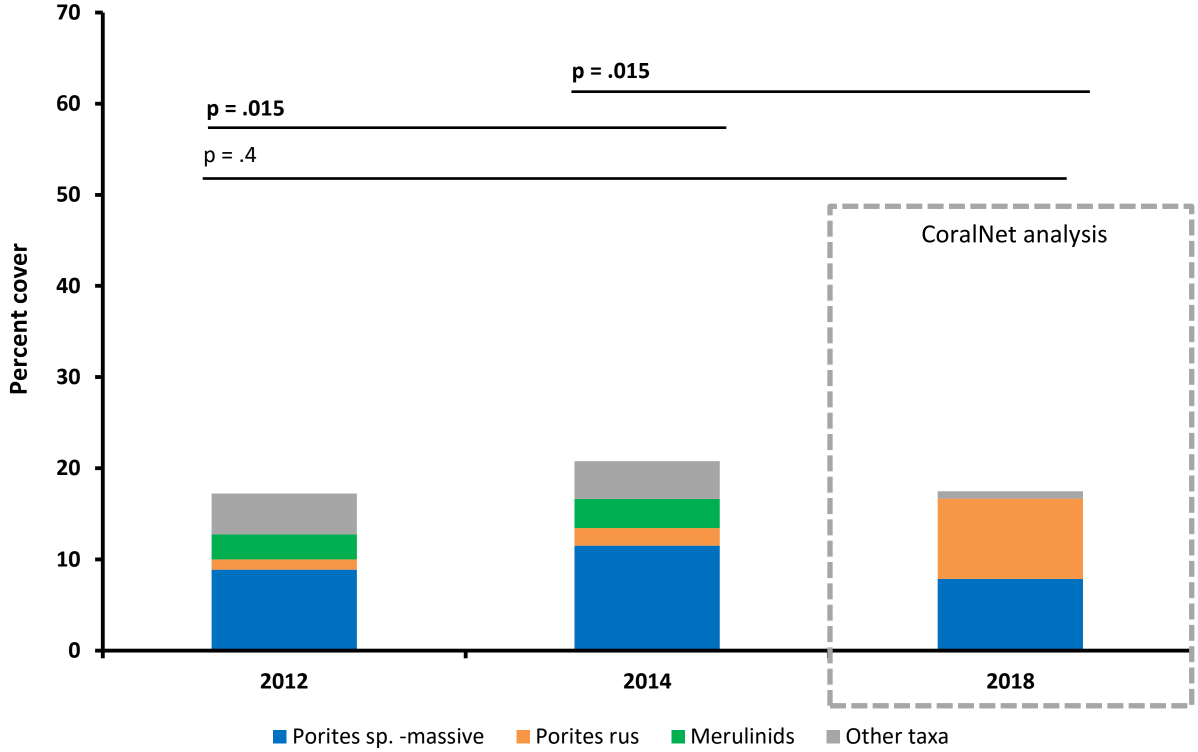


Figure 3.52. Percent cover of coral taxa for the Piti monitoring site between 2012 and 2018. Photo transect images obtained in 2012 and 2014 were analyzed by human observers, while images from 2018 have thus far only been analyzed using the CoralNet algorithm (full automation). Comparisons of results generated by the CoralNet algorithm and human observers for the same set of images indicate the CoralNet algorithm achieved a moderate degree of accuracy for measures of percent cover for *Porites rus* and massive *Porites* spp. (no greater than ±2.3% absolute cover or ±23% of human observer-generated values). Note that survey years are not presented in regular annual increments, and thus the elapsed period of time between each pair of neighboring data varies from two to four years.

3.2.3.3 ASSOCIATED BIOLOGICAL COMMUNITIES

Macroinvertebrates

An in-depth analysis of changes in macroinvertebrate communities at the Piti site between 2012 and 2018 has not yet been carried out, but, as was observed for the East Agana and modified Tumon sites during a similar period, a preliminary analysis indicates that the density of sea cucumbers declined by 60% during this period (Partover.test, p = 0.04). Further analysis is required to determine which sea cucumber species/species groups declined during this period. A statistically significant decline in the mean density of *Tridacna* spp. between 2012 and 2018 was also detected (Paired Wilcoxon signed ranks test, paired stations only, p = 0.03). Further analysis is required to understand the possible driver(s) of these significant declines. Changes in other macroinvertebrate groups at the Piti site between 2012 and 2018 will also be examined.

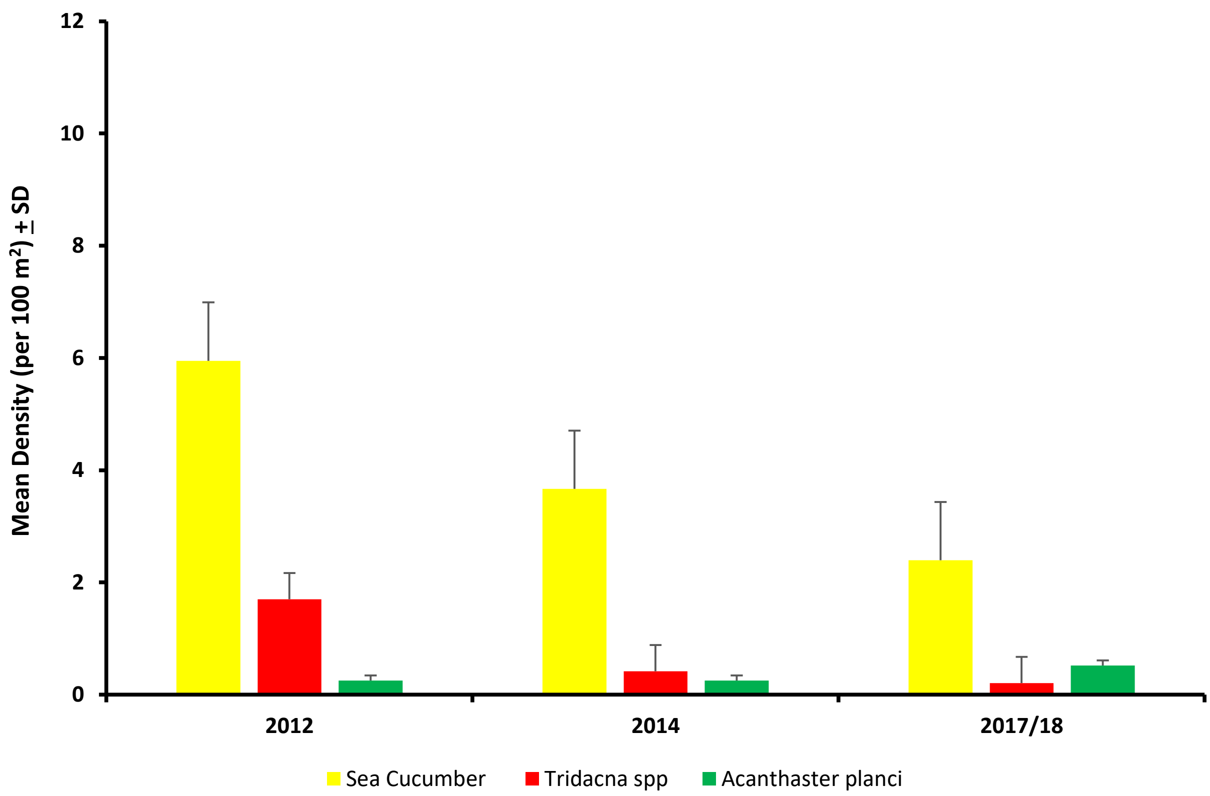


Figure 3.53. Mean density (ind/100 m^2) for macroinvertebrate species/groups of interest for the Piti site between 2012 and 2018. Error bars represent standard deviation.

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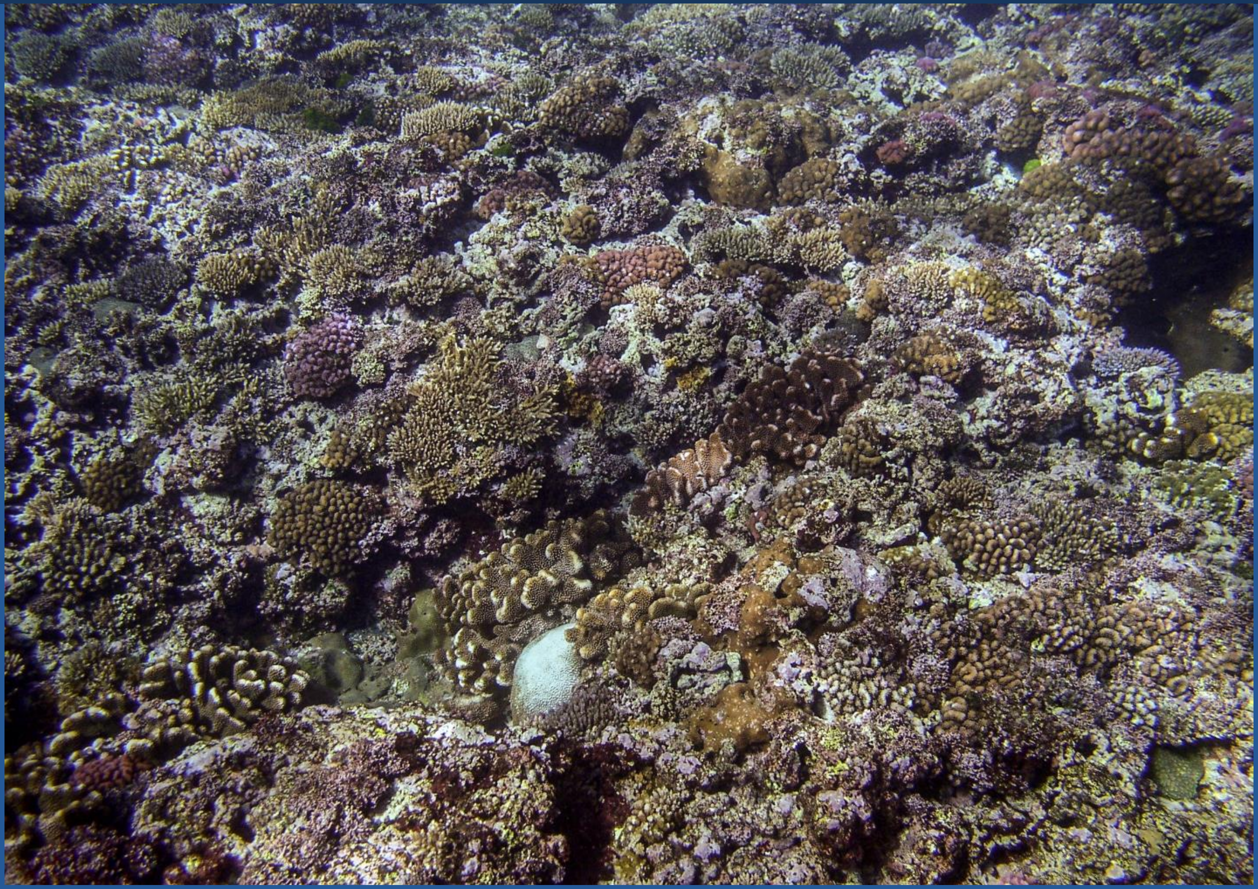
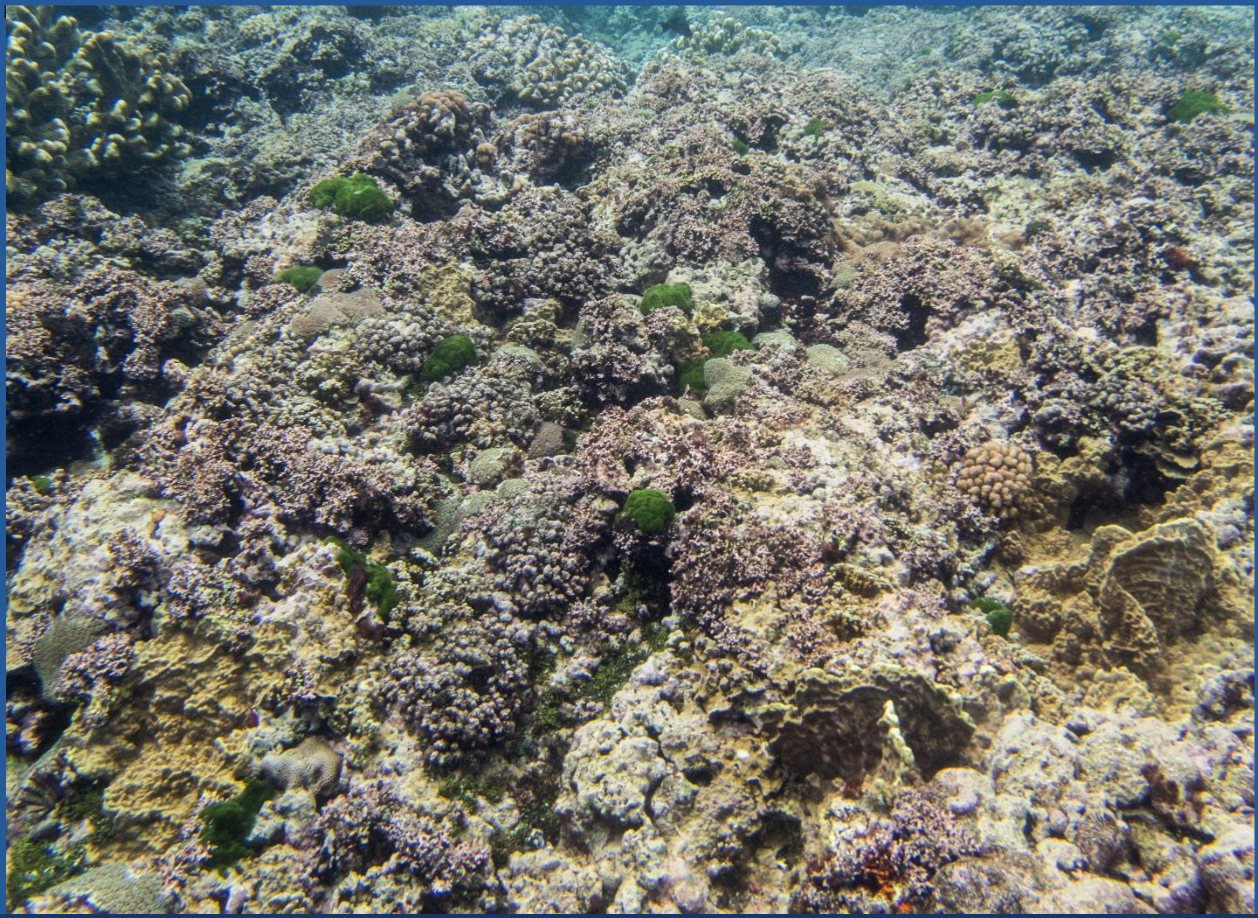
Photo (next page): Coral reef communities along the same stretch of the shallow (2.5 m), wave-exposed reaches of the seaward slope in West Agana Bay in 2007 (top) and in 2018 (bottom). Prior to the onset of multiple, severe coral bleaching events beginning in 2013 the coral community at this reef area, as with other areas around the island exposed to a moderate amount of wave energy, was among the most stunning, and hosted coral species rarely found outside of this relatively narrow band of reef. The reef communities in this “goldilocks” reef zone appeared to be resilient to local stressors, such as crown of thorns outbreaks, impacted herbivore populations, and degraded water quality, while their deeper counterparts lost significant amounts of coral over the last few decades or were dominated by just a handful of stress-tolerant coral species. But the abundance of stress-susceptible corals, especially *Acropora* spp., made these shallow reef front communities especially vulnerable to heat and light stress during the multiple, severe coral bleaching events that affected Guam’s reefs between 2013 and 2017. The data collected at slightly greater depth (5 m) along the reef front during these events showed significant declines around the island, and the loss of almost 60% of all corals along the east coast. While data weren’t collected at the shallower depths represented in these images, observations suggest that the loss of coral was even greater, with some corals that were locally abundant almost completely disappearing from Guam’s reefs. The GLTMP is shifting some of the program’s resources towards tracking the recovery of these communities and will be prepared to document the impacts of future bleaching events on Guam’s shallow reefs front communities.





Appendix A.

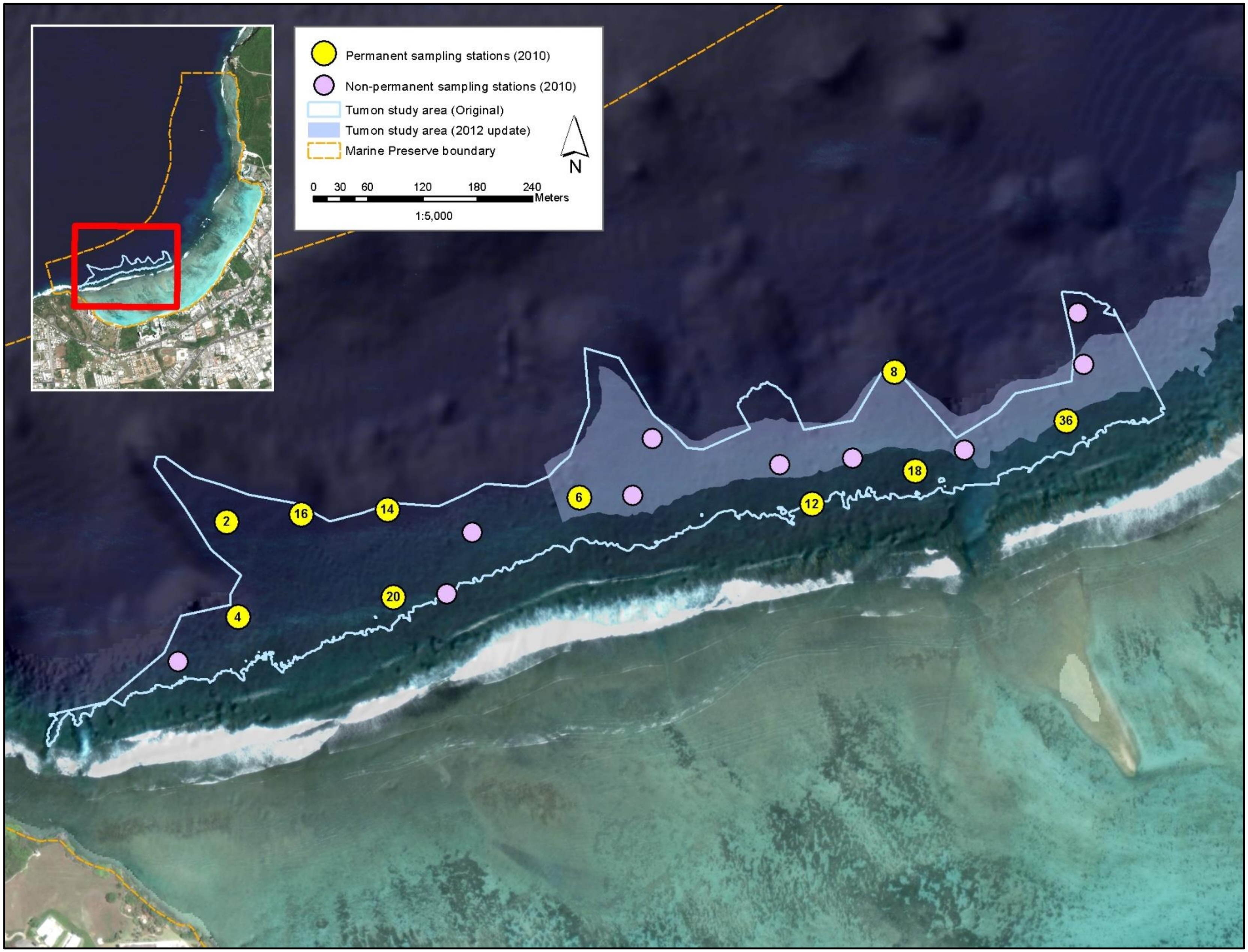
Guam Long-term Coral Reef Monitoring Program data collection activities at High Priority Reef Areas between 2009 and 2018

Appendix A.

Site	Survey year	No. perm. (P) stations surveyed	No. non-perm. (NP) stations surveyed	Fish Belt Transect		Fish SPC		Benthic cover		Corals		Macro-inverts		Rugosity	
				P	NP	P	NP	P	NP	P	NP	P	NP	P	NP
Achang	2014	11	3	-	-	8	3	11	3	8	3	11	3	8	3
	2018	10	10	-	-	10	10	10	10	9	0	10	0	9	0
Cocos-East	2014	3*	4	-	-	3	4	3	2	0	0	3	2	2	0
	2018	10	0	-	-	0	0	10	0	3	0	7	0	3	0
East Agana Bay	2010	10	10	10	10	10	10	10	10	10	10	5	10	0	0
	2012	10	0	-	-	0	0	10	0	10	0	10	0	10	0
	2014	10	3	-	-	0	0	10	0	10	0	10	0	10	0
	2015	10	0	-	-	10	10	10	0	10	0	10	0	10	0
	2017	10	12	-	-	10	12	10	12	10	0	10	0	9	0
	2018	10	0	-	-	0	0	10	0	0	0	10	0	10	0
Fouha Bay	2015	3, 5, 5	-	-	-	5, 5	-	13	-	13	-	13	-	13	-
Piti Bay	2012	4, 6	4, 6	-	-	6	8	10	10	10	10	10	10	8	10
	2014	4, 6	1, 1	-	-	10	2	10	2	10	2	10	2	4	1
	2018	10	10	-	-	10	10	10	10	3	0	3	0	3	0
Tumon Bay-2009	2009	2	5		2	1	4	2	5	2	5	0	0	0	0
Tumon Bay (original)	2010	10	10	10	10	10	10	10	10	10	10	8	7	0	0
Tumon Bay (modified)	2012	12	9	-	-	2	2	12	9	12	9	12	9	12	9
	2014	12	5	-	-	0	5	12	4	12	4	12	4	12	4
	2015	12	10	-	-	12	10	12	10	12	10	12	10	12	10
	2017	12	10	-	-	12	10	12	10	12	2	12	2	12	2
	2018	12	0	-	-	0	0	12		4	0	12	0	12	0

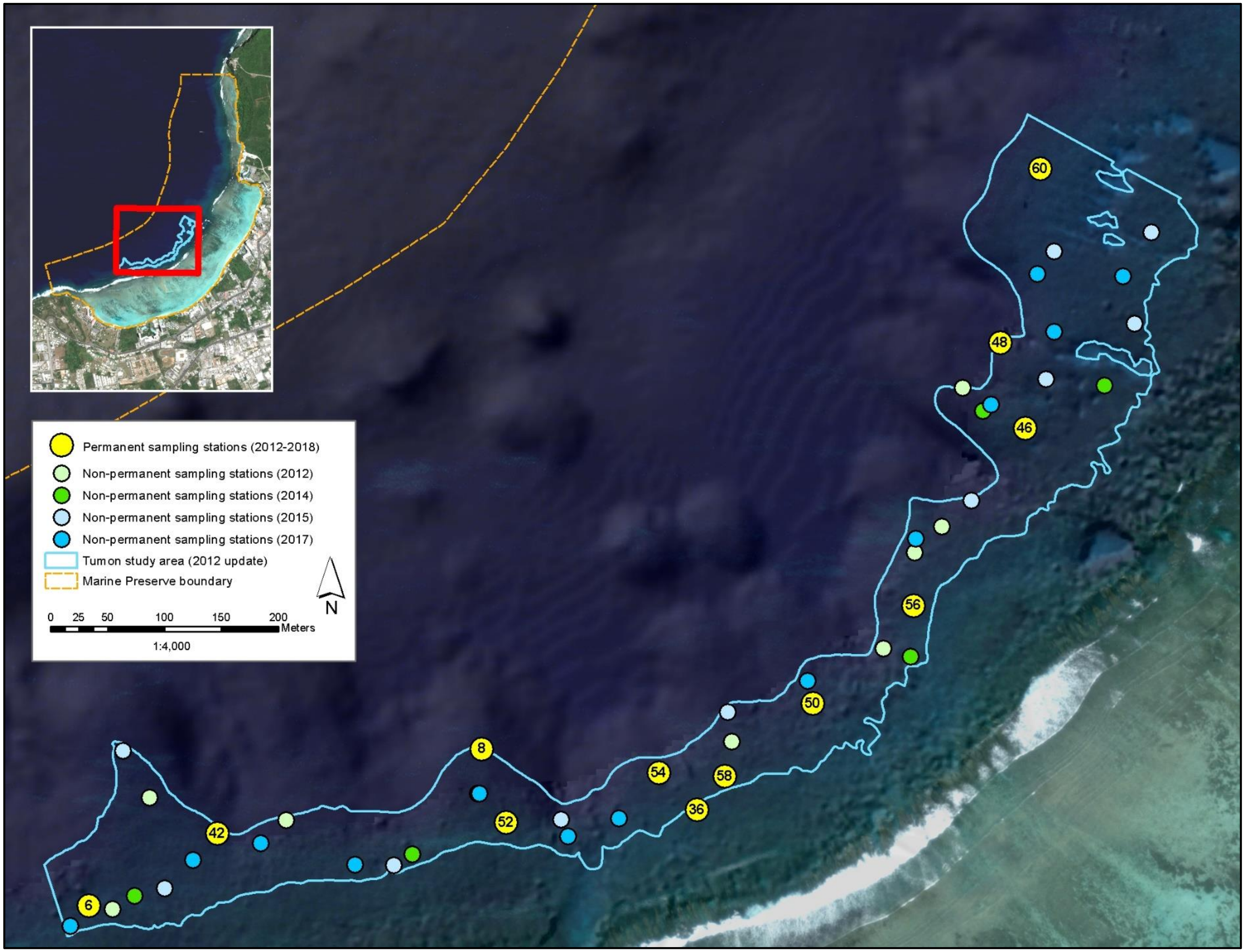
Appendix B.

Map of the original Tumon Bay site boundaries and the location of sampling stations surveyed in 2010


Permanent sampling stations (2010)
Non-permanent sampling stations (2010)
Tumon study area (Original)
Tumon study area (2012 update)
Marine Preserve boundary
N
0 30 60 120 180 240 Meters
1:5,000
2
16
14
4
20
6
12
8
18
36

Appendix C.

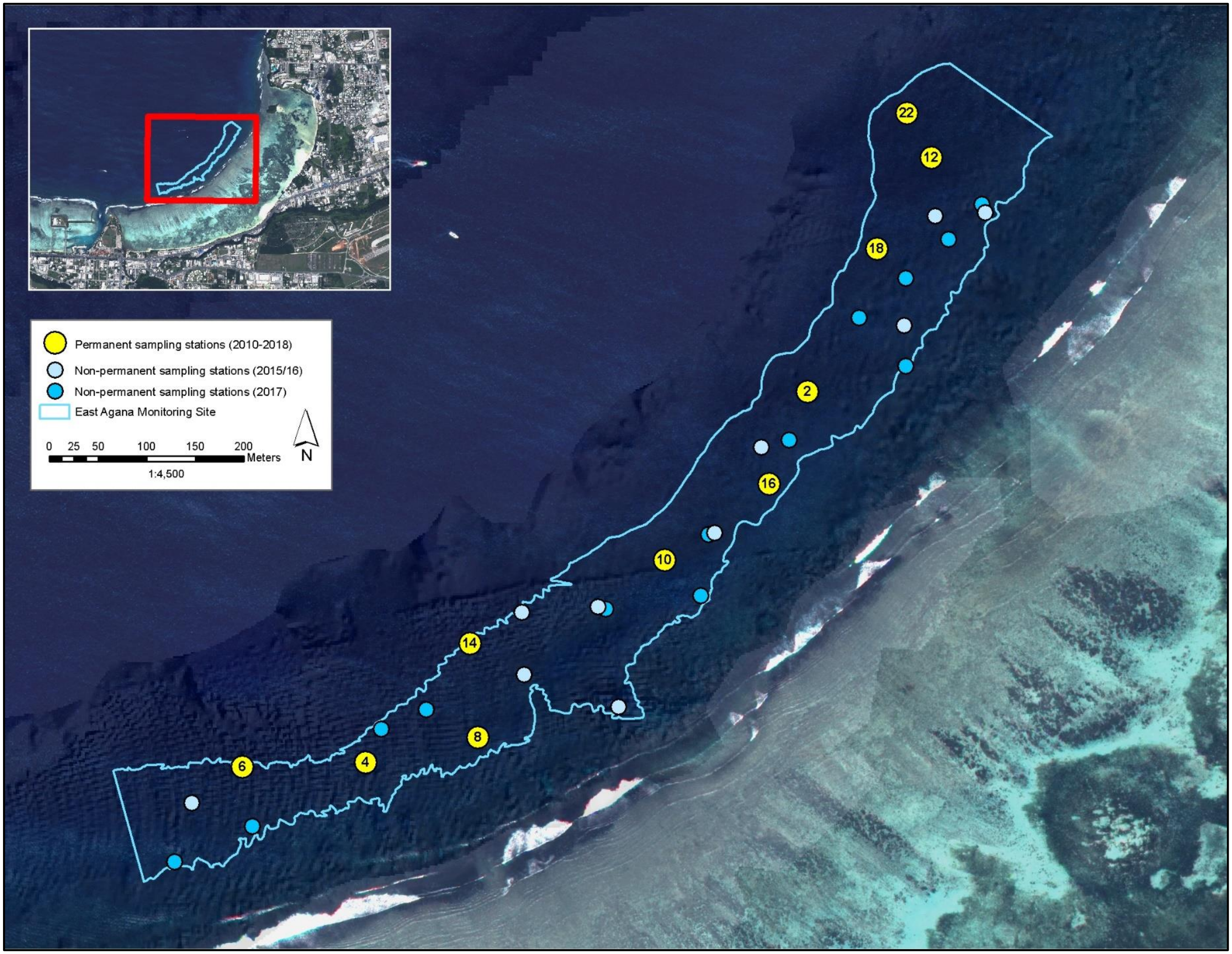
Map of the modified Tumon Bay site boundaries and the location of sampling stations surveyed between 2012 and 2018



Permanent sampling stations (2012-2018)
Non-permanent sampling stations (2012)
Non-permanent sampling stations (2014)
Non-permanent sampling stations (2015)
Non-permanent sampling stations (2017)
Tumon study area (2012 update)
Marine Preserve boundary
N
0 25 50 100 150 200
Meters
1:4,000
60
48
46
56
50
8
54
58
36
52
42
6

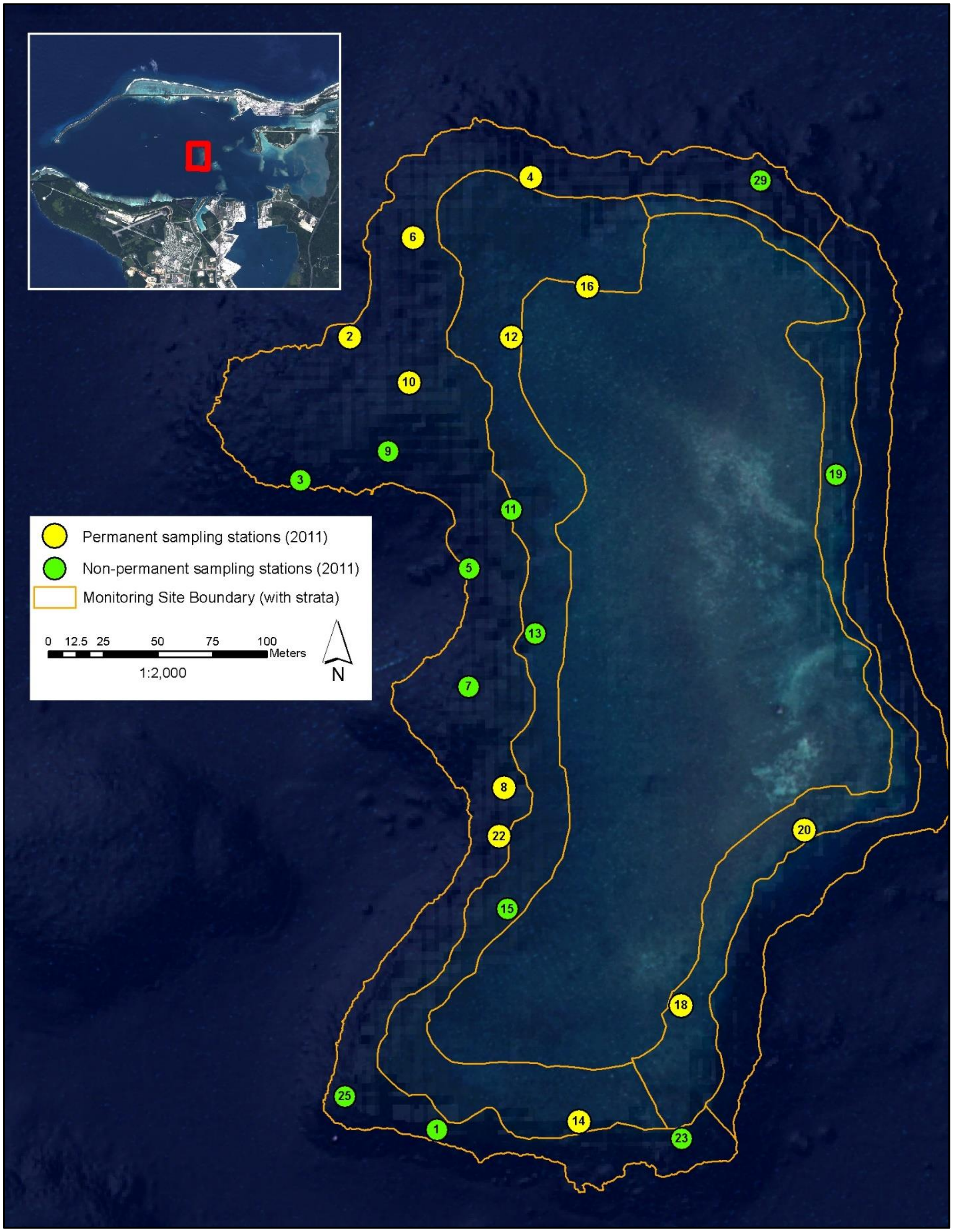
Appendix D.

Map of the East Agana Bay site boundaries and the location of sampling stations surveyed between 2010 and 2018


Permanent sampling stations (2010-2018)
Non-permanent sampling stations (2015/16)
Non-permanent sampling stations (2017)
East Agana Monitoring Site
0 25 50 100 150 200 Meters
1:4,500
N
22
12
18
2
16
10
14
8
6
4

Appendix E.

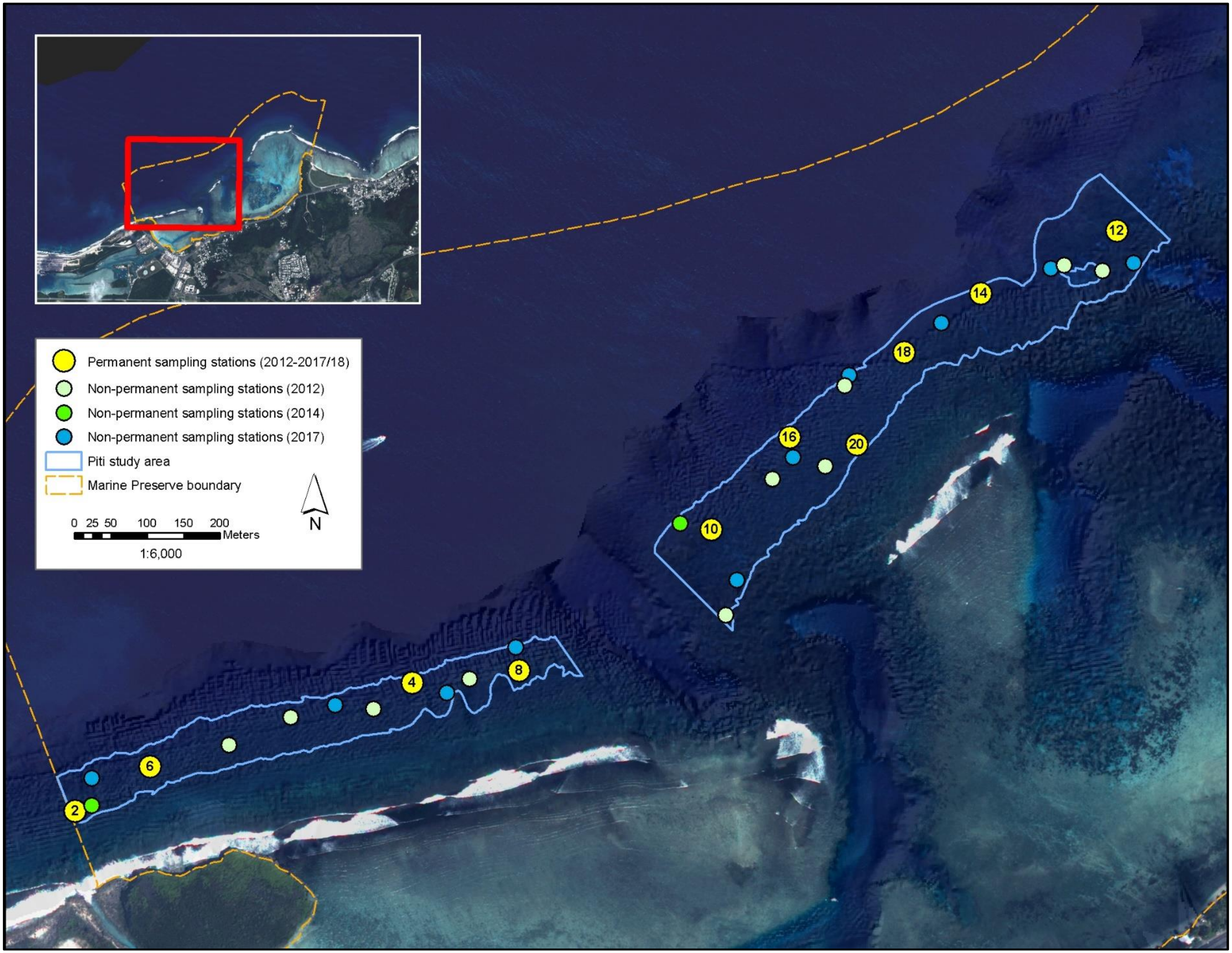
Map of the Western Shoals site boundaries and the location of sampling stations surveyed in 2011



Permanent sampling stations (2011)
Non-permanent sampling stations (2011)
Monitoring Site Boundary (with strata)
0 12.5 25 50 75 100
Meters
1:2,000
N
4
29
6
16
2
12
10
9
3
19
11
5
13
7
8
22
20
15
18
25
1
14
23

Appendix F.

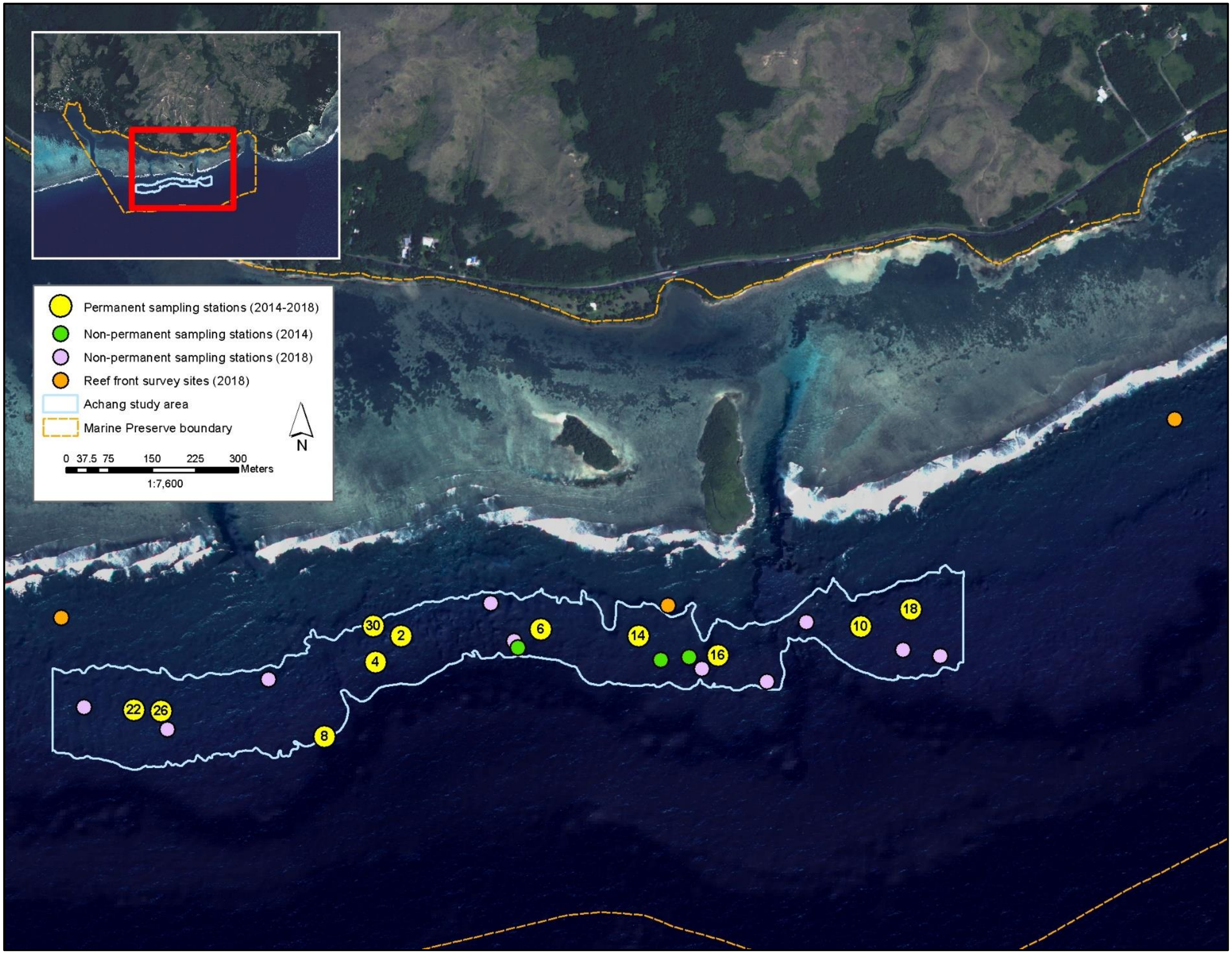
Map of the Piti site boundaries and the location of sampling stations surveyed between 2012 and 2018



Permanent sampling stations (2012-2017/18)
Non-permanent sampling stations (2012)
Non-permanent sampling stations (2014)
Non-permanent sampling stations (2017)
Piti study area
Marine Preserve boundary
0 25 50 100 150 200
Meters
1:6,000
N
2
4
6
8
10
12
14
16
18
20

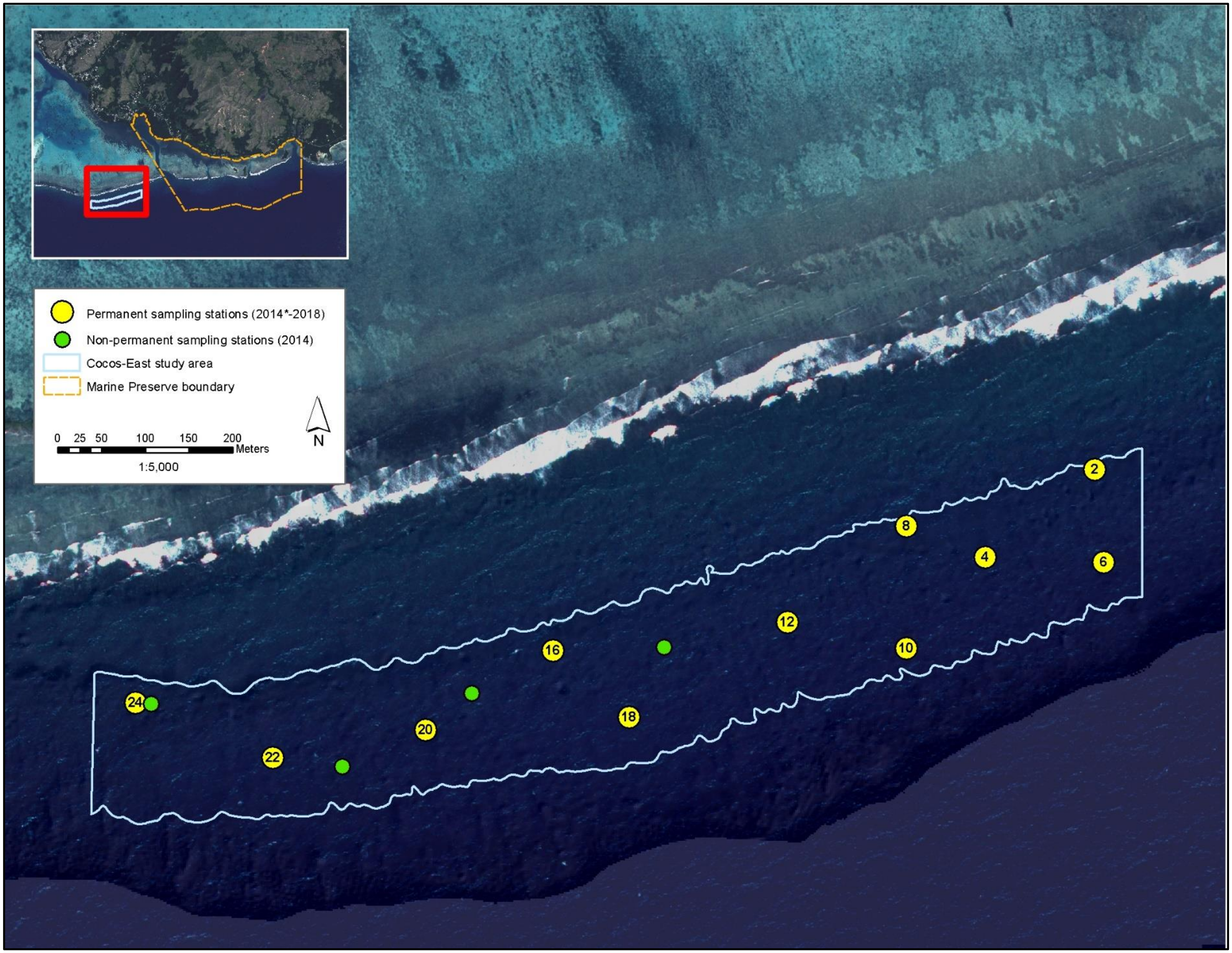
Appendix G.

Map of the Achang site boundaries and the location of sampling stations surveyed in 2014 and 2018


Permanent sampling stations (2014-2018)
Non-permanent sampling stations (2014)
Non-permanent sampling stations (2018)
Reef front survey sites (2018)
Achang study area
Marine Preserve boundary
N
0 37.5 75 150 225 300
Meters
1:7,600
30
2
4
6
14
16
10
18
22
26
8

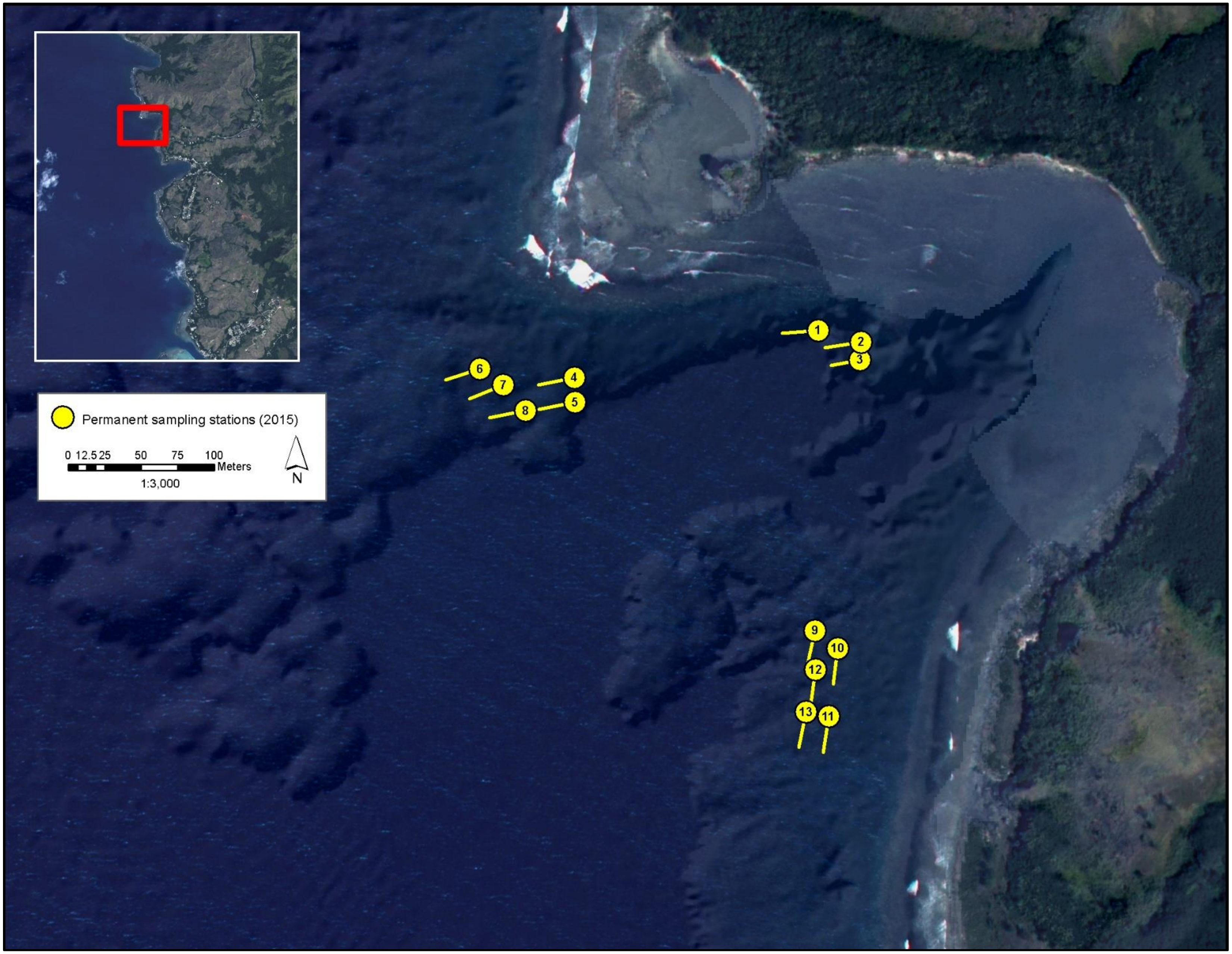
Appendix H.

Map of the Cocos-East site boundaries and the location of sampling stations surveyed in 2014 and 2018


Permanent sampling stations (2014*-2018)
Non-permanent sampling stations (2014)
Cocos-East study area
Marine Preserve boundary
0 25 50 100 150 200
Meters
1:5,000
N
2
8
4
6
12
16
10
24
20
18
22

Appendix I.

Map of the Fouha Bay site boundaries and the location of sampling stations surveyed in 2015


Permanent sampling stations (2015)
0 12.5 25 50 75 100
Meters
1:3,000
N
1
2
3
4
5
6
7
8
9
10
11
12
13

Appendix J.

Comprehensive list of conferences attended by GLTMP staff between 2009 and 2018

Appendix J. Comprehensive list of conferences attended by GLTMP staff between 2009 and 2018.

- Presentation (DB): "Assessing the resilience of Guam's reefs to climate change impacts", 4th Guam Coral Reef Symposium, March 27, 2018, Guam
- Abstract co-author (DB): "Bleaching mitigation and restoration of Micronesian staghorn Acropora", presented by Whitney Hoot on behalf of Dr. Laurie Raymundo, 2018 Society for Ecological Restoration Australasia (SERA), September 25–28, Brisbane, Australia
- Abstract co-author (DB): Guam's tropical reefs: Biodiversity and community dynamics of a unique ecosystem in flux," presented by Dr. Tom Schils, 2017 Island Sustainability Conference, April 19–21, Guam
- Presentation (DB): "Home is where the waves are: Corals in Guam's exposed reef fronts appear resilient to local stressors but vulnerable to regional warming," 13th International Coral Reef Symposium, June 19–24, 2016, Honolulu, Hawai'i; Co-authors: P. Houk, T. Reynolds, V. Brown, L. Raymundo
- Presentation (RM): "Let the reef be your guide: An adaptive approach to monitoring on Guam," 13th International Coral Reef Symposium, June 19–24, Honolulu, Hawai'i; Co-authors: D. Burdick, P. Houk
- Abstract co-author (DB): "An ounce of prevention: Building rapid response capacity for acute reef impacts on Guam," presented by V. Brown, 13th International Coral Reef Symposium, June 19–24, Honolulu, Hawai'i
- Abstract co-author (DB): "Guam's staghorn Acropora populations require managing for resilience," presented by V. Lapacek, 13th International Coral Reef Symposium, June 19–24, Honolulu, Hawai'i; Co-authors: L. Raymundo, J. Guest
- Presentation (DB): "Home is where the waves are: Corals in Guam's exposed reef fronts appear resilient to local stressors but vulnerable to regional warming," 2016 Island Sustainability Conference, April 11-15, Guam; Co-authors: P. Houk, T. Reynolds, V. Brown, L. Raymundo
- Abstract co-author (DB): "Guam's staghorn Acropora populations require managing for resilience," presented by V. Lapacek, 2016 Island Sustainability Conference, April 11-15, Guam; Co-authors: L. Raymundo, J. Guest
- Presentation (DB): "The status of Guam's shallow coral reefs," 36th U.S. Coral Reef Task Force meeting, September 22–23, 2016
- Presentation (RM): "Let the reef be your guide: Adaptive monitoring techniques," Guam Coral Reef Symposium, April 14, 2015, Guam; Co-authors: D. Burdick, P. Houk
- Abstract co-author: "Back-to-back bleaching episodes results in extensive loss of shallow staghorn *Acropora* in Guam," presented by L. Raymundo, 2015 Guam Coral Reef Symposium, June 24, 2015
- Presentation (DB): "A quantitative description of Guam's reef front coral communities and a preliminary analysis of their robustness to local stressors," 3rd Asia-Pacific Coral Reef Symposium, June 23–27, 2014, Taiwan; Co-authors: P. Houk, T. Reynolds, L. Raymundo
- Abstract co-author (DB): "The aftermath of Guam's 2013 coral bleaching event," presented by T. Reynolds, 3rd Asia-Pacific Coral Reef Symposium, June 23–27, 2014, Taiwan; Other co-authors: P. Houk, L. Raymundo
- Presentation (DB): "Where are Guam's canaries in the coal mine? Mapping Guam's staghorn coral thickets," Guam Coral Reef Symposium, June 24, 2013, Guam
- Poster presentation (DB): "The effectiveness of macroalgal reduction and *Diadema antillarum* addition in maintaining algal turfs and facilitating coral recovery," 11th International Coral Reef Symposium, July 7–11, 2008, Fort Lauderdale, Florida
- Presentation (DB): "Coastal Mapping Products," 3rd Regional Conference of the Pacific Association of Land Professionals, March 17–20, 2009, Guam

Appendix K.

Comprehensive list of workshop and training participation by GLTMP staff between 2007 and 2018

Appendix K. Comprehensive list of workshop and training participation by GTLMP staff between 2007 and 2018

- Climate-smart Design Workshop: Incorporating climate-smart design considerations into coral reef management efforts, 24–25 September 2018, Guam; participants (DB, AH)
- Extreme tides forecasting workshops, 19 July 2018, Guam: participants (DB, RLM)
- PRIMER multivariate statistics software training, 25–29 June 2018, Coffs Harbor (AH); 14–18 March 2016, Ponte Vedra Beach, Florida (DB); 4–8 November 2013, Plymouth, UK (RM)
- NOAA CRCP CoRIS data management workshop, 31 January 2018, Guam; presenter (DB) and participants (DB, AH)
- Guam Coastal Climate Change Resilience Workshop II: Climate change and coastal ecosystems in Guam-Management, sustainability forecasts and community engagement, 30 March 2017, Guam; presenter (DB) and participants (DB)
- SECORE Guam 2017 Coral Restoration Workshops, 15–24 April 2017, Guam: presenter (DB) and participant (DB)
- Coral Reef Conservation Program Card Workshop, 30–31 January 2017, Guam: presenter (DB) and participants (DB)
- Micronesia Challenge Scorecard Meeting (3rd Marine Measures Working Group Meting), 23–25 August 2016; participant (RLM)
- Species identification of ESA-listed Indo-Pacific corals workshop, 25–26 June 2016, Honolulu, Hawai'i; presenter/participant (DB)
- Coral Bleaching Symposium, 19 May 2016, Guam; participants (DB, RLM)
- Recreational Tour Operator workshop, 29 September 2016, Guam; presenter/participant (DB)
- Guam Coastal Climate Change Resilience Workshop I: Climate change and coastal ecosystems in Guam-Management, sustainability forecasts and community engagement, 2 March 2016, Guam; Co-facilitator (DB) and participants (DB)
- NOAA PIFSC Reef Fish Rapid Ecological Assessment method training, 27 September 2014, Guam (DB and AH)
- 7th Micronesia Challenge Measures Working Group Meeting, 21–23 September 2014, Guam; participant (DB)
- 2014 SECORE Workshop Guam, 14–24 July 2014, Guam; presenter (DB) and participants (DB)
- Climate Change Adaptation Outreach and Planning Training, 10–14 March 2014, Guam; participant (DB)
- 2013 SECORE Workshop Guam, 25 July–4 August 2013, Guam; presenter (DB) and participants (DB, RLM)
- Coral Health Impacts Workshops, 14–18 January 2013, Guam; presenter/facilitator (DB), participant (RLM)
- Motorboat Operators Certification Course and Open-water Module, 26–30 March 2012, Honolulu, Hawai'i; participant (DB)
- Finalizing the Regional MPA Monitoring Protocol: Coral Reef Monitoring and 3rd Micronesia Challenge Marine Measures Group Workshop (2nd Marine Measures Working Group Meeting), 6–11 February 2012, Palau
- Presentation (DB): "Stormwater impacts to Guam's aquatic resources: Why we need to protect streams, wetlands, and reefs," Co-presented with V. Brown, Guam Stormwater Workshop, 27–29 July 2011, Guam
- Responding to Climate Change: Training of Trainers, 3–7 June 2011, Palau; participant (DB)

Appendix K. Continued.

- Data Management and Analysis Workshop, 8–12 November 2010, Saipan, CNMI; participating (DB)
- CSI for Coral Reefs: Investigative and Enforcement Forensics Field Training Workshop, 14–18 June 2010, Guam; participant (DB)
- Moving Toward Measuring Our Effectiveness: The 2nd Meeting of the MC Measures Working Group and PICRC-JICA Coral Reef Monitoring Project Meeting, 15–19 February 2010, Palau; participant (DB)
- Guam Reef Resilience and Climate Change Workshop, 17–20 August 2009, Guam; presenter/participant (DB)
- Hawai'i Geospatial Modeling and Analysis Workshop: SWARS Focus, 10–14 August 2009, Honolulu, Hawai'i; participant (DB)
- Guam Conservation Action Plan (CAP) Workshop, 6–7 August 2009, Guam; participant (DB)
- Getting Maps and FIA Data in the Hands of the Users Workshop/State-wide Assessment and Resource Strategy Kickoff, 27 April–1 May 2009, Palau; participant (DB)
- NOAA Guam Natural Resources Damage Assessment (NRDA) Workshop, 4–6 November 2008, Guam (DB)
- Save Our Reefs: Recreational Users Stewardship Workshop, 25 September 2008, Guam; presenter (DB)
- Moving Toward Measuring Our Effectiveness: The 1st Meeting of the Micronesia Challenge Measures Working Group, 2–6 June 2008, Pohnpei; participant (DB)
- PaCREIOS Workshop, November 2008, Honolulu, Hawai'i; presenter/participant (DB)
- Watershed and Stormwater Management Workshop, 11–13 February 2008, Guam; participant (DB)
- Responding to Climate Change: A Workshop for Coral Reef Managers, 27–30 August 2007, American Samoa; participant (DB)
- Coral Disease Assessment and Outbreak Training, 27 February–3 March 2007, Guam; participant (DB)

Appendix L.

Comprehensive list of publications produced by the GLTMP or to which GLTMP staff contributed

Appendix L. Comprehensive list of publications produced by the GLTMP or to which GLTMP staff contributed.

Minton, D., D. Burdick, and V. Brown. In prep. Changes in coral community structure across a sediment gradient in Fouha Bay, Guam.

Raymundo, L., D. Burdick, W. Hoot, R. Miller, V. Brown, T. Reynolds, and J. Gault. In review. Successive bleaching events cause mass coral mortality in Guam, Micronesia.

Burdick, D. and L. Raymundo. 2018. An interim report of the *Comprehensive Long-term Coral Reef Monitoring at Permanent Sites on Guam* project. Report submitted to the NOAA Coral Reef Conservation Program.

Maynard, J., S. Johnson, D. Burdick, A. Jarrett, J. Gault, J. Idechong, R. Miller, G. Williams, S. Heron, and L. Raymundo. 2017. Coral reef resilience to climate change in Guam in 2016. NOAA Coral Reef Conservation Program. NOAA Technical Memorandum CRCP29. Available at https://www.coris.noaa.gov/activities/guam_coral_resilience/

Raymundo, L., D. Burdick, V. Lapacek, R. Miller, V. Brown. 2017. Anomalous temperatures and extreme tides: Guam staghorn *Acropora* succumb to a double threat. Marine Ecology Progress Series 564:47-55. Available at https://www.int-res.com/abstracts/meps/v564/p47-55/ or upon request.

Fenner, D. and D. Burdick. 2016. Field identification guide to the threatened corals of the U.S. Pacific Islands. NOAA National Marine Fisheries Service, Pacific Islands Regional Office, Protected Resources Division.

Hoot, W. and D. Burdick. 2016. Guam Coral Bleaching Response Plan. Bureau of Statistics and Plans.

Reynolds, T., D. Burdick, P. Houk, L. Raymundo, S. Johnson. 2014. Unprecedented coral bleaching across the Mariana Archipelago. Coral Reefs 33: 499. Available at https://link.springer.com/article/10.1007/s00338-014-1139-0

Boulay, J., D. Burdick, A. Halford, J. McIlwain, and I. Baums. 2014. Genetic connectivity and spatial clonal structure in a dominant staghorn coral on reefs around Guam. Chapter 5, Dissertation in Biology, The Pennsylvania State University.

Burdick, D., R. Miller. 2012. Comprehensive long-term monitoring at permanent sites on Guam: 2012 status report. Report submitted to the NOAA Coral Reef Conservation Program. Available at https://repository.library.noaa.gov/view/noaa/991

Burdick, D., V. Brown. 2011. Comprehensive long-term monitoring at permanent sites in Guam: Report of program status and presentation of preliminary baseline data and power analyses results for Tumon Bay, East Agana Bay, and Western Shoals sites. Report submitted to the NOAA Coral Reef Conservation Program. Available at https://www.coris.noaa.gov/search/catalog/search/resource/details.page?uuid=%7B9AF65D1F-668E-4D2B-99A0-4B0D2907F1A8%7D

Appendix L. Continued.

Minton, D., D. Burdick, J. den Haan, S. Kolinksi, and T. Schils. 2009. Comparison of a photographic and in situ method to assess the coral reef benthic community in Apra Harbor, Guam. Prepared for Naval Facilities Engineering Command Pacific, Pearl Harbor, Hawai'i.

Goldberg, J., K. Adams, J. Albert, J. Asher, P. Brown, V. Brown, D. Burdick, B. Carroll, P. Craig, D. Fenner, C. Fillmed, V. Fread, M. Gawel, A. George, Y. Golbuu, L. goldman, C. Graham, A. Hall, M. Hasurmai, L. Jacob, D. Jacobson, E. Joseph, J. Kenyon, W. Kostka, T. Leberer, M. Luckymis, E. Lundblad, S. Malakai, J. Maragos, A. Marcus, S. Marino, D. Mathias, J. McIlwain, J. Miller, D. Minton, M. Nadon, S. Palik, N. Pioppi, L. Raymundo, B. Richards, M. Sebater, R. Schroeder, P. Schuup, E. Smith, A. Takesy, and B. Zgliczynski. 2008. Status of Coral Reef Resources in Micronesia and American Samoa: 2008. pp. 199-212. In: Wilkinson (ed.), Status of Coral Reefs of the World: 2008.

Burdick, D., V. Brown, J. Asher, C. Caballes, M. Gawel, L. Goldman, A. Hall, J. Kenyon, T. Leberer, E. Lundblad, J. McIlwain, J. Miller, D. Minton, M. Nadon, N. Pioppi, L. Raymundo, B. Richards, R. Schroeder, P. Schupp, E. Smith, and B. Zgliczynski. 2008. Status of the Coral Reef Ecosystems of Guam. Bureau of Statistics and Plans, Guam Coastal Management Program. iv + 76 pp. Available at https://www.researchgate.net/publication/236590561_Status_of_the_Coral_Reef_Ecosystems_of_Guam

Burdick, D., V. Brown, J. Asher, M. Gawel, L. Goldman, A. Hall, J. Kenyon, T. Leberer, E. Lundblad, J. McIlwain, J. Miller, D. Minton, M. Nadon, N. Pioppi, L. Raymundo, B. Richards, R. Schroeder, P. Schupp, E. Smith, and B. Zgliczynski. 2008. The State of the Coral Reef Ecosystems of Guam. pp. 465-509. In: J.E. Waddell and A.M. Clarke (eds.). The State of the Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569 pp.