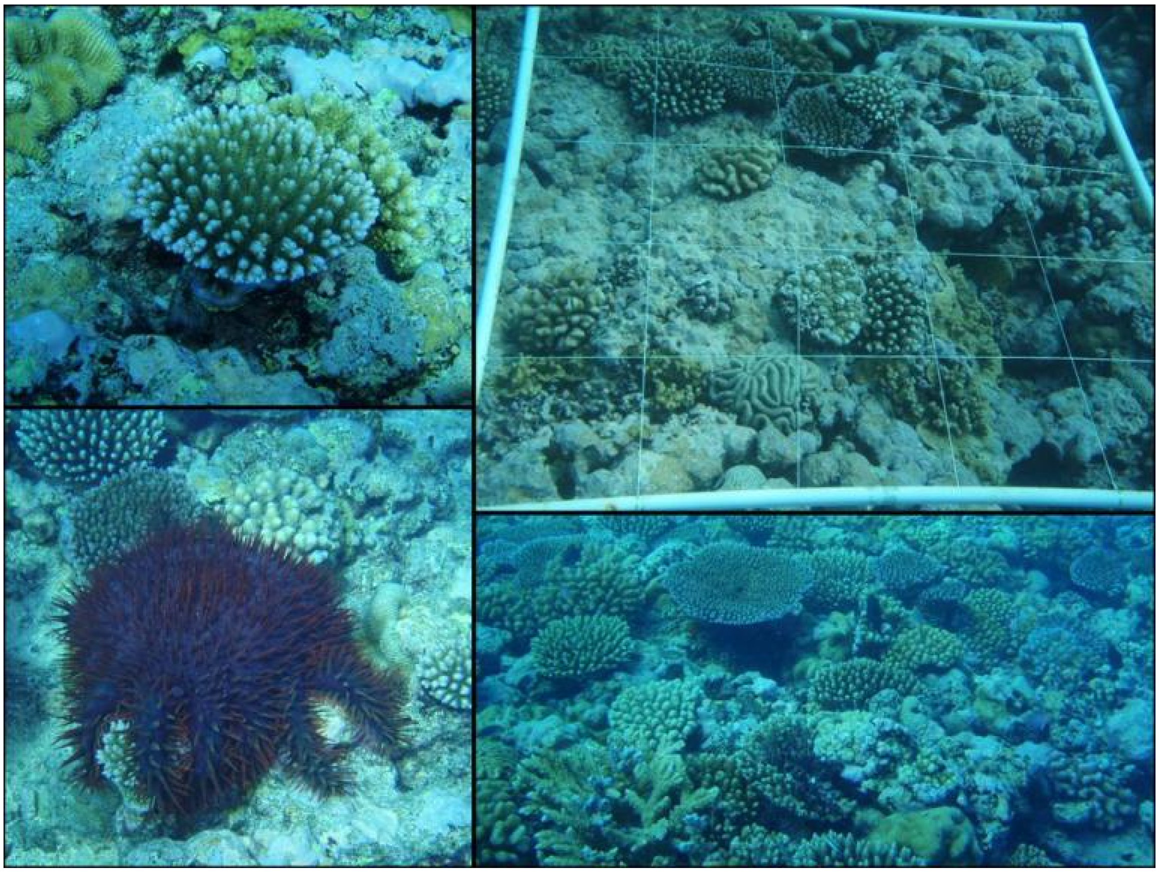
CORAL REEF SURVEY FOR AITUTAKI

For the Cook Islands National Environment Service



Photographs taken on the western fore reef of Aitutaki (2008)

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EXECUTIVE SUMMARY

Natural disturbances such as crown-of-thorns starfish outbreaks and coral bleaching in recent years have played a major role in shaping the reefs of Aitutaki today. Although, anthropogenic disturbances may play a major role as well, this remains difficult to comprehend due to lack of a consistent reef monitoring program on Aitutaki. The purpose of this study is to examine the current state of Aitutaki's reef as well as re-establish its monitoring program. Based on information provided by this survey, the reefs of Aitutaki may have recovered subsequent to the disturbance in the 1990s, however these were patchy possibly a result of the different environmental regimes experienced at each site. Coral cover range from 34% (at *Pacific RC*) to 8% (at *Pacific RI*), and size classes were predominantly in the 8 - 16 cm class (~ 8 - 10 year-old colonies) particularly at the more pristine reefs (*Pacific RC* and *Airport*). This suggests that these reefs recruited immediately after the COTS outbreak in the '90s. The high cover of crustose coralline algae (CCA) at *Atuatane* suggests that Aitutaki's reefs are still in the early stages of recovery. However, high CCA cover can hinder the growth and survival of newly settled corals, which may be the case on Aitutaki. The larger colonies only recorded at *Maina* in the 64 – 128 cm class suggested that the location of this site or possibly the establishment as a Marine Protected Area (MPA or *ra`ui*) may have provided a refuge (in terms of being remote) for corals and other marine life. Anthropogenic disturbances as well as COTS at *Maina* may be minimal. Low coral cover and high turf algae (TA) noted at *Atuatane (I)* and *Tokai'i* as well as small coral colony sizes due to die-backs suggested that these sites are experiencing poor conditions for coral growth and survival. The 2005 National Environment Service survey of Manuae proposed the possibility of Manuae being a source population for Aitutaki based on observed ocean currents at the time. Information obtained from NOAA'S Oceanwatch website on ocean surface currents around these islands also supports this possibility. Assuming that Manuae is a source population for Aitutaki, a decline in marine resources on Manuae may affect the recovery of Aitutaki's reefs.

INTRODUCTION

Aitutaki is located at 18º 52' S and 159º 46' W, about 260 km north of Rarotonga (Figure 1). The area of the mainland of this almost-atoll island is about 16 km^2 with a moderate-sized lagoon lined by 15 small islands (*motu*) around its perimeter. This predominantly sandy lagoon with numerous micro-atolls host a range of marine organisms, making it one of the most beautiful lagoons in the world that provides many benefits to the people of Aitutaki. These benefits include food resources, recreational activities, and eco-tourism. The increase in development over the last twenty years to meet the demand of the tourism industry along with natural disturbances (e.g., global warming, crown-of-thorns starfish or COTS outbreaks, and hurricanes) pose a threat to the existence of this delicate ecosystem. However, this is not limited to Aitutaki; similar effects are evident on other coral reefs around the world (Wilkinson, 2000).

The purpose of this survey is to examine the state of Aitutaki's reef as well as collect baseline information for future comparisons. During the 1990's, the reef of Aitutaki went through several natural disturbances: a bleaching event in the early '90s followed by a COTS outbreak degraded the reef to its current state. With any monitoring program, it is of foremost interest to distinguish natural and anthropogenic disturbances on reefs as management approaches differ accordingly. However, this has been difficult in Aitutaki because monitoring programs over the years have been inconsistent or records of previous surveys of this type (which could bring value to this report) could not be located (particularly the 1993 and 1995 surveys conducted by the Cook Islands National Environment Service or CINES). Although, the Ministry of Marine Resources (MMR) has conducted coral surveys in the past, their focus has been on quantifying exploitable resources rather than utilizing these resources as bio-indicators for assessing environmental impacts, using methodologies that are not comparable to this survey.

While impacts on reef community changes may not be directly caused by land-based activities, a consistent long-term monitoring program will provide a historical pattern reflecting these changes, which may enable us to pinpoint the causes of reef degradation and make the appropriate management plan to minimize the impact.

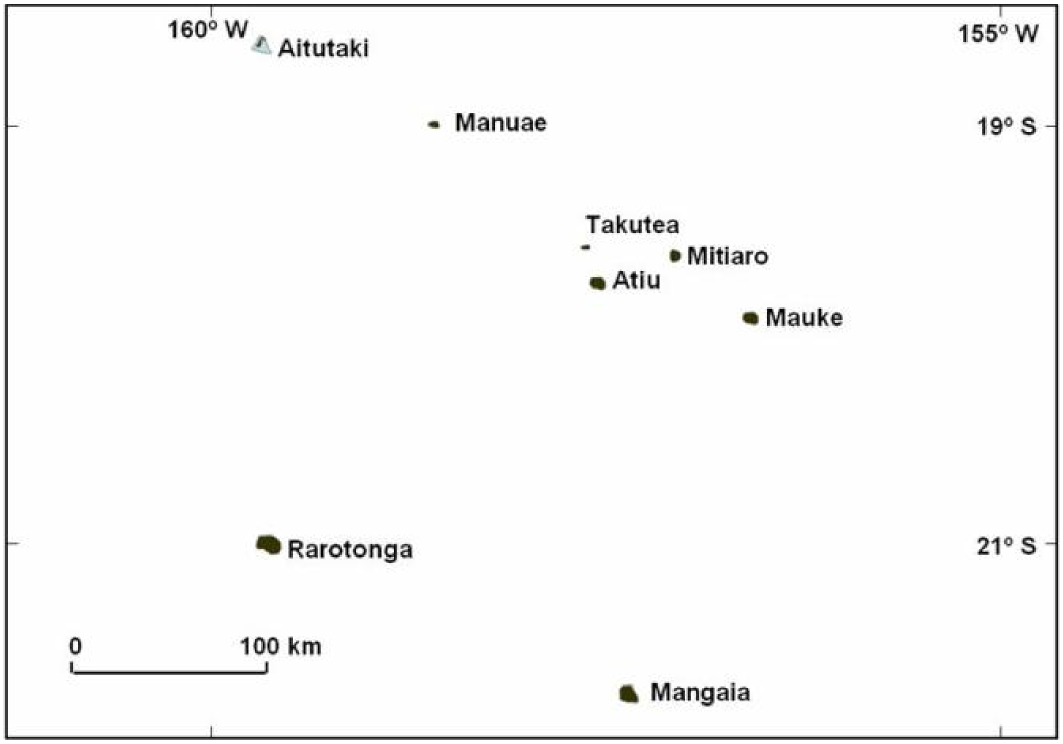

Figure 1. Top: Map of the Southern Cook Islands group. Bottom: map of Aitutaki (modified from Google Earth).

MATERIALS AND METHODS

The survey focused on the northwestern side of Aitutaki, an area most likely impacted by land-based development (see Figure 1; Appendix A). Three sites were established within the lagoon: *Main*a (control site; also an MPA), *Tokai'i* (non-MPA), and *Atuatan*e (adjacent to the newly established landfill). Four fore reef sites were established: *Atuatane* (directly offshore from the *Atuatane* lagoon site), *Pacific RC* (control site; northern side of major channel in the Pacific Resort area), *Pacific RI* (impact site; southern side of channel), and *Airport* site located at the western end of the runway where a proposed development is expected.

All sites were marked with a rebar and a GPS reading taken (Appendix B). The survey examined the following: 1) percent cover among corals and other benthos, 2) size distribution among corals, 3) species density of corals and macro-invertebrates, 4) species diversity of corals, and 5) a species inventory for all fore reef and lagoon sites. The remnant of larger colonies referred to in this survey as "die-back" corals were also noted. General observations (i.e., for species inventory data) were also made at other locations within the lagoon around the main island.

Transect deployment

Four 50-m transects (replicates) were deployed for all fore reef sites. Transects were placed following the reef contour at a depth of 7 m parallel to shore and laid consecutively at intervals of 10 m for *Atuatane*. For the remaining three sites, transects were stacked due to the frequent interruption of the reef by channels (see Appendix A for transect deployment).

Four 50-m transects were also deployed for all lagoon sites. Transects were deployed following the reef contour at depths ranging from 1 to 1.5 m laid consecutively at intervals of 10 m (see Appendix A for transect deployment) with the exception of *Atuatane*, which was laid at intervals of 10 m or more due to the patchiness of the reef at this site.

Benthic and macro-invertebrate surveys

Point Intercept (PI) and coral colony size was used to examine benthic communities. A two-meter belt transect (1 m on each side) was used for quantifying macro-invertebrates (i.e., sea urchins, sea cucumbers, *Tridacna* spp., *Trochus* spp., and COTS) at all sites. All species were recorded and identified to the lowest taxonomic level possible (i.e. genus and species). Species identification was verified using Randall and Myers (1983) and Veron (2000). Photographs were also taken at each site for a digital record (see CD attachment to the report).

Point Intercept (PI) Method

A 1-m^2 quadrat frame was tossed every 5 m along a 50-m transect for a total of 10 quadrats. The quadrat is lined with strings equally spaced dividing the quadrat into 25 sections providing 16 points where the strings intercept. Any substratum falling under each intercept was recorded and its percent cover calculated. Substrates included categories of corals, soft corals, algae (i.e., turf, crustose coralline, and macro), and other abiotic substratum (i.e., sand and pavement).

Coral Colony Size

Coral colony sizes were measured within each 1-m^2 quadrat. At every 20 m interval a 1 x 1 quadrat was tossed haphazardly to analyze coral communities (n = 8). The surface area of a coral within the quadrat was obtained by measuring the maximum length and width (perpendicular to length) along the general contour of each colony. A coral was only included in the quadrat if at least half of the colony falls within the edges of the quadrat frame. Information obtained from this method included population densities and geometric diameters. For geometric diameter (cm), colonies were grouped into several size classes: A (0 to <2 cm), B (2 to <4 cm), C (4 to <8 cm), D (8 to <16 cm), E (16 to <32 cm), F (32 to <64 cm), and G (64 to <128 cm).

DATA ANALYSIS

Microsoft Excel spreadsheet, PivotTable, and PivotChart were used for basic computations. PRIMER and STATISTICA software were used for graphical and comparative analysis. All four transects were used as replicates for the analysis of fore reef and lagoon sites.

Percent cover calculations

For benthic communities, the total number of points recorded for each category identified using the PI method was divided by 160 (total number of intersects per quadrat x 10 quadrats), and multiplied by 100 (see Eq. 1).

$$(1) \qquad \text{Percent cover} = \frac{\text{Category sum per transect}}{160} \cdot 100\%$$

An average percent cover for each site was calculated from the replicates.

Colony size calculation

The area of each colony was calculated using Eq. 2a, b and c:

(2a) Geometric diameter = $(\text{length} \cdot \text{width})^{1/2}$

(2b) Colony area = $\pi \cdot (\text{Geometric diameter}/2)^2$

(2c) Colony density (colonies/ m^2) = n/8.00 m^2

where n is the total number of colonies and 8.00 m^2 is the total area surveyed by 8 quadrat tosses.

Average density

Average density for macro-invertebrates were calculated for each site using Eq. 3:

$$(3) \qquad \text{Average density} = \frac{\text{Number of individuals per site / number of replicates}}{\text{Belt area } (100\ m^2 \text{ for inverts})}$$

Species diversity (see Clark & Warwick, 2001 for details)

Species diversity for corals was measured using the Shannon – Weiner index (H`), seen in Eq. 4:

$$(4) \qquad H` = - \textstyle\sum_i p_i (\log p_i)$$

where H` is the index of species diversity, and p_i is the proportion of total count belonging to the *i*th species.

Margalef's species richness (d) is a measure of the number of species present, making some allowance for the number of individuals. Species richness is calculated using Eq. 5 (S= number of species; N = number of individuals):

$$(5) \qquad d = \frac{(S - 1)}{\log (N)}$$

Pielou's evenness (J`) is a measure of equitability or how evenly individuals are distributed among different species. Evenness is calculated using Eq. 6:

$$(6) \qquad J` = \frac{H`}{\log (S)}$$

Statistical analysis

A similarity matrix (Bray-Curtis similarity) was constructed using PRIMER for fore reef and lagoon sites from percent cover values for each benthic category. Values were square-root transformed (for benthic communities) before matrix constructions. Coral and benthos abundances, as well as taxonomic checklists, were used to create Bray-Curtis similarity matrices.

ANOSIM and SIMPER

Analysis of Similarity (ANOSIM) testing was employed to evaluate the relationship between sites. These tests compare sites based upon ranked, species similarity measures. Coral species abundances were log transformed to create a Bray-Curtis dissimilarity matrix seen in Eq. 7:

$$d_{il} = 100\left\{1 - \frac{\sum_{j=1}^{n} | y_{ij} - y_{lj} |}{\sum_{j=1}^{n} (y_{ij} + y_{lj})}\right\} \quad (7)$$

where Σ represents the summation over all coral species, where the terms y_{ij} and y_{1j} represent the abundance of one species at two consecutive sample sites. The greater the dissimilarity between sites, the larger d (equation 4). The tests yielded R-statistics, which serve as a measure of site separation. R-values can range between -1 and 1. R values > 0.75 show complete separation between sites; R values > 0.5 show overlapping but clearly different sites; and R values < 0.25 shows sites that are barely distinguishable from each other. P-values were calculated for each R-statistic using a permutated test of random rearrangement, and comparing the true R-value with the randomly generated distribution. Similarity percentages (SIMPER) were subsequently calculated to examine the percent contribution of each coral or identified category to the measured ANOSIM differences (Clarke and Warwick, 2001). Data were log-transformed for SIMPER analysis and a 50% contribution cutoff implemented. ANOSIM results were graphically interpreted using non-metric, multi-dimensional scaling (MDS) (Clarke and Warwick, 2001). MDS is an ordination procedure that projects a dissimilarity matrix into two-dimensional space while preserving as much of the variation (distance) between sites as possible. A low stress value is an indicator of low error, similar to a measure of standard deviation (Clarke and Warwick, 2001).

RESULTS

Corals

Benthic communities

Benthic communities on the fore reef differed among sites with the highest coral cover recorded at *Pacific RC* (33.6%). Coral cover at *Atuatane, Airport*, and *Pacific RI* was 14.4%, 17.5%, and 7.9% respectively. Crustose coralline algae (CCA) cover was highest at *Atuatane* (70.2%) compared to all fore reef sites, while cover at *Airport*, *Pacific RI*, and *Pacific RC* was 45.9%, 30.9% and 23.6% respectively. Turf algae (TA) cover was highest at *Pacific RI* (60.9%), while cover at *Atuatane*, *Airport,* and *Pacific RC* was 15.3%, 34.7%, and 42.8% respectively. Figure 2 and Table 1 provides details on benthic community percent coverage for all fore reef sites.

Coral cover among lagoon sites was highest at *Maina* (55.9%), with *Tokai'i* and *Atuatane* at 5.5% and 14.2 % respectively. Crustose coralline algae cover was 25.5% at *Atuatane*, 5.9% at *Tokai'i*, and 0.2% at *Maina*. Filamentous turf algae (TA) cover at the control site (*Maina*) was 31.9%, while cover at the two impact sites (*Atuatane* and *Tokai'i*) were 29.8% and 88.3% respectively. See Figure 2 and Table 1 for lagoon benthic community coverage details.

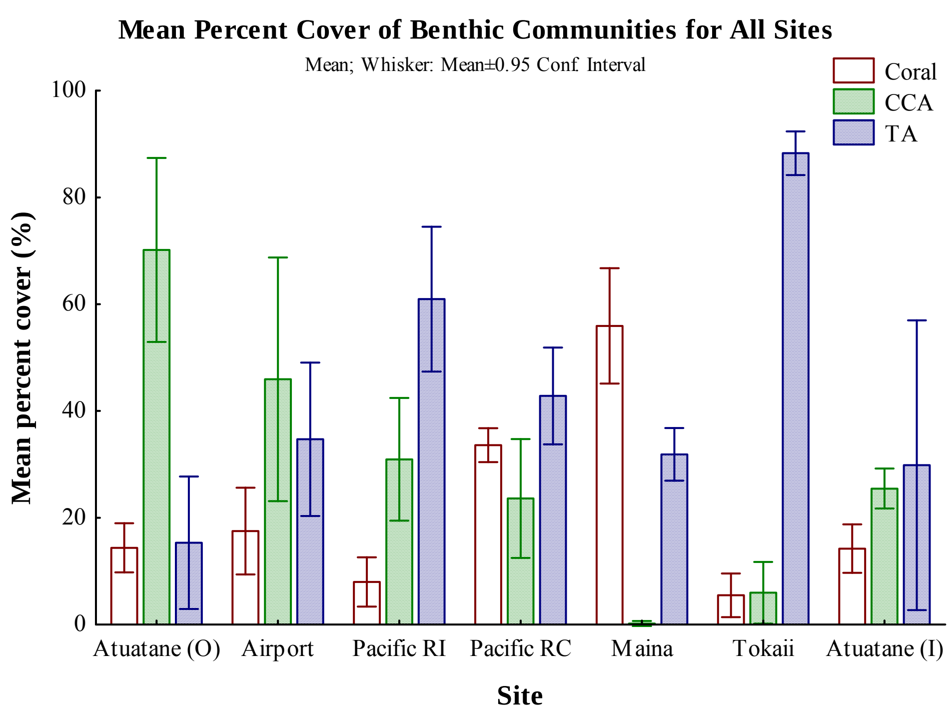

Figure 2. Mean percent cover of fore reef and lagoon benthic communities by site for 2008.

Table 1. Average percent cover and standard deviation (SD) of hard coral, crustose coralline algae, and turf algae for fore reef and lagoon sites.

	Site	Hard coral		Coralline algae		Turf	
		Average	*SD*	*Average*	*SD*	*Average*	*SD*
Fore reef	*Atuatane (O)*	14.375	2.887	70.156	10.830	15.313	7.798
	Airport	17.500	5.103	45.938	14.348	34.688	9.021
	Pacific RI	7.969	2.904	30.938	7.226	60.938	8.516
	Pacific RC	33.594	2.001	23.594	7.004	42.813	5.694
Lagoon	*Maina*	55.938	6.780	0.156	0.313	31.875	3.104
	Tokaii	5.469	2.571	5.938	3.626	88.281	2.571
	Atuatane (I)	14.219	2.858	25.469	2.359	29.844	17.058

ANOSIM (Appendix C) generated for benthic communities on fore reef and lagoon sites using major categories (i.e., hard corals, CCA, and TA) reported a Global R value of 0.841, indicating significant differences between sites ($p = 0.001$). Pairwise comparisons among fore reef sites indicated that *Atuatane* strongly differed from *Pacific RI* ($R = 0.969$; at $p < 0.05$). SIMPER (Appendix D) indicated a dissimilarity value of 14.6% between *Atuatane* and *Pacific RI* with differences explained by TA (51%), CA (29%), and hard corals (20%). *Atuatane* also strongly differed from *Pacific RC* ($R = 1.000$) with a dissimilarity value of 15%, explained by CA (36%), TA (36%), and corals (28%). *Atuatane* and *Airport* differed but overlapped to some extent ($R = 0.354$); average dissimilarity was 8.1%, with TA contributing to 54% of the dissimilarity. *Airport* and *Pacific RI* ($R = 0.729$), *Airport* and *Pacific RC* ($R = 0.521$), and *Pacific RI* and *Pacific RC* ($R = 1.000$) were all significantly different at $p < 0.05$. All pairwise comparisons made among lagoon sites *Maina, Atuatane (I),* and *Tokai'i* showed strong separation among sites ($R = 1.000$) at $p < 0.05$. MDS analysis provided a graphical representation of the magnitude of each categories among sites: hard corals (Figure 3a), CCA (Figure 3b), and TA (Figure 3c). A stress value of 0.01 indicated a high degree of reliability in this result.

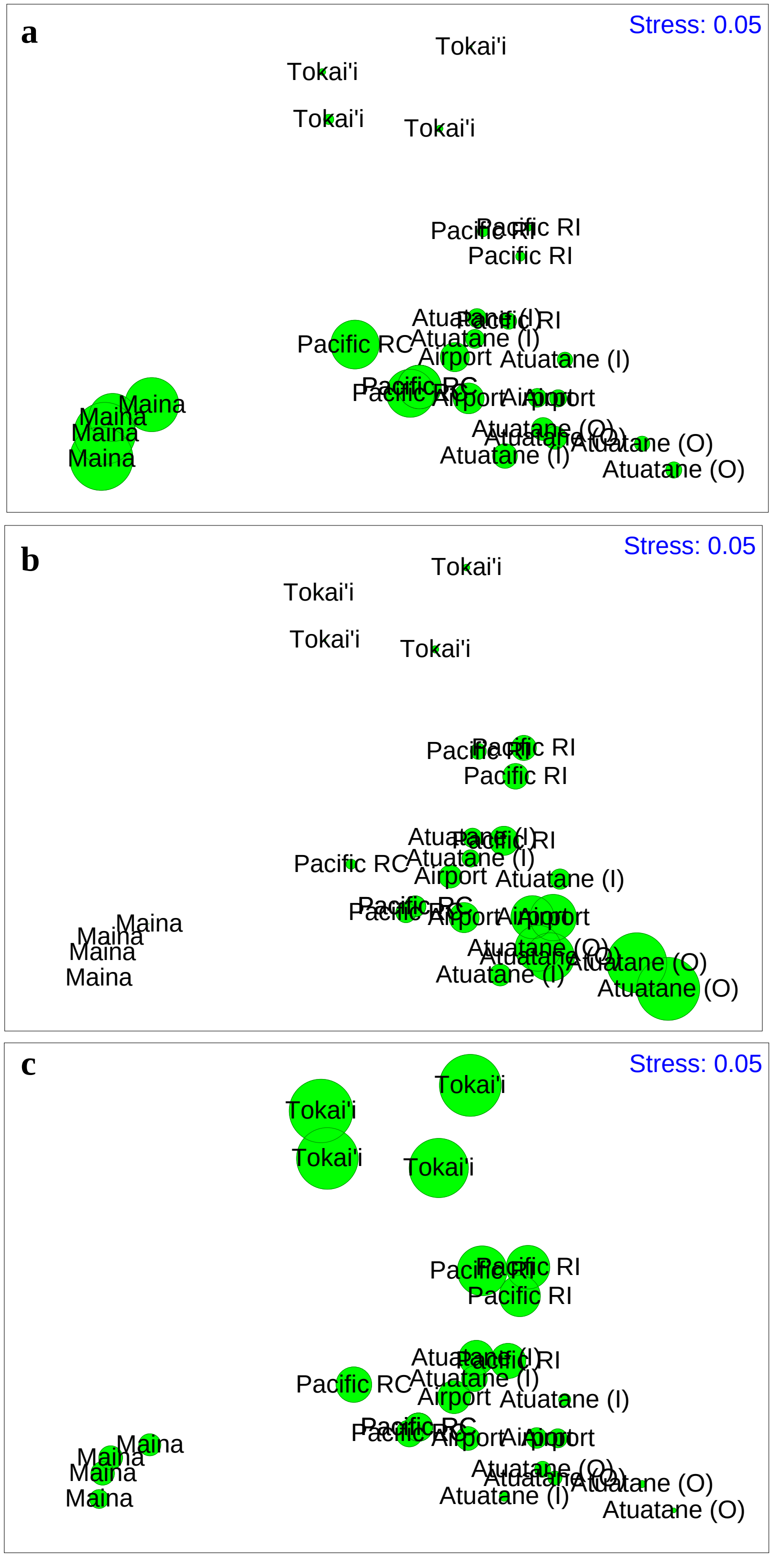

Figure 3. Multi-dimensional scaling (MDS) for fore reef and lagoon benthic communities generated from point-quadrat data using four replicates. Categories are: a) total hard coral cover, b) crustose coralline algae cover, and c) turf algae cover.

Size classes

Size class data for hard corals on all fore reef sites indicated that corals were predominantly in classes B to E, with a few colonies in classes A and F (Figure 4). Recruitment (class A) was low on the fore reef, with the highest recorded at *Pacific RI* (average of 1.3 ind./m^2). Numbers in class B were also low, ranging from an average of 1.8 ind./m^2 at *Pacific RC* to 3.6 ind./m^2 at *Pacific RI*. Class C ranged from an average of 3.6 ind./m^2 at *Airport* to 5.9 ind./m^2 at *Atuatane*. The highest size class noted among fore reef sites was class D ranging from an average of 7.4 ind./m^2 at *Pacific RI* to 14.6 ind./m^2 at *Pacific RC*. Class E ranged from an average of 2.8 ind./m^2 at *Pacific RI* to 7.6 ind./m^2 at *Pacific RC*. Large colony numbers in class F were low at all sites (average of 1 ind./m^2 or less) with no large colonies recorded at *Pacific RI.*

Size class data among all lagoon sites indicated that the majority of corals were in class D, ranging from 3.6 ind./m^2 at *Maina* to 8.4 ind./m^2 at *Atuatane* (Figure 5). Recruitment (class A) ranged from an average of 1.0 ind./m^2 at *Atuatane* and *Maina* to 1.5 ind./m^2 at *Tokai'i*. *Atuatane* had the highest number of colonies per m^2, with the majority of corals in class B, C, and D. Size classes at the control site *Maina* appeared to follow a normal distribution, with large colonies recorded in class G only at this site. Impact site *Tokai'i* had no large colonies recorded in class F or G.

ANOSIM (Appendix E) generated for coral size classes on fore reef and lagoon sites reported a Global R value of 0.256, indicating weak differences between sites ($p = 0.001$). All pairwise comparisons among fore reef sites were weak, with the exception of *Pacific RI* and *Pacific RC* which differed ($R = 0.526$; at $p < 0.05$). SIMPER (Appendix F) for *Pacific RI* and *Pacific RC* had a 33.7% dissimilarity value with 72% of the differences explained by class E (20%), B (18%), D (17%), and C (16%). MDS analysis provided a graphical representation of the differences among fore reef (Figure 6a) and lagoon sites (Figure 6b). MDS analysis showed replicates from *Pacific RI* and *Pacific RC* being furthest apart for fore reef sites, confirming their differences (see Figure 6a). A stress value of 0.15 indicated a high degree of reliability in this result.

Pairwise comparisons for lagoon sites indicated that *Maina* showed significant differences with *Atuatane* ($R = 0.513$) and was different but overlapped with *Tokai'i* ($R = 0.451$) at $p < 0.05$ (see Appendix E). *Atuatane* and *Tokai'i* were not different ($R = 0.093$). SIMPER (see Appendix F) for *Maina* and *Atuatane* had a 36.7% dissimilarity value with 80% of the differences explained by class B (19%), F (18%), C (18%), D (14%), and A (11%). MDS analysis for lagoon sites confirmed the ANOSIM analysis (see Figure 6b). A stress value of 0.16 indicated a high degree of reliability in this result.

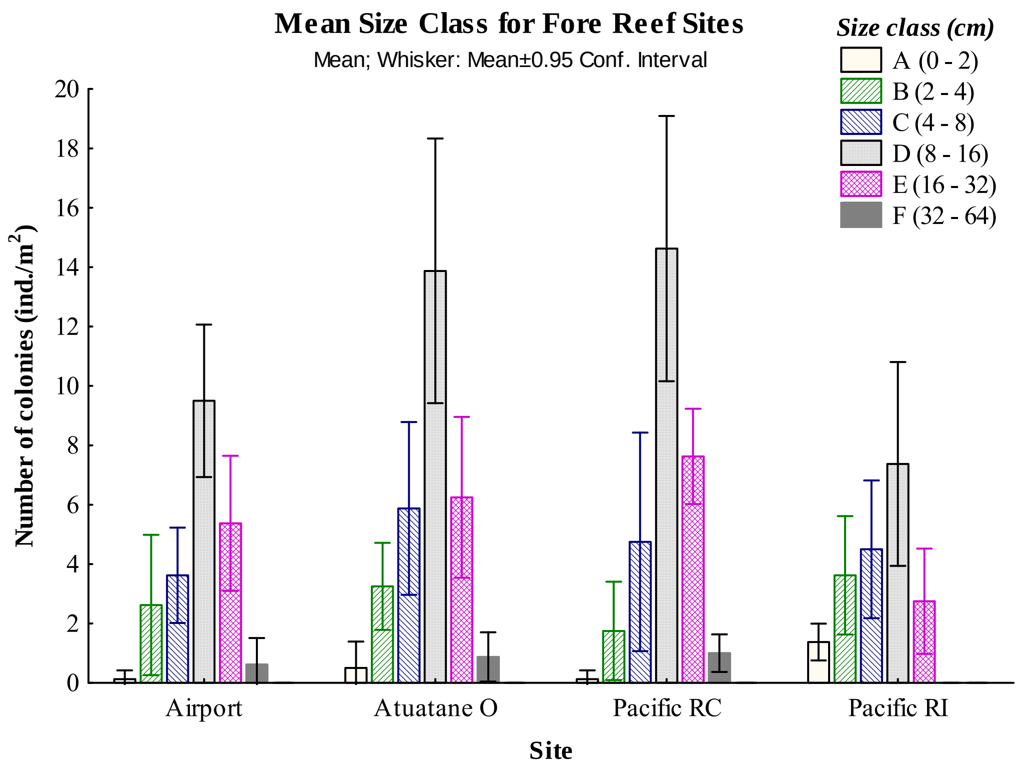

Figure 4. Mean coral size classes for fore reef sites using coral genera.

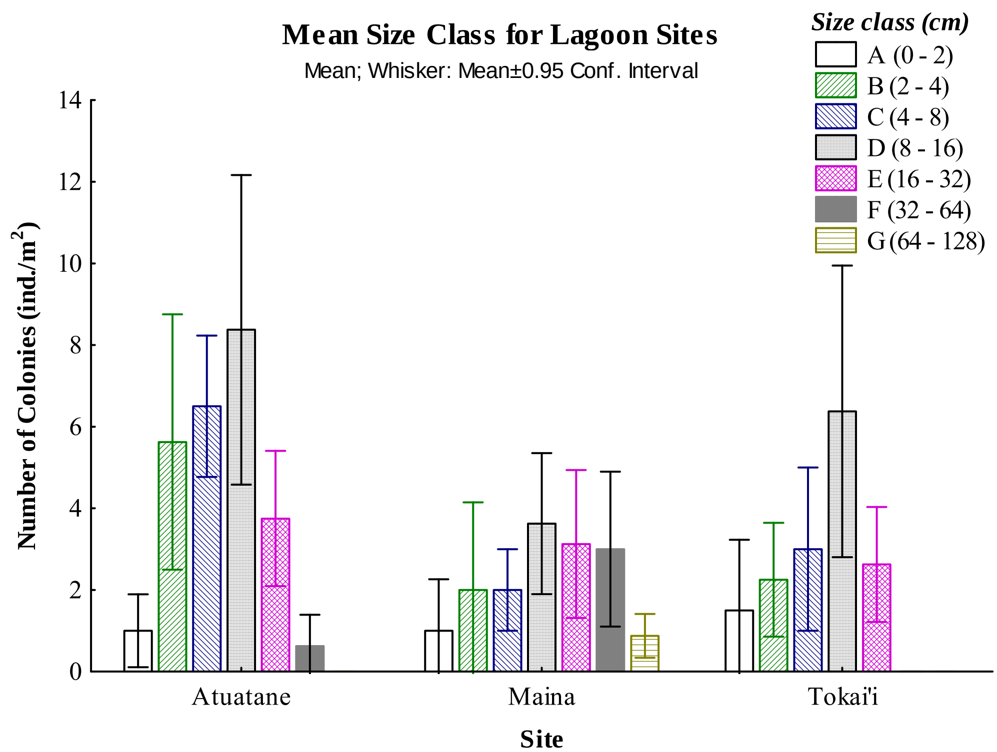

Figure 5. Mean coral size classes for lagoon sites using coral genera.

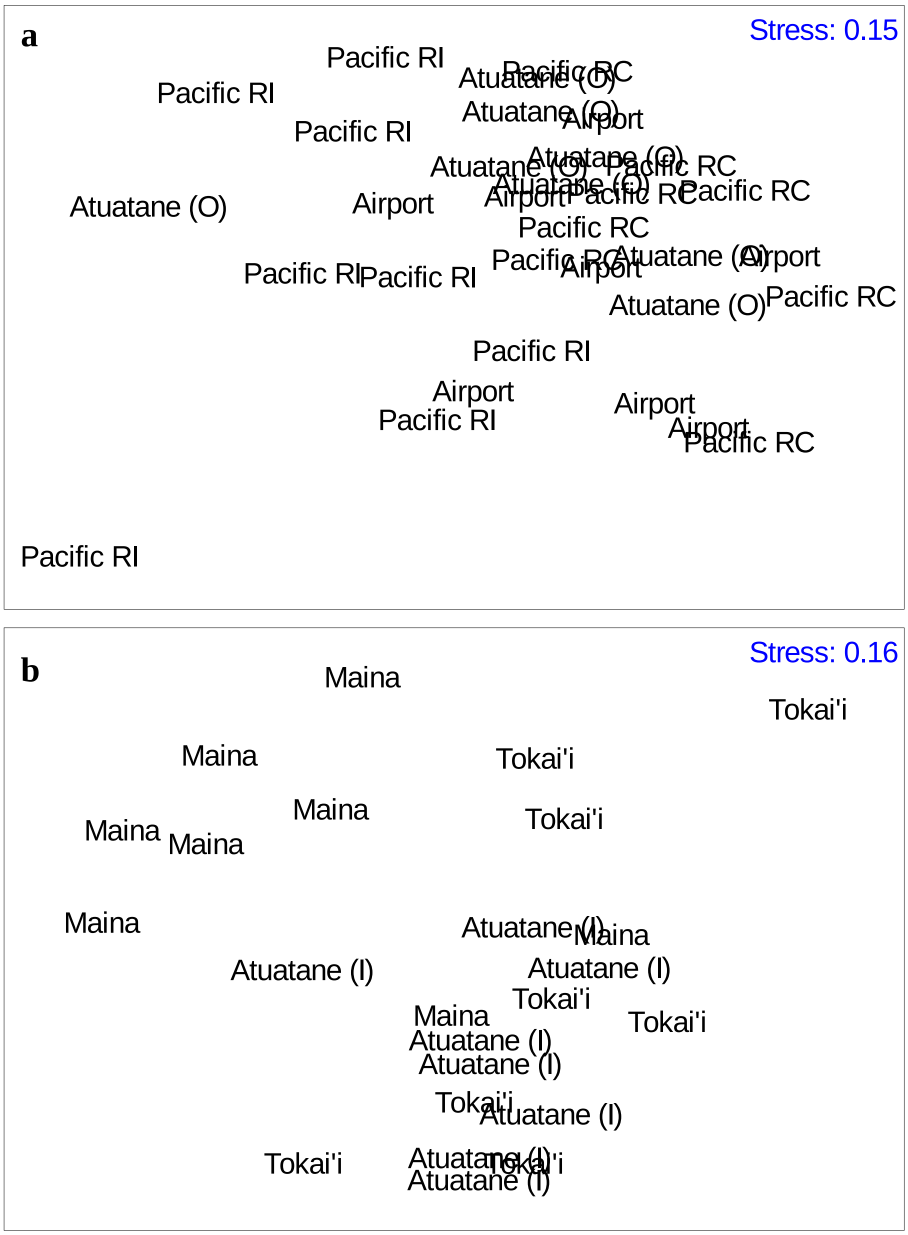

Figure 6. Multi-dimensional scaling (MDS) for: a) fore reef and b) lagoon coral size classes generated from the sum of eight 1-m^2 quadrat data for each site.

Biological statistics

A total of 39 coral species were observed at lagoon sites representing 9 families; the highest number of coral species were recorded at *Maina* (27 coral species representing 7 families; Appendix G), while *Atuatane* had the lowest (19 coral species representing 9 families). Fore reef sites had 41 coral species representing 11 families, with the highest found at *Pacific RC* (30 coral species representing 9 families) and lowest at *Airport* (23 coral species representing 8 families). Coral species diversity and evenness values generated by PRIMER (Table 2) indicated that *Maina* had greatest values of richness (4.142) the highest value of evenness (0.842) and greatest diversity (2.563) for lagoon sites, while *Tokai'i* had the lowest values of number of species (14 ind./ 8 m^2), species richness (2.688), and species diversity (2.003). *Pacific RC* had the greatest values of richness (4.200), and species diversity (2.572), while *Airport* had the greatest value of evenness (0.832) for all fore reef sites.

Table 2. Biological statistics for all sites generated on PRIMER using quadrat data.

Site	**S(ind./ 8** m^2**)**	**N (ind./ 8** m^2**)**	**d**	**J`**	**H`**
Atuatane (O)	24	245	4.181	0.786	2.499
Airport	20	175	3.679	0.832	2.492
Pacific RI	20	157	3.758	0.808	2.420
Pacific RC	24	239	4.200	0.809	2.572
Maina	21	125	4.142	0.842	2.563
Tokai'i	14	126	2.688	0.759	2.003
Atuatane (I)	17	207	3.000	0.751	2.127

Macro-invertebrates

Echinometra mathaei was the most dominant invertebrate on the fore reef with mean density ranging between 0.1 and 0.6 ind./m^2 (≈ 1 individual in areas ranging between 2 – 10 m^2), while all other invertebrates were less than 0.1 ind./m^2 (1 individual/10 m^2). Mean density of most invertebrates at lagoon sites were also less than 0.1 ind./m^2 with the exception of *Tridacna maxima* at *Maina*, which were greater than 0.4 ind./m^2 (1 individual/2.5 m^2; Figure 7).

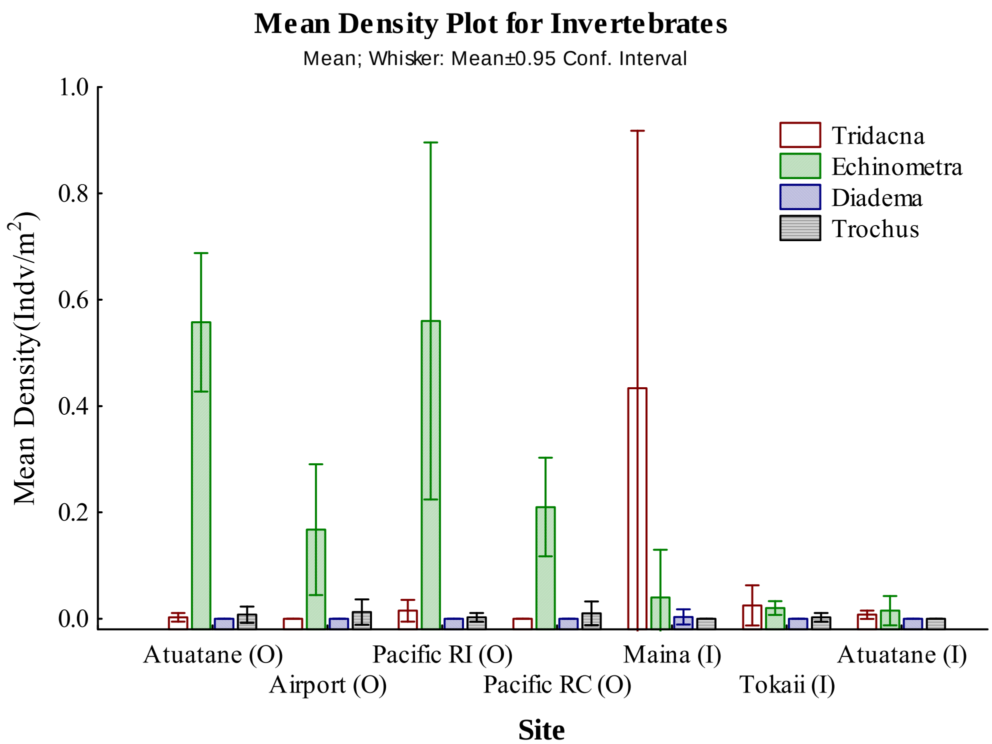

Figure 7. Mean density of both lagoon and fore reef invertebrates. All sites had four replicates with the exception of *Maina* (I), where three replicates were used.

Linking Aitutaki and Manuae through oceanic currents

Images taken from the National Oceanographic and Atmospheric Administration's (NOAA) Oceanwatch website (Figure 8) provide some information on the general current patterns between Aitutaki and Manuae. I propose a hypothesis that Manuae (located southeast of Aitutaki) is a potential source population for Aitutaki. The images indicate that the predominant current in this part of the southern Cook Islands during the summer months (a period when most corals and other invertebrates and vertebrates spawn) is northwestward. Based on a current speed ranging from 0.06 to 0.17 m/sec (presented in the image), it would take 6 to 16 days for passive planktonic larvae to drift from Manuae to Aitutaki (a distance of approximately 87 km). Corals can remain competent within this period as planktonic larvae prior to settlement (up to 20 days noted by Richmond and Hunter, 1990).

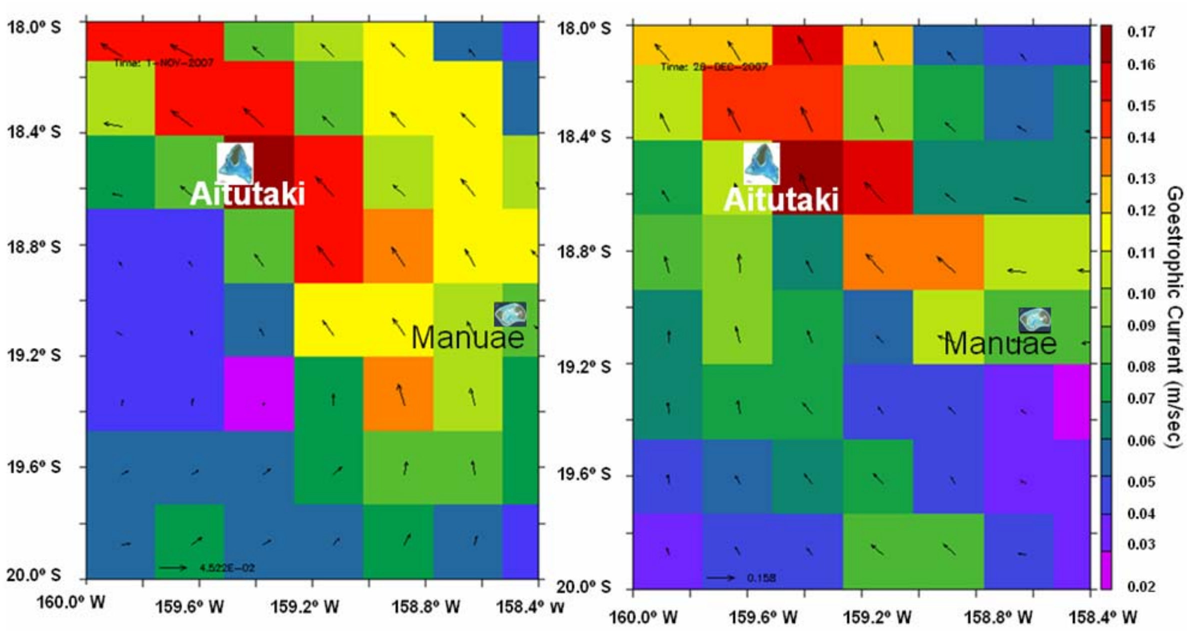

Figure 8. Geostrophic current with a 10-day composite for the month of November (left) and December (right) 2008. Modified from http://las.pfeg.noaa.gov/oceanWatch/oceanwatch (note: islands are not to scale).

DISCUSSION AND CONCLUSIONS

The high coverage of CCA at fore reef sites may well indicate that Aitutaki's reefs are in the early stages of recovery. Interestingly, sites dominated by CCA seem to have less corals, while sites with less CCA have more corals. For example *Atuatane (O)* had the highest cover of CCA (70.2%) but had the second lowest coral cover (14.4%). Similar observations were noted on Rarotonga (Rongo *et al*., 2006), where the CCA-dominated side (southern exposure) had an extremely low coral cover. While CCA are known to induce settlement and metamorphosis in corals, Harrington *et al.* (2004) found on the Great Barrier Reef (Australia) that certain CCA (in particular *Titanoderma prototypum*) are preferred over others as substrate for coral settlement. However, they found that *T. prototypum* had lower coverage on the reefs studied. Although, this preferential settlement of corals to certain CCA may explain why reefs on Rarotonga and Aitutaki are depauperate, information on the identity and estimates of CCA coverage were not recorded in this survey but should be included in future surveys.

Good coral assemblages found at *Pacific RC* and *Airport* may be a result of the numerous spur-and-grove formations found at these sites, which allow for better circulation particularly at shallower depths (10 m or less). However, reef formation at *Atuatane* (O) was less complex, possibly contributing to the lower coral cover found at this site. *Pacific RI* on the other hand, appeared to be directly impacted by stress factors originating from the land and lagoon, which flush through either the major channel (see *Appendix A*) in close proximity to the site or the main boat channel in Arutanga (about 1 km south). These factors may explain the lowest coral cover (8 %) and highest TA cover (61%) recorded for all fore reef site. Although, coral cover was good at *Pacific RC* and *Airport*, observations noted that depths greater than that surveyed (>10m) were depauperate of corals (particularly on the reef slope). Healthy coral assemblages seem to exist only at the shallower depths (< 10 m) for most fore reef sites, with the exception of *Atuatane*. Interestingly, the dead colonies that lined the deeper perimeter of these assemblages may suggest that a recent COTS attack may have occurred a few years prior, which failed to degrade the shallower reefs at *Pacific RC* and *Airport* because of strong surges encouraged by the spur-and-groove formations.

Most corals on both fore reef and lagoon sites were in the 8 - 16 and 16 - 32 cm classes, indicating that these corals are survivors of recruits that settled after some disturbance (such as the COTS attack in the '90s), supported by the fact that most reefs lack colonies in the 64 – 128 cm class. In contrast, *Maina* recorded large colonies in the 64 – 128 class, which suggests that favorable conditions for coral growth and survival may exist here. Although, this may be attributed to the establishment of an MPA (*ra`ui*) at this site, large colonies also suggest that disturbances experienced at the site may be minimal due to its remoteness. Information on the current patterns within the lagoon and around Aitutaki may be of value to understand the contribution of this site as a source population for assisting the recovery of Aitutaki's reefs.

Much of the damage on lagoon corals may be due to poor water quality for coral growth and survival, attributed to the use of the lagoon as well as land-based activities, which resulted in the abundance of die-back corals noted on what used to be very large colonies. These were particularly evident at *Tokai'i* and *Atuatane (I),* which was common among several genera (e.g. *Montipora, Cyphastrea*, *Leptoria,* and *Acropora*). This suggests that the impacts of COTS may have been limited to the fore reef. This was particularly true for Rarotonga, where the impact due to COTS in the 90s was limited to the fore reef. Furthermore, observations made at sites in close proximity to the mainland noted the dominance of *Pocillopora damicornis, Acropora vaughani,* and *Montipora hispidus,* species commonly found in turbid environments (Veron, 2000). The dominance of these species may suggest that the lagoon is experiencing high sedimentation originating from a variety of sources. For example, dredging projects carried out in the last decade or so (noted along the Amuri coast), coastal developments, and elevated nutrient levels that promote algal growth (which holds sediments that re-suspend during rough conditions and tidal changes; Purcell, 2000).

Invertebrate densities were low in this survey, with mean values less than 0.1 ind./m^2 (≈1 ind./10 m^2) for most invertebrates with the exception of *Tridacna* recorded at *Maina* where mean densities were greater than 0.4 ind./m^2 (≈ 1 ind./2.5 m^2). Further analysis indicated that over 80% of the *Tridacna* were greater than 5 cm in size, suggesting that recruitment may be limiting. When the mean density of *Tridacna* was compared to a survey conducted for Manuae in 2005 (Rongo *et al*., 2005; Manuae is a sand cay island southeast of Aitutaki), densities were two to seven-fold less for Aitutaki. The 2005 survey also proposed the possibility of Manuae being a source population for Aitutaki based on observed ocean currents at the time. Information recently obtained from NOAA's Oceanwatch website (see Figure 8) on ocean surface currents around these islands supports this possibility. Although the 2005 survey of Manuae recorded a mean density of *Tridacna* between 0.8 and 3.0 ind./m^2, interviews with landowners of Manuae indicated that *Tridacna,* other invertebrate populations (i.e., *ariri* and *kaura*), as well as fish populations have noticeably declined over the years, which they attribute to heavy fishing pressure by visiting boats. Assuming that Manuae is a source population for Aitutaki, a decline in marine resources there may affect the recovery of Aitutaki's reefs.

RECOMMENDATIONS

- Water quality testing should be conducted for the Aitutaki lagoon similar to that carried out for Rarotonga. This is important for correlating natural or anthropogenic events to changes in the marine environment.
- Future research should identify the types of reef settings on Aitutaki. This information is important to draw relationships between anthropogenic disturbances and coral reef assemblages. The inherent variation that results from these physical setting (i.e., environmental regime; Van Woesik and Done, 1997) must be accounted for.
- In order to correlate changes in the marine environment to natural events and anthropogenic activities, monitoring of sites should be consistent (at least every two years).
- Additional sites should be established: 1) two on the eastern exposure and two on the southern exposure for the fore reef, and 2) two on the northeastern exposure within the lagoon. Monitoring these additional sites will provide more information on the impact of natural events and anthropogenic activities.
- Information on human populations, pig populations, and land-use practices (i.e., agriculture, building developments, septic tanks, etc.) should be obtained and integrated into a Geographic Information System (GIS) program where changes can be monitored over time and correlated to changes in the marine environment.
- Establish Manuae as a MPA due to its potential role as a source population for Aitutaki.

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GLOSSARY

ANOSIM: Analysis of Similarities. Analysis generated by PRIMER which examines the "analysis of similarities" hypothesis for differences between groups of community samples (defined a priori), using permutation/randomization methods on similarity matrix.

CCA: Crustose coralline algae.

CINES: Cook Islands National Environment Service.

CLUSTER: hierarchical clustering into sample (or species) groups. Analysis generated by PRIMER.

COTS: crown-of-thorns starfish.

GD: geometric diameter.

MDS: Multi-Dimensional Scaling. Analysis generated by PRIMER. 2D results are produced together with a scatter plot. Plots can be rotated and flipped.

MMR: Ministry of Marine Resources.

NOAA: National Oceanographic and Atmospheric Administration.

PI: Point Intercept. A method used to quantify benthic communities (i.e. corals, algae, sponges, etc.).

PRIMER: statistical analysis program which covers a wide range of univariate, graphical and multivariate routines for analyzing the species/sample abundance (or biomass) matrices that arise in biological monitoring of environmental impact and more fundamental studies in community ecology.

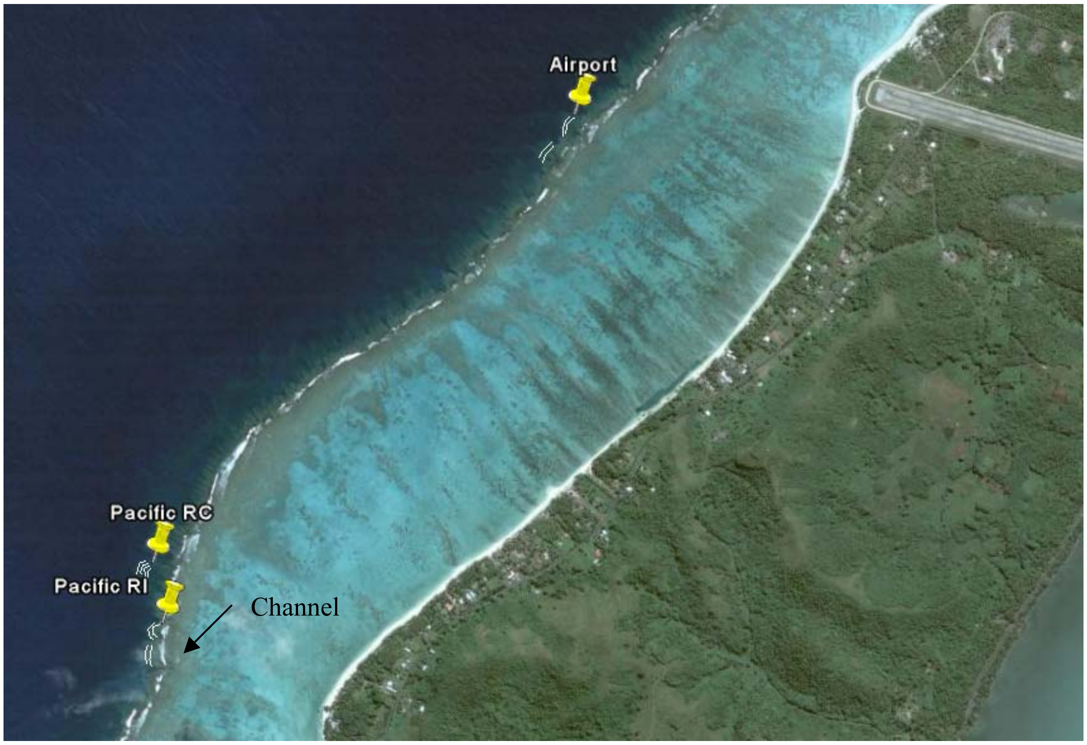
SIMPER: Similarity percentages generated by PRIMER which examines the percent contribution of each coral or identified category to the measured ANOSIM differences.

STATISTICA: statistical analysis program.

TA: Turf algae.

APPENDICES

Appendix A. Google Earth picture of fore reef and lagoon sites surveyed.



Appendix B. GPS readings for survey sites.

Site	GPS Location
Tokai'i	18º 54′ 16.50″ S; 159º 47′ 57.02″ W
Maina	18º 54′ 02.68″ S; 159º 49′ 03.92″ W
Atuatane Inner	18º 52′ 00.33″ S; 159º 48′ 08.42″ W
Atuatane Outer	18º 52′ 48.19″ S; 159º 49′ 12.93″ W
Pacific Resort Impact	18º 50′ 38.66″ S; 159º 48′ 03.37″ W
Pacific Resort Control	18º 50′ 32.10″ S; 159º 48′ 03.23″ W
Airport	18º 49′ 41.41″ S; 159º 47′ 13.14″ W

Appendix C. Analysis of Similarities (ANOSIM) for benthic communities using percent cover of Corals, CCA, and TA obtained from point-quadrat data with four replicates.

Global Test

Sample statistic (Global R): 0.841
Significance level of sample statistic: 0.1%

Pairwise Tests

	Sites	R Statistic	Significance Level %
Fore reef	Atuatane (O), Airport	0.354	2.9
	Atuatane (O), Pacific RI	0.969	2.9
	Atuatane (O), Pacific RC	1.000	2.9
	Airport, Pacific RI	0.729	2.9
	Airport, Pacific RC	0.521	2.9
	Pacific RI, Pacific RC	1.000	2.9
Lagoon	Maina, Tokai'i	1.000	2.9
	Maina, Atuatane (I)	1.000	2.9
	Tokai'i, Atuatane (I)	1.000	2.9

Appendix D. Similarity Percentages (SIMPER) for benthic communities using data from the major categories of hard corals, crustose coralline algae, and turf algae obtained from point-quadrat data with four replicates.

Transform: Log(X+1)
Cut off for low contributions: 100.00%

Atuatane (O) & Airport
Average dissimilarity = 8.06

Category	**Atuatane (O)** *Av.%Cover*	**Airport** *Av.%Cover*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
Turf	15.31	34.69	4.37	1.61	54.18	54.18
CA	70.16	45.94	2.25	1.40	27.91	82.09
Corals	14.38	17.50	1.44	1.51	17.91	100.00

Atuatane (O) & Pacific RI
Average dissimilarity = 14.56

Category	**Atuatane (O)** *Av.%Cover*	**Pacific RI** *Av.%Cover*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
Turf	15.31	60.94	7.43	2.70	50.98	50.98
CA	70.16	30.94	4.23	2.91	29.05	80.03
Corals	14.38	7.97	2.91	1.71	19.97	100.00

Airport & Pacific RI
Average dissimilarity = 8.67

Category	**Airport** *Av.%Cover*	**Pacific RI** *Av.%Cover*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
Corals	17.50	7.97	3.68	1.92	42.41	42.41
Turf	34.69	60.94	2.85	2.26	32.85	75.26
CA	45.94	30.94	2.15	1.42	24.74	100.00

Atuatane (O) & Pacific RC
Average dissimilarity = 14.99

Category	**Atuatane (O)** *Av.%Cover*	**Pacific RC** *Av.%Cover*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
CA	70.16	23.59	5.46	3.06	36.40	36.40
Turf	15.31	42.81	5.43	2.11	36.20	72.59
Corals	14.38	33.59	4.11	4.18	27.41	100.00

Airport & Pacific RC
Average dissimilarity = 7.69

Category	**Airport** *Av.%Cover*	**Pacific RC** *Av.%Cover*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
Corals	17.50	33.59	3.17	2.49	41.17	41.17
CA	45.94	23.59	3.14	1.51	40.90	82.08
Turf	34.69	42.81	1.38	1.83	17.92	100.00

Pacific RI & Pacific RC
Average dissimilarity = 10.47

Category	**Pacific RI** *Av.%Cover*	**Pacific RC** *Av.%Cover*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
Corals	7.97	33.59	6.89	4.55	65.75	65.75
CA	30.94	23.59	1.87	1.34	17.84	83.60
Turf	60.94	42.81	1.72	2.12	16.40	100.00

Maina & Tokai'i
Average dissimilarity = 31.32

Category	**Maina** *Av.%Cover*	**Tokai'i** *Av.%Cover*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
Corals	55.94	5.47	14.17	5.69	45.25	45.25
CA	0.16	5.94	10.77	3.13	34.40	79.65
Turf	31.88	88.28	6.37	8.84	20.35	100.00

Maina & Atuatane (I)
Average dissimilarity = 29.35

Category	**Maina** *Av.%Cover*	**Atuatane (I)** *Av.%Cover*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
CA	0.16	25.47	18.65	10.43	63.55	63.55
Corals	55.94	14.22	7.83	6.64	26.69	90.24
Turf	31.88	29.84	2.87	1.93	9.76	100.00

Tokai'i & Atuatane (I)
Average dissimilarity = 20.48

Category	**Tokai'i** *Av.%Cover*	**Atuatane (I)** *Av.%Cover*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
CA	5.94	25.47	8.39	2.71	40.96	40.96
Turf	88.28	29.84	6.88	2.20	33.59	74.55
Corals	5.47	14.22	5.21	2.19	25.45	100.00

Appendix E. Analysis of Similarities (ANOSIM) for coral size classes on fore reef and lagoon sites using data from eight 1-m^2 quadrats per site.

Coral size class

Global Test

Sample statistic (Global R): 0.256
Significance level of sample statistic: 0.1%

Pairwise Tests

	Sites	R Statistic	Significance Level %
Fore reef	Airport, Atuatane (O)	0.015	36.9
	Airport, Pacific RC	0.040	28.4
	Airport, Pacific RI	0.210	1.7
	Atuatane (O), Pacific RC	-0.051	77.1
	Atuatane (O), Pacific RI	0.262	1.1
	Pacific RC, Pacific RI	0.526	0.1*
Lagoon	Atuatane (I), Maina	0.513	0.3*
	Atuatane (I), Tokai'i	0.093	11.8
	Maina, Tokai'i	0.451	0.3*

* = significant values

Appendix F. Similarity percentages –Genus contributions (SIMPER) for coral size class data on fore reef and lagoon sites using data from eight 1-m^2 quadrats per site.

Airport & Atuatane (O)
Average dissimilarity = 22.14

	Airport	**Atuatane (O)**				
Class	*Av. Abun*	*Av. Abun*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
B	2.63	3.25	5.15	1.42	23.25	23.25
E	5.38	6.25	4.32	0.96	19.51	42.76
C	3.63	5.88	3.79	1.26	17.11	59.87
D	9.50	13.88	3.47	1.37	15.66	75.53
F	0.63	0.88	3.43	1.09	15.51	91.03
A	0.13	0.50	1.99	0.65	8.97	100.00

Airport & Pacific RC
Average dissimilarity = 21.45

	Airport	Pacific RC				
Class	*Av. Abun*	*Av. Abun*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
B	2.63	1.75	5.34	1.35	24.91	24.91
C	3.63	4.75	4.33	1.35	20.16	45.07
F	0.63	1.00	3.87	1.28	18.03	63.10
D	9.50	14.63	3.68	1.56	17.16	80.26
E	5.38	7.63	3.27	1.42	15.24	95.50
A	0.13	0.13	0.97	0.52	4.50	100.00

Atuatane (O) & Pacific RC
Average dissimilarity = 20.59

	Atuatane (O)	Pacific RC				
Class	*Av. Abun*	*Av. Abun*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
B	3.25	1.75	4.79	1.38	23.29	23.29
C	5.88	4.75	4.39	1.40	21.31	44.59
E	6.25	7.63	3.59	0.70	17.42	62.01
F	0.88	1.00	2.99	1.11	14.51	76.52
D	13.88	14.63	2.96	0.99	14.39	90.91
A	0.50	0.13	1.87	0.65	9.09	100.00

Airport & Pacific RI
Average dissimilarity = 29.06

	Airport	Pacific RI				
Class	*Av. Abun*	*Av. Abun*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
B	2.63	3.63	6.42	1.36	22.11	22.11
A	0.13	1.38	5.48	1.88	18.87	40.98
E	5.38	2.75	5.39	1.32	18.55	59.52
C	3.63	4.50	4.90	1.14	16.86	76.39
D	9.50	7.38	4.39	0.95	15.10	91.49
F	0.63	0.00	2.47	0.69	8.51	100.00

Atuatane (O) & Pacific RI
Average dissimilarity = 28.46

	Atuatane (O)	Pacific RI				
Class	*Av. Abun*	*Av. Abun*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
E	6.25	2.75	6.40	1.48	22.48	22.48
D	13.88	7.38	5.47	1.18	19.22	41.70
A	0.50	1.38	4.66	1.87	16.38	58.08
C	5.88	4.50	4.49	1.00	15.76	73.84
B	3.25	3.63	4.03	1.20	14.18	88.01
F	0.88	0.00	3.41	1.09	11.99	100.00
G	0.00	0.00	0.00	#######	0.00	100.00

Pacific RC & Pacific RI
Average dissimilarity = 33.72

	Pacific RC	Pacific RI				
Class	*Av.abun*	*Av. Abun*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
E	7.63	2.75	6.75	1.58	20.03	20.03
B	1.75	3.63	6.12	1.43	18.14	38.16
D	14.63	7.38	5.84	1.19	17.33	55.49
C	4.75	4.50	5.46	1.27	16.19	71.69
A	0.13	1.38	5.13	1.90	15.22	86.90
F	1.00	0.00	4.42	1.44	13.10	100.00

Atuatane (I) & Maina
Average dissimilarity = 36.74

	Atuatane (I)	Maina				
Class	*Av. Abun*	*Av. Abun*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
B	5.63	2.00	6.92	1.48	18.85	18.85
F	0.63	3.00	6.62	1.43	18.02	36.87
C	6.50	2.00	6.45	2.04	17.57	54.44
D	8.38	3.63	5.23	1.48	14.25	68.69
A	1.00	1.00	4.20	1.27	11.44	80.13
G	0.00	0.88	3.96	1.60	10.79	90.92
E	3.75	3.13	3.34	1.31	9.08	100.00

Atuatane (I) & Tokai'i
Average dissimilarity = 28.66

	Atuatane (I)	Tokai'i				
Class	*Av. Abun*	*Av. Abun*	*Av.Diss*	*Diss/SD*	*Contrib%*	*Cum.%*
C	6.50	3.00	6.23	1.20	21.73	21.73
B	5.63	2.25	6.08	1.42	21.23	42.95
D	8.38	6.38	5.68	1.21	19.82	62.77
A	1.00	1.50	4.44	1.22	15.50	78.27
E	3.75	2.63	3.70	1.31	12.90	91.17
F	0.63	0.00	2.53	0.73	8.83	100.00

Maina & Tokai'i
Average dissimilarity = 40.37

	Maina	Tokai'i				
Class	**Av. Abun**	**Av. Abun**	**Av.Diss**	**Diss/SD**	**Contrib%**	**Cum.%**

F	3.00	0.00	9.13	1.52	22.61	22.61
D	3.63	6.38	6.42	1.72	15.90	38.51
A	1.00	1.50	5.67	1.27	14.05	52.56
B	2.00	2.25	5.57	1.29	13.80	66.36
C	2.00	3.00	4.96	1.28	12.29	78.65
G	0.88	0.00	4.74	1.59	11.75	90.40
E	3.13	2.63	3.87	1.28	9.60	100.00

Appendix G. Checklist of coral Genus for fore reef sites.

FORE REEF GENUS	Maina	Tokai'i	Atuatane I	Atuatane O	Pacific RI	Pacific RC	Airport
ACROPORIDAE							
Acropora abrotanoides						X	X
Acropora cerialis	X	X					
Acropora humilis	X	X	X	X	X	X	X
Acropora hyacinthus					X	X	X
Acropora surculosa				X		X	
Acropora schmitti	X						
Acropora digitifera	X			X		X	
Acropora inermis		X	X				
Acropora quelchi	X				X	X	X
Acropora listeri					X		X
Acropora retusa				X	X	X	X
Acropora verweyi	X					X	
Acropora vaughani		X	X				
Astreopora gracilis		X					
Montipora calcerea	X	X	X		X		
Montipora efflorescenes						X	X
Montipora tuberculosa		X					
Montipora purple	X	X	X	X			
AGARICIIDAE							
Cardineroseris planulata			X				

Leptoseris explanata					X		
Pavona varians	X						
Pavona venosa							X
FAVIIDAE							
Cyphastrea chalcidicum	X						
Cyphastrea.sp1		X		X	X	X	X
Echinopora lamellosa				X			
Favia stelligera	X	X		X	X	X	X
Favia matthaii			X				
Favia favus	X			X			
Favites flexuosa		X	X	X	X	X	X
Favites abdita						X	X
Leptastrea purpurea	X	X	X	X	X	X	X
Leptastrea bottae			X				
Leptoria Phrygia	X	X	X	X	X	X	X
Montastrea curta		X	X	X	X	X	X
Platigyra pini	X		X	X		X	X
Goniastrea edwardsi	X	X	X	X	X	X	X
Goniastrea retiformis	X						
Goniastrea pectinata	X			X	X		
FUNGIDAE							
Fungia scutaria	X						
Fungia concinna	X	X		X			
Herpolitha limax	X						
MERULINIDAE							
Hydnophora microconos				X	X	X	X
MILLEPORIDAE							
Millepora platyphyla					X	X	
MUSSIDAE							
Acanthastrea echinata	X	X		X	X	X	
Acanthastrea hillae	X	X			X	X	
Lobophylia hemprichii	X	X	X	X	X	X	X
OCCULINIDAE							
Galaxea fascicularis		X	X				
POCILLOPORIDAE							
Pocillopora verrucosa	X			X	X	X	X
Pocillopora meandrina				X	X	X	
Pocillopora eydouxi					X	X	
Pocillopora setchelli						X	
Pocillopora damicornis	X	X	X				
PORITIDAE							
Porites lichen			X				
Porites lutea				X			
SIDERASTREIDAE							
Coscinaraea columna				X		X	
Psammocora superficialis	X	X	X	X	X	X	X
ALCYONIDS (soft corals)							
Sarcophyton spp.				X	X	X	
Cladiella spp					X		X
TOTAL GENUS	**27**	**22**	**19**	**26**	**26**	**30**	**23**
TOTAL FAMILIES	**7**	**8**	**9**	**9**	**9**	**9**	**8**