Rarotonga fore reef community survey for 2014

Prepared by:

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NATIONAL ENVIRONMENT SERVICE
TU`ANGA TAPOROPORO
COOK ISLANDS

SPC Secretariat of the Pacific Community

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Front cover photo: *Asparagopsis taxiformis* at Avana fore reef; taken by Teina Rongo in 2014.
Back cover photo: Research team diving at Avarua, Rarotonga; taken by Barbara Hanchard in 2014.

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EXECUTIVE SUMMARY

Coral reef monitoring on Rarotonga has been ongoing for around 20 years, with surveys conducted in 1994, 1999, 2000, 2003, 2006, 2009, 2011, and this present survey in 2014. Results from these surveys showed that the crown-of-thorns starfish (COTS) outbreak that occurred from 1995 to 2001, and to a lesser extent storm surge associated with the 2003 to 2005 cyclones and several coral bleaching events, were the main causes of the degraded state of Rarotonga's fore reef communities for much of the 2000s. While the 2006 survey indicated that mean hard coral cover for all sites were around 1%, it was noted that conditions were set for recovery to occur. Mean coral cover was around 5% in 2009, around 8% in 2011, and 16% in 2014, which clearly showed that coral communities on the fore reef has been recovering since 2006. In support, coral size class data also showed a significant increase of larger colonies in 2014 when compared with 2006. Although acanthurids (e.g., surgeonfish *Ctenochaetus striatus*) showed a sudden increase in 2006, their abundance with most other fish species surveyed has remained relatively stable from 2009 and onwards. On the other hand, coral-associated pomacentrids (damselfish) and chaetodontids (butterflyfish) showed an increase since 2006, which is consistent with the increase in hard coral cover during this recovery period. Based on a conservative rate for coral recovery of 2% per year (taken from 2006 to 2014 survey results), we estimated that coral cover will reach the pre-COTS conditions of the 1990s (at > 30%) by 2022 — a period of 21 years since the end of the COTS outbreak in 2001. In contrast, the recovery period estimated from the 1970s COTS outbreak that also degraded the fore reef slopes of Rarotonga appeared to take less than 10 years. Certainly, factors such as cyclones, nutrient overloading, runoff sediments, and climate change impacts (i.e., coral bleaching and perhaps ocean acidification) that have all seen an increase in the last few decades are likely contributors to this slower recovery recently. While efforts to minimize the impacts of climate change through negotiations with the global community to reduce greenhouse gas emissions must continue, it is equally important that efforts to minimize local anthropogenic impacts must be forthcoming as well. Establishing new *ra`ui* areas and enforcing the management of current ones along with good land-use practices (to reduce runoff sediments and nutrient inputs) will be important at this stage to facilitate recovery, and most importantly to build the resilience of these reefs to the impacts of climate change that are already occurring and predicted to worsen. It is also critical that coral reef monitoring is on-going to provide managers the information they need to make informed decisions. However, considering that reef monitoring in the past on Rarotonga has been plagued by inconsistencies (e.g., methodology, interval between surveys, different data collectors) and especially limited funding, the continuation of this monitoring remains uncertain.

1. INTRODUCTION

Coral reefs make up only 0.2% of marine areas, yet they host approximately one-third of all described marine biodiversity (Reaka-Kudla, 1997). However, it is widely accepted that coral reefs around the world are in serious decline with 30% already degraded while another 60% loss is predicted in the next few decades (Wilkinson, 2002; Wilkinson, 2004; also see Hughes et al., 2003). The causes of reef degradation range from nutrient enrichment, increased sedimentation from terrestrial runoff, overfishing, and global climate change (Lapointe, 1997; Jackson et al., 2001; Hoegh-Guldberg, 1999; Hoegh-Guldberg et al., 2007; Veron et al., 2008, 2009).

On Rarotonga in the Cook Islands (Figure 1), reefs have experienced several disturbance events over the last few decades (Table 1; see Rongo and van Woesik, 2013). In the 1970s, Devaney & Randall (1973) documented the first reported crown-of-thorns starfish (COTS; Figure 2) outbreak on Rarotonga's fore reefs, which coincided with a Pacific-wide outbreak (Sapp, 1999). Although Devaney & Randall (1973) suggested that most of the damage occurred between Ngatangiia/Matavera (northeastern exposure) counter-clockwise to Arorangi (western exposure), considering the authors' limited time on the Rarotonga, it is likely that the remaining fore reefs were destroyed by COTS in later years. Dahl (1980) documented COTS destruction within the lagoon area on the southern exposure of the island in 1976. A second COTS outbreak in the mid-1990s to around 2001 that was limited to fore reef communities also reduced coral cover from more than 30% to around 1% in 2006 (Rongo et al., 2006), but recovery seemed to be well on the way in subsequent years. For example in 2011, mean coral cover ranged from 10 to 15% around Rarotonga. While reef recovery to pre-COTS conditions after the 1970s outbreak occurred over a period of less than 10 years according to anecdotal reports, recovery from the 1990s outbreak has been slow even over a decade later.

Coral bleaching has also impacted these reefs particularly in 1991 and 1994 during a regional warming and associated calm periods and extreme low tides that caused high coral mortality within the lagoon and to a lesser extent some fore reef areas (Goreau & Hayes, 1995). Similar bleaching events associated with extreme low tides were observed in subsequent years (e.g., 1998, 2006, and 2009) where corals on the reef flats experienced aerial exposure for several hours (Rongo & van Woesik, 2013). Although cyclones are normally infrequent in the southern Cook Islands, the impacts of the five cyclones that swept through this region between 2003 and 2005 were difficult to determine especially when corals during this period were depauperate considering the major COTS outbreak in previous years.

Given that Rarotonga's reefs has remained degraded for much of the 1990s and 2000s, it was suggested that such reef state compounded by the high frequency of disturbance events (e.g., cyclone, coral bleaching, etc.) may have facilitated the establishment of dinoflagellates associated with ciguatera poisoning; disturbances to reefs open space for the opportunistic ciguatoxic dinoflagellates to colonize, which ultimately led to the increased incidence of ciguatera poisoning noted in recent years (Rongo and van Woesik, 2013). Because ciguatera poisoning rendered reef fish unusable in the last few decades on Rarotonga, Rongo & van Woesik (2013) suggested that decreased fishing pressure due to the higher risk of ciguatera may have also led to the increase of fish abundance especially herbivorous species that are particularly important during this recovery period.

Although coral reef monitoring has been on-going for around 20 years on Rarotonga, it has been inconsistent in terms of methodology, intervals between surveys, data collectors, and also the government ministries involved. The first monitoring was undertaken by the National Environment Service in 1994 (Miller et al., 1994), and subsequent monitoring by the Ministry of Marine Resources in 1999 (Ponia et al., 1999), then the National Environment Service in 2000 (Lyon, 2000), 2003 (Lyon, 2003), 2006 (Rongo et al., 2006), and 2009 (Rongo et al., 2009). The survey in 2011 was carried out privately (Rongo and van Woesik, 2013). The present survey was a collaborative effort between the Climate Change Division of the Office of the Prime Minister (Climate Change Cook Islands) and the National Environment Service to continue this monitoring effort. This information will help quantify spatial and temporal changes in the benthic and fish communities on the fore reefs of Rarotonga to provide managers the information they need to make informed decisions.

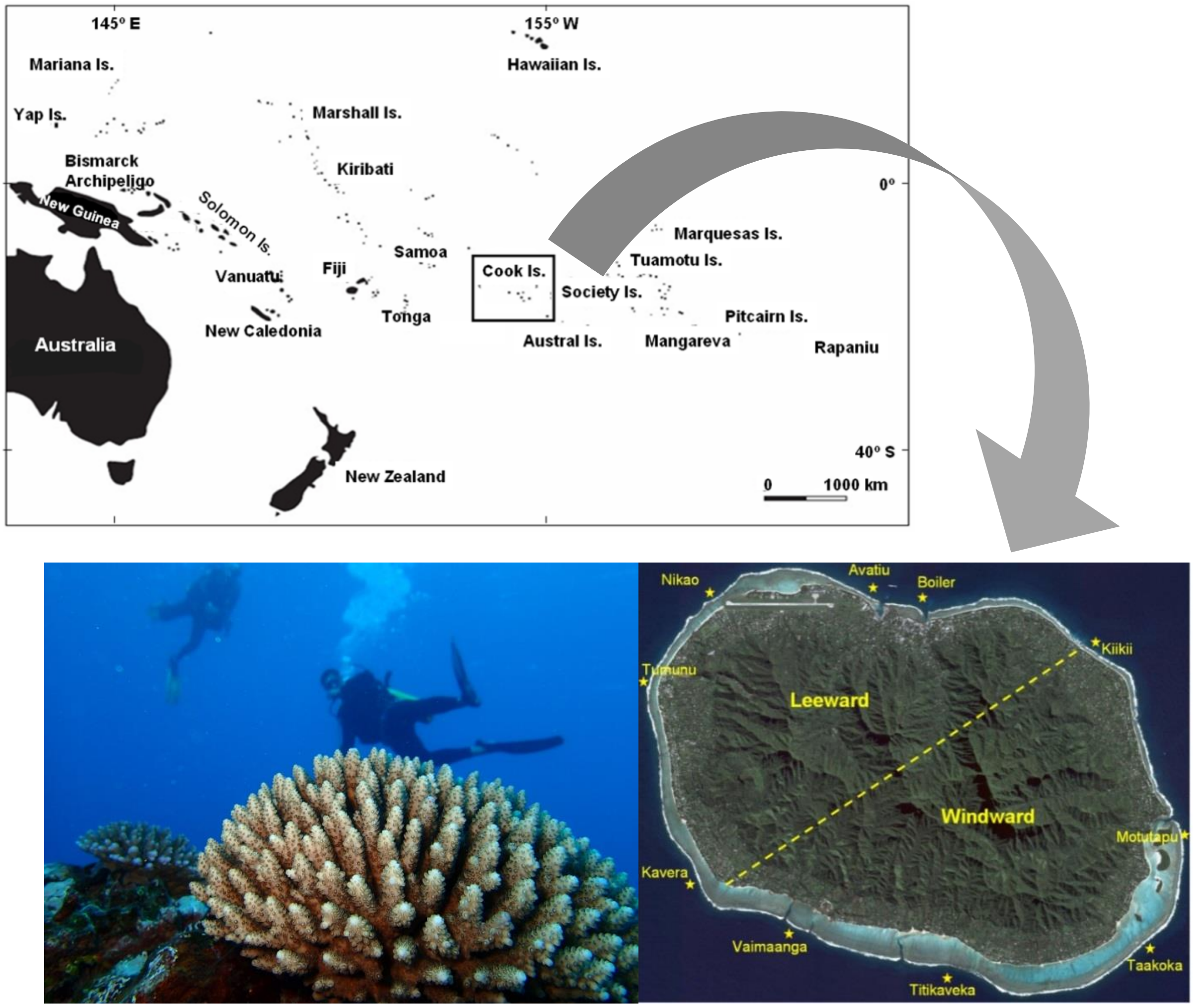


Figure 1. *Top*: Map of the Pacific with the location of the Cook Islands indicated in the boxed region. *Bottom right:* the island of Rarotonga with the yellow dotted line delineating the windward and leeward exposures; sites surveyed marked with yellow stars (photo taken from Google Earth). Note: Boiler on this map is referred to as Avarua in this survey. *Bottom left*: *Acropora* colony in the foreground with members of the survey team in the background (photo by Teina Rongo).

Figure 2. Crown-of-thorns starfish (COTS). Scientific name: *Acanthaster planci.* Māori name: *taramea* (photo by Teina Rongo).

Table 1. Natural disturbances (including cyclones, crown-of-thorns starfish outbreaks, and coral bleaching) impacting Rarotonga, Cook Islands, between 1970 and 2011. Cyclone and wind data taken from Asian Development Bank (2005), de Scally et al. (2006), Baldi et al. (2009), and New Zealand's National Institute of Water and Atmospheric Research database (www.cliflo.niwa.co.nz). Cyclone, storm, and gale refer to Category ≤ 3 systems, and major cyclones refer to Category 4 and 5 systems. Wind speeds reported here are those noted for Rarotonga. *Acanthaster planci* outbreak data and coral bleaching information were taken from Devaney and Randall (1973), Dahl (1980), Goreau and Hayes (1995), Lyon (2003), Rongo et al. (2006, 2009), Rongo and van Woesik (2011), and the present survey. Severity factor is based on the damage noted in Rarotonga from 1994 to 2011, with 5 being the most severe. SST refers to sea surface temperature. Modified from Table 1 in Rongo and van Woesik (2013).

Year	**Natural disturbance**	**Severity factor**	**Description of impact**
1970	*Acanthaster planci* outbreak begins; Cyclone (Dolly)		*Dolly*: high winds damaged ~40% of Rarotonga's export banana crop; information on wave damage not available
1971	*A. planci* outbreak		
1972	*A. planci* outbreak; Cyclone (Agatha)		Extensive damage from *A. planci* outbreak noted in lagoon areas on the northwestern exposure; *Agatha*: wind speeds up to 134 km/h that damaged ~75% of Rarotonga's export banana crop; information on wave damage not available
1973	*A. planci* outbreak		
1974	*A. planci* outbreak		
1975	*A. planci* outbreak		
1976	*A. planci* outbreak ends; Storm (Kim)		Lagoon coral cover declined from *A. planci* outbreak; *Kim*: wind speeds up to 135 km/h, causing some fishing vessel damage
1978	Cyclone (Charles)		*Charles*: wind speeds up to 135 km/h; wave height of 11 m; reported to have caused damage to the wharf
1987	Major cyclone (Sally)		*Sally*: wind speeds up to 156 km/h and wave height of 12 m
1989	Gale (unnamed)		*Gale*: wind speeds up to 105 km/h; no information on swells
1991	Cyclone (Val); Coral bleaching		*Val*: wind speeds up to 74 km/h and wave height of 14 m; severe bleaching of lagoon corals from extreme low tides
1992	Cyclone (Gene)		*Gene*: wind speeds up to 115 km/h; flooding and big swells with coastal damage on western exposure
1993	Cyclone (Nisha)		*Nisha*: wind speeds up to 74 km/h; big swells
1994	Coral bleaching	1	Coral bleaching from high SSTs impacted corals on fore reef slopes on the northern to western exposure
1995	*A. planci* outbreak begins	3	Large numbers noted on the northern fore reef exposure
1996	*A. planci* outbreak	4	Extensive damage of fore reef slopes on the northern exposure
1997	Cyclone (Pam); *A. planci* outbreak	5	*Pam*: wind speeds up to 150 km/h; wave height of 14 m; record rainfall of 107 mm in 6 hr; *A. planci* damage on the northeastern exposure
1998	*A. planci* outbreak; Coral bleaching	3	*A. planci* damage on eastern and southeastern exposure; coral bleaching of lagoon corals from extreme low tides
1999	*A. planci* outbreak	2	Extensive damage of fore reef slopes on the southern exposure
2000	*A. planci* outbreak	2	Extensive damage of fore reef slopes on the southwestern and western exposure
2001	*A. planci* outbreak ends; Storm (Oma, Trina)	4	*A. planci* outbreak significantly reduced fore reef coral cover; *Oma*: wind speeds up to 130 km/h and heavy rain; *Trina*: wind speeds up to 102 km/h with big swells
2002		0	
2003	Major cyclone (Dovi); Titikaveka Irritant Syndrome (TIS)	5	*Doyi*: wind speeds up to 66 km/h and wave height of 17 m; strong swell/surge along coastal areas; *TIS*: harmful algal bloom causing eye and respiratory irritation in residents
2004	Major cyclone (Heta)	5	*Heta*: wind speeds up to 72 km/h and wave height of 17.4 m; major coastal damage
2005	Major cyclone (Meena, Nancy, Olaf, Percy); Gale (Rae)	5	Severe coastal damage from the four major cyclones; *Meena*: wind speeds up to 161 km/h and wave height of 17 m; *Nancy*: wind speeds up to 165 km/h and wave height of 22 m; *Olaf*: wind speeds up to 95 km/h and wave height of 16 m; *Percy*: wind speeds up to 76 km/h and wave height of 19 m; *Rae*: wind speeds up to 75 km/h
2006	Coral bleaching	1	Coral bleaching of lagoon corals observed in Ngatangiia on the southeastern exposure from extreme low tides
2007		0	
2008		0	
2009	Coral bleaching	1	Minor bleaching observed on reef flats on the northern exposure from extreme low tides
2010	Cyclone (Pat)	0	*Pat*: Rarotonga did not receive a direct hit as Aitutaki did, however unknown if storm surge disturbed the fore reefs
2011		0	
2012		0	
2013		0	
2014	Coral bleaching	2	Minor bleaching observed on the fore reefs, and extensive bleaching in the lagoons around Rarotonga; bleaching during this period was also observed on other islands in the southern Cook Islands (e.g., Aitutaki, Mangaia)

1.1. PRIMARY OBJECTIVES

The objectives of this study were to carry out rapid marine assessments on the fore reefs of Rarotonga in the southern Cook Islands. The survey took place from 15 May to 21 August 2014. The marine assessments largely focused on collecting information on coral reef biodiversity (i.e., fish, macro-algae, corals, and other macro-invertebrates). This information will enable stakeholders such as resource managers, political decision-makers, and the general public to plan and make informed decisions pertaining to the management of Rarotonga's resources based on scientifically valid, quantitative data. Climate Change Cook Islands and the National Environment Service were supported by the Secretariat of the Pacific Community, the European Union, and the Global Climate Change Alliance who generously provided funding for this survey.

1.2. RESEARCH TEAM

The research team was composed of individuals from the relevant ministries within the Cook Islands Government (i.e., Climate Change Cook Islands and the National Environment Service). There were also local avid divers who volunteered their assistance with the field work.

1.3. MATERIALS AND METHODS

1.3.1. Sites

The survey revisited previously established sites at Avatiu, Avarua, Kiikii, Motutapu, Taakoka, Titikaveka, Vaimaanga, Kavera, Tumunu, and Nikao (see Figure 1; see Rongo et al., 2006, 2009). *Appendix A* provides the Global Positioning System coordinates of the sites.

1.3.2. Transect deployment

Four 50-m transects (replicates) were deployed at all sites along the fore reef. Transects were placed following the reef contour at depths around 7 – 10 m parallel to shore and laid consecutively at intervals of 10 m.

1.3.3. Biological surveys

The survey methods used were selected because they are widely accepted protocols for rapid marine assessments. Validation of these methods is their publication in peer-reviewed scientific journals. For example, Houk et al. (2005) contains methodology for coral community and benthic surveys. In addition, the methods selected complement those of previous fore reef surveys conducted in Rarotonga (Miller et al., 1994; Ponia et al., 1999; Rongo et al., 2006, 2009; Rongo & van Woesik, 2013). A brief description of each general biota or coral survey is described below.

1.3.3.1. Coral communities

Coral population structure and relative abundance are influenced by disturbances (Bak and Meesters, 1998). The point-quadrat method is used to collect data for coral community analysis (Houk et al., 2005). Along each 50-m transect deployed, the point-quadrat method was used to record the benthos with a 1-m^2 quadrat frame tossed haphazardly every 5 m. A total of 10 quadrats were tossed per transect (40 quadrats per site). The quadrat used to record the benthos was partitioned into 25 sections with string, providing 16 points of intersection. The reef benthos under each intercept was recorded to the genus level. The benthic survey focused on measuring the percent cover of hard coral, crustose coralline algae (CCA), pavement (mainly turf algae <1 cm in height [Steneck, 1988], and carbonate substrate), and macro-algae (>1 cm in height [Steneck, 1988]).

1.3.3.2. Coral colony size

At every 20 m interval, a quadrat was tossed haphazardly to record coral communities for a total of eight quadrats per site. Coral colony sizes were measured within each 1-m^2 quadrat. 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 fell 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 four size classes (see *Section* 1.3.4.2 below); class A colonies were considered new recruits for this survey.

1.3.3.3. Macro-invertebrates & fish

Macro-invertebrates were surveyed using a belt size of 2 m along the 50-m transects (1 m on each side of transect). A belt size of 5 m (2.5 m on each side of transect) was used for fish surveys. Identifications were made to the highest taxonomic resolution possible (i.e., genus and species). Common names were obtained from the Cook Islands Biodiversity (http://cookislands.bishopmuseum.org/) website where possible.

1.3.3.4. Biological diversity

For each island, an identification checklist was generated for all coral, macro-invertebrates, and fish identified. Identifications were made to the highest taxonomic resolution possible (i.e., genus and species) for the purposes of adding to the species inventory for the Cook Islands. Photographs were taken of all species when possible, and some samples collected for identification purposes using taxonomic references or outside taxonomic expertise. Species identification were verified using Randall and Myers (1983), Myers (1989, 1999), Veron (2000), Randall (2005), and photographs provided by Gustav Paulay..

1.3.4. Data analysis

Microsoft Excel spreadsheet, PivotTable, and PivotChart were used for basic computations. PRIMER 6 and STATISTICA 12 software were used for graphical and comparative analysis.

1.3.4.1. Percent cover calculations

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

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

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

1.3.4.2. 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) Population density (colonies per m^2) = $n/6\ m^2$

where n is the total number of colonies of any given species and 8 m^2 is the total area surveyed using eight quadrat tosses per site.

Size classes were sorted into four categories based on geometric diameter: A (< 4 cm), B (4 to < 8 cm), C (8 to < 16 cm), D (16 to < 32 cm), and E (≥ 32 cm).

1.3.4.3. Average density

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

$$(3) \qquad \text{Average density} = \frac{\text{Number of individuals per site / number of replicates}}{\text{Belt area (100 m}^2\text{ for invertebrates and 250 m}^2\text{ for fish)}}$$

1.3.4.4. Species diversity

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

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

where H` is the index of species diversity, and p_i is the proportion of total count belonging to the *i*th species (see Clark & Warwick, 1994).

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:

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

PRIMER 6 software was used to generate this index.

1.3.4.5. Statistical analysis

Comparative analysis was carried out on benthic categories, macro-invertebrates, and fish communities to determine relationships between sites. PRIMER 6 was used to generate a Principal Component Analysis (PCA), vector plots, and ordination of data using 2D plots. Bubbles on 2D plots were used for graphical representation of the respective categories. Mean error plots were generated using STATISTICA 12.

2. RESULTS

2.1. BENTHIC COMMUNITIES

Turf algae showed a significant decline in cover between 2006 and 2014 for all sites, however it was still the most dominant benthic cover in 2014 except at three sites on the southern exposure (Taakoka, Titikaveka, and Vaimaanga) where coralline algae was dominant (Figure 3a,b). Patches of macro-algae (mainly *Asparagopsis*) were present at sites along the eastern exposure and the western exposure; extensive areas in close proximity to the Avana passage (Motutapu site) were dominated by *Asparagopsis*. In terms of hard coral cover, a total of 44 coral species were recorded during the survey representing 11 families (Appendix B). Clearly there was a significant increase in hard coral cover noted for most sites in 2014 (see Figure 3a,b), yet coral cover varied greatly among sites ranging from 5% at Vaimaanga to 28% at Avarua.

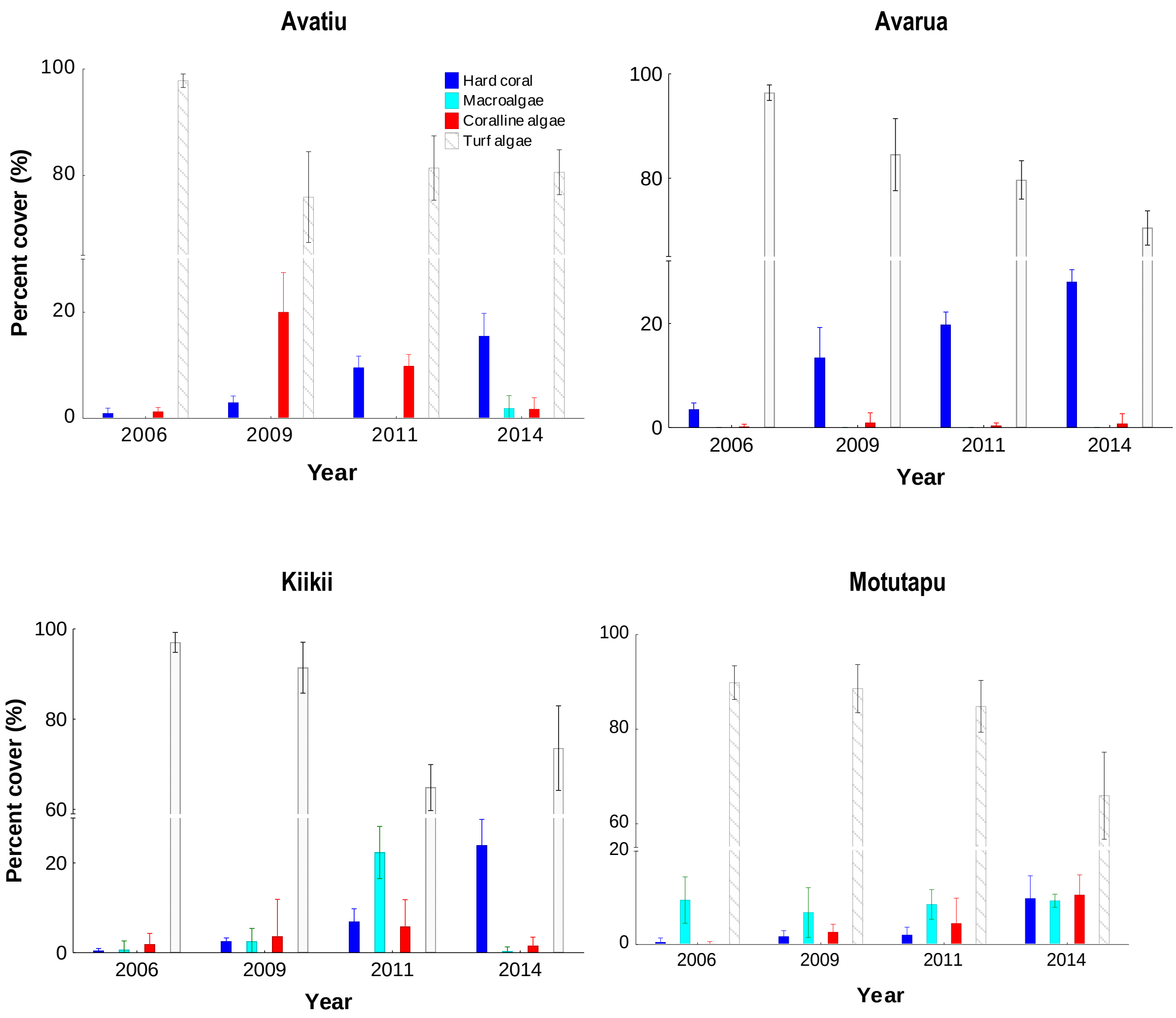


Figure 3a. Percent coral cover for sites Avatiu, Avarua, Kiikii, and Motutapu surveyed on Rarotonga in 2006, 2009, 2011, and 2014. Plots indicate mean values with a ± 95% confidence interval.

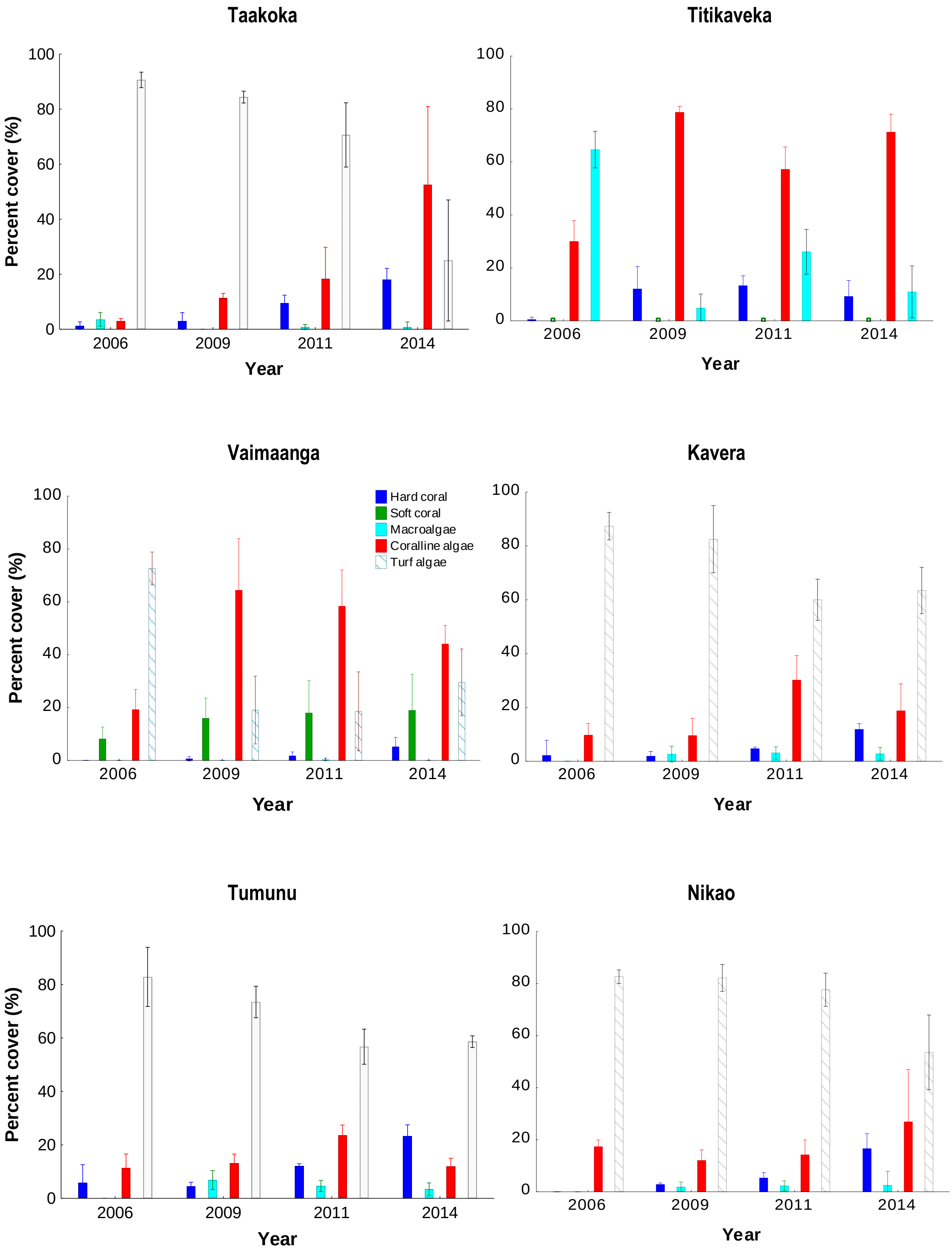
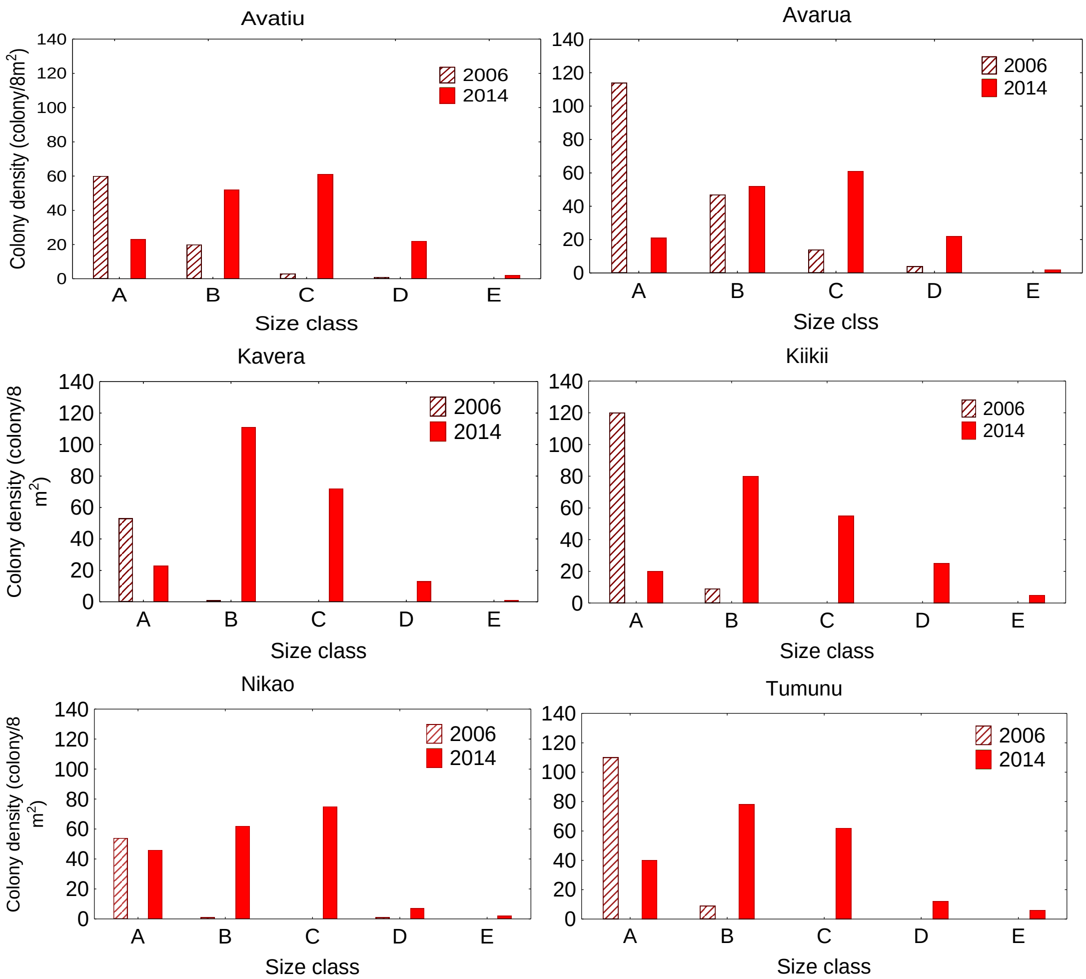


Figure 3b. Percent coral cover sites Taakoka, Titikaveka, Vaimaanga, Kavera, Tumunu, and Nikao surveyed on Rarotonga in 2006, 2009, 2011, and 2014. Plots indicate mean values with a ± 95% confidence interval.

2.1.1. Coral size and density

Coral colony size clearly showed a shift towards larger size classes when comparing data recorded in 2006 and 2014 (Appendix C). While class A (< 4 cm) was dominant in 2006, B (4 < 8 cm) and C (8 < 16 cm) became the most dominant sizes class in 2014 for all sites examined (Figure 4). This shift was also graphically represented in Figure 5, where the chart showed that 86% of colonies were those less than 4 cm in geometric diameter in 2006, while a drop in this class to 27% was noted in 2014. In addition, around 68% of the colony sizes were those recorded in class B (4 to < 8 cm), and C (8 to < 16 cm) combined (see Figure 5). Around 4% of colonies were in class D corals (see Figure 5; Figure 6).



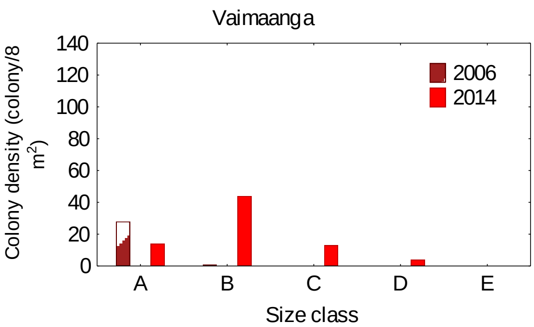


Figure 4. Average coral density by size class; A (< 4 cm), B (4 to < 8 cm), C (8 to < 16 cm), D (16 to < 32 cm) and E (≥ 32 cm) for hard corals for each site.

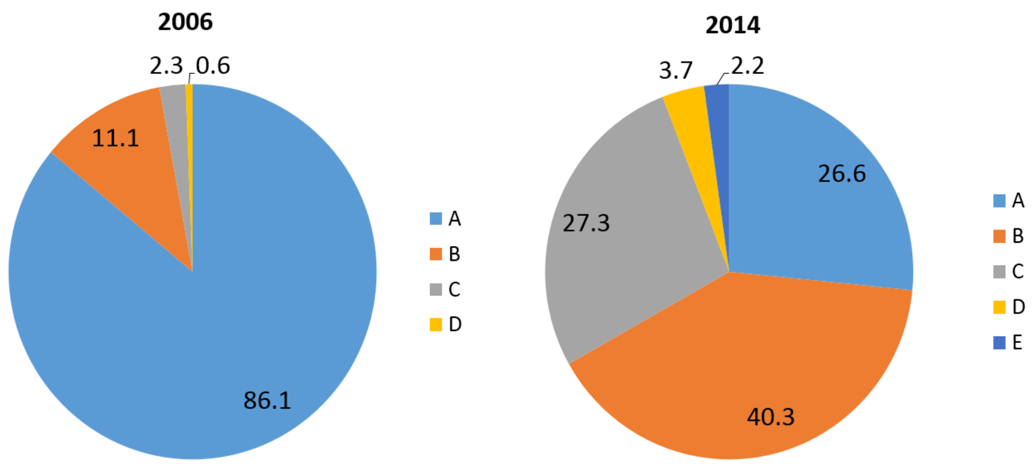


Figure 5. Percent size class with all sites lumped for 2006 and 2014 respectively.

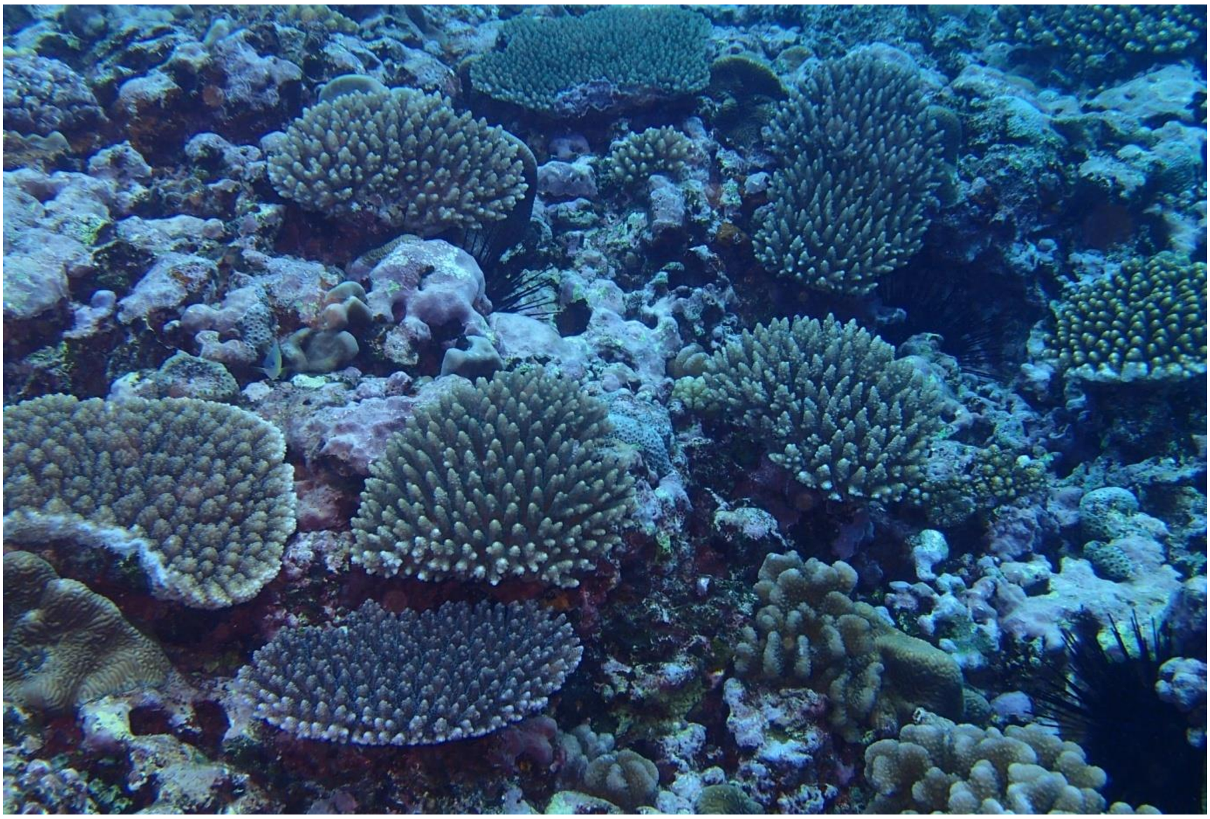


Figure 6. Large colonies (class D: 16 to 32 cm in diameter) of *Acropora* species were common only on the shallow reef slope areas of Rarotonga, away from transect lines at around 5 m or less. Photo taken by Teina Rongo at Titikaveka.

Principal Component Analysis using coral genera indicated that in 2006 and 2014, 96% and 97% of the variation was explained by the first two axes respectively (Figure 7 & Table 2). In 2006, eigenvectors (graphically illustrated on the vector plot; see Figure 7) indicated that *Porites* (0.575), and *Montastrea* (-0.404) had the most weight on the first axis; on the second axis *Leptoria* (0.422) had the most weight. In 2014, eigenvectors indicated that *Montipora* had the most weight in the first axis (-0.597), *Acropora* on the second axis (0.808), and *Leptastrea* on the third axis (-0.640) (see Table 2).

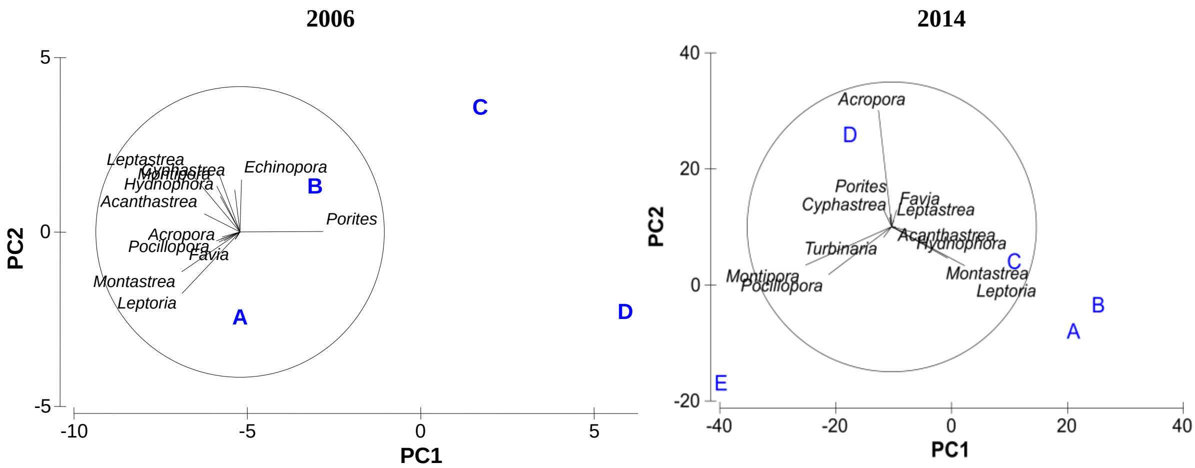


Figure 7. Principal Component Analysis (3 axes) for all coral genera and size classes recorded for 2014; all sites were lumped for this analysis. The percentage values for size class and the contribution of each genera to the class were used for this analysis.

Table 2. Eigen-analysis of coral genera from 2006 and 2014 for all sites combined. Eigenvector values in red indicate the family with the most weight on the respective axis.

2006				2014			
Eigenvalues							
PC	Eigenvalues	%Variation	Cum.%Variation	PC	Eigenvalues	%Variation	Cum.%Variation
1	27.1	73.3	73.3	1	774	72.4	72.4
2	8.53	23	96.3	2	260	24.3	96.7
3	1.36	3.7	100	3	21.7	2	98.8
Eigenvectors							
Variable	**PC1**	**PC2**	**PC3**	**Variable**	**PC1**	**PC2**	**PC3**
Leptoria	-0.401	-0.422	-0.446	*Leptoria*	0.506	-0.268	0.042
Montastrea	-0.404	-0.274	0.263	*Montastrea*	0.386	-0.216	0.533
Leptastrea	-0.346	0.411	0.144	*Acropora*	-0.091	0.808	0.356
Porites	0.575	0.003	0.163	*Hydnophora*	0.148	-0.037	0.024
Acanthastrea	-0.248	0.124	-0.265	*Pocillopora*	-0.436	-0.328	0.173
Cyphastrea	-0.150	0.41	-0.037	*Leptastrea*	0.016	0.047	-0.640
Hydnophora	-0.136	0.244	-0.125	*Porites*	-0.005	0.091	-0.090
Montipora	-0.161	0.314	0.297	*Acanthastrea*	0.096	-0.043	-0.041
Pocillopora	-0.163	-0.062	0.335	*Favia*	0.032	0.118	-0.214
Favia	-0.146	-0.069	0.233	*Cyphastrea*	-0.054	0.115	-0.026
Acropora	-0.133	-0.051	0.274	*Montipora*	-0.597	-0.266	0.165

2.1.2. Coral bleaching

Although coral bleaching was observed during this survey, these were not quantified because only a few were recorded and most were off the transect lines; those observed appeared to be recovering. Most bleached coral showed partial bleaching (Figure 8) with the majority observed on the northern exposure of Rarotonga. Indeed, the peak of the bleaching event likely occurred several weeks before the survey, which was consistent with the regional thermal stress outlook provided by National Ocean and Atmospheric Administration for the months of January and April, 2014, where the Cook Islands region was on *Alert Level 1* for coral bleaching (http://coralreefwatch.noaa.gov/satellite/bleachingoutlook/) (Figure 9). This bleaching event was also noted on other islands in the southern Cook Islands (see Rongo and Dyer, 2015).

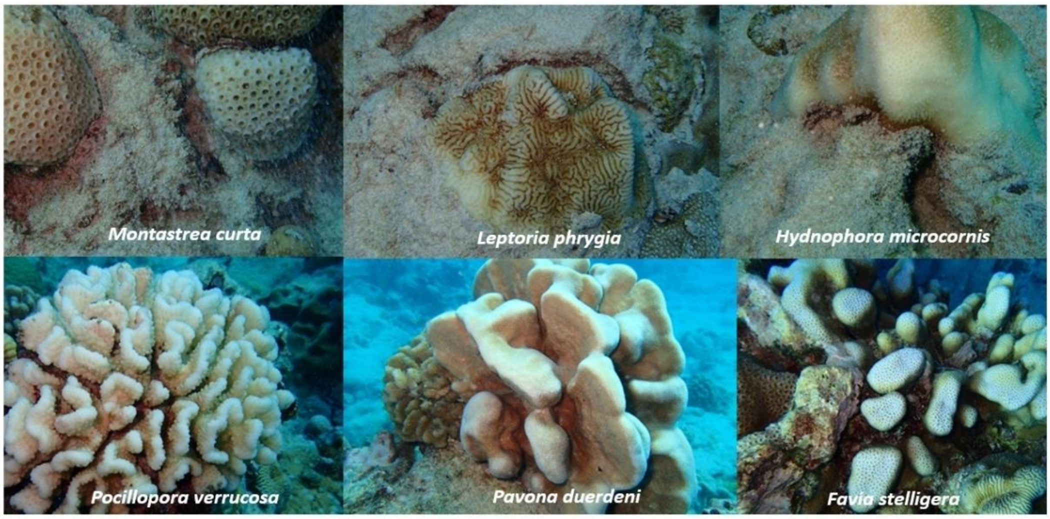


Figure 8. Several of the coral species that were observed to be bleached during the survey; most colonies showed partial bleaching and very few colonies were observed to have died as a result of this bleaching event (photo taken by Teina Rongo on the fore reefs of Avarua in 2014).

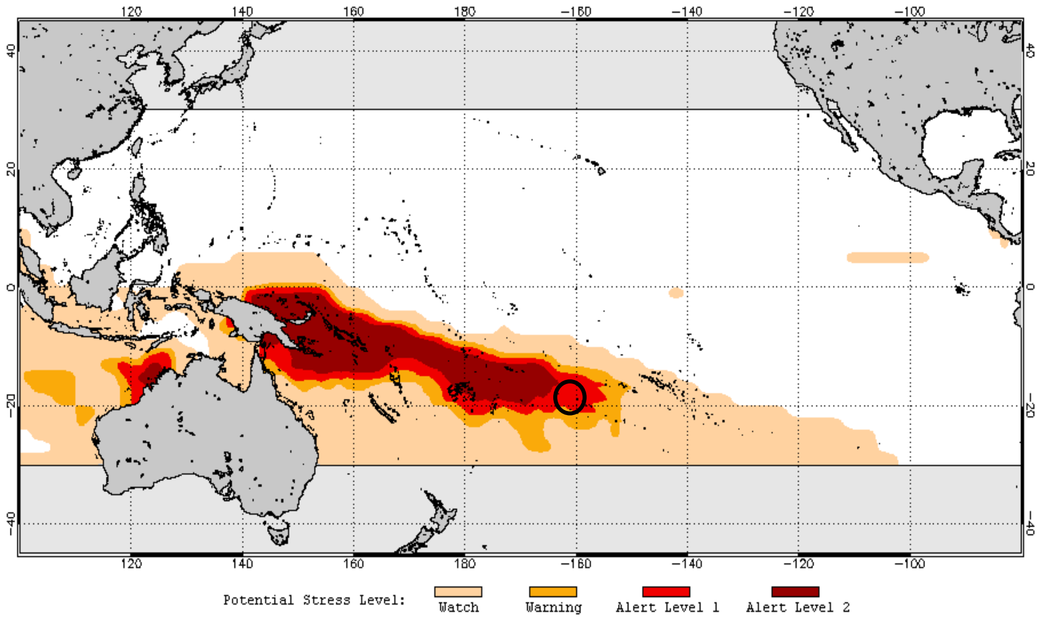


Figure. 9. Sea surface temperature anomaly for the Pacific region indicating areas of potential bleaching activities for the months of January to April 2014. Black circle area indicates the southern Cook Islands. Taken from: http://coralreefwatch.noaa.gov/satellite/bleachingoutlook/

2.2. FISH COMMUNITIES

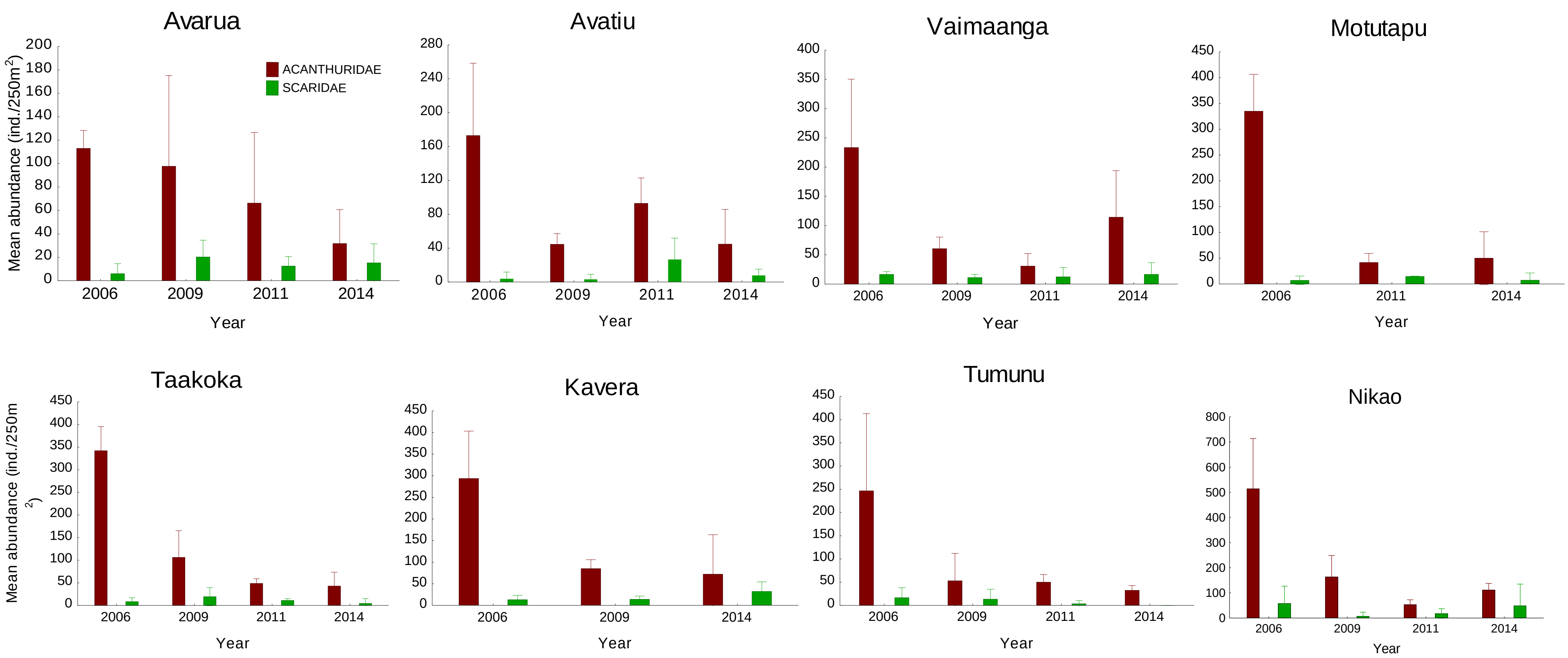
A total of 110 fish species were recorded during the survey representing 24 families (Appendix D). While the number of species and species richness were highest at Kavera, the number of individuals recorded was highest at Titikaveka (1915 ind./1000 m^2; Table 3). Species diversity was highest at Motutapu, and evenness was equally high at Avatiu and Avarua (see Table 3).

Table 3. Biodiversity measures for fishes at all sites. S = number of species, N = number of individuals, d = species richness, J` = evenness, and H` = diversity. Highest values are indicated in red.

Sample	S	N	d	J'	H'(loge)
Kavera	57	995	8.113	0.7482	3.025
Avatiu	42	664	6.309	0.8809	3.293
Avarua	42	664	6.309	0.8809	3.293
Kiikii	50	1186	6.923	0.8158	3.191
Motutapu	54	889	7.805	0.8272	3.300
Taakoka	39	634	5.89	0.7801	2.858
Titikaveka	48	1915	6.219	0.6888	2.666
Vaimaanga	32	776	4.659	0.6816	2.362
Tumunu	31	845	4.451	0.8132	2.793
Nikao	54	1361	7.345	0.7724	3.081

Mean abundance for acanthurids showed a significant decline between 2006 and 2014 for most sites, except for Titikaveka and Vaimaanga (Figure 10). Mean abundance ranged from 514 ± 62 ind./250 m^2 in Nikao to 113 ± 5 ind./250 m^2 in Avarua in 2006. In 2014, mean abundance ranged from 112 ± 8 ind./250 m^2 at Nikao to 32 ± 9 ind./250 m^2 at Avarua. Scarids on the other hand did not show a similar pattern; most sites showed no significant difference between 2006 and 2014. In 2006, abundance ranged from 58 ± 22 ind./250 m^2 in Nikao to 6 ± 3 ind./250 m^2 at Avarua. In 2014, mean abundance ranged from 50 ± 27 ind./250 m^2 in Nikao to nothing at Tumunu and Arorangi.

Principal Component Analysis of fish families indicated that 76% of the variation was explained by the first three axes (Figure 11 & Table 4). The eigenvectors (graphically illustrated on the vector plot) indicated that acanthurids had the most weight in the first axis (-0.912), pomacentrids on the second axis (0.858), and scarids on the third axis (0.842). Bubble plots showed the direction of change with a general increase in pomacentrids and chaetodontids between 2006 and 2014. However, a decline was noted in acanthurids over this period.



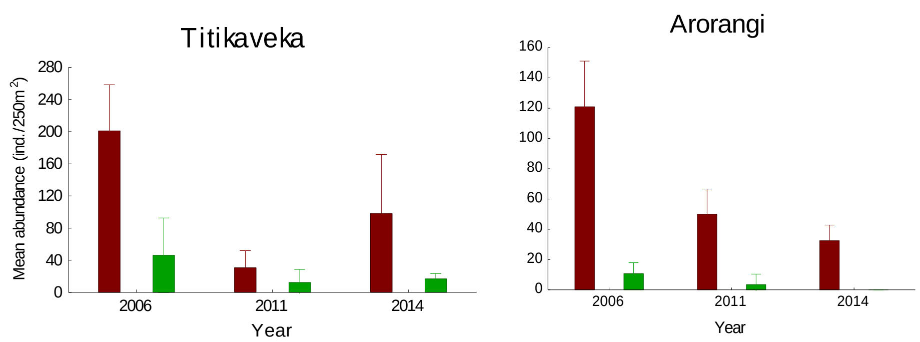


Figure 10. Mean abundance (individuals per 250 m^2) for families of acanthurids and scarids for all sites from 2006 to 2014. Plots indicate mean values with a ± 95% confidence interval.

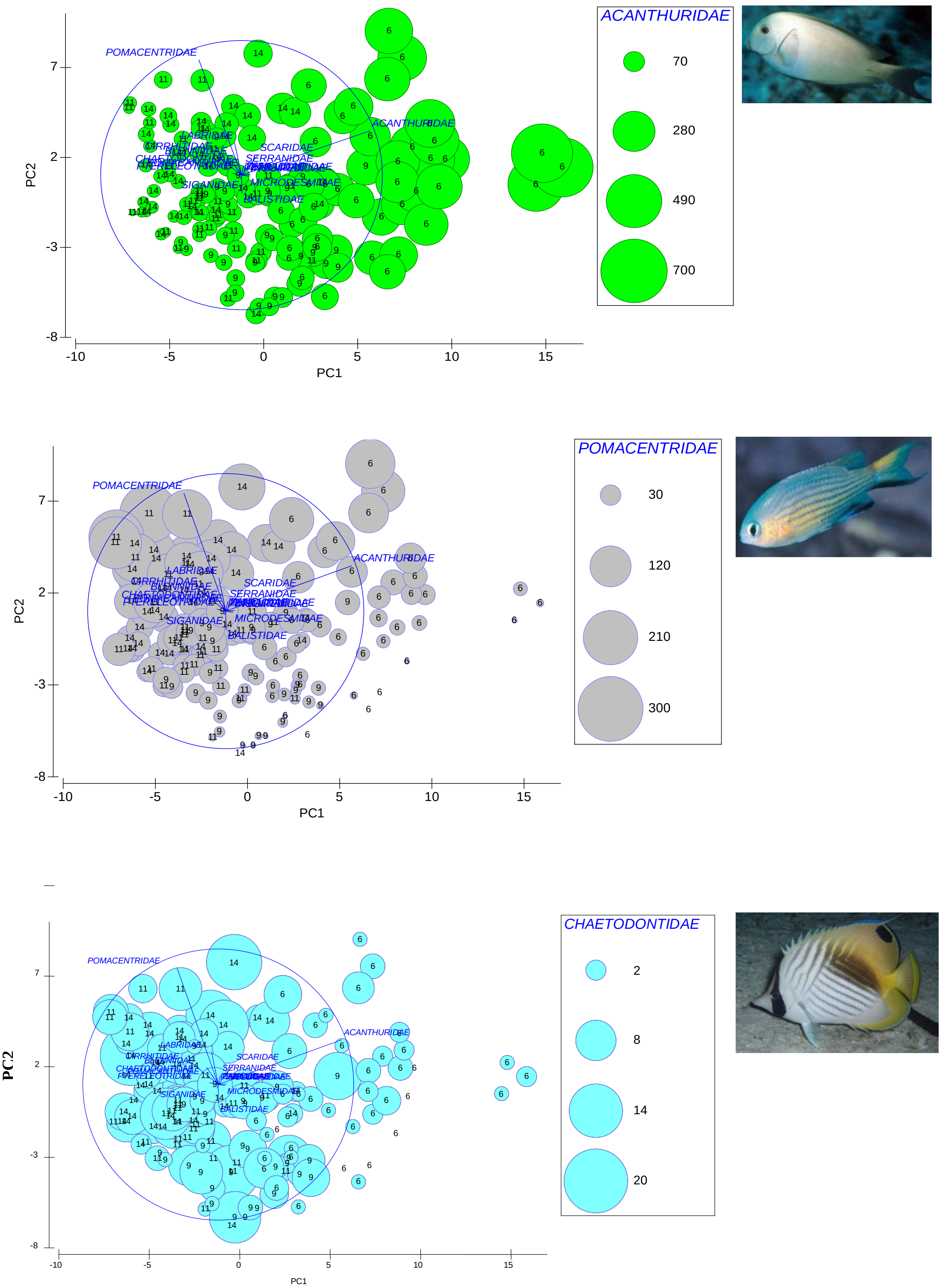


Figure 11. Principal Component Analysis (3 axes) for all fish families recorded for 2006 (6), 2009 (9), and 2014 (14). Bubble values represented three families (Acanthuridae, Pomacentridae, and Chaetodontidae). Data were square-root transformed. Acanthurid and pomacentrid photo taken from Randall (2005), and chaetodontid taken by Teina Rongo.

Table 4. Eigen-analysis of fish families in 2014 for all sites. Eigenvector values in red indicate the family with the most weight on the respective axis.

Eigenvalues

PC	Eigenvalues	%Variation	Cum.%Variation
1	22.8	46.5	46.5
2	10.4	21.3	67.8
3	4.02	8.2	76.0

Eigenvectors

Variable	PC1	PC2	PC3
ACANTHURIDAE	-0.912	0.330	-0.161
POMACENTRIDAE	0.304	0.858	0.074
LABRIDAE	0.050	0.242	-0.336
SCARIDAE	-0.117	0.151	0.842
BALISTIDAE	-0.002	-0.136	0.050
CIRRHITIDAE	0.196	0.160	-0.197
CHAETODONTIDAE	0.046	0.069	0.146

2.3. MACRO-INVERTEBRATE COMMUNITIES

Generally, *Echinometra* spp.*, Echinothrix diadema,* and *Dendropoma maxima* were the most common invertebrates on the fore reefs of Rarotonga (Figure 12). Although the abundance of urchins were highly variable and no clear trend was noted from 2006 to 2014. Clearly, *Echinometra* spp. (*kina*)*,* which consist of two species, were the most abundant invertebrate with numbers ranging from 386 ± 86 ind./ 100 m^2 at Nikao to 107 ± 25 ind./ 100 m^2 at Avatiu in 2014. On the other hand, *vana* ranged from 73 ± 13 ind./ 100 m^2 at Nikao to 19 ± 3 ind./ 100 m^2 at Avarua in 2014.

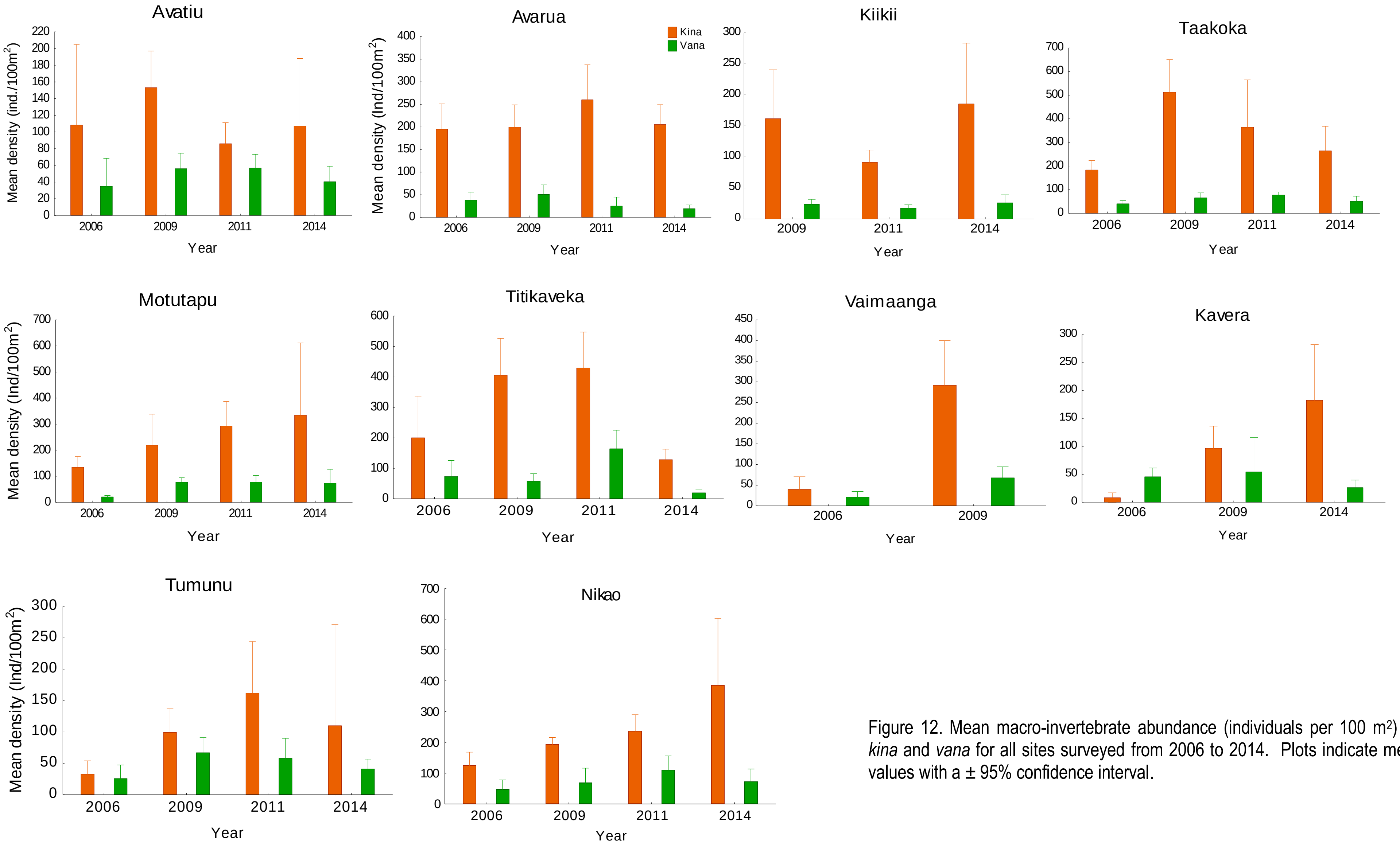


Figure 12. Mean macro-invertebrate abundance (individuals per 100 m^2) for *kina* and *vana* for all sites surveyed from 2006 to 2014. Plots indicate mean values with a ± 95% confidence interval.

Principal Component Analysis and vector plots (Figure 13 & 14) indicated a shift in urchin abundance since 2006. Principal Component Analysis of macro-invertebrates indicated that 89% of the variation was explained by the first three axes (Table 6). The eigenvectors (graphically illustrated on the vector plot; see Figure 13 & 14) indicated that *kina* (*Echinometra* spp.) had the most weight in the first axis (0.964), *Dendropoma maxima* on the second axis (0.955), and *vana* (*Diadema* and *Echinothrix*) (0.620) and Holothurians (0.755) on the third axis. Bubble plots showed a general increase in all the urchin species between 2006 and 2014.

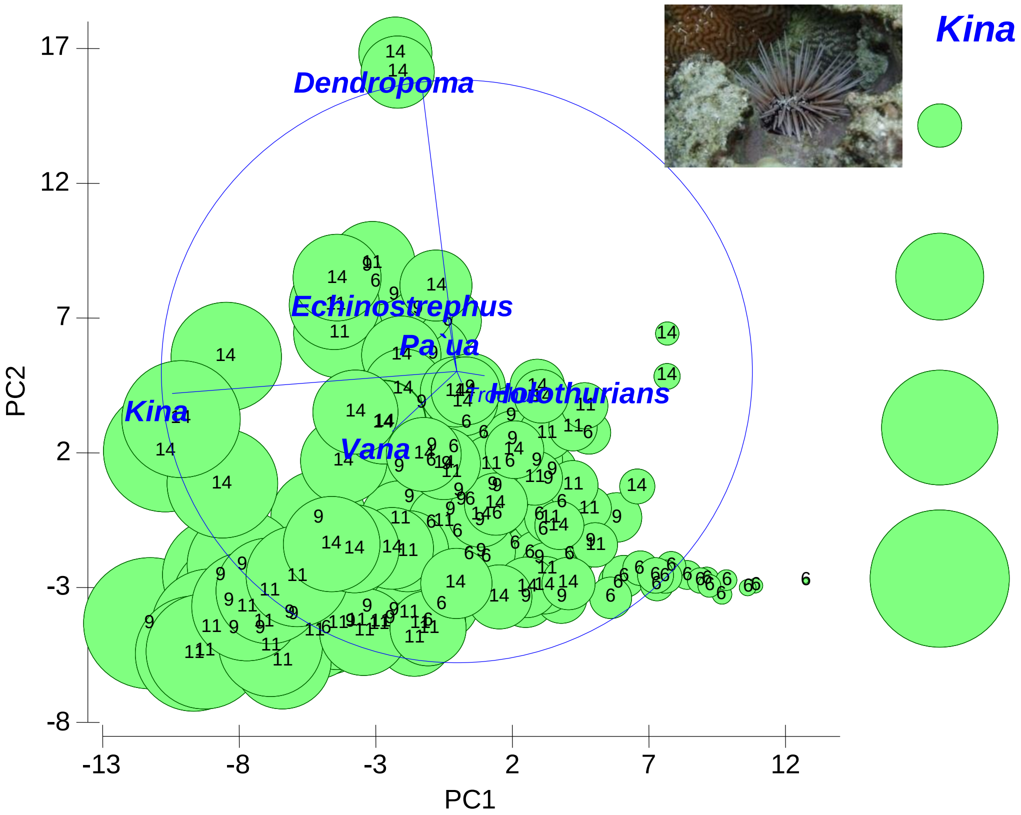


Figure 13. Principle Component Analysis (PCA) for *kina* using all replicates with all the invertebrate categories for all sites from 2006 (6), 2009 (9), 2011 (11), and 2014 (14). Ordination of replicates were superimposed on the vector plot. Square root transformation was carried out on the data prior to PCA. Bubble values indicate the abundance (individuals per 100 m^2) of invertebrates for each replicate. Photo by Teina Rongo.

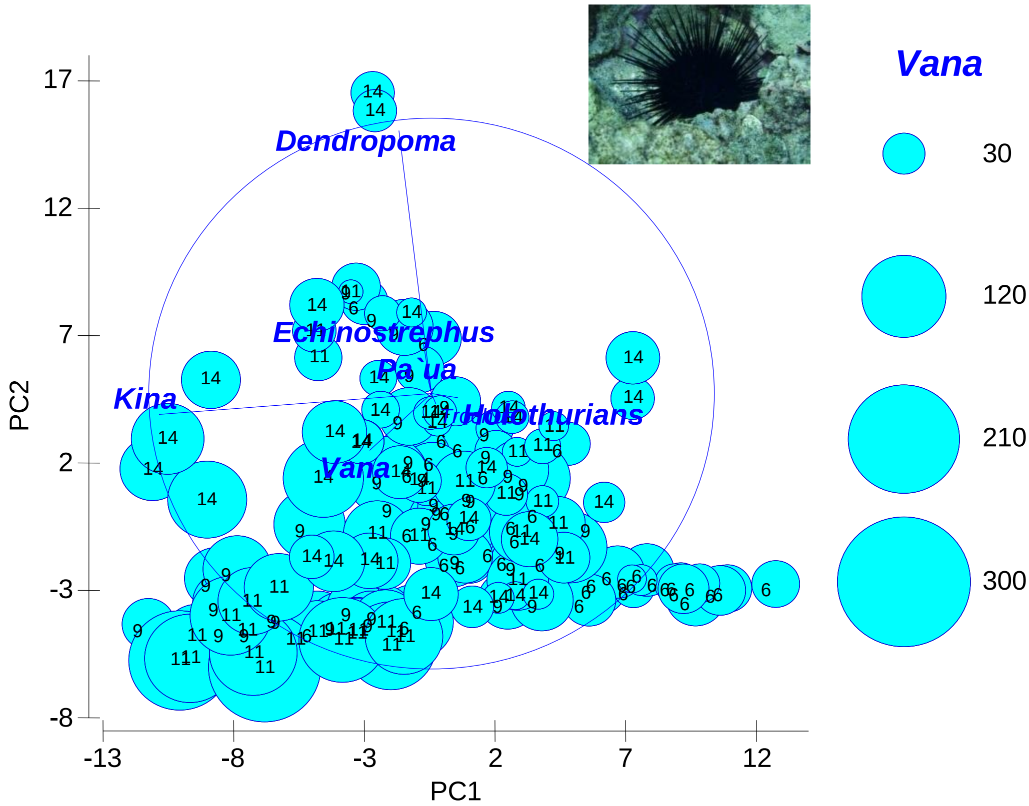


Figure 14. Principle Component Analysis (PCA) for *vana* using all replicates with all the invertebrate categories for all sites from 2006 (6), 2009 (9), 2011 (11), and 2014 (14). Ordination of replicates were superimposed on the vector plot. Square root transformation was carried out on the data prior to PCA. Bubble values indicate the abundance (individuals per 100 m^2) of invertebrates for each replicate. Photo by Teina Rongo.

Table 6. Eigen-analysis of macro-invertebrates in 2014 for all sites.

Eigenvalues

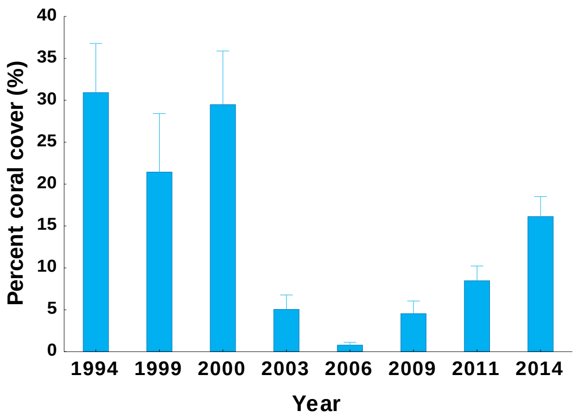
PC	Eigenvalues	%Variation	Cum.%Variation
1	24.6	48.7	48.7
2	16.6	32.7	81.4
3	4.03	8.0	89.3

Eigenvectors

Variable	PC1	PC2	PC3	PC4	PC5
Kina	-0.964	-0.076	-0.085	0.152	-0.185
Vana	-0.219	-0.206	0.620	-0.515	0.506
Echinostrephus	-0.029	0.188	0.164	0.734	0.617
Trochus	0.016	-0.038	0.002	-0.098	-0.003
Pa`ua	-0.013	0.056	0.009	0.057	0.080
Dendropoma	-0.115	0.955	0.107	-0.246	-0.041
Holothurians	0.094	-0.015	0.755	0.315	-0.566

3. DISCUSSION

Indeed reefs around Rarotonga are recovering from the crown-of-thorn starfish outbreak (COTS) that degraded the fore reef between 1995 and 2001. Comparison to previous years showed that mean hard coral cover in 2014 was still below that estimated prior to the 2000s (Figure 15 *left*). In addition, mean cover for Rarotonga in 2014 was also below that estimated for most of the southern islands except for Aitutaki (Figure 15 *right*; see Appendix B for coral species checklist); Aitutaki's reefs has been degraded by COTS for much of the 2000s (Rongo, 2008; Bruckner, 2013). When compared to the average estimated from 2,667 indo-Pacific reefs of 22.1%, Rarotonga's reefs are also well below this average. Previous survey results indicated that mean hard coral cover for all sites were around 1% in 2006, 5% in 2009, 8% in 2011, and 16% in 2014; clearly hard coral cover has been increasing since 2006. Considering that during an eight-year period (2006 to 2014), an increase of coral cover from 1% to 16% would suggest an approximate coral recovery rate of 2% per year. Given this conservative rate, we estimated that coral cover will reach the pre-COTS conditions of the 1990s (at >30%) by 2022 — a period of 21 years since the end of the COTS outbreak in 2001. In contrast, recovery period estimated from the 1970s COTS outbreak that also degraded the fore reef slopes of Rarotonga (Devaney & Randall, 1973; Dahl, 1980), took less than 10 years based on anecdotal reports. Certainly, factors such as increased cyclone frequency (de Scally, 2008), coral bleaching (Rongo & van Woesik, 2013), and nutrient overloading (e.g., Anderson et al., 2004) and perhaps ocean acidification (e.g., Kleypas et al, 1999) all play an important role in determining the current state of Rarotonga's reefs.



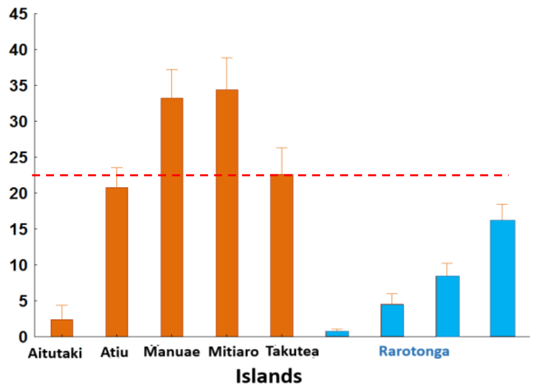


Figure 15. *Left*: Mean percent coral cover for all sites lumped for each year. Data taken from 1994 (Miller, 1994), 1999 (Ponia et al., 1999), 2000 (Lyon, 2000), 2003 (Lyon, 2003), 2006 (Rongo et al., 2006), 2009 (Rongo et al., 2009), 2011 (Rongo & van Woesik, 2013), and 2014 from the present survey. *Right*: Mean coral cover for islands in the southern Cook Islands in 2013 (Rongo et al., 2013; brown bars) with Rarotonga coral cover taken from the 2006 to 2014 surveys (blue bars). Dotted red line represents the Indo-Pacific average of 22.1% estimated in 2003 (Bruno & Selig, 2007).

Asparagopsis taxiformis was the most common macro-algae observed on the reef slopes, particularly at depths less than 10 meters (Figure 16). Although not reflected in the survey result, macro-algae were observed to be most common on the western and eastern exposures of the island. For example, extensive areas of the reef slope at Motutapu were dominated by *A. taxiformios* and of *Amphiroa* spp. Both species of red algae are chemically defended and would therefore deter grazing by herbivorous fish species (e.g., Meyer et al., 1994). As noted in previous surveys (Rongo et al., 2006; 2009), this survey also found that the Ngatangiia reef area (i.e., Motutapu and areas around the Avana passage) had one of the highest cover of macro-algae. The high cover of macro-algae on these reefs may reflect the deteriorating conditions of the Ngatangiia lagoon due to heavy use and poor land-use practices that are likely creating eutrophic conditions in the vicinity.

Figure 16. Left: *Asparagopsis taxiformis* is the most common macro-algae on the fore reef of Rarotonga at depths between 2 to 10 m (photo taken by Teina Rongo at Motutapu in 2014). Right: *Amphiroa* spp., the other species of macro-algae recorded on the fore reefs of Rarotonga (photo taken by Teina Rongo from the same site in 2014).

Recovery of hard corals on Rarotonga were also consistent with the increase of pomacentrids recorded since 2006. In particular, *Chromis vanderbilti* was the most common damselfish on reef slopes around Rarotonga followed by *Pomachromis fuscidorsalis.* This is because increased live coral cover and associated structural complexity provides shelter for many damselfish species. Acanthurids on the other hand showed a decline since 2006. Rongo and van Woesik (2013) suggested that major reef disturbances (i.e., COTS outbreaks and cyclones) that occurred prior to 2006 on Rarotonga resulted in a shifted towards a more algal-dominated community. Consequently, more food was available to grazers that likely supported large recruitment of acanthurids (mainly *Ctenochaetus striatus*) as observed in 2006. They also suggested that these early algal successions consisted mainly of the palatable types, but shifted towards the unpalatable types over the years because no major disturbances have occurred since 2005 to remove them. Consequently, this shift may have contributed to the general decline in acanthurid populations noted since 2006 as less food was available. It is unlikely that this decline is a result of overfishing, given that the impact of ciguatera poisoning on local fishers in the last few decades has caused a shift away from reef fish consumption (Rongo & van Woesik, 2011).

In 2006, a large number of small colonies of *Leptoria phrygia* that would be considered recruits were clearly remnants of what used to be larger colonies; recruits belonged to several species of *Acropora, Favia* and *Pocillopora,* which comprised of around 12% of the colonies within class A (Rongo et al., 2006). Interestingly, larger colonies (class D) recorded in 2006 were predominantly *Porites* (see Rongo et al., 2006) that obviously escaped predation by COTS. However in 2014, *Acropora* were among the top three most common corals in the larger size class (16 to < 32 cm). Based on observation from the pre-COTS period in the 1990s (T. Rongo; pers. obs.), large plate-like colonies of *Acropora* species were the most dominant coral on the reef slope. The increase of *Acropora* species in the larger size classes in 2014 clearly suggests that reefs are recovering and that we are shifting back into an *Acopora*-dominated community. The other large branching corals on the reef slopes were

Pocillopora species (mainly *P. eyedouxi* and *P. verrucosa*) that were also noted during the 2006 survey; it was suggested that these colonies survived the COTS outbreak because the *Trapezia* crabs that live in these corals defend their host aggressively (e.g., Weber & Woodhead 1970; Glynn 1976; Pratchett & Vytopil, 2000).

While conditions on Rarotonga are favorable for bottom-up control (e.g. Anderson et al.., 2004), maintaining a healthy herbivorous community (e.g., acanthurids, scarids, and urchins) for exerting top-down control may be important at this point to facilitate recovery. It was proposed that ciguatera poisoning on Rarotonga has been expected to decline (Rongo et al., 2009) (also noted in current hospital records); as a result, reef fishing activities were also expected to increase, which may compromise reef recovery. Indeed, there is a need to start considering some management measures to avoid overfishing, particularly for important functional groups such as herbivores (e.g., scarids, acanthurids, kyphosids, siganids, and urchins).

Observed oceanographic changes (i.e., stronger currents and rougher sea conditions) as indicated by Rongo & Dyer (2015) for most of the island groups is a concern because such changes may decrease the recruitment of many marine organisms to natal reefs (see Kingsford et al., 2003 and references therein). For example, increased flow rate from 1.6 cm/sec to 9.8 cm/sec decreased recruitment in a coral species from 20% to 2% respectively (Harii & Kayanne, 2002). Rongo and Dyer (2015) indicated that recruitment of many seasonal reef fish species throughout the Cook Islands has declined. In Manihiki, a species of parrotfish (tōmore; *Scarus* spp.) that normally recruit in the thousands within the lagoon are rarely seen today. In many of the southern islands, *Siganus spinus* and *Siganus argenteus* — two important food fish that usually recruit in large numbers in the past — are also rarely seen today. In addition, Rongo and Dyer (2015) suggested that the effect of stronger currents and increased frequency of storm surge in recent decades may be responsible for increased sediment transport within many lagoons throughout the Cook Islands. Sedimentation in the marine environment can be detrimental to coral growth and recruitment (e.g., Rogers, 1990), which may explain the slow recovery of Rarotonga's reefs noted in this report.

Although sites in this survey were located at depths ranging from 7 to 10 meters, it was obvious that coral cover at most sites decreased with depth and shallower areas showing higher cover; coral cover at deeper locations were observed to be depauperate of corals and will likely take longer to recover. With coral recovery occurring on Rarotonga, establishing new *ra`ui* or enforcing the management of the current *ra`ui* around the island should be considered, especially when reef fishing activities are expected to increase following the decline in ciguatera poisoning in recent years. In addition, good land-use practices to reduce runoff sediments and continued efforts to reduce nutrient inputs will be critical at this stage to facilitate recovery, and most importantly to build the resilience of these reefs to the impacts of climate change.

Although conditions during previous survey years have been favorable to trigger coral bleaching, this was not monitored because coral cover has been too low to notice any bleaching. Whilst some bleached corals were noted during this survey, these were only noted but not measured. Considering that coral cover has increased over the years, we expect coral bleaching to become more evident and therefore bleaching should be included in future monitoring. Ocean acidification has been mentioned frequently in the literature, yet information on its impacts in the region are unavailable and research on this issue should be encouraged for the Cook Islands. Continuation of this monitoring survey in the future is important because it will help us understand both spatial and temporal changes on these reefs. This information can help elucidate factors degrading these reefs and what we can do to minimize their impact. However, considering that reef monitoring in the past on Rarotonga has been plagued by inconsistencies (e.g., methodology, interval between surveys, different data collectors) and especially limited funding, the continuation of this monitoring remains uncertain.

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The research team consisted of:

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- Ben Tautu (National Environment Service) – macro-invertebrates
- Graham McDonald (volunteer)– fish
- Barbara Hanchard (volunteer) – benthic communities
- Teariki Charles Rongo (volunteer) – macro-invertebrates

LITERATURE CITED

Anderson et al. (2004). Water quality programme: Rarotonga and Aitutaki lagoons. Ministry of Marine Resources Report, 42 pp.

Bak & Meesters. (1998) Coral population structure: the hidden information of colony size-frequency distributions. *Marine Ecology Progress Series* 162, 301 – 306.

Bruckner, A. (2013) Mitigating the impacts of *Acanthaster planci* (crown-of-thorns starfish, COTS) outbreak on coral reefs in Aitutaki, Cook Islands. Khaled bin Sultan Living Oceans Foundation Publication # 9, 33 pp.

Bruno & Selig. (2007) Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. *PLoS ONE* 2, e711.

Clarke KR, Warwick RM. (1994) Change in Marine Communities: An Approach to Statistical Analysis and Interpretation. Plymouth Marine Laboratory. 144 p.

Dahl, A.L. (1980). Report on marine surveys of Rarotonga and Aitutaki. South Pacific Commission. 13 pp.

Devaney, D.M., Randall, J.E. (1973) Investigations of *Acanthaster planci* in Southeastern Polynesia during 1970–1971. Atoll Res. Bull. 169, 1–35.

de Scally, F. (2008) Historical tropical cyclone activity and impacts in the Cook Islands. *Pacific Science* 62 (4): 443–459.

Glynn PW. (1976) Some physical and biological determinants of coral community structure in the Eastern Pacific. *Ecological Monographs* 46:431– 456

Harii, S., H. Kayanne, and H. Takigawa. (2002) Larval survivorship, competenncy periods and settlement of two brooding corals, Heliopora coerulea and Pocillopora damicornis. Marine Biology 141: 39 -46.

Hoegh-Guldberg, O. (1999) Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* 50:839-66.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., Hatziolos, M.E. (2007) Coral reefs under rapid climate change and ocean acidification. *Science* 318, 1737–1742.

Houk et al. (2005) Assessing the effects of non-point source pollution on American Samoa's coral reef communities. *Env. Mon. Assess.* 107: 11-27.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nyström, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B., Roughgarden, J. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* 301, 929 – 933.

Jackson et al. (2001) Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293, 629 – 638.

Kleypas et al. (1999) Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science* 284, 118 – 120.

Lapointe, B.E. (1997) Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. *Limnology and Oceanography* 42(5 part 2):1119-1131.

Lyon, S.J. (2000) Base line survey and long term monitoring programme of the outer reef, Rarotonga, Cook Islands. Prepared for the Cook Islands National Environment Service. 17 pp.

Lyon, S.J. (2003) Rarotonga fringing reef survey. For the Environment Service, Tu'anga Taporoporo, Cook Islands. 20 pp.

Meyer, K.D., Paul, V.J., Sanger, H.R., Nelson, S.G. (1994) Effects of feeding extracts and secondary metabolites on feeding by the herbivorous surgeonfish Naso lituratus. Coral reefs 13, 105 – 112.

Miller et al. (1994) Report on baseline surveys for monitoring the fringing reef of Rarotonga, Cook Islands. Prepared for the Cook Islands National Environment Service. 29 pp.

Myers, RF. (1989) Micronesian reef fishes: a practical guide to the identification of the coral reef fishes of the Tropical Central and Western Pacific. Coral Graphics, USA, 298 pp.

Myers, RF. (1999) Micronesian reef fishes: a field guide for divers and aquarists. Coral Graphics, USA, 216 pp.

Ponia et al. (1999) Rarotonga fringing reef fish and coral monitoring survey. Ministry of Marine Resources. Misc. Report:99/20. Rarotonga, Cook Islands. 23 p.

Pratcett & Vytopil (2000).Coral crabs influence the feeding patterns of crown-of-thorns starfish. *Coral reef* 19:36.

Randall, J.E. (2005) Reef and shore fishes of the South Pacific: New Caledonia to Tahiti and the Pitcairn Islands. University of Hawai`i Press. Honolulu, USA, 707 pp.

Randall RH & Myers RF. (1983) The Corals. Guide to the Coastal Resources of Guam. Volume 2. University of Guam Press. 128 p.

Reaka-Kudla, M. L. (1997) The Global Biodiversity of Coral Reefs: A Comparison with Rain Forests. In Biodiversity II, M. L. Reaka-Kudla, D. E. Wilson, E. O. Wilson, Eds. (Joseph Henry Press, Washington, DC, 1997), pp. 83-108.

Rogers, CS. (1990) Response of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress Series* 62: 185-202.

Rongo, T. (2008) Coral reef survey for Aitutaki. Report for the Cook Islands National Environment Service. 33 pp.

Rongo, T., and Dyer, C. (2015) Using local knowledge to understand climate variability in the Cook Islands. Government of the Cook Islands. 55 pp.

Rongo, T., van Woesik, R. (2011) Ciguatera poisoning in Rarotonga,southern Cook Islands. Harmful Algae 10, 345–355.

Rongo, T. & van Woesik, R. (2013) The effects of natural disturbances, reef state, and herbivorous fish densities on ciguatera poisoning in Rarotonga, southern Cook Islands. *Toxicon* 64, 87 – 95.

Rongo et al. (2006) Reef survey for Rarotonga. Report for the Cook Islands National Environment Service. 81 pp.

Rongo et al. (2009) Rarotonga fore reef community survey for 2009. Report for the Cook Islands National Environment Service. 36 pp.

Rongo, T., Evans, J., Passfield, K., Cramp, J., Sudek, M., Tautu, B., McDonald, G., Rongo, T.C., & B. Hanchard. (2013) Cook Islands Marine Park: coral reef survey of Aitutaki, Manuae, Mitiaro, Takutea, and Atiu in the southern Cook Islands. Government of the Cook Islands. 64 p.

Sapp, J. (1999) What is natural? Coral reef crisis. Oxford University Press, New York.

Steneck, R.S. (1988) Herbivory on coral reefs: a synthesis. Proc. 6th InternationalCoral Reef Symposium, Australia 1:37-49.

Veron, J.E.N. (2000) Corals of the World. Australian Institute of Marine Science, Townsville, Australia.

Veron, J.E.N. (2008) Mass extinctions and ocean acidification: biological constraints on geological dilemmas. Coral Reefs 27, 459–472.

Veron, J.E.N., Hoegh-Guldber, O., Lenton, T.M., Lough, J.M., Obura, D.O., Pearce-Kelly, P., Sheppard, C.R.C., Spalding, M., Stafford-Smith, M.G., Rogers, A.D. (2009) The coral reef crisis: the critical importance of <350 ppm CO2. Mar. Pollut. Bull. 58, 1428–1436.

Wilkinson, C. (2002) Status of Coral Reefs of the World. Global Coral Reef Monitoring Network and Australian institute of Marine Science, Townsville, Australia.

Wilkinson, C. (2004) Status of Coral Reefs of the World. Global Coral Reef Monitoring Network and Australian institute of Marine Science, Townsville, Australia.

Weber & Woodhead. (1970) Ecological studies of the coral predator *Acanthaster planci* in the South Pacific. *Marine Biology* 6: 12-17.

APPENDICES

Appendix A. Global Positioning System coordinates for fore reef sites surveyed on Rarotonga in the southern Cook Islands from 15 May to 21 August 2014.

SITES	DATE SURVEYED	GPS
Avatiu	19/05/2014	21º 12.027' S 159º 47.157' W
Avarua	15/5/2014	21º 12.161' S 159º 46.563' W
Kiikii	24/5/2014	21º 12.180' S 159º 44.800' W
Motutapu	18/8/2014	21º 14.944' S 159º 43.244' W
Ta`akoka	15/8/2014	21º 16.061' S 159º 43.614' W
Titikaveka	14/6/2014	21º 16.699' S 159º 45.645' W
Vaimaanga	21/8/2014	21º16.059' S 159º 48.024' W
Kavera	12/6/2014	21º 15.389' S 159º 49.442' W
Tumunu	19/8/2014	21º 13.086' S 159º 50.053' W
Nikao	20/5/2014	21º 12.013' S 159º 49.124' W

Appendix B. Checklist of hard coral species recorded at islands surveyed in 2013 (Rongo et al., 2013) and Rarotonga in 2014 (the present survey).

	Manuae	Mitiaro	Takutea	Atiu	Rarotonga
ACROPORIDAE					
Acropora digitifera		1		1	1
Acropora gemmifera	1	1	1	1	1
Acropora sp				1	1
Acropora humilis	1	1	1	1	1
Acropora lutkeni	1			1	1
Acropora hyacinthus				1	1
Acropora nasuta			1	1	1
Acropora palmerae	1				1
Acropopa schmitti	1	1	1	1	
Acropora tenuis		1	1		
Acropora veweyi				1	1
Astreopora expansa	1	1	1	1	
Astreopora gracillis			1	1	
Astreopora myriopthalma					1
Montipora (pink)	1				1
Montipora digitata		1			
Montipora floweri	1	1	1	1	1
Montipora foveolata			1		1
Montipora meandrina	1				
FAVIIDAE					
Cyphastrea chalcidicum	1	1	1	1	1
Echinopora lamellosa					
Favites flexuosa				1	1
Favia rotumana	1	1		1	1
Favia stelligera	1	1	1	1	1
Leptoria phrygia		1		1	1
Leptastrea purpurea			1	1	1
Goniastrea pectinata				1	1
Gonistarea russelli					1
Goniastrea edwardsi					1
Goniastrea annularis					1
Montastrea curta	1	1	1	1	1
Platigyra pini		1			
AGARICIIDAE					
Pavona duerdeni	1			1	1
Pavona meldavensis	1	1			
Leptoseris sp	1				
DENDROPHYLLIIDAE					
Turbinaria reniformis					1
MERULINIDAE					
Hydnophora exesa	1				
Hydnophora microcornis				1	1
MUSSIDAE					
Lobophylia hemprichii				1	1
Acanthastrea brevis		1	1		
Acanthastrea echinata	1	1	1	1	1
MILLEPORIDAE					
Millepora platyphyla		1	1	1	1
POCILLOPORIDAE					
Pocillopora damicornis					1
Pocillopora danai					1
Pocillopora eyedouxi		1		1	1
Pocillopora meandrina	1	1	1	1	1
Pocillopora verrucosa	1	1	1	1	1
Pocillopora woodjonesi				1	
PORITIDAE					
Porites lichen			1	1	
Porites lobata		1	1		1
Porites rus					1
Porites lutea	1	1	1	1	1
SIDERASTREIDAE					
Psammocora niestraszi	1	1		1	1
Psammocora profundacella	1	1		1	1
Psammocora stellata	1				
Coscinaraea columna	1				1
ALCYONIDS (soft corals)					
Sinularia spp				1	1
Cladiella spp				1	1
Lobophyton spp					1
TOTAL NO. OF SPECIES	**25**	**25**	**21**	**35**	**44**
TOTAL NO. OF FAMILIES	**8**	**8**	**6**	**10**	**11**

Appendix C. Percent contribution of coral genera in each class for 2006 and 2014.

2006					2014					
Genus	A	B	C	D	**Genus**	**A**	**B**	**C**	**D**	**E**
Leptoria	27.7	3.1	0	0	*Leptoria*	29	29	19.9	0	0
Montastrea	19.9	10.2	0	0	*Montastrea*	20	25	10.8	0	0
Leptastrea	14.6	24.5	15	0	*Acropora*	7.1	11	13.4	37.8	5
Porites	9.58	22.4	50	100	*Hydnophora*	13	6	6.5	2.7	0
Acanthastrea	10.1	6.1	5	0	*Pocillopora*	9.7	2	6.1	13.5	36
Cyphastrea	3.02	8.2	10	0	*Leptastrea*	4.1	4	11.6	5.4	5
Hydnophora	2.89	4.1	5	0	*Porites*	4.8	5	6.9	8.1	5
Montipora	2.23	9.2	5	0	*Acanthastrea*	4.5	6	4.3	0	0
Pocillopora	2.36	3.1	0	0	*Favia*	3	3	5.8	5.4	0
Favia	2.1	2.01	0	0	*Cyphastrea*	1.9	3	4.3	8.1	5
Acropora	1.57	2.01	0	0	*Montipora*	0.7	0	4	16.2	41
Coscinarea	1.18	2.01	0	0	*Goniastrea*	0	2	2.5	0	0
Goniastrea	1.31	1.01	0	0	*Coscinarea*	1.1	0	0.7	0	0
Psammocora	0.52	1.01	5	0	*Psammacora*	0	0	2.2	0	0
Echinopora	0	1.01	5	0	*Favites*	0.7	1	0	0	0
Lobophylia	0.26	0	0	0	*Lobophylia*	0	0	0	0	0
Pavona	0.26	0	0	0	*Turbinaria*	0	0	0.4	0	5
Turbinaria	0.26	0	0	0	*Astreopora*	0	0	0.4	0	0
Favites	0.13	0	0	0	*Echinopora*	0	0	0	0	0
					Millepora	0	0	0	2.7	0
					Pavona	0	0	0.4	0	0

Appendix D. Checklist of fish species recorded at each site surveyed in 2014.

FAMILY	COMMON NAME	Kavera	Avatiu	Avarua	Kiikii	Motutapu	Taakoka	Titikaveka	Vaimaanga	Tumunu	Nikao
ACANTHURIDAE	**Surgeons, Tangs, Unicorns**										
Acanthurus nigrofuscus	Brown Surgeonfish	90	0	0	86	82	143	230	158	130	155
Acanthurus achilles	Achilles Tang	0	0	0	0	0	0	0	2	0	0
Acanthurus nigricans	Whitecheek Surgeonfish	0	0	0	0	0	0	0	4	0	0
Acanthurus nigroris	Blue-lined Surgeonfish	0	0	0	13	0	0	0	0	0	0
Acanthurus nigricaudus	Blackcheek Surgeonfish	20	13	13	0	0	0	0	25	0	2
Acanthurus leucopareius	Whitebar Surgeonfish	0	6	6	0	0	0	20	0	0	4
Acanthurus olivaceus	Orangeband Surgeonfish	51	29	29	10	34	0	0	0	0	17
Acanthurus triostegus	Convict Tang	0	59	59	0	0	0	105	50	0	60
Acanthurus guttatus	Whitespotted Surgeonfish	0	0	0	0	0	0	18	6	0	0
Ctenochaetus striatus	Bristletooth Surgeonfish	101	13	13	30	16	2	305	190	0	190
Ctenochaetus hawaiensis	Hawaiian Surgeonfish	7	2	2	0	17	0	2	0	0	0
Naso lituratus	Orangespine Unicorn	16	5	5	10	27	27	40	23	0	18
Zebrasoma scopas	Brushtail Tang	2	0	0	0	24	0	0	0	0	0
Zebrasoma veliferum	Pacific Sailfin Tang	2	0	0	2	0	0	0	0	0	0
BALISTIDAE	**Triggerfish**										
Melichthys vidua	Pinktail Triggerfish	1	0	0	2	3	1	3	2	0	1
Melichthys niger	Black Triggerfish	0	0	0	0	0	0	4	0	0	0
Rhinecanthus rectangulus	Wedgetail Triggerfish	0	3	3	10	4	5	2	0	5	2
Pseudobalistes flavimarginatus	Giant triggerfish	0	1	1	0	0	0	0	0	0	0
Pseudobalistes fuscus	Blue Triggerfish	0	0	0	0	0	0	2	0	0	0
Sufflamen bursa	Scythe Triggerfish	1	29	29	17	7	1	1	0	13	19
Sufflamen chrysopterum	Flagtail Triggerfish	0	0	0	0	0	0	0	0	0	1
CARACANTHIDAE											
Caracanthus maculatus	Spotted Coral Croucher	4	3	3	12	8	19	10	0	12	1
CIRRHITIDAE	**Hawkfish**										
Cirrhitops hubbardi	Hubbard's Hawkfish	6	9	9	15	19	15	11	0	12	10
Paracirrhitus arcatus	Arc-eye Hawkfish	29	26	26	44	19	34	28	5	43	39
Paracirrhitus forsteri	Freckled Hawkfish	0	0	0	0	0	1	0	0	0	0
Paracirrhtes hemistictus	Spotted Hawkfish	1	0	0	0	0	0	6	0	0	0
Neocirrhtes armatus	Flame Hawkfish	11	15	15	46	25	23	2	5	30	4
CHAETODONTIDAE	**Butterflyfish**										
Chaetodon auriga	Threadfin Butterfly	0	0	0	0	0	0	0	2	0	0
Chaetodon citrinellus	Speckled Butterfly	1	4	4	1	2	0	0	0	0	12
Chaetodon lunula	Raccoon Butterfly	3	0	0	0	0	0	0	0	0	0
Chaetodon quadrimaculatus	Four-spot Butterfly	10	4	4	17	2	16	8	0	8	6
Chaetodon reticulatus	Reticulated Butterfly	3	0	0	2	2	0	12	2	0	2
Chaetodon unimaculatus	Teardrop Butterfly	6	14	14	0	0	2	21	2	0	6
Chaetodon pelewensis	Dot-and-Dash Butterfly	0	2	2	2	0	3	0	0	0	1
Chaetodon ornatissimus	Ornate Butterfly	0	7	7	2	2	0	6	0	0	3
Chaetodon ulietensis	Pacific Double Saddled Butterfly	0	0	0	0	0	0	4	0	0	0
Heniochus monoceros	Masked Bannerfish	0	0	0	0	2	0	0	0	0	1
Forcipiger flavissimus	Longnose Butterfly	2	2	2	7	4	0	2	2	0	5
BLENNIIDAE	**Blenny**										
Aspidontus taeniatus	Mimic Cleaner	3	2	2	3	1	0	4	4	4	3
Cirripectes variolosus	Red-speckled Blenny	9	0	0	6	15	10	64	0	10	12
Plagiotremus tapeinosoma	Piano Blenny	8	32	32	1	0	4	0	0	5	2
Enneapterygius sp	Striped Triplefin	2	0	0	5	11	7	0	0	0	0
GRAMMISTINAE											
Grammistes sexlineatus	Sixline Soapfish	0	0	0	1	0	0	0	0	0	0
GOBIIDAE	**Goby**										
Eviota sp	Pygmy Goby	0	0	0	0	0	1	0	0	0	0
Valenciennea strigata	Bluestreak Goby	0	0	0	2	0	0	0	0	0	0
LABRIDAE	**Wrasses**										
Anampses caeruleopunctatus	Blue spotted Wrasse	4	0	0	0	3	4	8	0	0	0
Anampses twisti	Yellow-breasted Wrasse	0	0	0	0	0	0	0	3	0	0
Coris aygula	Clown Coris	1	0	0	0	0	0	0	2	0	0
Coris gaimard	Yellow-tail Coris	0	0	0	0	2	0	0	0	0	0
Coris roseoviridis	Vivid rose Coris	3	1	1	6	9	14	0	0	0	0
Cirrhilabrus scottorum	Scott's Wrasse	0	0	0	0	7	0	0	0	0	0
Gomphosus varius	Bird Wrasse	4	2	2	6	2	4	18	11	1	12
Halichoeres hortulanus	Checkerboard Wrasse	1	0	0	0	0	0	0	1	0	0
Halichoeres margaritaceus	Weedy Surge Wrasse	6	24	24	74	54	0	0	0	49	10
Halichoeres marginatus	Dusky Wrasse	4	0	0	0	1	0	3	5	2	7
Halichoeres ornatissimus	Ornate Wrasse	49	8	8	47	41	34	37	33	34	10
Hemigymnus fasciatus	Barred Thicklip Wrasse	0	0	0	0	0	0	0	1	0	0

Stethojulis bandanensis	Redshoulder Wrasse	11	4	4	12	4	2	0	0	2	17
Thalassoma lutescens	Sunset Wrasse	20	10	10	23	18	22	30	24	19	30
Thalassoma quinquevittatum	Fivestripe Wrassse	29	26	26	79	34	21	14	0	83	20
Thalassoma purpureum	Surge Wrasse	0	0	0	0	0	0	0	0	1	0
Laabroides bicolor	Bicolor Cleaner Wrasse	1	0	0	1	0	0	4	1	0	0
Labroides dimidiatus	Bluestreak Cleaner Wrasse	1	0	0	0	1	1	0	0	2	1
Macropharyngodon meleagris	Leopard Wrasse	6	8	8	0	1	3	0	0	7	0
Chelinus chlorourus	Floral Wrasse	0	0	0	0	2	0	0	0	0	0
Chelinus trilobatus	Tripletail Wrasse	0	0	0	0	0	0	2	0	0	0
Pseudocheilinus tetrataenia	Fourline Pygmy Wrasse	7	0	0	12	12	17	16	0	5	5
Pseudojuloides atavai	Tahitian Wrasse	1	0	0	0	1	1	0	0	0	0
Oxycheilinus unifasciatus	Ringtail Wrasse	0	0	0	0	0	0	0	0	0	0
MONACANTHIDAE	**Filefish**										
Cantherhines sanwichiensis	Squaretail Filefish	1	4	4	2	1	0	5	0	2	3
MULLIDAE	**Goatfish**										
Mulloidichthys martinicus	Yellowbar Goatfish	0	0	0	0	0	0	4	0	0	0
Parapeneus bifasciatus	Island Goatfish	0	0	0	0	0	0	0	0	0	2
Parupeneus multifasciatus	Multibar Goatfish	5	2	2	4	9	2	4	0	0	4
MURAENIDAE	**Moray Eels**										
Echidna nebulosa	Snowflake eel	0	0	0	0	0	1	0	0	0	0
Gymnothorax javanicus	Giant Moray	0	0	0	1	0	0	2	0	0	0
Gymnothorax meleagris	Whitemouth Moray	0	0	0	1	1	0	0	0	0	2
PINGUIPEDIDAE	**Sandperch**										
Parapercis millepunctata	Spotted Sandperch	2	0	0	2	8	1	4	3	1	4
POMACANTHIDAE	**Angelfish**										
Centropyge flavissimus	Lemonpeel Angelfish	14	20	20	20	45	42	6	0	21	10
Pomacanthus imperator	Emperor Angelfish	1	0	0	0	0	0	0	0	0	0
POMACENTRIDAE	**Damselfish and Clownfish**										
Chromis agile	Reef Chromis	0	50	50	0	0	0	0	0	0	0
Chromis vanderbilti	Vanderbilt's Chromis	205	76	76	175	115	37	320	130	110	165
Plectroglyphidodon imparipennis	Brighteye Damselfish	1	30	30	76	12	0	4	0	28	35
Plectroglyphidodon johntonianus	Johnston Damselfish	7	31	31	63	25	28	33	0	33	48
Dascyllus trimaculatus	Three-spot Dascyllus	0	4	4	0	0	0	0	0	0	12
Pomachromis fuscidorsalis	Tahitian Damselfish	10	0	0	45	50	2	20	0	63	115
Chryseptera brownriggii (yellow tail)	Surge Damselfish	0	0	0	0	0	0	0	0	1	0
Stegastes fasciolatus	Pacific Gregory	85	7	7	71	71	81	360	0	80	74
PTERELEOTRIDAE	**Dartfish**										
Nemateleotris magnifica	Fire Dartfish	2	20	20	23	12	2	0	0	0	2
Ptereleotris evides	Two-tone Dartfish	0	0	0	4	4	0	0	0	0	0
SCARIDAE	**Parrotfish**										
Chlorurus sordidus	Bullethead Parrotfish	15	0	0	17	6	16	28	22	41	42
Scarus altipinnis	Filament Fin Parrotfish	0	0	0	0	0	0	2	0	0	1
Scarus frenatus	Bridled Parrotfish	5	0	0	5	1	0	1	3	0	2
Scarus globiceps	Violet-lined Parrotfish	6	3	3	2	1	0	0	1	0	26
Scarus psittacus	Pale-nose Parrotfish	79	12	12	72	16	4	90	50	0	99
Scarus schlegeli	Yellowbar Parrotfish	16	24	24	3	0	0	0	0	0	18
Scarus forsteni	Bluepatch Parrotfish	8	22	22	9	2	0	0	4	0	10
Chlorurus frontalis	Reefcrest Parrotfish	0	0	0	0	4	0	0	2	0	0
SIGANIDAE	**Rabbitfish**										
Siganus argenteus	Forktail Rabbitfish	3	0	0	0	0	0	0	0	0	0
SERRANIDAE/ANTHIINAE	**Anthias**										
Pseudanthias olivaceus	Olive Anthias	0	0	0	0	0	0	10	0	0	0
SERRANIDAE	**Groupers**										
Cephalopholis urodeta	Flagtail Grouper	1	0	0	4	0	0	1	0	0	1
Cephalopholis argus	Peacock Grouper	5	0	0	0	2	2	24	4	0	0
Epinephalus hexogonatus	Hexagon Grouper	1	3	3	9	5	6	2	0	0	1
Epinephalus fasciatus	Blacktip Grouper	0	0	0	0	0	1	0	0	2	1
SCORPAENIDAE											
Pterois antennata	Spotfin Lionfish	0	0	0	1	0	0	0	0	0	0
Sebastapistes cyanostigma	Yellow-spotted Scorpionfish	1	0	0	3	20	25	0	0	2	1
TETRADONTIDAE	**Pufferfish, Toby**										
Canthigaster solandri	Blue-spotted Toby	0	6	6	0	1	1	4	2	0	2
Canthigaster amboinensis	Spider-eye Toby	1	0	0	0	0	0	6	0	1	2
Arothron meleagris	Guinea fowl Puffer	0	0	0	0	0	0	0	0	0	1
TRIPPLEFIN	**Triplefins**										
Enneapterygius sp.	Triplefin	0	0	0	0	0	0	0	0	0	3
ZANCLIDAE	**Moorish Idol**										
Zanclus cornutus	Moorish idol	4	0	0	0	2	1	5	4	0	1
	TOTAL FAMILIES	**24**									
	TOTAL SPECIES	**110**									

Appendix E. Checklist of macro-invertebrate species recorded at each site surveyed in 2014.

Site	Kina	Vana	*Echinostrephus*	Trochus	Pa`ua	*Dendropoma*	Holothurian
Avarua	228	23	27	0	1	70	0
Avarua	176	14	13	0	2	42	0
Avarua	230	24	5	0	0	60	0
Avarua	188	15	11	0	3	123	0
Avatiu	153	46	13	0	2	7	0
Avatiu	144	33	16	0	0	8	0
Avatiu	45	29	3	0	0	12	0
Avatiu	87	54	2	0	0	7	0
Nikao	553	72	8	0	0	44	0
Nikao	279	50	4	0	1	160	1
Nikao	271	109	2	0	0	41	1
Nikao	441	59	2	0	0	104	0
Kiikii	182	19	2	0	1	56	2
Kiikii	108	19	4	0	1	54	2
Kiikii	258	34	3	0	0	47	6
Kiikii	194	32	8	0	0	431	4
Kavera	172	19	2	0	0	57	2
Kavera	106	19	4	0	0	49	2
Kavera	258	35	3	0	0	47	6
Kavera	194	32	8	0	0	401	4
Titikaveka	123	14	0	1	0	0	0
Titikaveka	136	17	0	0	0	0	0
Titikaveka	153	31	0	0	0	0	0
Titikaveka	102	16	0	0	0	0	0
Taakoka	248	55	0	5	0	7	0
Taakoka	288	66	0	1	0	8	0
Taakoka	184	50	0	2	0	1	0
Taakoka	338	34	0	2	0	7	0
Tumunu	192	33	13	0	1	21	1
Tumunu	203	50	8	0	2	29	1
Tumunu	25	32	5	0	2	56	0
Tumunu	20	49	2	0	0	93	0
Motutapu	443	106	9	0	6	29	0
Motutapu	507	90	6	0	2	64	0
Motutapu	263	70	6	0	0	58	0
Motutapu	124	29	26	0	0	21	0