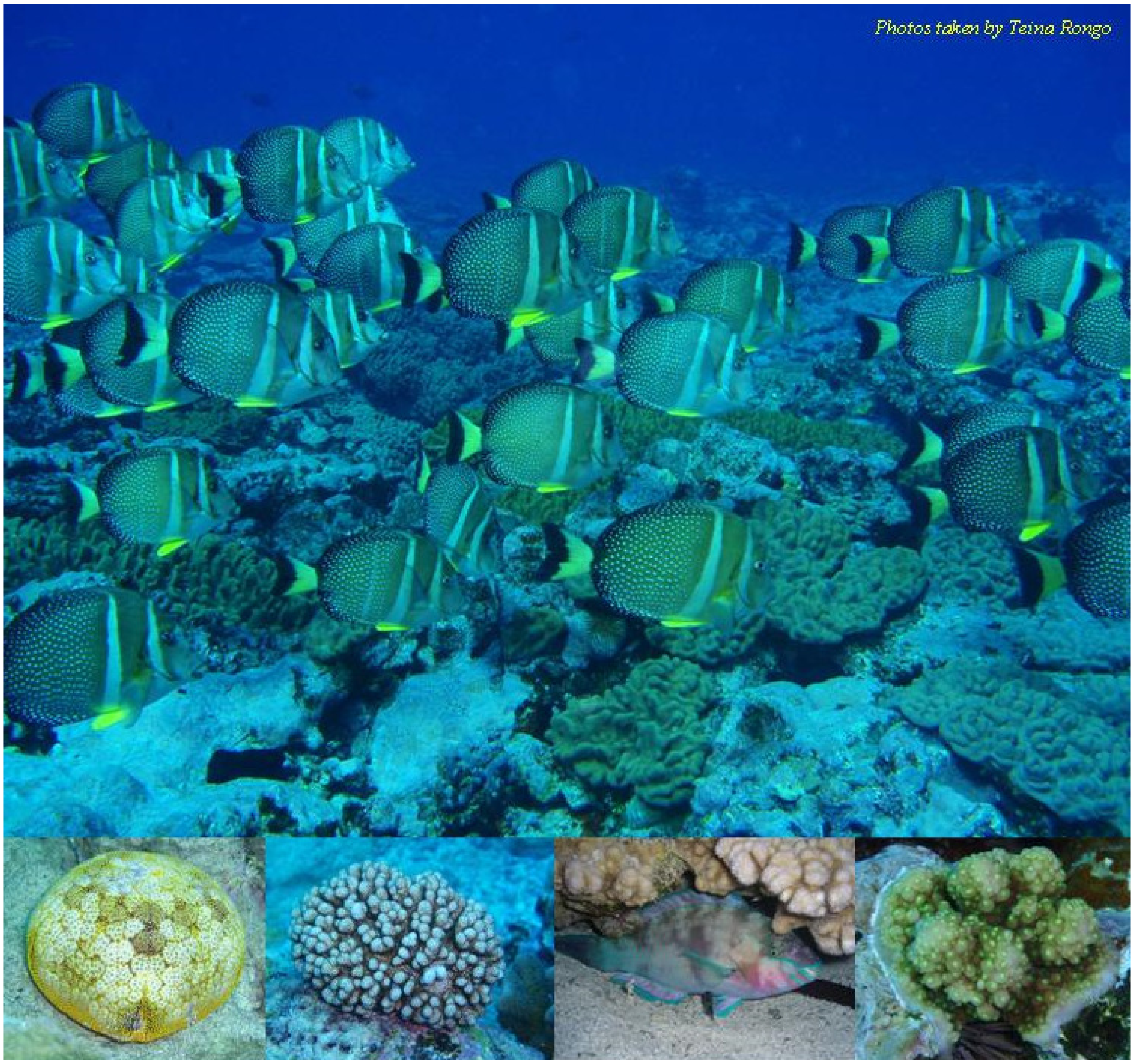
Rarotonga Fore Reef Community Survey 2009



Cook Islands National Environment Service
Technical report

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EXECUTIVE SUMMARY

Previous reef surveys on Rarotonga have shown that the crown-of-thorns outbreak in the late 1990s degraded the fore reefs to its current state: depauperate of corals. The 2006 survey indicated that average coral cover at most sites was less than 5 %, however it was noted that recovery was well on its way. This is consistent with the present survey, which indicated that most sites have doubled their average percent coral cover after three years with some sites showing a greater than three-fold increase (i.e., Boiler and Titikaveka). In support, coral size class data showed a significant increase of larger colonies when compared with the 2006 survey. Reef recovery was also evident in the fish communities at the trophic level, as coral-associated fishes such as planktivores and corallivores have increased in abundance. While the abundance of herbivores remain relatively high, it is important that a healthy herbivorous community persist during this stage to facilitating reef recovery on Rarotonga through top-down control of algal communities and promote recruitment of corals. The incidence of ciguatera has been declining in recent years, consequently reef fishing has been observed to be increasing on Rarotonga. Such a scenario can lead to overfishing of herbivorous species and may jeopardize the recovery of reefs. Although information on rates of runoff sediments are lacking, sedimentation is certainly a contributing factor degrading the reefs and a growing concern on Rarotonga as slope-lands are being developed. Global efforts to reduce the impact of climate change is important for the long-term maintenance of coral reefs, however we also need to focus on minimizing factors degrading our reefs on a local scale. Perhaps implementing fishing restrictions, re-enforcing the management of the *ra`ui* system to ensure sufficient grazing is maintained, good land-use practices to reduce sedimentation, and continued efforts by Ministry of Health to reduce nutrient inputs will all be critical at this stage to foster recovery and prevent our reefs from shifting into an undesirable state.

INTRODUCTION

It is widely accepted that coral reefs around the world are experiencing shifts towards a less desirable state (Wilkinson, 2004), with causes ranging from natural disturbances, eutrophication, overfishing, and global climate change. On Rarotonga (Figure 1), reefs have experienced several natural disturbances over the last few decades. In the 1970s, Devaney & Randall (1973) reported the first known crown-of-thorns starfish (COTS) outbreak on Rarotonga, which coincided with an outbreak that extended across the Pacific Ocean (Sapp, 1999). The second COTS outbreak that occurred on Rarotonga from 1995 to 2001 saw a decline in coral cover from more than 40 % at most sites to less than 5 % in 2006 (Rongo *et al*., 2006). Coral bleaching has also contributed to the degradation of these reefs, particularly the events noted in 1991 and 1994 during elevated sea surface temperatures associated with El Niño episodes. Other bleaching events were associated with extreme low tides such as those observed in 2001, and also during the present survey where corals on the reef crest were exposed for several hours (Plate 1 & 2). Although cyclones are infrequent in the southern Cook Islands, the five cyclones which swept through this region in 2005 may have impacted the reefs as well.

Coral cover has remained low since the COTS outbreak of the 1990s, and this is believed to have promoted the establishment of ciguatoxic algae (as more reef space are available for algal growth), resulting in the increased incidence of ciguatera fish poisoning in recent years that has rendered marine resources unusable. Incidentally, this has resulted in the increase of fish abundance (particularly among herbivores) on Rarotonga.

The present survey is a follow-up of the 2006 survey to quantify spatial and temporal changes in the benthic and fish communities around Rarotonga. We suggest additional studies to complement the current survey and also offer some recommendations for managers to consider.

MATERIALS AND METHODS

The present survey carried out between June and July 2009 examined 10 of the 11 fore reef sites previously established in 2006 (Figure 1; see Rongo *et al*., 2006 and the supplementary report [Rongo, 2008] for a full description of these sites). The Arorangi (Manuia Beach) site was not surveyed because of bad weather and time constraints. However, this site will be monitored in future surveys as it was identified as a potential high impact site in the supplementary report (Rongo, 2008). For consistency, survey methods implemented in the 2006 survey were also carried out in the present survey (refer to Rongo *et al*., 2006 for details).

Figure 1. Map of Rarotonga (21° 12’ S, 159° 43’ W) with 10 fore reef sites surveyed (yellow) with proposed additional sites (red). Taken from Google Earth.

DATA ANALYSIS

Microsoft Excel, PivotTable, and PivotChart were used for basic computations. PRIMER 6 and STATISTICA 6 were used for graphical and comparative analyses. All analyses were similar to those carried out in the supplementary report to the 2006 survey (Rongo, 2008). For all Eigen analyses, only eigenvectors with values > 0.2 were reported in the tables. Because of the importance of herbivory on reefs (Ogden & Lobel, 1978; Bellwood *et al.*, 2006), analyses were predominantly on herbivorous species in this report.

RESULTS

Coral communities

The mean percent cover for all sites indicated that turf algae dominated most sites, with the exception of Titikaveka and Vaimaanga, which were dominated by coralline algae (Figure 2). Mean turf algae cover ranged from 73 ± 3.7 % at Tumunu to 91 ± 3.6 % at Kiikii (Appendix A). Coralline algae among sites were highly variable among sites, with the lowest cover (0.9 ± 1.2 %) at Boiler and the two highest at Vaimaanga (64.4 ± 12.3%) and Titikaveka (78.8 ± 1.4%). Ordination of the sites with respect to benthic communities clearly separated Boiler, Titikaveka, and Vaimaanga from the rest (Figure 3). Vector plots superimposed on the ordination indicated that soft coral cover decreased with sites going from left to right, while coral cover decreased from top to bottom (see Figure 3). Eigen analysis of the PCA for all major benthic categories showed that 93.2 % of the variations were explained in the first three axes (Table 1). Coralline algae and soft corals had the most weight on the first axis (-0.672 and -0.484 respectively), hard corals on the second axis (0.645), and macro-algae on the third axis (-0.695).

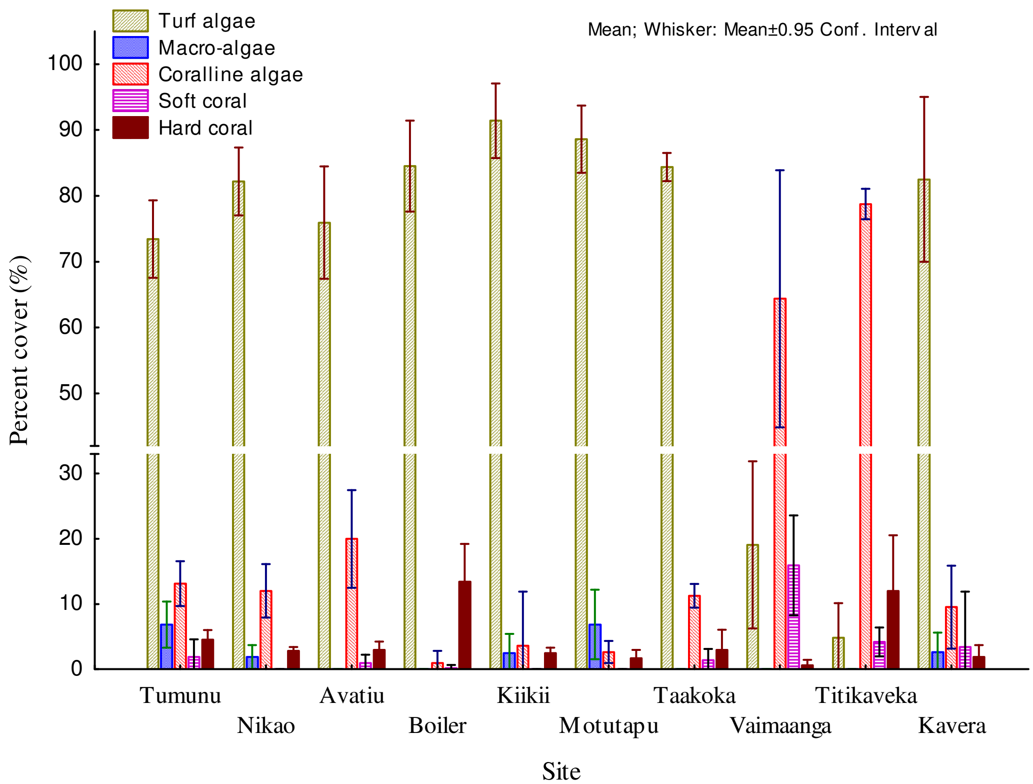


Figure 2. Mean percent cover for benthic communities for all 2009 sites. Break on the y-axis between 33 and 42 %.

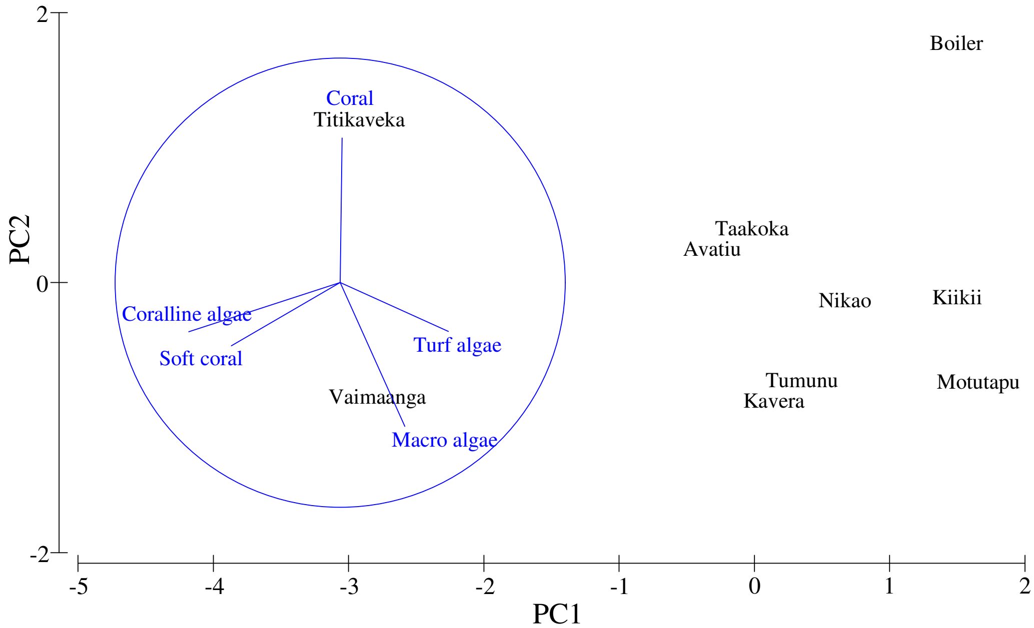


Figure 3. Principal Component Analysis (3 axes) in all major benthic categories for all 2009 sites. Data were square-root transformed.

Table 1. Eigen analysis for PCA of all major benthic categories for all 2009 sites. Highest values are indicated in blue.

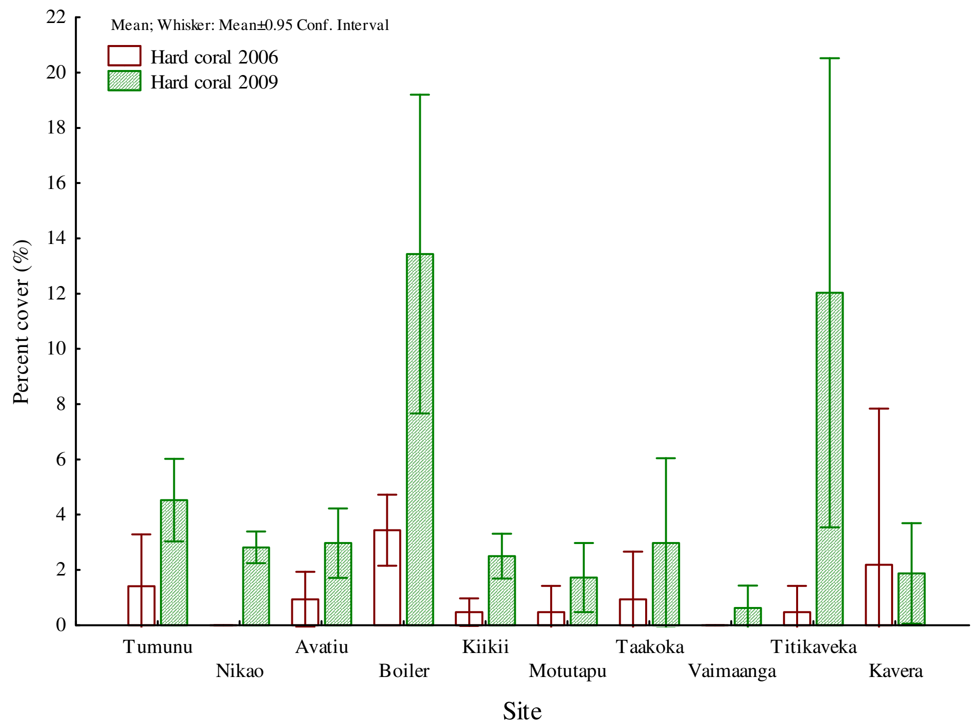
Eigenvalues

PC	*Eigenvalues*	*%Variation*	*Cum.%Variation*
1	2.79	64.8	64.8
2	0.791	18.4	83.2
3	0.432	10.0	93.2

Eigenvectors

Variable	*PC1*	*PC2*	*PC3*
Turf algae	0.481	-0.218	0.491
Macro algae	0.288	-0.640	-0.695
Coralline algae	-0.672	-0.219	-0.109
Soft coral	-0.484	-0.282	0.217
Coral	0.009	0.645	-0.466

Hard coral cover in 2009 ranged from 0.63 ± 0.5% at Vaimaanga to 12.03 ± 5.3% and 13.4 ± 3.6% at Titikaveka and Boiler respectively (see Figure 2). The high variance of coral cover at all sites (see Appendix A) indicated the patchiness of coral communities. Between 2006 and 2009, a significant increase was noted at most sites (Figure 4 top). Non-parametric test indicated significant increases at Tumunu, Nikao, Avatiu, Boiler, Kiikii, and Titikaveka (Mann-Whitney: $z = -2.338$, $p = 0.019$; $z = -2.494$, $p = 0.013$; $z = -2.165$, $p = 0.030$; $z = -2.309$, $p = 0.021$; $z = -2.309$, $p = 0.020$; and $z = -2.309$, $p = 0.021$ respectively). However no such increase was noted at Motutapu, Taakoka, and Kavera. Soft corals did not have any significant change since 2006 (Figure 4 bottom) and remained common from the southern to the western exposures of Rarotonga (i.e., Taakoka, Titikaveka, Vaimaanga, and Kavera).



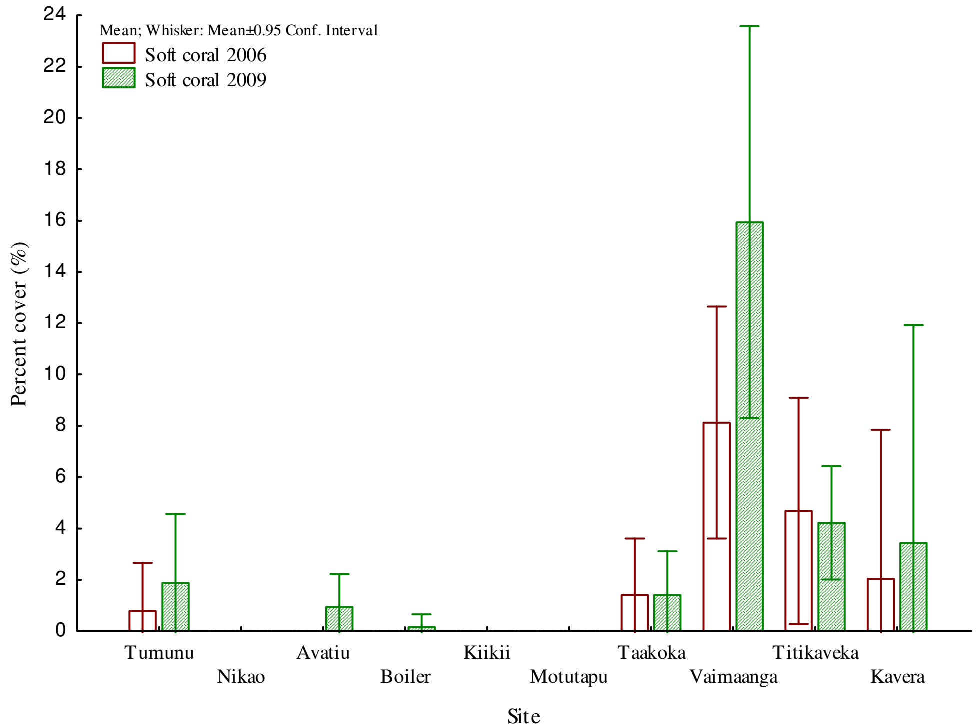


Figure. 4. Mean percent hard coral cover for 2006 and 2009 (top); and mean percent soft coral cover for 2006 and 2009 (bottom). Open columns represent 2006 sites and filled columns represent 2009 sites.

Macro-algae was noted at some sites where it was previously absent in 2006. *Asparagopsis taxiformis* (Delile) was the only macro-algae recorded on the fore reef during the survey (including the 2006 survey), with high cover noted at Motutapu and Tumunu (Figure 5).

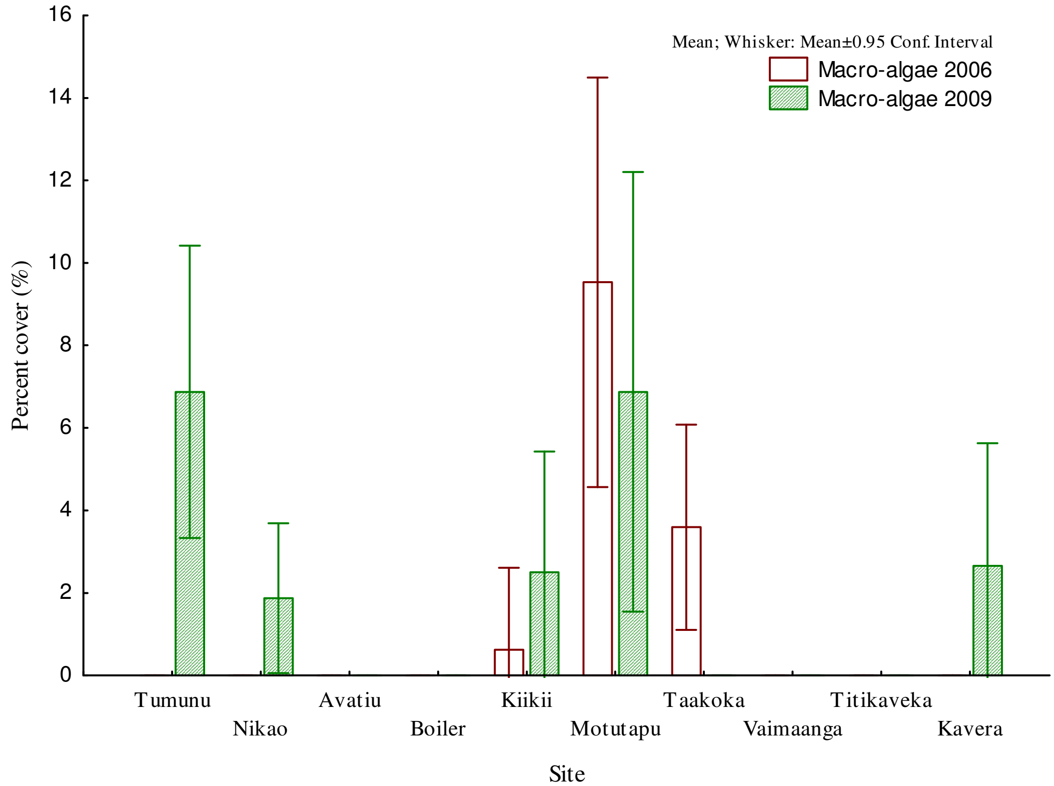


Figure. 5. Mean percent macro-algae cover for 2006 and 2009. Open columns represent 2006 sites and filled columns represent 2009 sites.

When comparing 2006 and 2009 sites, we noted that turf algae remained greater than 70 % at most sites (Figure 6) for both years, with the exception of Vaimaanga and Titikaveka. However, there was a general decline noted for all other sites. Coralline algae on the other hand increased significantly at Tumunu, Avatiu, Motutapu, Vaimaanga, and Titikaveka (see Figure 6).

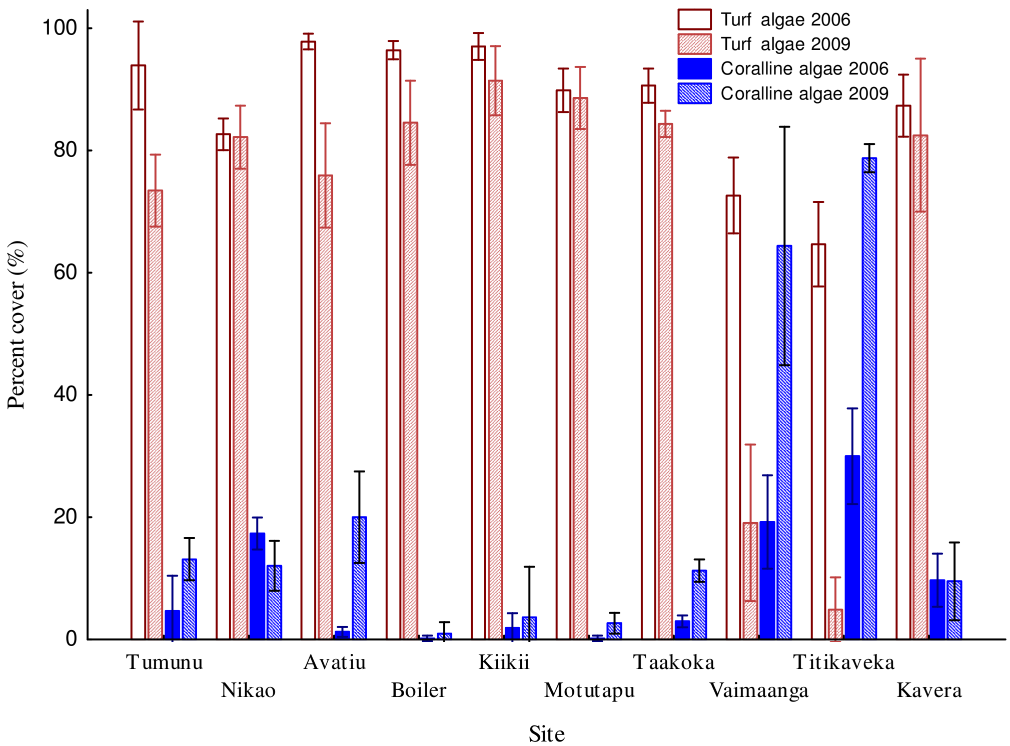


Figure 6. Mean percent cover of turf algae and coralline algae for 2006 and 2009 sites.

Coral diversity

A total of 34 coral species (including at least three species of soft corals) were recorded within the quadrats representing 13 genera. The most common corals recorded at most sites were *Leptoria, Montastrea, Pocillopora, Leptastrea, Porites, Acanthastrea,* and *Hydnophora* (in that order). Number of individual colonies (N), evenness values (J\`), and species diversity (H\`) (Table 2) were the highest at Boiler. Avatiu had the highest species richness (d). Titikaveka had the highest number of species (S) and the second highest number of individual colonies and species richness but had the lowest evenness. The lowest number of species, number of individuals, richness, and species diversity were reported at Vaimaanga. The biodiversity measures were graphically represented in Figure 7. Eigenvalues indicated that most of the variations were explained in the first two axis (99.9 %) with the number of individuals (N = -0.99) having the most weight in the first axis and number of species (S = -0.89) in the second axes.

Table 2. Biodiversity measures for corals at all sites. S = number of species, N = number of individuals, d = species richness, J` = evenness, and H` = species diversity. Highest values are indicated in blue.

Site	S	N	d	J'	H'(log2)
Avatiu	16	82	3.404	0.8378	3.351
Boiler	15	185	2.682	0.8707	3.402
Kiikii	13	98	2.617	0.8321	3.079
Avana	15	105	3.008	0.8437	3.296
Taakoka	17	122	3.331	0.7445	3.043
Titikaveka	18	152	3.384	0.7005	2.921
Vaimaanga	8	50	1.789	0.7835	2.350
Kavera	15	107	2.996	0.7983	3.119
Tumunu	16	142	3.027	0.8484	3.393
Nikao	15	107	2.996	0.8307	3.245

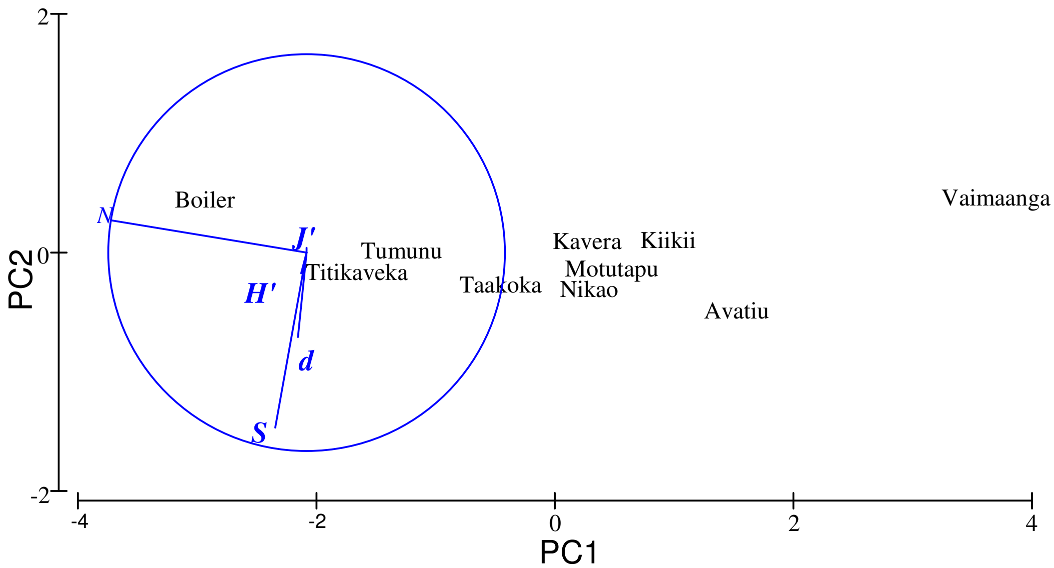


Figure 7. Principal Component Analysis (3 axes) for coral biodiversity measures at all 2009 sites. Data were square-root transformed.

Colony sizes

Colony size data indicated a general increase of colonies in the larger class (Figure 8) from 2006 to 2009, with some sites (i.e., Tumunu, Avatiu, Boiler, and Kiikii) showing a significant decrease in class A colonies (colonies with geometric diameter ≤ 4 cm). The most common corals within class A for all sites belong to the following genera: *Leptoria* (32 %), *Montastrea* (24 %) and *Acanthastrea* (10 %) (Appendix E). Some of these colonies, particularly *Leptoria*, are remnants of what used to be larger colonies. A total of 11 % of class A colonies belong to *Acropora, Montipora*, and *Pocillopora*.

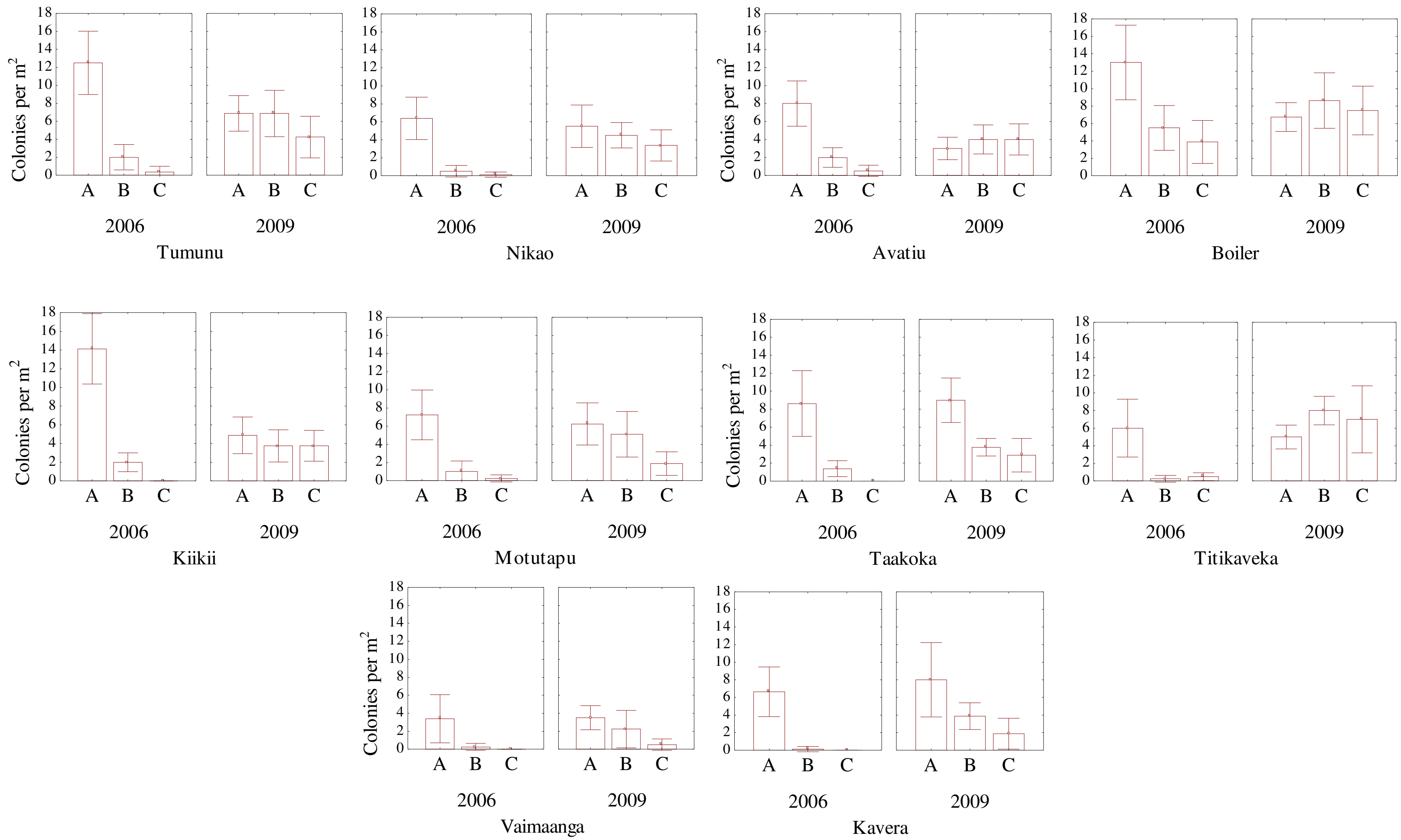


Figure 8. Mean coral colony sizes grouped based on their geometric diameter (A = colonies ≤ 4 cm; B ≤ 8 cm; C > 8 cm) for 2006 and 2009 sites.

Ordination superimposed on a PCA for coral genus showed that Titikaveka, Vaimaanga, Boiler, and Motutapu were clearly different from all other sites. Vector plots indicated that hard corals generally decreased downwards in the ordination plot, and soft corals increased diagonally from top right to bottom left (Figure 9). Eigenvalues showed that 88.1 % of the variations were explained in the first three axes (Table 3), with eigenvectors showing *Acanthastrea* spp. having the most weight of the first axis (0.530), *Leptastrea* spp. on the second axis (-0.639), and soft coral on the third (-0.550).

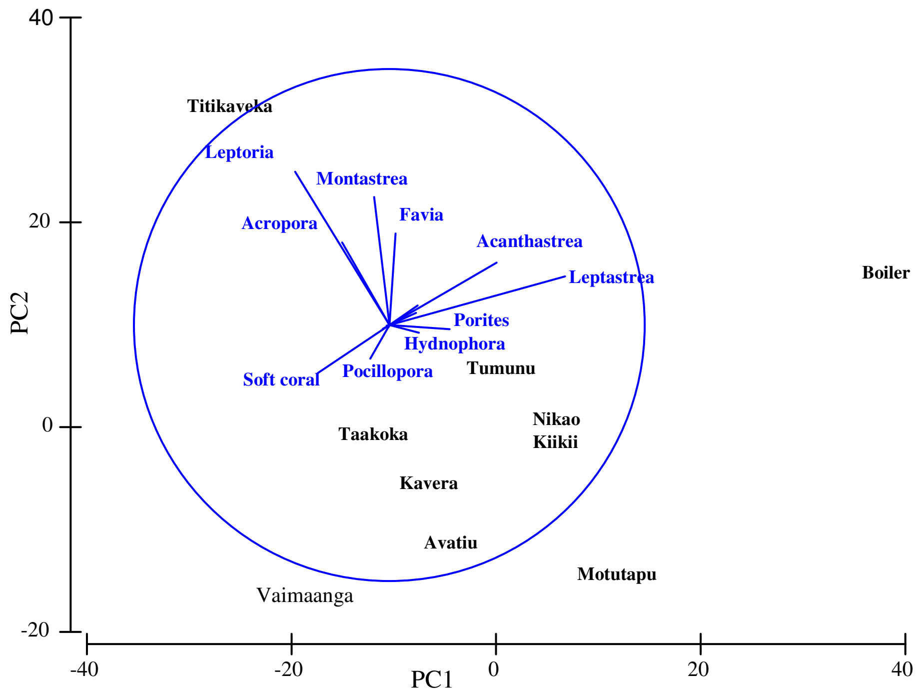


Figure 9. Principal Component Analysis (3 axes) using coral genera from all 2009 sites. Data were square-root transformed.

Table 3. Eigen-analysis for PCA of all major benthic categories for all 2009 sites. Highest values are indicated in blue.

Eigenvalues

PC	*Eigenvalues*	*%Variation*	*Cum.%Variation*
1	353	60.7	60.7
2	115	19.8	80.6
3	44.1	7.6	88.1

Eigenvectors

Genus	*PC1*	*PC2*	*PC3*
Acanthastrea	0.530	-0.011	-0.235
Cyphastrea	0.076	0.018	0.334
Leptastrea	0.528	-0.639	-0.123
Leptoria	-0.107	0.301	-0.051
Montastrea	0.474	0.533	0.415
Porites	0.295	0.404	-0.549
Soft coral	-0.243	0.113	-0.550

Fish

A total of 95 fish species were recorded during the survey representing 17 families. While the number of species, species richness, and diversity were highest at Boiler, evenness was equally high at Avatiu and Motutapu (Table 4). The number of individuals recorded was the highest at Nikao (883 ind./800 m^2). Eigenvalues indicated that most of the variations were explained in the first axis (96.6 %) with the number of individuals (*N* = -0.99) having the most weight in the first axis. The biodiversity measures were graphically represented in Figure 10.

Table 4. 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 blue.

Site	*S*	*N*	*d*	*J'*	*H'(loge)*
Tumunu	32	528	4.945	0.7060	2.447
Nikao	37	883	5.307	0.5630	2.033
Avatiu	41	396	6.687	0.7477	2.777
Boiler	60	720	8.968	0.7000	2.866
Kiikii	39	552	6.019	0.7247	2.655
Motutapu	41	396	6.687	0.7477	2.777
Taakoka	40	757	5.883	0.5944	2.193
Vaimaanga	35	667	5.229	0.6674	2.373
Kavera	47	728	6.98	0.6604	2.543

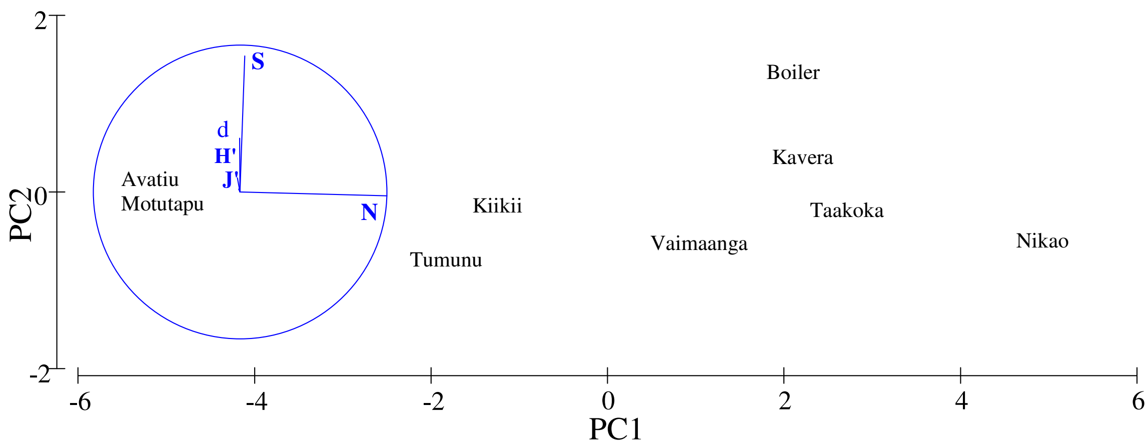


Figure 10. Principal Component Analysis (3 axes) for fish biodiversity measures at all sites in 2009. Biodiversity data were square-root transformed before PCA was performed.

Principal Component Analysis of fish families indicated that 94.2 % of the variation was explained by the first three axes (Figure 11 & Table 5). The eigenvectors (graphically illustrated on the vector plot) indicated that Pomacentrids had the most weight in the first axis (0.767), Acanthurids on the second axis (0.813), and Scarids on the third axis (0.898).

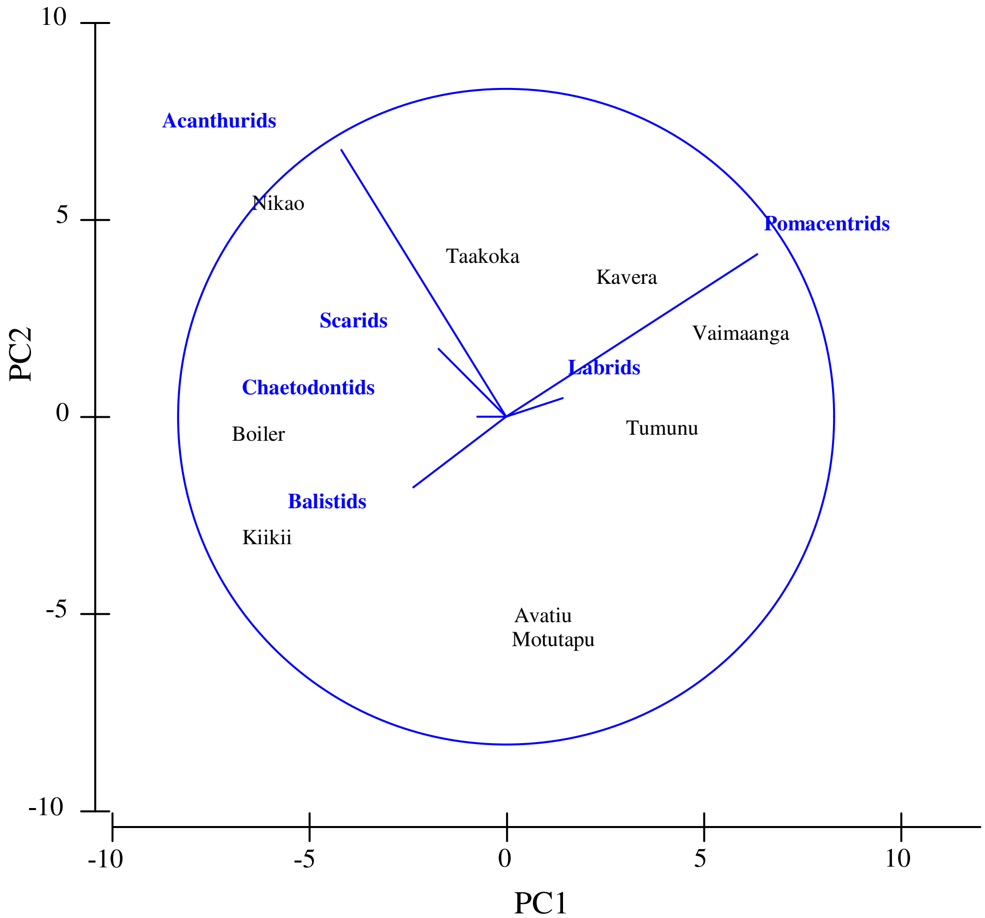


Figure 11. Principal Component Analysis (3 axes) for fish families at all sites in 2009. Data were square-root transformed before PCA was performed.

Table 5. Eigen-analysis for PCA of fish families for all 2009 sites.

Eigenvalues			
PC	*Eigenvalues*	*%Variation*	*Cum.%Variation*
1	22.5	49.1	49.1
2	15	32.7	81.8
3	5.68	12.4	94.2

Eigenvectors			
Family	*PC1*	*PC2*	*PC3*
Acanthurids	-0.502	0.813	-0.264
Balistids	-0.283	-0.216	0.051
Labrids	0.173	0.057	-0.208
Pomacentrids	0.767	0.496	0.104
Scarids	-0.205	0.207	0.898
Chaetodontids	-0.087	0.001	-0.260

Acanthurid abundance in 2009 ranged from 44.5 ± 7.9 ind/200 m^2 equally at Avatiu and Motutapu to 163.8 ± 53.4 ind/200 m^2 at Nikao (Figure 12 & Appendix B) The high variance in the data is likely the result of schooling among this family (Plate 3). With the exception of Boiler and Tumunu, there was a significant decline in the average abundance of Acanthurids from 2006 to 2009 at most sites (see Figure 12). Using the six major families (Acanthurids, Pomacentrids, Scarids, Labrids, Balistids, and Chaetodontids), the ordination clearly separated the two survey years (Figure 13). Vector plot indicated that Acanthurid abundance was higher in 2006 while Chaetodontids seem to have increased in 2009. Pomacentrids on the other hand did not show any difference between the two periods. Eigenvalues indicated that 80% of the variation was explained by the first three axes. Scarids and Acanthurids having the most weight on the first axis, Pomacentrids on the second, Pomacentrids again on the third, and Chaetodontids on the fourth (Table 6).

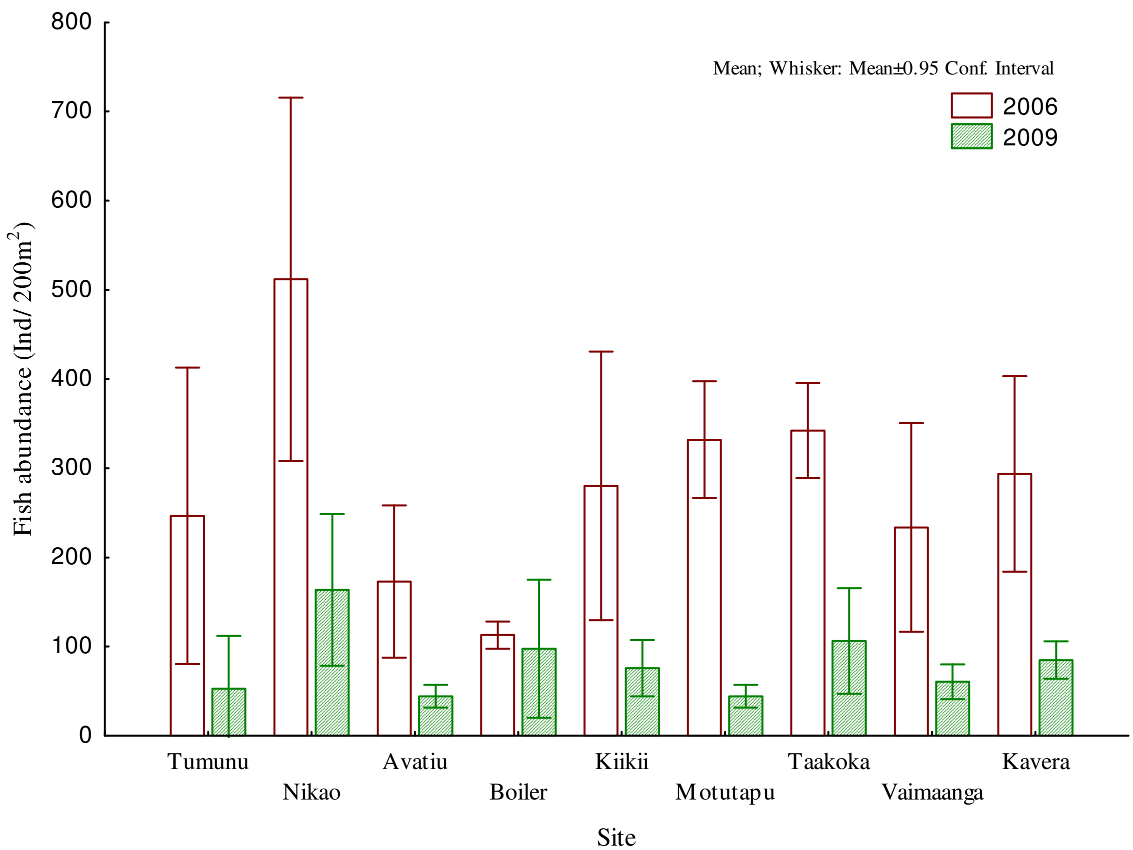


Figure 12. Mean abundance of Acanthurids for 2006 and 2009 at all sites. Open columns represent 2006 sites and filled columns represent 2009 sites.

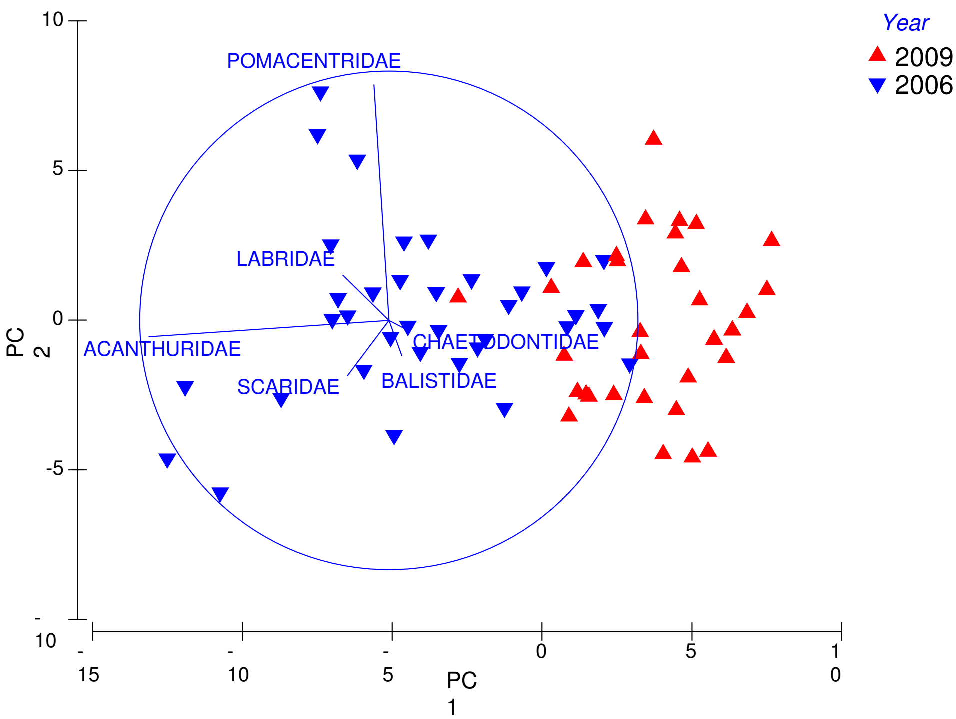


Figure 13. Principal Component Analysis (4 axes) for fish families for 2006 and 2009 using replicates from all sites. Data were square-root transformed before PCA was performed.

Table 6. Eigen-analysis of the major fish families from 2006 and 2009.

Eigenvalues

PC	*Eigenvalues*	*%Variation*	*Cum.%Variation*
1	1.58	34.8	34.8
2	1.23	27.1	61.9
3	0.811	17.9	79.8
4	0.384	8.5	88.3

Eigenvectors

Family	*PC1*	*PC2*	*PC3*	*PC4*
ACANTHURIDAE	-0.472	0.090	-0.389	0.292
BALISTIDAE	0.192	-0.185	-0.159	0.187
LABRIDAE	-0.405	0.374	-0.301	0.438
POMACENTRIDAE	-0.228	0.629	0.657	-0.075
SCARIDAE	-0.674	-0.624	0.352	-0.064
CHAETODONTIDAE	0.265	-0.180	0.421	0.824

Ordination among years between 1994 (Miller *et al.*, 1994), 1999 (Ponia *et al.*, 1999), 2006, and 2009 based on trophic levels (Figure 14) (particularly with herbivores and planktivores) clearly reflected changes in benthic community. Vector plot clearly indicated the two extreme reef conditions; coral-dominated conditions were indicated by planktivores in 1999, while low coral conditions were indicated by herbivores in 2006. In support, eigenvalues indicated that much of the variation was explained in the first two axes (97.4 %) with most attributed to herbivores in the first axis and planktivores in the second (Table 7).

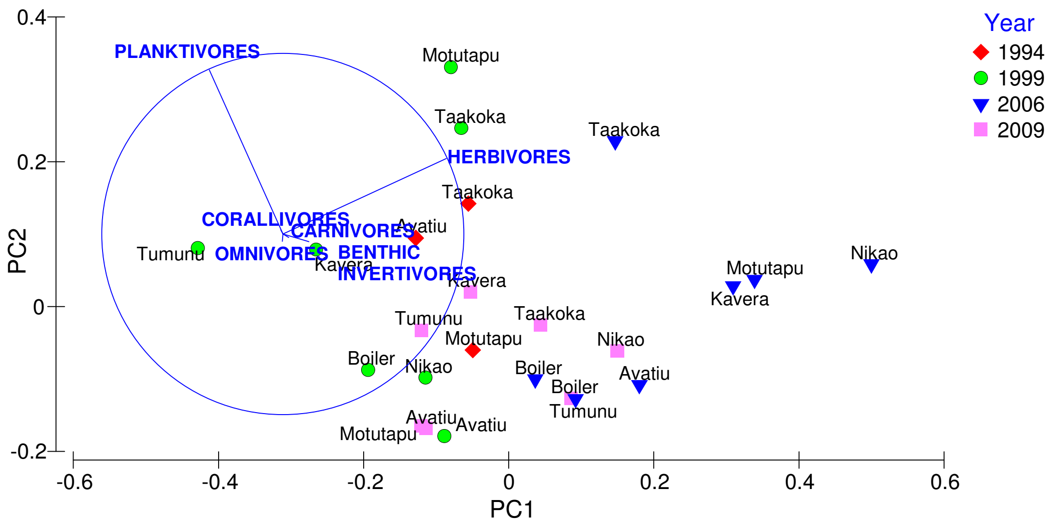


Figure 14. Principal Component Analysis of fish trophic levels with ordination of sites super-imposed on the plot for years 1994, 1999, 2006 and 2009. Data were square-root transformed.

Table 7. Eigen-analysis of fish families from 1994 to 2009 for all sites.

Eigenvalues			
PC	*Eigenvalues*	*%Variation*	*Cum.%Variation*
1	4.06E-2	66.3	66.3
2	1.91E-2	31.1	97.4

Eigenvectors		
Trophic level	*PC1*	*PC2*
BENTHIC INVERTIVORES	-0.144	0.042
CARNIVORES	-0.033	0.020
CORALLIVORES	0.012	-0.022
HERBIVORES	-0.901	-0.417
OMNIVORES	0.003	0.041
PLANKTIVORES	0.407	-0.907

Urchins

The urchin *Echinometra* spp. was the most common invertebrate on the fore reef with density ranging from 1.0 ± 0.24 ind./m^2 at Tumunu to 5.13 ± 0.86 ind./m^2 at Taakoka (Figure 15 & Appendix C). The larger urchin *Echinothrix* spp. was the second most abundant with densities ranging from 0.24 ± 0.05 ind./m^2 at Kiikii to 0.78 ± 0.11ind./m^2 at Motutapu (see Figure 15). The most common Holothurid found on the fore reef was *Stichopus chloronotus*, with the highest density (0.47 ± 0.29 ind./m^2) reported at Avatiu. Occasionally, *Holothuria atra* and *Thelenota ananas* were also recorded at some sites. All other invertebrates were below 0.5 ind./m^2.

While a general increase of urchin density (lumping all urchins at each site) was noted between 2006 and 2009, significant increases were noted at Tumunu, Nikao, Motutapu, Taakoka, Vaimaanga, and Kavera (Figure 16; Appendix D). Ordination of sites using replicates for 2006 and 2009 clearly separated the two periods (Figure 17), with *Echinothrix* increasing in 2009. Eigen analysis indicate that 91.7 % of the variation was explained in the first two axes with *Echinometra* having the most weight in the first axis, and *Echinothrix* in the second (Table 8).

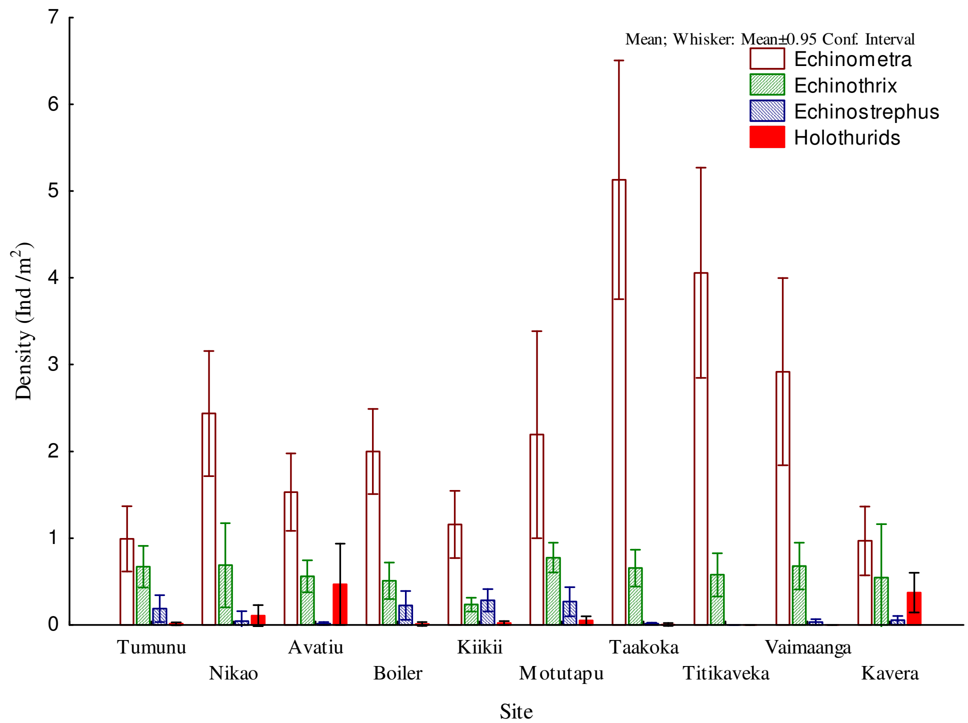


Figure 15. Mean density of the most common macro-invertebrates recorded in 2009.

Figure 16. Mean urchin density for 2006 and 2009 sites. Open columns represent 2006 sites and filled columns represent 2009 sites.

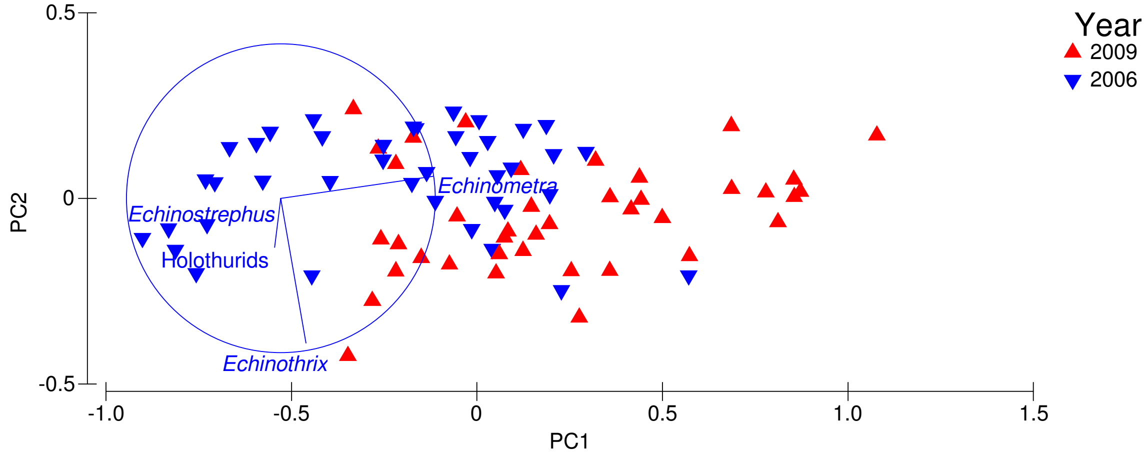


Figure 17. Principal Component Analysis with ordination plot superimposed for 2006 and 2009 invertebrates. Data were log-transformed.

Table 8. Eigen-analysis of fish families from 1994 to 2009 for all sites.

Eigenvalues				
PC	*Eigenvalues*	*%Variation*	*Cum.%Variation*	
1	0.194	82.3	82.3	
2	2.21E-2	9.4	91.7	
3	1.14E-2	4.8	96.5	
Eigenvectors				
Invertebrate		*PC1*	*PC2*	*PC3*
Echinometra		-0.986	0.142	0.084
Echinothrix		-0.163	-0.937	-0.287
Echinostrephus		0.001	-0.013	-0.330
Holothurids		0.041	-0.318	0.895

DISCUSSION AND CONCLUSION

The present survey indicated that hard coral cover at sites surveyed and those observed at other fore reef sites around Rarotonga remain well below that reported from pre-COTS conditions, even after 10 years since the COTS outbreak. The high variation in coral cover at most sites suggests the patchiness of coral communities on the fore reef. However, the present survey showed a general increase in hard coral cover at all sites since 2006, indicating that recovery is taking place (as predicted in the 2006 report). This was evident especially at Boiler and Titikaveka, where hard coral cover increased over three-fold. But unlike Boiler, conditions at Titikaveka were the most pristine with good visibility, high cover of coralline algae, and patches of larger Acroporid colonies observed at depths less than 6 m; this was consistent with supplementary analysis (Rongo, 2008) identifying Titikaveka as a low-impact site.

Boiler was perhaps the most interesting site (identified in supplementary analysis as highly impacted). Several large colonies of *Porites* spp. were observed having partial mortality (Plate 4), which may have been the result of heavy sedimentation from terrestrial sources especially as Boiler is located in the most developed area of Rarotonga and in close proximity to the two largest streams in Avarua. However, coral cover, colony density, evenness, and diversity were the highest when compared with all sites. While it is possible that Boiler is receiving coral recruits from reef flat communities in the area (healthy coral communities observed on reef flat areas from Paradise Inn [Tupapa] to Avarua Catholic Church [see Plate 1]), it is also possible that (on a larger scale) this area is a "sink" (receiving larval supply from distant sources), as Boiler's location is on the leeward side of the island where "eddy effect" may be experienced (see Cowen, 2002). This may explain the new record of starfish *Culcita novaeguineae* (bottom left picture on title page; possibly originating from French Polynesia), why aquarium fish collectors are continuously collecting on this side of the island, as well as the consistent supply of `*ature* (*Selar crumenophthalmus*) in Avatiu harbor. Although, this assumption needs confirmation through more biodiversity and hydrodynamic studies to understand connectivity among reefs around Rarotonga as well as within this region, relevant ministries should consider improving the condition of this area and not wait for scientific confirmation.

Although hard coral cover was the lowest at Vaimaanga at less than 1 %, this site is less likely to be affected by land-based impacts because of the low level of development in this area (identified as a low-impact site in the supplementary report). The dominance of soft coral (with coverage increasing since 2006) may indicate an alternate stable state, possibly hindering the establishment of hard corals (Plate 5). Shifts from hard coral- to soft coral-dominated reefs after major disturbances such as COTS outbreaks have been reported in the literature (see review by Norstrōm *et al*., 2009). The few hard corals recorded at this site were large colonies of *Pocillopora eydouxi,* which may have been survivors of the COTS outbreak in the 1990s.

Coral size class data also indicated that recovery, where an increase in larger colonies was noted at almost all sites. However, the majority of corals recorded were of the encrusting and massive types (i.e., *Leptoria*, *Leptastrea*, and *Montastrea*), most of which were remnants of larger colonies represented in all size classes. Thus these corals may not be good indicators of recruitment; including encrusting corals into recruitment class data may be misleading as a small colony could be decades old (Hughes and Jackson, 1980). However, corals from the genus *Acropora* and *Pocillopora* contributing to 8 % of size class A were clearly recruits, indicating that recruitment is occurring at some level (possibly low). Perhaps a more comprehensive examination of recruitment rates on Rarotonga's reefs will help us better understand this process locally.

Indications of reef recovery were also noted among fish communities at the trophic level, particularly with planktivores. The high planktivore abundance recorded in 1999 was the result of high coral cover despite the COTS predation occurring during this period. In 2006, planktivore (e.g., *Chromis vanderbilti*) numbers declined coincidentally with coral mortality associated with the COTS outbreak. In the present survey, their numbers increased along with corallivores (e.g., butterflyfishes). Although recovery seems to be occurring, changes to the benthic community have resulted in the reduction of fish species diversity, particularly among Pomacentrids (damselfishes). The loss of corals has been associated with the increase of herbivorous fishes in response to increased algal growth (Wilson *et al.*, 2006). This was clearly the situation on Rarotonga in 2006, however, herbivorous fish abundance declined in the present survey. While this may support the assumption of recovery, a decline could also indicate that the reef is losing structural integrity (Sano *et al*., 1987; Garpe *et al*., 2006) that could hamper recover.

In contrast to the decline in herbivorous fish abundance, a general increase in urchin density was noted at most sites. Although it is difficult to determine the reason for the increase, grazing by urchins has been identified as important for exerting top-down control on algal growth to facilitate coral recruitment and reef recovery (Sammarco, 1980; Carpenter and Edmunds, 2006). This may explain the diverse coral communities observed at locations around Rarotonga (e.g., lagoon area of Kavera and reef flat of Nikao and Avarua), where urchin density was estimated at over 10 ind./m^2 (Plate 6, 7). However, high urchin density can also be detrimental to reef recovery through predation on juvenile corals (Sammarco, 1980) and bioerosion (Eakin, 2001). For example, the negative impact of high urchin density was noted at Uva Island, Panama, where densities increased to 50 ind./m^2 on the reef flat and 20 ind./m^2 on the fore reef (Eakin, 2001). These urchin densities may not have been reached yet on Rarotonga, possibly because of the high abundance of Diodontids (porcupinefish) and Balistids (triggerfish) that prey on urchins.

Asparagopsis taxiformis (Delile) (Plate 8) was the only macro-algae recorded on the fore reef during the present survey (including the 2006 survey). This alga has been reported to be of low preference for herbivorous fishes (Meyer *et al.*, 1994). The absence of preferred algae such as *Dictyota* spp. and *Padina* spp. observed on the fore reef in the past suggests that herbivory is generally high on Rarotonga. As noted in the 2006 survey, the present survey also indicated that the highest cover of *A. taxiformis* was at Motutapu. This may indicate that nutrient enrichment or runoff sediments are impacting this site, possibly transported through the Avana passage. Observations of areas in close proximity to the passage, particularly on the Motutapu side (where the current is flowing towards), showed high cover of this alga at depths less than 10 m. This site was particularly low in hard and soft coral cover. If coral recruitment supply depends on lagoon coral communities (which are dying; pers. obs.) then conditions at Motutapu including Taakoka (nearby site) may reflect the deteriorating conditions in Muri lagoon from heavy use and poor land-use practices.

While the results of this survey show that recovery is in the early stages, and as conditions on Rarotonga are already favorable for bottom-up control (e.g. Anderson *et al*., 2004), top-down control by maintaining a healthy herbivorous community (e.g., Acanthurids, Scarids, and urchins) may be important at this point to foster recovery. As it has been proposed that ciguatera fish poisoning on Rarotonga is expected to decline (Rongo *et al.*, 2009) (also noted in the current hospital records), the increase of reef fishing in recent years in response to the decline of ciguatera may jeopardize the recovery of our reefs. The need to manage the use of our marine resources is urgent to ensure that overfishing is avoided, particularly among herbivores (e.g., Scarids, Acanthurids, Kyphosids, Siganids, and urchins). Perhaps implementing fishing restrictions and reinforcing the management of the *ra`ui* system and establishing new *ra`ui* sites may be critical. Furthermore, this would ensure that populations of herbivores and their predators are kept in balance so that herbivory does not become detrimental to reef recovery.

Patches of coral-dominated areas on the fore reef and within the lagoon around Rarotonga were identified through observations made by towing and snorkeling. These were observed on the southern fore reef exposure of Rarotonga in close proximity to major passages in the area. For example, Titikaveka (the most pristine area reported in this survey) was down-current from the Avaavaroa passage. Furthermore, healthy fore reef areas observed around Rutaki and Kavera were in close proximity to the Rutaki passage. In contrast, the abundance of macro-algae and the low coral density on the fore reef at Motutapu near the Avana passage reflect the conditions in Muri lagoon. To date, more studies are accumulating to supporting the idea that reefs are self-seeding (see review by Jones *et al.*, 2009). This suggests that the recovery of fore reefs may depend on lagoon communities for larval supply of corals. Thus, protecting these remaining healthy coral communities in the lagoon (i.e., Kavera, Titikaveka [Papaaroa to Avaavaroa], and Avarua [Avatiu to Maraerenga]) or improving the conditions of our lagoons may be critical.

While efforts to minimize eutrophication are currently implemented by the Ministry of Health, there is also a need for relevant Ministries to manage land-based activities that are contributing to runoff sediments and most importantly to manage the use of marine resources to ensure overfishing is avoided and that sufficient grazing by herbivores are maintained during this recovery stage. Under eutrophic conditions (currently experienced on Rarotonga), the removal of herbivores can result in the dominance of algae (e.g., Littler & Littler, 1985), which can negatively impact recovery. An overfished reef in the face of climate change and increasing coastal development may take decades to recover or may never. Such a scenario is currently experienced in the Caribbean, where reefs to date have not recovered. Unless preventative measures are taken, our reefs will no doubt suffer the same fate.

RECOMMENDATIONS

- Develop a management plan for inshore fisheries (e.g., catch limitations, gear restrictions, and enforcing the *ra`ui* system) to ensure that top-down control of algal communities by herbivores are maintained at levels that would assist recovery.
- Lagoon sites previously established in 2006 should be revisited to examine changes over time. Additional sites (see Figure 1) on the fore reef (i.e., Kavera by the Rarotongan Beach Hotel) and lagoon (i.e., Avaavaroa lagoon area) should be established to understand their potential role as “sink” and “source” populations respectively for recruitment.
- The high biodiversity measures noted in Avarua (Boiler) and to an extent Avatiu may indicate that the area is a possible “sink”. This suggests that efforts to reduce deleterious activities impacting this area should be foremost. For example, 1) implement good land-use practices to reduce sedimentation and nutrient runoffs delivered from the Avarua catchments (Takuvaine and Avatiu), 2) limit the type of fishing (e.g., spearfishing and net fishing), and 3) limit other activities (i.e., dredging) in this area. Improvements to this

area will not only help recovery but also preserve biodiversity that may be sourcing from other reefs around the island or region. In addition, the tourism industry will also benefit as the area is frequently used for SCUBA diving and glass-bottom boat observations.

- The degraded conditions at Motutapu noted in the present survey as well as in 2006 are a clear indication that anthropogenic activities remain problematic in the Muri area. Perhaps development in this area should be limited, with particular focus in the wetland areas that are currently being filled for development. Wetlands are natural filters for land-based runoff entering the ocean, and should be protected from any type of development.
- As an integral part of the monitoring program, sediment load at major streams and the extent to which it is delivered offshore should be quantified as tools for monitoring land-based developments (i.e., landscaping on sloped lands).
- Hydrodynamic (i.e., current) studies are needed to aid our understanding of connectivity among reefs around Rarotonga and their link to other reefs in the region. This information will be critical for identifying locations for establishing *ra`ui* sites.
- Subsequent surveys will employ other statistical analysis such as ANOVA to examine variability among years within each site and Komolgorov-Smirnov for coral size frequency distribution.

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Appendix A. Descriptive statistics for all 2009 benthic communities at all sites using point quadrat data.

		Coral cover			Soft coral			Turf algae			Coralline algae		
Site	N	Mean	Std Dev	Variance	Mean	Std Dev	Variance	Mean	Std Dev	Variance	Mean	Std Dev	Variance
Tumunu	4	12.03	5.34	28.48	1.88	1.69	2.86	73.44	3.70	13.67	13.13	2.17	4.69
Nikao	4	2.81	0.36	0.13	0	0	0	82.19	3.25	10.55	12.03	2.57	6.61
Avatiu	4	2.97	0.79	0.62	0.94	0.81	0.65	75.94	5.36	28.78	20.00	4.70	22.14
Boiler	4	13.44	3.63	13.15	0.16	0.31	0.10	84.53	4.34	18.85	0.94	1.20	1.43
Kiikii	4	2.50	0.51	0.26	0	0	0	91.41	3.55	12.60	3.59	5.21	27.18
Motutapu	4	1.72	0.79	0.62	0	0	0	88.59	3.20	10.25	2.66	1.07	1.14
Taakoka	4	2.97	1.93	3.74	1.41	1.07	1.14	84.38	1.35	1.82	11.25	1.14	1.30
Titikaveka	4	12.03	5.34	28.48	4.22	1.39	1.92	4.84	3.32	11.04	78.75	1.44	2.08
Vaimaanga	4	0.63	0.51	0.26	15.94	4.80	23.05	19.06	8.04	64.71	64.38	12.27	150.52
Kavera	4	1.88	1.14	1.30	3.44	5.34	28.52	82.50	7.86	61.72	9.53	4.00	15.98

Appendix B. Descriptive statistics of fish families (ind./200 m^2) for 2006 and 2009 sites.

Site	Stats	ACANTHURIDAE	BALISTIDAE	LABRIDAE	POMACENTRIDAE	SCARIDAE	CHAETODONTIDAE
Avatiu 2006	Mean	173.00	6.75	22.50	11.75	4.00	0.75
	Std. Dev	53.61	1.50	9.68	5.50	4.90	0.50
	Variance	2874.00	2.25	93.67	30.25	24.00	0.25
Avatiu 2009	Mean	44.50	8.75	9.75	17.00	3.25	5.25
	Std. Dev	7.94	4.27	6.29	8.41	3.77	3.86
	Variance	63.00	18.25	39.58	70.67	14.25	14.92
Boiler 2006	Mean	113.00	10.00	17.00	27.00	6.00	2.75
	Std. Dev	9.63	5.48	4.97	12.27	5.35	3.59
	Variance	92.67	30.00	24.67	150.67	28.67	12.92
Boiler 2009	Mean	97.75	19.50	4.50	9.75	20.25	10.25
	Std. Dev	48.66	9.15	3.00	5.32	9.03	5.25
	Variance	2367.58	83.67	9.00	28.25	81.58	27.58
Kavera 2006	Mean	293.75	3.25	20.00	21.50	13.00	1.25
	Std. Dev	68.82	1.26	3.74	16.36	6.48	0.96
	Variance	4736.25	1.58	14.00	267.67	42.00	0.92
Kavera 2009	Mean	85.00	5.50	8.75	57.00	14.00	3.50
	Std. Dev	13.14	3.42	2.22	53.80	4.69	2.52
	Variance	172.67	11.67	4.92	2894.67	22.00	6.33
Kiikii 2006	Mean	280.25	9.25	33.25	42.75	35.75	0.25
	Std. Dev	94.60	2.63	3.30	25.62	24.66	0.50
	Variance	8948.25	6.92	10.92	656.25	608.25	0.25
Kiikii 2009	Mean	75.75	12.50	3.75	5.00	31.50	2.25
	Std. Dev	19.82	2.52	1.89	4.76	18.86	0.96
	Variance	392.92	6.33	3.58	22.67	355.67	0.92
Motutapu 2006	Mean	332.00	6.25	32.25	22.25	7.00	2.25
	Std. Dev	41.04	3.30	1.71	8.54	5.23	1.71
	Variance	1684.67	10.92	2.92	72.92	27.33	2.92
Motutapu 2009	Mean	44.50	8.75	9.75	17.00	3.25	5.25
	Std. Dev	7.94	4.27	6.29	8.41	3.77	3.86
	Variance	63.00	18.25	39.58	70.67	14.25	14.92

Appendix B (continued).

Site	Stats	ACANTHURIDAE	BALISTIDAE	LABRIDAE	POMACENTRIDAE	SCARIDAE	CHAETODONTIDAE
Nikao 2006	Mean	512.00	2.75	18.75	9.00	58.00	1.00
	Std. Dev	128.13	1.50	2.22	7.02	43.24	0.82
	Variance	16416.67	2.25	4.92	49.33	1869.33	0.67
Nikao 2009	Mean	163.75	7.50	5.75	17.25	8.25	6.75
	Std. Dev	53.44	1.91	6.90	17.78	9.54	3.10
	Variance	2855.58	3.67	47.58	316.25	90.92	9.58
Taakoka 2006	Mean	342.25	3.25	36.75	114.50	8.50	2.00
	Std. Dev	33.61	1.26	6.40	57.53	5.32	2.45
	Variance	1129.58	1.58	40.92	3309.67	28.33	6.00
Taakoka 2009	Mean	106.25	3.00	13.50	32.75	19.50	3.25
	Std. Dev	37.23	0.82	7.85	17.73	12.56	2.06
	Variance	1386.25	0.67	61.67	314.25	157.67	4.25
Tumunu 2006	Mean	246.75	8.75	22.00	40.50	16.75	1.25
	Std. Dev	104.54	4.03	14.72	20.37	13.89	0.96
	Variance	10928.92	16.25	216.67	415.00	192.92	0.92
Tumunu 2009	Mean	53.00	5.50	4.00	49.75	13.50	2.25
	Std. Dev	37.03	3.11	2.58	9.67	13.48	2.63
	Variance	1371.33	9.67	6.67	93.58	181.67	6.92
Vaimaanga 2006	Mean	233.50	2.25	14.75	46.25	16.50	1.75
	Std. Dev	73.52	1.26	4.35	15.82	3.11	0.96
	Variance	5405.67	1.58	18.92	250.25	9.67	0.92
Vaimaanga 2009	Mean	60.75	2.25	14.25	66.50	11.25	5.00
	Std. Dev	12.28	0.50	4.43	4.20	3.40	1.41
	Variance	150.92	0.25	19.58	17.67	11.58	2.00

Appendix C. Descriptive statistics for invertebrates from all 2009 sites.

Site	Stats	*Dendropoma*	*Echinometra*	*Echinothrix*	*Echinostrephus*	Holothurids
Avatiu	Mean	0.22	1.53	0.56	0.02	0.47
	Std. Deviation	0.32	0.28	0.12	0.01	0.29
	Variance	0.10	0.08	0.01	0	0.09
Boiler	Mean	0.94	2.00	0.51	0.23	0.01
	Std. Deviation	0.53	0.31	0.13	0.10	0.01
	Variance	0.28	0.10	0.02	0.01	0
Kavera	Mean	0.02	0.97	0.55	0.05	0.37
	Std. Deviation	0.02	0.25	0.39	0.03	0.14
	Variance	0	0.06	0.15	0	0.02
Kiikii	Mean	0.46	1.16	0.24	0.28	0.02
	Std. Deviation	0.49	0.24	0.05	0.08	0.01
	Variance	0.24	0.06	0	0.01	0
Motutapu	Mean	0.16	2.19	0.78	0.27	0.05
	Std. Deviation	0.06	0.75	0.11	0.11	0.03
	Variance	0	0.56	0.01	0.01	0
Nikao	Mean	0.31	2.44	0.69	0.04	0.11
	Std. Deviation	0.20	0.45	0.31	0.07	0.08
	Variance	0.04	0.21	0.09	0.01	0.01
Taakoka	Mean	0.03	5.13	0.66	0.02	0.01
	Std. Deviation	0.03	0.86	0.13	0.01	0.01
	Variance	0	0.75	0.02	0	0
Titikaveka	Mean	0	4.06	0.58	0	0
	Std. Deviation	0	0.76	0.16	0	0
	Variance	0	0.58	0.02	0	0
Tumunu	Mean	0.19	0.99	0.67	0.19	0.01
	Std. Deviation	0.03	0.24	0.15	0.10	0.01
	Variance	0	0.06	0.02	0.01	0
Vaimaanga	Mean	0	2.92	0.68	0.03	0
	Std. Deviation	0	0.68	0.17	0.02	0
	Variance	0	0.46	0.03	0	0

Appendix D. Descriptive statistics of urchins for 2006 and 2009 sites.

Site		2006	2009
Avatiu	Mean	1.63	2.11
	Std. Deviation	0.55	0.26
	Variance	0.30	0.07
Boiler	Mean	2.33	2.73
	Std. Deviation	0.29	0.32
	Variance	0.09	0.10
Kavera	Mean	0.54	1.57
	Std. Deviation	0.15	0.43
	Variance	0.02	0.19
Kiikii	Mean	1.52	1.68
	Std. Deviation	0.39	0.28
	Variance	0.15	0.08
Motutapu	Mean	1.58	3.24
	Std. Deviation	0.26	0.87
	Variance	0.07	0.75
Nikao	Mean	1.74	3.17
	Std. Deviation	0.45	0.29
	Variance	0.21	0.08
Taakoka	Mean	2.28	5.80
	Std. Deviation	0.31	0.74
	Variance	0.10	0.54
Titikaveka	Mean	2.75	4.64
	Std. Deviation	1.15	0.74
	Variance	1.32	0.55
Tumunu	Mean	0.59	1.85
	Std. Deviation	0.05	0.21
	Variance	0.00	0.05
Vaimaanga	Mean	0.63	3.63
	Std. Deviation	0.14	0.64
	Variance	0.02	0.41

Appendix E. Breakdown of colonies within class A by genus.

Genus	Tumunu	Nikao	Avatiu	Boiler	Kiikii	Motutapu	Taakoka	Titikaveka	Vaimaanga	Kavera	Total	% Contribution
Acanthastrea	6	5	2	10	20	3	2	1	0	1	50	10
Acropora	1	2	0	0	2	1	0	3	2	0	11	2
Coeloseris	1	0	1	0	0	0	0	0	0	0	2	0
Coscinarea	0	3	0	0	0	1	0	0	0	0	4	1
Cyphastrea	0	1	0	3	3	8	0	0	0	0	15	3
Favia	1	0	1	3	4	0	3	6	3	0	21	4
Favites	1	0	0	0	0	0	0	0	0	0	1	0
Goniastrea	1	0	0	0	0	0	2	0	0	0	3	1
Hydnophora	4	0	1	2	2	5	3	1	0	2	20	4
Leptastrea	0	0	2	6	14	4	0	0	0	4	30	6
Leptoria	18	12	4	11	21	24	27	9	13	26	165	32
Montastrea	11	16	6	7	28	9	7	18	6	15	123	24
Montipora	0	11	0	0	2	1	0	0	0	0	14	3
Pavona	0	0	1	0	0	0	0	0	0	0	1	0
Pocillopora	7	0	5	2	4	1	5	1	4	1	30	6
Porites	3	1	1	0	13	1	2	0	0	4	25	5
Psammacora	0	0	0	0	0	0	2	0	0	0	2	0

Plate 1. Reef crest of Avarua town during an extreme low tide on 24 May 2009, with exposed corals experiencing partial bleaching. Dark area is the only zone where macro-algae, predominantly *Turbinaria*, are still found on Rarotonga.

Plate 2. Reef flat of Avarua town area during an extreme low tide on 24 May 2009, with Konini Rongo assisting in estimating urchin density in this area.

Plate 3. Acanthurids at Vaimaanga. Schooling fishes of this family as well as Scaridae were common on fore reef sites around Rarotonga. Taken on 13 July 2009.

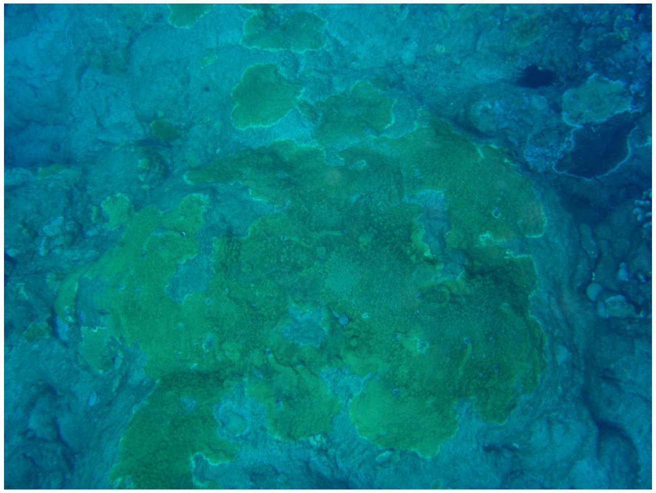

Plate 4. Large *Porites* spp. colony suffering partial mortality. Taken at Boiler at a depth of 10 m on 9 June 2009.

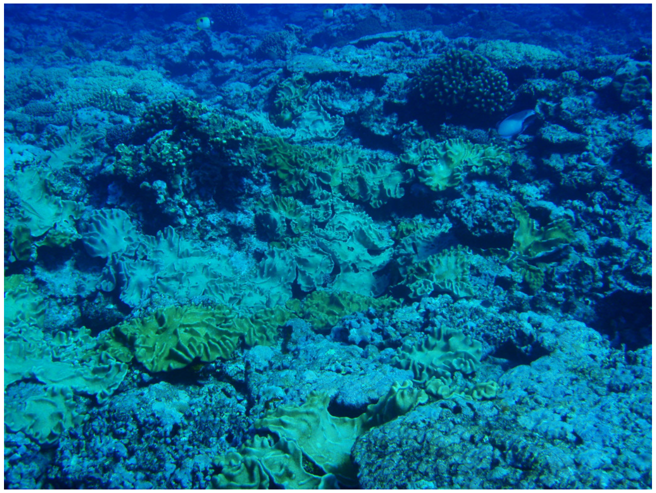

Plate 5. Benthic communities at Vaimaanga, dominated by soft corals and coralline algae. Taken on 13 July 2009.

Plate 6. Reef flat of Avarua town area showing a patch of *Turbinaria ornata* grazed by urchins (*Echinothrix diadema*), allowing corals to establish. Taken on 24 May 2009.

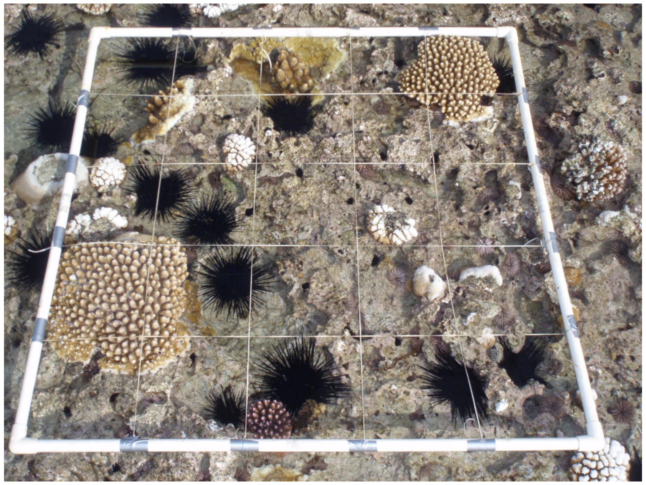

Plate 7. One-m^2 quadrat showing approximate density of *Echinothrix diadema* (common large urchin) on the reef flat of Avarua town area. Taken on 24 May 2009.

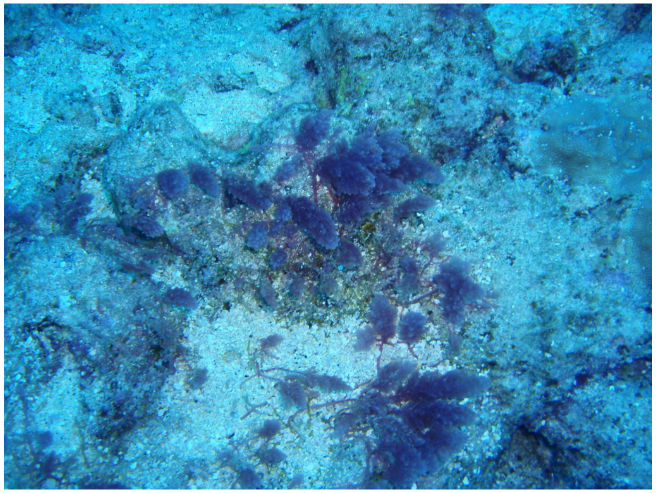

Plate 8. The only macro-algae recorded on the fore reef in the present survey: *Asparagopsis taxiformis*. Taken on 15 June 2009 at Motutapu.