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Declining coral health and fish diversity in the South Pacific

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Declining Coral Health and Fish Diversity in the South Pacific

by Paul McCurdy

A Thesis Submitted to the Faculty of

The Wilkes Honors College

in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Arts in Liberal Arts and Sciences

with a Concentration in Marine Science

Wilkes Honors College of

Florida Atlantic University

Jupiter, Florida

May 2007

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This thesis was prepared under the direction of the candidate's thesis advisor, Dr. Jim Wetterer, and has been approved by the members of his supervisory committee. It was submitted to the faculty of The Honors College and was accepted in partial fulfillment of the requirements for the degree of Bachelor of Arts in Liberal Arts and Sciences.

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Acknowledgements

First and foremost, I would like to thank Abigail Alling, Orla Doherty and the rest of the Planetary Coral Reef Foundation for all their help and permission to use their data. In addition, I would like to thank Dr. Jim Wetterer, Dr. Jon Moore, Dr. Stephanie Fitchett, and Dr. Terje Hoim for all their beneficial comments and suggestions. I would like to thank Dr. Nancy and Dr. Elliott McCurdy for their inspirational and financial support. I would also like to thank all my professors at the Wilkes Honor's College and Harbor Branch Oceanographic Institution for preparing me for this endeavor.

Abstract

Coral reefs harbor ~1-9 million species, including 30% of all marine fish species. Reef health worldwide is declining due to many factors: e.g. pollution, sedimentation, dynamite fishing, and global warming. Working with the Planetary Coral Reef Foundation and the crew aboard the R/V Heraclitus, I examined coral health and fish diversity in the Solomon Islands, Melanesia. In 2006, I surveyed coral and fish on Sagharughombe reef, Solomon Islands using SCUBA and compared the results with surveys done in 2000 and 2002. Coral surveys indicated a significant decline in health over the six-year period. Fish surveys found no clear trend in species abundances and species richness, but a significant decline in species diversity over the years. The decline in coral health we observed may have contributed to diminished fish diversity. To protect marine biodiversity, coral reefs must be better protected and declines in coral health must be halted.

To all the people that suffered from

the April 2007 Solomon Islands Tsunami

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Introduction

Coral reefs provide a unique three-dimensional habitat for millions of invertebrates and vertebrates. These same reefs are the basis of many tropical coastal economies around the globe. However, increasing anthropogenic pressure and climate change have taken a toll on many reefs worldwide (Wilkinson 1999, Wilkinson 2002, Wilkinson 2004 and Hoegh-Guldberg 1999). As coral health deteriorates, these ecosystems run the risk of complete destruction.

The predominant reef-building corals are stony corals (Anthozoa, Scleractinia), which use dissolved calcium and carbon dioxide from the ocean to create a calcium carbonate skeleton. Coral growth rates vary from region to region and species to species. For example, Davies (1983) found that some Caribbean Acroporids, which are branching corals, grow 2.5-26.6 cm per year in length, and *Montastrea annularis*, a massive coral, has a linear growth of 0.81-2.5 cm per year. Over long periods of time, coral skeletons build up and form extensive structures called coral reefs. Many of these structures have existed for hundreds of millions of years. Currently, corals occupy about 600,000 square miles of the earth's surface (Nybakken 2001). Approximately one-sixth of the world's coastlines are fringed by coral reefs (Birkeland 1997).

Coral reefs are called the "rainforests of the sea" due to their great biodiversity. With respect to higher taxa, more diversity exists on coral reefs than any other marine ecosystem (Reaka-Kudla 1997). Karlson (1999) estimated that ~91,000 species, or 4-5% of all described species, are found on coral reefs, and Reaka-Kudla (1997) estimated that ~1-9 million species exist on coral reefs. This tropical environment, which accounts for

less than 1% of the oceans surface, provides habitat for roughly 30% of the total marine fish species (Vernon 1995, Reaka-Kudla 1997).

Many coastal human communities rely on these prosperous reefs for both their diet and income. Anthropogenic activities impact reefs as human populations continue to grow (Wilkinson 2004). Activities such as fishing and deforestation are needed to sustain human growth, however these same actions can damage corals indirectly by modifying predator/prey, competitor, pathogen, and mutualist interactions (Edinger *et al.* 1998). In addition, many fishing practices damage corals and can destroy entire reefs (Polunin and Roberts 1996).

Climate change contributes to coral reef decline, as well. Increased sea surface temperatures can cause frequent coral bleaching events (Hoegh-Guldberg 1999). Coral bleaching is when corals expel their symbiotic zooxanthellae, a photosynthetic dinoflagellate, due to stress. Temperature increases of as little as 1-2 °C can cause bleaching. If corals cannot recapture zooxanthellae soon after a bleaching event, they can soon die (Hoegh-Guldberg 1999). Global warming has already destroyed or severely damaged an estimated 25% of the worlds reefs (Goreau *et al.* 2000). In the Central Pacific, certain areas of the Phoenix Islands have shown almost complete coral mortality due to the 2002 bleaching event (Alling *et al.* submitted). The Intergovernmental Panel on Climate Change (IPCC 2007) predicts that the warming trend will continue and bleaching events may occur annually.

Since corals play a functional role in creating the foundation of the ecosystem, their degeneration may have adverse effects on other coral reef organisms. For instance, the branching coral *Pocillopora damicornis* harbors up to 16 species of crustaceans and

fish that use it for both food and shelter (Lassig 1977). When this coral becomes unhealthy or dies, the obligate species can lose their habitat and possibly become locally extinct. If coral health continues to deteriorate, overall diversity may decline.

For my thesis research, I worked with the Planetary Coral Reef Foundation and the crew aboard the R/V Heraclitus, studying coral health and fish diversity on Sagharughombe Reef in the Solomon Islands, Melanesia.

Methods

In 2006, I surveyed coral and fish using SCUBA and compared the results with previous surveys done in 2000 and 2002.

Study Site

The Sagharughombe Reef (S08°07.0' E156°54.7') in Western Province, Solomon Islands is located 10 kilometers east of Gizo, the provincial capital of Western Province. The reef lies adjacent to Kennedy Island, a small islet that gained its fame during WWII when, in a heroic rescue, John F Kennedy pulled his fellow soldiers ashore after the PT109 sank in the area (National Geographic: The Search for Kennedy's PT109). Nowadays, dive tour operators visit the vast reefs around Sagharughombe regularly.

Sagharughombe Reef lies on the northeast end of a vast lagoon system. On the lagoon side of the reef, coral growth occurs on a steep slope to 20 meters depth. At 20 meters, sand substrate dominates the bottom and gradually reaches about 70 meters depth. On the eastern side of the reef, there is a steep drop off, reaching 300+ meters in the Blackett Strait. On the northwest tip and southeast tips, there are channels separating Sagharughombe from its neighboring reefs.

The reef flat ranges from about 3 meters below the surface on the northwest end to 1 meter below the surface in the central section and southeastern end. Tidal influence was negligible during the study period.

Coral health and fish diversity were surveyed on four transects on the reef.

Transect GPS coordinates are as follows:

Site Name	Transect Site	Lat. Buoy A	Long. Buoy A	Lat. Buoy B	Long. Buoy B
Sagharughombe, SI (shallow zone)	1	S08°06.981'	E156°54.664'	S08°06.975'	E156°54.656'
Sagharughombe, SI (shallow zone)	2	S08°07.072’	E156°54.790’	S08°07.075’	E156°54.800’
Sagharughombe, SI (deep zone)	3	S08°06.818’	E156°54.612’	S08°06.827’	E156°54.618’
Sagharughombe, SI (deep zone)	4	S08°06.882’	E156°54.605’	S08°06.872’	E156°54.596’

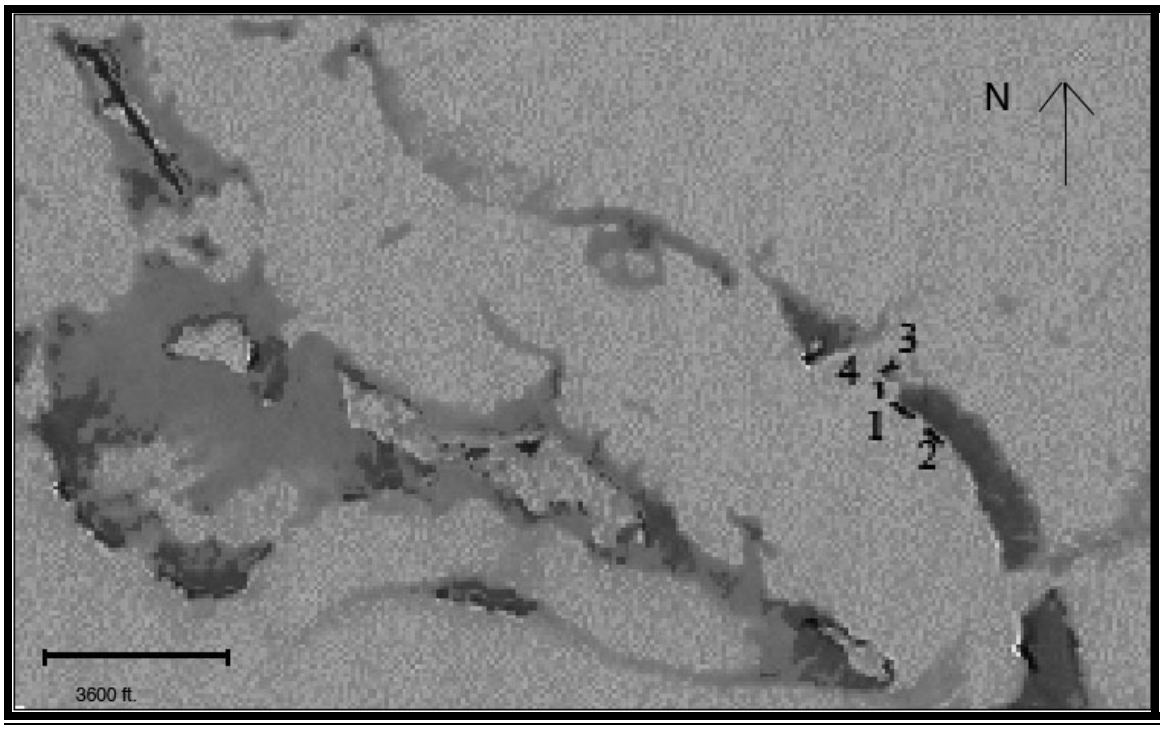

Figure 1. Satellite image of Sagharughombe Reef with locations of transects. Source for this data set was the Global Land Cover Facility, www.landcover.org.

Vitareef

The Vitareef methodology, developed by Dr. Phil Dustin of College of Charleston, was implemented to determine the health of scleractinian corals on the reef.

In this methodology, individual coral colonies are identified to the genus level. Then, the health of each colony is assessed based on a set of codes, which represent almost all states of health and conditions found on hard stony corals. The Vitareef codes are as follows:

2. Unblemished: The colony appears perfectly healthy.
3. Damaged but healed: Areas of the coral have been damaged, but healthy coral tissue has overgrown the damaged area.
4. Edge damage: A condition resulting from filamentous algae trapping sediment and slowly choking the live tissue.
5. Damage to tissue and skeleton: Damage to skeleton resulting from various actions (i.e. fish bites, anchor damage, wave damage, diver damage, etc.).
6. Excessive sedimentation on live tissue: Sedimentation sits on the coral colony without smothering the live tissue beneath it.
7. Damage to tissue: Skeleton is intact, but coral tissue is damaged (i.e. snail and crown-of-thorn predation).
8. Tissue bleaching: The condition in which the coral tissue expels the symbiotic zooxanthellae that live within its cell walls, resulting in a 'bleached' white appearance (may initially appear similar to tissue damage, however, upon closer inspection, tissue is intact in bleached corals).
9. Excessive mucous: A coral exudes mucous in order to protect itself from sedimentation and other environmental stresses.
10. Black band disease: A complex infection that gradually kills the coral colony. Often a thick black line separates healthy tissue from recently dead tissue.

11. Filamentous algae overgrowth: Parts of the colony are overgrown by filamentous algae.
12. Sedimentation with tissue necrosis: Excessive sedimentation causes necrosis of the underlying tissue.
13. White band disease: An infection that gradually kills the coral colony. Often a thin white line separates healthy tissue from recently dead tissue.
14. Healed with secondary algal colonization: A past scar is covered and contained by algae.
15. Recently dead: The entire coral colony is dead, but the genus of the colony is still recognizable indicating that the death was recent.
16. Macroalgae overgrowth: The colony is overgrown by macroalgae.
17. Colony decreasing in size: This code is used in conjunction with codes 4, 5, 7, 10, 11, 12, 13 and 16. It is also used with 19 if the invertebrate growth is actively encroaching over the surface of the colony (i.e. sponges, tunicates).
18. Almost unblemished: The colony appears healthy except for a small area.
19. Invertebrate overgrowth: Invertebrates covering much of the coral colony (i.e. Christmas tree worms, bioeroding mussels, tunicates, sponges, etc.).

SCUBA diving was used to gather the Vitareef data on the reef. For each zone of the reef, at least five hundred coral colonies were identified to the genus level and evaluated based on the Vitareef codes. After the dive, each coral genus and the codes corresponding to the corals' conditions were entered into a spreadsheet and analyzed using the Vitareef program (see Appendix A). Coral health was calculated by summing the percentage of

unblemished (Vitareef code #2) and almost unblemished (Vitareef code #18) colonies for each transect zone.

Fish Observations

In addition to the Vitareef data collection, fish species and abundances were surveyed on each reef. Transects were laid in the same area that Vitareef data were obtained. Four transects were laid in the study site. Transect surveys were conducted at a depth between 5 and 10 meters. A 20-meter line was laid, using the measuring tape as a guide, and weighted buoys were placed at either end of the 20-meter line. A bearing was taken underwater from buoy A to buoy B, and the boat tender saved the GPS coordinates of each buoy at the surface. The transect 'zone' created consisted of an 80 m^2 area (central 20 meter line with 2 meter spans either side). Fish observations included identification to species level and counting the abundances of each species for forty-five minutes (see Appendix B). Fish diversity was calculated using the Shannon-Weiner Biodiversity and the Simpson's Biodiversity Indices (for equations see Appendix C).

Results

The Vitareef transect surveys of Sagharughombe Reef in the Solomon Islands indicate a significant decline in coral health over the six year period (Fig. 2; Single Factor ANOVA $p<0.0001$). In 2000, 2002 and 2006 the mean percentage of healthy corals on the four transects were 49.00%, 33.39%, and 24.94%, respectively. There was a significant decline in heath from 2000 to 2002 ($p<0.000001$), from 2002 to 2006 $p<0.001$) and from 2000 to 2006 ($p<0.00000001$).

The fish transect surveys of the Sagharughombe Reef in the Solomon Islands in 2000, 2002 and 2006 do not show any clear trends with respect to species abundances and species richness (Table 1). There were a total of 259 different fish species recorded on Sagharughombe Reef (see Appendix B). However, there was a decreasing trend in Shannon-Weiner diversity over the years, and Simpson's diversity significantly declined as well (Fig. 4; Sign Test $p<0.05$).

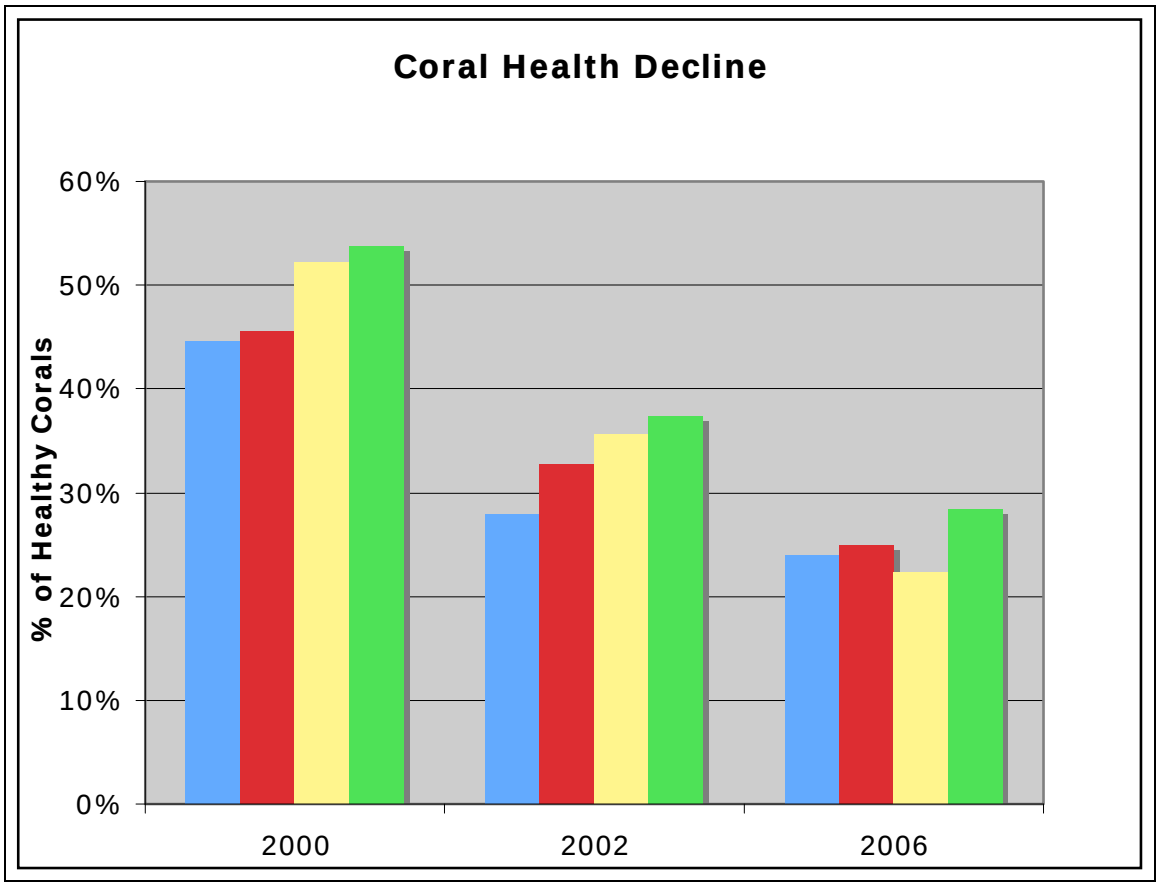

Figure 2. Coral health in four transects surveyed in 2000, 2002, and 2006 ($p<0.001$ for 2000 vs. 2002; 2002 vs. 2006, and 2000 vs. 2006).

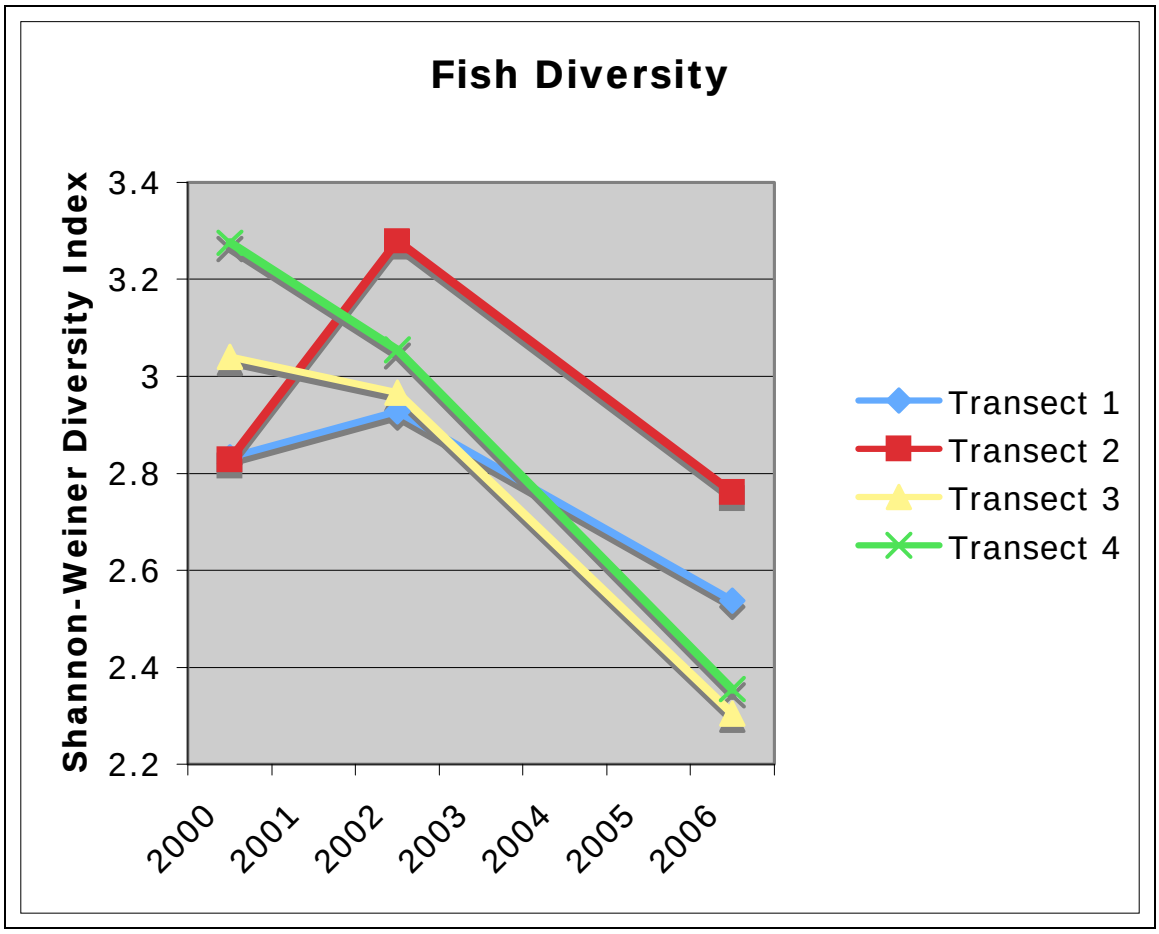

Figure 3. Fish diversity in four transects surveyed in 2000, 2002, and 2006 (Shannon-Weiner Index).

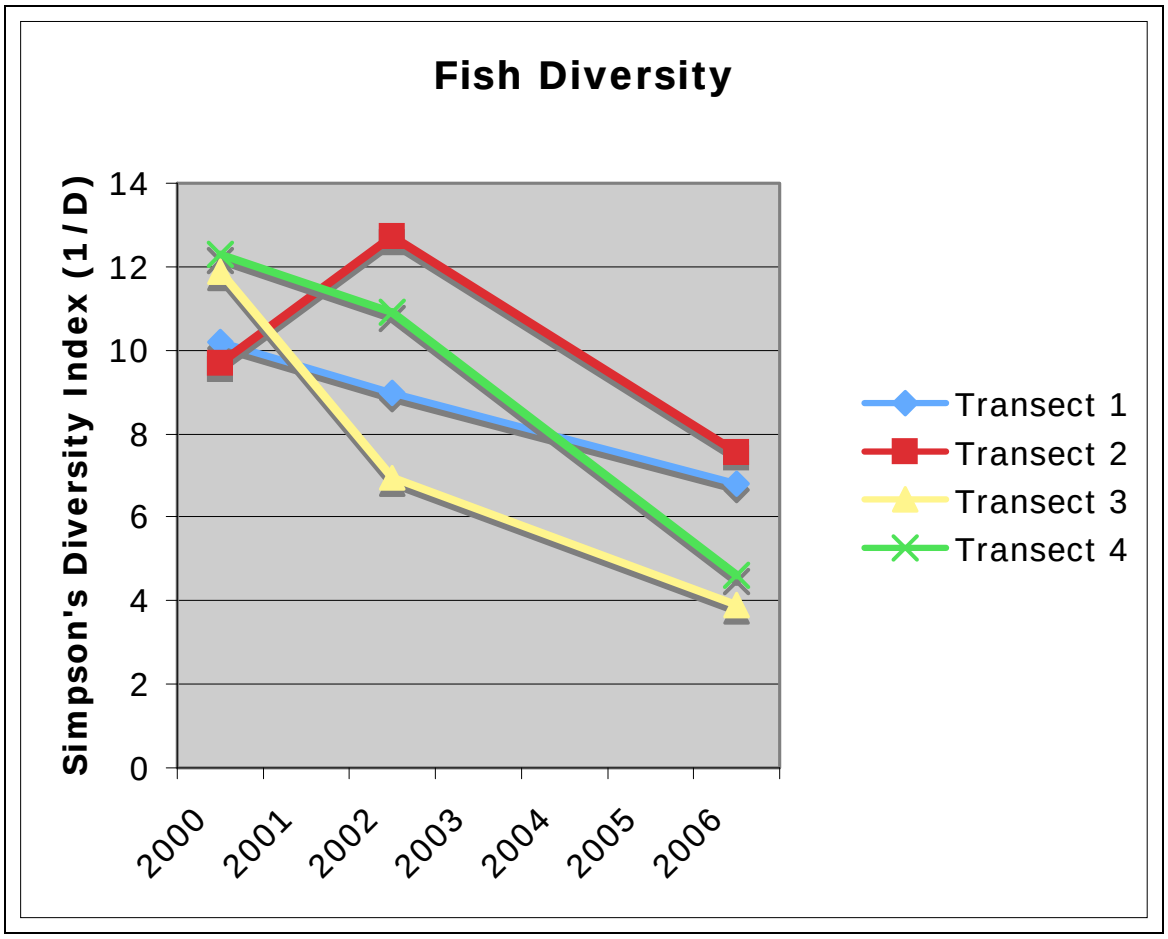

Figure 4. Fish diversity in four transects surveyed in 2000, 2002, and 2006 (Simpson's index; $p<0.05$).

Fish Surveys on Sagharughombe Reef, Solomon Islands							
Year	Transect #	Species Richness	Fish Abundance	Shannon-Weiner Diversity	Simpson's Diversity (D)	Index of Diversity (1-D)	Index of Diversity (1/D)
2000	1	63	1412	2.83	0.10	0.90	10.19
	2	73	1399	2.83	0.10	0.90	9.69
	3	67	944	3.04	0.08	0.92	11.89
	4	76	1041	3.28	0.08	0.92	12.30
2002	1	70	913	2.93	0.11	0.89	8.99
	2	79	906	3.28	0.08	0.92	12.72
	3	97	2817	2.97	0.14	0.86	6.94
	4	82	1222	3.05	0.09	0.91	10.91
2006	1	69	1709	2.54	0.15	0.85	6.80
	2	96	3336	2.76	0.13	0.87	7.57
	3	91	2890	2.30	0.26	0.74	3.89
	4	88	2549	2.35	0.22	0.78	4.60

Table 1. Fish diversity at four transect locations on Sagharughombe Reef, Solomon Islands in 2000, 2002, and 2006.

Discussion

Results from the surveys indicate a decline in both coral health and fish diversity on the Sagharughombe Reef, Solomon Islands from 2000 to 2006. Coral decline might have contributed to some decline in fish diversity. Corals create an intricate habitat for fish, and some fish have evolved an obligate association with certain corals. As coral health and cover declines, these obligate species can be displaced from their habitat as shown by Jones *et al.* (2004).

The most drastic coral health decline occurred between 2000 and 2002. Major bleaching events affected regions of the South Pacific during these years and were noticed during the April 2000 Vitareef survey (see Appendix A). "Almost continuous bleaching (occurred) throughout the period 2000-2002 (Wilkinson 2002)." From 2002 to 2006, no major bleaching events took place, but coral health continued to decline, though the decline was not as steep as the earlier period. A minor bleaching event was occurring during the January 2006 Vitareef survey (see Appendix A). Bleaching seemed to increase in intensity during our stay. It is likely that this extensive bleaching plays a major role in the declining coral health seen at Sagharughombe Reef in the Solomon Islands.

Sedimentation from terrestrial run-off, domestic sewage, and outbreaks of crown-of-thorn starfish (*Acanthaster planci*) might have contributed to coral health decline, as well. Logging occurs throughout the region, especially on Kolombangarra, a nearby island. Sedimentation and eutrophication resulting from intense logging can lead to coral decline (Rogers 1990). Domestic sewage from the nearby village on Mbangbanga might be causing eutrophication problems on the reef. Few corallivorous crown-of-thorn starfish were seen on the transect surveys in 2006, although the local dive operator, Dive

Ghizo, removed over one hundred crown-of-thorn starfish from a neighboring reef near Kennedy Island during our stay in 2006.

A significant decline in fish diversity occurred from 2000 to 2002. In the 2000 to 2002 time period, the Shannon-Weiner Index for fish diversity decreased in two out of the four transects. The Simpson's index for fish diversity significantly declined in three out of four transects in the same time period. The discrepancy is due to the difference in how factors influence each index. Both indices take into account the number of species present and the relative abundance of each species, but the Shannon-Weiner places more importance on the maximum evenness of each species.

In the 2002-2006 time period, fish diversity declined more rapidly than in 2000 to 2002. This may largely be due to a lag effect described by Tillman *et al.* (1994). There tends to be a lag period between loss of habitat and species extinction. Coral health degraded quickly during the 2000 to 2002 period, but the greater decline in fish diversity occurred in the subsequent years. A study on the Great Barrier Reef, Australia by Lewis (1998) demonstrated a similar decline in fish diversity on damaged patch reefs.

The current decline in coral health and fish diversity on the Sagharughombe Reef in Western Province, Solomon Islands might have devastating effects in the local region. In the recent years, a relatively unstable government caused most tourist companies and conservation groups to pull out of the Solomon Islands. Governmental stability has gradually increased, and some tour operators have returned. Most tourism in this region focuses on fishing and diving. If the reefs health and fish diversity continue to decline, so might the tourism in this region. This scenario would have devastating effects on the reemerging economy.

Coral bleaching has probably caused the most harmful effects on coral health at this particular reef, as seen by the concurrent bleaching and coral health decline from 2000 to 2002. The increase in water temperature is linked to anthropogenic global warming (IPCC 2007). In order to prevent the detrimental effect caused by coral bleaching, countries worldwide need to decrease their greenhouse gas output to curb anthropogenic global warming.

The creation of marine protected areas, also known as MPAs, can preserve coral health and fish diversity, as well. Research has shown that MPAs can prevent marine biodiversity loss by banning fishing and other extractive practices (Agardy 1994, Halpern & Warner 2002, and Lubchenco 2003). Although this method of preservation can effectively control "top-down" disturbances on the reef, it cannot prevent damage from larger scale processes like pollution, sedimentation and global warming, as demonstrated by Jones *et al.* (2004). On the other hand, MPAs cause a spillover effect when fish and other organisms flourish in bordering regions (Grafton *et al.* 2005). MPAs also act as a genetic bank for species with larval dispersal. This has immediate benefits to neighboring reefs.

Appendix A

Vitareef Data for Coral Health on Sagharughombe Reef, Solomon Islands in April 2000

	Shallow (3-5m)	Shallow (3-5m)	Deep (7-9m)	Deep (7-9m)
Transect #	1	3	2	4
Unblemished	22.56%	14.91%	29.35%	25.9%
Damaged but healed	1.4%	1.4%	0.63%	1.55%
Edge damage	26.16%	32.45%	23.9%	21.13%
Tissue & Skeleton Damage	8.87%	7.14%	8.39%	5.28%
Excessive sedimentation on live tissue	13.7%	12.11%	7.63%	5.545
Tissue Damage	5.79%	0.47%	2.94%	0.64%
Bleaching	**6.32%**	**18.94%**	**17.46%**	**25.52%**
Excessive Mucous	10.1%	7.92%	4.88%	3.61%
Black Band Disease	0.09%	0%	0%	0%
Filamentous algae overgrowth	15.28%	21.58%	16.58%	22.04%
Sedimentation with tissue necrosis	10.45%	4.35%	8.14%	8.51%
White Band Disease	0.26%	0%	0.13%	0%
Healed with secondary algal colonization	4.57%	1.55%	2.94%	0.77%
Recently dead	0.79%	2.64%	0.94%	0.52%
Macroalgae overgrowth	19.84%	5.285	9.82%	3.35%
Colony decreasing in size	56.54%	59.94%	51.81%	49.23%
Almost unblemished	22.04%	37.27%	16.15%	27.84%
Invertebrate overgrowth	28.97%	32.14%	23.9%	18.69%
Health (Unblemished + Almost Unblemished)	44.6%	52.18%	45.5%	53.74%

Vitareef Data for Coral Health on Sagharughombe Reef, Solomon Islands in September 2002

	Shallow (3-5m)	Shallow (3-5m)	Deep (7-9m)	Deep (7-9m)
Transect #	4	2	1	3
Unblemished	23.04%	17.84%	22.96%	17.32%
Damaged but healed	0.17%	0%	0.3%	0%
Edge damage	40.07%	43.27%	45.33%	50.55%
Tissue & Skeleton Damage	11.85%	15.2%	14.22%	22.15%
Excessive sedimentation on live tissue	16.86%	26.02%	13.78%	15.29%
Tissue Damage	11.85%	9.65%	5.93%	11.08%
Bleaching	**8.01%**	**5.26%**	**1.33%**	**8.42%**
Excessive Mucous	8.51%	7.6%	13.63%	9.67%
Black Band Disease	0%	0%	0%	0.16%
Filamentous algae overgrowth	6.01%	7.89%	5.78%	12.01%
Sedimentation with tissue necrosis	7.85%	8.77%	10.37%	2.5%
White Band Disease	0%	0%	0%	0%
Healed with secondary algal colonization	1.67%	0.58%	1.04%	0.94%
Recently dead	2.67%	0.29%	0.74%	0.62%
Macroalgae overgrowth	3.84%	7.89%	4%	4.37%
Colony decreasing in size	57.26%	64.62%	62.22%	64.9%
Almost unblemished	14.36%	14.91%	4.89%	18.25%
Invertebrate overgrowth	31.55%	29.24%	25.93%	22.78%
Health (Unblemished + Almost Unblemished)	37.4%	32.755	27.85%	35.57%

Vitareef Data for Coral Health on Sagharughombe Reef, Solomon Islands in January 2006

	Shallow (3-5m)	Shallow (3-5m)	Deep (7-9m)	Deep (7-9m)
Transect #	1	2	3	4
Unblemished	9.83%	7.26%	10.82%	16.85%
Damaged but healed	0.49%	0.78%	0.37%	0%
Edge damage	3.9%	4.8%	2.61%	4.12%
Tissue & Skeleton Damage	4.25%	4.58	2.24%	1.12%
Excessive sedimentation on live tissue	0.59%	0.22%	0%	0%
Tissue Damage	3.61%	2.46%	8.96%	1.87%
Bleaching	**11.86%**	**15.87%**	**6.72%**	**3.755%**
Excessive Mucous	1.38%	1.34%	0%	0%
Black Band Disease	0%	0%	0%	0%
Filamentous algae overgrowth	3.31%	3.02%	3.73%	8.24%
Sedimentation with tissue necrosis	0.4%	0.11%	0%	0%
White Band Disease	0.05%	0%	0%	0%
Healed with secondary algal colonization	28.71%	30.95%	47.01%	16.1%
Recently dead	1.88%	1.45%	2.24%	0.37%
Macroalgae overgrowth	1.58%	2.23%	2.61%	2.25%
Colony decreasing in size	16.4%	15.31%	19.78%	18.73%
Almost unblemished	14.13%	17.43%	11.57%	11.61%
Invertebrate overgrowth	21.59%	22.46%	29.48%	15.73%
Health (Unblemished + Almost Unblemished)	23.96%	24.69%	22.39%	28.46%

Appendix B

Fish Surveys at Four Transect Locations on Sagharughombe Reef, Solomon Islands in 2000, 2002 & 2006

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Angelfish	three spot	*Apolemichthys trimaculatus*					1							
Angelfish	bicolor	*Centropyge bicolor*	3		2	12	4		1				2	6
Angelfish	dusky	*Centropyge bispinosus*	3					3				2	4	
Angelfish	midnight	*Centropyge nox*							2					
Angelfish	pearlscale	*Centropyge vroliki*	5	2	3	4	3	3	2	3	4	2	7	5
Angelfish	blue girdled	*Pomacanthus navarchus*	2	4	2	1	1	1			2	2		1
Angelfish	six banded	*Pomacanthus sexstriatus*				1								
Angelfish	blue faced	*Pomacanthus xanthompetopon*	1	3	2									
Angelfish	regal	*Pygoplites diacanthus*	5	5	3	6	4	4	3	2	6	4		3
Anthia	threadfin	*Psudanthias huchtii*					40						60	
Anthia	lyretail	*Pseudanthias squamipinnis*					30							
Anthia	Purple	*Pseudanthias tuka*	200	80	60	80		250		30	8	50	250	10
Anthia	Peach	*Pseudanthias dispar*										30		
Anthia	unidentified	Unidentified sp				10								
Barracuda	yellowtail	*Sphyraena flavicauda*					50							
Batfish	orbicular	*Platax orbicularis*							1					
Bigeye	glasseye	*Heteropriacanthus cruentatus*									2			
Blanquillo	striped	*Malacanthus latovittatus*		2										

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Blenny	lined fangblenny	*Meiacanthus lineatus*					1							
Blenny	bluestriped fangblenny	*Plagiotremus rhinorhynchos*			1		2		1			1		
Blenny	blennies	Unidentified sp	5		10	10	5	3			1			
Blenny	fang blennies	Unidentified sp	3		2								3	
Butterflyfish	threadfin	*Chaetodon auriga*										2		1
Butterflyfish	eastern triangle	*Chaetodon baronessa*	4	3	3	7	2	2		2	5	3	3	2
Butterflyfish	Bennett's	*Chaetodon bennetti*	3	4			2	2		1				
Butterflyfish	pacific saddletail	*Chaetodon ephippium*	2	2				2	3		2		4	3
Butterflyfish	Klein's	*Chaetodon kleinii*			1	1	8	8						1
Butterflyfish	lined	*Chaetodon lineolatus*							2					
Butterflyfish	raccoon	*Chaetodon lunula*										3		
Butterflyfish	spot tail	*Chaetodon ocellicaudus*					1							
Butterflyfish	eight banded	*Chaetodon octofasciatus*					3							
Butterflyfish	ornate	*Chaetodon ornatissimus*				3								1
Butterflyfish	dot and dash	*Chaetodon pelewensis*					2							2
Butterflyfish	latticed	*Chaetodon rafflesi*			3				4	4	2		5	3
Butterflyfish	ovalspot	*Chaetodon speculum*										1		
Butterflyfish	redfin	*Chaetodon trifasciatus*	5	7	10	4	4		7	7	2	3	8	3
Butterflyfish	pacific double saddled	*Chaetodon ulietensis*	2	2		5			2			2	2	1
Butterflyfish	vagabond	*Chaetodon vagabundus*	1	4	4	2	3	3		2	1		1	4
Butterflyfish	forcepfish	*Forcipiger flavissimus*							1		5	2		4
Butterflyfish	longnosed	*Forcipiger longirostris*	7	5	2	1	1							2
Butterflyfish	pyramid	*Hemitaurichthys polylepis*							3					
Butterflyfish	longfin bannerfish	*Heniochus acuminatus*										3		
Butterflyfish	pennant bannerfish	*Heniochus chrysostomus*		2		2		2	2	3	2	1	1	

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Butterflyfish	masked bannerfish	*Heniochus monoceros*					1							
Butterflyfish	singular bannerfish	*Heniochus singularis*		4			3							4
Butterflyfish	humphead bannerfish	*Heniochus varius*	4	5	3	6	2	2		2	4	6		1
Cardinalfish	three saddled	*Apogon bandanensis*								3				
Cardinalfish	split banded	*Apogon compressas*								20	60			
Cardinalfish	ochre striped	*Apogon compressus*	10		20									
Cardinalfish	yellow striped	*Apogon cyanosoma*				12								
Cardinalfish	narrowstrip	*Apogon exostigma*								4				
Cardinalfish	gray	*Apogon fuscus*	10											
Cardinalfish	girdled	*Archamia zosterophora*								7				
Cardinalfish	five lined	*Cheilodipterus quinquelineatus*	10						12	10				
Cardinalfish	unidentified	Unidentified sp									37			
Cornetfish	cornetfish	*Fistularia commersonii*					1		1					
Damselfish	spiny chromis	*Acanthochromis polyacanthus*					50	30	50	50	30	100	100	150
Damselfish	golden damsel	*Amblyglyphidodon aureus*	200	10	50	30	50	50	10	100				
Damselfish	staghorn	*Amblyglyphidodon curacao*	10					2			10		20	
Damselfish	white belly	*Amblyglyphidodon leucogaster*	30	100	150	30	40	20	30	20	20	5	60	20
Damselfish	dusky anemonefish	*Amphiprion melanopus*									2			
Damselfish	Clark's anemonefish	*Amphiprion clarkii*							2	5				4
Damselfish	clown anemonefish	*Amphiprion percula*					3							
Damselfish	anemone fish	*Amphiprion spp.*	10	2	10	2							3	
Damselfish	midget chromis	*Chromis acares*									2			
Damselfish	ambon chromis	*Chromis amboinensis*	200	200	250			200	200	200	50	6	250	60

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Damselfish	black axel chromis	*Chromis atripectoralis*									2			
Damselfish	darkfin chromis	*Chromis atripes*					30			30		20	35	15
Damselfish	scaly chromis	*Chromis lepidolepis*										4	80	1
Damselfish	black bar chromis	*Chromis retrofasciata*	100	40	100	50	30	30	100	20	7		7	10
Damselfish	Ternate chromis	*Chromis ternatensis*										250		
Damselfish	Vanderbilt's chromis	*Chromis vanderbilti*										20		
Damselfish	blue green chromis	*Chromis viridis*									15		15	
Damselfish	Weber's	*Chromis weberi*												9
Damselfish	black chromis	*Chromis xanthura*	50	5	4	20					8	1	4	
Damselfish	bicolor chromis	*Chromis margaritifer*										40	6	
Damselfish	Rolland's demoiselle	*Chrysiptera rollandi*							15	5	2			
Damselfish	Talbot's demoiselle	*Chrysiptera talboti*									3		2	
Damselfish	humbug dascyllus	*Chrysiptera spp.*	5					20	30	40				
Damselfish	black tailed dascyllus	*Dascyllus melanurus*								10				
Damselfish	reticulated dascyllus	*Dascyllus reticulatus*	50		40	40	100	50	50	40	1	20	70	30
Damselfish	threespot dascyllus	*Dascyllus trimaculatus*					100	20	5					
Damselfish	white damsel	*Dischistodus perspicillatus*						4						
Damselfish	black vent	*Dischistodus melanotus*	10					2			3			
Damselfish	black damsel	*Neoglyphidodon melas*							20					
Damselfish	yellow fin damsel	*Neoglyphidodon nigroris*	20	20	3			2	5	5	7	6	50	4
Damselfish	Johnston's damsel	*Plectroglyphidodon johnstonianus*											3	
Damselfish	jewel damsel	*Plectroglyphidodon lacrymatus*											8	
Damselfish	ambon damsel	*Pomacentrus aboinensis*				50								2
Damselfish	lemon damsel	*Pomacentrus moluccensis*									40	30		15
Damselfish	charcoal damsel	*Pomacentrus brachialis*										60		50
Damselfish	scaly damsel	*Pomacentrus lepidogenys*										2		

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Damselfish	black axil damsel	*Pomacentrus nigromanus*		50	50	30			100				18	5
Damselfish	other chromis species	Unidentified sp		30	150	250								
Damselfish	other damsel species	Unidentified sp	250	10	250	50	200	200	50	50			200	
Dartfish	blackfin	*Ptereleotris evidens*										3		
Emperor	longfin	*Letfirinus erythropterus*		1	2									
Emperor	long face	*Lethrinus olivaceus*				1						1		
Emperor	orange striped	*Lethrinus obsoletus*				1								
Emperor	bigeye	*Monotaxis grandoculis*	1	1	10	3	1	2	3	2	4	7	9	4
Emperor	unidentified	Unidentified sp					1							
Filefish	broom	*Amanses scopas*			1									
Fusilier	scissor tailed	*Caesio caerulaurea*										100		50
Fusilier	deep bodied	*Caesio cuning*		4	5	5			15		10	200		15
Fusilier	lunar fusilier	*Caesio lunaris*					40	15			30	150		140
Fusilier	yellowback	*Caesio teres*									250	100	13	
Fusilier	yellow lined fusilier	*Caesio varilineata*					150	40	20	20				
Fusilier	yellow tail falser fusilier	*Paracaesio xanthura*					70							
Fusilier	ruddy	*Pterocaesio pisang*		30		40	1050				200	1000	1500	500
Fusilier	tessellated	*Pterocaesio tessellata*										100		1000
Fusilier	bluestreak	*Pterocaesio tile*		100	50	20	150	30	30		500	500		100
Fusilier	three striped	*Pterocaesio trilineata*		50	30									
Fusilier	undentified	Unidentified sp									50			

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Goatfish	yellowstripe	*Mulloidochtys flavolineatus*										2		
Goatfish	dash and dot	*Parupeneus barberinus*	3			4			1	1		9		
Goatfish	two barred	*Parupeneus bifasciatus*			1					2	3	2	1	4
Goatfish	yellowsaddle	*Parupeneus cyclostomus*		1	1	1		2	3			1	1	
Goatfish	multibarred	*Parupeneus multifasciatus*	1	2			4	2	4		1	1	2	1
Goatfish	sidespot	*Parupeneus pleurostigma*				2								
Goby	old glory goby	*Amblygobius rainfordi*							2	5				
Goby	goby	Unidentified sp			5			10	10	10			2	
Grouper	white lined rockcod	*Anyperodon leucogrammicus*											1	
Grouper	peacock	*Cephalopholis argus*	2	1	1									
Grouper	blue spotted rockcod	*Cephalopholis cyanostigma*			1	1	5	2	4	5				3
Grouper	leopard rockcod	*Cephalopholis leopardus*				1	3	2	1	1				
Grouper	coral cod	*Cephalopholis miniata*				4	15	2	1	1				
Grouper	starry	*Cephalopholis sp.*	1	1									2	
Grouper	flagtail grouper	*Cephalopholis urodeta*					4	2	1			3	1	
Grouper	whitespotted	*Epinephelus caeruleopunctatus*												1
Grouper	black tipped rockcod	*Epinephelus fasciatus*					3	1						
Grouper	blacksaddle grouper	*Epinephelus howlandi*				1								
Grouper	dwarf spotted rockcod	*Epinephelus merra*						1		1				
Grouper	coronation trout	*Variola louti*							2	1				
Hawkfish	two spotted	*Amblycirrhitus bimacula*			1									
Hawkfish	dwarf	*Cirrhitichthys falco*					1	1						
Hawkfish	longnose	*Oxycirrhites typus*					1							

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Hawkfish	arc-eye	*Paracirrhites arcatus*	3											
Hawkfish	freckled	*Paracirrhites forsteri*				3				2		3		
Hawkfish	halfspotted	*Paracirrhites hemistictus*					1	1						
Jack	orangespotted trevally	*Carangoides bajad*										2		14
Jack	whitefin trevally	*Carangoides equula*					20							
Jack	blue trevally	*Carangoides ferdau*							25				3	
Jack	yellow spotted trevelly	*Carangoides fulvoguttatus*					40							
Jack	bluefin trevally	*Caranx melampygus*					10	2					3	3
Jack	rainbow runner	*Elagatis bipinnulata*									1	200		
Jack	jack spp.	Unidentified sp	1		1						2	1		
Leatherjacket	scrawled leatherjacket	*Aluterus scriptus*											2	
Lizardfish	lizardfish sp	Unidentified sp								1				1
Mackerel	mackerel tuna	*Euthynnus affinis*					7							5
Mackerel	dogtooth	*Gymnosarda unicolors*					2		2					
Moorish Idol	Moorish idol	*Zanclus cornutus*	10	9	5	4	5	3	5	2	7	6	2	10
Moray Eel	giant moray	*Gymnothorax javanicus*												1
Parrotfish	bumphead parrot	*Bolbometopon muricatum*			1		1					1		
Parrotfish	bicolor	*Cetoscarus bicolor*	1									1		4
Parrotfish	Bleeker's	*Chlorurus bleekeri*										5		3

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Parrotfish	pacific longnose	*Hippopscarus longiceps*										3		
Parrotfish	turquoise-capped	*Scarus dimidiatus*										9	7	
Parrotfish	yellowfin	*Scarus flavipectoralis*									1	3	4	
Parrotfish	bullet head	*Scarus sordidus*											3	
Parrotfish	unidentified	Unidentified sp	30	40	20	40	50	30	30	30	2	2	2	20
Rabbitfish	golden rabbit	*Siganus guttatus*												1
Rabbitfish	lined	*Siganus lineatus*	6											
Rabbitfish	masked	*Siganus puellus*	1			2	2	2	2				2	
Rabbitfish	peppered	*Siganus punctatissimus*		6	3									
Rabbitfish	foxface	*Siganus vulpinus*	5	7	5	2	2		2		1	2	5	6
Ray	bluespotted ribbontail	*Dasyatis kuhlii*										2		
Ray	spotted eagle ray	*Aetobatus narinari*												1
Rudderfish	highfin rudderfish	*Kyphosus cinerascens*					25							
Sandperch	latticed	*Parapercis clathrata*								1				
Shark	black tip reef shark	*Carcharhinus melanopterus*	1											
Shark	white tip reef shark	*Triaenodon obesus*										1		
Snapper	small tooth jobfish	*Aphareus furca*	1		1	1	1	1	1	1		2	1	3
Snapper	green jobfish	*Aprion virescens*												1
Snapper	two spot	*Lutjanus biguttatus*	2	2	1							1	6	
Snapper	red bass	*Lutjanus bohar*					30		2			2	1	12

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Snapper	flametail	*Lutjanus fulvus*		2				1				12		
Snapper	paddletail	*Lutjanus gibbus*				9						16		9
Snapper	bluelined	*Lutjanus kasmira*		2								40		
Snapper	one spot	*Lutjanus monostigma*	1			1	1					6		
Snapper	black banded seaperch	*Lutjanus semicinctus*	1	1	1	2				1			1	3
Snapper	black and white	*Malcolor macularis*		7			15						7	10
Snapper	black snapper	*Malcolor niger*	1		1	1	30	2	1			2		21
Snapper	unidentified	Unidentified sp										3		
Spinecheek	two line spinecheek	*Scolopsis bilineatus*	3	3	2	4			7	5				1
Spinecheek	pearly monocle bream	*Scolopsis margaritifer*							3	2	1			
Squirrel & Soldierfish	shadowfin soldierfish	*Myripristis adjusta*							1					
Squirrel & Soldierfish	epaulette soldierfish	*Myripristis kuntee*							3					
Squirrel & Soldierfish	tailspot squirrelfish	*Sargocentron caudimaculatum*					2							
Squirrel & Soldierfish	crown squirrelfish	*Sargocentron diadema*							1					
Squirrel & Soldierfish	squirrel/solder spp.	Unidentified sp	10	10	5	30	5	3			1	6	11	1
Surgeonfish	ringtail	*Acanthurus blochii*				7								
Surgeonfish	black	*Acanthurus gahhm*		3										
Surgeonfish	mimic	*Acanthurus pyroferus*	5	10	10	20	30	5	20	20	8	11	9	4
Surgeonfish	Thomson's	*Acanthurus thompsoni*				12	50							
Surgeonfish	twospot bristletooth	*Ctenochaetus binotatus*					2	2		5		2	4	10
Surgeonfish	lined bristletooth	*Ctenochaetus striatus*						7		2				
Surgeonfish	Tomini	*Ctenochaetus tominiensis*	3											
Surgeonfish	whitemargin unicornfish	*Naso annulatus*					20							

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Surgeonfish	blacktongue unicornfish	*Naso hexacanthus*					5							2
Surgeonfish	orangespine unicornfish	*Naso lituratus*	1			2	5	2						
Surgeonfish	bignose unicorn	*Naso unicornis*												8
Surgeonfish	Vlaming's	*Naso vlamingi*					30						1	
Surgeonfish	brushtail tang	*Zebrasoma scopas*	15	10	12	10	10	7	1	1	4	8	8	4
Surgeonfish	sailfin tang	*Zebrasoma veliferum*		3		5	2	1					2	
Surgeonfish	unidentified	Unidentified sp										13		4
Sweetlip	giant sweetlip	*Plectorhinchus albovittatus*					1							
Sweetlip	harlequin	*Plectorhinchus chaetodonoides*		1										
Sweetlip	Lesson's	*Plectorhinchus lessonii*		1									3	
Sweetlip	oriental	*Plectorhinchus vittatus*		1		1								
Triggerfish	clown	*Balistoides conspicillum*	1	1					1					
Triggerfish	orange striped	*Balistapus undulatus*	1	4	7	2	10	10	12	5	1	5	8	4
Triggerfish	titan	*Balistoides viridescens*	1	1		1	1	1				1	2	1
Triggerfish	oceanic triggerfish	*Canthidermis sufflamen*					20							
Triggerfish	pink tail	*Melichthys vidua*	1	1	2	5	20		7		2	3	5	2
Triggerfish	redtooth	*Odonus niger*				15	50					40		
Triggerfish	yellowmargin	*Pseudobalistes flavimarginatus*										2	4	1
Triggerfish	scythe	*Sufflamen bursa*					2	2	2					
Triggerfish	half moon	*Sufflamen chrysopterus*				2								
Trumpetfish	trumpetfish	*Aulostomus chinensis*	2	4	2	2	1	1	1		5	2	4	
Trunk/puffer	puffer	*Arothron spp.*	2	1		2								

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Trunk/puffer	blackspotted	*Arothron nigropuctatus*							1		1	2		
Trunk/puffer	spotted toby	*Canthigaster solandri*												1
Trunk/puffer	striped boxfish	*Ostracion solorensis*	1											
Wrasse	spotted	*Anampses meleagrides*											1	
Wrasse	Diana's hogfish	*Bodianus diana*					4							8
Wrasse	mesothorax	*Bodianus mesothorax*		2	2	3			1			1	4	1
Wrasse	floral maori	*Cheilinus chlorourus*											1	
Wrasse	redbreasted	*Cheilinus fasciatus*	3	3	2	10			2	2	3	4	7	1
Wrasse	maori	*Cheilinus spp.*		3	7						2			
Wrasse	tripletail	*Cheilinus trilobatus*					3							
Wrasse	Napoleon wrasse	*Cheilinus undulatus*					2	1	1	1			3	1
Wrasse	slingjaw	*Epibulus insidiator*	1				2	2	4	6		2		
Wrasse	bird	*Gomphosus spp.*	1					1	1					
Wrasse	bird	*Gomphosus varius*					1					1		
Wrasse	checkerboard	*Halichoeres hortulanus*	2			2	1	1	1		2		12	
Wrasse	dusky wrasse	*Halichoeres marginatus*											2	
Wrasse	tailspot	*Halichoeres melanurus*	15		2	4		3		3	4		4	
Wrasse	two tone	*Halichoeres prosopeion*		5	6	7	4	4	3				1	3
Wrasse	zigzag	*Halichoeres scapularis*						1						
Wrasse	barred thicklip	*Hemigymnus fasciatus*					2		3					3
Wrasse	black eye thicklip	*Hemigymnus melapterus*	1						2		3	1	3	
Wrasse	tubelip	*Labrichthys unlineatus*					1	1	1	1			1	
Wrasse	striped cleaner	*Labroides dimidiatus*									2	6		2
Wrasse	bicolor cleaner	*Labroides bicolor*				1			1			1		1
Wrasse	cleaner	*Labroides spp.*	15	5	8	20	10	12	3	10	5			

			2000				2002				2006			
Family	**Common Name**	**Latin Name**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 1**	**Site 2**	**Site 3**	**Site 4**
Wrasse	blackspotted	*Macropharyngodon meleagris*					1		1	1				
Wrasse	dragon wrasse	*Novaculichthys taeniourus*										3		
Wrasse	Arenatus' wrasse	*Oxycheilinus arenatus*							1					
Wrasse	cheeklined maori	*Oxycheilinus digrammus*											1	
Wrasse	six stripe	*Pseudocheiliniu s hexataenia*								2	1		11	
Wrasse	chiseltooth	*Pseudodax moluccanus*										2		4
Wrasse	eightstripe	*Pseudochelinius octotaenia*									1			
Wrasse	blue lined	*Stethojulis bandanensis*											1	
Wrasse	slender	*Suezichthys gracilis*						17						
Wrasse	bluntheaded	*Thalassoma amblycephalum*							5	2		1		
Wrasse	six-bar	*Thalassoma hardwicke*	3					3	1	2	3	3	7	
Wrasse	crescent	*Thalassoma lunare*		1			2		3		2	1		
Wrasse	sunset	*Thalassoma lutescens*									1			
Wrasse	yellowtail coris	*Coris gaimard*	1			1								
Wrasse	other wrasse species	Unidentified sp	20	3	10	5						21	30	12

Appendix C

Shannon-Weiner Index (H')

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

p_i: The relative abundance of each species, calculated as the proportion of individuals of a given species to the total number of individuals in the community: $\frac{n_i}{N}$

n_i: The number of individuals in each species; the abundance of each species.

N: The total number of all individuals: $\sum_{i=1}^{S} n_i$

S: The number of species. Also called species richness.

Adapted from Charles Krebs. 1989. Ecological Methodology. HarperCollins, New York.

Simpson's Index (D)

$$D = \sum_{i=1}^{S} p_i^2$$

p_i: The relative abundance of each species, calculated as the proportion of individuals of a given species to the total number of individuals in the community: $\frac{n_i}{N}$

n_i: The number of individuals in each species; the abundance of each species.

N: The total number of all individuals: $\sum_{i=1}^{S} n_i$

Index of Diversity (D')

D'=1/D (D' can also be defined as 1-D)

* Simpson's Index has an inverse relationship with biodiversity. To make the information easily understood in the graphs, this study uses the Index of Diversity (D'=1/D).

Adapted from E.H. Simpson. 1949. Measurement of diversity. *Nature* 163:688.

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