PERGAMON

Marine Pollution Bulletin 44 (2002) 1281–1293

MARINE POLLUTION BULLETIN

www.elsevier.com/locate/marpolbul

Coral reef health and effects of socio-economic factors in Fiji and Cook Islands

Tegan Churcher Hoffmann *

The Coral Reef Alliance (CORAL), 417 Montgomery Street, Suite 205, San Francisco, CA 94105, USA

Abstract

This research focuses on coral reef health in the South Pacific region, an area of high global coral diversity. Coral reef health surrounding four island case studies in the Cook Islands and Fiji have been assessed in areas that have not been previously surveyed. This study compares four islands with barrier and fringing reefs that have different levels of economic development, population pressure, land-use practices, and marine management practices. This interdisciplinary research methodology includes both ecological and social data collection to further understanding of human environment interactions. In comparing the reefs with different socio-economic factors, this research shows that reefs with traditional systems of resources management are healthier, population pressure is not the main factor causing the demise of the reefs and agro-industry is the main industry causing the degradation of the reef in these four South Pacific Islands. In addition, researchers need to use a whole reef perspective to examine coral reef health.

Keywords: Biodiversity; Coral reef; Community-based conservation; Marine resource management; Ecosystem health

1. Introduction

This research focuses on the South Pacific region, an area of high global coral diversity. This study evaluates reef health surrounding two islands in the Cook Islands, Aitutaki and Rarotonga, and two in Fiji, Ovalau and Vatulele. In these four island study sites this research examines their inter-island and intra-island linkages, examining the socio-economic variables that may be correlated with differences and variability of coral reef health at a point in time, 1999. This approach analyzes the environmental history and transformation of social institutions as well as biodiversity at multiple time and spatial scales, including the local, [1] regional, and global levels. Each island has distinct differences based not only on reef type, environment, and ecology, but also upon different marine social institutions; my study compares four islands with barrier and fringing reefs that have different levels of economic development, population pressure, land-use practices, and marine management practices.

Based upon these case studies I argue that contrary to many scientific claims, coral reef environmental change is connected with human geographic factors, such as changes in social institutions such as marine property regimes. Natural processes such as hurricanes and sea surface temperature changes are important factors in coral reef change, but, in the area of study, my research demonstrates that the economic development of the reef and reef resources, as well as the transformation of certain marine property institutions, have contributed to the decline of coral reef health. As marine resources become more developed, the externalities associated with commercial development of each business sector developing the marine resources also increase, potentially increasing degradation of the reef environment. Furthermore, the change from private or communal property systems to one of open access may also lead to deterioration of the reef through the further exploitation of reef resources. There are no easy solutions to developing coastal environments without harming the delicate marine ecosystems.

* Tel.: +1-510-848-0110x302.
E-mail address: thoffmann@coral.org (T.C. Hoffmann).

[1] Local means living and working in the village community and includes fisher people, government officials, resource managers as well as business owners.

PII: S0025-326X(02)00260-6

This study compares sites and considers significant differences of coral diversity, percent coral coverage, as well as the abundance of certain biotic factors and the clonal condition of the coral. By collecting secondary sources on the coral reef and interview data from the local people and regional experts working on these islands, this study is intended to give insight into reef health and changes to the fishery productivity on the reef. This research will point out to marine and reef scientists that the complexity of the reef requires a comprehensive type of approach if the scientific community is to understand the death, degradation, and growth of the coral reef.

Through the examination of four island case studies my study has six key findings: (1) In the cases of Ovalau and Rarotonga where there are combined types of marine tenure regimes on the island, non-point and point source pollutants upcurrent still affect traditional areas downcurrent; (2) agro-industry externalities have the greatest effect upon the mortality index (MI) and hard coral species diversity; (3) biotic factors affecting corals, such as disease and predators, occur naturally in a coral reef system; (4) large-scale studies of changes in reefs and causes of degradation are difficult to carry-out. Variability in data and the uniqueness of each reef make large-scale studies inaccurate; (5) human population is not the main factor causing declines in reef health in these four island case studies. And, (6) reefs with traditional systems of marine management, such as in the case of Rarotonga, help control harvesting of marine resources.

2. Methods

2.1. Study sites

Island study sites were selected in two different South Pacific countries, Fiji and the Cook Islands, and were selected based upon their different human and physical geography, levels of economic development, and histories of marine tenure (see Fig. 1).

Furthermore islands were selected with two types of coral reefs—fringing and barrier reefs. Different islands and sites around the islands have various levels of wave energy intensity and different physical events that have affected the reefs, such as sea surface temperature (SST) anomalies. All islands have had storms and hurricanes that have physically damaged the reef, as well as SST changes. Events may vary between islands; as well as between island study sites.

The four islands chosen as study sites each have unique political and economic histories that have shaped the marine property regimes that are presently in place. The more developed the island and reef resources, and the earlier they became developed by colonizers, the more likely colonizers claimed rights to the waters and traditional fishing grounds and customary marine tenure systems were not acknowledged (Grove, 1995; Nietschmann, 1997). The type of property institutions governing the reef in turn affects how people and industry choose to use and access the marine resources and waters of the island. Thus, this relates to the intensity of

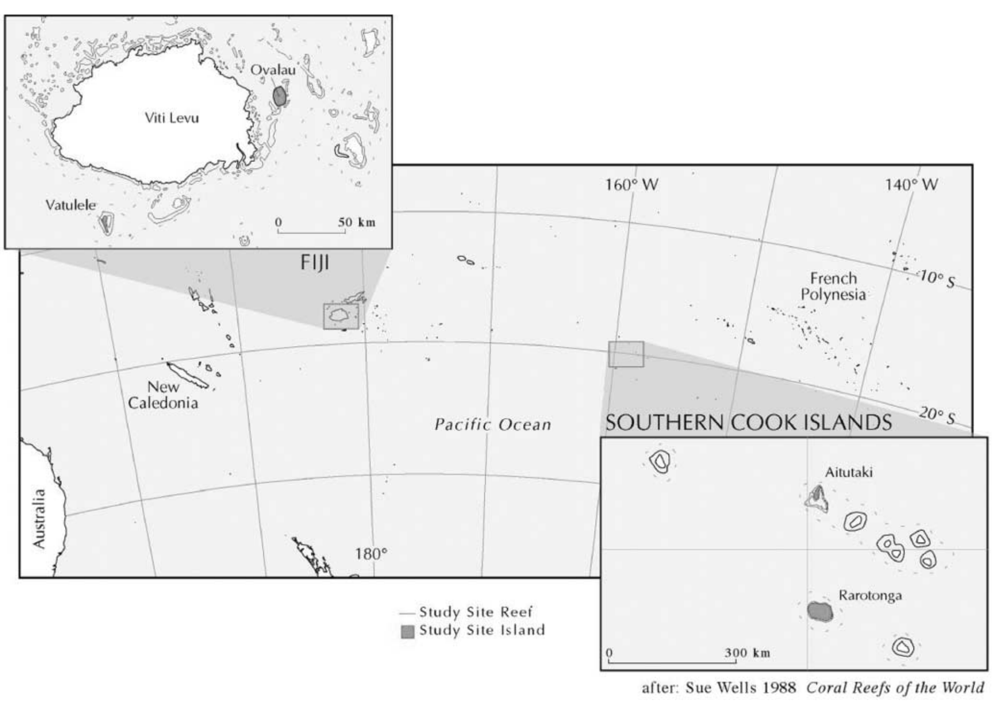

Fig. 1. The Cook Island and Fiji study sites in the South Pacific.

Table 1
Island study site characterization

Island	Island land area (km^2)	Present population	Average geometric population growth rate 1966–1996 (%)	Level of tourism development	Marine property laws	Level of harvesting marine resources	Level of agro/industrialization	Ave. of externalities totals per island[a]
Aitutaki, Cook Islands	16.8	2389	−0.3	Mid-size	Common property resource	Subsistence, mariculture industry and commercial harvesting	Commercial agriculture heavy industry	15.2
Rarotonga, Cook Islands	67	11,225	0.4	Mass tourism	Common property resource	Subsistence, mariculture industry and commercial harvesting	Commercial agriculture	12.3
Ovalau, Fiji	103	8647	0.8	Small-scale	Common property resource and customary marine tenure	Subsistence and commercial harvesting	Heavy industry and commercial agriculture	14
Vatulele, Fiji	31.6	914	2.3	Small-scale	Customary marine tenure	Subsidence and small-scale commercial fishing	No agro/industry	3.5

Turva (1988), Bureau of Statistics (1996) and Cook Islands Statistics Office (1999).
[a] See Table 4 for more detail on the externalities and the Appendix A for an explanation of how externalities were determined.

exploitation and degradation of the marine environment as result of the externalities associated with the economic development of the reef (Hardin, 1968).

As given in Table 1, all four islands have different levels of intensity for the forms of economic development of the reef and types of marine property systems in place. Aitutaki has a mid-sized tourism industry, mariculture and commercial harvesting of marine resources, but declining agro-industry. In addition, it has a property system of common access that is owned by the government. Tour operators compete to access the waters and fishers compete to harvest the fish. In comparison, Rarotonga has a larger tourism industry and an extremely small commercial fishery; commercial agriculture has declined over the years, but is still a large part of the income on the island. Like Aitutaki, the marine areas are recognized as Crown Land. In the common access areas surrounding Rarotonga there is competition between tour operators, as well as fishers to access waters and resources. Although, Rarotonga has the same laws as Aitutaki, [2] it has recently created traditional restricted fishing areas called Ra'ui. [3] Ovalau has small-scale tourism, a heavy agro-industry, and commercial fisheries. The island has two property systems in place. The Port Authority governs the reef from Nalulu to Toki entrance. This is a common property regime. The remainder island communities have customary tenure of the reefs. They sell access rights to fishers and dive operators. The two different systems may be due to the fact that at the time Fiji was recognizing and documenting traditional fishing grounds, Levuka town did not make any traditional claims to the reef since the town was settled by immigrants and booming with trade and industry in the 1800s. Vatulele has a small-scale commercial fishery, no commercial agriculture, and small-scale tourism. The communities have customary tenure of the reefs and sell access to dive operators, and a hotel.

The creation of these marine resource markets and market development on the islands changed the communities' relationships with the sea. Furthermore, the growth of these markets changed environmental conditions. Aitutaki has the largest number of externalities, 15.2, due to the fact that is has had heavy agro-industry, and presently has mariculture and a big commercial fishery as well as mid-size tourism industry. [4] In comparison, Rarotonga has marine resource market development and thus fewer externalities, 12.3. Ovalau also has a high level of externalities, 14, that are a result of heavy agro-industry and a commercial fishery. Amongst all four islands, Vatulele has the lowest level of marine market development and the fewest externalities, 3.5.

2.2. Methodology

Three methods were used: interviews with local people who live and work in coastal communities, the work

[2] Aitutaki has recently implemented the Ra'ui system.
[3] See Chapter 5 of Hoffmann's Dissertation.

[4] See Table 7 for a description of externalities and the scale of intensity. For a complete explanation see Chapter 3 of Hoffmann's Dissertation.

of other researchers, and fieldwork to determine coral reef health as well as document baseline data on basic ecology of the reef. All ecological data were collected between September 1999 and December 1999. September and October were spent on the islands of Ovalau and Vatulele in Fiji, and November and December were spent in Rarotonga and Aitutaki, Cook Islands. Additional interview data was collected in June 2001 in Suva, Fiji and Rarotonga, Cook Islands.

2.2.1. Field surveys

By comparing islands, this study ranks and isolates variables, such as areas with commercial fishing pressure, the effect of rivers and their sediment inputs, and the role of different marine property institutions. Several methods were used to monitor the biology and reef health indicators of each site. Islands are characterized and described, specifically documenting information on the recent past and present variables: population, size, isolation, reef zones, species diversity, natural stresses, land-use practices, marine exploitation, human disturbances, precipitation, SST, fishing practices, bleaching events, current patterns, and Crown-of-Thorns Starfish outbreaks. These data were collected from a wide range of sources. The islands were surveyed in a range of apparent sub-environments. All quantitative ecological data were collected in the back reef of either a fringing or barrier reef using a 25 m contiguous transect tape.

Once sites on the island were chosen, a global positioning system (GPS) was used for location of the sites. Three readings were recorded on a survey boat after the GPS was operating for twenty minutes and an average was taken to determine positions. After the GPS data were recorded, a random number was picked to select the placement of the first transect. This number represented the distance northward from the boat to the beginning of transect #1 in meters. The second and third transects was then placed at 100 m intervals. Data collection for ecological comparison of sites and islands used a wide range of techniques and methods (Porter and Meier, 1992; Santavy and Peters, 1997; Edinger et al., 1998).

2.2.2. Quantitative field data collection

By carrying out ecological assessments around each island this research resulted in observations and acquired baseline data on coral reef health, contributing to a proxy of reef health.

(1) *Field analysis of transects*: 25 m × 1 m transects with three replicates were done to determine the reef health. Within each contiguous quadrat the following factors were determined:

- Percent live and dead cover of hard corals and soft corals.
- Number of hard coral and soft species.
- The number of corals affected by predators, parasites and pathogens [5] was counted by examining potential biotic factors. Examples of these factors are coral diseases, such as black band disease, parasitic organisms such as *Plagioporus* spp., or bleaching. In addition a coralline algae disease, coralline lethal orange disease (CLOD), was documented.
- The genus of coral affected by the biotic factors when known.
- Clonal condition of the coral polyps was documented. This qualitatively documents the appearance of the coral tissues. Comments were documented describing the coloration of the tissue and the appearance of mucus.
- Presence and absence of coral disease and bioindicators such as filamentous algae and Cyanophyta (Naranjo et al., 1996).

Data were collected on indicator species, coral affected by parasites and disease, and clonal conditionusing methods recommended by Santavy and Peters (1997). Diseases were counted in each quadrat. Naturally occurring pathology usually occurs at 0.5–1%, with a dominant disease constituting 20% infestation on the reef (Bruckner et al., 1997; Hunter, personal communication, 1998).

(2) *Water quality data collection:* Temperature and Secchi disk readings were done once at each site. Three samples were taken at each site for determination of basic water parameters: nitrate, nitrite, salinity, and Ph. A LeMotte Salt Water Test Kit was used. [6]

(3) *Social science research methods:* The social science research methods were comprised of interviewing people and collecting secondary sources. Census data appeared accurate and up-to-date. Cook Island and Fiji interviewees were selected who were well-informed about their community and the recent history of the marine environment. Oral histories were elicited to document their perceptions on changes on the islands to contribute to a longitudinal understanding of the impacts of development. They were asked open-ended questions on coral reef health, changes on the reef in their lifetime, fishing practices, coastal development, and history of the marine property institutions. Informants included government officials, community leaders, dive and tour operators, researchers, and representatives from a non-governmental organization.

2.2.3. Statistical analysis

Analyses of data include a variety of statistical tools. Mortality indices (MI) are calculated for each site of coral cover (Gomez, 1994)

[5] Identification of predators, parasites and pathogens is based upon my knowledge and identification keys.

[6] No significant statistical differences were found in water quality data. Furthermore, equipment was not sensitive enough to find differences, if any, in the water quality.

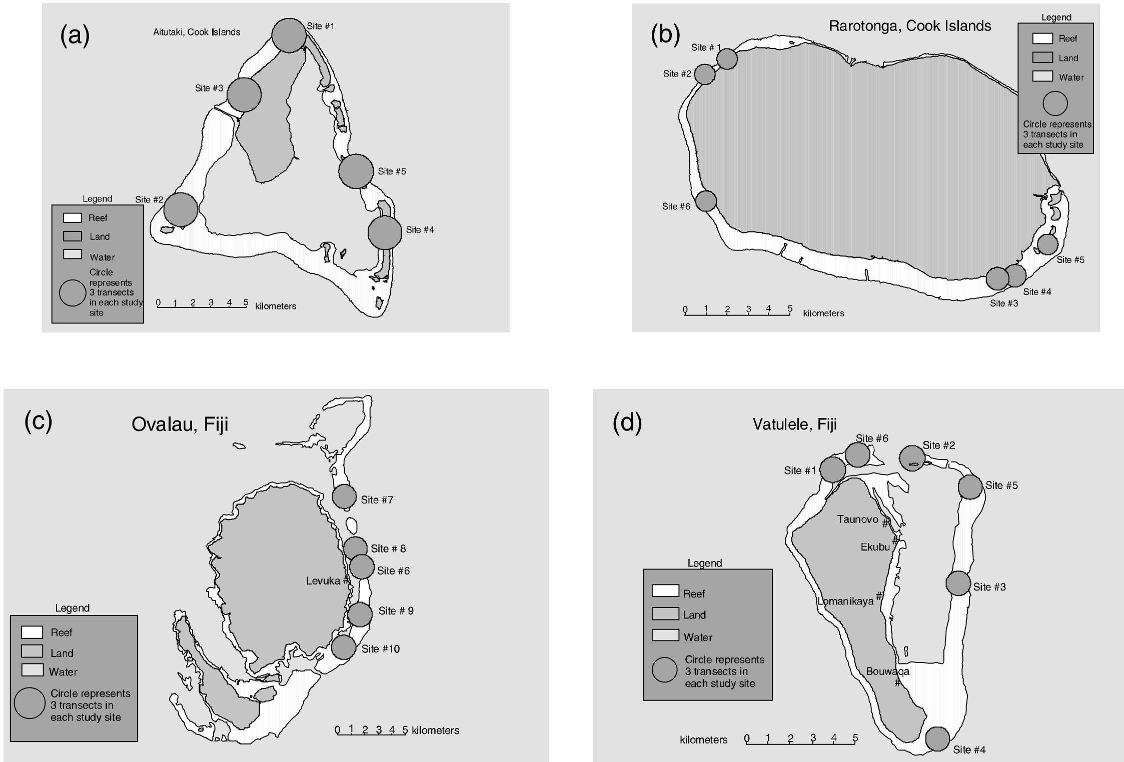

Fig. 2. (a) Aitutaki study sites, Cook Islands, (b) Rarotonga study sites, Cook Islands, (c) Ovalau study sites, Fiji and (d) Vatulele study sites, Fiji.

$$\mathrm{MI} = \frac{\text{dead coral coverage}}{\text{live coral coverage} + \text{dead coral coverage}}$$

Non-parametric methods are used to correlate coral reef health and geographic variables and to compare study sites. Spearman Rho correlation coefficient cross correlates the components of variability and identify key human geographic mechanisms of coral reef health, and the Wilcoxon test is used to distinguish significant differences between the island study sites. Histograms and graphs help identify trends and patterns in MI and disease, parasite infestations, and bioindicator prevalence.

3. Results

As previously described, each site was composed of three, 25 m transect lines with counts done every meter for a total of 75 quadrats for each site [7] (see Fig. 2(a)–(d)). Island and site means are described in Table 2. Sites in Rarotonga and Ovalau have the highest MI values. Sites in Vatulele and Rarotonga have the highest hard coral species diversity and the largest number of corals affected by biotic factors including parasites and diseases, predators such as the Crown-of-Thorn Starfish (COTS), and the parasites *Plagioporus* spp. Furthermore, soft corals were predominant in Ovalau and Vatulele. The reefs in Ovalau have less soft coral diversity and site 9 and 10 had extremely high soft coral percent coverage. The coral clonal condition, bleaching, tissues loss and discoloration, and mucus production, had the greatest number of corals with tissue discoloration and mucus in Ovalau and Vatulele. It is relevant to point out that Ovalau has significantly higher MI values than Vatulele. The presence of filamentous algae was higher in Rarotonga and Vatulele and Cyanophyta was high in Aitutaki.

Data on the number of corals affected by biotic factors includes information on four variables: bleaching or an entire coral colony, the presence of COTS on the transect, the parasitic trematode *Plagioporus* spp., and CLOD, which affects coralline algae (see Table 3).

Data in the Table 4 below summarizes geographic categories. The following correlative analysis will compare and link relationships with ecological data displayed in Table 5 on island means and the geographic factors below.

[7] Data by quadrat can be seen in my dissertation (Hoffmann, 2001). In this dissertation data for each island study site is presented in graphs. The graphs on percent coral coverage quantify the percent coverage of hard and soft coral for each quadrat. Both hard and soft coral species diversity per quadrat is displayed. In addition, the presence the bioindicators filamentous algae and Cyanophyta are shown as well as the number of coral impacts. The number of coral impacts is composed of quantification of the clonal condition and the number of affected coral and coralline algae by a biotic factor.

Table 2
Means of ecological data for study sites on all islands

	MI	Hard coral species diversity	Number of corals affected by biotic factors	Percentage soft coral coverage	Soft coral species diversity	Coral clonal condition	Presence of filamentous algae	Presence of Cyanophyta
Aitutaki								
Aitutaki site 1	0.77	0.85	0.09	0	0	0	0.09	0.07
Aitutaki site 2	0.73	3.59	0.07	0	0	0.12	0.02	0.07
Aitutaki site 3	0.62	1.96	0	0	0	0.03	0.23	0.03
Aitutaki site 4	0.94	0.63	0	0	0	0.13	0	0.04
Aitutaki site 5	0.84	1.44	0.04	0	0	0.12	0.02	0.39
Aitutaki Island means	0.78	1.70	0.04	0	0	0.08	0.07	0.12
Rarotonga								
Rarotonga site 1	0.87	3.25	0	0	0	0.13	0.07	0.13
Rarotonga site 2	0.83	3.69	0.67	0	0	0.13	0.12	0.07
Rarotonga site 3	0.94	0.33	0.02	0	0	0.01	0.09	0.07
Rarotonga site 4	0.93	0.57	0.04	1	0.16	0.05	0.15	0.04
Rarotonga site 5	0.88	1.48	0.77	0	0	0.16	0.16	0.08
Rarotonga site 6	0.87	1.96	0.34	0	0	0.16	0.43	0.11
Rarotonga Island means	0.89	1.88	0.31	0.17	0.03	0.11	0.17	0.09
Ovalau								
Ovalau site 6	0.92	–	0.29	–	–	0.08	0.05	0.03
Ovalau site 7	0.73	4.08	0.07	2.61	0.53	0.07	0.12	0.04
Ovalau site 8	0.77	1.89	0.04	3.63	0.48	0.31	0.05	0.03
Ovalau site 9	0.93	0.91	0.07	8.91	0.68	0.05	0.12	0.01
Ovalau site 10	0.94	0.16	0	18.63	1.36	0.11	0.03	0
Ovalau Island means	0.86	1.76	0.10	8.45	0.76	0.12	0.07	0.02
Vatulele								
Vatulele site 1	0.68	7.06	1.14	0.25	0.09	0.12	0.2	0.13
Vatulele site 2	0.77	5.92	0.58	5.71	1.44	0.01	0.49	0
Vatulele site 3	0.72	8.77	1.55	4.93	1.01	0.07	0.16	0.09
Vatulele site 4	0.83	2.72	0.87	0.51	0.16	0.15	0.04	0.04
Vatulele site 5	0.78	5	0.12	2.56	0.59	0.24	0.04	0.01
Vatulele site 6	0.62	6.35	1.5	0.43	0.08	0.15	0.07	0
Vatulele Island means	0.73	5.97	0.96	2.40	0.56	0.12	0.17	0.05

Correlation is calculated using the non-parametric Spearman correlation coefficient. Only correlations with an absolute value of 0.50 or higher are recorded with a 0.05 or less significance (see Table 5).

The MI is positively correlated with agro-industry externalities. MI and hard coral species diversity were negatively correlated (see Fig. 3(a)).

Hard coral species diversity and agro-industry externalities and total externalities are negatively correlated (see Fig. 3(b)).

The number of corals affected by biotic factors is positively correlated with hard coral species diversity (see Fig. 3(c)).

The number of coral affected by biotic factors is negatively correlated with agro-industry externalities and with total externalities (see Fig. 3(d)).

The presence of filamentous algae and reef type were positively correlated. This means that there is a linear relationship with the presence of filamentous algae and with fringing reefs. The presence of Cyanophyta and percentage of soft coral coverage and the soft coral species diversity is negatively correlated.

Finally, the last correlation is weak, −0.45, but with a high significance of 0.04 between the hard coral species diversity and the type of property regime (see Fig. 4). The negative correlation means that the higher the hard coral species diversity the more likely there is a relationship with a traditional system of management.

3.1. Intra-island and inter-island site comparison

Islands and study sites were selected based upon differences in the property regimes and the economic development of marine resources. Data from study sites are compared using a non-parametric statistical analysis, the Wilcoxon test, testing the difference between the

Table 3
Number of corals affected

	Bleaching of entire coral	COTS	*Plagioporus* spp.	CLOD
Aitutaki				
Aitutaki site 1	0	0	2	0
Aitutaki site 2	3	1	0	0
Aitutaki site 3	0	0	0	0
Aitutaki site 4	0	0	0	0
Aitutaki site 5	2	0	0	0
Rarotonga				
Rarotonga site 1	0	0	3	0
Rarotonga site 2	0	0	0	0
Rarotonga site 3	0	0	1	0
Rarotonga site 4	0	0	1	0
Rarotonga site 5	8	0	2	0
Rarotonga site 6	3	0	1	0
Ovalau				
Ovalau site 6	22	0	0	0
Ovalau site 7	4	0	0	0
Ovalau site 8	0	0	1	0
Ovalau site 9	4	0	0	0
Ovalau site 10	0	0	0	0
Vatulele				
Vatulele site 1	10	0	0	5
Vatulele site 2	6	0	0	3
Vatulele site 3	6	0	15	0
Vatulele site 4	4	0	1	0
Vatulele site 5	0	0	2	0
Vatulele site 6	5	0	0	22

variability and dispersion of two sample populations. Coral data will be reported as having a significant difference only when the p value is less than 0.05. Since coral data have natural variability, the variance in each site is high, making it difficult to show significant differences.

3.1.1. Ovalau and Vatulele: significance of property regimes and agro-industry

Vatulele site #3 and #5 and Ovalau site #8 and site #9 are all study sites on the windward side of the island that have barrier reefs. Vatulele site #3 and site #5 have traditional marine tenure regimes and little economic development of marine resources and thus low levels of externalities associated with the development of these markets. Ovalau site #8 and site #9 are in areas controlled by the Port Authority and are classified as government regulated reef areas. Furthermore, these two sites have high externalities associated with marine harvesting and agro-industry. The Pacific Fishing Company (PAFCO) effluent pipeline flows out into these sites. Ovalau site #7 and site #10 are under traditional marine tenure. Current patterns in the Ovalau reef system show that currents head south towards site #9 and #10 (Tanata and Lovell, 1995).

Ovalau sites #7, #8, #9, and #10 have lower means for hard coral species diversity than the two Vatulele study sites. Ovalau site #8 has a mean of 1.89 and site #9 has a mean of 0.91 (see Table 2). Vatulele site #3 has a mean of 8.77 and site #5 has a mean of 5 (see Table 2). Hard coral species diversity is significantly different between Vatuele site #5 and Ovalau site #8 (Wilcoxon score: 18.58 and $p < 0.04$). Vatulele site #5 and Ovalau site #9 are significantly different (Wilcoxon score: 19.27 and $p < 0.05$). Furthermore, Ovalau site #7 has a mean of 4.08 and site #10 has a mean of 0.16 for hard coral species diversity (see Table 2). There is no significant difference between Ovalau site #7 and the two Vatulele sites, but there is a significant difference between Ovalau site #10 and Vatulele site #3 (Wilcoxon score: 24.84 and $p < 0.04$). There is no significant difference between the four Ovalau sites. Site #7 is higher and site #10 is significantly lower than Ovalau sites #8 and #9. The MI for Ovalau sites #9 and #10 have higher values than Vatulele sites #3 and sites #5. Both of Ovalau sites #9 and #10 are south of the PAFCO pipeline (see Table 2). Thus the water from the PAFCO effluent follows the current patterns inside the barrier reef system and goes south.

The percentage of soft coral coverage is greater in Ovalau sites #9 and #10 with means of 8.91 and for the latter 18.63 (see Table 2). Soft coral species diversity (see Table 2) is significantly different between Vatulele #5 and Ovalau #10 (Wilcoxon score: 6.65 and $p < 0.04$).

Data for the affected corals, clonal condition, presence of filamentous algae, and Cyanophyta are all related to the MI (see Table 2). Vatulele site #3 has a high species diversity and low MI, but also has the highest values for number of corals affected by biotic factors, the presence of Cyanophyta and filamentous algae. Vatulele site #5 has the highest number of values documenting the clonal condition (see Table 2). The MI for Ovalau site #9 and site #10 is extremely high. There is a significant difference between the number of affected corals Ovalau site #9 and Vatulele site #3 (Wilcoxon score: 18.19 and $p < 0.004$) and Ovalau site #7 and Vatulele site #3 (Wilcoxon score: 6.65 and $p < 0.0004$). The reef in Vatulele had incidence of CLOD. There are no significant differences in the coral clonal condition. Ovalau site #8 and Vatulele site #3 have a significant difference in the presence of Cyanophyta (see Table 2) (Wilcoxon score: 3.96 and $p < 0.05$) and in the presence of filamentous algae (see Table 2) (Wilcoxon score: 3.59 and $p < 0.05$).

3.1.2. Rarotonga and Aitutaki: the significance of property regimes and marine harvesting externalities

Rarotonga sites #1 and #6 and Aitutaki site #3 are all sites with fringing reefs on the windward side of the island. The Rarotonga sites are both Ra'ui that are closed to harvesting marine resources. All three sites have high levels of agro-industry development and

Table 4
Island site geographic categories

	Windward or leeward	Reef type	Property	Tourism externalities	Harvesting externalities	Agro-industry externalities	Externalities total
Aitutaki							
Aitutaki site 1	Windward	Fringing	Government	3	6	2	11
Aitutaki site 2	Leeward	Barrier	Government	4	6	6	16
Aitutaki site 3	Windward	Fringing	Government	4	6	7	17
Aitutaki site 4	Leeward	Barrier	Government	3	6	7	16
Aitutaki site 5	Leeward	Barrier	Government	3	6	7	16
Aitutaki Island means				3.4	6	5.8	15.2
Rarotonga							
Rarotonga site 1	Windward	Fringing	Traditional	1	0	9	10
Rarotonga site 2	Windward	Fringing	Government	1	2	9	12
Rarotonga site 3	Leeward	Fringing	Traditional	6	0	6	12
Rarotonga site 4	Leeward	Fringing	Government	6	2	6	14
Rarotonga site 5	Leeward	Barrier	Government	9	3	6	18
Rarotonga site 6	Windward	Fringing	Traditional	2	0	6	8
Rarotonga Island means				4.17	1.17	7	12.33
Ovalau							
Ovalau site 6	Windward	Barrier	Government	4	3	9	16
Ovalau site 7	Windward	Barrier	Traditional	3	2	6	11
Ovalau site 8	Windward	Barrier	Government	4	3	8	15
Ovalau site 9	Windward	Barrier	Government	4	3	9	16
Ovalau site 10	Windward	Barrier	Traditional	2	2	8	12
Ovalau Island means				3.4	2.6	8	14
Vatulele							
Vatulele site 1	Leeward	Fringing	Traditional	3	2	0	5
Vatulele site 2	Leeward	Fringing	Traditional	1	2	0	3
Vatulele site 3	Windward	Barrier	Traditional	1	2	0	3
Vatulele site 4	Windward	Fringing	Traditional	0	2	0	2
Vatulele site 5	Windward	Barrier	Traditional	1	2	0	3
Vatulele site 6	Leeward	Barrier	Traditional	3	2	0	5
Vatulele Island means				1.5	2	0	3.5

Table 5
Correlation of all island means

MI	Agro-industry externalities	0.50
MI	Hard coral species diversity	−0.78
Hard coral species diversity	Agro-industry externalities	−0.52
Hard coral species diversity	Total externalities	−0.60
Number of coral affected by biotic factors	Agro-industry externalities	−0.60
Number of coral affected by biotic factors	Total externalities	−0.51
Number of coral affected by biotic factors	Hard coral species diversity	0.69
Presence of filamentous algae	Reef type (fringing)	0.51
Presence of Cyanophyta	Percentage of soft coral coverage	−0.62
Presence of Cyanophyta	Soft coral species diversity	−0.59

tourism development. The Data highlight the differences among these three sites (see Table 2).

Hard coral species diversity mean is higher in Rarotonga site #1, 3.69, and the values are equal with Rarotonga site #6 and Aitutaki site #3 at 1.96 species per quadrat. The MI on Aitutaki is lower than the sites of Rarotonga (see Table 2). The number of affected corals by biotic factors, the coral clonal condition, and the presence of Cyanophyta have higher values in both Rarotongan study sites compared with the Aitutaki site (see Table 2). There is no significant difference in any of these data. The presence of filamentous algae has a mean of 0.43 in Rarotonga site #6,which is higher than Aitutaki site #3 (see Table 2). Rarotonga site #1

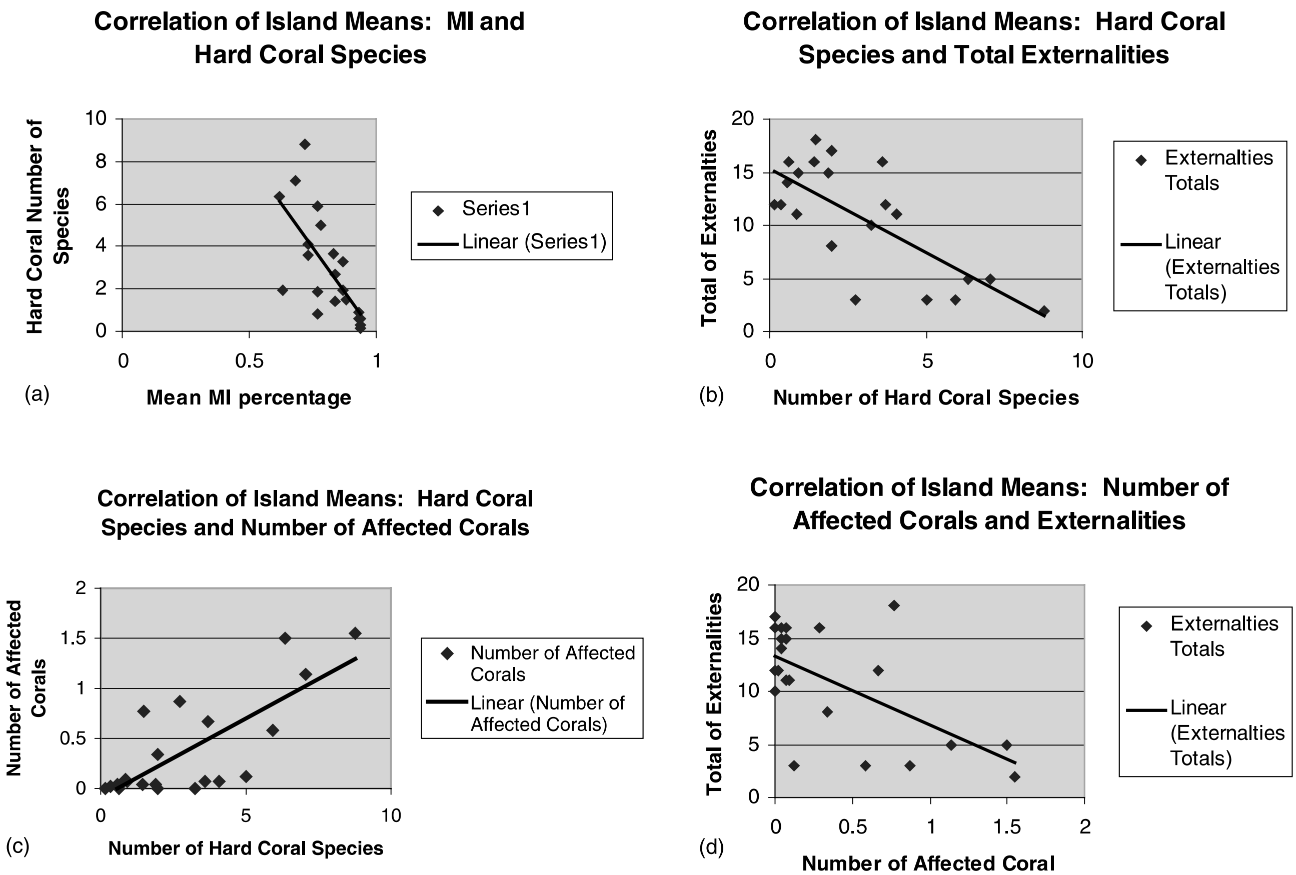

Fig. 3. (a) Correlation of island means: MI and hard coral species, (b) correlation of island means: hard coral species and total externalities, (c) correlation of island means: hard coral species and number of affected corals and (d) correlation of island means: number of affected corals and externalities.

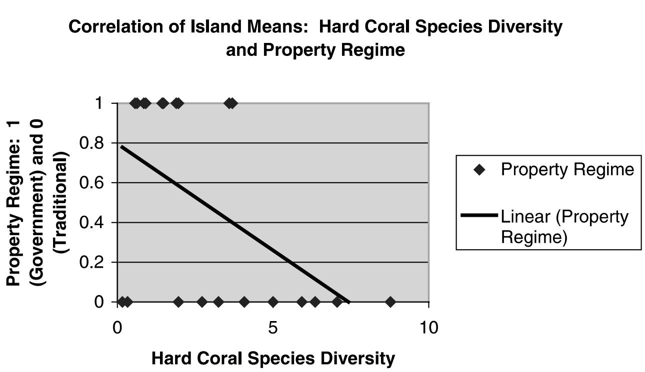

Fig. 4. Correlation of island means: hard coral species diversity and property regime.

has a lower level of filamentous algae than Aitutaki site #3.

3.1.3. Rarotonga and Aitutaki: the significance of tourism externalities

Rarotonga site #5 and Aitutaki site #2 are study sites on the leeward side of the island with a barrier reef. Both have high levels of marine harvesting and agro-industry. Rarotonga site #5 has a high density of tourist facilities and activities and Aitutaki site #2 does not. Neither of these sites have soft coral coverage. Aitutaki site #2 has a greater mean, 3.59 than Rarotonga site #5, 1.48 for hard coral species diversity (see Table 2). Aitutaki site #2's MI is also lower than Rarotonga site #5 (see Table 2). Furthermore, the number of corals affected by biotic factors, the coral clonal conditions, presence of Cyanophyta, and presence of filamentous algae are all variables that have higher values on Rarotonga site #5, even though the MI is higher, than Aitutaki site #2 (see Table 2).

4. Discussion: reef health and change, development, and property regimes

4.1. Island means and correlation analysis

4.1.1. Ovalau

The reefs surrounding Ovalau have been affected by the PAFCO effluent and harbor surrounding Levuka. All sites, #6, #9, and #10 that are south of the effluent have higher MI means of 0.92, 0.93, and 0.94. The

Ovalau sites north of the pipeline have MI means of 0.73 and 0.77. This pattern is also the same for hard coral species diversity. The sites in the north have higher values than the sites south. Sites #9 and #10 have means of 0.91 and 0.16, while sites #7 and #8 have means of 4.08 and 1.89. The data describing the number of affected coral, coral clonal condition, presence of Cyanophyta, and presence of filamentous algae are high in sites #6, #9, and #10 compared to sites #7 and #8 due to the high MI. Site #6 had twenty-two bleached corals while having a MI of 0.92. Although, there are no significant differences according to the Wilcoxon score, there is a significant relationship when doing a Spearman correlation coefficient for all of the Fijian study sites. The Spearman correlation coefficient shows a strong positive correlation of 0.64 with a probability of 0.03 between the MI and the externalities associated with agro-industry. Furthermore, the hard coral species diversity and the agro-industry correlation have an even stronger relationship with a negative correlation of −0.82 and a probability of 0.004. Finally, the soft coral percent coverage is positively correlated, 0.63 with a probability of 0.05, with agro-industry. Based upon this data patterns have emerged on the reefs of Ovalau. The reefs have been heavily affected by the waters in the Levuka area and are carried south. Thus the hard corals of the south have died, but are recovering. This recovery is dominated by soft coral. This "phase shift" is a common pattern seen in degraded reefs (Done, 1997).

4.1.2. Vatulele

The reefs of Vatulele have much lower MI values and much higher hard coral species diversity than the reefs of Ovalau. Some quadrats had up to twenty different species of coral. Site #4 has a much higher MI and lower hard coral species diversity due to the location of the study site. This site is heavily influenced by large waves. The reefs of Vatulele have many biotic factors affecting the corals and coralline algae. Low live coral coverage in the Pacific is not in itself a sign of poor health. Few reefs have more than 50% live coral coverage due to high wave energy, tropical storms, or dominance of coralline algae (Wilkinson, 1998). Vatulele Island resort, while research was ongoing, had up to 200 COTS a day, and while surveying, CLOD was documented at all of the sites on the leeward side of the island. Site #6 had twenty-two coralline algae with CLOD. It has been suggested by locals that plume from the Sigatoka River is the cause for this increase in biotic factors affecting the reefs of Vatulele.

4.1.3. Aitutaki

The reefs on the east part of the island versus the reefs on the west side of the island have higher MI's and overall lower hard coral species diversity. Aitutaki site #4 and #5 on the east leeward side of the island had runoff from the past agro-industry and present plantations affect these two sites due to current patterns in the lagoon. MI's for site #4 and #5 are 0.94 and 0.84 and hard coral species diversity is 0.63 and 1.44. By contrast sites #1, #2, and #3 have lower MI's of 0.77, 0.73, and 0.62 and overall higher values of hard coral species diversity of 0.85, 3.59, and 1.96. Site #1 is hit by heavy waves and is next to the airport; it has lower MI and higher species diversity than site #4. Furthermore, site #5 was covered with the Cyanophyta.

4.1.4. Rarotonga

Rarotongan reefs have high levels of *Plagioporus* spp. (Aeby, 1991) affecting *Porites* spp. correlated with sewage. Partial bleaching of corals and the presence of filamentous algae also affected the corals. Sites #3, #4, and #5 have high levels of tourism development and associated externalities. Sites #3, #4, and #5 have mean MI's of 0.94, 0.93, and 0.88, while sites #1, #2, and #6 have mean MI's of 0.87, 0.83, and 0.87. Hard coral species diversity is lower for sites #3, #4 and #5 with values of 0.33, 0.57, and 1.48. Sites #1, #2, and #3 all have higher values of hard coral species diversity, which are 3.25, 3.69 and, 1.96. These sites, #3, #4, and #5, have the highest MI's on the island as well as the highest levels of filamentous algae. This is unusual because leeward sides of islands generally have 15–20% more species diversity than windward sides of islands due to wave energy and reef formations and structure (Edinger et al., 1998). Perhaps the windward reefs have higher hard coral species diversity because of the flushing of fresh ocean water upon the reef environment, cleansing the habitat from pollutants.

4.2. Intra-island and inter-island site comparison

4.2.1. Ovalau and Vatulele: significance of property regimes and agro-industry

As already discussed in the above section, the impact of the upstream PAFCO effluent upon Ovalau sites #9, and #10 may have increased the MI, lowered the hard coral species diversity, and created a phase shift from hard coral species to soft coral species (Done, 1992). This shift is a change from a community dominated by reef building organisms to one dominated by non-reef building organisms such as soft coral and fleshy algae.

4.2.2. Rarotonga and Aitutaki: the significance of property regimes and marine harvesting externalities

Significant differences were not identified between any of these sites using any of the ecological variables. The data shows, however, higher mean values in the hard coral species diversity in the Ra'ui sites than in the Aitutaki. This is interesting because is older and has a more developed reef, as well as higher coral diversity [8] (Paulay, 1988).

Furthermore, reefs with traditional systems of marine management such as in the case of Rarotonga help control harvesting of marine resources. More studies need to be done for longer periods of time to understand the effect upon the habitat the Ra'ui may have. These data suggest that there is a relationship between these Ra'ui areas and new coral growth.

4.2.3. Rarotonga and Aitutaki: the significance of tourism externalities

No significant differences were identified between these two sites, but every variable tested has a higher or lower value in the Rarotongan site, suggesting poorer health. The MI is greater in Rarotonga and the hard coral species diversity is lower, whereas the number of affected corals, coral clonal condition, presence of Cyanophyta, and presence of filamentous algae are all higher on the Rarotonga site #5. Coral reef systems are sensitive to changes in the physical and chemical environment, and this is well documented in the literature (Pastorok and Bilyard, 1985; Dubinsky and Stambler, 1996). The impact of sewage upon the coral reef system depends upon current patterns and flushing rates of the lagoon. Eutrophication, as a result of sewage discharge, can give rise to more numerous, extensive algal blooms and biomass, as well as reduced diversity of invertebrates. Furthermore, the increase in coral mortality has been attributed to algal growth because of the direct smothering of colonies by fast growing algae that is stimulated by the additional nutrients or through the indirect competition for space (Walker et al., 1982).

4.3. Correlation of all island means

Despite great variability in the coral data there were some strong correlative relationships with geographic factors seen in the data. Correlative relationships found in the data suggest that the agro-industry is strongly related to the death of hard corals. Further, reefs with agro-industry within close proximity also have reduced hard coral species diversity. Hard coral species diversity is also lower in areas with higher total externalities.

The relationship between property and hard coral species diversity must be considered. There is a correlation with traditional systems of marine resource management and lower market development and the externalities associated with market development. In other words, there are more traditional systems of reef management and use when the market is less economically developed. In the cases of Ovalau and Rarotonga, where there are combined types of marine tenure regimes on the island, non-point and point source pollutants upcurrent still affect traditional areas downcurrent. Ovalau site #10 and site #7 perfectly illustrates this example. There is a strong relationship considering that Ra'ui have only been in place for at most two years in Rarotonga and the reefs of Ovalau have been heavily affected by pollutants in areas not owned by the communities.

Table 6
Island population per square kilometer

Island	Island land area (km^2)	Population per square kilometer
Aitutaki, Cook Islands	16.8	142
Rarotonga, Cook Islands	67	168
Ovalau, Fiji	103	84
Vatulele, Fiji	31.6	29

Based on the four island case studies one can see that economic development and marine property institutions, play a greater role in the decline of reef health than human population growth (Ehrlich, 1968). This study suggests that these four islands exemplify a pattern that is typical of other South Pacific Islands (see Table 6). If one looked solely at population as a factor influencing reef health one would assume that the Rarotongan reefs would have the highest MI: the two sites in Rarotonga do have MI's of 0.93 and 0.94, whereas Ovalau has three sites of 0.92, 0.93, and 0.94. Furthermore, Rarotonga has an overall higher hard coral species diversity than Ovalau. This is even more significant because scientists have documented that Fijian reefs have higher species diversity than those in the Cooks (Paulay, 1988; Veron, 1986). Site by site comparisons between the study sites show how the property regime and level of market development affect the reef. The overall hard coral species diversity is lower in Aitutaki than in Rarotonga.

The presence of filamentous algae on fringing reefs also had a strong positive correlation, not surprising. Fringing reefs are closer to the shoreline, which are areas where usually there are more nutrients in the water column. A weak positive correlation also exists between the tourism market and the fringing of 0.43 with a probability of 0.05.

The remainder of the relationships are between the ecological variables. There is strong relationship between the MI and hard coral species diversity, which is negatively correlated at −0.78. There is also a strong positive correlation of 0.69 between hard coral species diversity and the number of affected coral by biotic factors. This would explain the negative correlative relationships between agro-industry externalities and total externalities with the number of coral affected by biotic factors. The final negative correlative relationship is

[8] The Ra'ui will be further investigated and discussed in Chapter 5 of dissertation and in an article in press for Coastal Management Journal.

between soft coral species diversity and soft coral percent cover and the presence of Cyanophyta. These findings suggest that these two organisms are competing to re-colonize degraded reefs.

Using a whole reef perspective and examining the environmental history of development and geographic factors is crucial to unravel the causes of degradation (Edinger et al., 2000). Especially since reefs are extremely complex systems, it is difficult to carry-out large-scale studies on the health of the reef and causes of degradation. High variability in data and the uniqueness of each reef make large-scale studies inaccurate.

These four islands are a small sample of thousands of islands in the South Pacific. More studies will be needed to assess reef health throughout the Pacific to make more general statements about reef health in the South Pacific and establish relationships with market developed and property regimes.

Table 7
Site analysis for externalities and the scale of intensity

Externality	The meaning of 0–3 scale—with 3 being the highest
Sewage and waste disposal	(0) No hotels (1) Within 3 km area fewer than 35 rooms[a] (2) Within 3 km between 35–200 rooms (3) Within 3 km more than 200 rooms
Anchor damage	(0) No tourist water-based tours (1) Fewer than 20 people taking watertours or renting boats daily[b] (2) Between 20–50 people taking watertours or renting boats daily (3) More than 50 people taking watertours or renting boats daily
Coastal development	(0) No hotels within 1 km (1) Within 1 km area less than five hotels (2) Within 1 km between 5–10 hotels (3) Within 1 km more than 10 hotels
Destructive/ exploitative fishing	(0) No fishing (1) Subsistence fishing and collecting (2) Small-scale commercial fishing for local markets (3) Commercial fishing for export
Inputs and outputs from mariculture	(0) No mariculture (1) Within 3 km area, less than three mariculture farms[c] (2) Within 3 km area between 3–5 mariculture farms (3) Within 3 km area more than 10 mariculture farms
Industrial pollution	(0) No industry (1) Industrial effluent in the past within 3 km (2) Industrial effluent within 10 km (3) Industrial effluent within 3 km
Sedimentation	Stream within 3 km has runoff from: (0) No streams within 3 km (1) Subsistence agriculture (2) Small-scale agriculture (3) Commercial agriculture
Manure, fertilizers and petrochemicals	Stream within 3 km has runoff from: (0) No stream within 3 km (1) Subsistence agriculture (2) Small-scale agriculture (3) Commercial agriculture

[a] Rooms were used to determine intensity of the externality since the size of hotels can vary so much.

[b] Which is worse, bigger boats with more people, or more, smaller boats with fewer people? Both scenarios, have impacts—bigger boats have bigger anchors, but the boat holds more people and therefore there could be fewer boats on the water. The other scenario is smaller boats with smaller anchors, but potentially more boats on the water. I decided to base it on the number of people rather than type of boat.

[c] Distances and the scale changes chosen to compare the externalities and the level of intensity are based upon my experience.

Acknowledgements

The United States Environmental Protection Agency Star Fellow # U915636 and the University of California Pacific Rim Research Program provided financial support to conduct this research. I would like to thank Lisa Wedding for her field assistance. Helen Fox, Jere Lipps, Bernard Nietschmann, David Stoddart, and Michael Watts provided intellectual support. For more information on this project see Tegan Churcher Hoffmann's Dissertation, Reefs of Life to Reefs of Death: The Political Ecology of Coral Reef Health in Fiji and the Cook Islands, 2001, Department of Geography, University of California Berkeley. This article is not necessarily the views of CORAL.

Appendix A

Within each island study site, I have categorized localized market sectors, as well as point-source externalities associated with each sector. Externalities were calculated and added up for each island and for each island site based upon the above criteria (see Table 7).

References

Aeby, G.S., 1991. Behavioral and ecological relationships of a parasite and its hosts within a coral reef system. Pacific Science 45, 263–269.

Bruckner, A.W., Bruckner, R.J., Williams, E.H., 1997. Spread of a black-band disease Epizootic through the coral reef system in St Ann's Bay, Jamaica. Bulletin of Marine Science 61, 919–928.

Bureau of Statistics, F., 1996. The Population Census. Bureau of Statistics, Suva, Fiji.

Cook Islands Statistics Office, 1999. Cook Islands Annual Statistical Bulletin. Ministry of Finance and Economic Management, Rarotonga, Cook Islands.

Done, T.J., 1992. Phase shifts in coral reef communities and their ecological significance. Hydrobiologia 247, 121–132.

Done, T.J., 1997. Coral reef community adaptability to environmental change at the scales of regions, reefs and reef zones. American Zoologist 37, 169A.

Dubinsky, Z., Stambler, N., 1996. Marine pollution and coral reefs. Global Change Biology 2, 511–526.

Edinger, E.N., Jompa, J., Limmon, G.V., Widjatmoko, W., Risk, M.J., 1998. Reef degradation and coral biodiversity in Indonesia: effects

of land-based pollution, destructive fishing practices and changes over time. Marine Pollution Bulletin 36, 617–630.
Edinger, E.N., Limmon, G.V., Jompa, J., Widjatmoko, W., Jeffrey, M., Risk, M.J., 2000. Normal coral growth rates on dying reefs: are coral growth rates good indicators of reef health? Marine Pollution Bulletin 40, 404–425.
Ehrlich, P.R., 1968. The Population Bomb. Ballantine Books, New York.
Gomez, E.D., 1994. A review of the status of Philippine reefs. Marine Pollution Bulletin 29, 62–68.
Grove, R., 1995. Green Imperialism: Colonial Expansion, Tropical Island Edens, and the Origins of Environmentalism, 1600–1860. Cambridge University Press, Cambridge.
Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248.
Hoffmann, T.C., 2001. Reefs of life to reefs of death: the political ecology of coral reef health. PhD dissertation. Department of Geography, University of California at Berkeley.
Naranjo, S.A., Carballo, J.L., Garcia Gomez, J.C., 1996. Effects of environmental stress on Ascidian populations in Algeciras Bay (southern Spain). Possible marine bioindicators? Marine Ecology-Progress Series 144, 119–131.
Nietschmann, B., 1997. Protecting Indigeous coral reefs and Sea Territiories, Miskito Coast, RAAN, Nicaragua. In: Stevens, S. (Ed.), Conservation Through Cultural Survival. Island Press, Washington, DC, pp. 193–224.
Pastorok, R.A., Bilyard, G.R., 1985. Effects of sewage pollution on coral-reef communities. Marine Ecology Progress Series 21, 175–190.
Paulay, G., 1988. Effects of Glacio-Eustatic Sea Level Fluctuations and Local Tectonics on the Marine Faunas of Oceanic Islands. Doctoral, University of Washington, Seattle, Washington.
Porter, J.W., Meier, O.W., 1992. Quantification of loss and change in Floridian reef coral populations. American Zoologist 32, 625–640.
Santavy, D.L., Peters, E.C., 1997. Microbial pests: coral disease in the Western Atlantic. In: Proceedings of the 8th International Coral Reef Symposium, pp. 607–612.
Tanata, R.B. and Lovell, E., 1995. Baseline water quality and coral reef for PAFCO-Levuca. IAS Environmental Report No. 78. Institute of Applied Sciences, University of the South Pacific, Suva.
Turva, A.M., 1988. Cook Island Quarterly Report Statistical Bulletin. Statistics Office, Rarotonga, Cook Islands.
Veron, J.E.N., 1986. Corals of Australia and the Indo-Pacific. Angus & Robertson, North Ryde, NSW, Australia.
Walker, D.I. et al., 1982. Coral death from sewage and phosphate pollution at Aqaba, Red Sea. Marine Pollution Bulletin 13, 21–25.
Wilkinson, C. (Ed.), 1998. Status of Coral Reefs of the World: 1998. Australian Institute of Marine Science, Townsville, Australia.