

Assessment of Coral Reef Disturbance Histories in the Line Islands Using Coral Damage and Morphological Dominance Patterning

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ABSTRACT:

Coral reefs are in decline worldwide under the pressure of a number of environmental and anthropogenic stressors. Human populations have impacted coral reef ecosystems through a variety of activities including fishing, pollution, and even tourism. These pressures can amplify environmental stressors such as global warming and storm activity that are faced by much of the world's reefs. In this study, coral damage in the Line Islands was compared to the current coral morphological dominance patterns at each study site to suggest differences in the environmental and anthropogenic disturbance histories in study sites both within and between Christmas, and Fanning Islands, and Palmyra Atoll. Results indicate that the coral damage variables of coral rubble and broken coral colonies are good quantitative indicators of past disturbance histories that when combined with morphological dominance patterns can suggest valuable relationships between damage, recovery, and overall coral ecosystem health.

INTRODUCTION:

Coral reefs are among the most valuable yet most threatened of the world's ecosystems. Reefs provide subsistence food for a number of native populations, and also serve as major tourist draws (West 2003). Reefs also have a tremendous economic value, with an estimated value from ecosystem services and tourism of 375 billion dollars annually (Constanza et al 1997). However, this precious resource is in decline around the world as a result of a number of anthropogenic related factors such as global warming, overfishing, pollution, and even tourism (Hughes 2003). Recent research clearly demonstrates that this decline can't be compared to any historical episodic fluctuations, and has reached unprecedented levels in recent human history (Pandolfi 2003, Pandolfi 2005).

One of the leading causes of overall reef decline, and a tremendous threat to the future health of coral reefs is global warming (Hughes 2003). Corals are stenothermic organisms, with a narrow temperature tolerance. This limits coral growth to waters in a narrow temperature band, and provides a large negative selection pressure with temperature changes of only a few degrees (Glynn 1973). In general, much of the Indo-Pacific region has had very stable water temperatures over the last 1.75 million years (Thibault 2005). However, in the last hundred years a warming trend above and beyond normal fluctuations has been recorded in both terrestrial and oceanic environments (Hughes 2003). In the Line Islands alone during the past four years, sea surface temperatures have exceeded the mean by more than one degree centigrade on ten separate

occasions (NOAA 2005). However, the impact of these high temperature events has been inconsistent, with actual coral bleaching events occurring in a patchy manner. Recent research indicates this may be due to differences between the species of the coral zooxanthellae symbiotes, some of which may possess greater resistance to increased temperatures (Knowlton 2003, Brown 2002). While the exact bleaching histories of different sites within the Line Islands is not known, it is possible that one or more of the documented bleaching temperature events has led to coral bleaching, and contributed at least in part to some coral death and increased levels of susceptibility to other forms of natural disturbance.

While the occurrence of coral bleaching isn't always consistent, other disturbance events have been shown to elicit reliable and predictable changes in coral reefs. One of these is a shift in morphological dominance patterns in reefs as a result of certain environmental factors and disturbance regimes (Huston 1985). The most important environmental factors determining the dominant morphologies of coral are light and wave energy, with sedimentation, temperature, plankton availability, and the frequency of mortality caused by a number of factors such as grazing, storms, and tidal exposure also playing a part (Huston 1985).

Coral reefs are relatively unique in that they operate as non-equilibrium ecosystems where competitive exclusion by a few faster growing species is prevented by intermittent disturbance events. This has been called the "intermediate disturbance hypothesis" (Connell 1978). One of the most common and influential forms of ecosystem disturbance and selection near the surface is wave energy, which strongly selects for corals with increased structural strength capable of resisting the hydraulic stress (Rodgers 2003, Storlazzi 2005). During large wave events, wave energy extends to greater depths, selectively damaging coral morphologies that might have a greater advantage under normal baseline conditions (Huston 1985). However, once below the wave base other environmental factors have greater influence on reef morphology. The most important of these is light, and the interaction between coral polyps and their zooxanthellae.

These dinoflagellate symbiotes produce energy through photosynthesis for the coral polyps that gather additional nutrients through filter feeding. In shallow water, the tall, narrow, structurally strong and fast growing branching corals such as *Acropora*,

Pocillopora and *Stylophora* are usually most common (Chappell 1980). It has been suggested that these corals use their ability to grow tall quickly to shade out their competitors. However, this strategy requires a large amount of available sunlight because the narrow branching structure is not ideal for light gathering. At increasing depths columnar and upright plate structures are found with larger surface areas that can absorb more light (Chappell 1980). These morphologies then give way to large coral massive and horizontal plate morphologies. Corals at increasing depth tend to have larger polyps better at filter feeding, increasing the total amount of energy that the coral can absorb. However, in spite of the larger polyps and large surface area there is still comparatively less sun energy available at deeper reef depths. For this reason, corals at greater depths tend to grow more slowly (Huston 1985) Recovery from disturbances at these depths is therefore much slower.

This study sought to use study sites of equal environmental stress, but differing levels of anthropogenic influence. Regional and local effects expected in the sites of Christmas and Fanning include habitat loss, habitat fragmentation, local fishing, and pollution of coral reefs. Christmas Island is inhabited by more than 5,000 people, and was the site of numerous nuclear tests by both the US and British. It has an active shark finning industry, and there is active fishing throughout the island. Fanning Island, the second island in this study, is the home to about 3,000 people. There, subsistence fishing is common, with additional pressure posed by visits from Norwegian Cruise Lines ships, which bring about 600 people to the island each month. Palmyra Atoll was occupied by the US Army during WWII, and several alterations were made to the island including an airstrip, two causeways, and the dredging of the central lagoon. However very few changes were made to reef outside of the central lagoon. In the sixty years since the military occupation Palmyra has been virtually uninhabited. It is currently a protected site under to the care of the Nature Conservancy, and USFWS. There are currently four permanent residents on Palmyra.

The increase in human activity on these islands likely has many effects. One anthropogenic reef disturbance is over fishing, where humans have fished down the trophic levels of reefs, leading to trophic cascade effects and a permanent alteration of reefs away from their pristine state (Jackson 2001). The effects of overfishing can

amplify other anthropogenic effects on reefs. This can be seen with eutrophication of coral reefs, where increased nutrients from agricultural runoff causes increased algae growth that can be unchecked because of the fishing depleted stocks of herbivorous reef organisms (Chazottes 2002). This in turn can lead to algae out competing corals, decreases in total coral cover, and a less healthy overall coral ecosystem (Huston 1985). Long term chronic stress on reefs, anthropogenic or otherwise, has been shown to cause lower levels of recruitment compared to those that have only suffered from single acute disturbances (Connell et al 1999). Increased anthropogenic disturbance, and limited recovery can therefore be expected to lead to further declines in coral reef health.

Even recreational reef use has been shown to have adverse impacts on reef ecosystems. One study (Hawkins 1999) on the effects of recreational scuba diving found that divers caused coral breakages and abrasion on all types of corals. Because of this uniform damage, Hawkins found a moderate increase in the dominance of fast growing corals where diving was most prevalent, and an increase in the overall coral mortality from background stresses such as high sea surface temperatures. Plathong (2000) showed that relatively low amounts of snorkeling caused a decrease in the amount of fragile branching corals at shallower depths. Moreover, Garrabou (1998) found further negative impacts where divers eliminated many of the exposed coral colonies and decreased coral cover. In all cases, the numbers of divers and their behaviors have disturbance impacts and have ecological consequences on reef community structure and diversity.

With all of the possible sources of damage to reefs from a variety of environmental and anthropogenic sources, it is very difficult to conclusively determine the timing and type of disturbance events and what ecosystem effects will be without extensive research and a historical reef baseline. This is an important task for reef managers, many of whom don't have the capability for long term research, and instead have to rely on rapid assessment techniques to find hotspots most in need of conservation and restoration efforts. To aid in this process SC Jameson developed the Coral Damage Index (CDI), a measure of baseline coral damage that can be expected within a pristine ecosystem (Jameson 1999). This index includes a baseline value for coral rubble (as a percent of total coral cover), which serves as a proxy for comparatively older disturbance events, and live broken coral colonies which represent recent damage. After a survey of a

number of studies of marine reserves with little to no human impact in both the Red Sea and Caribbean, Jameson determined that the baseline values for coral rubble and broken coral colonies were 3% and 4% respectively. The use of a coral damage index has the potential to be a very powerful tool, allowing reef managers to quickly and easily identify areas that have been degraded past an established baseline point. While this coral damage index does not specifically suggest the cause of the reef degradation, it does point out areas that are most significantly damaged and allows for a focusing of further study and conservation efforts.

This study tested the overall applicability of this coral damage index, and also used the predictor variables of coral rubble and broken coral colonies in conjunction with a comparison of morphological dominance patterns to characterize the nature of past disturbances in the Line Islands study sites. Coral and algae cover, in conjunction with past disturbances were also used to possibly indicate whether more extensive and healthier ecosystems are better able to recover after being damaged by disturbance events.

MATERIALS AND METHODS:

This study consisted of an analysis of coral reefs within Christmas, Fanning, and Palmyra Islands. Data gathering took place in three sites for each island, with two sites on each island representing the back reef, with one site in a more exposed fore reef location. In Christmas the three sites consisted of Clam City ($1^{\circ} 56.417' N \times 157^{\circ} 29.214' W$), Cook Island ($1^{\circ} 57.580' N \times 157^{\circ} 29.053' W$), and Paris Point ($1^{\circ} 56.424' N \times 157^{\circ} 29.357' W$). The three sites in Fanning Island were Norweigan Cruise Lines mooring ($3^{\circ} 51.786N \times 159^{\circ} 22.170W$), Whaler's Anchorage ($3^{\circ} 54.605N \times 159^{\circ} 23.477W$), and a mooring south of the lagoon channel ($3^{\circ} 50.506N \times 159^{\circ} 21.640W$). The three sites in Palmyra were Tiger Shark Point ($5^{\circ} 52.255N \times 162^{\circ} 06.612W$), NW of channel ($5^{\circ} 52.622N \times 162^{\circ} 06.993W$), and Coral Gardens (no GPS available). Three one meter wide and thirty meter long snorkeling transects were made at each study site, where depths ranged from 0.5 to 7 meters. Snorkelers used a measuring transect tape and stopped every three meters on alternating sides of the tape to assess a quadrat of reef, for a total of eleven quadrates per transect. Each quadrat was then analyzed for total coral

cover, coral rubble, and broken coral colonies. The percent abundance of corals in the following morphological groups: massive/submassive, digitate, digitate plate, plate, foliaceous, columnar, free living, encrusting/dome, branching, and other was also analyzed along with filamentous, branching, and encrusting coralline algae. Quadrates were photographed with an underwater camera and analyzed on a computer at a later date.

Analysis of data gathered throughout all three islands was done with multivariate statistical analyses (nMDS ordinations and multivariate randomization tests, conducted using the software PRIMER) to determine variation in the composition and structure of coral communities in different locations. These analyses allowed a comparison of coral communities between all of my transects, and provided a list of which independent variables were most responsible for the overall patterns of similarity or dissimilarity among transects. The objective for this analysis was to determine how the abundance of different coral morphologies varied with site and whether different morphological groups tended to dominate in areas subjected to different amounts of disturbance. Analyses of variance and statistical significance within single data categories was conducted using ANOVA software, with significance assessed at $p < 0.05$.

RESULTS:

Analysis of coral data shows a significant difference in the coral composition of the three islands. There is no significant difference in coral cover between the islands of Christmas and Fanning, which have average live coral cover values of 19.1% and 18.8% respectively. However, Fanning's high coral cover numbers are largely due to a very productive third site, without which Fanning would average only 6.8% coral cover, one third of Christmas Island (Table I). Palmyra has a much higher percentage of live coral compared to both other islands, with 32.2% of all bottom surface covered by live coral (Table I). In the category of coral rubble, Christmas and Fanning were again very similar, with no significant difference. Their coral rubble values of 29.4% and 27.4% were nearly five times greater than the Palmyra result of 5.73% (Table 1, Figure I). In all three islands coral rubble, categorized by Jameson 1999 as an indicator of past disturbance, was readily noticeable. However, the averages for broken coral colonies (BCC) and dead

intact colonies (DIC) was very low, with averages of less than 1% for nearly all sites (Table I).

Table 1:

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Figure I:

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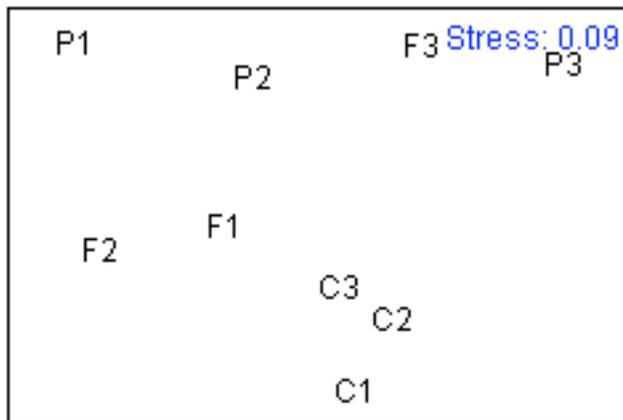
Lower values in total coral cover in Fanning and Christmas were matched by increased algal growth, leading to significantly similar total live substrate values at around 65% (Figure I, Table 1). While total algal coverage isn't significantly different, there is a significant difference in the types of algae that dominate between Christmas and Fanning. In Christmas, there is a significantly larger amount of encrusting coralline algae, with more than three times as much of this type as filamentous (Table I). This case is reversed in Fanning Island, where filamentous algae is the prevailing algal form on the reef. There, filamentous algae was nearly three times as abundant as encrusting coralline (Table I). Palmyra serves as an intermediate case for algal growth, with insignificant differences in the relative abundances of filamentous versus coralline algae (Figure I).

The types and abundances of coral morphologies varied significantly between the three islands, and within the islands in many cases as well. In Christmas Island, all three sites had consistent patterns, where the encrusting and dome corals typical of high stress locations dominated the reef, with a smaller amount of submassive corals and some short digitate corals also present. Fanning had a tremendous amount of variability between the three study sites. In the first and second sites, very low coral cover was observed, with a large amount of coral rubble present. Encrusting corals were the only morphology present in significant amounts. The third site was much more robust, demonstrating a high coral cover of 49%, and a wide array of morphologies (Figure 2). Palmyra had a consistently diverse coral population, with the fragile branching corals present in significant numbers in two of the three study sites. In the third site of Coral Gardens, a tremendous amount of morphological diversity was seen, with fragile morphotypes seen even in the shallow (0.5 m) study site.

Figure 2:

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Figure 3: PRIMER5 Multivariate ordination between islands



This diagram is a graphical representation of the patterns of similarity between islands and sites. P represents Palmyra, F represents Fanning Island, and C represents Christmas Island. The numerals of 1,2, and 3 represent the three study sites within each island.

These trends are confirmed by the PRIMER5 multivariate analysis of dissimilarity between sites and between islands (Figure 3). It can be seen that there is great similarity between all three Christmas Island sites, with Fanning sites 1 and 2 very different from site 3. This robust third site is relatively similar to the very robust Coral Gardens Palmyra site 3. ANOSIM (Analysis of Similarities) software to test for significance in difference in the groupings from the PRIMER5 ordination plot (Figure 3) found significant differences in the community composition and relative abundances of different benthic groups both between sites ($p < 0.001$), and between islands ($p < 0.03$). Differences were

generally driven by differences in algal cover, followed by coral rubble and then morphological differences (for more details see APPENDIX Table II).

DISCUSSION:

Results from this study make several interesting suggestions about the past disturbance histories of Christmas, Fanning and Palmyra. The high coral rubble vales at both Christmas and Fanning indicate the occurrence of a severe disturbance event, likely in the form of one or more tropical storms with high wave energy that caused the breakage of morphologies susceptible to high hydraulic stress. In Christmas, the encrusting, submassive and short digitate structures are now dominant, covering 19% of the reef area. However, the reef composition in Fanning was quite different. There we saw much lower coral cover at two of the three sites, and very high coral rubble (Table I). In these two sights, the affects of a severe disturbance were the most noticeable out of all of the study sites. This is especially surprising, given that the average depth for the first Fanning site was 6m, which should have lead to decreased wave energy compared to the Christmas Island study sites which sustained less damage overall. It is also puzzling why the third Fanning study site appeared so robust with nearly 43% coral cover when it was located only a kilometer from the first study site on the same leeward protected side of the island.

There are several possible explanations for these differences between Christmas and Fanning Islands. Consistant winter storms could have selected for a higher percentage of wave resistant morphologies at Christmas, inhibiting the growth of more fragile morphologies through yearly cyclic disturbance events. If this was the case and the same storm hit both Christmas and Fanning Islands, then the shallow reefs at Christmas could have been better prepared to deal with the high wave stress, leading to less change in reef composition. This however, would not explain the large amount of coral rubble present at Christmas, which indicates that this island also suffered dramatic coral losses. It could also be the case that both islands experienced a large disturbance event, but that Christmas Island had a better source of undisturbed reefs nearby to serve as larval pools that facilitated higher rates of recruitment after the disturbance event.

Qualitatively, the coral rubble at Christmas appeared to be more amorphous, possibly representing coral “pavement” that is continually broken off and then reformed in a natural cycle of damage and regeneration in high wave energy coral ecosystems. If this is the case, it is possible that there was not in fact an abnormally large disturbance event at Christmas. This can’t be argued with Fanning Island, where much of the coral rubble appeared to be broken fragments of branching corals, the abundance of which suggests that a large patch of these was present before a disturbance event and was completely destroyed. The third site of Fanning, though it did have high coral cover, also suffered a lot of damage. There was significant coral rubble in this site as well, with overturned tabletop corals suggesting wave energy that extended far below the surface. The gradients of disturbance within Fanning suggests that there was an inconsistent level of storm impact between the three sites, with the second site being hit the hardest, followed by the first, and the third facing the least disturbance.

Palmyra is quite different in terms of coral rubble and reef damage from the other two islands. In this island overall coral rubble was quite low, and the diversity of coral morphologies was quite high. In this island, branching corals continued to persist even in the shallower study sites of comparable depth to Christmas and Fanning. There are two possible explanations for this. Firstly, it is possible that Palmyra didn’t face the same intensity of storms as Fanning and Christmas, and therefore suffered less damage. It is reasonable to assume that these islands would face different weather events as a result of spatial variation, since they are more than a hundred miles apart. However, one would expect similar overall trends in storm activity and intensity due to their similar position on a global scale. A second explanation is that Palmyra had a healthier, more robust fore reef to start with, before the disturbance event that could have hit all three islands. This would have sheltered the lagoonal area from more intense waves, and protected the branching corals and other more delicate morphologies that persisted after the event and can be observed today. The incredibly productive third Palmyra study site of Coral Gardens is extremely well protected by both a fore reef and a small island, and its abnormally high productivity is likely due to a nearly complete absence of severe environmental disturbance. This includes global warming, which would have threatened that site significantly as it had an average water depth of only 0.5 meters. Since there did

not appear to be any significant bleaching or dead coral colonies at this site, it is likely that this site and the others in the waters immediately surrounding Palmyra have not suffered from severe bleaching events in the last few years and damage can therefore only be attributed to other disturbance events.

More data is needed on the past storm history and bleaching water temperatures around the Line Islands to gain a full picture of the disturbance history of the three islands of this study. However, the fact that all of the broken fragments have since died and been re-colonized by various forms of algae indicates that a time lapse on the order of several years must have occurred between the disturbance and the time of this study. However, in the case of Fanning and to a smaller extent in Christmas, there appeared to be very little recruitment and recovery after the disturbance events faced by these two islands. This could mean that the reefs have not yet had time to recover, with only the fast growing algae having had time to become the dominant group on the reefs, or that sources of larvae for recruitment are insufficient in these sites for adequate reef recovery.

While the effects of a very apparent environmental disturbance event have been clearly shown through this study, results also can suggest some possible future trends regarding the recovery and recruitment in the study sites following this disturbance event. Throughout Christmas Island encrusting coralline algae was the dominant form of algae found on the reef, with almost five times more coralline algae present than filamentous algae (Table I). This is important, as coralline algae produces a reef building carbonate base that facilitates the recruitment of new coral polyps. Assuming that there is an adequate larval source pool in Christmas, recovery after the disturbance event can be expected. Fanning had a very different response to the past natural disturbance, with filamentous algae dominating the damaged reef areas in tremendously high amounts, nearly three times as prevalent as coralline algae (Table I). This abundance of filamentous algae, which is the primary food source for herbivorous fishes, is likely to correspond with an increase in the prevalence of herbivores and a possible alteration of reef fish community structure. With less substrate available for recruitment and high grazing pressure, possible reef recovery may be much slower at the highly damaged sites in Fanning.

CONCLUSION:

The methodologies tested in the study show great promise for future rapid assessment reef evaluations. The Jamesson 1999 Coral Damage Index appears to be of limited value, as its baseline values of coral rubble and broken coral colonies limit the applicability of the index to sites that have not been exposed to significant natural disturbance. In practical application, this is a prohibitive barrier, as nearly every coral reef on earth faces a complicated array of environmental disturbances varying from wave and storm energy to global warming related bleaching events. However, the index's predictor variables of coral rubble and broken coral colonies do appear to be valuable tools that provide a quantitative measure of reef damage while providing suggestions about the relative timescale of the damaging event.

Reviewing the data, it is apparent that in the past several years Christmas, Fanning, and Palmyra have all been exposed to one or more severe disturbance events that have resulted in coral damage and a degradation of overall reef health. It can also be seen through the increased prevalence of highly wave resistant coral morphologies in Christmas and Fanning Islands, coupled with high coral rubble values, that these islands either faced a separate disturbance event of greater intensity than in Palmyra, or were less prepared for the event and were damaged more. The exact influence of anthropogenic influences in overall trends of reef disturbance is impossible to determine with current data, though it is interesting to note that Palmyra, the island in this study with the highest amount of coral cover, lowest values of coral rubble, and highest prevalence of fragile morphologies is also the island that has experienced the least amount of human impact.

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APPENDIX

Table II

SIMPER ANALYSIS

Similarity Percentages - species contributions

Groups C & F

Average dissimilarity = 71.86

Species	Group C		Group F		Diss/SD	Contrib%	Cum.%
	Av.Abund	Av.Abund	Av.Diss	Av.Diss			
Enc Cor Algae	43.85	13.53	20.73	1.57	28.85	28.85	
Total CR	29.39	27.41	16.32	1.24	22.71	51.56	
Filamentous Alg	5.78	28.64	14.37	1.17	20.00	71.57	
encrusting/dome	12.91	4.31	7.67	0.64	10.67	82.24	
Digitate plate	0.00	7.76	4.23	0.48	5.89	88.13	
massive/submass live	5.39	0.26	3.21	0.47	4.46	92.59	

Groups C & P

Average dissimilarity = 75.81

Species	Group C		Group P		Diss/SD	Contrib%	Cum.%
	Av.Abund	Av.Abund	Av.Diss	Av.Diss			
Enc Cor Algae	43.85	16.01	20.11	1.58	26.52	26.52	
Total CR	29.39	5.79	14.79	1.06	19.51	46.03	
Filamentous Alg	5.78	18.83	10.86	1.03	14.33	60.36	
encrusting/dome	12.91	9.23	10.18	0.75	13.43	73.79	
Digitate plate	0.00	8.73	4.66	0.35	6.15	79.93	
Digitate	0.62	7.52	4.46	0.55	5.88	85.81	
massive/submass live	5.39	0.07	3.28	0.46	4.33	90.14	

Groups F & P

Average dissimilarity = 71.86

Species	Group F		Group P		Diss/SD	Contrib%	Cum.%
	Av.Abund	Av.Abund	Av.Diss	Av.Diss			
Filamentous Alg	28.64	18.83	15.24	1.24	21.21	21.21	
Total CR	27.41	5.79	14.60	1.06	20.31	41.52	
Enc Cor Algae	13.53	16.01	11.74	0.86	16.34	57.86	
Digitate plate	7.76	8.73	8.70	0.57	12.11	69.97	
encrusting/dome	4.31	9.23	6.62	0.64	9.22	79.19	
Digitate	4.29	7.52	5.89	0.68	8.19	87.38	

Branching	0.00	5.19	3.00	0.29	4.18	91.56
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