CORAL HEALTH AND DISEASE: A COMPARISON OF COOK'S AND OPUNOHU BAYS IN MOOREA, FRENCH POLYNESIA

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Abstract. Coral health is an imperative aspect of coral reef ecosystems. Coral provides shelter, habitat, and nutrients for many organisms. Anthropogenic pollution that enters the oceans through runoff has negative effects on coral health such as inhibiting photosynthesis, growth, and reproduction. This study focuses on Cook's and Opunohu Bays in Mo'orea, French Polynesia. Each of the bays were assessed for substrate, algae, and coral composition as well as for a specific coral disease called Porites Trematosiasis (por trem) which is found exclusively on *Porites* coral heads. A total of forty-eight 10x10m plots were used to gather this information. From the data that concluded that sites were significantly better indicators for coral health and substrate difference as well as por trem than the bays, a comparison to past studies was made about the coral health and its change in the last twenty years. The coral health in Mo'orea has deteriorated in the past twenty years from natural causes such as cyclones, bleaching events, and *Acanthaster planci* outbreaks, but anthropogenic causes seem to have made a negative difference as well.

Key words: coral reef health; Porites; *Porites trematodiasis; Mo'orea, Cook's Bay; Opunohu Bay*

INTRODUCTION

Coral is the building block of a reef ecosystem. Because coral is a photosynthetic organism created by symbiosis of the coral polyp and zooxanthallae, it fulfills many functions for the ecosystem (Hoffmann 2002). It provides structure and a substrate for algae, habitat to live in, and a food source for countless organisms (Szmant 2002). Coral is biodiverse and its health is imperative in order to ensure a biodiverse and thriving ecosystem(Selig, Casey, and Bruno 2010). Coral reefs are becoming increasingly threatened globally. Central to this breakdown is the diminishing health of coral (Weil, Smith, and Gil-Agudelo 2006). There are many abiotic and biotic factors that contribute to the health of coral including sewage, land runoff, sedimentation, temperature, overfishing, industrial and agricultural practices, and tourism (Adjeroud et. al 2005, Richmond 1993, Hoffmann 2002). With expanding industries and population, the pressure on reefs is increasing(Downs et. al 2005). The amount of sediment that comes from infrastructure and agriculture affects the coral by covering it so that there is reduced growth, reproduction, photosynthesis, and recruitment (Duane 2006, Tribollet et. al 2011). The agrochemicals and untreated sewage contribute to higher levels of nitrogen and phosphorus which cause eutrophication (Duane 2006). The process of eutrophication enhances algal growth, which creates intraspecific competition for substrate and nutrients. Many species of algae also carry disease-causing pathogens that can be transferred to coral (Nugues et. al 2004)). Emerging coral diseases are rapidly deteriorating coral reefs (Aeby et. al 2011). In the *Porites spp.* there are several diseases that associate with specific environmental factors, such as Porites growth anomalies, *Porites* trematodiasis, Pink-line disease, *Porites* ulcerative white spot disease, and *Porites* tissue loss syndrome (Aeby et. al 2011, Rayindran and Raghukumar 2006, Raymundo et. al 2003). Specifically, *Porites* trematodiasis is a disease that affects massive, bouldering *Porites* heads causing discoloration and pink nodes on the surface of the coral (Aeby et. al 2011). It is a disease that is caused by parasitic flatworm that depends upon three different hosts in its life cycle (Williams et. al 2010). It lives in a mollusk, coral, and reef fish (Williams et. al 2010). Therefore when infected organisms are present, it spreads easily and the denser an ecosystem is with these organisms, the more frequent the potential spread of the disease (Aeby et. al 2011).

In Moorea, French Polynesia there are two prominent bays, Cook's and Opunohu, which have extensive watersheds that flow into them. The two valleys have long histories of agricultural and pastoral practices that have developed in the past twenty years (Duane 2006). With these watersheds, runoff is a very important issue regarding coral reef health. There has been extensive research on coral health on the reefs surrounding Moorea that has created a timeline in the coral health and the major events that have caused this health to deteriorate and to what degree (Adjeroud et. al 2005, Berumen and Pratchett 2006, Done et. al 1991, Faurea 1989, Gleason 1993, Hutchings et. al 2004, and Pratchett et. al 2011). Some of the causes of abrupt decline in coral health are *Acanthaster planci* (crown-of-thorns starfish) outbreaks, bleaching events, and cyclones (Adjeroud et. al 2005, Done et. al 1991,Gleason 1993,). Since the 1980s there have been 15 cyclones, seven leaching events and several *A. planci* outbreaks (Adjeroud et. al 2005). With knowledge of these events from the past years, a comparison of the state of coral health presently against the state of coral health twenty years ago is assessable.

There are four main coral genera that make up the majority of the reefs circumscribing Moorea; *Acropora*, *Montipora*, *Porites*, and *Pocillopora* (Berumen and Pratchett 2006). Each of these genera have diseases, predation, and bleaching with which they affiliate (Faurea 1989, Berumen and Pratchett 2006). This study focuses on the presence of *Porites* trematodiasis on the *Porites spp.* in the sites found in Cook's and Opunohu Bays. It also accounts for the substrate of each plot as well as another bioindicators of health, percent algae cover (Hutchings and Peyrot-Clausade 2002). The bioindicators also will help to identify the main causes of the disease because of the abiotic factors that are usually associated with the disease or deterioration. Comparing the two bays, therefore will be very useful because there are different anthropogenic inputs and amounts of these inputs between them. Because there has been considerable land cover change, new industrial and agricultural practices, and population increase, possible causes of damage could be hypothesized. With this information, in addition to the previous studies, further measures of conservation or protection could be enacted.

The bays are hypothesized to have significantly different amounts of live coral, the live coral to increase as the distance from the river mouths increases, the substrate to be significantly different between both the bays and the sites, and for Cook's Bay to have more por trem than Opunohu Bay.

METHODS

Study Sites

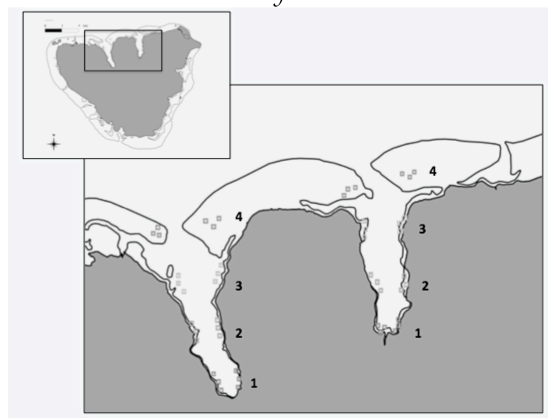

Fig. 1 Map of Mo'orea, detail of Opunohu and Cook's Bay and all of the plots at the sites.

To test the coral health in each bay I surveyed both of the bays using 10 by 10m plots measured by a transect. There were three plots in each of the 16 study sites between both Cook's Bay and Opunohu Bay for a total of 48 plots. The plots were at least 10 m apart from each other but not exactly parallel to each other because of environmental and spatial conditions. The study areas were categorized into East and West sides of each bay and into four sites according to distance from stream and/or runoff mouths; at the mouth of the bays on the fore reef, in two midranges in the bays, and at the innermost section by the mouth of the streams that run into the bays. To collect the data I swam up and down the plot covering a 2m wide section each length of the plot (Fig.2). I recorded all of the data in field using a dive slate.

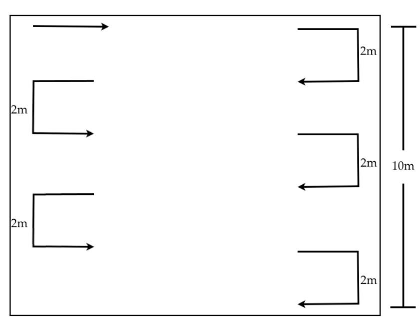

Fig. 2 Swimming pattern for data collection

Substrate Composition

To find the abiotic and biotic contributions to the status of coral health, I also used the plots to measure substrate, percent of each abiotic substrate type; sand/sediment, live coral, coral rubble, and dead coral/coral conglomerate platform.

Algae

I measured the percentage of algae in each plot, but did not include it in substrate because algae tends to cover the abiotic substrate. The algae was also identified down to species using photos to ensure accuracy.

Coral Composition and Disease

For coral health I identified the coral genera found. I only looked for four genera (*Porites, Pocillopora, Acropora, and Montipora*) because they are the most prevalent coral genera on Mo'orea. I concentrated on *Porites* for disease accounting for presence or absence of *Porites* Trematodiasis on *Porites* spp. coral heads in the plot. I recorded a 1 or 0 for presence or absence if there was any of the disease found in the plot.

Comparison of Coral Health

To compare the current health to twenty years ago, I condensed information from a number of studies to make a timeline of the coral cover, species composition, events that contributed to abrupt coral destruction or degradation. I then compared it to my data.

Changes in Biotic and Abiotic Factors over the past twenty years

To find the changes in both biotic and abiotic factors I referenced past studies about the coral reef health and the timeline of events. To find the biotic factors that have changed, I looked at past studies to see how land cover has changed and how population has grown.

Statistics

For my statistics I applied PCA to look at substrate difference between the two bays and all of the four sites and to see the coral genera composition difference between sites and bays. I used MANOVA to see the significance of sites and bays for substrate and for coral composition. I used Pearson's Chi-squared test to look at the significance of the presence/absence of *Porites* trematodiasis between bays and sites. I also used canonical figures to show how each of the sites grouped and how similar they were using all algae species, substrate composition, and coral genera composition. JMP 9 was used for all statistical analysis (JMP).

RESULTS

Study Sites

The groupings are important to understand coral health between the two bays because coal health is dependent upon many factors that are accounted for here such as algae and sediment. By having clusters, principle component analysis, and canonical figures, the commonality between the sites can be seen and the bigger picture is much more clear.

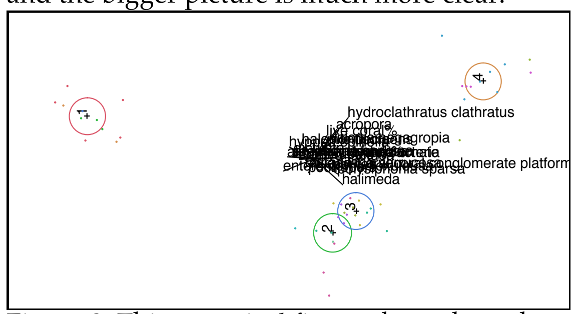

Figure 3. This canonical figure shows how the specific substrate percentage and organism species categories provide strong support for grouping the sites in which the plots are found. The categories seem to group the sites somewhat consistently. These classifications provide a wide range of variables in the plots but also allow for similarities to arise. Group one lacked any coral and was mostly homogenous between plots at their respective east or west location in both bays. Sites two and three in both bays were very similar and a good representation of much of the bay in general. The site fours were very similar in specific substrate types, and lacked two of the types that the site twos and threes contained.

Substrate Composition

The substrate composition did not have significance between the bays. Although as hypothesized, the substrate composition did change as the distance from the river mouth increased (Fig. 5). Using a MANOVA to compare the substrate between both bays and between all four sites for each bay enforced that the sites were much better groupings for substrate composition (Pillai's Trace bay=.0269, Pillai's Trace site=.0001). The PCA analysis of the sites confirms how the sites are a much better way to group the plots according to substrate (Fig. 4). The specific breakdown of the substrate shows how different site one plots were to all of the other sites (Fig. 5 and Fig. 6).

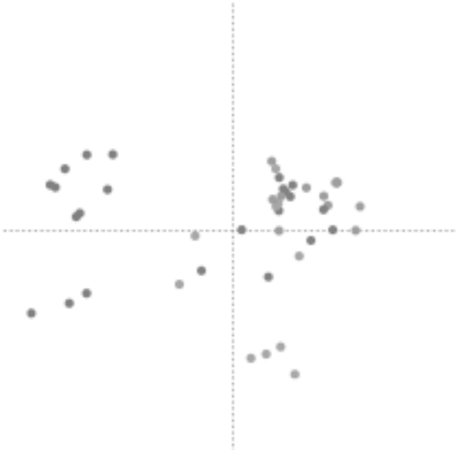

Fig. 4 Principle Component Analysis of substrate composition. Each color represents a one of the four sites. All of the substrates were used to see how similar each plot in the sites were to each other. I used the principle component 1 which summarizes 68.2% of the substrate percentages for all of the plots (JMP). This principle component analysis shows how each of the sites between both bays are related. The dark markings (dots) furthest left represent the four site ones which did not contain any coral which and were made up predominately of algal cover, hence why they group together the best. The lightest markings represent the four site twos, the next shade darker represent site three, and the darkest site fours. The marking that dominate the right side of the graph seem to clump and intermix together, but darkest gray(site fours) seems to be the most similar within site group of the three. The site fours were considerably farther away from the shoreline and were not inside the bays as all of the other sites were. Their species composition definitely had overlap with all other sites, but the substrate percentages were much more similar, which may explain their closer grouping. The site twos and threes between both bays were similar in species composition especially within the algae category which may explain the lack of close grouping and the mixing of the two.

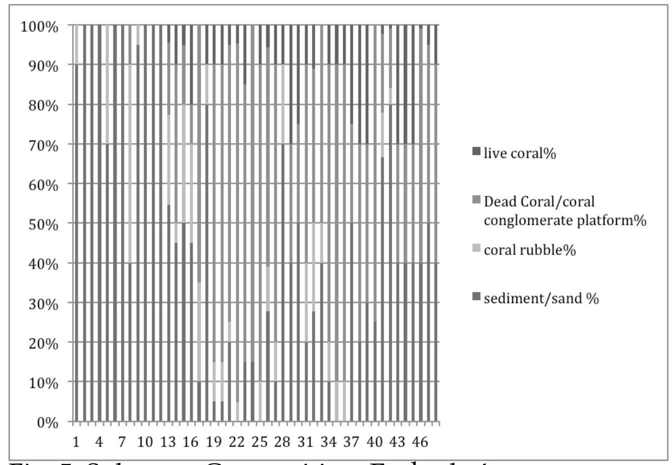

Fig. 5 Substrate Composition. Each plot's composition is represented.

Substrate is a very good indicator of coral health because it gives percentages of what is alive or dead and what other substrate that coral interacts with. The two bays are labeled as well as each plot and which directional side of the bay. There is no coral found right at the mouth of the bays because of the river mouth flows. Sediment/sand is the lowest out of all of the substrates across all of the plots and sites. Coral rubble reduces with distance from mouth of the river, but dead coral/ coral conglomerate platform seems to be the most predominant substrate cover over all of the plots. Site four west in Opunohu had the most live coral with Cook's bay east site four trailing close behind. However in the opposite sides of each of these bays, the live coral was dramatically less.

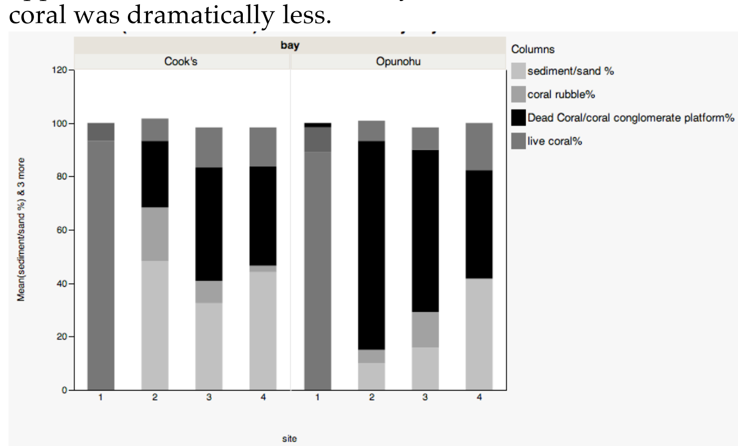

Fig. 6 The substrate types were graphed according to site and bay. Each of the bars represents six plots within a bay because of both east and west sides of the bay at a certain site were grouped.

Algae

Algae were used for a canonical grouping but did not have significance in the specific coral disease and therefore did not need its own statistical analysis. Algae were an important factor to look at for overall similarity, but were not a major component of the results.

Coral Composition and Disease

Coral genera composition did not differ significantly by bay but it did by site (Pillai's Trace bay=.2155, Pillai's Trace site=.0001). This rejected the hypothesis of having the bays have difference in coral composition. Another hypothesis that did not show significance was the amount of live coral being less in Cook's than Opunohu. It was rejected through Pearson's Chi-squared test for the bays (*p*=.6994).

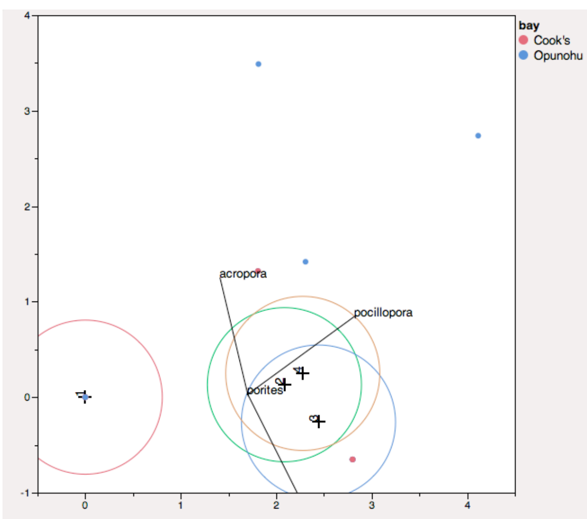

Fig. 7 Coral species composition canonical by site and bay. Each circle(with site number inside) is a separate site combining both bays and both east and west sides of the bays, but the same relative distance from the river mouth. The coral four coral species are the determining factors for how they grouped. The gray dots represent the respective bays.

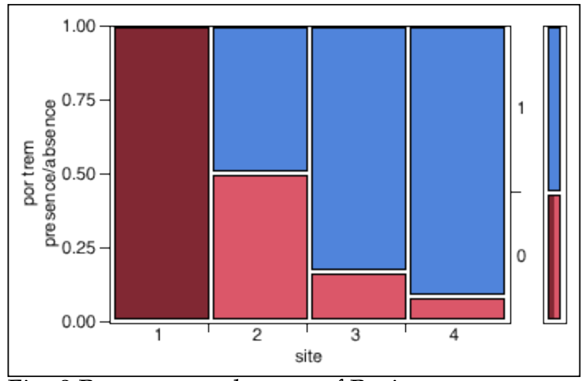

Fig. 8 Presence or absence of Porites Trematodiasis by site. The 1 represents the presence and the 0 the absence.

Pearson's Chi-squared test shows that there is significance in presence or absence of *Porites* trematodiasis between sites (DF=3, likelihood ratio=31.457, *p*=.0001). In site four there is a significantly higher prevalence of the disease. It would obviously not be present in the site ones because there is no coral for it to be infecting. However, there is a trend of more disease the father away from the river mouth of each of the bays.

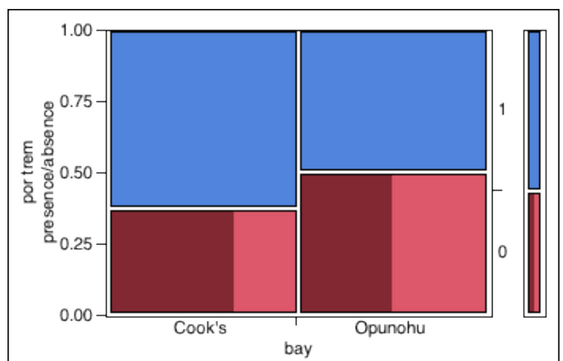

Fig. 9 Presence/absence of *Porites* trematodiasis in Cook's and Opunohu Bays. The 1 represents the presence and the 0 represents the absence.

In the Chi-squared test between the two bays there is no significance of the presence or absence of *Porites* trematodiasis (DF=1, likelihood ratio=.764, *p*=.3821). It is interesting to see the results that bay does not limit the disease but distance from the mouth of the bay. This lack of disease difference between bay is important to understand because of the biology behind the disease, therefore each bay supports the organisms necessary for this transmission of parasite.

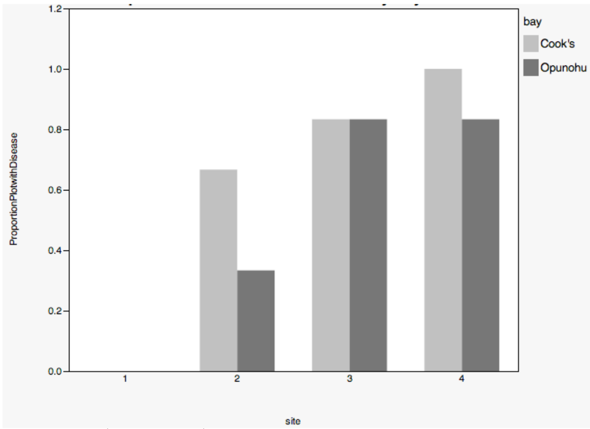

Fig. 10 This graph separates site and bay to look at the presence/absence of por trem. It is a proportion because it combines six plots per site, therefore it cannot be on a 1/0 scale because of the lack of uniformity of presence/absence in the plots (see Appendix A Fig. 11).

Discussion

The coral health between the two bays differed more upon the site location than upon the bays. For the presence or absence of *Porites* trematodiasis (por trem) the bays were very similar in the location of and prevalence of the disease. The bay was not a factor it seemed, but the distance from the river mouths is in both bays. The most disease was found in site four in both bays, and in decreased amounts in sites three and two, and none found in site one in either bays. There is no coral in sites one therefore there is no coral disease in these sites. However, an interesting trend of more live coral, which *Porites* was the most abundant, the more disease was present. The amount of live *Porites* heads would be an important indicator to take into consideration because of the specific substrate that this disease needs. Since there was much more live coral in sites four than in other sites, there was also much more por trem. There was also an overwhelming difference in the live coral percentages in each site and between east and west locations of each sites, the disease prevalence was differing accordingly. In Cook's Bay east site four all three plots were the most diseased plots of the whole study. Most if not all of the live *Porites* heads were diseased there indicating a concerning problem for live coral. Because por trem is a disease that is dependent upon three organisms for spread and survival, a healthy coral reef is imperative. Where there is the ability for a mollusk to burrow in the Porites head and for a Chaetodon to feed on the same, the disease will spread (Aeby 2006). It is also important to take into account the prevalence of disease and the amount of coral cover in the area. The disease was most prevalent in an area where there was 30 percent live coral, the most live coral found in any of the plots. There was less disease where there was less live coral. This conclusion matches the results of another study which indicated that moderate coral cover (30-60%) hosted the most por trem over less or more coral cover (Aeby 2006). The reasoning behind this that there is a threshold at which there is a balance of just enough live coral to recruit the mollusk and fish but not a clean enough environment for the disease to be absent (Aeby 2006). Although port rem specifically is not yet proven to be more prevalent in a polluted area, many other coral diseases such as black band and white plague type-II are found where there are high amounts of sewage and industrial waste (Aeby 2006). These wastes also change substrate cover because of diseased coral having much slower growth and reproduction rates (Szmant 2002).

Substrate cover is an important indicator of coral reef health (Downs et. al 2005). The bays were not significant factors for the difference in substrate. The sites within the bays were found to be significant factors for changing substrate of the plots ($p>$. 0001). From Pillai's Trace the bays were found to be insignificant factors ($p>$ .0269). In all site ones in both bays the plots were almost all sediment/sand and then covered in algae (Fig. 6). They were homogenous in the species of algae found within the plots as well. There was some coral rubble found but it was predominately phaeophyta and chlorophyta species that made up the plots in all four site ones in both bays. The sites ones had this composition of sediment and algae because of the proximity to the river mouths.

There are main river mouths that carry agrochemicals, sewage, and any other runoff from the valley's watersheds (Duane 2006). With this input to both of the bays, and having it increased greatly with growing population and industry, high sediment loads were steadily flowing into the bays at all of the site ones. With this nutrient loading that came from the runoff, there were high amounts of nitrogen and phosphorus that explain why there was such an abundance of algae (Szmant 2002). While this substrate cover was expected and relatively common, the substrate cover in the sites that are further distances from the river mouths is the concerning issue (Hutchings, Payri, and Gabrie 1994). In plots in sites two and three, which were very similar and group together in substrate composition, there seemed to be some damage from the amounts of sediment and algae found in the plots. Dead coral/coral conglomerate platform, coral rubble, and sediment/sand made up the majority of the plots in sites two and three. In Cook's Bay there was more sediment and in Opunohu Bay there was more coral conglomerate platform, but there was almost the same amount of live coral. The lack of live coral and prevalence of dead coral could be an effect of anthropogenic causes. Although there was a large cyclone and *Acanthaster planci* outbreaks in the past two years, these locations were too close in to be affected by either of these (Adjeroud et. al 2005). Therefore the sediment buildup is a problem for coral reproduction, feeding, and photosynthesis and the algae is not only competition for the coral but also can carry pathogens that can harm coral (Bentis, Kaufman, and Golubic 2000).

The amount of dead coral is a problem because it is evident that coral did once thrive in this environment (Adjerourd et. al 2005). Since coral provides food and shelter for the coral reef ecosystem that includes many communities such as the reef fish community, this ecosystem is at risk in these areas. In both bays there seemed to be a relatively large fish community of both herbivores and coralivores. However, if coral continues to decrease and die in these areas, there will be a huge lack of nursery, food source, and habitat for these marine communities. In sites four there was an interesting trend between the east and west in both bays. In the eastern plots the coral was more dead and the west was more alive and had more por trem. Although the sites four had the most live coral, there was still a large amount of dead coral and sand. There was a definite change though from sediment to sand on the ocean floor and there was still sediment found on the coral, especially in the east sites. This change in coral cover though and the amount of live coral increasing correlates with less sediment and algae.

Another interesting aspect of the site four differences between the east and west is the different coral genera composition. There are four main coral genera that make up most of the reefs surrounding Mo'orea and they were all found in the Cook's and Opunohu Bays. However, there was a significant difference between sites' coral composition (p>. 0001). There was an overall lacking of *Acropora* both branching and table in all of the sites and it was only found in five plots in Opunohu. There was no *Acropora* found in Cook's bay at all. There was some branching in sites two and three in the east side of Opunohu but only in one plot in each of the sites. At site four on the east side of Opunohu, there were *Acropora* tables, which used to be much more prevalent in the fore reef (Gleason 1993). The lack of *Acropora* could be due to the bleaching events in the past decade because this genera is usually affected greatly by these events, and the branching species could have been greatly damaged in cyclones explaining why there was none found in any of the site fours (Adjeroud et. al 2005). In the west side of site four of Opunohu there was a large amount of *Pocillopora* that was larger than any of the other sites but seemed to be extremely predated and bleached. The east sides of site four in Opunohu and Cook's had much more live coral. The west side of site four in Cook's was a stark difference in substrate. There was much more algae on the dead coral heads and the sand also had algae growing in a majority of the floor. These differences between the east and west side of the fore reefs of both Opunohu and Cook's Bays are difficult to explain because sides of each are somewhat similar. It also seems unusual because along all other sites in both bays on both sides there are very similar coral compositions with *Porites* heads being the predominant genera and with *Montipora* and *Pocillopora* present but in smaller amounts. There were similar water depth, and water temperatures. However, the amount of growth of coral could be explained by many different variables that were not tested in this research such as the annual calcification due to ocean acidification. This aspect of coral health is important in understanding coral health and growth but takes years of monitoring to find conclusions (Bessat and Buigues 2001). There are also currents and boat traffic that could contribute to the amount of wave energy that each side of the mouths of the bays get that was not taken into consideration with this study. The recent outbreak of *Acanthaster planci* also would affect site four plots because of their location on the fore reef but this was not accounted for in this study.

Coral reef ecosystems are complex and rely upon many different biotic and abiotic factors in order to function. This study was limited by a number of factors including time, resources, experience, test sample, locations, etc. but there are many more aspects that could make for more concrete conclusions. There have been many coral health assessment studies that are inconclusive about anthropogenic effects (Bette, Page, and Dinsdale 2001, Bruno and Selig 2008, Done et. al 1991, Kaczmarsky 2008,Sandin et. al 2008). The problem with anthropogenic effects is that there are such a large amount of variables that are extremely difficult to tease apart. Coral reef ecosystems also have many confounding variables naturally that contribute to their decline in health and with global climate change, it is difficult to assign each negative attribute of deterioration to a specific cause. Many studies are now calling for a more holistic approach to coral health especially with diseases and the study of disease emerging specifically in the Indo-Pacific (Downs et. al 2005). Mo'orea's history of coral health can be somewhat applied to this study although not exactly accurate because of the different locations that much of the data measured in previous years (Adjeroud et. al 2005). The timeline and natural events that occurred were very useful in understanding the overall health of the reef however and therefore future research is necessary to better understand how natural and anthropogenic effects interact for all of the coral reef ecosystem.

For future research on this topic, water testing should be done. It would be very interesting to see which chemicals are in the water, if they increase significantly during a certain growing season or during the rainy season, and if there are certain traces of chemicals that are being used for agriculture or industrial purposes. It would also be interesting to see if the disease is prevalent at greater depths, so this would require scuba diving to see if the disease would still persist. A much larger survey around the island, at all of the bays, and at all locations where there is runoff would be interesting to see if the substrate cover was similar and if por trem was present. The fish community would also be important to look at because of the life cycle that fish and mollusk support. An limiting factor was time, so a longer study to see how the disease changes, increases, spreads, decreases, and taking samples of the coral tissue to see how it affects growth and reproduction at a cellular level would be very important aspects to fully understand the implications of coral disease and really how important the regulation of anthropogenic inputs is.

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APPENDIX A

bay	**site**	0	1	**proportion of plots with disease**
Cook's	1	6	0	0
Cook's	2	2	4	0.666666667
Cook's	3	1	5	0.833333333
Cook's	4	0	6	1
Opunohu	1	6	0	0
Opunohu	2	4	2	0.333333333
Opunohu	3	1	5	0.833333333
Opunohu	4	1	5	0.833333333

Fig. 11 Table of Proportional Presence/absence of por trem by bay and site. This data was used for Fig. 10.