Characterization of "dead zones" and population demography of *Porites compressa* along a gradient of anthropogenic nutrient input at Kahekili Beach Park, Maui

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Final Report for Project C11722 "Characterization of dead zones and population demography of *Porites compressa* along a gradient of anthropogenic nutrient input at Kahekili Beach Park, Maui"

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Abstract

Long-term monitoring conducted by the Hawaii Coral Reef Assessment and Monitoring Program (CRAMP) and the Maui Branch of the Hawaii Department of Land and Natural Resources (DLNR), Division of Aquatic Resources (DAR) show up to 67% decreases in coral cover over a 10 to15 year period at observed reefs on Maui Island.

In 2009, a one-year study investigating rates and proximal causes of mortality was conducted at six sites around Maui. Results showed that rates of mortality did not vary by site and suggested baseline levels of chronic mortality punctuated by episodic events resulting in larger percentages of tissue loss per colony. Potential stressors and patterns of loss in coral cover appeared to vary by site.

This study was designed to describe site specific rates and patterns of mortality at one of the six sites. Kahekili Beach Park in Kaanapali, Maui, was selected based on the 40% loss of coral coverage documented through DAR/CRAMP monitoring from 1995 to 2005, recent evidence that sewage effluent is being introduced to the reef via injection wells, and observations of areas of discrete areas of nearly 100% loss in coral cover known as "dead zones". "Dead zones" are characterized by low coral cover with high abundance of standing but dead coral skeleton. Low coral coverage alone is not necessarily indicative of degradation. The presence of standing but dead skeleton and rubble suggest that live coral coverage used to be present but has been degraded through historical mortality events. The reef along the study area was mapped to describe areas of historical loss in cover using a qualitative condition index, estimates of coral coverage, and coverage of standing but dead coral skeleton. Colonies of *Porites lobata* and *Porites compressa* were observed along transects located in areas of good, intermediate, and poor condition in order to determine whether rates of mortality vary with condition and if mortality in areas of poor condition is ongoing or the result of a historical episodic event. Abiotic water quality characteristics were measured along transects to determine whether freshwater input potentially associated with effluent is present along the reef.

Varying levels of degradation were mapped along the reef. Cluster analysis showed patches of degradation to be significantly clustered. Coral mortality was found to be chronic primarily associated with turf algal competition. Spatial and temporal gradients were found along the reef with highest rates of mortality associated with warmer months of August and September 2011. Rates and causes of mortality do not appear to vary by degree of historical degradation.

Background

Coral reefs around Maui Island have experienced rapid and severe declines in coral cover over the past 10 to15 years, with losses of up to 67% coral cover at Coral Reef Assessment and Monitoring (CRAMP) long-term monitoring sites (Williams et al. 2008). The CRAMP dataset, while sufficient to identify degraded sites where further management efforts should be focused, lacks the resolution to describe demographic processes responsible for decline (Hughes et al. 2010). A 2009 study, "Quantifying causes of coral decline around Maui Island", funded through the Climate Change and Marine Disease Local Action Strategy (CCMD LAS) conducted more frequent, colony scale surveys in order to produce data on mortality rates of the corals *Porites lobata* and *Montipora patula* at six of the nine long term monitoring sites around Maui. These data allowed the comparison of rates and proximal causes of mortality between sites. Results from this initial one year study did not show significant relationships between rates and incidence of mortality with site, site classification or species. Significant relationships did exist between rates and incidence of mortality and temporal variation and macro-algal benthic coverage. Site specific causes and patterns of mortality were also observed suggesting that a more spatially rigorous sampling regime focusing on individual sites is more appropriate in order to identify drivers of decline in coral coverage around Maui Island (Ross et al. 2010).

The reef fronting Kahekili Beach Park in North Kaanapali, Maui has been an area of concern for some time. Outbreaks of invasive algae (Smith et al. 2005) and recently documented effluent seeps have been observed in association with declines in coral cover from 33% to 55% during the period from 1995 to 2005 (Williams et al. 2008). Qualitative observations from the 2009 Maui Decline study suggested a gradient of coral cover decline and turf algal competition associated with warmer than ambient freshwater seeps (82°F; Dailer, personal communication) with high levels of $\delta^{15}N$ (Dailer et al. 2010, Hunt and Rosa 2009), an isotope associated with anthropogenic nutrient input often via sewage effluent (Risk et al. 2009). Hypotheses associated with this gradient of decline include: decreased recruitment, loss of skeletal integrity and subsequent collapse of older colonies, possible localized acidification from fresh water seepages, and increased occurrence of competition with macro and turf algae. In addition to overall decreases in coral cover, "dead zones", defined here as areas of nearly 100% coral loss, have been observed along the length of the reef. Given the patchy distribution of these zones they could be associated with seepage events resulting in catastrophic mortality. Also, one of these "dead zones" exhibiting one of the highest levels of degradation is located along the deeper of two long-term monitoring stations in the area. It is hypothesized that the mortality documented through the DAR/CRAMP monitoring effort may be due largely to declines in this area.

The goal of the work described here was to map and describe processes driving degradation including "dead zones" observed at Kahekili Beach Park. Coral population and community size structures were described in order to investigate the role of recruitment and historical mortality in the observed degradation. Marked colonies were followed at a fine temporal scale in order to determine rates and proximal causes of mortality to investigate the role of ongoing mortality in observed degradation. Finally, environmental variables were measured in order to describe their role in rates of ongoing mortality.

Methods

<u>Site Description</u>

Kahekili Beach Park is part of the recently established Kahekili Herbivore Fisheries Management Area where the removal of herbivorous species has been prohibited in response to stress from seasonal algal blooms, including large episodes of the invasive alga *Acanthophora spicifera*. Management concerns also include the close proximity of the Lahaina Wastewater Reclamation Facility, wherein approximately 3.5 million gallons per day of secondary effluent are discharged into four injection wells. Additionally, non-point source runoff from upslope fallow agricultural lands, nearby resorts, and golf courses all contribute to stressors in the nearshore waters (Darla White, Personal Communication). The beach and shoreline are composed of exposed limestone and sand. There are several large resorts along the beach. The beach is frequently used by SCUBA and snorkel enthusiasts and tourists (Jokiel et al. 2001). "Dead zones", or patches of nearly 100% losses in coral coverage, are found along the length of the reef including the 7m depth DAR/CRAMP long-term monitoring transect located at the site. The patches are generally made up of standing but dead *Porites compressa* skeleton or rubble. They are generally ellipsoid in shape, with a max diameter of ~10m and a width of ~4m, and found perpendicular to shore (Fig 1).

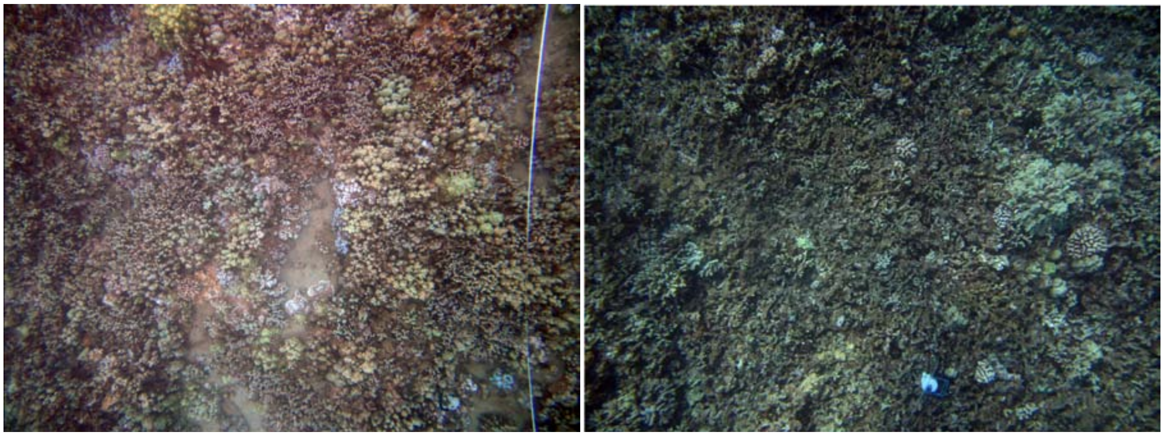

Figure1. An area of normal coral coverage (left) with several species of coral including live *P. compressa* compared to a "dead zone" (right) characterized by low coral coverage, high coverage of standing but dead skeleton and *P. compressa* rubble.

Mapping

Transects were laid perpendicular and parallel to shore (Fig 2) to form contiguous 5x5m cells. Digital images, GPS coordinates for each corner point, as well as visual estimates of benthic coverage of coral (total and by species), standing but dead *Porites compressa* skeleton and rubble, dominance of turf, macro, or crustose coralline algae, and a qualitative condition index were recorded for each cell. The dominant reef located directly in front of Kahekili Beach Park was mapped from South to North over the course of approximately one month.

Data from the mapping were analyzed using Getis-Ord Gi statistic cluster analysis in ArcMap in order to determine whether areas of low, intermediate and severe degradation were statistically significantly clustered.

Figure 2. Transects were laid perpendicular and parallel to shore to form contiguous 5x5m cells to be visually assessed for benthic coverage.

Transect Selection

Transects were selected based on qualitative categorization of reef condition (low, intermediate or, severe degradation). Transects were laid parallel to shore along depth contours. A total of 18 transects were maintained throughout the project (Fig 3). The proportion of transects of low, intermediate and severe degradation were stratified based on census data.

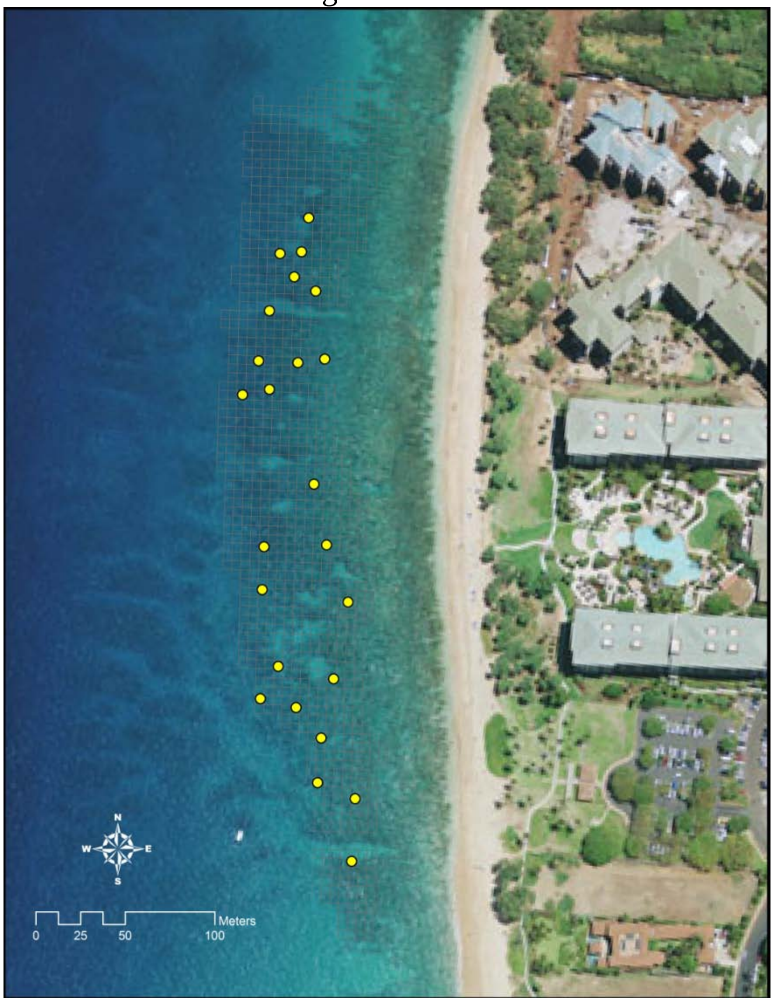

Figure 3. Eighteen transects (yellow) were selected stratified by condition based on mapping component. Transects were relocated every 1.5 months for observation of colonies.

Coral Mortality

One colony each of *P. lobata* and *P. compressa* were selected at each meter along a 10 meter transect for a total of 10 colonies per species per transect. Colonies were re-identified using placement of transects and photos printed on underwater paper. Colonies were revisited, photographed, and inspected for signs and proximal causes of mortality every two months for a period of six months. Photographs were compared to those from previous months and any new mortality was assessed semi-quantitatively as the percentage of live tissue surface area lost since the previous census. Photographs of initial versus final condition of the colonies provided a useful check on bi-monthly estimates. Colonies observed for mortality differed in size.

Potential causes of mortality were assigned based on the size, shape/pattern, and proximity of patches of mortality to potential stressors. For example, many of the observed incidences of mortality were located directly adjacent to crevices excavated by *Alphaeid* shrimp.

If mortality was directly adjacent to such a burrow the potential cause of mortality would be recorded as "shrimp".

Transect Characterization

Each transect was characterized in terms of benthic cover, coral colony density, rugosity, prevalence of turf algal competition, temperature, salinity, pH, and sediment composition. These data are potentially relevant to observed changes in tissue cover of coral colonies.

Benthic cover

Cover data were collected in June 2011 using contiguous but non-overlapping 0.25 m^2 photo-quadrats taken along10m transects. Point-counts were conducted using PhotoGrid software (Bird 2001). Twenty-five randomly selected points were superimposed on each photograph and substrate directly beneath the center of the point was recorded. Data were analyzed to determine the percentage of surveyed benthos covered by coral (total and by species), turf, crustose coralline and macro algae, and bare substrate.

Coral colony density and size structure

Species and maximum diameter were recorded for all coral colonies within a 10m x 1m belt transect. A coral colony was defined as an autonomous area of live tissue. Counts of colonies along 10m x 1m belt transects were divided by total area surveyed to obtain density in number of colonies/ m^2. Community and population size structure were compared using measures of density of adults and recruits (colonies <5cm in maximum diameter) and statistics of log-transformed distributions of maximum diameter such as mean size, skewness, kurtosis and variance (Bak and Meesters 1998).

Rugosity

A 15m lightweight chain was draped over the substrate along the same 10m transects. Rugosity was reported as the ratio of the length of chain required to cover the contours of the substrate by the linear distance of the taut transect line. Rugosity measurements were taken in June 2011.

Turf algal competition

Species, maximum diameter (cm), presence of turf algal competition type were recorded for all affected colonies along each 10m x 2m belt transect. Prevalence of turf algal competition, the proportion of affected vs. total colonies, was calculated by dividing the density of affected colonies by the density of all colonies along the same transects. Prevalence was calculated overall as well as by host species. Surveys were conducted in June 2011.

Temperature

Temperature was recorded using Onset HOBO Pendant ® data loggers. Loggers were placed for three intervals in June, September and November of 2011 corresponding with visits to observe marked colonies. Gaps in the data were due to loss of temperature loggers and insufficient memory to log between retrievals/replacements. Temperature data were analyzed by mean, maximum, and minimum temperature by time interval.

Sediment composition

Sediment composition and grain size were assessed at each site. Bulk samples were taken in June 2011. Two subsamples consisting of ~60 to 100g of sediment which was wet sieved through stacked sieves with opening diameters of 2.8mm, 500µm, 250µm, and 63µm. These fractions were termed rubble, gravel, coarse, fine, and silt respectively in accordance with the Wentworth scale. Samples from each level were filtered and air dried for two weeks. The samples were weighed three times on separate days. The average weight of each fraction was used to determine the percentage by weight that each fraction contributed to the total sample.

In order to determine the inorganic-organic carbon fraction ~30g of each subsample was air dried to a constant weight. Ten grams from each subsample was then ground with mortar and pestle to a fine, homogenous material, dried at 100˚C for 10 hours and weighed. The material was then placed in a muffle furnace at a temperature of 500˚C for 12 hours, cooled and weighed. Finally the sediment was placed in the muffle furnace at 1000˚C for 2 hours, cooled and weighed. The weight taken after the 500˚C burn in the muffle furnace represents the portion of the sample not including organic matter and the weight taken after the 1000˚C burn represents the portion of the sample remaining after the removal of carbonate.

Abiotic water quality characteristics

Temperature, salinity, and pH were measured every meter along each transect in September 2011, November 2011 and January 2012 using an YSI ProPlus Multi-parameter hand held unit. Relative wave action was measured using the 'clod card' technique (Jokiel and Morrissey 1993) in which Plaster of Paris blocks of a standardized size were placed on the reef for a period of time not in excess of 24 hours. An additional set of blocks was placed in still water of comparable temperature for a similar period of time. A diffusion index factor (DF) was obtained by dividing the still water calibration value by the weight loss during field exposure. The clod card technique was repeated in September 2011, November 2011, and January 2012 corresponding with observations of coral colonies.

Results

Mapping

Maps were constructed by color coding each cell by ranges of values of qualitative condition index, coral, *P. compressa* rubble and *P. compressa* skeleton coverage in order to visualize spatial patterns of reef degradation (Fig4). Cluster analyses were conducted using Getis-Ord G_i statistic to quantitatively assess whether high and low values of coral and *P. compressa* rubble are statistically significantly clustered. Maps constructed through these analyses show that there are significant clusters of high and low coral coverage and high values of *P. compressa* rubble (Fig5).

Coral Mortality

Incidence of mortality, defined here as the percentage of colonies to be affected by mortality during an interval of observation, ranged from 0 to 47.4% of colonies affected. Mean incidence did not vary by interval. September had the highest mean incidence of mortality with 26.2% of colonies affected. Incidence of mortality by species showed similar trends to overall incidence with a range of 0 to70.0% for *P. lobata* and 0 to 66.7% incidence for *P. compressa*. The September interval had the highest incidence of mortality for both species with means of 28.7% for *P. lobata* and 27.0% for *P. compressa*.

Incidence of mortality varied significantly with *P. compressa* benthic coverage in January (p=0.052, r = -0.464) and November (p=0.044, r = -0.479). There were also significant relationships between January incidence of mortality and algal competition (p=0.001, r = 0.699) and sediment composition with an increased incidence of mortality in transects with higher proportions of terriginous/silicate components in their sediments (p=0.029, r = 0.562).

Mortality was also quantified as a proportion of surface area lost in affected colonies. The mean percentage of live tissue surface area lost per affected colony ranged from 0.9% to 15%. January had the highest percentage of surface area lost with a mean of 6.49% although the mean by month did not vary significantly. Mean surface area lost by transect varied with North-South gradient in September (p=0.045, r = -0.492) with percentage surface area lost decreasing as you move North. While there were several other significant univariate relationships between surface area lost and environmental variables such as algal competition in January (p=0.043, r=0.5712), there were no clear trends between intervals making interpretation of these relationships challenging.

Causes associated with mortality included turf algal competition, shrimp and snail competition, fish predation, unknown (breakage), sedimentation, and bleaching stress. Algal competition was the most common cause responsible for 77.0% of all observed mortality events followed by *Alphaeid* shrimp competition (18.3%) and other (4.7%) including snail and fish predation, sedimentation stress, and bleaching.

Transect Characterization

Benthic cover

Measurements of total coral coverage along transects ranged from 24.0 to 63.6% with a mean of 43.4%. Total coral coverage had a weak relationship with North-South gradient (p=0.075, r = -0.429) decreasing as you move North along the reef. The lowest value of total coral coverage occurred along a transect located in the cluster of low coral coverage seen in Figure 4. Transect level measures of coral coverage agreed with census data used to rank condition. A one way ANOVA of coral coverage vs. condition showed that transects ranked as having poor condition had significantly lower coral coverage than areas of good condition (p=0.0001, r^2=58.7%).

Measurements of *P. lobata* coverage ranged from 4.2 to 37.5% with a mean of 19.86%. As in total coverage *P. lobata* coverage varied significantly (p=0.003, r= -0.658) with North-South gradient with higher coverage in the South than North. *P. lobata* coverage varied significantly with condition, with areas of good condition showing higher coverage (mean = 28.3, σ= 5.9) than areas of poor condition (mean = 13.8, σ= 7.4)

Measurements of *P. compressa* coverage ranged from 1.5 to 29.5% with a mean of 12.4%. Coverage of *P. compressa* showed a non-significant quadratic relationship with North-South gradient with lower values in the center of the reef than the north or south ends. *P. compressa* coverage did not vary significantly with condition assigned during the mapping component.

Coral colony density and size structure

Mean colony size as a measure of maximum diameter by transect ranged from 8.9 to 17.9 cm with a mean of 12.8cm. Individual colonies ranged in size from 1-100cm in maximum diameter. Colony densities ranged from 18 to 37.6 colonies/m^2 with a mean of 27.0 colonies/m^2.

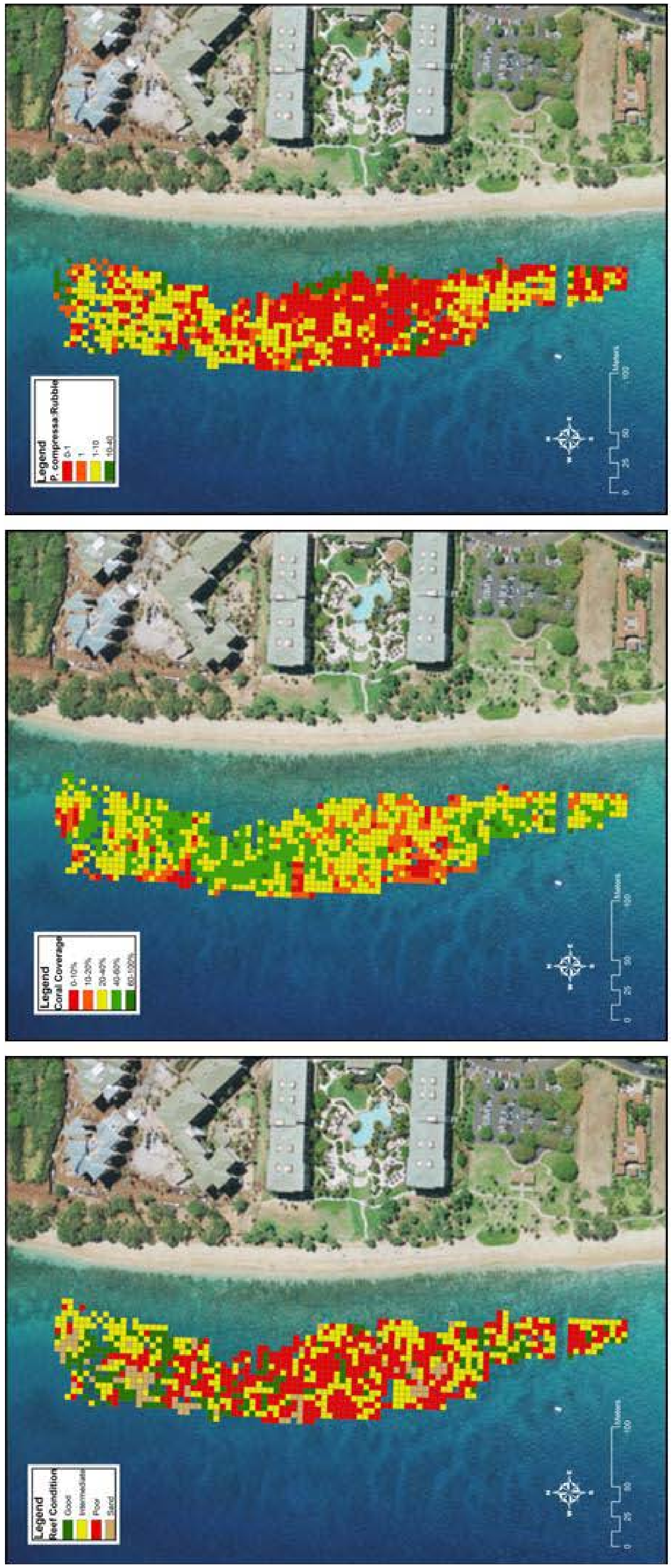

Figure 4. Maps of condition (left), percent coral coverage (center), and ratio of live to dead *P. compressa* (right).

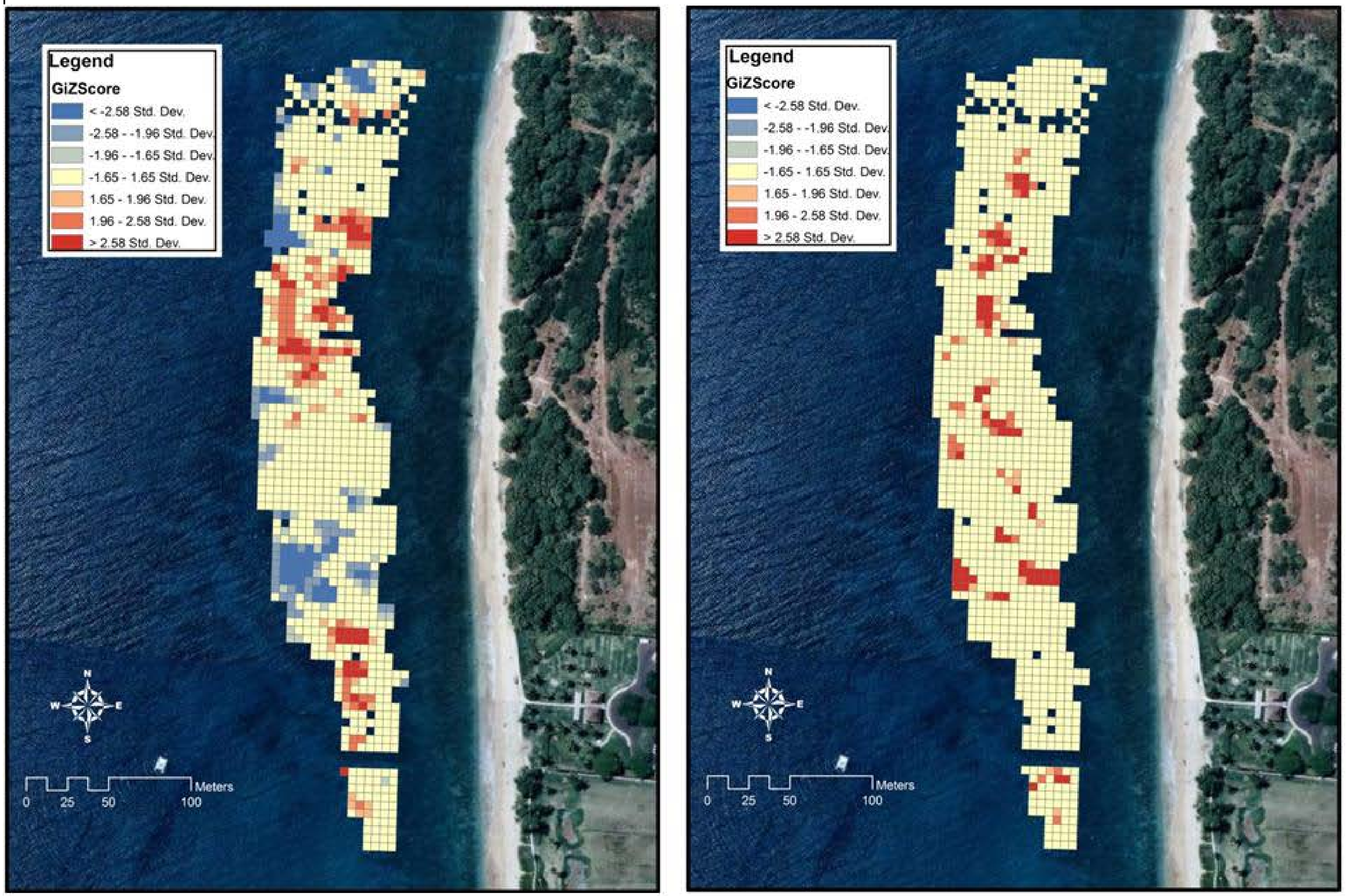

Figure 5. Maps produced through Getis-Ord cluster analysis. Low G_i Z score (blue) represent areas of significantly clustered low values of coral coverage (left) and *P. compressa* rubble coverage (right) and high G_i Z scores (red) represent areas of significantly clustered high values of coral coverage (left) and *P. compressa* rubble coverage (right).

Statistics describing the log-transformed size frequency distributions of the coral community by transect were tested against measured environmental variables. Skewness was positively correlated with North-South gradient showing a trend toward higher frequencies of larger colonies as you move north along the reef (p=0.021, r = 0.539). Kurtosis showed a positive correlation with East-West gradient, in other words, as you move East toward shore colonies tend to have a larger proportion of colonies of similar size (p=0.014, r = 0.568). Transects with higher percentage coral coverage had higher mean log-transformed maximum diameter (p=0.003, r=0.651) and lower skewness values (p=0.008, r= -0.604).

Colonies of *P. compressa* ranged in maximum diameter from 1to75cm with a mean of 12.4cm. Mean size of colonies by transect ranged from 8.5 to 19.7cm with a mean of 12.5cm. Statistics of log-transformed values showed a significant relationship between coral coverage and mean log-transformed size of colonies (p=0.026, r = 0.523). Colonies of *P. lobata* ranged from 1-100 cm in maximum diameter with a mean of 16.6cm. Transect means ranged from 10.7 to 24.6 cm maximum diameter with a mean of 18.1cm. *P. lobata* skewness of log-transformed diameter varied significantly with qualitative condition (p=0.001, r^2=62.72%) with transects of good (mean = -0.4915, σ = 0.0775) and intermediate (mean = -0.61, σ = 0.19) condition showing negative values and transects of poor (mean = 0.01, σ = 0.33) condition showing positive values.

Recruits were defined as any colony smaller than 5cm in maximum diameter. Recruit density ranged from 1.1 to 10.9 recruit/m^2 with a mean value of 5.4 recruits/m^2. *P. compressa* recruit density ranged from 0.6 to 5.7 recruits/m^2 with a mean of 1.9 recruits/m^2. *P. compressa* recruit density varied positively with North-South gradient (p= 0.034, r=0.501), and negatively with coral coverage (p= 0.006, r= -0.623).

Rugosity

Rugosity ranged from 12.4 to 17.2 with a mean of 14.5. Rugosity was significantly positively correlated with coral coverage (p=0.005, r= 0.628).

Turf algal competition

Prevalence of turf algal competition in all species of corals ranged from 0 to 3.4% with a mean of 1.4% of colonies affected. Prevalence of algal competition including all species varied significantly by North-South gradient with higher levels of algal prevalence in the South than the North (p=0.029, r= -0.514). *P. lobata* showed significantly higher prevalence of algal competition (mean = 4.28, σ = 3.71; p-value = 0.000, r^2=26.34%) than *P. compressa* (mean = 1.28, σ = 1.41) or all species grouped together (mean = 1.43, σ = 1.07). *P. compressa* prevalence of algal competition varied significantly with January wave action measurements (p=0.04, r= 0.689) with higher levels of wave action leading to higher levels of algal competition.

Temperature

Temperature was measured using *in situ* loggers for 3 intervals: Interval I) from June 25, 2011 to August 22, 2011, Interval II) from September 25, 2011 to November 13, 2011, and Interval III) from November 20, 2011 to January 15, 2012. Temperature data were analyzed as mean, maximum, and minimum values by time period. Mean temperatures did not vary by interval. Minimum and maximum values were significantly lower (p= 0.000, r^2=43.76%) in the last time period (mean min=23.01ºC, mean max=24.69 ºC) than in intervals I (mean min = 24.48, mean max= 26.17) and II (mean min = 34.48, min max = 26.30). Temperature did not vary significantly with any other environmental explanatory variables.

Sediment composition

Sediment grain size and composition did not vary significantly with any other environmental variable. Medium grain size (500µm sieve) was the most common size followed by coarse (2.8mm), fine (250µm), and silt/clay (63µm).

Sediments were primarily composed of calcium carbonate (mean = 84.22% of sample, σ = 7.60% of sample) followed by terrigenous or silicate compounds (mean = 12.01 % of sample, σ = 7.46% of sample) and organic components (mean = 3.77% of sample, σ = 0.64% of sample).

*Abiotic water quality characteristic*s

There was a significant negative correlation between January temperature readings and North-South gradient ($p = 0.0001$, $r = 0.873$). A similar but non-significant relationship was observed in the relative measurements of wave action taken in January using clod cards with North-South gradient ($p = 0.095$, $r= -0.589$). January temperatures varied significantly with North-South gradient ($p = 0.004$), January clod card indices ($p = 0.015$) and their interaction ($p = 0.015$). The inclusion of a measure of the distance from the most consistent effluent seep in the area was also significant ($p = 0.001$) in an added last test in the previously described model. It should be noted that all factors included in the model are related to each other as well as the response and should be interpreted with caution.

Discussion

The goal of this study was to determine what processes are driving the degradation of coral reef at Kahekili Beach Park in Kaanapali, Maui. This required that we identify areas of historical degradation, or "dead zones", in order to further study them. The mapping component of this study showed that there are discrete, significantly clustered patches of varying degrees of degradation along the length of the reef at Kahekili Beach Park. The fact that these patches are clustered helps us to understand the scale at which processes are affecting this reef. If the degradation was homogenous throughout the reef then you would look for stressors at a larger scale than if you see isolated degradation as seen here.

Patches of degradation varied in size but generally fell into three categories of degradation. The first classification consisted of small patches of intense or acute degradation resulting in very low coral cover generally in association with high concentration of *P. compressa* rubble or standing but dead skeleton. These smaller more intensely degraded patches coincided with the hotspots of high values of *P. compressa* rubble coverage in the Getis-Ord cluster analysis shown in Figure 5. The second class of patches tended to be larger in area, were moderately degraded, and coincided with the hotspots of low values in the Getis-Ord cluster analysis of coral coverage in Figure 5. The most pronounced of these patches of intermediate degradation occurred just North of the beach park in front of the southernmost of four resorts in the area. Interestingly, this area of moderate degradation is surrounded by areas of higher than average coral coverage. The third classification consisted of reef in relatively good condition with little to no sign of degradation.

Once categorical classifications of degradation had been established, we were able to address potential drivers of decline. Based on our analysis of community and population size structure, there does not appear to be a failure of recruitment in these areas. *P. compressa* juvenile density varied with North-South gradient showing more recruits in the Northern end of the reef, however this coincided with a decrease in coral coverage. It is common knowledge that observations of recruits increase with decreased coral coverage due to the density dependent relationship between open space and the ability of larvae to settle and survive. While recruitment failure does not appear to be the cause of decline in these dead zones, qualitative observations of the nature of substrate inside and outside of "dead zones" suggest that while recruits may settle and survive they may be scoured off of substrate in storms or wave events in dead zones where substrate is primarily comprised of loose rubble.

Measures of skewness and kurtosis of log-transformed size-frequency distributions showed that there are differences in community and population level distributions varied with position in North-South and East-West gradients along the reef as well as with categorical condition index, and coral coverage. Interpretation of these trends can be complicated but the general trend in the context of field observations were as follows:

- A trend towards larger mean size of colonies in areas with higher coral coverage.
- A larger number of outliers of larger size in areas of good or intermediate condition,
- A higher proportion of colonies in a narrower band around the mean in water closer to shore.

These observations are of practical importance because with proper interpretation these statistics can provide information on drivers of degradation. For instance, in areas of low coral coverage, such as "dead zones", the mean colony size is smaller than in areas of higher coral coverage, and the range of colony sizes is narrow and centered at intermediate sizes. This could be indicative of a pulse of recruits that arrived at the same time and are of similar size. Alternatively, and probably more likely in this case, colonies in areas of low coral coverage may be affected most strongly by a single driver, and colonies of a certain size class may be better suited to survive exposure to that stressor resulting in a trend toward a more a uniform size distribution.

Once patterns of historical mortality and population demography had been addressed, we used marked colonies to investigate rates of mortality in the area. Rates and incidence of mortality were within the ranges observed in the previous island wide study. However, the role of turf algal competition appears to be much more influential at Kahekili than any of the other sites observed in the 2009 study. Indeed turf algal competition was the variable most commonly associated with observations of mortality. Turf algal coverage appeared to increase in the warmer months of August and September coinciding with the highest incidence of mortality in both species observed. Although rates of mortality varied by species, it was associated with coral coverage, sediment composition, and prevalence of algal competition. While associations with environmental variables were observed, the trends were not consistent across months making interpretation challenging.

Several environmental variables were measured to test for relationships between their levels and rates of mortality. Benthic coverage, rugosity, and depth were all correlated as would be expected. Temperature was significantly lower in January than November or September but did not vary significantly with any other variables. Prevalence of turf algal competition was higher at the southern end of the reef and also higher in *P. lobata* than in *P. compressa*. Sediment composition did not show strong spatial relationships. Components often associated with run-off such as high proportions of terrigenous or organic components, and silt/clay grain sizes were low along the entire study area.

Abiotic water quality characteristics did not vary significantly between intervals however, it is important to note that water quality and wave action parameters are extremely variable and require high sample sizes in order to interpret long-term trends. Our limited number of opportunities to sample water variables led to some observations that were difficult to interpret. For instance, an outlier in the month of September, in an area of poor condition at the Southern end of the reef had lower mean values of pH and salinity, and higher values of temperature than all other transects. While values such as these could be dismissed as outliers, given the documented presence of nutrient rich, warmer than ambient, freshwater input via waste water injection wells, such values could be valid data points. Such relationships while thus far inconclusive warrant further attention.

Conclusions

Our investigations into historical mortality via mapping and population demography suggest that there were historical losses in coral coverage resulting in large areas of dead coral skeleton. The recovery of these areas does not appear to be limited by recruitment availability but may be limited by survival of recruits in loose substrate. Statistics related to the size distribution of coral communities and populations suggest that there may be different processes resulting in different patterns (i.e. moderate vs. severe types)of degradation.

Observations of ongoing mortality suggest that turf algal competition is an important factor in the mortality of *Porites* at Kahekili Beach Park. The increase in coral mortality in the warmer months of August and September is consistent with findings from the earlier Maui wide study; however, this warmer season with lower wave action might be particularly important in an area such as Kahekili where algal interactions play such a strong role in population dynamics. There are spatial patterns in rates of mortality with losses of higher percentages of surface area in the south than in the north. Several environmental variables including algal competition and benthic coverage varied with North-South gradient. These relationships in turn affected the rates of mortality observed in these areas.

The mortality observed in the course of this study is chronic and slow moving as compared to storm, disease, or bleaching events. Rates, causes, or patterns (i.e. chronic vs. acute) do not vary by condition index; in other words, they do not appear to vary inside vs. outside of dead zones. Rates of mortality do vary spatially with location along the reef. That is to say that while there is spatial variation in rates of mortality and in prevalence of algal competition, it is not associated with previous incidents of degradation. This suggests that while ongoing mortality is more prevalent in some areas it is not necessarily more prevalent in areas where degradation has occurred in the past. Also, though *P. compressa* is the species most commonly associated with "dead zones" , turf algal competition was more prevalent in *P. lobata*. This observation reiterates the observation that the patterns in population demography (i.e. degradation of *P. compressa*) are not necessarily associated with ongoing trends.

Observations made through this research provide us with some answers as to what types of mortality are occurring at on the reef fronting Kahekili Beach Park. The mapping component provides us with an important baseline and photo documentation of benthic coverage and condition describing areas of historical degradation. Results based on colony scale observations and transect based surveys of environmental variables point to the importance of turf algal competition in addition to macro-algal competition via ephemeral blooms in 2001 and 2003. Results of spatial analyses show that there are indeed relationships between mortality, community and population structure, and location along the reef. All of these findings are important steps toward understanding the role of site specific processes in the decline of the reef at Kahekili Beach Park, Maui.

Recommendations/Further Research

The following recommendations are possible next steps in continuing the process toward understanding stressors affecting Maui's coral communities:

- Continued observations of marked colonies to obtain a minimum of one full year of data on rates of mortality. These data are particularly important given the temporal/seasonal variation in rates and causes of mortality.
- Comprehensive water quality testing on finer spatial and temporal scales. The findings from this study including the location, severity of degradation, and rates of coral mortality that can be used to guide these testing efforts.
- Analysis of long-term monitoring photoquadrats along the CRAMP transect affected by "dead zone" in order to determine whether origins of "dead zones" was chronic or catastrophic. The long-term monitoring station at this site has a record dating to 1995. Current analysis of digital photoquadrats from 1999 to present through an ongoing NSF CAMEO grant does not include the period from 1995 to 1999 during which the decline in coral coverage was initially observed at Kahekili Beach Park.
- More in depth investigation into coral population demography including rates of settlement, survival, and substrate preference of recruits should be conducted to determine whether recruitment failure plays a role in the degradation of Kahekili Beach Park.
- Further multivariate analysis of the complex relationships between environmental variables and patterns of historic and ongoing mortality. Also, comparative analysis to determine the best optimum scale and strategy for studying sites with patchy distributions of mortality, such as Kahekili Beach Park.

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