Quantifying Causes of Maui Coral Decline

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Table of Contents

Abstract

Surveys were conducted between March 2009 and January 2010 to quantify impacts of environmental stressors on individual coral colonies at various sites along the Maui coastline. Environmental factors of interest included sedimentation, temperature, turbidity, coral disease, algal cover, herbivore and corallivore density and biomass. Estimates of percentage of coral surface area lost based on observations of marked colonies ranged from 7.6% at Maalaea to 1.4% at Olowalu. Most colonies showing decline (67.6%) lost ≤5 % of their surface area. The most common stressor associated with mortality was competition with algae observed in 44% of the colonies with tissue loss. Maalaea was the most affected by algal competition, which was associated with 85% of the incidents of observed mortality. More colonies lost tissue between May and September than any other time. Mortality was not necessarily progressive. The same colony could lose tissue in different patches and with different causes over time. Maalaea had the highest proportion of declining colonies (85.0%) and the highest loss of coral surface area (7.6%). Molokini had the lowest proportion of declining colonies (45%) but the fourth highest loss of coral surface area (3.5%) due to death of a large *P. lobata* colony associated with a bleaching event. Thus, decline in tissue cover during the study resulted from a combination of chronic and episodic mortality events. The most common stressors associated with tissue loss are turf algal competition (impacted inshore sites) and bleaching (comparatively healthy offshore site). Chronic stressors observed during this study caused low but persistent levels of mortality that may reduce the ability of corals to cope with more drastic episodic events. Results lend support to the contention that observed decadal decline in coral cover is due to natural and anthropogenic factors acting within a complex ecological framework that result in chronic reduction in coral tissue cover as well as acute mortality.

Background

Coral reefs around Maui Island have experienced rapid and severe declines in coral cover over the past 10-15 years. Nearly 25% of all live coral cover has been lost from transects monitored by Division of Aquatic Resources (DAR) in collaboration with the Hawaii Coral Reef Assessment and Monitoring Program (CRAMP) at nine long-term monitoring stations around Maui Island since 1998 (Williams et al. 2007). While there is clear evidence of substantial coral decline at monitoring sites around Maui Island in recent years, the stressors associated with those declines and patterns of mortality within and between colonies and sites are uncertain. There are, however, strong indications that human impacts have been very important. Notably, cover has declined at several West Maui sites where anthropogenic impacts from shoreline development and human use are comparatively high, and conversely, sites which are remote or offshore have experienced increases or sustained high coral cover (Williams et al. 2007). A question remains as to whether entire coral colonies die suddenly due to acute, episodic events or if they tend to gradually decline in the face of increasingly detrimental environment. At one location, Honolua Bay, where total benthic coral cover declined from 42% to 9% between 1994 and 2006, there are indications that terrestrial sedimentation has been a factor in recent coral loss. These corals may be suffering from long-term chronic sediment stress, but perhaps the decrease was due to acute mortality resulting from a combination of heavy rainfall with oceanographic conditions that temporarily acted to retain sediment within the bay (Dollar and Grigg 2004).

The goals of this project were to generate data on the extent and proximal cause of coral tissue loss, on differences in mortality rate at six of DAR's long-term monitoring sites around Maui Island, and on biotic and abiotic factors linked to reef decline. The approach used provided more detailed information on processes of mortality by making observations on individual coral colonies at shorter intervals (2 months) rather than measuring coral cover along transects at longer intervals (1 year). This approach has the advantage in that it allows for a trained biologist to observe in detail the stressors associated with individual coral colonies. Annual observations may provide information on mortality, but cannot be used to estimate rates of rapid mortality or associations with environmental stressors. While this methodology provides valuable fine scale information, the experimental design is labor intensive so the sample size must realistically be smaller and resulting in lowered statistical power. The method is semi-quantitative in that the observer must interpret changes in complex colony growth forms. Conclusions as to the cause of tissue loss by this method can be subjective, but are based on the judgment of a skilled observer with intimate and frequent contact with the coral colonies in their environment. The method is biased towards mortality which is more conspicuous and easily quantified than growth. Despite the methodological limitations, the data on rates and stressors associated with mortality generated by this project provide a useful baseline that complements the 10-15 years of monitoring data on per cent coral cover from each of the study sites and will be used to direct further research focused on causes of reef degradation.

Methods

All surveys were conducted along pre-existing permanent transects maintained as part of a long-term monitoring program administered by the Maui branch of DAR in collaboration with CRAMP. Sites included Honolua Bay, Kahekili Beach Park, Maalaea, Kanahena Cove, Molokini and Olowalu (Fig 1). Sites were classified based on decline in coral cover as degraded (Honolua, Kahekili, Maalaea), comparatively healthy (Kanahena, Molokini) and intermediate but at risk (Olowalu). Each site consists of one transect at a depth of ~3m and one transect at a depth of ~10m. Three meter sites were used at all sites with the exception of Molokini where the 10m site was more easily and safely accessible.

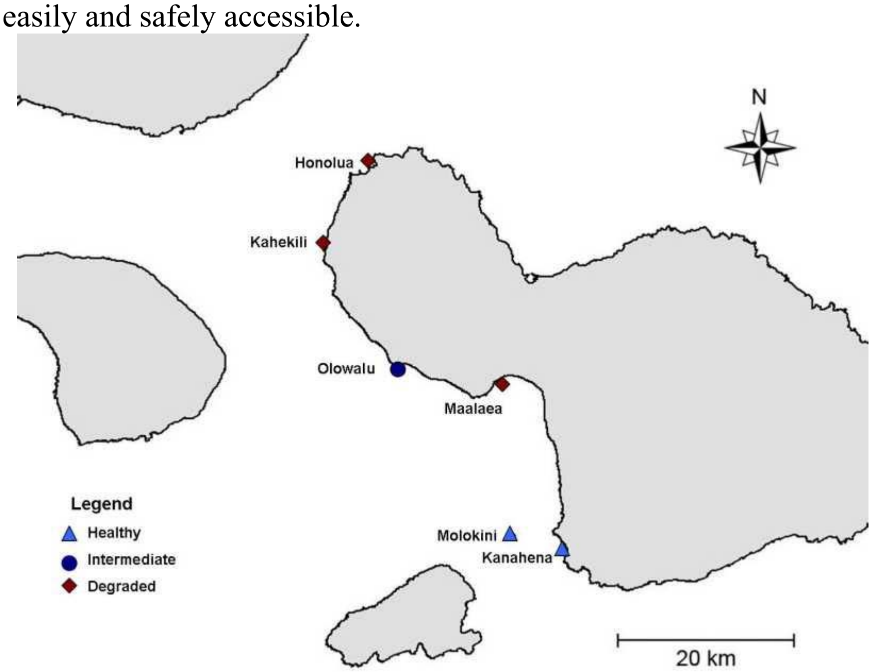

Figure 1. Sites around Maui island classified as healthy, intermediate and degraded based on levels of coral cover decline from DAR/CRAMP long-term monitoring data

Site Descriptions

Honolua Bay is a Marine Life Conservation District (MLCD) in a semi-enclosed bay bordered by north and south basalt cliffs with sand, rock and boulder shoreline. The north and south bay reef flats crest and slope to a central 8 to 13 m deep coarse sand channel with beds of *Halimeda incrassata*. South reef coral has colonized basalt while the north reef is more developed with higher coral coverage. Coverage on both reefs increase with depth. An intermittent stream enters the bay at the south end of the beach. During periods of high stream flow there is often a 0.5-1m layer of freshwater and fine sediment/silt at the surface of the water column. The bay is exposed to north swell and is a popular surf spot during the winter months. The bay is also a popular snorkel and SCUBA site with several resident snorkel charters. Surveys were conducted along the transect located on the north reef (Jokiel et al. 2001).

Kahekili Beach Park is part of a recently established Herbivore Enhancement Area where the removal of herbivorous species has been restricted in response to blooms of the invasive alga *Acanthophora spicifera*. Management concerns also include nutrient input by nearby agricultural fields and a sewage treatment plant in close proximity to the site with four injection wells. The beach and shoreline are composed of exposed limestone rubble and sand. There are several condominiums along the beach. The beach is frequently used by SCUBA and snorkel enthusiasts and tourists (Jokiel et al. 2001).

The Maalaea site is located directly outside Maalaea small boat harbor. The site is also adjacent to several condominiums, a shopping center, residential and agricultural areas. The reef flat is composed primarily of calcium carbonate and is heavily dominated by fleshy macroalgae. This site is exposed to south swell and is often used by surfers and fishermen. The swell and proximity to agricultural fields can result in elevated turbidity.

Kanahena Cove is within the Ahihi Kinau Natural Area Reserve (NAR). The cove was not included in the recent closures of coastal areas within the reserve and it is as yet unknown whether this has increased the use of the area for recreational swimming/snorkeling. There is some residential development north of the bay, but relatively little compared to other survey sites. The shoreline is basalt rock and boulder habitat with patches of encrusting and lobate corals (Jokiel et al. 2001). Management concerns include trampling of corals in the shallower areas of the cove.

Molokini is a cinder cone islet with a 30m deep crater surrounded by highly transparent, low nutrient oceanic water up to 150m deep. The reef inside the crater is a boulder, sand, and rich coral reef habitat supporting an abundant and diverse fish community. The islet is currently an MLCD and Island Seabird Sanctuary but was previously used as a U.S. bombing range. Molokini is heavily used by commercial snorkel and dive boats with over 1000 visitors per day (Jokiel et al. 2001). This is the only site where surveys were conducted along the deeper transect for safety and accessibility reasons. Snorkel and dive boats moor along the inside edge of the island making it logistically difficult and hazardous to safely locate the shallow transect.

The Olowalu site has complex subtidal topography with an extensive spur and groove system, sand channels and aggregated coral formations (large *Porites lobata* heads). Coral cover increases seaward. The site is exposed to south swell and corresponding sedimentation and high turbidity. The coast is a narrow olivine sand beach with a basalt cobble subtidal zone with a gradually sloping seaward reef platform. There is currently little development adjacent to the site although a development project is pending (Jokiel et al. 2001).

Measurement of Coral Tissue Mortality

Ten colonies each of *Porites lobata* and *Montipora patula* were selected haphazardly along the first ~20m of the surveyed area and tagged with unique color combinations of cable ties affixed to non-living substrate. Colonies were revisited, photographed, and inspected for signs and proximal causes of mortality every two months for a period of 10 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. Initial colony two-dimensional area was calculated from mean diameter. Rate of tissue loss or gain for the colony surface area was estimated by multiplying the initial estimated surface area by the semi-quantitative estimate of percentage of surface area lost in order to convert percentage lost to live tissue surface area lost (cm^2). Total initial surface area and percentage change at each site were calculated.

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". In situations where a new patch of mortality was observed adjacent to a large fleshy algae and the pattern of mortality was consistent with documented cases of algal abrasion the mortality would be attributed to "Algae".

Site Characterization

Each site was characterized in terms of benthic cover, coral density, rugosity, level of coral disease, herbivore and corallivore density, temperature, and sediment composition. These data are potentially relevant to observed changes in tissue cover of coral colonies.

Benthic cover.

Initial cover data were collected in May 2009 using 1 m^2 photo-quadrats taken along two 25m transects separated by 5m. Point-counts were conducted using PhotoGrid software. Fifty randomly selected points were superimposed on each photograph and substrate directly beneath the center of the point was recorded. Data was analyzed to determine the percentage of surveyed benthos covered by coral, algae, and bare substrate. While data were collected using the same methodology along the same transects in January 2010, two transects were not sufficient to detect changes in total coral cover over the short 10 month period of this study (Brown et al. 2004). The data are sufficient to characterize the specific area of study.

Coral colony density.

All coral colonies completely inside the same 1m^2 quadrats used to calculate benthic cover were traced using ImageJ ™ software. A coral colony was defined as an autonomous area of live tissue. Species and maximum diameter (cm) were recorded for each colony. Counts of colonies along 25m x 1m belt transects were divided by total area surveyed to obtain density in number of colonies/ m^2. Densities were calculated overall as well as by species.

Rugosity

A 15m lightweight chain was draped over the substrate along the first 10m of the two 25m transects surveyed at each site. 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 March 2009 and January 2010.

Coral disease

All corals colonies were counted along two 25m x 2m belt transects separated by 5m. Species and maximum diameter (cm) were recorded for all colonies. Disease type and description were recorded for each colony exhibiting disease. A coral colony was defined as an autonomous area of live tissue. Disease prevalence, the proportion of diseased vs. healthy colonies, was calculated by dividing the density of diseased colonies by the density of all colonies along the same transects. Prevalence was calculated overall as well as by disease type, and host species. Surveys were conducted in May 2009 and January 2010.

Herbivore abundance

All observed fish were counted along two 25m x 5m belt transects separated by 5m. Fish species and estimated total length (cm) were recorded. Density was calculated as the number fish per m^2. Biomass was calculated (g/m^2) using length-mass fitting parameters obtained from the Hawaii Cooperative Fishery Research Unit (HCFRU) and FishBase (www.fishbase.org). The proportion of herbivores and corallivores in overall populations were calculated as functions of density and biomass. The number and species of all urchins were recorded along two 25m x 1m belt transects separated by 5m in order to determine density (individuals/m^2).

Temperature

Temperature was recorded using Onset HOBO Water Temp Pro v2 ™ loggers. Loggers were placed in May of 2009 for a period of eight months. Loggers were removed and simultaneously replaced in October of 2009. Gaps in the data were due to loss of temperature loggers and insufficient memory to log between retrievals/replacements. Kahekili has no data due to the loss of two temperature loggers, presumably due to removal by concerned citizens despite the use of signage and cryptic placement of the equipment.

Sediment composition

Sediment composition and grain size were assessed at each site. Two samples were taken in May 2009 and in January 2010. In order to determine the grain-size distribution at each site we took two subsamples from the initial and final samples. Each subsample consisted 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.

Total suspended sediment was recorded as grams of suspended sediment per volume (L) of sea water. Two 2-Liter samples were taken at each site on each of the 6 trips. The samples were filtered through 0.43µm filters. The filters were air dried for at least one week and weighed at least three times until weight remained constant. The last three weights were averaged and divided by the volume of water filtered.

Results

<u>Coral Tissue Mortality</u>

Over the 10 months of observation, 72 of the total 116 (62.1%) colonies suffered some level of mortality. Maalaea had the highest proportion of total colonies that exhibited mortality (85.0%). Molokini had the lowest proportion of total colonies that exhibited mortality (45.0%). The proportions of colonies suffering mortality were not significant between sites (χ^2 =8.807, p = 0.117) or between species within sites (Table1).

Table1. Proportions of colonies exhibiting tissue loss by site, overall and by species. Results of Chi-squared tests of difference between number of affected *Porites lobata* and *Montipora patula* by site.

Site	Overall	*P. lobata*	*M. patula*	χ^2 , p-value
Honolua	0.58	0.60	0.56	0.038, 0.845
Kahekili	0.50	0.40	0.60	0.800, 0.371
Kanahena	0.68	0.60	0.78	0.693, 0.405
Maalaea	0.85	0.90	0.80	0.392,0.531
Molokini	0.45	0.70	0.60	0.220, 0.639
Olowalu	0.67	0.75	0.60	0.450, 0.502

Percentage of live tissue surface area lost ranged from 0-100%. Of the 72 colonies experiencing mortality the majority (67.6%) experienced ≤ 5% tissue loss over the duration of the study. Of the 72 colonies to lose tissue, only 1 suffered complete mortality with 100% loss of tissue. The colony in question was a colony of *M. patula* from the Maalaea site. The colony was periodically covered by turf algae and the invasive alga *Acanthophora spicifera* for at least 4 months leading up to its death (Fig 2). The mean proportion of colonies to suffer mortality differed temporally (F = 10.960, p-value = 0.000) ranging from 6.0± 9.0 %- 34.0± 8.0 % of colonies exhibiting tissue loss between each visit. The temporal patterns were consistent between sites. The highest proportions of colonies to exhibit mortality were observed between the May, July, and September 2009 surveys. The lowest proportion of colonies to lose tissue occurred between the March and May 2009 surveys (Table 2). Twenty-eight of the 72 colonies (38.9%) suffered mortality between more than two surveys.

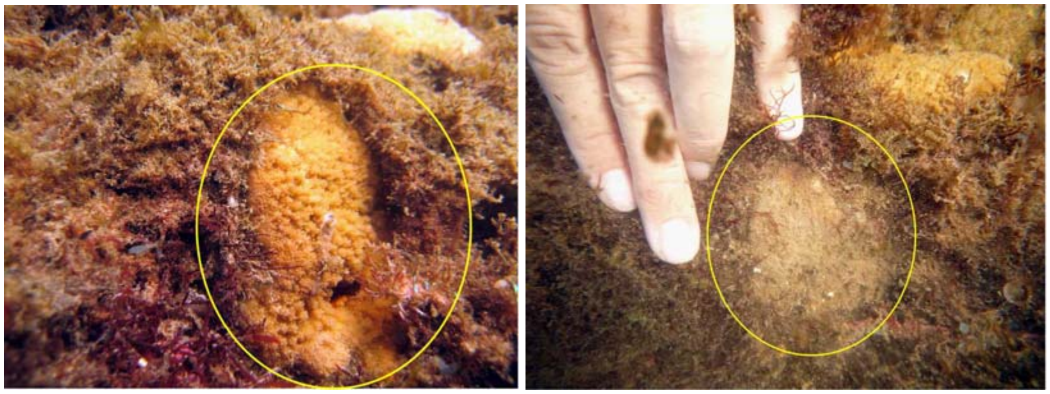

Figure 2. *M. patula* colony (circled in yellow) in October 2009 (left) and January 2010 (right) experienced 100% tissue loss over the course of 2 months. Mortality was associated with the mat of turf and macroalgae being pulled back from the dead skeleton (right).

Table 2. Proportion of colonies to lose tissue by census month. Significance based on 95% Tukey's pair wise comparison of one-way ANOVA. The mean proportion of colonies to lose tissue across all sites observed during months designated "A" did not differ significantly from each other but did differ significantly from months designated "B" and vice versa.

Site	May	July	September	November	January
Honolua	0.21	0.37	0.26	*	0.16
Kahekili	0.05	0.25	0.30	0.10	0.10
Kanahena	0.00	0.32	0.42	0.26	0.26
Maalaea	*	0.45	0.40	0.15	0.25
Molokini	0.00	0.25	0.20	0.15	0.10
Olowalu	0.06	0.39	0.22	0.11	0.17
Significance	A	B	B	A	A
Mean	0.06	0.34	0.30	0.15	0.17
s.d.	0.09	0.08	0.09	0.06	0.07

In most cases the mortality was not obviously progressive and in 23 of the 28 cases (82.1%) there were multiple unrelated suspected causes differing by visit. Of the 72 colonies to lose tissue, algal competition was the most common stressor associated with tissue loss (44.0%) (Fig3). Algal competition was most severe at Maalaea where 58.8% of the colonies to lose tissue could be attributed to algal competition. Of the colonies experiencing mortality only one colony (1.4%) had a cause other than competition with other biotic sources such as Alpheid shrimp, Vermetid snails, corallivorous predators, neighboring coral colonies, and algae. The colony in question experienced 80% loss of live tissue over the course of 6 months (Fig 4). Most of the tissue loss occurred following a bleaching event documented by Maui DAR.

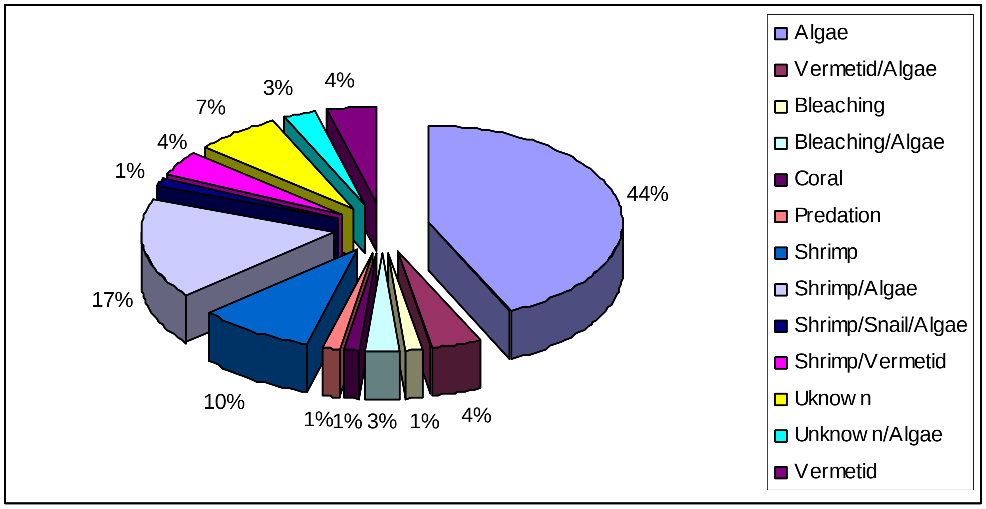

Figure 3. Stressors associated with tissue loss in coral colonies that lost tissue (proportion).

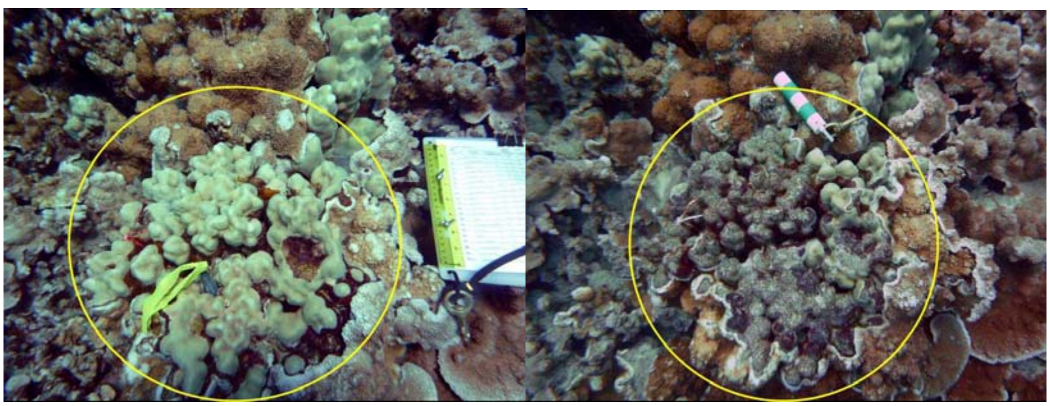

Figure 4. *Porites lobata* colony (circled in yellow) in March 2009 (left) and January 2010 (right) experienced 80% tissue loss over the course of 6 months. Mortality was associated with a bleaching event reported by Maui DAR.

The total percentage of live tissue surface area lost (cm^2) by site ranged from 7.6% at Honolua to 1.4% at Olowalu (Table 3). The two sites with the highest percentage of tissue lost had been classified as degraded, the third and fourth highest tissue loss were observed at Kanahena (3.5%) and Molokini (3.5%), the two sites classified as healthy. The two sites with the lowest percentage of tissue lost Kahekili (3.4%), and Olowalu (1.4%) were classified degraded and intermediate to at risk respectively.

Table 3. Percentage of colonies with tissue loss and percentage of overall surface area of tissue lost (cm^2) by site.

Site	% Colonies	% Tissue
Honolua	57.89	4.25
Kahekili	50.00	3.37
Kanahena	68.42	3.54
Maalaea	85.00	7.56
Molokini	45.00	3.48
Olowalu	66.67	1.39

Benthic Cover

The percentage of benthic cover comprised of turf algae increased from March 2009 surveys to January 2010 surveys at Honolua, Kahekili, and Maalaea. The reverse was true of Kanahena, Molokini, and Olowalu where coverage of turf algae decreased over time (Fig 5). Temporal changes in percentage of benthic surface area covered by coral, turf and macroalgae were not significant due to low statistical power associated with limitations of the sampling regime (Table 4).

Colony Density

There was no significant change in coral colony densities at any site between surveys (Table 5). Kahekili had the highest overall colony density and Kanahena had the lowest. Colony densities differed between the two species of interest at Olowalu and Maalaea ($\alpha = 0.1$). There were fewer colonies of *M. patula* per m^2 than *P. lobata* at Maalaea with the opposite trend found at Olowalu (Table 6).

Table 5. Densities (individuals/m^2) of all spp. of coral from May 2009 and January 2010 surveys.

Site	May,2009	Jan, 2010	t, p-value
Honolua	18.12 ± 0.68	8.3 ± 2.51	-5.33, 0.12
Kahekili	44.45 ± 23.94	39.79 ± 3.45	-0.27, 0.83
Kanahena	3.33 ± 0.32	8.57 ± 1.13	6.57, 0.1
Maalaea	8.44 ± 6.59	7.96 ± 4.18	-0.09, 0.94
Molokini	20.08 ± 0.73	15.94 ± 3.05	-1.86, 0.31
Olowalu	43 ± 25	28.25 ± 6.95	-0.8, 0.57

Table 6. Densities of corals by species for May 2009 and January 2010 surveys.

	May, 2009		**Jan, 2010**	
Site	***P. lobata***	***M. patula***	***P. lobata***	***M. patula***
Honolua	5.74 ± 0.15	2.68 ± 0.25	3.44 ± 1.55	1.85 ± 0.22
Kahekili	4.61 ± 2.84	13.27 ± 3.59	16.94 ± 2.07	5.36 ± 0.58
Kanahena	0.54 ± 0.14	1.09 ± 0.05	2.31 ± 1.42	2.04 ± 1.47
Maalaea	7.46 ± 6.43	0.21 ± 0.08	7.18 ± 4.42	0.35 ± 0.25
Molokini	3.45 ± 1.09	4.09 ± 0.83	1.37 ± 0.45	3.19 ± 0.72
Olowalu	1.08 ± 0.11	7.01± 2.53	0.86 ± 0.54	2.58 ± 0.82

Table 4. Mean proportions of benthic surface area (m^2) at each site covered by coral, turf and macroalgae during March 2009 and January 2010 surveys.

	Honolua Jan	Honolua March	Kahekili Jan	Kahekili March	Kanahena Jan	Kanahena March	Maalaea Jan	Maalaea March	Molokini Jan	Molokini March	Olowalu Jan	Olowalu March
Coral	0.140	0.175	0.437	0.220	0.189	0.237	0.061	0.099	0.839	0.610	0.160	0.209
s.d.	0.021	0.010	0.009	0.093	0.050	0.029	0.052	0.041	0.013	0.404	0.059	0.022
t, p-value	-2.16,0.270		3.29, 0.188		-1.18,0.448		-0.82, 0.562		0.8, 0.570		-1.10, 0.47	
Turf Algae	0.484	0.134	0.235	0.085	0.008	0.056	0.420	0.165	0.000	0.047	0.002	0.135
s.d.	0.106	0.034	0.030	0.042	0.011	0.054	0.152	0.164	0.000	0.023	0.002	0.190
t, p-value	4.45,0.141		4.10, 0.152		-1.25,0.430		1.62, 0.353		*		-0.99, 0.504	
Macroalgae	0.026	0.062	0.004	0.034	0.000	0.000	0.354	0.525	0.000	0.000	0.003	0.002
s.d.	0.025	0.038	0.002	0.031	0.000	0.000	0.092	0.185	0.000	0.000	0.001	0.003
t, p-value	-1.11, 0.466		-1.36,0.404		*		-1.17, 0.451		*		0.11,0.93	

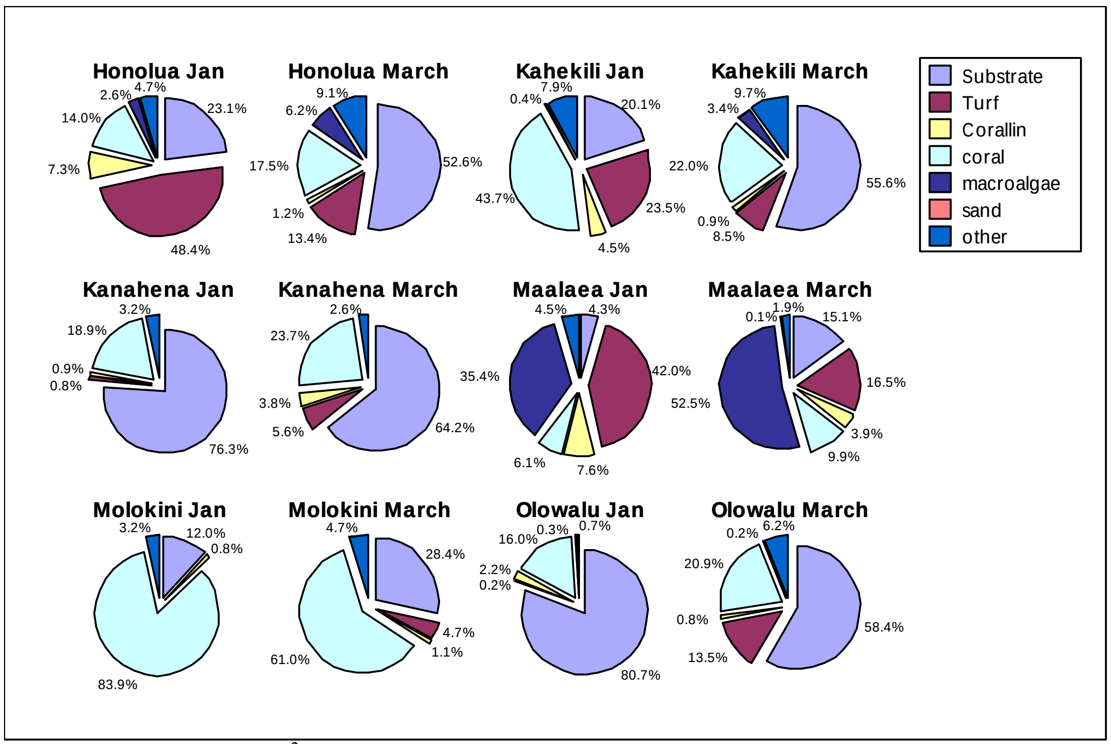

Figure 4. Proportions of total benthic surface area (m^2) covered by biotic and abiotic components at each site during March 2009 and January 2010 surveys.

Rugosity

There were no significant changes in rugosity between the March 2009 and January 2010 surveys. Rugosity was highest at Honolua Bay and lowest at Kanahena cove (Table 7).

Table 7. Results of two –sample t-test of mean rugosity ratios from March 2009 and January 2010 surveys.

Site	May 2009	Jan 2010	t, p-value
Honolua	2.52 ± 0.15	1.75 ± 0.15	1.58, 0.36
Kahekili	1.33 ± 0.32	1.4 ± 0.20	-0.27, 0.832
Kanahena	1.24 ± 0.01	1.32 ± 0.02	-5.31, 0.118
Maalaea	1.09 ± 0.08	1.11 ± 0.01	-0.36, 0.779
Molokini	2.17 ± 0.18	1.41 ± 0.01	5.88, 0.107
Olowalu	1.48 ± 0.08	1.6 ± 0.01	-2.34, 0.257

Coral Disease

Disease prevalence, proportion of all observed colonies with disease, was highest at Kanahena cove (Table 8). The most commonly observed diseases were *Porites* trematodiasis and growth anomalies (GA) (Fig 6). Of diseased colonies from all sites, growth anomalies were the most common disease (59.0% March 2009 and 52.6% January 2010 for all observed incidents of disease) and *Porites* trematodiasis infections were the second most common (20.5% March 2009 and 21.1% Jan 2010). While the incidence of *Porites* trematodiasis was relatively high and increased between surveys at Honolua, Kahekili and Maalaea the disease was completely absent from Olowalu and Molokini. *Montipora* White Syndrome (MWS) (the only observed tissue loss disease) was most common at Olowalu (25.0% in May and 33.3% in Jan.) and Molokini (16.7% in Jan) (Fig 7). Growth Anomalies and *Porites* trematodiasis were noted on permanently marked colonies but were not associated with tissue loss mortality.

Table 8. Mean percentages of total colonies exhibiting disease with and without incidents of *Porites* trematodiasis by site for May 2009 and January 2010 surveys.

Site	March 2009	Trematodiasis	Jan 2010	Trematodiasis
Honolua	0.278 ± 0.088	8.389 ± 2.891	1.734 ± 1.637	16.308 ± 9.03
Kahekili	0.786 ± 0.559	0.864 ± 0.577	0.43 ± 0.073	0.662 ± 0.200
Kanahena	1.294 ± 0.013	24.722 ± 7.464	1.909 ± 2.397	8.693 ± 2.633
Maalaea	0.758 ± 0.424	6.302 ± 0.060	0.4 ± 0.566	3.416 ± 0.871
Molokini	0.404 ± 0.296	0.404 ± 0.296	1.129 ± 0.659	1.129 ± 0.659
Olowalu	0.504 ± 0.293	0.504 ± 0.293	0.529 ± 0.020	0.529 ± 0.020

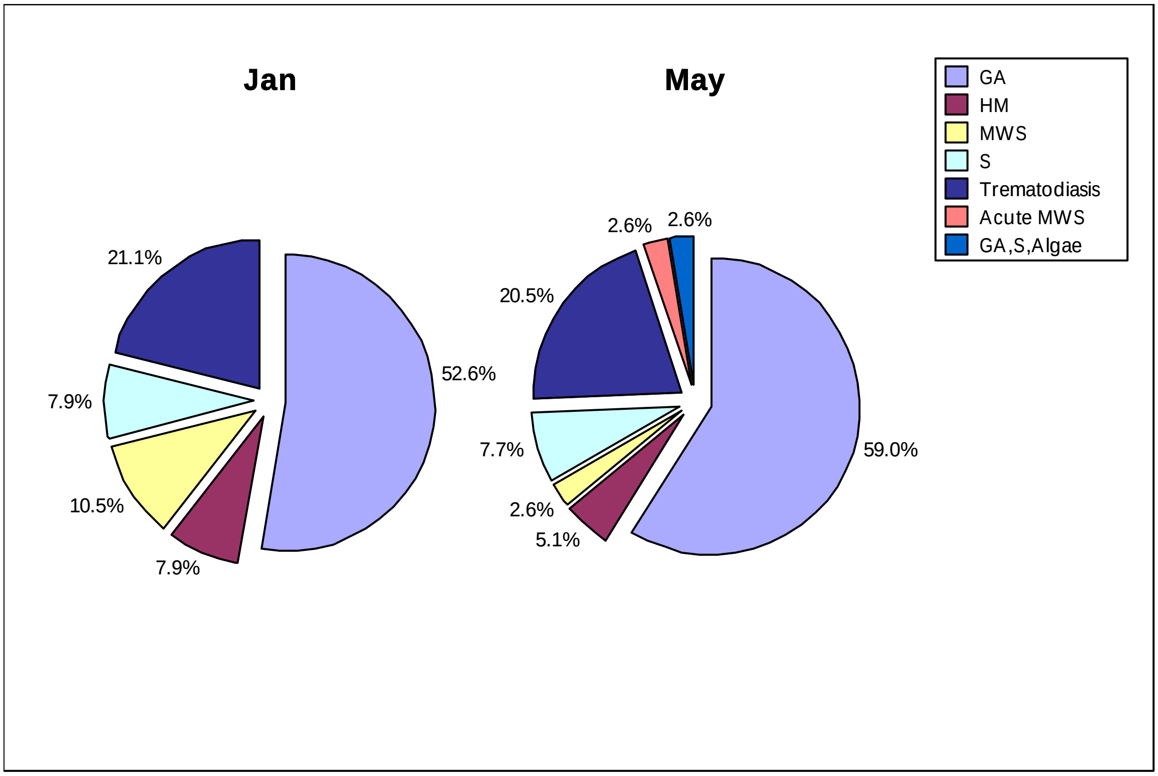

Figure 6. Percentage of cases of disease incidence from all sites by disease type for May 2009 and January 2010 surveys.

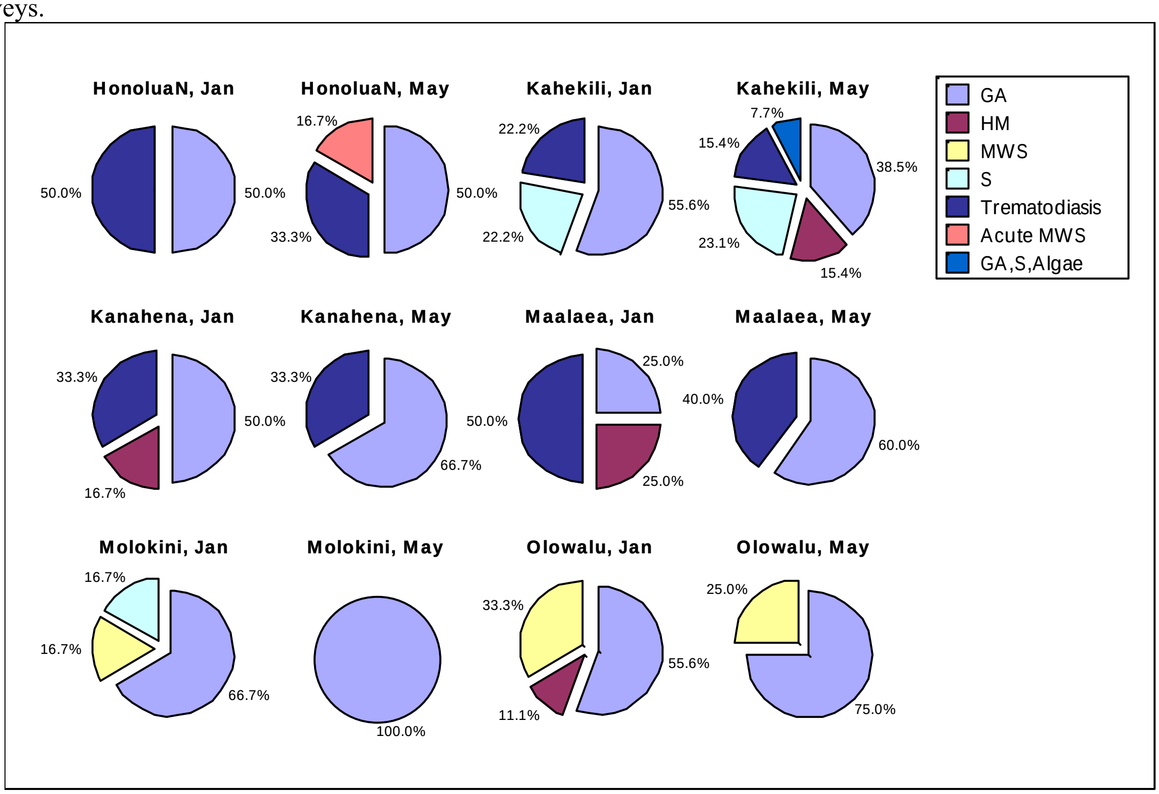

Figure 7. Percentage of disease incidence by disease type for all sites for May 2009 and January 2010 surveys.

Herbivore Abundance

Biomass, density, and dominant species changed by site over time. Fish densities and biomass were averaged by site to compensate for the inherent temporal variability involved in surveys of mobile organisms. Within each site the species with the highest biomass were not necessarily the species with the highest density and species composition varied between sites (Fig 8). Olowalu and Honolua had the highest herbivore biomass and Maalaea had the highest herbivore density. Olowalu had the highest biomass of corallivores and Kahekili had the highest density (Table 9). Urchin densities did not differ significantly between the March 2009 and January 2010 surveys (Table 10).

Table 9. Mean biomass (g/m^2) and density (individuals /m^2) for herbivorous and corallivorous fishes by site.

Site	Trophic	Biomass	Density
Honolua	**Corallivores**	1.22 ± 1.28	1.5 ± 0.55
Kahekili	**Corallivores**	0.51 ± 0.83	3.36 ± 2.34
Kanahena	**Corallivores**	1.22 ± *	1 ± *
Maalaea	**Corallivores**	0.29 ± 0.30	1.5 ± 0.71
Molokini	**Corallivores**	1.06 ± 0.99	1.75 ± 0.96
Olowalu	**Corallivores**	1.54 ± 0.65	2 ± 0
Honolua	**Herbivores**	3.91 ± 5.62	4.5 ± 7.96
Kahekili	**Herbivores**	1.75 ± 2.29	4.47 ± 5.10
Kanahena	**Herbivores**	3.12 ± 3.10	2.6 ± 2.03
Maalaea	**Herbivores**	0.87 ± 0.93	21.87 ± 44.91
Molokini	**Herbivores**	0.8 ± 0.69	4 ± 4.41
Olowalu	**Herbivores**	3.95 ± 6.21	7.85 ± 12.20

Table 10. Results of two-way t-tests of differences in mean densities (individuals /m^2) of urchins by site between the March 2009 and January 2010 surveys.

Site	Survey	Mean Density	t, p-value
Honolua	**Jan**	0.12 ± 0.06	-2, 0.295
Honolua	**March**	0.2 ± 0.00	
Kahekili	**Jan**	0.12 ± 0.00	-3, 0.205
Kahekili	**March**	0.18 ± 0.03	
Kanahena	**Jan**	0.12 ± 0.06	-0.39, 0.762
Kanahena	**March**	0.02 ± 0.28	
Maalaea	**Jan**	0.1 ± 0.03	-0.44, 0.734
Maalaea	**March**	0.18 ± 0.25	
Molokini	**Jan**	0.04 ± 0.00	-1, 0.5
Molokini	**March**	0.06 ± 0.03	
Olowalu	**Jan**	0.16 ± 0.00	0.00, 1
Olowalu	**March**	0.16 ± 0.23	

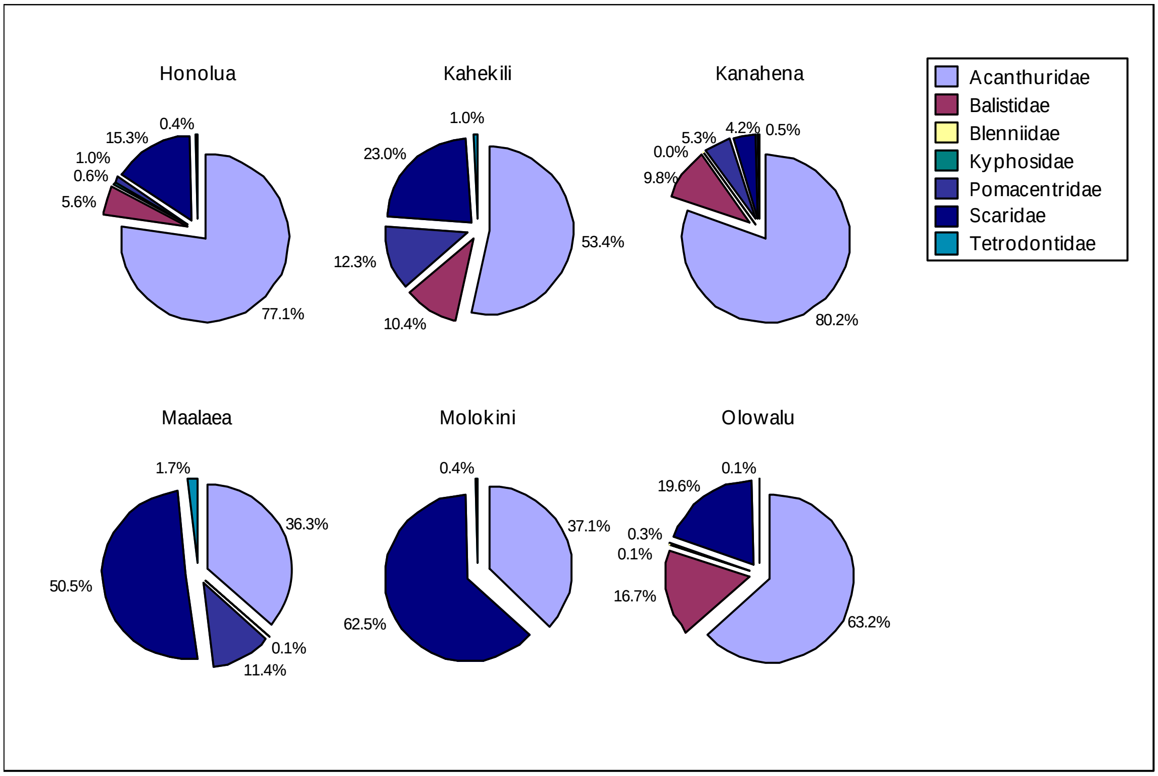

Figure 8. (A) Biomass (g/m^2) of herbivorous fishes by species for each site.

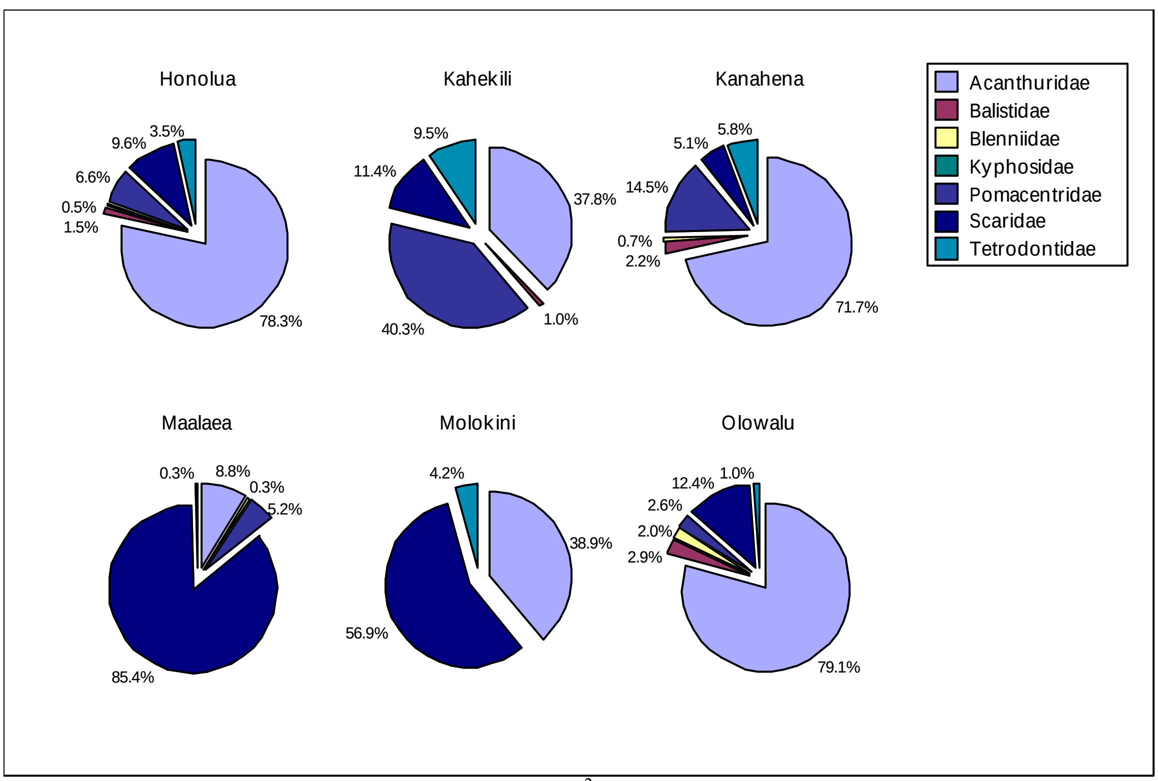

Figure 8. (B) Density of herbivorous fishes (individuals/m^2) by species for each site.

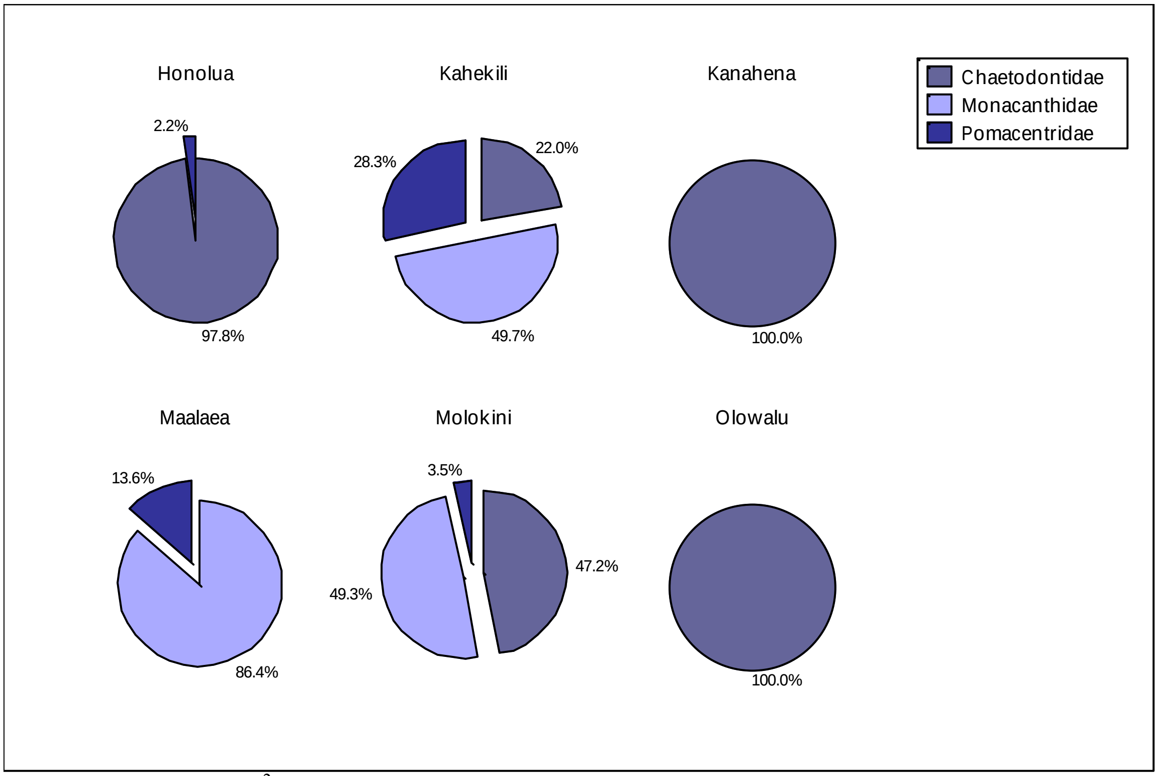

Figure 8. (C) Biomass (g/m^2) of corallivorous fishes by species for each site.

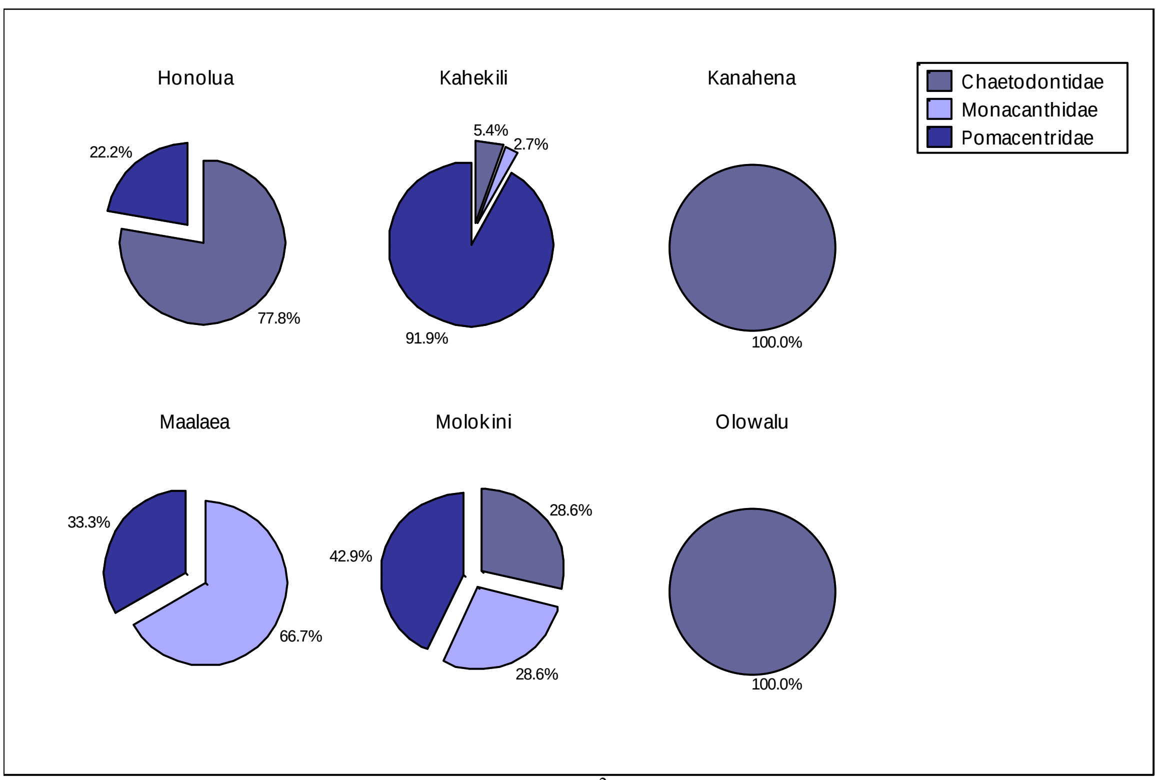

Figure 8. (D) Density of corallivorous fishes (individuals/m^2) by species for each site.

Temperature

Mean, maximum, and minimum temperatures do not differ appreciably between sites. While the dates of minimum temperatures occurred at different times all maximum temperatures occurred in October (Table 11).

Table 11. Mean, minimum and maximum temperatures for all sites for the period from May 2009- Sept 2009 and Oct 2009-January 2010.

Site	Mean	Min	Date	Max	Date
Honolua	25.652 ± 0.774	23.824	1/2/2010	27.273	10/24/2009
Kanahena	25.795 ± 0.981	23.21	2/4/2010	28.97	10/9/2009
Maalaea	25.731 ±0.760	23.598	11/30/2009	27.984	10/9/2009
Molokini	26.074 ± 0.692	24.18	5/15/2009	27.715	10/10/2009
Olowalu	26.284 ±0.887	23.67	11/28/2009	28.628	10/10/2009

Sediment Composition and Grain-Size

Sediment composition was found to be very similar between sites as well as within sites over time. Olowalu had the lowest percentage of $CaCO_3$ and the highest percentage of non-calcareous, non-organic sediment (Table 12). Sediment grain-size differed over time and between sites (Table 13). The gravel fraction size made up the highest percentage of total weight at Honolua (68.1± 1.5% May) during the first sampling interval and Kanahena (83.8± 2.5 % May, 86.3 ± 5.8 % Jan), Maalaea (89.0 ± 4.4% May, 78.8 ± 0.6% Jan), and Molokini (75.4 ± 1.2% May, 37.0 ± 0.1 % Jan) during both samples. The coarse fraction size made up the highest percentage of total weight for Honolua (49.2± 0.2% Jan) during the second sampling interval, Olowalu (56.9±7.7% May) during the first sampling period and Kahekili (82.8±11.7% May, 72±3.2 % Jan) during both sampling periods. The fine fractionation made up the highest percentage of total weight at Olowalu (60.3±5.1% Jan) during the second sample. Honolua and Molokini had the highest percentage of silt compared to the other sites (Table 13). Mean total suspended solids (g/L) did not differ between sites (Table 14).

Table 12. Mean percentages of total weight by calcareous, proteinaceous, and other sediment types for all sites.

Site	Survey	H_2CO_3 %	LOI %	$CaCO_3$ %	Other %
Honolua	**May**	40 ± 0.00	4 ± 0.05	87.33 ± 0.04	8.67 ± 0.02
Honolua	**Jan**	41.44 ± 0.01	4.02 ± 0.04	90.45 ± 0.03	5.53 ± 0.01
Kahekili	**May**	38.51 ± 0.12	3.65 ± 0.04	84.39 ± 0.30	11.96 ± 0.26
Kahekili	**Jan**	38.11 ± 0.31	3.62 ± 0.10	84.01 ± 0.76	12.37 ± 0.66
Kanahena	**May**	41.54 ± 0.29	3.71 ± 0.11	90.96 ± 0.74	5.33 ± 0.63
Kanahena	**Jan**	40.49 ± 0.13	3.69 ± 0.02	88.69 ± 0.31	7.62 ± 0.28
Maalaea	**May**	42.37 ± 0.17	3.73 ± 0.05	92.76 ± 0.43	3.51 ± 0.37
Maalaea	**Jan**	42.02 ± 0.13	3.48 ± 0.03	92.23 ± 0.26	4.29 ± 0.29
Molokini	**May**	42.59 ± 0.01	3.32 ± 0.07	93.65 ± 0.10	3.03 ± 0.03
Molokini	**Jan**	42.82 ± 0.17	3.13 ± 0.01	94.33 ± 0.39	2.54 ± 0.38
Olowalu	**May**	18.56 ± 0.03	5.16 ± 0.05	40.03 ± 0.03	54.82 ± 0.09
Olowalu	**Jan**	21.35 ± 0.46	4.89 ± 0.49	46.17 ± 1.24	48.94 ± 0.76

Table 13. Grain-size data as mean percentage of total weight (g) contributed by gravel (2.8mm), coarse (500µm), fine (250µm), and silt (63µm) fractionations of sediment.

Site	Survey	Gravel	Coarse	Fine	Silt
Honolua	**May**	68.1 ± 1.5	26.9 ± 0.3	4 ± 0.1	1.1 ± 0.3
Honolua	**Jan**	28.5 ± 0.3	49.2 ± 0.2	20.4 ± 0.5	2 ± 0.1
Kahekili	**May**	2.7 ± 0.1	82.8 ± 11.7	14.4 ± 2.1	0.2 ± 0.0
Kahekili	**Jan**	2.9 ± 0.0	72 ± 3.2	24.8 ± 3.2	0.2 ± 0.0
Kanahena	**May**	83.8 ± 2.5	12.3 ± 0.1	3.3 ± 0.1	0.7 ± 0.1
Kanahena	**Jan**	86.3 ± 5.8	11.8 ± 1.6	1.4 ± 0.3	0.5 ± 0.0
Maalaea	**May**	89 ± 4.4	7 ± 0.5	3.5 ± 0.3	0.5 ± 0.1
Maalaea	**Jan**	78.8 ± 0.6	13.5 ± 0.0	7.2 ± 0.0	0.5 ± 0.0
Molokini	**May**	75.4 ± 1.2	16.8 ± 01.0	6.6 ± 0.3	1.1 ± 0.1
Molokini	**Jan**	37 ± 0.1	32.5 ± 0.0	28.4 ± 0.5	2 ± 0.1
Olowalu	**May**	2.4 ± 0.1	56.9 ± 7.7	40 ± 3.3	0.7 ± 0.2
Olowalu	**Jan**	7.9 ± 0.7	30.6 ± 3.0	60.3 ± 5.1	1.2 ± 0.1

Table 14. Mean total suspended solids (g/L) averaged over all samples by site.

Site	Avg wt/vol
Honolua	0.019 ± 0.013
Kahekili	0.018 ± 0.008
Kanahena	0.015 ± 0.002
Maalaea	0.016 ± 0.005
Molokini	0.015 ± 0.003
Olowalu	0.013 ± 0.003

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Conclusions/Recommendations

Coral tissue mortality

The results of this study suggest that the rapid loss of coral cover experienced at sites around Maui may be due to a combination of chronic mortality as well as episodic events. Findings from the DAR/CRAMP long term monitoring benthic cover data show that there is an ~2% annual loss of coral cover around Maui Island (Williams et al. 2007). While the results based on overall benthic cover from this study were not designed with sufficient power to show a statistically significant decrease in overall coral cover within sites over the 10 months of observation, the results from the observations of individually marked colonies show that more than half of the observed colonies experienced some degree of mortality resulting in up to 7.6% loss of live coral tissue. These findings demonstrate the presence of chronic mortality. This result is biased toward showing a greater decline because the method of observing individual colonies does not take into account new recruitment and growth of colonies. The most common causes of chronic mortality were natural competition with Alpheid shrimp, vermetid snails, neighboring corals and turf algae. Competition with the invasive algae *A. spicifera* at the Maalaea site was the only example of an anthropogenic influence directly associated with mortality. While invasive algae occur at several of the other sites, Maalaea was the only site where a colony lost live tissue due to direct competition with macro algae (Fig 2).

The percentage of observed mortality was low and did not appear to be progressive, suggesting that there may be events of a more episodic nature contributing to the high mortality around Maui Island, such as the rapid loss of tissue experienced by the colony of *P. lobata* following a reported bleaching event at Molokini (Fig 4). The mortality experienced by this single large colony increased the overall loss of coral tissue at Molokini from 1.1% to 3.5% over 10 months.

No quantitative correlations between mortality and levels of measured biotic and abiotic stressors such as disease, temperature, or sedimentation were observed. In addition to the relatively stable levels of disease over time, the most common diseases: growth anomalies (GA), and *Porites* trematodiasis, are not generally associated with rapid or chronic loss of tissue.

While no catastrophic losses of coral cover were observed during the course of the study, the potential causes of mortality are apparent through qualitative observation of these sites. Four examples are of particular concern. The first example is Honolua Bay. Although no mortality could be attributed to direct sedimentation input (Fig 9), the corals that are still alive in shallower waters nearer to the stream are obviously suffering from bleaching and tissue loss.

Figure 9. Left: the intermittent stream that runs into the south end of the beach at Honolua bay. Right: Honolua Bay with sediment input from the stream.

In a second example, observations of aggressive turf algae colonizing and overgrowing live coral tissue at Kahekili (Fig 10) were qualitatively more frequent with proximity to known plumes of freshwater input with extraordinarily high levels of the stable isotope $\delta^{15}N$ an isotope frequently associated with fecal matter (Dailer et al. 2010). None of the colonies marked at Kahekili were engaged in aggressive competition, but such algal competition was observed on adjacent colonies during the disease surveys.

Figure 10. Turf algae overgrowing live coral tissue at Kahekili.

In a third example, while no mortality due to disease was noted during this study, two tissue loss diseases; *Montipora* White Syndrome (MWS) (3 sites) and Acute MWS (1 site) were noted. MWS is usually found throughout the Hawaiian archipelago at low levels. Acute MWS is a more recently described disease; consequently there is limited quantitative data on the distribution and prevalence of this disease. Recently an outbreak of MWS was reported in the Ahihi Kinau NAR and an outbreak of Acute MWS was reported in Kaneohe Bay. The outbreak in Ahihi Kinau was associated with a 37.7% loss of *M. capitata* cover over a period of 18 months from 48.5 ± 20.9 % to 30.2 ± 6.2%. While the presence of the disease does not ensure an outbreak, the fact that outbreaks can and do occur in the Main Hawaiian islands means that disease has the potential to cause considerable mortality on an episodic basis.

Finally, while Maalaea does not have as clear cut a gradient or cause of degradation as previous examples, several potential causes of degradation were evident. While turbidity is common in areas exposed to swell, terrigenous run off was apparent on more than one occasion and during the October trip a nearby sugar cane field was being burned and the prevailing winds were blowing ash and dust directly over the site greatly increasing the turbidity. Future research may include experimental and molecular studies to determine whether chemicals used in the agriculture of sugar cane are found in or detrimental to corals.

Recommendations

- Continued research should be focused on site specific concerns.
- Future research can enhance the wealth of temporal data from existing long-term transects by providing spatial data on mortality and environmental variables along gradients of observed site specific stressors such as sediment, nutrient rich freshwater input and disease.
- Continued research should also include assessments of rates of mortality in corals actively engaged in competition with the more aggressive forms of turf algae. Samples of turf should be collected and identified to determine whether or not there are species more prone to competition with corals or more common along gradients of anthropogenic stressors.

- The data gathered during this project, while valuable, is only a baseline for mortality rates and there is almost certainly temporal variation in rates of mortality. Corals are slow growing organisms and current methods for accurate estimations of growth rates require a longer interval of observation than the duration of this project allowed. The DAR's long-term monitoring program includes an archive of digital photographs of permanently marked photoquadrats. Analysis of these photos could be used to produce data on rates of growth and recruitment in a relatively short period of time and provide a stronger baseline, though not as detailed, for rates of mortality. Such information would improve the accuracy of estimated rates of decline in coral cover based on observations of individual colonies.
- Continued research should also include a more comprehensive sampling regime for environmental variables such as water quality and wave action. The number of trips for this study were limited due to budgetary reasons and often scheduled during optimal conditions for logistical reasons. This prevented researchers from collecting comprehensive data on the full range of turbidity and wave action.

In summary, the findings of this study suggest that decline of coral cover around Maui Island was caused by a combination of long term chronic processes and episodic events. Qualitative observations at several of the sites suggest that there are chronic stressors, some anthropogenic, that could cause chronic loss of tissue and decrease corals ability to cope with episodic events. Spatial studies targeting site specific stressors and species of concern are the next step toward effective mitigation of causes of coral decline around Maui Island. The DAR/CRAMP long-term monitoring data and findings from this project provide direction for such directed research.

References

Brown et al. 2004. Development of benthic sampling methods for the Coral Reef Assessment and Monitoring Program (CRAMP) in Hawai‘i. Pacific Science 58(2):145-158.

Dollar and Grigg. 2004. Anthropogenic and natural stresses on selected coral reefs in Hawaii: A multi-decade synthesis of impact and recovery. Pacific Science 58: 281-204.

Dailer et al. 2010. Using $\delta^{15}N$ values in algal tissue to map locations and potential sources of anthropogenic nutrient inputs on the island of Maui, Hawaii, USA. Marine Pollution Bulletin. In press.

Jokiel et al. 2001. Hawaii Coral Reef Initiative Coral Reef Assessment and Monitoring Program (CRAMP). Final Report 1999-2000. Prepared for National Ocean Service, National Ocean and Atmospheric Agency, Silver Spring, Maryland, January 29, 2001. 66 pp.

Williams et al. 2008. Status of Maui's coral reefs. Hawaii Division of Aquatic Resources Information Sheet. http://hawaii.gov/dlnr/dar/pus/MauiReefDeclines.pdf