

NOAA Project Final Report

- I.** **Title:** Ability of protected reefs to resist alien algae
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II. Abstract

Once invasive species are established in an ecosystem, it is usually not feasible to physically eradicate these species through reactive procedures. It is more practical to focus efforts on preventing invasions by understanding and re-establishing the natural habitat, foodwebs, and grazer and predator abundances. The ability of marine protected areas (MPAs) to facilitate recovery of fisheries stocks has been demonstrated in over a hundred case studies presented in the literature. However, whether MPAs are able to restore natural ecosystem processes by allowing the persistence of key components of the system such as predators and grazers is less understood. To objectively and quantitatively assess the ability of MPAs to restore ecosystem health, and thereby resist invasion of alien algae, the primary research objectives of this project were to experimentally determine and measure the differences between coral reefs inside and outside MPAs. Our results indicate that protection positively favors the success of crustose coralline algae (CCA) that binds the substratum and facilitates coral recruitment. Scleractinian corals are the foundation of the coral-reef ecosystem and so the facilitation of recruitment and survival of corals is fundamental to the coral-reef ecosystem. Predation by fishes on corals is much more intense than was previously realized. Corals are especially vulnerable at the juvenile stage in which they can be removed with a single bite.

Executive summary

Studies have indicated that compared to disturbed systems, undisturbed ecosystems that approach a more natural and healthy state, are more resistant to invasions by alien species (Elton 1958, Paulay et al 2002, Occhipinti-Ambrogi A. and Savini D. 2003). Based on this premise, the goal of our project was to objectively and quantitatively assess the ability of marine protected areas (MPAs) to maintain ecosystem health, and thereby resist invasion of alien algae.

We approached this goal by assessing a set of ecological factors that are characteristic of healthy reef systems and comparing these between reefs with different levels of marine protection. Since it is difficult to scientifically quantify degrees of marine protection, reefs were categorized by the biomass quantity of herbivorous fish present at each site. Fish biomass was assumed to be positively related to increasing levels of management. Applying this approach, we wished to determine the relationship between each of the ecological factors with increasing biomass levels of herbivorous fish. Our study included a comparison of 8 coral reef sites located on the island of Oahu and the island of Hawaii. Sites were chosen primarily to span a low to high biomass range of herbivorous fishes (reflecting degrees of marine protection).

Our first objective was to determine and compare the quantity and quality of grazing intensity induced by herbivorous fishes between reefs. Since a high standing biomass of algae might indicate low grazing intensity, we compared the cover of both macro- and filamentous algae between sites. Our second objective was to compare the cover of crustose coralline algae between sites and assess differences in typical interactions of CCA with turf, macroalgae and grazing fishes. Our third objective was to determine the prevalence of coral colonies between reefs. The above three objectives were assessed by means of our taking and analyzing photoquadrats. Our fourth objective was to examine how juvenile corals survive factors such as competition with algae, predation by fish and sedimentation effects, and to see if probability of survival increased with juveniles size. Using tiles we transplanted three size classes of coral juveniles into the field and monitored their survival over time. Our final objective was to calculate how rates of reef accretion compare with rates of bioerosion between sites. These experiments are still ongoing. We set out calcium carbonate blocks into the field during the summer of 2004 and will determine their level of erosion vs. accretion 12 months later. We will also calculate net growth of the coral at each site and estimate levels of erosion by invertebrates via photoquadrats.

Principle Investigator Dr. Charles Birkeland of the Hawaii Cooperative Fisheries Research Unit (HCFRU) oversaw the progress of the project, while graduate student of the Zoology department, University of Hawaii, Danielle Jayewardene performed the work involved in the project. Work was field-based, requiring the use of SCUBA.

We found no or very little macroalgae at our study sites, limiting our ability to detect any real differences and/or trends between sites. Turf was prevalent at all sites, varied between sites, but showed no expected relationship of decreasing in cover with increasing biomass levels of herbivorous fish. Coral was prevalent at all sites, varied between sites, but did not as expected increase with increasing biomass levels of herbivorous fish.. We did find that prevalence of crustose coralline algae increased with increasing biomass levels of herbivorous fish.

Herbivorous fish, probably parrotfish specifically, promote the growth of CCA. Based on similar indications in the scientific literature (Steneck 1983, Littler and Littler 1997), we might assume that CCA in turn promotes coral recruitment (Morse et al. 1988, Morse and Morse 1996). However, as stated, we did not find that herbivorous fish (protection) increased coral cover. This might be explained by our coral juvenile survival data. Although we found no difference in survival success of the smallest size class between sites on Oahu (not our regular study sites), we found interesting survival differences between sites for the intermediate and large size class of juveniles. These upper size classes were predated upon at Hanuama Bay MLCD, while unaffected at the other sites. This is probably explained by the combination of a high biomass of predators and low background level of *P.compressa* ("prey") at the Hanuama Bay MLCD compared to the other study sites. Our results also indicated that the probability of juvenile survival is greater the larger the coral is. These findings tie into the coral cover and CCA cover at our study sites. Although herbivorous fish (protection) promotes CCA growth, assumed to promote coral recruitment, coral survival is limited by higher levels of predation at the same sites (higher biomass of herbivorous fish at protected sites probably reflect higher biomass of all fish, including predatory fish), nullifying the positive affect on coral growth.

We will carry out additional work during 2005 by focusing on the factor of grazing at a set of our study sites. We will also look more closely at predation affects and compare these both between sites and within Hanauma Bay MLCD.

We have addressed our project goal by meeting the project objectives. Although, we were not able to conclude that areas with a greater biomass of herbivorous fish (reflecting protection) promote a collective trend in reef processes such as overall high levels of grazing characterized by a low prevalence of algae, high coral cover, high CCA cover, successful coral juvenile survival and less bioerosion thought to be characteristic of healthier coral reef systems, we found that protection positively favors the success of CCA that binds the substratum and facilitates coral recruitment. Scleractinian corals are the foundation of the coral-reef ecosystem and so the facilitation of recruitment and survival of corals is fundamental to the coral-reef ecosystem. Predation by fishes on corals is much more intense than was previously realized. Corals are especially vulnerable at the juvenile stage in which they can be removed with a single bite. Their survival increases as they reach a larger size because at a larger colony size, there is a greater chance for tissue to remain from which the colony can regrow.

The project results have been disseminated by means of verbal presentations on several occasions including at the 10th International Coral reef Symposium 2004, the Albert Tester Memorial Symposium 2004 at the University of Hawaii and at HCRI-RP quarterly meetings. Project results will also be included in a variety of workshops and presentations conducted by Dr Charles Birkeland, as well as presented and published by Danielle Jayewardene as part of her PhD Dissertation.

IV. Purpose

Problems and impediments

No problems or impediments.

Objectives of the project

Invasions of alien species are most successful in environments in which the habitat has been degraded and altered, and where opportunistic invasive species are better adapted to the modified conditions than are the established species. Invasions are also facilitated when some key components of the community, such as predators or grazers, are reduced to unnaturally low population levels at which they do not perform their role effectively in the community. Studies have indicated that compared to disturbed systems, undisturbed ecosystems that approach a more natural and healthy state, are more resistant to invasions by alien species (Elton 1958, Paulay et al 2002, Occhipinti-Ambrogi A. and Savini D. 2003). Once invasive species are established in an ecosystem, it is usually not feasible to physically eradicate these species through reactive procedures. It is more practical to focus efforts on preventing invasions by understanding and re-establishing the natural habitat, foodwebs, and grazer and predator abundances. So far bioinvasion studies have focused mainly on the properties of the species that have successfully established themselves in non-native environments. Fewer studies have examined the properties of the actual ecosystems within which the species have established themselves, although it may potentially be these properties that are the key to invasive susceptibility of ecosystems (Occhipinti-Ambrogi A. and Savini D. 2003). The idea that alien species have a difficult time invading a diverse and "healthy" coral reef community (Paulay et al. 2002), highlights the importance of understanding the factors within this healthy ecosystem that create this resilience to invasion.

Based on this premise, the goal of our project was to objectively and quantitatively assess the ability of marine protected areas (MPAs) to maintain ecosystem health, and thereby resist invasion of alien algae. We approached this goal by assessing a set of ecological factors that are characteristic of healthy reef systems and comparing these between reefs with different levels of marine protection.

Since it is difficult to scientifically quantify degrees of marine protection, reefs have been categorized by the biomass quantity of herbivorous fish present at each site. Fish biomass is an objective value, and can be assumed to be positively related to increasing levels of management. A higher level of protection thus promotes a higher biomass level of herbivorous fish.

Applying this approach, we wished to determine the relationship between each of the key ecological processes and factors assessed, and increasing biomass levels of herbivorous fish. Further, combining the trends of all processes, we wished to tease out whether areas with a greater biomass of herbivorous fish promote a collective trend in reef processes such as overall high levels of grazing, a low biomass of standing algae (both alien and native), an abundance of

crustose coralline algae (CCA), high coral cover, successful survival of juvenile corals, and greater net reef accretion vs. net reef bioerosion.

Extending this thought further, based on the empirical evidence that sites with effective marine management are related to increased levels of fish biomass (Polunin and Roberts 1993, Palumbi 2001; 2002, Roberts et al. 2001a & b, Russ 2002), we wanted to test the principal hypothesis that successful no take marine protected areas can maintain a coral reef ecosystem in a condition that approaches a more natural, resilient state compared to sites with less or no protection.

Our study included a comparison of 8 coral reef sites located on the island of Oahu and the island of Hawaii: Hanauma Bay MLCD (Jokiel et al. 2001) and Portlock on Oahu and Puako FMA, Aneahoomalu FRA, Wawaloli, Wawaloli FMA, Kealakakua MLCD and Ke'ei FRA in Kona (Tissot et al. 2004) (Map 1). Sites were chosen primarily to span a low to high biomass range of herbivorous fish (reflecting degrees of marine protection) (Fig.1). The ecological processes and factors that we assessed were as follows:

1. Grazing intensity

Herbivores are often keystone species in facilitating coral settlement and growth by grazing down algae (McClanahan, 1997). This is shown by the reduction in grazing pressure often triggering shifts in community structure, causing coral and crustose coralline algae to be overgrown and excluded by faster growing erect algae. The community structure is subsequently changed from a high diversity coral based ecosystem to a macroalgae dominated system, with decreased genetic-, species- and functional-diversity (Hixon and Brostoff 1981, Moberg and Folke 1999). Grazing pressure not only influences species composition, but also affects the level of productivity, bioerosion, nutrient concentration, succession and a range of other ecological processes (McClanahan 1997, Moberg and Folke 1999, Babcock et al. 1999).

Our first objective was to determine and compare the grazing intensity induced by herbivorous fishes between reefs. We indirectly assessed this by comparing the prevalence of algae, both in their filamentous and macroalgal form, since a high standing biomass of algae might indicate low grazing intensity.

2. Prevalence of crustose coralline algae (CCA)

The binding action of loose coral rubble by crustose coralline algae (CCA) creates firm substratum. This favors recruitment of juvenile coral, as some CCA is known to contain chemical cues that facilitate settlement and metamorphosis of coral planulae (Johnson and Mann 1986, Belliveau and Paul 2002). For example, reefs in American Samoa and Palmyra have recovered from hurricane disturbances as a result of CCA binding loose rubble and solidifying the substratum. In contrast, in Palau the apparent lack of binding of loose coral rubble by CCA has slowed the recovery of reefs following the effects of disturbance events in 1979. The reefs instead maintain extensive masses of loose rubble (pers. comm. Birkeland). Further, CCA helps control macroalgal growth, mainly through competition for space. CCA is often the first colonizer on bare patches, and initial colonization and competition between fleshy algae versus CCA may determine whether there is a shift towards macroalgal or coral dominance on the reef (Johnson and Mann 1986, Belliveau and Paul 2002).

This leads to our second objective, which was to compare the prevalence of crustose coralline algae between sites.

3. Prevalence of coral

Reef morphology appears to be one of the most important factors in determining the organization of reef communities. High coral cover generates high topographic diversity offering a wide range of shelter, food and juvenile recruitment sites (Letourneur 1996 and Jones et al. 2004). A recent study from a Papa New Guinea, shows that a decline in coral cover causes a parallel decline in fish biodiversity (Jones et al. 2004). Furthermore, declining coral cover can trigger phase shifts from coral-dominated to macroalgae-dominated states (Williams et al. 2001). The consequences of this include reduced recruitment of corals (Hughes and Tanner 2000), reduced abundance of herbivorous fishes and their rates of herbivory, and reduced abundance of coral-eating fishes (McClanahan et al 1999). Overall, dead coral is more susceptible to disturbance and bioerosion than live coral. Live coral is thus essential in the long term since hermatypic coral colonies are the important builders of the reef framework through the calcification process (Lindahl et al. 2001).

Our third objective was to compare prevalence of coral between reefs.

4. Success of juvenile coral survival

The importance of understanding processes such as coral recruitment as opposed to only adult coral abundance for ecosystem function is becoming increasingly clear. Juvenile corals at early life history stages following settlement are often more susceptible than adults to environmental factors and disturbances (Babcock et al 2003).

Our fourth objective involved examining how juvenile corals survive factors such as competition with algae, predation by fish and sedimentation effects. We assessed whether these factors depend on the size of the coral, i.e., if the probability of survival increases or decreases the larger the juvenile.

5. The balance between reef accretion and bioerosion

Bioerosion, the loss of reef calcium carbonate, is another major structuring force of the reef framework. On a healthy reef net accretion equals or exceeds erosion (Hibino and Woesik 2000). Disturbances worldwide have increased the amount of dead coral substrate which may potentially change the dynamics between erosion and accretion. Interesting direct and indirect effects due to increased eutrophication, sediment loading, global warming leading to bleaching, pollution, crown-of-thorns breakouts and other mass mortality events, all increase the amount of available dead coral substratum for initial bioeroders to colonize. Damaged reefs are also often dominated by algae, attracting herbivores, increasing the potential for external bioerosion. The total impact becomes greater, escalates and causes the reef to be more susceptible to loss by physical damage. According to Glynn (1997), bioerosion is self-reinforcing (Hutchings and Peyrot-Clausade 2002, Spencer and Viles 2002).

As a final objective, we aimed to calculate how rates of reef accretion compared with rates of bioerosion. We wished to determine whether there is net reef growth or net bioerosion, and determine whether these two processes differ in direction or amount between sites.

V. Approach

Methods

For the purpose of categorizing our study sites based on ranging biomass levels of herbivorous fish we selected study sites where fish biomass data was already available. Along the Kona coast, we chose sites and used current data collected in 2003/04 by the West Hawaii Aquarium Project, WHAP (www.coralreefnetwork.com/kona/default.htm). On Oahu, we used data collected in 2000 by the Hawaii Coral Reef Assessment and Monitoring Program, CRAMP (cramp.wcc.hawaii.edu). In order to link the observations and experiments gained from our fieldwork with the herbivorous fish biomass data, it was necessary that our sites were compatible with the WHAP and CRAMP sites. At the Kona sites, WHAP has collected their fish data bimonthly since 1998 by running 2 x (2 x 25m) parallel permanent fish transects at a depth between 9-13m. At Hanauma Bay on Oahu, CRAMP has run 2 x 50m parallel transects at a depth of 10m between years 1998-2001. At Portlock, biomass data has been assessed from rapid fish transects. Based on these methods, our field work at all sites has been focused around the sites of the fish transects at depths near 10m. However, at Hanauma Bay we also set out experiments at a shallower depth of 5 m and at different locations within the Bay to enable within site comparisons.

In order to make quantitative assessments of our objectives, the following standardized methods were designed to determine and compare each of the ecological factors between study sites.

1. Grazing pressure

Grazing pressure was assessed by comparing percent cover of filamentous and macroalgae between sites. This is an indirect method of assessing grazing intensity. It is based on the assumption that increased grazing leads to a lower prevalence of macroalgae and also filamentous algae. Percent cover was determined by analyzing photoquadrats that were taken at each site. The methodology for taking and analyzing photoquadrats is described in detail at the end of this section.

2. Prevalence of crustose coralline algae (CCA)

We assessed the prevalence of CCA by quantifying the percent cover of CCA present at each of the sites. This was also done by taking photoquadrats in the field. CCA was not identified down to genus or species level, but was lumped as one overall CCA category. This was to avoid error due to incorrect identification.

3. Prevalence of coral colonies

We have assessed the prevalence of coral colonies by quantifying the percent cover of coral at each of the sites. This has also been done by means of photoquadrats. Corals have been identified down to species level.

4. Success of juvenile coral survival

We examined success of juvenile coral survival by transplanting juveniles into the field using tiles and monitoring their survival over time. Setting out terracotta tiles rather than direct transplantation onto the substrata standardized the measurements as well as avoided

manipulation of coral within protected areas. Survival of three size classes of juvenile corals was determined, involving two different methods of preparation.

The smallest size class tested was newly settled larvae of *Pocillopora damicornis*. The larvae were attracted to terracotta tiles in the lab at the Hawaii Institute of Marine Biology (HIMB) before being set out in the field. This was done by holding coral heads of *P. damicornis* (10- 20 cm in size) in microcosm tanks (approx. 1m x 1m x 0.5m), and leaning 6 x 6 inch terracotta tiles against the walls of the tanks providing substrata for settling planulae. *P. damicornis*, which is a brooding coral species with internal gamete fertilization, releases planulae once a month according to the lunar cycle. These traits are the justification for using this particular species, as spawning coral species show external fertilization and release gametes only once a year. As soon as the planulae were released and settled on the tiles, they were counted and mapped on underwater paper. We managed to attract up to 60 juveniles per tile. Eight of the tiles holding the highest number of spat were set out at each site. The juveniles were monitored at one-week intervals for up to 5 weeks. Survival was defined as the number of spat remaining alive per tile. Unfortunately, we did not find appropriate facilities such as HIMB in Kona to allow for the attraction of spat onto tiles, so tiles with spat were only set out at the Oahu sites.

To determine whether factors affecting survival differed depending on the size of the juveniles, replicates of two larger size classes were also exposed to natural mortality factors in the field. The intermediate size class consisted of approx. 1 inch high *Porites compressa* nubbins and the large size class consisted of approx. 2 1/2 inch high *Porites compressa* nubbins. *P. damicornis* nubbins were not used since they were too readily eaten by fish in the field, invalidating comparison between sites. The two size classes of *P. Compressa* nubbins were attached to tiles using *Sea Goin' Pox* Putty and transplanted into the field similar to the spat. Nubbins were monitored at one week intervals for 4 or more weeks. Survival was defined as the maintenance of nubbins in their initial size and healthy state. If a fish bit off half the nubbin, the nubbin was considered to have 50% survival.

A total of 8 replicate tiles were set out per study site. The tiles were set out at two substations holding 4 tiles each.

5. The balance between reef accretion and bioerosion

We determined bioerosion by experimentally measuring the level of bioerosion of calcium carbonate blocks set out on the reef, and accretion by determining the calcification budgets of the calcifying community characteristic to sites.

Following the methodology of Hibino & Van Woesik (2000), replicate calcium carbonate blocks were attached to dead reef substrate and left out for 12 months at each of the sites. The uniform blocks were cut from dead coral tissue of *Porites lobata*. Dead *P. lobata* was collected from the north shore where large blocks are washed up on shore and dried out following the winter storms. Using a rock saw, any bioeroded material was cut away from the dead coral blocks, leaving a clean, non-impacted calcium carbonate core. This raw material was cut squarely into 1 cm x 5 cm x 5 cm blocks. Once the blocks were cut, they were soaked in freshwater for 24 hours then dried in an oven at 60°C for another 24 hours, and weighed. This was to eliminate any microorganisms that may be residing in the calcium carbonate as well as standardize the dry-

weighing of the blocks. Thereafter numbers were engraved into each of the blocks, the bases siliconized and attached to the reef using *Z-spar epoxy putty*. After 12 months the blocks will be removed from the reef, and the rate of structural bioerosion for the blocks determined from the total measure of lost (or gained) weight for replicates per site (blocks remain in the field and will not be retrieved until the summer of 2005. Thus the following methods have yet to be applied). Before re-measurement, the blocks are prepared by a bleaching, soaking and drying process according to the method by Hibino & Van Woesik (2000). Thin cross sections may also be cut through the blocks (using a diamond geological blade) to quantify the loss of area due to internal bioerosion. A total estimate of structural bioerosion for each site can be calculated from the bioerosion rates determined from the blocks and the percent cover of non-coral substrate prone to bioerosion. Percent cover of non-coral substrate is determined through the photoquadrat methodology.

At each site, 8 replicate blocks were set out at 2 substations holding 4 blocks each. At the Kona sites, the blocks were set out around the WHAP fish transects at a depth of approx. 10m. At Hanauma Bay, 2 sets of 8 blocks were set out at 10m depth. One by the CRAMP fish transects on the right hand side of the bay and one set of blocks on the left hand side of the Bay. At Portlock 8 blocks have were set out at 10 m depth by the underwater amphitheatre.

Coral accretion is assessed by determining the percent cover of different calcifying species present at a site, finding the growth rate of each species in the literature and using this to calculate the accretion rate of the calcifying community at each site. Percent cover of calcifying species has been determined using the photoquadrat methodology. Budgets of accretion versus bioerosion will be calculated by subtracting structural bioerosion from the total growth rate for each site (Hubbard et al. 1990, Hubbard 1992, 1997).

Photoquadrat methodology

We chose to take photoquadrats instead of using visual estimates or point quadrats in order to identify and quantify the benthos at study sites (Foster et al. 1991, Meese & Tomich 1993, Dethier et al 1993). Taking photoquadrats was more time efficient in the field, since more replicate quadrats were gathered with less time spent underwater. Furthermore, since photoquadrats provide a permanent database of the benthos, it is always possible to go back and re-analyze data if necessary, or to make temporal comparisons with future data. The drawback of the method was the extra time required analyzing the images in the laboratory.

We based our photoquadrat methodology largely on the methodology used by WHAP in Kona.

In the field:

Each photoquad was taken using an Olympus 5050 camera. The camera was mounted onto a 75 cm high rod, with resulting images covering an area of approx. 60x40cm of substrate.

For study sites in Kona where benthic cover was correlated with WHAP's fish data, photoquads were taken along a theoretical grid set around their 2 (2x 30m) parallel fish transects marked by permanent pins at each site. To get an appropriate representation of the area, 10 x individual 20m length transect lines were placed within this grid. The transect lines were laid out randomly by generating 10 random numbers between 1 and 50, and starting the transect at the point of each of

these numbers in the grid (Fig.2). Along each transect, one image/meter was taken, totaling 20 images/transect and 200 images/site.

At Hanauma Bay, photoquadrats were taken at multiple sites within the bay enabling between sites as well as within site comparisons of percent cover. Sites included the 10 m depth CRAMP site and a 5 m depth site on the right hand side of the bay, and 10 m depth site on the left hand side of the bay.

In the lab:

The images taken were analyzed using an image analysis program called PhotoGrid designed by UH Botany graduate student Chris Bird. PhotoGrid generated random points on each of the images. The substrate that fell directly below each point was identified and classified into categories including coral species, macroalgae, turf, and CCA. When all images for a site were analyzed in this manner, an overall percent cover was determined for each category or species. This percent cover was then compared between sites.

To determine how many images/transect and points/image actually needed to be analyzed in order to get an accurate representation of percent cover at a site (whilst being time efficient), we ran a test for one of our more heterogeneous study sites, the Wawaloli FMA. All 200 images taken at this site were analyzed, and percent cover of the main categories compared when analyzing 10 points/image vs. 20 and 30 points/image (Figs.). We also determined whether there was a point at which analyzing more images/ transect was not worthwhile time-wise. The results indicated that the number of points/ image really had little effect on the overall estimate of main categories such as coral, turf and CCA cover. Based on this, we decided to analyze 20 points/image. Although the graphs also indicated that it was adequate to analyze as few as 5 images/transect, we decided to analyze as many as 15 images/transect to allow for the accurate percent cover estimation of coral on a species level (we also ran a species level analysis indicating this). These two choices made analysis more time efficient whilst maintaining our ability to estimate an accurate cover. In total, 150 images/site, i.e. 3000 points/site compared to 6000 points/site, were analyzed and used to determine percent cover for all study sites.

Project management

Principle Investigator Dr. Charles Birkeland of the Hawaii Cooperative Fisheries Research Unit (HCFRU) oversaw the progress of the project, providing assistance and advice. Graduate student of the Zoology department, University of Hawaii, Danielle Jayewardene performed the work involved in the project. Work was mostly field-based, requiring the use of SCUBA and thus dive buddies for Danielle. Dive buddies were voluntary, and included graduate students Jeremy Claisse, Sarah McTee, Sam Kahng, Lance Smith, Amanda Myers, Jan Dierking, Marc Hughes, Pakki Reath and Katie Howard.

The Hawaii Coral Reef Initiative Research Program (HCRI-RP) provided the grant providing the majority of funds for the project. The Hawaii Cooperative Fisheries Unit (HCFRU) provided supporting funds and resources. The West Hawaii Aquarium Project (WHAP) provided additional support by means of use of the DAR boat on the Kona coast of Hawaii.

IV. Findings

Actual accomplishments and findings

Our choice of study sites spanning a biomass range of herbivorous fishes, also spanned a range of levels of protection from “not take” Marine Life Conservation Districts (MLCDs) to partial protection in the Fishery Management and Replenishment Areas (FMAs/FRAs), to unprotected sites allowing take. This range of study sites allowed the use of one-way ANOVA for the determination of differences between sites and Pearsons correlation analysis to determine trends potentially forming along the biomass range of study sites. However, for a couple of the factors, using either of these analyses was inappropriate due to a large proportion of the sites showing limited or no response to the treatment.

1. Grazing pressure

Unexpectedly, we found very little macroalgae at all the study sites surveyed (Fig.4). 5 out of 7 sites have no macroalgae at all, while Kealakakua Bay MLCD and Hanauma Bay MLCD have only 0.2% and 2.3% macroalgal cover. We put no importance on the counterintuitive fact that macroalgae was found at the two “no take” MLCDs where biomass of herbivorous fishes was actually the highest. This is because cover is zero or so low at all sites that it erodes our ability to detect any significant differences or trends between sites. To approach this problem, we would need to survey sites that are known to have higher prevalence of macroalgae to detect differences and relationships between biomass of herbivorous fishes and macroalgal cover.

Filamentous algae (turf) were prevalent at all sites, ranging from 21% to 48% cover between sites (Fig. 4). Although we detected significant differences in cover between sites using one-way ANOVA (*see appendix*), we detected no significant relationship between the biomass of herbivorous fishes and turf cover using Pearson’s correlation (Fig. 5).

2. Prevalence of Coral

Overall coral cover ranged from 25% to 58% (Fig.4) between sites. As with turf cover, although we detected significant differences in cover between sites using one-way ANOVA (*see appendix*), we found no significant increase (or decrease) in coral cover with increasing biomass levels of herbivorous fishes at our sites using Pearson’s correlation (Fig. 6).

Looking at coral cover at the species level (Fig. 7), encrusting *Porites lobata* made up the largest proportion of coral cover at all our study sites ranging between 17%-33%. The finger coral *Porites compressa* was the species with second highest coral cover at all sites ranging between 5%-33%. In proportion to *P.lobata* cover, *P.compressa* was highest at Aneahoomalu FRA, Puako FMA, Keei FRA and Kealakakua MLCD, sites observationally also characterized by high prevalence of finger coral. *P.compressa* cover was lower at the 2 Wawaloli sites and at the Hanauma Bay site, which are known to be subject to high levels of wave energy during certain periods of the year. The two Wawaloli sites have an almost equal prevalence of *Pocillopora meandrina* as *P.compressa*, a species able to withstand high wave energy environments.

3. Prevalence of CCA

CCA cover ranged from 3% to 28% cover between sites (Fig. 4). Again, using one-way ANOVA (*see appendix*), we detected significant differences between sites, and unlike turf and coral cover, found a significant relationship of increasing CCA cover with increasing biomass of herbivorous fishes ($r = 0.94$, P-Value = 0.002) (Fig. 8). This is an important, but not surprising positive relationship that has been found before. Grazing by herbivorous fishes, specifically parrotfish clear up space promoting the growth of CCA (Steneck 1983, Littler and Littler 1997). Using Pearson's correlation, we also found a significant positive trend between the biomass of parrotfish and CCA cover ($r = 0.886$, P-Value = 0.008) (Fig. 9).

4. Survival of coral juveniles

Due to logistical limitations we could not set out experimental tiles to determine survival for the small size class of juvenile corals (spat) at sites in Kona, Hawaii. However, we did obtain comparative results for three sites on Oahu; Hanauma Bay MLCD, Coconut Island Scientific Reserve and the unprotected site Portlock. Over a 4 week monitoring period, using one-way ANOVA (*see appendix*), we detected no significant difference in survival between these different sites. Survival, defined by the proportion of spat remaining alive after 4 weeks, ranged between 23%-36% (Fig.10).

Unlike the small size class, we obtained survival results for the intermediate and large size classes of coral juveniles (*P. compressa* nubbins) for all our study sites. Survival was very high for both these size classes for all sites except at the Hanauma Bay MLCD where the proportion of nubbins remaining alive was very low (Fig.11). Our observations indicate that the factor affecting the nubbins was predation by *Cantherines dumerilii* and/or *Arothron hispidus* and *Arothron meleagris*. Although monitoring continued for over 4 weeks, at Hanauma Bay 100% of the intermediate sized nubbins and 50% of the large nubbins were removed by predation in the span of a week.

The difference in predation affect between sites can be explained by many factors. Hanauma Bay MLCD has a higher biomass of herbivorous fishes compared to all other sites. Thus the bay most likely has a higher biomass of predatory (corallivorous) fishes also, specifically *Cantherines dumerilii* and/or *Arothron* species, and there is likely intense predation pressure on the corals. At some of the Kona sites, where biomass of predatory fish is also relatively high and bite marks on coral in the field are observed to be prevalent, the high background level of the targeted *P.compressa* (Fig. 7) probably nullifies the predation effect on our experimental nubbins. Due to this lack of predation effect on the nubbins at the Kona sites, we could not analyze relationships between biomass of predatory fishes and our nubbins survival experiments. To detect if predation might limit coral cover, we correlated the biomass of these predatory fishes with overall coral cover and specifically *P.compressa* cover in the field, but we did not detect a significant negative relationship (Figs.12 & 13). This might be explained by predation having a greater affect on the biomass and three dimensional growths of coral rather than cover per se. Visual quadrates quantifying actual bite marks in the field would detect a possible negative relationship between biomass of predatory fishes and predation on corals.

The difference in predation effect between the two upper size classes indicates that the probability of survival of juvenile coral increases with increasing size of the coral. A bite by a predator is more devastating to a smaller coral than a larger by removing proportionately more coral tissue in the small coral.

5. Bioerosion

The calcium carbonate blocks set out in the field are required to determine the bioerosion vs. accretion budgets for each site. These blocks were set out during the summer of 2004, and will be retrieved from the field 12 months later during the summer of 2005. It is at this point that we can fully determine the bioerosion vs. accretion budgets.

Summary

We found no or very little macroalgae at our study sites, limiting our ability to detect any real differences and/or trends between sites. Turf was prevalent at all sites, varied between sites, but showed no expected relationship of decreasing in cover with increasing biomass levels of herbivorous fishes. Based on these findings, we could not make a conclusion as to whether herbivorous fishes (protection) control grazing pressure on macroalgae or turf on coral reefs.

Coral was prevalent at all sites, varied between sites, but did not as expected increase with increasing biomass levels of herbivorous fishes. We did not detect a relationship. Again, based on these results, we cannot conclude that herbivorous fishes (protection) promote or limit the growth of coral.

However, we did find that prevalence of CCA increased with increasing biomass levels of herbivorous fishes. Herbivorous fishes, probably parrotfish specifically (protection), promote the growth of CCA (Steneck 1983, Littler and Littler 1997). Based on findings in the scientific literature, we might assume that CCA in turn promotes coral recruitment (Morse et al. 1988, Morse and Morse 1996). However, as stated, we did not find that herbivorous fishes (protection) promote coral cover. This might be explained by our coral juvenile survival data. We found no difference in survival success of the small size class between sites on Oahu. Protection did not promote survival (it is worth noting that we did not conduct these studies at our regular study sites). Further, we found that there were differences in survival between sites as well as between size classes of the intermediate and large size classes of juveniles. Predation at Hanuama Bay affected the experimental nubbins substantially, while not at the other sites. This might be due to the combination of a high biomass of corallivorous fishes and low background level of *P. compressa* ("prey") at Hanuama Bay compared to the other study sites. The survival differences in size classes indicated that the probability of survival of juvenile corals is greater the larger the size of the coral. These findings tie into the coral cover and CCA cover at our study sites. Although herbivorous fishes (protection) promote CCA growth, assumed to promote coral recruitment, coral survival is limited by higher levels of predation at the same sites (higher biomass of herbivorous fish at protected sites probably reflect higher biomass of all fishes, including corallivorous fishes), nullifying the positive affect on coral cover.

Problems

Since the study sites we chose held such low levels of macroalgae, we could not make an assessment as to whether herbivorous fishes negatively affect macroalgae by grazing it down. To address this problem directly, we would have to choose and assess alternative sites that are known to have macroalgal growth. We did not realize that the sites we chose, although spanning

an appropriate biomass range of herbivorous fish, held no macroalgae. Fortunately our next year's HCRI-RP funded project will focus on grazing experiments assessing the cropping ability of herbivorous fishes.

Additional work

Funded by HCRI-RP, our project this coming year will focus on grazing experiments by determining the cropping affect of herbivorous fishes on macroalgal biomass. We will do this by calculating and comparing the net grazing pressure generated by the resident herbivorous fish community at each site based on species specific bite rates and existing biomass data. Studies from reefs in Belize (Williams et al. 2001), show that as coral cover is lost and replaced by algal cover, there comes a point when the amount of substratum occupied by algae simply overwhelms the ability of the resident herbivorous fish to crop it down. Similarly, we will also determine what level of grazing pressure is needed to crop down a standing algal biomass, and whether there is a threshold level of algal biomass above which even an increased number of herbivorous fishes simply cannot crop down the algae. Further, we will tease out whether there are differences in the cropping effect induced by larger herbivorous fishes (parrotfish) compared to smaller herbivorous fishes. Finally, many marine organisms including algae, are defended against consumption by predators by means of secondary metabolites (Hay et al. 1994). We will chemically test algal communities for presence and levels of algal toxins, when the algae are heavily grazed upon down through the spectrum of not being grazed upon at all.

To tease out whether *Cantherines dumerilii* and *Arothron* species have a significant predatory affect on the coral framework, we will observationally quantify bite marks on coral colonies in the field at all our study sites and correlate this with the biomass of these corallivorous fishes.

Since our study site on each reef was at a depth of 10m set around the WHAP and CRAMP fish transects, we also plan to conduct a within site study at the Hanauma Bay MLCD comparing cover of coral, specifically *P. compressa*, with observational bite marks and predation upon experimental nubbins. We have already taken photoquadrats at three separate sites within the Bay and using one-way ANOVA see significant differences in benthic cover between sites (Fig. 13, Map 2, see appendix).

VII. Evaluation

Attaining project goals & objectives

The overall goal of our project has been to understand properties of healthy reef ecosystems assumed to be promoted by marine protection, which in turn are assumed to be more resistant to invasions by alien species. To understand these properties, we aimed at determining a set of ecosystem processes and factors characteristic of healthy coral reefs and comparing these factors between sites with ranging levels of protection.

While we have made modifications to parts of our methodology during the progress of our work, we have attained our overall project goal by meeting our individual project objectives. We have assessed and compared prevalence of algae between sites with varying levels of protection, as well as assessed the prevalence of coral colonies and crustose coralline algae. We have also compared the probability of survival of coral juvenile between sites. We have yet to determine and compare the bioerosion vs. accretion budgets at all sites, due to temporal duration of the experiments set out on the reef required to determine these budgets. We will obtain these results after the summer of 2005.

Although, we were not able to conclude that areas with a greater biomass of herbivorous fish (reflecting protection) promote a collective trend in reef processes such as overall high levels of grazing characterized by a low prevalence of algae, high coral cover, high CCA cover, successful coral juvenile survival and less bioerosion thought to be characteristic of healthier coral reef systems, we found that protection positively favors the success of CCA that binds the substratum and facilitates coral recruitment. Scleractinian corals are the foundation of the coral-reef ecosystem and so the facilitation of recruitment and survival of corals is fundamental to the coral-reef ecosystem. There has been much research of connectivity among reefs as information to aid in the location and design of Marine Protected Areas. However, some areas have common larval input but high post-settlement mortality and so most of the proliferation is asexual by budding and separating or fragmenting. Even though there is ample connectivity, most of the coral populations in Hanauma Bay are relatively isolated. Caution should be used in predicting connectivity on the basis of current patterns and larval supply. Predation by fishes on corals is much more intense than was previously realized. Corals are especially vulnerable at the juvenile stage in which they can be removed with a single bite. Their survival increases as they reach a larger size because at a larger colony size, there is a greater chance for tissue to remain from which the colony can regrow.

Dissemination of results

The project results have been presented on six occasions during the course of the project. Progress and final results of the project have been presented at four different HCRI-RP quarterly meetings. These meetings bring together an audience of fellow scientists from different departments at the University of Hawaii, as well as Federal and State employees from organizations such as DLNR, DAR, NOAA, USFWS, TNC. The coral juvenile survival results have been presented at the annual Albert Memorial Testers Symposium at the University of

Hawaii. These data have also been presented and discussed at the 10th International Coral Reef Symposium in Okinawa, Japan, a venue that brings together the leading coral reef scientists and special interest groups from across the world. The final findings of the project will be included in future workshops held by Dr. Charles Birkeland who speaks at a range of meetings and venues. The results also directly constitute Danielle Jayewardene's PhD dissertation and thus will be presented on numerous occasions throughout her career as well as be published in peer reviewed scientific journals. Finally, a colorful pamphlet for outreach purposes will be printed highlighting the important role of crustose coralline algae in binding loose coral rubble creating firm substratum, favoring recruitment of juvenile coral and competing with macroalgae for space on the reef.

VIII **Signature of Principle Investigator** _____

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Appendix:

Map 1: Study sites on Oahu and along the Kona coast of Hawaii.

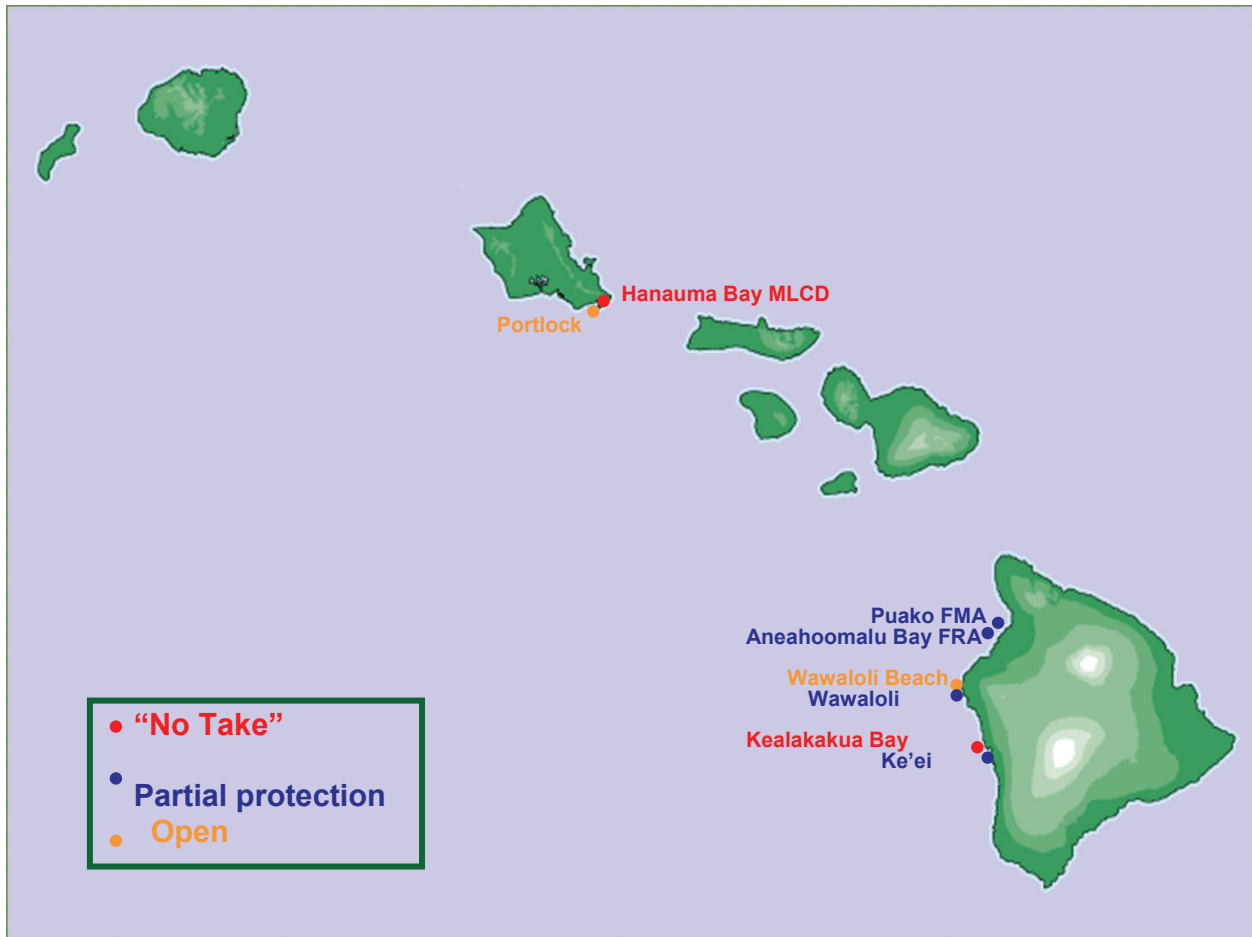


Fig. 1: Biomass range of herbivorous fishes (*Acanthuridae* and *Scaridae*) at a range of sites in Kona and on Oahu. Marked bars indicate our chosen study sites.

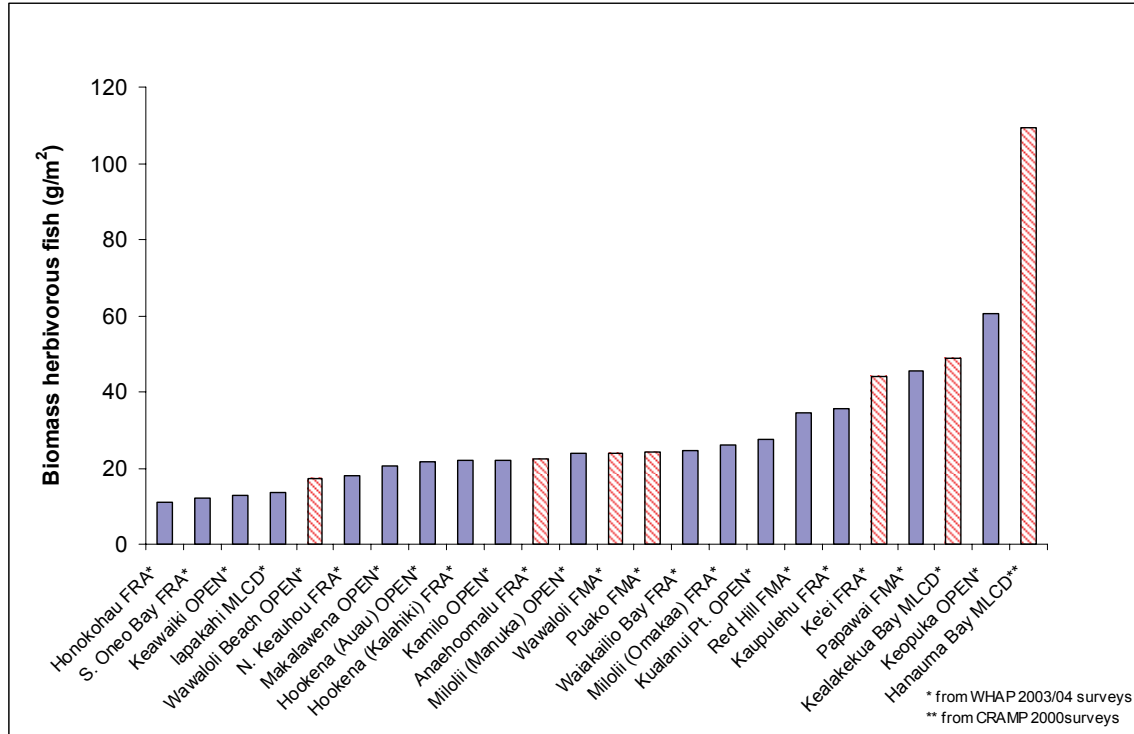


Fig. 2: Example of theoretical grid set around 2 x (2x 30 m) WHAP fish transects.

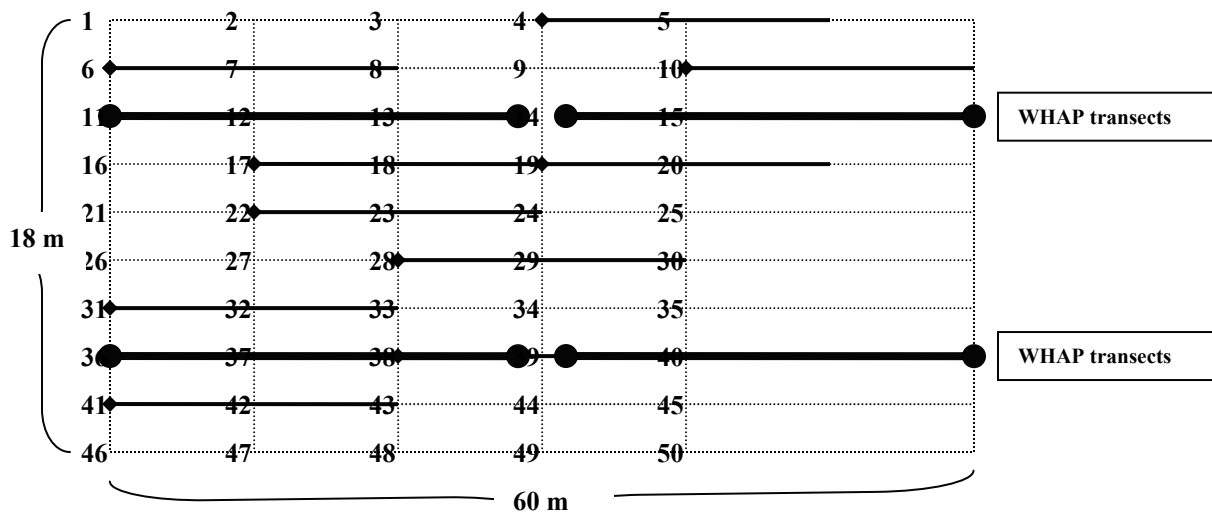


Fig. 3a, b & c: Determining the ideal number of pts/image and images/transect to analyze to adequately estimate turf, CCA and coral cover at sites.

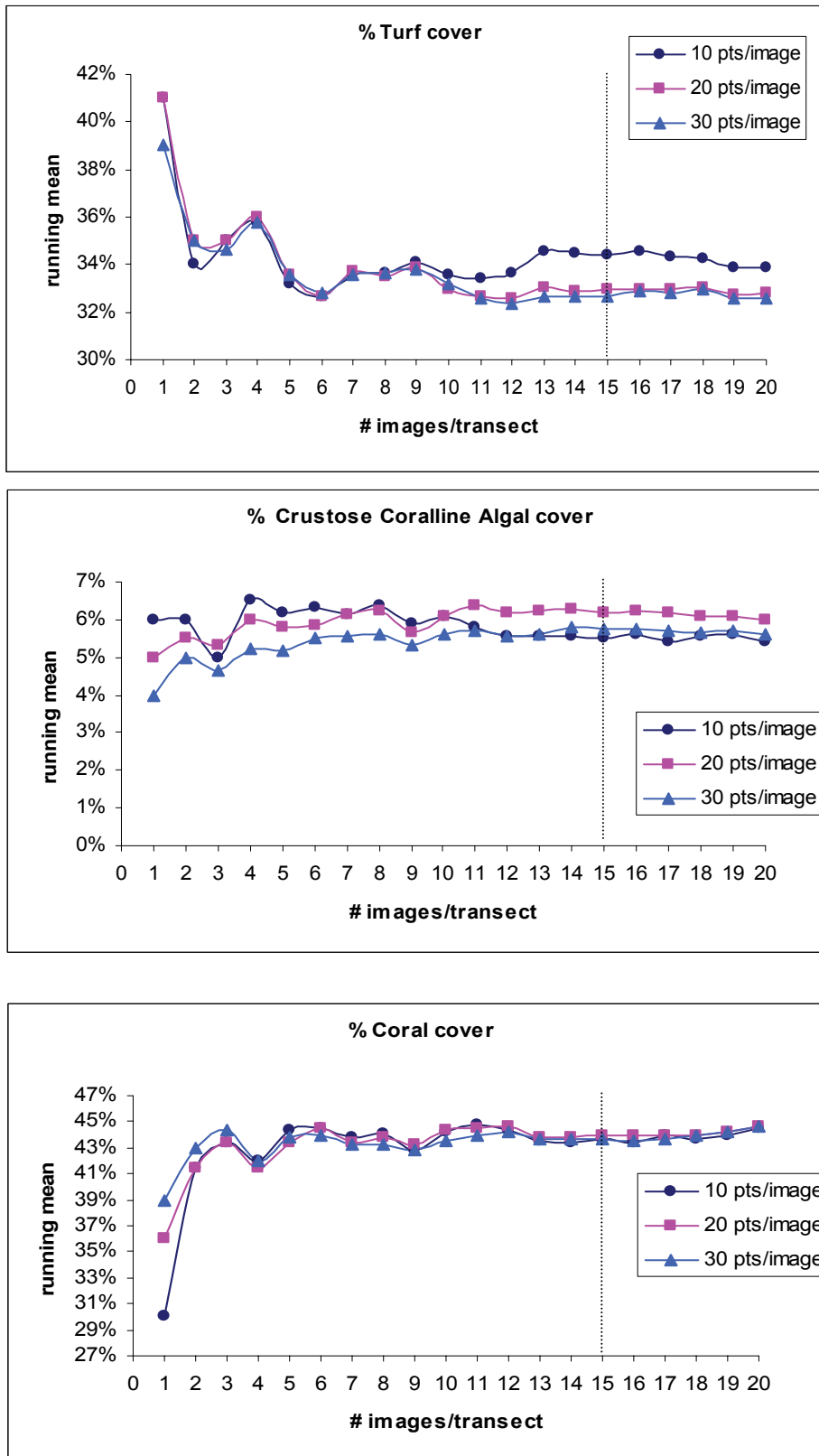


Fig. 4: Percent macroalgal, turf, crustose coralline algal and coral cover at study sites.

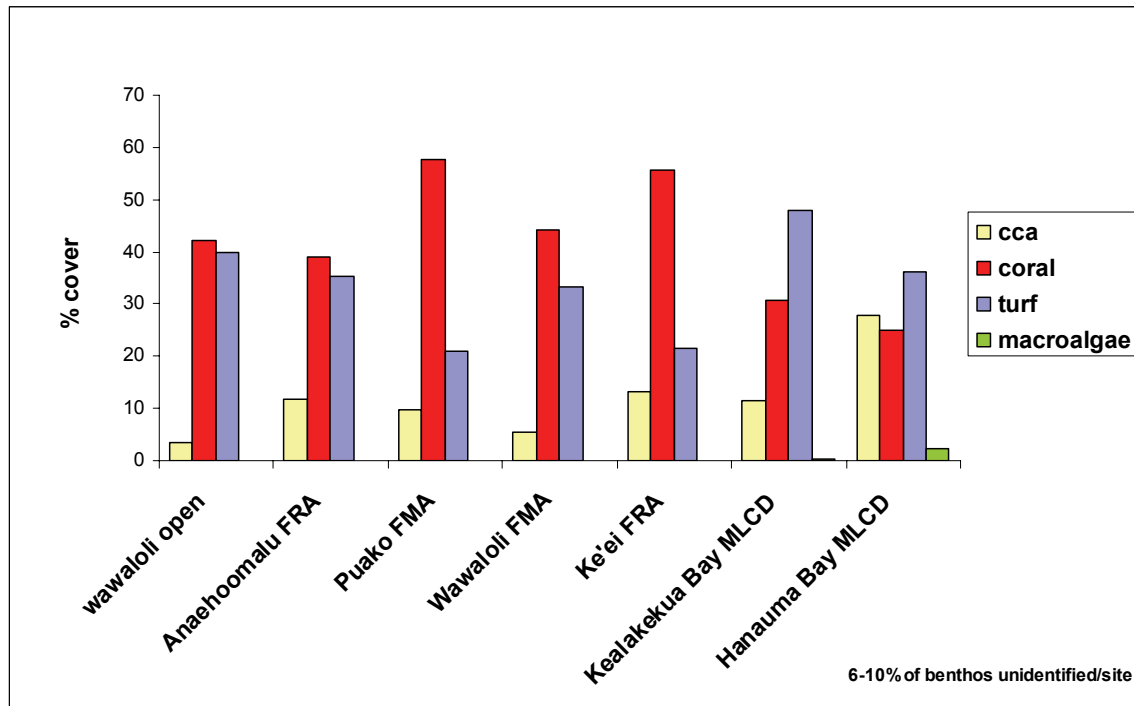


Fig. 5: Relationship between biomass of herbivorous fishes (*Acanthuridae* and *Scaridae*) and percent turf cover.

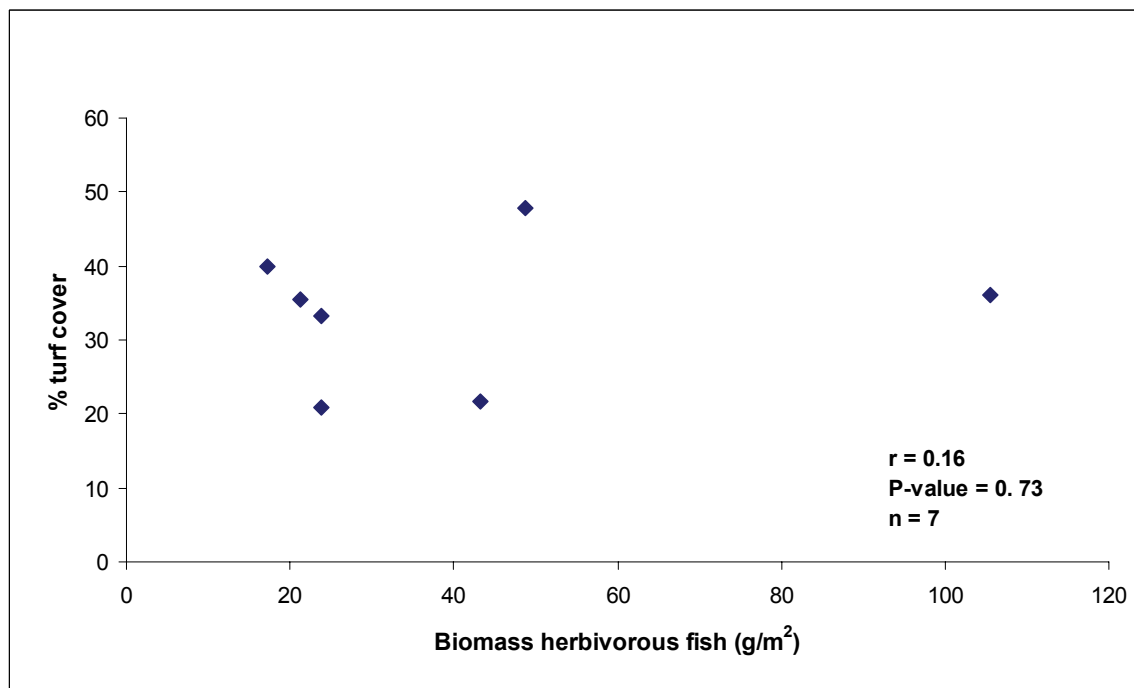


Fig. 6: Relationship between biomass of herbivorous fishes (*Acanthuridae* and *Scaridae*) and percent coral cover.

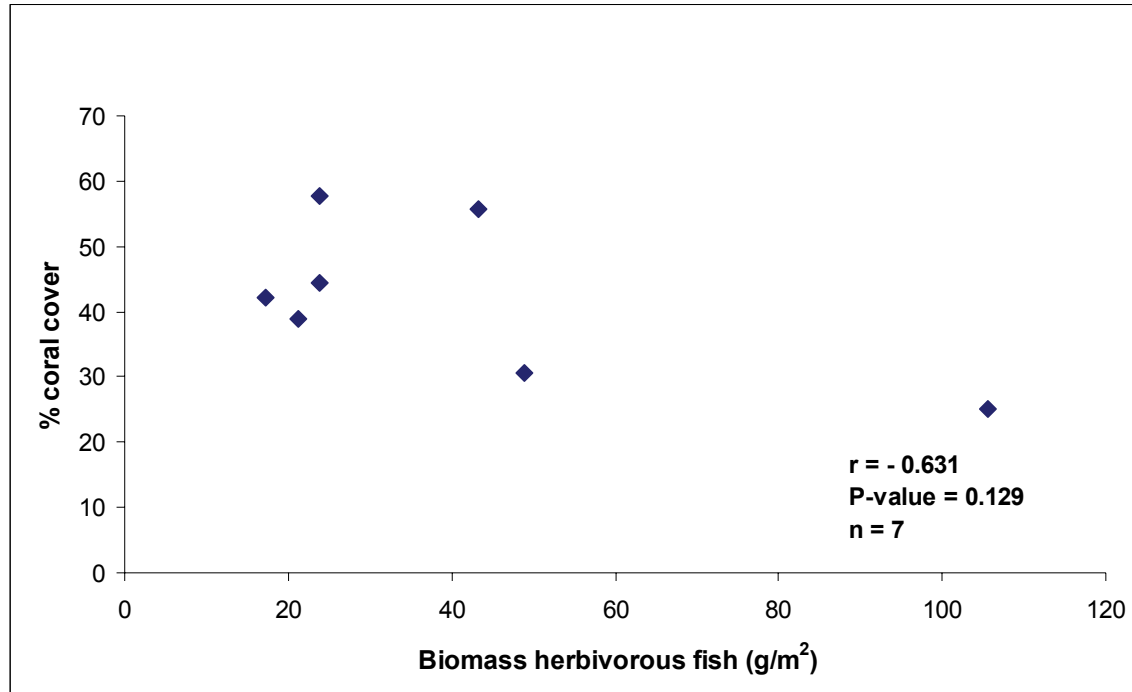


Fig. 7: Percent cover of coral species at our study sites.

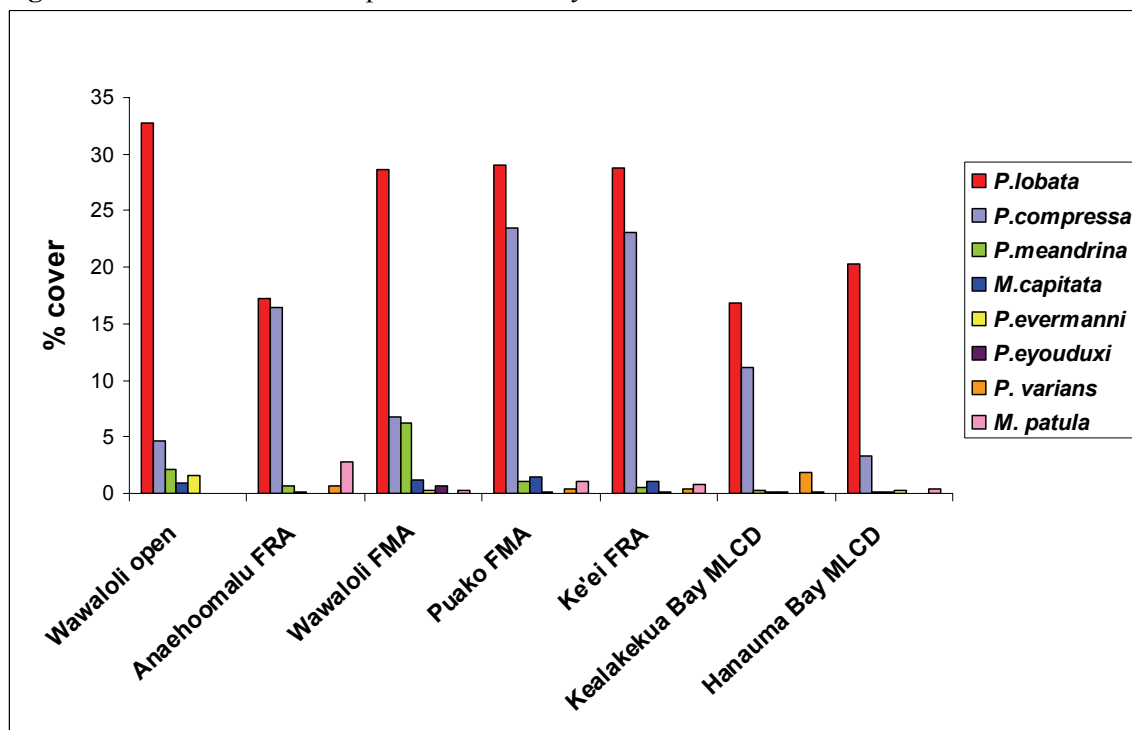


Fig. 8: Relationship between biomass of herbivorous fishes (*Acanthuridae* and *Scaridae*) and percent crustose coralline cover.

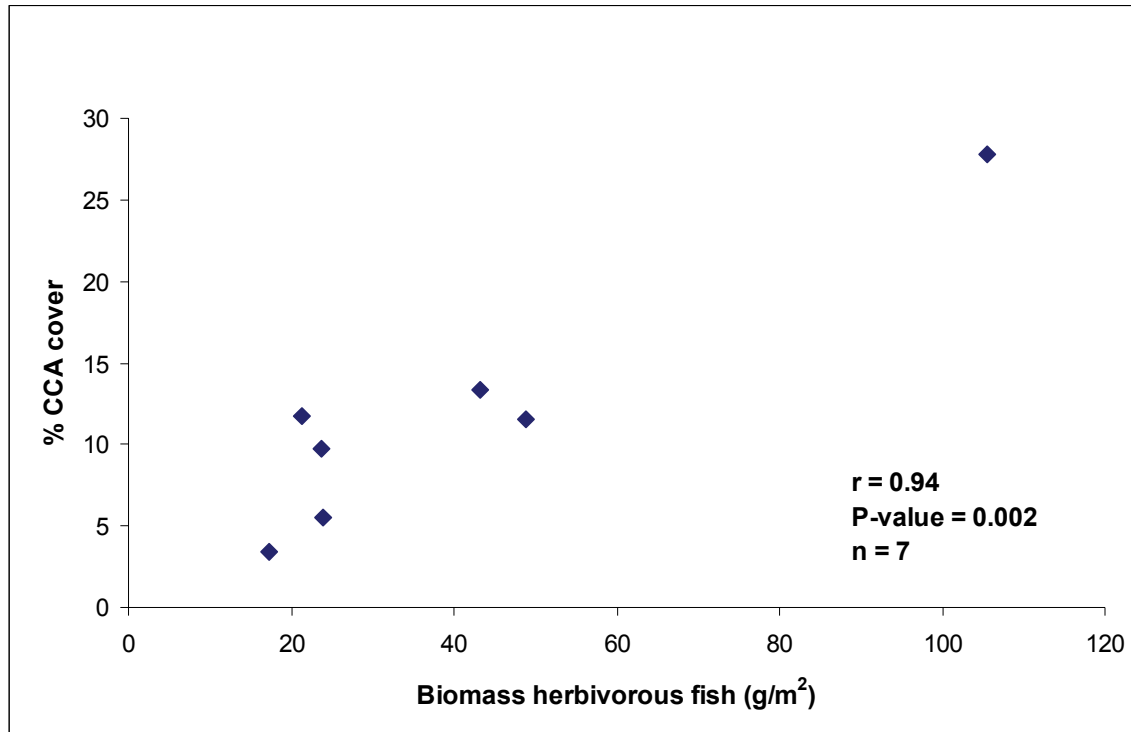


Fig. 9: Relationship between biomass of parrotfish and crustose coralline algal cover.

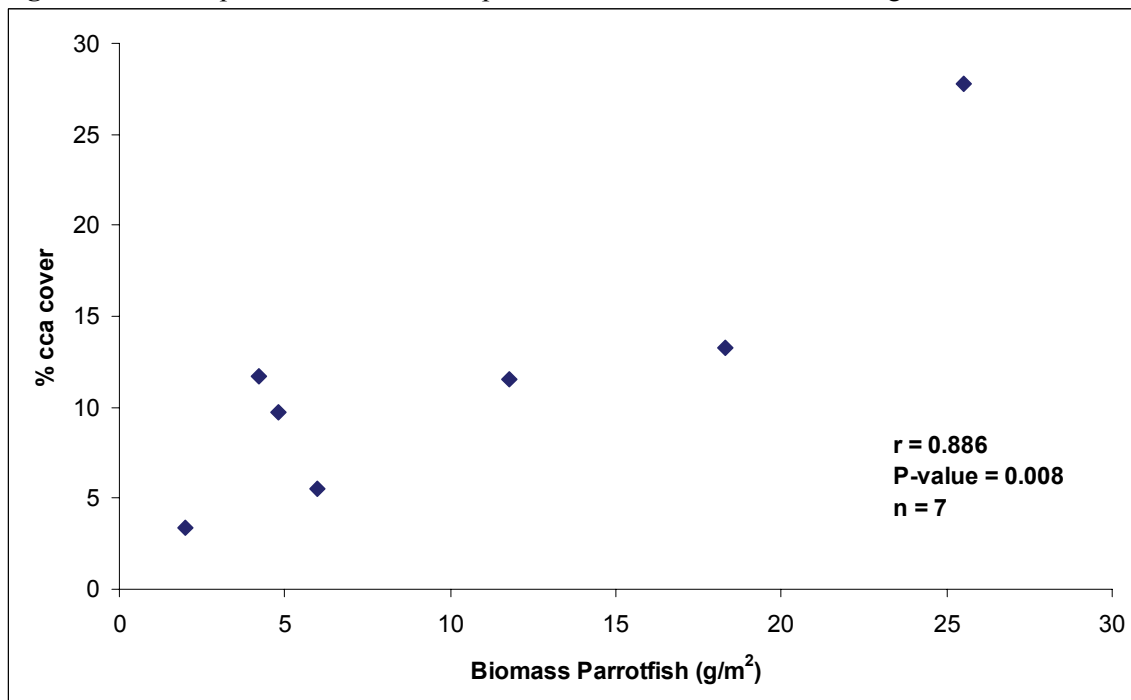


Fig. 10: Survival of small size class of coral juveniles (spat) after 4 week monitoring period for sites with different levels of protection on Oahu.

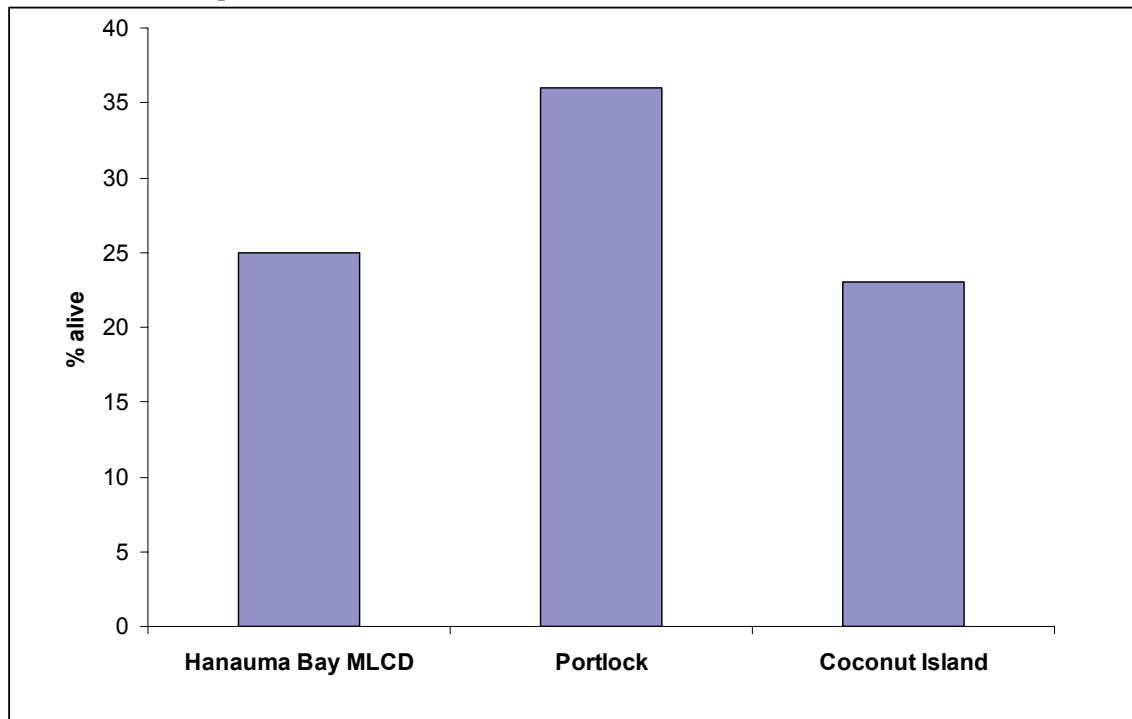


Fig. 11: Survival of intermediate and large size class of coral juveniles after 4 week monitoring period at all study sites.

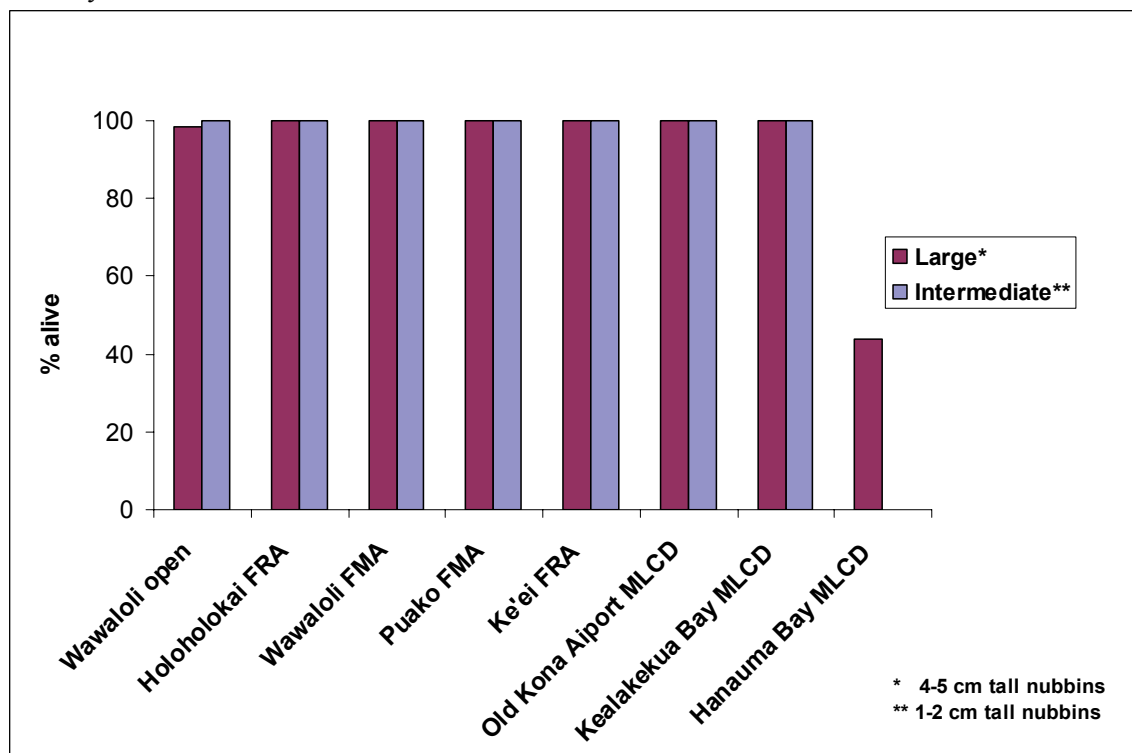


Fig. 12: Relationship between biomass of corallivorous fish (*Cantherines dumerilii* and *Arothron meleagris*) and percent cover coral.

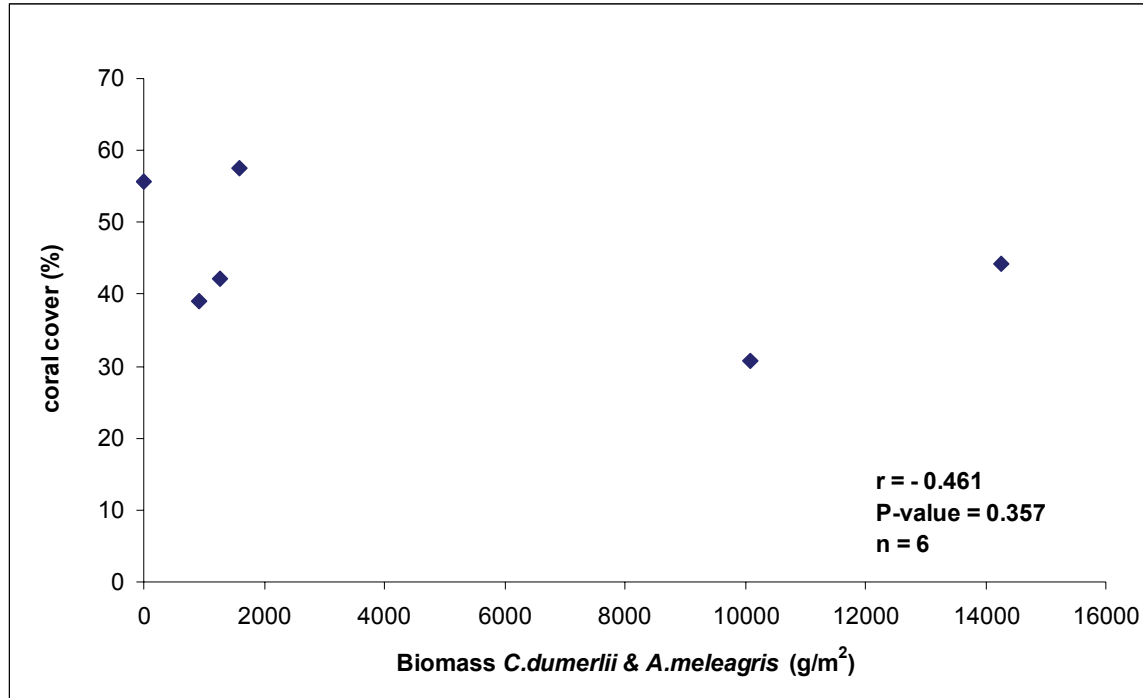


Fig. 13: Relationship between biomass of corallivorous fish (*Cantherines dumerilii* and *Arothron meleagris*) and percent cover *Porites compressa* coral.

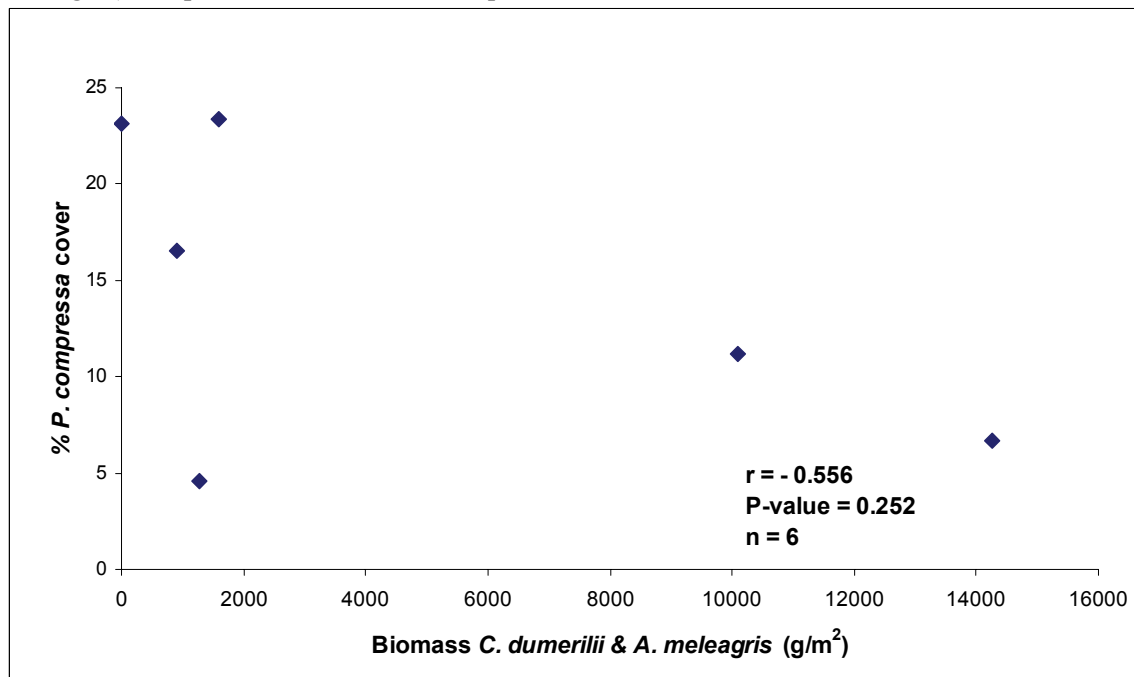
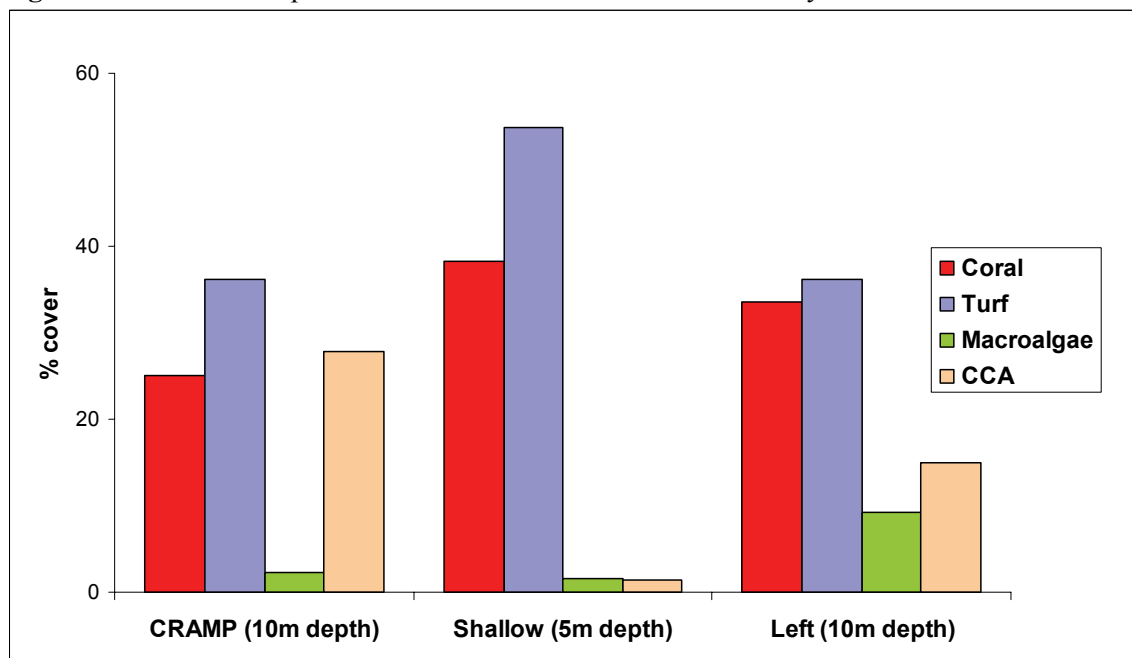
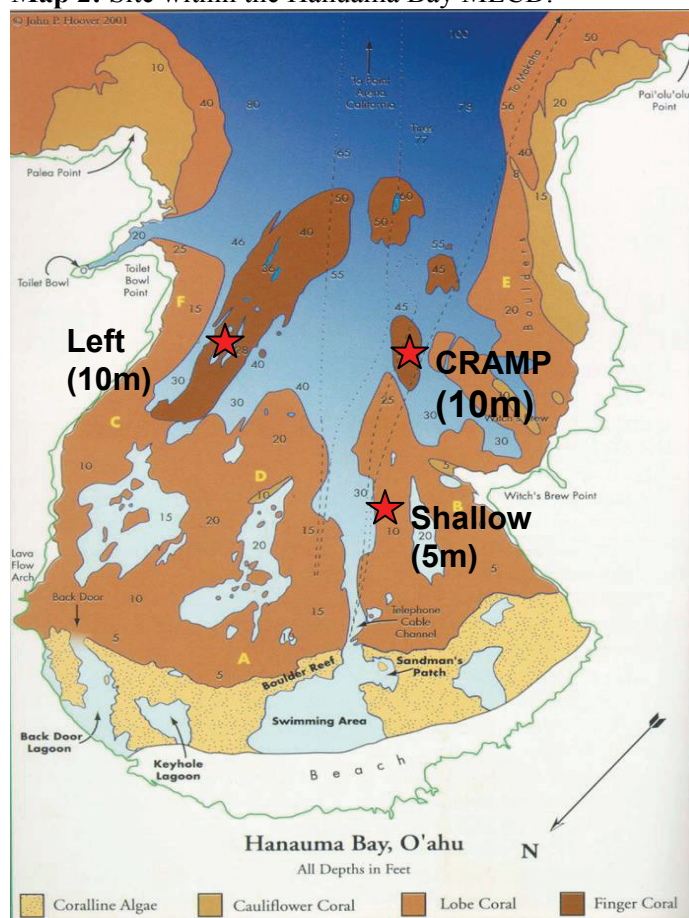


Fig. 14: Within site comparison of benthic cover at the Hanauma Bay MLCD.



Map 2: Site within the Hanauma Bay MLCD.



One-way Analysis of Variance_all sites_turf

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	6	76121	12687	36.95	0.000
Error	946	324829	343		
Total	952	400950			

Individual 95% CIs For Mean

Based on Pooled StDev

Level	N	Mean	StDev	
A-bay FR	148	35.88	18.14	(--*--)
K-bay ML	148	47.97	21.53	(--*--)
Puako FM	141	22.16	12.93	(--*--)
Waw Open	148	40.41	23.36	(--*--)
H-bay ML	74	36.62	18.45	(--*--)
Keei FRA	146	22.19	13.81	(--*--)
Waw FMA	148	33.72	18.84	(--*--)
Pooled StDev = 18.53				

One-way Analysis of Variance_all sites_coral

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	6	79472	13245	36.45	0.000
Error	923	335438	363		
Total	929	414909			

Individual 95% CIs For Mean

Based on Pooled StDev

Level	N	Mean	StDev	
A-bay FR	140	42.07	17.65	(--*--)
K-bay ML	139	33.42	19.90	(--*--)
Puako FM	148	58.34	17.80	(--*--)
Waw Open	140	45.25	19.94	(--*--)
H-bay ML	65	28.92	18.51	(--*--)
Keei FRA	150	55.57	20.18	(--*--)
Waw FMA	148	44.93	19.00	(--*--)
Pooled StDev = 19.06				

One-way Analysis of Variance_all sites_cca

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	6	18597	3100	27.99	0.000
Error	652	72203	111		
Total	658	90800			

Individual 95% CIs For Mean

Based on Pooled StDev

Level	N	Mean	StDev	
A-bay FR	110	15.95	10.70	(--*--)
K-bay ML	113	15.31	9.43	(--*--)
Puako FM	101	14.41	10.47	(--*--)
Waw Open	59	8.73	4.51	(--*--)
H-bay ML	71	29.37	15.72	(--*--)
Keei FRA	125	15.96	11.74	(--*--)
Waw FMA	80	10.38	6.40	(--*--)
Pooled StDev = 10.52				

One-way Analysis of Variance_spat_Oahu

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	749	374	0.34	0.717
Error	21	23291	1109		
Total	23	24040			

Individual 95% CIs For Mean
Based on Pooled StDev

Level	N	Mean	StDev	
Hanauma	8	24.87	31.53	(-----*-----)
Portlock	8	35.75	36.90	(-----*-----)
Coconut	8	23.12	31.18	(-----*-----)
Pooled StDev = 33.30				0 20 40 60

One-way Analysis of Variance_Hanauma_turf

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	15995	7998	19.39	0.000
Error	220	90745	412		
Total	222	106740			

Individual 95% CIs For Mean
Based on Pooled StDev

Level	N	Mean	StDev	
Right_10	74	36.62	18.45	(-----*-----)
Right_5m	74	54.39	25.43	(-----*-----)
Left_10m	75	36.20	15.89	(-----*-----)
Pooled StDev = 20.31				32.0 40.0 48.0 56.0

One-way Analysis of Variance_coral

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	5394	2697	6.02	0.003
Error	203	91021	448		
Total	205	96415			

Individual 95% CIs For Mean
Based on Pooled StDev

Level	N	Mean	StDev	
Right_10	65	28.92	18.51	(-----*-----)
Right_5m	69	41.59	24.37	(-----*-----)
Left_10m	72	34.79	20.11	(-----*-----)
Pooled StDev = 21.17				28.0 35.0 42.0

One-way Analysis of Variance_Hanauma_cca

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	6114	3057	16.20	0.000
Error	138	26043	189		
Total	140	32157			

Individual 95% CIs For Mean
Based on Pooled StDev

Level	N	Mean	StDev	
Right_10	71	29.37	15.72	(--*--)
Right_5m	12	8.75	7.42	(-----*-----)
Left_10m	58	19.22	11.95	(--*--)

-----+-----+-----+-----
10 20 30

Pooled StDev = 13.74

One-way Analysis of Variance_Hanauma_macroalgae

Analysis of Variance

Source	DF	SS	MS	F	P
Factor	2	531.4	265.7	6.32	0.003
Error	85	3576.5	42.1		
Total	87	4108.0			

Individual 95% CIs For Mean
Based on Pooled StDev

Level	N	Mean	StDev	
Right_10	21	8.095	4.024	(-----*-----)
Right_5m	14	7.857	3.780	(-----*-----)
Left_10m	53	13.019	7.680	(-----*-----)

-----+-----+-----+-----+
6.0 9.0 12.0 15.0

Pooled StDev = 6.487