ENHANCING CORAL REEF RESILIENCE AND RESTORATION SUCCESS: LESSONS LEARNED FROM LAOLAO BAY, SAIPAN AND MAUNALUA BAY, OAHU

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ABSTRACT

Coral reefs worldwide are suffering from multiple local and global stressors such as land-based sources of pollution, invasive species, overfishing, ocean warming, and ocean acidification. With local and global threats on the rise, coral reef managers are turning to ecosystem-level restoration projects for greater ecological impact. These projects usually require supplemental funding, strong partnerships, and take years to complete. Groups working in Laolao Bay, Saipan and Maunalua Bay, Oahu obtained funding to conduct such ecosystem-level restoration work. Both projects aimed to restore marine resources and ecosystems by improving water and habitat quality by addressing land-based sources of pollution and invasive alien algae issues. Specifically, practitioners in Laolao Bay Saipan attempted to address land-based erosion by restoring the Laolao watershed through revegetation, improving the Laolao Bay road infrastructure, and through outreach. Personnel working in Maunalua Bay Oahu, attempted to address the invasive species problem by manually removing 11 hectares of the invasive alga, *Avrainvillea amadelpha*, at Paiko reef flat and through successful community engagement. I measured the effectiveness of both ecosystem restoration projects by quantifying coral physiological response to land-based restoration activities in Laolao Bay, and by quantifying the amount of resuspendible sediment present during and after algae removal in Maunalua Bay. Both projects were successful and achieved initial results. In Laolao Bay, watershed restoration activities resulted in reduction in erosion and in improved coral health at deeper sites. In Maunalua Bay, removal of *A. amadelpha*, resulted in fine sediment mobilization and flushing. Both projects incorporated communities at different levels and underwent the conservation action plan (CAP) process.

Those supporting efforts to insure the future of coral reefs need to incorporate and address the complex social issues surrounding such an important resource. Science and management will always play an important role, but to implement successful, sustained conservation actions, human compliance is often required. Humans are often viewed as the problem (rightfully so in numerous examples), but should also be viewed as the solution. It is possible to use science and management and instill conservation beliefs in communities and achieve sustained conservation success. The future of coral reefs requires resilient ecological AND social systems.

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List of Abbreviations

ARRA	American Recovery and Reinvestment Act
BECQ	CNMI Bureau of Environmental and Coastal Quality
BMP	Best Management Practices
C	Celsius
CAP	Conservation Action Plan
cm	centimeter
cm^3	cubic centimeter
CNMI	Commonwealth of the Northern Mariana Islands
COTS	Crown of Thorns Starfish
CRAMP	Coral Reef Assessment and Monitoring Program
CRM	CNMI Coastal Resources Management
CYP1A1	Cytochrome P450 1A1
DEQ	CNMI Division of Environmental Quality
DFW	CNMI Division of Fish and Wildlife
FWS	US Fish and Wildlife Service
g/m^2	grams per square meter
H_0	Null Hypothesis
H_a	Alternative Hypothesis
km	kilometer
km^2	square kilometer
KML	Kewalo Marine Laboratory
LBSP	Land Based Sources of Pollution
m	meter
MINA	Mariana Islands Nature Alliance
MPA	Marine Protected Area
NGO	Non-Governmental Organization
NOAA	US National Oceanic and Atmospheric Administration
NTU	Nephelometric Turbidity Units
PBST	Phosphate-Buffered Saline Containing Tween
PRF	Paiko Reef Flat
SEM	Standard Error of the Mean
SOD	Superoxide Dismutase
TNC	The Nature Conservancy
US	Unites States
USD	US Dollar
V	Volts
YSI	Yellow Springs Instruments
μg	microgram
μg/liter	microgram per liter

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

1.1.1 Importance of coral reefs

Coral reefs are productive coastal ecosystems, which thrive in clear, shallow, oligotrophic, tropical marine waters. Wilkinson (2004) estimates that about 500 million people rely of coral reefs and associated services such as food and coastal protection. Coral reefs house about 4-5 % of all species and have the greatest diversity per unit area of any marine ecosystem (Karlson 1999). Of the 75-100 million tons of marine fisheries harvested each year, coral reef fisheries account for 9 million tons (Smith 1978). Burke et al. (2011) estimates that globally over 275 million and 850 million people live within 30 km and 100 km of coral reefs respectively.

Coral reefs provide the three-dimensional structure required for fish and other organisms to survive and thrive. Coral reefs are large carbonate structures that buffer shorelines from oceanic swells and prevent coastal erosion. Worldwide, coral reefs protect 150,000 km of coastline in 100 countries by absorbing wave energy and reducing coastal erosion (Burke et al. 2011). This is extremely important in low-lying atolls like the Marshall Islands where the highest elevation on land measures only a few meters. In addition to structural benefits, coral reefs, with its diverse microbial and cyanobacterial associations, function as nitrogen fixers in oligotrophic waters (Sorokin 1993). In nutrient poor waters, the reefs take unavailable, atmospheric nitrogen and introduce it into the food chain, supporting the high diversity and abundance of life.

Coral reefs also have economic value. Cesar et al. (2003) estimate the value of global reefs at $29.8 billion annually. The coral reefs surrounding the western Pacific island of Saipan has a total economic value of about $61.2 million/year (van Beukering 2006). The coral reefs around the main Hawaiian Islands have a total economic value of about $364 million/year with a total overall asset value of all potential reef area of about $10 billion (Cesar and van Beukering 2004). Both value estimates considered use values such as; tourism, fisheries, coastal protection and non-use values such as, aesthetics, traditional, and cultural use.

1.1.2 Threats to coral reefs

The world's coral reefs currently face attacks by numerous environmental and anthropogenic agents, including increasing population growth and development, habitat destruction, pollution, sedimentation, disease, invasive species, and global climate change. Anthropogenic change rapidly decreases the overall health and resiliency of coral reefs (Scheffer et al. 2001). Jackson et al. (2015) reported a 41% decline in coral cover from 1970 to 2012 and a 337% increase in macroalgal cover from 1984 to 1998 in the Caribbean. Coral cover from 1960-2000 in the Great Barrier Reef declined steadily from about 50-20% while bleaching events and crown of thorns (COTS) outbreaks increased (Bellwood et al. 2004). Increasing ocean temperatures and ocean acidification are causing concern for coral reefs worldwide (Pandolfi et al. 2011). Even pristine reefs in remote areas are subject to the effects of climate change (Selkoe et al. 2009). From 2014 through 2016, warming oceans were responsible for bleaching events globally. The Great Barrier Reef Marine Park Authority reported that 50% of their reefs were lost due to the recent 2015-2016 bleaching events (GBRMPA 2016). With increasing human population in the coastal areas, current and future management strategies need to address the complex social, cultural, and environmental issues associated with coral reefs.

In the absence of anthropogenic effects, coral reefs show greater resilience and ability to rebuild after routine acute natural disturbances, such as severe storms events (Connell et al. 1997). Instead of recovery, reefs are exposed to a host of human impacts and forced into alternative stable states usually dominated by algae (Scheffer et al. 2001; Jackson et al., 2015). Connell et al. (1997) demonstrated corals were not able to recover after chronic, long-term disturbances.

1.1.3 Management Tools

Ecosystem modifications

One method of restoring coral reefs is simply by “planting” live colonies to replace those lost. Coral transplantation is expected to accelerate natural recovery. Transplants can be whole coral colonies, coral fragments, single coral polyps, or even the seeding of coral larvae. Survivorship, growth rates, fecundity and genetic diversity have to be considered when restoring reefs using coral transplants (Rinkevich 2005). In order for coral transplantation to be effective, the natural conditions have to be conducive for coral survival (Jokiel et al 2006; Naughton & Jokiel 2001). Water and substrate quality must be at a level required for coral survival. Coral nurseries and coral gardening are helping in the advancement of this technique as a viable restorative option (Rinkevich 2006).

Invasive species are problematic in many parts of the world, and in Hawaii, invasive algae have harmed numerous coral reefs (Carlton & Eldridge 2009; Goodwin et al., 2006). One way to combat invasive species is to manually remove them. At Maunalua Bay, Oahu, the community removed acres of the invasive alga, *Avrainvillea amadelpha*. With the alga gone, bare substrate is available for native sea grass and native algae to inhabit (Peyton 2009; Minton & Conklin, 2012). Kaneohe Bay, Oahu, has similar problems with invasive algae. *Euchema* sp., and *Gracilaria salicornia* are found frequently smothering the coral reefs (Smith et al., 2002). The State of Hawaii, The Nature Conservancy of Hawaii, and the University of Hawaii developed the “supersucker” - a scaled up underwater vacuum system, integrated into a pontoon boat, used by trained divers to physically suction invasive algae off the coral reef (https://dlnr.hawaii.gov/ais/invasivealgae/supersucker/). Invasive fishes, such as the peacock grouper in Hawaii, and the lionfish in the Caribbean, have also been identified for targeted removal. Total eradication of an established invasive species is difficult and requires early intervention, small geographic extent, financial resources, and coordinated efforts (Myers et al. 2000).

An example of “adding” to the ecosystem is stock enhancement, and is generally defined as the “hatchery production of a particular species of fish to a particular size or stage, for release into an area or stock, to increase some aspect of fishing quality in the future (e.g., catch rates, total catch, biomass, abundance, etc.) (Molony et al., 2003). Usually, the first resources to disappear are the large groupers, jacks, giant clams, parrotfishes, *Trochus* spp., and limpets (*opihi*). Reef fishes reproduce and grow slower than their pelagic counterparts. Stock replenishment/enhancement is one way of seeding larvae and/or juveniles of a targeted species onto the reef. On the windward side of Oahu, cultured Pacific threadfin (*moi*) accounted for 10% of the recreational catch in the late 90’s (Friedlander and Ziemann 2003). Stock enhancement can have objectives (other than supporting fisheries yield). The release of herbivores to combat invasive algae has been ongoing here in Hawaii (Conklin and Stimson 2004; Stimson et al 2007).

Land-based ecosystem modifications can occur as well. Watersheds catch rainfall and drain areas of land. Naturally, upland forests, vegetation, wetlands, mangrove forests, and sea grass beds all work together to effectively decrease water velocity and volume, and filter out sediments (Golbuu et al. 2011). These services allow for the presence of coral reefs offshore. When watersheds are altered these services become compromised and coral reefs are pushed further and further offshore to escape the influence of the runoff (Wolanski et al 2009). The increase in coastal development has led to major alterations in Pacific Island watersheds (Wolanski et al. 2009). Some common alterations include: clearing of upland forests and vegetation; increase in impervious surfaces as a result of increased pavement, rooftops, etc.; channeling of rivers and streams; and the filling and development of wetlands.

Best Management Practices (BMP) include a vast range of approaches designed to prevent, reduce or treat polluted runoff. One of the goals of BMPs are to reduce the volume and velocity of the runoff. This is achieved by employing strategies to keep the water out of the streams and on land. Rain barrels, ponding basins, rain gardens, pervious surfaces, all allow for the retention of water. Water catchment systems (however crude) will be useful in decreasing the volume of water entering the hardened streams. If every household in Hawaii Kai (~11,000) filled one 55-gallon drum ever time it rained, that would amount to 605,000 gallons of water retained. Shelton III and Richmond 2016 demonstrated that after 21 months, upland revegetation and sediment filters prevented 112 tons of sediments from washing out into Fouha Bay, Guam.

Social modifications

The solutions required to solve a number of natural resource problems are social in nature. Although humans have undoubtedly been responsible for much of the decline in coral reef health, they are also part of the solution. This section will describe management actions aimed at altering human interaction with the resources targeted for conservation. The most common and efficient (not necessarily the most effective) way of managing human behavior is to introduce and enforce regulations prohibiting access and unwanted behaviors. Examples include prohibiting take, managing use, and promoting stewardship.

Marine Protected Areas (MPA) are powerful conservation tools. Alcala and Russ (1990) were able to demonstrate that a protected area increased the abundance of fish inside and outside the reserve. Fishing was better when 25% of the coast was closed off to fishing. When the entire coast was open to fishing, catch declined. With documented success of fishery abundances inside MPAs, researchers pondered if similar results were attainable for the corals themselves. Selig and Bruno (2010) conducted global analysis of MPA effectiveness in preventing coral loss. They compared coral cover, spanning 37 years, from

310 MPAs with unprotected areas. They demonstrated that coral cover remained constant within MPAs, while, coral cover declined in unprotected areas. Selig and Bruno (2010) also demonstrated that older MPAs were more effective in preventing coral loss. MPAs regulate human activities at the local scale, so climate change and water quality issues have to be dealt with accordingly. Richmond et al. (2007) was able to demonstrate that MPAs were not effective when adjacent watersheds were degraded.

Other examples of "human management" are limited entry fisheries, seasons, size restrictions, quotas, and gear restrictions. In the CNMI, purse seine and longline fishing vessels are prohibited from fishing in CNMI waters. The only way to catch pelagic species, such as tunas is with a hook, reeled in one at a time. Closer to shore, reef fishermen are prohibited from using scuba while spearfishing. Destructive methods such as dynamite blast fishing and using bleach or rotenone are also prohibited. Additionally, indiscriminate fishing methods using laynets, gillnets, and beach seines are prohibited (some cultural use exemptions). Only throw nets with a mesh size of at least one inch are allowed. Currently, size restrictions for a handful of reef fishes are in the comment period of the law-making process.

One problem with negative reinforcement management methods, such as regulations, is that not all citizens are aware of current regulations, or choose not to abide by them. The rewards of poaching exceed the penalty or fine. Another approach is to encourage and promote positive behaviors that benefit the resource and ecosystem. Being responsible and utilizing sustainable fishing practices should be recognized and promoted. Responsible activities are not limited to the marine environment. Conserving water, employing watershed best management practices in your backyard, and being conscious that what is discarded on land will make its way to the ocean, are ways of being a good land steward.

Community based management is a tool that effectively integrates the community with the resource/environment. It uses a "holistic approach to management by incorporating environmental, socioeconomic, and cultural considerations in decision making by stakeholders" (Kay and Alder, 2005). This bottom up management approach places responsibility on the community to locally manage and influence decisions related to their resources. The community takes partial "ownership" of the resource and is partially responsible for the success or failure of the management scheme. The community should be involved in the initial planning stages to the implementation, monitoring, and eventual evaluation stages.

1.1.4 Management approach

Western-style approach

Currently in the United States, the management of natural resources is split between various state and federal agencies. In Hawaii, the State manages marine resources from the shoreline up to three miles offshore. From 3-200 miles, the federal government has management authority. For federally protected species, different federal agencies manage terrestrial and marine species. The National Oceanic and Atmospheric Administration (NOAA) is responsible for protecting marine species. The US Fish and Wildlife Service (FWS) is responsible for terrestrial species, to include aquatic, freshwater species. When species habitat overlap, management becomes cumbersome. In the Pacific northwest region of the United States, NOAA is responsible for managing the federally listed salmonid species, except for bull trout, which is managed by FWS. In Hawaii, the federally listed sea turtle is managed by NOAA when at sea, but when on land, FWS has the management authority.

The western approach is based on centralized authority, regulations, and laws. Laws are made at the federal and state level and enforced wherever applicable. Enforcement of laws are carried out by federal and/or state representatives. Most penalties are often not severe and don't do a good job at deterring illegal practices. In the CNMI for example, getting caught fishing in a marine protected area may result in confiscation of your gear along with a minimal administrative fine. These cases are normally handled administratively. The public is expected to report violations to the authorities, but response times are slow due to the lack of enforcement personnel. On Oahu alone, less than 40 enforcement officers from the Hawaii Division of Conservation and Resources Enforcement are responsible for the enforcement of land use, hunting and fishing regulations across a land area of 1,500 km^2. The CNMI Division of Fish and Wildlife currently has about 10 enforcement staff responsible for patrolling a land area of 115 km^2. The areas increase drastically when marine patrols are considered.

The assessment and monitoring of natural resources are carried out by both federal and state scientists and resource managers. They collect data and monitor the resources to determine if ecosystems and populations are healthy and/or at risk and whether regulatory interventions are warranted. Scientific staff are academically trained. They attend western-style schools and are taught concepts developed from published reports and previous scientific studies. These scientists may not be aware of local/indigenous traditions, customs, and culture. Additionally, these staff usually depend on a funding source which may dictate their specific responsibilities and work duties. Both Hawaii and Saipan resource agencies (Hawaii Division of Aquatic Resources and CNMI Division of Fish and Wildlife) take advantage of federal grants to pay for the management of resources. The US Fish and Wildlife Service provides Wildlife and Sportfish Restoration grants to US states and territories. This money is specifically for recreational/non-commercial research and development projects. NOAA provides funding for commercial fishing research. Unless allowed, scientific staff are not allowed to cross over between grant programs, thus limiting their research focus.

Traditional management approach

Reef and lagoon tenure were the most important and widespread marine conservation measures used in Oceania (Johannes, 1978). Poachers were fined and punished by their chiefs for their illegal fishing activities. Sharing took place during peaceful times with some of the catch allocated to the village that managed the reef (Johannes, 1978). In pre-contact Hawaii fishing had certain "*kapu*" or restrictions. The Pacific threadfin (*moi*), for example, was reserved strictly for royalty. In other Pacific Islands fishing spots and even fish species were controlled and only certain clans, castes, age groups, and genders were allowed to fish.

Managing coastal marine ecosystems as a single unit in an increasingly urbanized society is becoming less and less effective. All the protections and enforcement can be in place at a marine protected area (MPA), but if land-based issues are present and ignored, management efforts can be futile. To effectively manage coastal systems, watersheds and land-based activities need to be managed as well. In the small Micronesian island of Pohnpei, an established MPA was not reaping all the benefits of protection. Victor et al. (2006) investigated the sedimentation process and how upland forest clearing was exposing corals to muddy river discharges. They concluded that large amounts of sediment were killing coral reefs and realized that managing the upland forests was crucial to successfully restore the MPA. Coral reefs are connected to the adjacent watersheds and should be managed accordingly as an integrated unit.

Taking responsibility for the resource is evident in Pacific Islands. When the resource benefited the community in multiple ways extra precautions were taken to ensure the continued survival of the resource. Seabirds are one good example. Their feathers could be used to make fishing lures and jewelry, but more importantly, they were used to locate schools of fish (Johannes, 1978). Several Pacific Islands restricted the harvesting of seabirds and/or their eggs for the reasons mentioned above.

Management of natural resources, including coral reefs, is really about managing human activities and their effects. As such, the social sciences are critically important to identifying goals and objectives, approaches and the allocation of limited financial, human and institutional resources to achieve desired outcomes. The concept of coupled natural and human systems has developed into a sub-discipline that seeks to bridge the social and biophysical sciences. A goal of this approach is to also bridge science to policy and knowledge to action. In my research, I sought to bring together the elements of island cultural practices, traditional ecological knowledge, community-based natural resource management, and modern scientific techniques in support of the protection of coral reefs and those who depend on them. The following section includes the specific scientific framework and hypotheses that needed to be addressed to achieve positive outcomes.

1.2 RESEARCH OVERVIEW

1.2.1 Measuring effectiveness of ecosystem restoration

My research was conducted alongside two large-scale ecosystem restoration projects in Maunalua Bay, Oahu and Laolao Bay, Saipan. My main goal was to collect information that was needed and useful to both projects. I wanted to use methods and technology that the Kewalo Marine Laboratory (KML) possessed and conduct a study not readily available to either project. My research provided an additional layer of information that could be used by both communities as reference and potentially to guide current and future conservation plans and activities.

The American Recovery and Reinvestment Act (ARRA) of 2009 made billions of dollars available for “shovel ready” projects of all kinds across the United States. Both Maunalua Bay, and Laolao Bay applied and received funds for conservation and restorative work. Maunalua Bay received $3.4 million dollars to remove *Avrainvillea amadelpha*, an invasive alien alga, from Paiko reef flat. Laolao Bay received $2.6 million dollars to address erosion issues in the Laolao Bay watershed. This gave me a unique opportunity to collaborate with government agencies, local NGOs and evaluate the effectiveness of large-scale restoration actions. Both Maunalua Bay and Laolao Bay completed a conservation action planning (CAP) process with The Nature Conservancy and involved community and non-governmental organizations. I wanted to compare planning strategies and project outcomes to see what worked and what did not. The takeaway message will be useful to both project sites in focusing future planning and implementation strategies. Additionally, the lessons learned can be applied, at some level, to all other conservation projects globally.

1.2.2 Project summary

Laolao Bay, Saipan

The health of Laolao Bay has deteriorated over the past several decades due various local threats including overfishing, polluted runoff, and sedimentation. Corals respond physiologically to environmental stress by increasing or decreasing levels of various regulatory proteins or biomarkers. These molecular biomarkers can be quantified and used by managers to evaluate coral health. Local government agencies have begun to restore the Laolao Bay watershed in hopes of improving coastal water quality and associated coral reef health in Laolao Bay. I measured coral biomarker expression before and after watershed restoration to see if restoration activities had an impact on coral physiological health.

Questions and hypotheses: (H_o = null hypothesis; H_a = alternative hypothesis)

Are there spatial differences in protein expression?

H_o: Protein biomarker expression will not change with increasing distance from shore.

H_a: Protein biomarker expression will decrease with increasing distance from shore.

Are there temporal differences in protein expression?

H_o: Protein biomarker expression will not change after watershed restoration activities.

H_a: Protein biomarker expression will decrease after watershed restoration activities.

Maunalua Bay, Oahu

Avrainvillea amadelpha is an algal invader that has caused substantial impacts to the Paiko Lagoon Peninsula reef flat (PRF) ecosystem in Maunalua Bay, Oahu. Community-based groups, in partnership with governmental agencies, have attempted to restore this area by manually removing 1,460 metric tons of *A. amadelpha,* covering 11 hectares. I measured sediment resuspension in Paiko reef flat, in cleared and uncleared areas, during and after the invasive algae removal project to see how sediment concentrations responded to algae removal.

Questions and hypotheses: (H_o = null hypothesis; H_a = alternative hypothesis)

Will the removal of *A. amadelpha* reduce the amount of sediment at Paiko reef flat?

H_o: Sediment concentrations will not change following the removal of *A. amadelpha*.

H_a: Sediment concentrations will decrease following the removal of *A. amadelpha*.

Will sediment concentrations decrease with increasing distance from shore?

H_o: Sediment concentrations will not change with increasing distance from shore.

H_a: Sediment concentrations will decrease with increasing distance from shore.

Will the removal of *A. amadelpha* decrease sediment flushing times?

H_o: Flushing times of fine sediment will not change following the removal of *A. amadelpha*.

H_a: Flushing times of fine sediment will decrease following the removal of *A. amadelpha*.

Will sediment flushing times decrease with increasing distance from shore?

H_o: Flushing times of fine sediment will not change with increasing distance from shore.

H_a: Flushing times of fine sediment will decrease with increasing distance from shore.

CHAPTER 2: INVASIVE ALGAL REMOVAL AND SUBSEQUENT SEDIMENT DYNAMICS AT PAIKO REEF FLAT, OAHU, HI

2.1 ABSTRACT

Invasive species are a global problem and have altered both terrestrial and marine ecosystems in Hawaii. *Avrainvillea amadelpha* is one algal invader that has caused substantial impacts to the Paiko reef flat (PRF) ecosystem. Community-based groups, in partnership with governmental agencies, attempted to restore this area by manually removing 1,460 metric tons of *A. amadelpha,* covering eleven (11) hectares. This study investigated the effectiveness of this restoration approach in the removal of the algae and the expected facilitation of sediment flushing from PRF. We collected sediment concentration data, at least once monthly, for fourteen (14) months using a sediment resuspender and turbidity meter. Sediment concentrations were significantly less in the cleared areas of PRF. Our data suggest sediment retention was exacerbated by the dense presence *A. amadelpha* and the absence of natural flushing from ocean swell. Our model found with algal removal, coarse and fine sediment flushing was possible. In shallow and deep areas flushing times for fine sediments were 3.67 years and 3.86 years respectively. In areas where *A. amadelpha* was still present, fine and coarse sediments were accumulating. The removal of *A. amadelpha* and the eventual flushing of fine sediments from PRF are the necessary first steps in the restoration of the near-shore marine and reef flat ecosystem at PRF. Although restoration efforts can be laborious, challenging, and slow, success can still be achieved through effective community and governmental partnerships.

2.2 CURRENT CHALLENGES AND ENVIRONMENTAL CONCERNS

2.2.1 Watershed condition

The Maunalua region consists of 10 watersheds in a highly urbanized area with a 2010 US Census count of 18,774 housing units and a population of 49,914 people. Prescott, 2009 assessed the Wailupe and Kuliouou neighborhoods and found the average house lot had about 68.5% and 65% impervious surfaces respectively. Additionally, the Wailupe and Kuliouou neighborhoods had 54% and 42.5% impervious surfaces (Prescott 2009). All the residential areas adjacent to Maunalua Bay have well developed stormwater drainage infrastructure with sidewalks, drains, and concrete-lined, channelized streambeds. All the streams that drain into Maunalua Bay are straightened and, all but one, are lined with concrete.

Urbanized watersheds, as those in the Maunalua region, have lost much of their natural hydraulic function. Water retention and natural infiltration are compromised when much of the natural wetlands, streambeds, and pervious surfaces have been altered to accommodate increasing development. Resulting water volume and velocity entering streams and eventually the ocean are increased. Fresh water has less opportunity to re-charge the groundwater, instead, runoff transports sediments and pollutants directly into the ocean.

2.2.2 Invasive Species

Invasive species commonly threaten coral reefs. In Hawaii, Hawaii's extreme isolation and low biodiversity magnifies this threat. Invasive species, which proliferate here, usually become problematic and jeopardize Hawaii's native species and ecosystems. Some of these invasive species were intentionally brought in as bio-control agents, research projects, aquaculture products, botanical specimens, and as additional game for fishermen.

Invasive marine algae in Hawaii are a serious problem. There are at least 21 introduced marine algal species in Hawaii (Schaffelke et al. 2006). Some algae are more notorious than others due to their negative impacts. *Gracillaria salicornia*, *Acanthophora spicifera*, and *Kappaphycus alvarezii* are red algae, which have damaging effects on Hawaii's coral reefs. They outcompete corals, native seagrass and algae for space, trap fine sediments, and can alter coral-dominated stable states.

In Hawaii, *Avrainvillea amadelpha,* or leather mudweed, is an invasive green marine alga in the order Bryopsidales. It is found throughout the tropics and was first reported on Oahu in 1981 (Brostoff 1989). It has spread across south Oahu and prefers soft, muddy or sandy reef flat habitats. In PRF, *A. amadelpha* is known to grow in dense stands and traps fine sediment, which can lead to displacement of native species and eventual ecosystem shifts (Smith et al. 2002). Martinez and Wolanski (unpublished data) observed that *A. amadelpha* was so dense that it was capable of delaying the outgoing tide in shallow areas close to shore.

2.2.3 Sedimentation

Sedimentation is a major threat to coral reefs. Perez et al. (2014) demonstrated that fine sediments had negative impacts on coral settlement and survival. In highly turbid areas, low coral cover is expected due to the lack of suitable substrata for coral recruitment and increased macroalgal competition (Jokiel et al. 2014). Fine sediments are problematic because they stay suspended in the water column longer and have the potential for greater dispersal. Fine sediments also have the potential for resuspension from tidal change and wind events. Suspended sediments were shown to reduce the sunlight needed for photosynthesis in zooxanthellae, which negatively affects coral growth (Anthony and Connolly 2004).

In Hawaii, heavy rains transport land-based sediments onto coastal reefs. In the urbanized Maunalua Bay watersheds, this problem is worsened by the high percentage of impervious surfaces, concrete-lined streams, and developed wetlands. Peak flows of freshwater are forced into hardened streams and delivered directly to the ocean. Sediments along with pollutants are transported into the coastal ecosystem. In December 2008, heavy rains effectively transported and eventually deposited about 20 tons of fine sediment into Maunalua Bay through the channel from the Kuliouou Watershed (Wolanski et al. 2009).

2.3 PROJECT DETAILS AND OBJECTIVES

Maunalua Bay, Oahu has a sedimentation problem exacerbated by the presence of dense populations of *A. amadelpha*. Paiko reef flat (PRF) (157° 43’ W, 21° 16’ N), located within Maunalua Bay, is the site where this problem is most prevalent. PRF covers about 50 hectares with about 15 hectares covered entirely by *A. amadelpha*. The Nature Conservancy along with Malama Maunalua obtained funding and removed about 11 hectares of *Avrainvillea amadelpha* from Paiko reef flat. This was the largest invasive algal removal project ever attempted and completed in Hawaii (Figure 2.1).

This study quantified the amount of re-suspended sediment at PRF during and after the removal of *A. amadelpha*. It compared the differences in sediment concentrations and flushing times among cleared, uncleared, shallow and deep areas.

Research Questions and Hypotheses: (H_o = null hypothesis; H_a = alternative hypothesis)

Will the removal of *A. amadelpha* reduce the amount of sediment at Paiko reef flat?

H_o: Sediment concentrations will not change following the removal of *A. amadelpha*.

H_a: Sediment concentrations will decrease following the removal of *A. amadelpha*.

Will sediment concentrations times decrease with increasing distance from shore?

H_o: Sediment concentrations will not change with increasing distance from shore.

H_a: Sediment concentrations will decrease with increasing distance from shore.

Will the removal of *A. amadelpha* facilitate sediment flushing times?

H_o: Flushing times of fine sediment will not change following the removal of *A. amadelpha*.

H_a: Flushing times of fine sediment will decrease following the removal of *A. amadelpha*.

Will sediment flushing times decrease with increasing distance from shore?

H_o: Flushing times of fine sediment will not change with increasing distance from shore.

H_a: Flushing times of fine sediment will decrease with increasing distance from shore.

Figure 2.1. Algal removal scheme and progress at Paiko reef flat. Photo by TNC Hawaii.

2.4 METHODOLOGY

2.4.1 Site selection

The Nature Conservancy and Malama Maunalua obtained funding (TNC 2012) and removed a total of 1,460 metric tons of *A. amadelpha* from 11 hectares in Paiko reef flat (Figure 2.1). Paiko reef flat was chosen because it had one of the densest strands of *Avrainvilla amadelpha* in the Maunalua Bay region. The algae were manually pulled out (by hand), shaken to remove excess sediment, placed in burlap bags, and transported to taro farmers for reuse as fertilizer. Special attention was made to remove only *A. amadelpha* and spare all native algae and seagrass.

Figure 2.2 Paiko reef flat project site, southeast Oahu, Hawaii. Dashed rectangle represents the algal removal site. Boxes within the dashed box represents the initial 6 replicate sites where the algae were removed.

2.4.2 Experimental Design

To allow for investigation, the algae were initially removed in a series of six replicate, one acre plots. Three were placed in shallow waters (closer to shore), and three in deeper waters (further away from shore) (Figure 2.2). The rationale was to compare differences between the cleared plots and uncleared adjacent areas. All of the initial six (6) cleared plots were located inside the eleven (11) hectare project area within the Paiko reef flat (Figure 2.2). Eventually, all the *A. amadelpha* within the project site were removed (Figure 2.1).

Sediment concentrations (Nephelometric Turbidity Units, NTUs) were collected at least once monthly from 8/11/10 to 9/6/2011 and again on 10/12/2013. Sediment concentrations were measured using a modified version of the sediment resuspender box method described by Wolanski et. al. (2005). The metal framed acrylic box had dimensions of 29 cm x 19 cm x19 cm with a total volume of 10,469 cm^3. The box had an open bottom and a plate connected to a rod that could be moved up and down manually. The box also had a two-inch hole on one of the vertical sides where the turbidity probe was inserted. During sampling, the box was placed on the substrate, as level as possible to ensure the resuspended material would not escape. The sediments were resuspended by moving the plate up-and-down for about 5-10 seconds within the box and allowed to settle for a few minutes. The sediment concentrations were measured every second using a Yellow Springs Instruments (YSI) multi parameter sonde.

A total of 60 sampling points, initially divided equally between cleared and uncleared adjacent areas, were randomly selected. On each sample day, all 60 points were sampled. Sediment concentration data were collected at depths ranging from 0.5 – 1.5 meters on Paiko reef flat. At all times, the resuspender box and turbidity probe were completely submerged. As the algal removal project progressed, all the sample points within the project site were cleared (n=50). At the end of the project, only 10 remaining points, that were outside and adjacent to the project site, remained uncleared.

Figure 2.3. Paiko reef flat showing the six plots initially cleared. Sediment resuspension was measured in labeled plots. Dashed line separates shallow plots (0.5 m – 1 m) from deeper plots (1m – 1.5 m). Photo by TNC Hawaii.

2.4.3 Data Analysis

Data from the YSI sonde was downloaded into Microsoft Excel and was sorted by date and site. Each sample stirring session was plotted and analyzed. Regression lines were fitted to obvious coarse and fine sediment curves. Because coarse sediments fall out faster in suspension, the resulting regression lines are more steep. Fine sediments take longer to settle out and have with flat regression lines. When no clear distinction was present, the sample point was discarded. In the following methods described by Wolanski et al. (2005), NTUs were converted to grams per square meter (g/m^2).

All measured sediment concentrations were labeled as cleared or uncleared, deep (further from shore) or shallow (closer to shore) averaged by sample day, and plotted over time. Linear regressions, averages, and 95% confidence intervals were calculated using Prism GraphPad V5.0b statistical software. Sediment flushing times were calculated following Ketchum (1950) and Dyer (1972).

$$\text{flushing time} = \frac{\text{y intercept} - (1/e * \text{initial concentration})}{\text{slope}}$$

Additional analyses were conducted on four factors, which contribute to fine sediment retention and/or flushing. The factors were the presence/absence of the algae and the distance from shore. The plots were either cleared or left uncleared of *A. amadelpha*, and/or in shallow waters near the shore or in deeper water further from shore (Figure 2.3).

2.5 RESULTS

2.5.1 Sediment concentrations

There was significantly more coarse sediment than fine sediment in all treatments – cleared, uncleared, shallow, and deep areas. Across all treatments, the average amount of coarse sediment ranged from 436.1 g/m^2 to 481.1 g/m^2. The amount of coarse sediment did not differ much between cleared and uncleared areas in either deep or shallow waters. Across all treatments, fine sediment averages were significantly less, and ranged from 154.1 g/m^2 to 277.4 g/m^2. There was significantly less fine sediment in cleared versus uncleared areas at Paiko reef flat (Figure 2.4; Table 2.1)

Table 2.1 Results of linear regression analyses and calculated flushing times. * indicates a significant trend.

Treatment	Mean ± 95% CI, g/m2	SE	Linear regression eq.	Flushing time, years
Cleared shallow (coarse)	436.1 ± 31.6	15.77	y = -0.0827x + 453.3	10.64
Uncleared shallow (coarse)	471.4 ± 35.9	17.63	y = -0.6414x + 406.9	*accumulating
Cleared deep (coarse)	446.1 ± 36.2	18.07	y = -0.2183x + 492.6	3.86
Uncleared deep (coarse)	481.1 ± 40.1	19.73	y = 0.3129x + 406.7	accumulating
Cleared shallow (fine)	209.5 ± 8.2	4.147	y = -0.1261x + 235.3	*3.67
Uncleared shallow (fine)	277.4 ± 9.4	4.759	y = 0.004121x + 276.9	accumulating
Cleared deep (fine)	154.1 ± 7.0	3.529	y = -0.05360x + 165.4	5.63
Uncleared deep (fine)	200.2 ± 8.1	4.087	y = 0.02885x + 196.4	accumulating

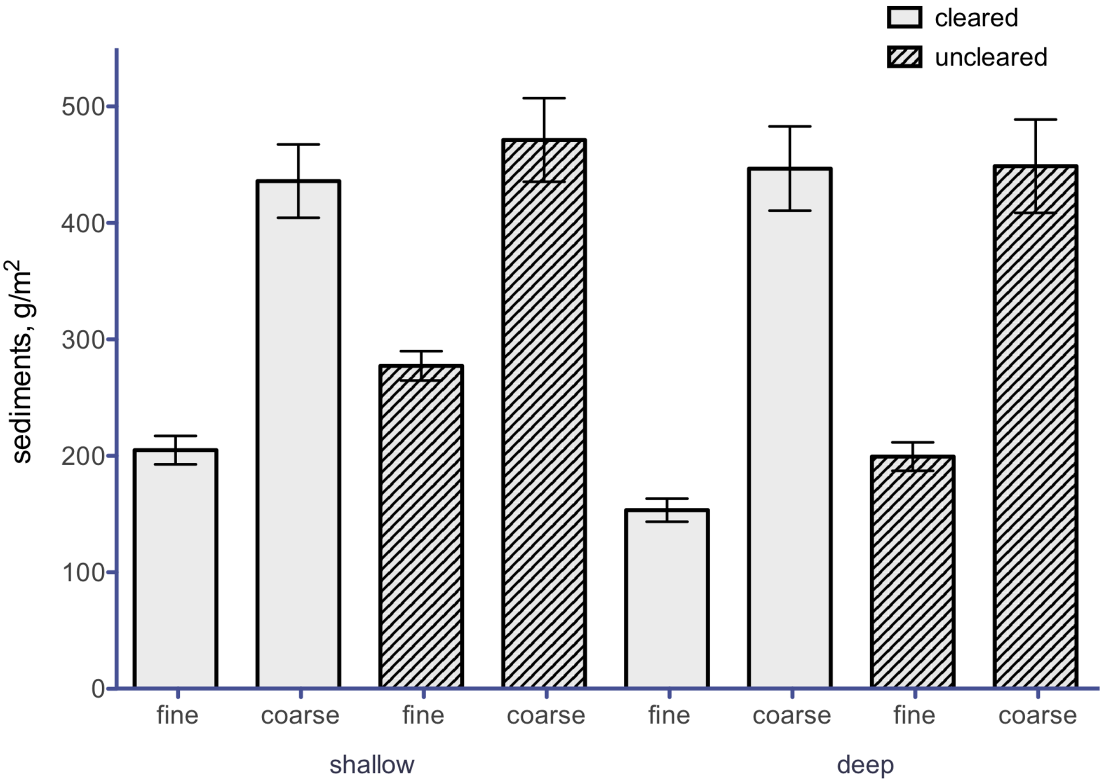


Figure 2.4. Sediment concentrations averages with 95% confidence intervals.

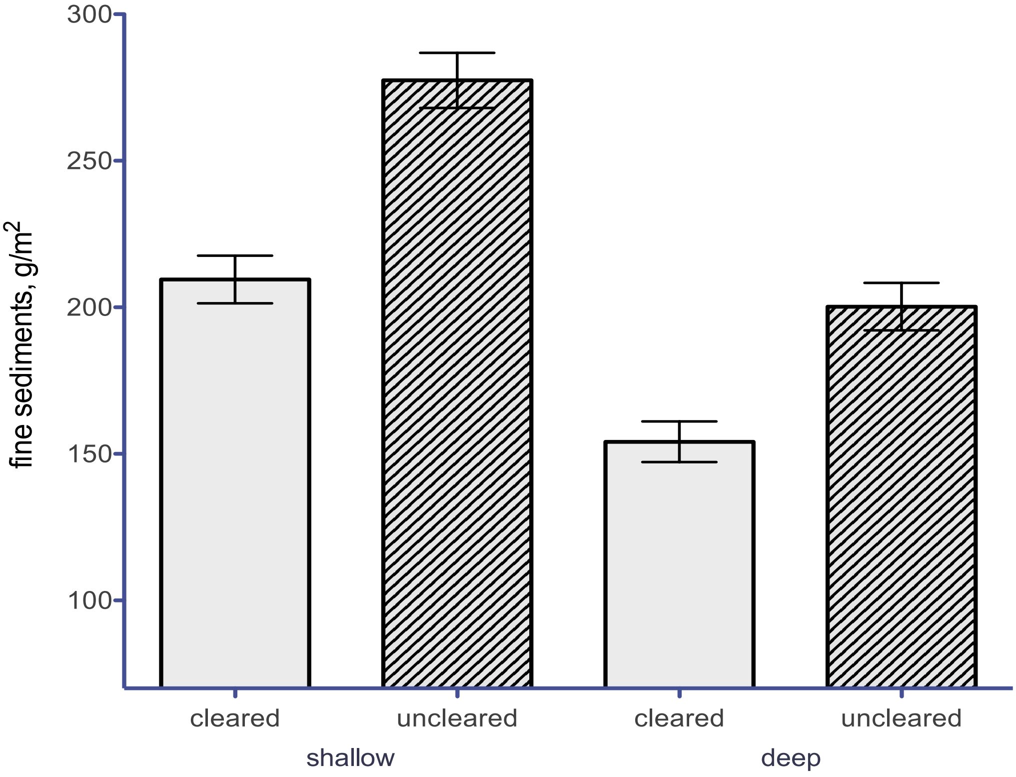


Figure 2.5. Fine sediment concentration averages with 95% confidence.

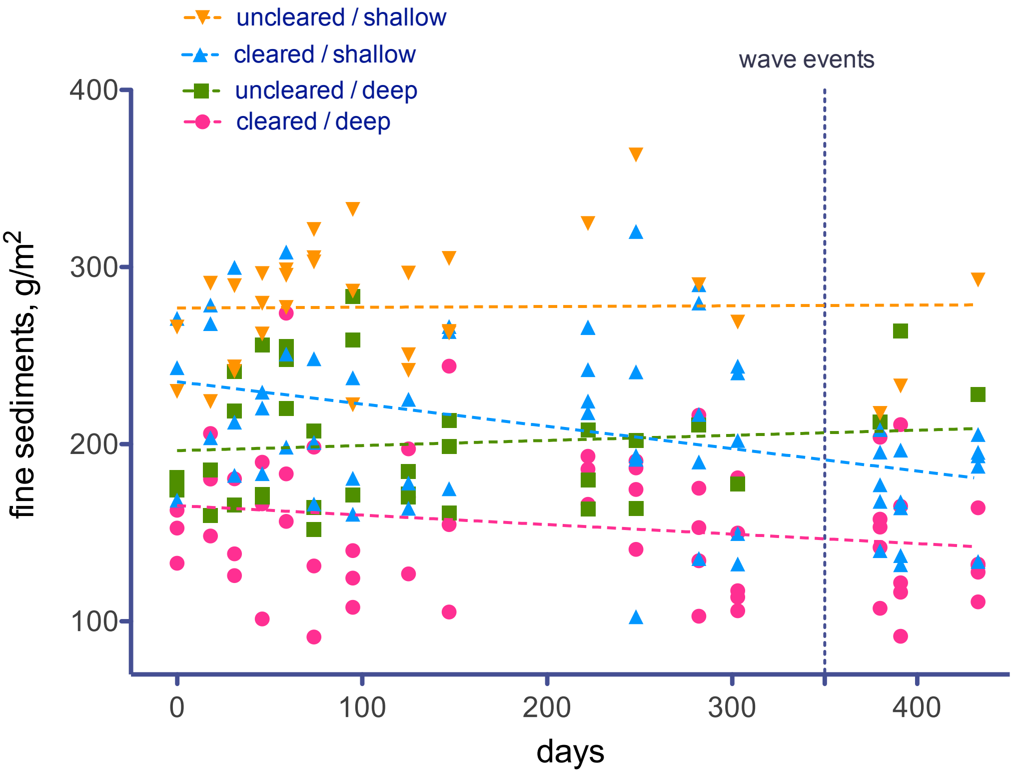


Figure 2.6. Linear regression analyses on fine sediment concentrations measured throughout project. Day zero represents 8/11/2010, the first successful full day of data collection. Negative trends seen in cleared areas.

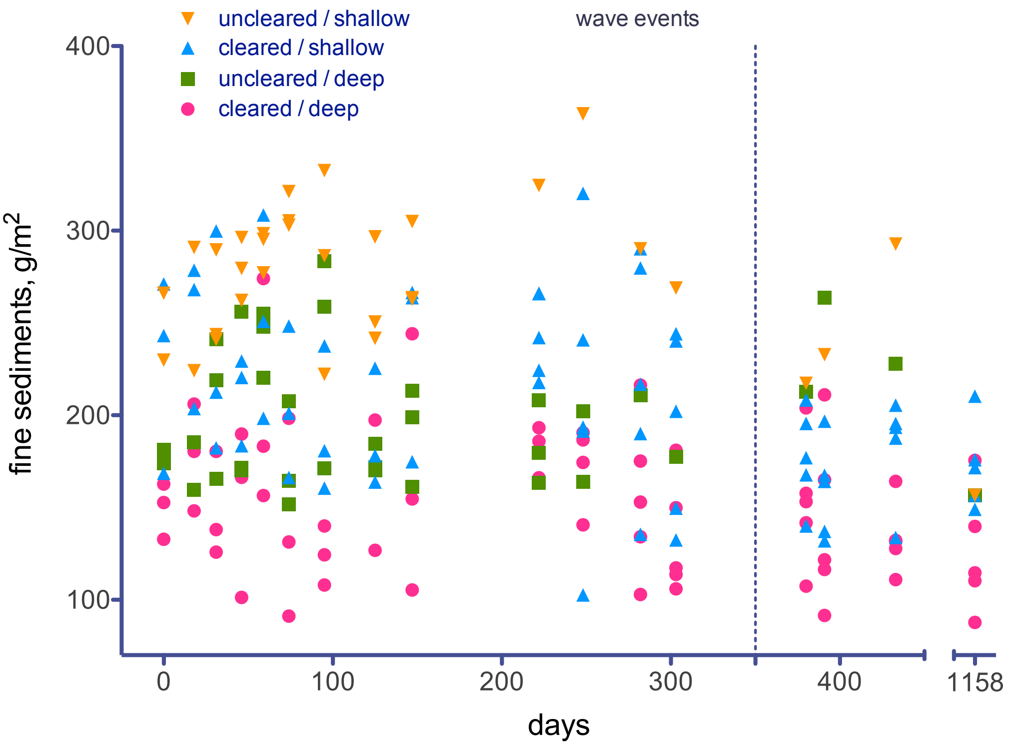


Figure 2.7. Same as figure 6 (without the trend lines). This figure shows the additional data point (day 1158) taken on 10/12/2013. Two years after the end of the sampling.

The presence of *A. amadelpha* and the distance from the shoreline had significant effects on the concentration of fine sediments. There was significantly more fine sediment in uncleared areas and areas closer to the shoreline (Figure 2.5). In shallow areas, closer to shore, fine sediment concentrations in cleared areas was significantly less with a mean of 209.5 g/m^2 compared to 277.4 g/m^2 in uncleared areas (Table 2.1). In deep areas, further away from shore, fine sediment concentrations in cleared and uncleared areas was 154.1 g/m^2 and 200.2 g/m^2 (Table 2.1). Deeper sites had less fine sediment in areas with or without *A. amadelpha*. There was no statistical difference between uncleared areas far from the shoreline and cleared areas close to the shoreline. Fine sediment average concentrations of 209.5 g/m^2 and 202.2 g/m^2 were determined (Table 2.1).

2.5.2 Sediment flushing times

With a total of 16 sample points, several trends over the 14-month sample period were observed. Negative trends were only observed in cleared areas with modeled flushing times of 3.67 years and 5.63 years for fine sediments in shallow and deep areas, respectively. A significant negative trend was observed for fine sediments in cleared, shallow areas. Coarse sediments had modeled flushing times of 10.64 years and 3.86 years for shallow and deep areas respectively. In contrast, all uncleared areas had positive trends showing accumulation of sediments. In uncleared, shallow areas, there was significant accumulation of coarse sediments with average concentrations of 471.4 g/m^2.

2.6 DISCUSSION

This algal removal project was the largest ever attempted and completed in Hawaii. Algal removal activities have been occurring throughout the state but at much smaller scales. The Maunalua Bay community along with The Nature Conservancy recognized the need to scale-up algal removal efforts to encourage the reestablishment of native flora and fauna. In support of the community-based partnerships and collaborations, this sediment study was initiated to measure the effectiveness of the effort by the documenting the change in sediment concentrations in conjunction with *A. amadelpha*.

The initial project cleared about nine hectares and 1,360 tons of *A. amadelpha* from PRF. 3,000 community members along with 12 schools and eight local businesses volunteered to participate. The initial project efforts effectively reduced the cover of *A. amadelpha* from 56.9 to 2.6 percent (Minton and Conklin 2012). To date, over 11 hectares and 1,460 metric tons of *A. amadelpha* were removed from PRF. Over 15,000 volunteers have been directly involved in removing algae from PRF. Additional data were collected on 10/12/2013, approximately two years after the end of the project (Figure 2.7). Data continued to show a decrease in sediment concentrations across all parameters tested, providing strong evidence that the initial and continued work conducted in the Bay have been successful. In April 2018, record breaking rainfall fell in the Maunalua Region which resulted in large amounts of water running off into Maunalua Bay. Malama Maunalua volunteers visited Paiko reef flat the next day and measured sediment depths and found no statistical difference when compared to pre-storm measurements (www.malamamaunalua.com).

The success of the project was, in large part, due to the overall involvement of the entire Maunalua Bay community and partners. Residents, recreational users, fishermen, lawmakers, researchers, resource managers, and business owners, all played a role in the projects successful planning and implementation. The project was community-driven with multiple government and academic partners. Preliminary results were presented to community members and stakeholders from Maunalua Bay. The ability to provide real-time information to community members and stakeholders was crucial in maintaining and increasing momentum in this community-based conservation effort.

The actual restoration activity required a hands-on approach. The algae needed to be manually removed. Using community members, groups, school students, and volunteers, placed the conservation activity directly in the community's hands. The act of removing algae by community volunteers increased their awareness of the invasive algal and sedimentation issue, forcing them to think of ways to become better stewards of their environment. Kittinger et al. (2013) demonstrated that the project heightened community awareness enabling conditions for restorative community action.

Our study demonstrated that the removal of *Avrainvillea amadelpha* was necessary for the export of fine and coarse sediment from PRF. In areas where the algae were still present, fine and coarse sediments were accumulating. Collective problems such as increasing human populations, feral ungulates, and further watershed development will only increase land-based sediments entering PRF. This is important specifically for fine sediments because they have far more damaging negative effects on corals and many other marine organisms (Rodgers 1990). The *A. amadelpha* at PRF grew in dense mats trapping fine and coarse sediment above, within, and below it. Terrigenous fine sediments are foreign, non-calcareous grains that originate from land-based sources. Fine sediments can directly smother reefs and indirectly filter the sunlight needed for photosynthesis (Rodgers 1990). Fine sediments can be easily resuspended by tidal change or wind and can remain suspended in the water column for long periods of time allowing for potential harm.

In areas where *A. amadelpha* was removed, fine sediments are predicted to flush in 3.67 years and 5.63 years in shallow and deep areas respectively. Minton and Conklin (2012) demonstrated that median sediment depths were significantly reduced from 3.4 cm to less than 2 cm following the removal of *A. amadelpha*. With the algae and fine sediment removed, the native benthic communities are improved.

During the summer months of 2011, the presence of strong wave events hit the south shore and accelerated the export of fine sediment from PRF with wave heights ranging from 2 - 3.5 meters. The strong wave events led to an increase in sediment export from Paiko reef flat. The increased volume of water across Paiko reef effectively mobilized and flushed out some of the fine and coarse sediment. Prior to the waves, our model suggested that the fine sediment in cleared areas would take approximately 6.7 years to flush out. Following the wave events, the expected flushing time of fine sediment in cleared shallow and deep areas decreased to about 3.67 and 5.63 years respectively suggesting that at PRF, intense flushing is required to access the shallower depths closer to shore. Longshore currents, which historically flushed these shallow areas, have shifted due to shoreline development and alterations over the years (i.e., seawalls, back-filled fishponds, marinas).

Although the future of coral reefs seems bleak, Wilkinson (2004) reported that 40% of the 16% of the coral reefs that were severely damaged during the 1998 bleaching event were recovering or have already recovered. These steps in the right direction, in terms of management, are good signs that should be modeled by other coral reef nations. The Great Barrier Reef MPA, Micronesian Challenge, and the Coral Triangle Initiative are examples of the international commitment in conserving coral reef resources for present and future generations.

With environmental concerns at an all-time high, future avenues for coral reef research, conservation, and restoration are almost guaranteed (dependent on funding availability). Chronic anthropogenic disturbances will not disappear anytime soon, Hughes et al. (2017) reports that future bleaching events will be more frequent to the point where coral assemblages will not recover to pre-bleaching mature assemblages. A combination of active and passive restoration techniques are needed to restore and protect degraded and healthy reefs respectively. To give coral reefs a chance of survival, we have to minimize our anthropogenic impacts on them. Corals have global problems to contend with such as those associated with climate change. As science moves forward, new information can: assist managers adapt to changing environmental and societal conditions; guide the creation of creative new strategies and legislation; and inform and equip communities with tools needed manage coral reefs.

CHAPTER 3: LAOLAO BAY, SAIPAN, WATERSHED RESTORATION AND CHANGE IN CORAL PHYSIOLOGICAL RESPONSE

3.1 ABSTRACT

Coral reef health in Laolao Bay, Saipan, Commonwealth of the Northern Mariana Islands has deteriorated over the past several decades due to resource over-harvesting, land-based sources of pollution, and climate change. The Bay is most susceptible to effects of land-based sources of pollution (LBSP), such as sedimentation and polluted runoff. Corals respond physiologically to environmental stress by increasing or decreasing levels of various regulatory proteins or biomarkers. These molecular biomarkers can be quantified and used by managers to evaluate coral health. Local government agencies have begun to restore the Laolao Bay watershed in hopes of improving coastal water quality and associated coral reef health. My research investigated the change of coral health in response to the Laolao Bay watershed restoration project. Molecular biomarkers, specifically, catalase, superoxide dismutase, and cytochrome P450 1A1 were quantified in the reef coral *Porites lobata* from samples collected before and after the restoration project. Results indicate that corals from deeper depths (~10 m) experienced LBSP-related stress just as those from shallower areas (~1 m). Results also suggest that restoration activities are needed to preserve deeper corals. The results of this study will 1) provide resource managers with key information on the specific stressors affecting the corals studied and 2) provide baseline information for future comparisons and for tracking the effectiveness of land-based mitigation measures. Knowing the causal effects of coral stress is important for the “real time” conservation and management of Laolao Bay coral reef ecosystem.

3.2 INTRODUCTION

3.2.1 Sedimentation

Sedimentation has occurred on coral reefs throughout time. Along with storms and Crown-of-Thorns Starfish (COTS) outbreaks, and other acute and intermediate disturbances, have played a role in maintaining the balance and diversity within ancient and modern reefs (Connell 1978). Early work acknowledged that sedimentation was correlated with coral mortality (Edmondson 1928). Sedimentation has recently accelerated due to an increase in human activities along the coasts. Increased sedimentation levels from coastal erosion have severely degraded many of the world's coastal reefs (Fabricius 2005; Rogers 1990). As a result, dramatic changes have been observed due to coastal development, deforestation, dredging, and the alteration of streams and wetlands.

Sedimentation can directly brush against corals and cause tissue damage. This can lead to bacterial infections and can cause corals to become more susceptible to disease. Sedimentation can also smother corals, preventing transfer of gasses and nutrients. Without the proper water flow regime, the exchange of carbon dioxide for oxygen and wastes for nutrients is negatively affected. Extreme sediment loading can effectively bury reefs alive. Corals, however have the ability to physically remove the sediment with their tentacles. They also can produce mucus to shed the sediments from their tissues (Brown and Howard 1985). Anthony (2000) demonstrated that *Acropora millepora* can remove sediment by ingestion.

Indirect effects of sedimentation are just as deleterious to reefs. Turbidity caused by suspended sediment effectively shades out light available for corals and their zooxanthellae. Davies (1991) demonstrated that sedimentation restricted photosynthesis and negatively affected coral growth. Te (2001) demonstrated that land-derived terrigenous sediments influenced light attenuation more than reef-derived carbonate sediments and that turbidity was more important than sediment trapping rate in affecting the photosynthetic ability and growth rates of corals. Reduced nutrition can decrease coral growth, calcification rates, and reproductive output (Rogers 1990). Any available energy is allocated for maintenance and for basic metabolic needs. Prolonged episodes of reduced photosynthesis will result in the death of corals and coral reefs.

With the increase availability and use of chemicals on land, runoff of chemical-laden sediments into coral reef ecosystems is not unusual. Chemicals such as insecticides, fungicides, herbicides, fertilizers, and hydrocarbons can attach to the sediment and produce adverse effects on corals (Ingersoll 1995). Even small amounts herbicides at brief exposures can greatly affect corals (Glynn et al. 1986). Insecticides, at low concentrations (0.3-1.0 μg/liter) were shown to reduce coral settlement and metamorphosis by 50 and 100%, respectively (Markey et al. 2007).

3.2.2 Watershed Best Management Practices

Watersheds catch rainfall and drain areas of land. Naturally, upland forests, vegetation, wetlands, mangrove forests, and sea grass beds all contribute to a decrease water velocity and volume, increase water percolation into the soil, and filter out sediments and pollutants. These ecosystem services allow for coral reefs to survive and hopefully thrive in clear and clean offshore waters. When watersheds are altered, these services become compromised and coral reefs are either pushed further and further offshore to escape the influence of the runoff, or die off. The increase in coastal development led to alterations in upland watersheds (Wolanski et al 2009). As more forests are cleared, less vegetation is available to filter runoff.

Best Management Practices (BMP) includes a vast range of approaches designed to prevent, reduce or treat polluted runoff. In order to protect coastal coral reefs, the volume and velocity of runoff should be reduced considerably. This is achieved by the use of water retention basins or devices. Some basins slow the runoff and allow it to percolate into the soil. Sediments can also settle out in slower moving waters or in ponding basins. Some water retention basins can be used to irrigate coastal farms. Water catchment systems (however crude) can be useful in decreasing the volume of water entering streams and eventually the ocean while making the water available for a variety of appropriate uses.

Some examples of watershed BMPs include revegetation activities. Upland plants provide the first level of resistance to flowing water. They effectively hold the earth around them with their roots while their stems and leaves reduce the velocity the flowing water. The water has a greater chance of percolating and entering the groundwater system. When the earth is barren and void of vegetation, the water is free to flow, unobstructed down gradient. During periods of prolonged heavy rain, runoff has the ability to flow in large volumes and at high velocities. These fast-moving waters have the potential to carry large volumes of sediment, pollutants, and toxicants to adjacent marine waters.

Other examples include the use of water catchment systems such as: ponding/retention basins, rain gardens, cisterns, and rain barrels. Reducing the amount of sheet flow and runoff entering streams reduces the delivery of sediments to the ocean. It also allows for recharge of the groundwater aquifers.

3.2.3 Assessing Coral Reef Condition

Ecological monitoring

Ecological monitoring is passive in nature and relies on targeted observations to explain past and current conditions – and to predict future ones. Since coral reefs grow slowly, documenting change requires large data sets, with multiple time and space points. On the other hand, coral reefs can respond quickly to catastrophic events, such as extreme storm events, crown of thorns out breaks, bleaching events, and in response to exposure to land-based pollution. In these instances, ecological monitoring will show significant negative change, when compared to a “healthy” coral reef.

There are many examples of how classical ecological monitoring tools are used to assess coral reef health (Houk et al. 2012; Jokiel et al. 2004; Rodgers et al. 2015). Metrics include percent coral cover, species richness, diversity, distribution, abundance, etc. (CPC, 1992). These studies normally require spatial and/or temporal components to establish a baseline and for subsequent comparison and interpretation. Ecological monitoring of coral reef ecosystems normally is comprised of decades of data. These long term monitoring programs, such as the Hawaii Coral Reef Assessment and Monitoring Program (CRAMP) and the data collected by the CNMI Marine Monitoring Team, are useful in identifying spatial and temporal changes, trends, and are essential for informing management.

A good case study is the Hawaii CRAMP, which began in in 1999 and was created to examine coral reef communities over larger spatial scales (Jokiel et al 2004). In 2012, results over the prior 14 years were summarized. The data set showed: some significant declines and increases in coral cover in Maui and Hawaii Island respectively; the varied coral cover due to COTS and other chronic disturbances; and potential recovery sites (Rodgers et al 2015).

The benefits of ecological monitoring are the relative ease and minimal costs associated with it. Knowledge of experimental design and statistics are required for the initial project set up. Subsequent activities consist of data collection, analysis, and interpretation. Data collectors need to be trained in scuba/snorkeling, the data collection process, and be proficient in identifying fish, coral, algal, and other invertebrate species. Data can be analyzed, interpreted, and visualized using one of the many available statistical software packages.

One advantage of ecological monitoring is the ability to scale efforts and reach multiple and even remote areas. The international program Reef Check is an example of a large-scale monitoring effort that uses numerous local monitoring events to keep a “pulse” on global coral reef condition. Reef Check was founded in 1996 and has volunteers in over 90 countries and territories. This large-scale monitoring initiative allows the assessment of status and trends of coral reefs on a global scale, can detect broad changes at multiple scales, and increases public support and awareness for coral reef conservation (Hodgson 1999).

Molecular-Based Methods

With advancements in molecular technologies, new approaches to assessing the physiological health of corals are now available. By quantifying molecular biomarkers of stress exposure, investigators can determine the health of corals - in real time. Corals respond to stress by up- or down-regulating proteins needed to cope with that stress. This information can identify cause-and effect relationships between stressors and coral responses. When used in a diagnostic manner, protein data can help managers target the key problems and measure the effectiveness of management actions. For example, when corals are in areas of high sedimentation and/or fleshy algal growth in response to nutrients resulting in oxidative stress, they respond by up-regulating superoxide dismutase (SOD). This molecular monitoring method can quantify the biomarkers expressed in the "exposed" coral which can then be compared to colonies in reference sites or under laboratory controlled conditions to determine stress levels. Managers can use this information to address potential sources and act to implement strategies to protect the coral reef.

With coral reefs facing multiple global and local threats, this ability to determine stress at sub-lethal levels is crucial in identifying direct causation and implementing real-time solutions prior to outright mortality. Molecular biomarkers of stress depend on understanding the underlying stress response mechanism and quantifying those of interest. The ability to quantify the levels of response provide a real-time tool to measure the efficacy of mitigation measures over days, weeks and months rather than years to decades.

In a laboratory setting, Rougee et al. (2006) investigated the effects of hydrocarbons on the reef coral *Pocillopora damicornis*. The study demonstrated that the protein biomarker

CYP1A1 was upregulated in response to the presence of hydrocarbons. Downs et al 2006 investigated an oil spill in Yap, Micronesia, and determined that polycyclic aromatic hydrocarbons were the cause of increased levels of multiple biomarkers, including cytochrome. Downs et al 2012, used cellular diagnostic analysis to investigate the molecular-level responses of corals to multiple stressors.

The benefits of this molecular approach are that health can be measured directly and quantified while the coral is still alive as with diagnostic blood tests in humans. It allows for real-time management and can provide information managers can use to address potential stress sources. It doesn't just document coral mortality over time and space. Unlike ecological methods, molecular methods are more expensive and require more stringent collection and analysis protocols. Coral tissue samples are required to be flash frozen immediately after collection to preserve cellular activity and integrity. Protein extractions and quantification require specialized staff, reagents, and equipment.

Although the technology exists, the access to remote sites and scalability may pose a problem. In Pacific Islands, the remote nature and access to materials adds to the challenge. The sample preservation protocol requires samples to be immediately stored in -20°C. This can be a deal breaker when there is no access to dry ice or -20°C storage. In Saipan, the only place that had such cold storage capabilities was the public hospital. A liquid nitrogen charged dewar, encased in a dry shipper, was preservation method tool of choice. It was the only shipping and storage option which required hazardous materials paperwork and costs $800 USD (one way Honolulu to Saipan).

3.3 PROJECT DETAILS AND OBJECTIVES

3.3.1 Laolao Bay Background

Laolao Bay is situated on the eastern coast of Saipan and includes about 9 km of coastline with a total area of 11 km^2 (Figure 3.1). Much of the bay is deep with depths of about 100 m just 1 km offshore. The northern side of Laolao Bay is protected from the prevailing trade winds and associated currents by the Kagman peninsula. This sheltered region allows for 3 km of coral reefs consisting of a reef flat, crest, and outer slope. The rest of the 6 km coastline is more exposed to the winds and wave action and has a very limited or no reef flat. The reefs are fringing and are right up against the cliffs. The reef flat that exists on the northern end of Laolao Bay is not as expansive as that on the western side of Saipan and is about 100 m from shore to reef crest. In contrast, the western side of Saipan has well defined lagoons with the reef crest as far as 3.5 km offshore.

Three watersheds drain in to Laolao Bay, the Dandan, Laolao, and Kagman watersheds, which drain about 2,400 hectares. The Laolao villages are still relatively undeveloped with scattered homes and businesses. The Dandan and Kagman villages are planned homesteads with more developed housing and residential infrastructure. There are no sewer or stormwater systems in these villages. All sewage is collected in individual septic tanks. Additionally, there are no stormwater collection systems. The current systems in place are rudimentary and act to guide and pond the water away from structures and roads in roadside depressions and channels, culverts, ditches, and in a few cases larger water retention basins. After heavy rains, runoff makes it way from the watersheds to the Bay. Land adjacent to Laolao Bay is still privately owned and for the most part, sloped and undeveloped. Access roads are a mixture of limited stretches of pavement and packed, crushed limestone (i.e. dirt roads). During periods of heavy rains, the unpaved road surfaces wash away, pick up pollutants, that accumulate in streams and are discharged into Laolao Bay.

Watershed geology differs across Laolao Bay. The eastern side of the bay is characterized by karst limestone bedrock, while the western side is characterized by volcanic soils and bedrock (Cloud 1959). Houk et al. 2011, found lower salinity levels at the eastern side during periods of no rainfall, suggesting connectivity to the aquifer via the karst limestone matrix. At periods of high rainfall, lower salinity levels were recorded at the western side of the Bay, due to higher runoff events.

Laolao Bay is a popular recreation and fishing site on the eastern side of Saipan. Because it is sheltered nature, its consistent dive-ability has made it a popular site year-round. Dive tour operators, fishermen, and recreational users drive to Laolao Bay daily to take advantage of the one of the few sandy beaches on the eastern side of Saipan.

3.3.2 ARRA Project Background

The Laolao Bay watershed was identified, through a process, as a site that would benefit from targeted management. Under the Coral Reef Initiative program, the Laolao Bay watershed was chosen as one of the Local Action Strategies sites in the CNMI. The CNMI Bureau of Environmental and Coastal Quality (BECQ) was awarded a \$2.6 million American Reinvestment and Recovery Act (ARRA) grant to pave a portion of Laolao Bay Drive, revegetate 5.7 hectares of badlands, perform ecological and water quality monitoring, and initiate coastal management activities at Laolao Bay.

Over a three-year period, project efforts were implemented in Laolao Bay. 640 meters of Laolao Bay Drive were paved, which included the installation of a curb and catch basin system, subgrade drain pipe (one meter diameter), concrete sediment and gabion sediment chambers. Additionally, roadside channels and six stream crossings were stabilized and imbedded with riprap to reduce water flow and prevent erosion. In the badlands, 5.67 hectares were revegetated with 1,600 plants from 12 native species. Additionally, over 5,000 linear feet of vetiver grass was planted.

In addition to engineering, construction, and plantings, the project also had an education and awareness component. Stakeholder workshops, revegetation and erosion control trainings, and signage for turtle protection and anti-littering was installed along the beach. Public service announcements were conducted over the radio and in the local movie theater for six months. Informational brochures and posters were distributed to local schools. Some students were also offered a chance to participate in a Laolao watershed hike to learn and observe the current issues and solutions.

3.3.3 Laolao Bay Biomarker Analysis Project Objectives

This research project took advantage of ARRA funding for restoration work and a coral health assessment of molecular biomarkers of stress at two time points across Laolao Bay. The results provide baseline data across Laolao Bay and will be used to test the effectiveness of watershed restoration efforts.

Research Questions and Hypotheses (H_o = null hypothesis; H_a = alternative hypothesis)

Are there spatial differences in protein expression in corals over gradients of watershed discharges?

H_o: Protein biomarker expression will not change with increasing distance from shore.

H_a: Protein biomarker expression will decrease with increasing distance from shore.

Are there temporal differences in protein expression?

H_o: Protein biomarker expression will not change after watershed restoration activities.

H_a: Protein biomarker expression will decrease after watershed restoration activities.

3.4 METHODS

3.4.1 Site Selection and Experimental Design

This study was conducted alongside the ARRA funded, Laolao Bay road and watershed improvement project. The research measured key protein expression profiles in corals before and after the ARRA project, at sites mirroring established CNMI marine monitoring team benthic sites and shoreline water quality sampling sites.

Coral samples from 10 sites, nine in Laolao Bay, and one reference site along the southern coast of Saipan at Boy Scout Beach (Fig. 3.1) were collected under a CNMI Division of Fish and Wildlife (DFW) scientific research permit (license# 02041-11). Sites 1-8 mirror CNMI marine monitoring team ecological survey and shoreline water quality sampling sites and have a shallow (reef flat) and deep (outer reef slope) component. The shallow sites ranged from about 0.5 m to 1 m in depth, while the deep sites ranged from 5 m to 10 m. These sites are along northern, sheltered edge of Laolao Bay, a more developed, defined reef where a narrow reef flat exists. Tuturam (site 9) is along the more exposed, western part of the Bay. Devoid of any reef flat, the site is better characterized as a fringing reef system. I chose this site, because of its locale adjacent to a potential flooding site. Tuturam samples were collected at depths of about 10m. Site 10, the reference site contained an outer reef slope site outside of Laolao Bay. Samples were collected at depths of about 14 m.

Sampling of corals was done at two different time points, one before (phase 1) and one after (phase 2) the watershed restoration project. Phase 1 sampling occurred in late November and early December of 2010 and phase 2 occurred in April 2013. Two (2) cm diameter coral tissue/skeletal samples (plugs) of *Porites lobata* were collected using a coral punch (punch), a metal pipe, tapered at one end with two cm inner diameter opening. When a suitable, healthy looking, *P. lobata* colony was identified, the punch was hammered into the coral about 1cm deep. The plug was then removed from the punch, wrapped in nytex fabric, and stored in a pre-labeled falcon tube. After five plugs were collected at each site, the falcon tube was stored in a cryo-container where the samples were stored before being shipped back to the Kewalo Marine Laboratory (KML) on Oahu, Hawaii. At KML, the samples were stored at -80°C. A total of 45 samples from Laolao Bay and five from Boy Scout Beach were collected at each sample phase.

Figure 3.1 Location of sampling points in Laolao Bay and Boy Scout Beach, Saipan (circled in yellow). The Tuturam site is circled in green.

3.4.2 Sample processing and analysis

At KML, plugs were removed from the -80°C freezer, placed in a ceramic mortar, containing liquid nitrogen and crushed into a fine powder with a pestle. Before use, the mortar and pestle were stored at -80°C, and during use the mortar was embedded in dry ice to maintain cool temperatures to prevent thawing. Protein extraction and quantification from resulting crushed coral powder followed the protocol from Murphy and Richmond (2016).

Target proteins were separated by size using sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and Western blot analysis. Protein concentrations of 50 µg were loaded into 4% polyacrylamide gels, run for 30 minutes at 80 V then for an hour at 100V. The proteins were then transferred to polyvinylidene diflouride (PVDF, 0.2 microns) membranes using a Bi-Rad semi-dry transfer system (Hercules, CA, USA) overnight in transfer buffer at 4°C, running at 40 V. The next day, the membranes were rinsed 3 times with deionized water and then washed in phosphate-buffered saline (PBS) containing 0.05 % Tween-20 (PBST) for 5 minutes. The membranes were blocked in 5% non-fat milk for 1 hour. An additional 4 washes for 15 mins, 10 mins, 5 mins, 5 mins with PBST were conducted. The membranes were then incubated overnight with the following antibodies: CYP1A1; Catalase; and SOD-1 from Santa Cruz Biotechnology Inc. (Santa Cruz, CA, USA). Before incubation for 2 hours with secondary antibodies, the membranes were washed 4 times in PBST for 15 mins, 10 mins, 5 mins, and 5 mins. Membranes were then blotted, detected using enhanced chemiluminescense (Pierce ECL, ThermoScientific (Rockford, IL), and imaged using the Li-COR C-DiGit blot scanner (Li-COR, Lincold, NE). The protein present in the bands was analyzed and quantified using Image Studio software (Li-COR, Lincoln, NE).

Because of laboratory limitations, capacity, and cost, only a fraction of the samples collected were analyzed, 20 total, 10 per phase, for each biomarker. Averages and standard deviations were calculated for samples collected at shallow and adjacent deep sites using the GraphPad Prism Program version 5.0. Because the Tuturam and Reference sites only had one sample, they were not included in the analysis.

3.5 RESULTS

3.5.1 Phase 1 – Before watershed restoration

There were some observable differences in the relative expression of CYP1A1, SOD, and catalase in corals from shallow and deep sites when compared to those from the Tuturam site. Before the watershed restoration project, there were no observable differences in protein expression, for all biomarkers, between shallow, reef flat, and deep, fore reef slope corals. For the Tuturam site corals, single measurements for each biomarker quantified were noticeably less. Compared to the shallow and deep sites, the reference site corals had noticeably less protein expression in CYP1A1 and Catalase. For SOD, the reference site corals had elevated expression, within limits of those in the shallow and deep sites.

3.5.2 Phase 2 - After watershed restoration

Protein expression after the completion of the project had more interesting results. For all proteins analyzed, expression was greater in corals from the shallow sites when compared to those from the deep sites. The biggest difference was the protein concentrations of SOD. Shallow site corals had about 5 times more expression than deeper sites. For CYP1A1 and catalase, corals from the shallow sites had about 2.5 times more expression than those from the deeper sites. Protein expression from the Turturam site corals matched the expression of colonies from the deep sites, and was noticeably less than the shallow site corals. The reference site showed elevated expression for all proteins tested. For catalase, the reference site had the highest expression. For CYP1A1 and SOD, the reference site had noticeably more protein expression than deeper sites, but less than shallow sites.

3.5.3 Phase 1 vs. Phase 2

There were no differences in catalase expression between phase 1 and phase 2 at shallow and deep sites. There was a 3 fold and 14 fold increase in catalase expression at Tuturam and the reference site respectively. At shallow sites, average expression of SOD increased about 4 times. At deep sites, SOD expression decreased 2.5 fold. For Tuturam and the reference site, expression of SOD increased 3.7 and 1.7 times respectively. There was a slight decrease in CYP1A1 expression at shallow sites and about a 2 fold decrease at deep sites. At Tuturam and the reference site, there was a slight and significant increase of CYP1A1 expression respectively. Biomarker expression was noticeably less, across all biomarkers, at deeper sites, after restoration.

Table 3.1. Western blot expression intensity values for *Porites lobata* collected from Laolao Bay and Boy Scout Beach, Saipan. Intensity values are relative to each biomarker.

	Phase 1			Phase 2		
Catalase	Average	St. Dev.	samples	Average	St. Dev.	samples
Shallow	490.5	194.77	4	570	62	4
Deep	357.75	152.44	4	210.6	357.07	4
Tuturam	53		1	167		1
Reference	63		1	895		1
SOD	Average	St. Dev.	samples	Average	St. Dev.	samples
Shallow	19612.5	13672.43	4	53375	24149.99	4
Deep	28595	22602.48	4	11275	8404.872	4
Tuturam	1660		1	6190		1
Reference	14900		1	26100		1
CYP1A1	Average	St. Dev.	samples	Average	St. Dev.	samples
Shallow	2117.5	368.6	4	1815	544.91	4
Deep	1577	856.69	4	745.05	917.97	4
Tuturam	35.6		1	122		1
Reference	1.18		1	1290		1

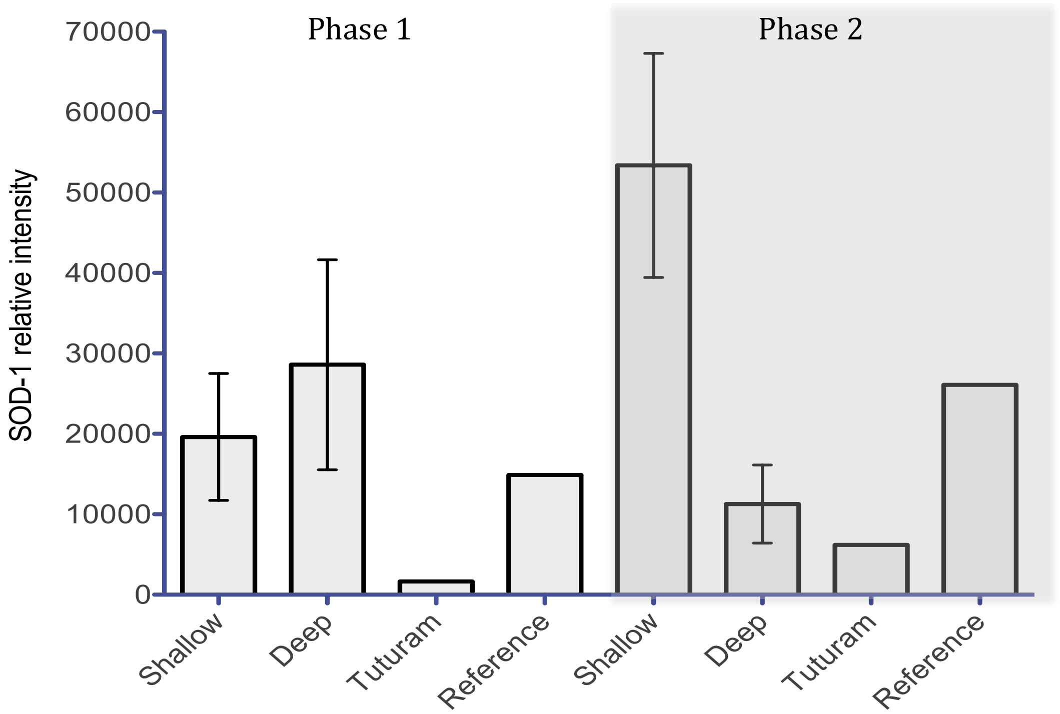


Figure 3.2. Average SOD biomarker concentrations with SEM error bars for Laolao Bay sites. Single measurements for Tuturam and reference sites.

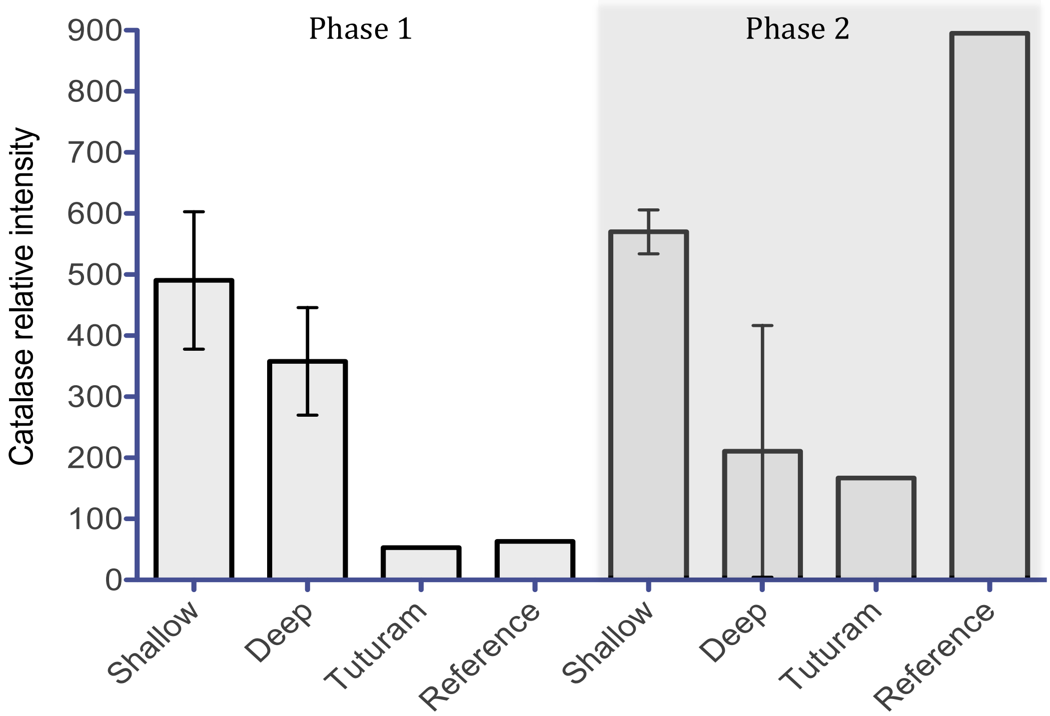


Figure 3.3. Average catalase biomarker concentrations with SEM error bars for Laolao Bay sites. Single measurements for Tuturam and reference sites.

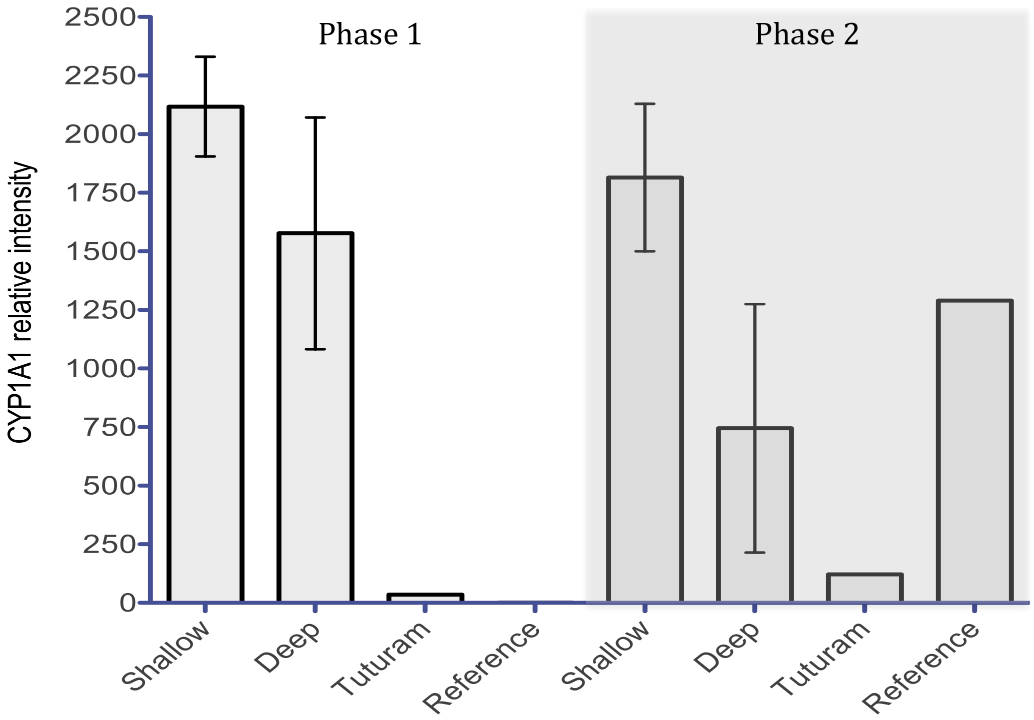


Figure 3.4. Average CYP1A1 biomarker concentrations with SEM error bars for Laolao Bay sites. Single measurements for Tuturam and reference sites.

3.6 DISCUSSION

3.6.1 Restoration Effectiveness and Management Implications

Addressing land-based sources of pollution is not a novel idea when considering the well-being of adjacent marine resources. Pacific Islanders understand the land-sea connection and have used that knowledge for centuries to conserve, protect, and maximize benefits from both land and sea. In the ancient Hawaiian ahupuaa land management system, the mountain and the sea are connected. Different parts of the watershed were utilized for different purposes. Upland farmlands took advantage of running rivers, which eventually flooded taro patches and fed coastal fishponds. The flowing water was managed and exploited at the same time. The activities that took advantage of the flowing river, acted to slow down its velocity, which effectively decreased the amount of water and sediment from entering the ocean. The ridge-to-reef management approach of our ancestors is still a common method in addressing current threats to coral reefs. In Palau and Pohnpei, moratoriums on mangrove and upland forest clearing were enacted to address chronic coastal sedimentation and coral reef decline (Richmond et al. 2007).

This project measured the molecular responses of corals to land-based restoration activities. It was designed to compare biomarker expression at several sites across Laolao Bay before and after watershed restoration. Two oxidative stress biomarkers (SOD and catalase) and one toxicant stress biomarker (CYP1A1) were investigated. Protein expression is expected to decrease with; 1) increasing distance from shore and depth and, 2) post watershed restoration. Expected decreases in expression after restoration were not always observed. At shallow sites, expression of catalase and SOD increased, suggesting oxidative stress is still present, and restoration activities have had no measurable effect on the health of shallow corals. Shallow sites are more susceptible to sedimentation, higher temperatures, and toxicant concentrations due to proximity to shore, less water flow and higher levels of stressor exposure.

At deep sites, expression for all biomarkers decreased after restoration, as much as 2 times for CYP1A1. This suggests that deep corals are experiencing less oxidative and pollutant stress and that restoration had a positive impact on the health of deep corals. The interesting result is the decrease in expression in all biomarkers, from shallow and deep sites during phase 2. After watershed restoration, deep sites had less expression than their adjacent shallow sites.

The reference site, located on the southern end of Saipan had unexpected results. During phase 2, the reference site had elevated expression for all biomarkers, especially catalase. Barring error, this suggests that corals at Boy Scout beach are likely responding to some kind of land-based stressor. Development along the south coast is limited, however, the airport and a rock quarry are within 2.5 km of the reference site. Having hiked this area and talked to others, there is a possibility that historic military debris and waste may be buried in this area, and leachate is reaching the reefs through both surface and groundwater runoff. As no water samples were collected, documentation of putative stressors is not possible.

The value of molecular biomarkers of exposure is in the ability to interpret data in a diagnostic manner to determine cause-and-effect relationships between stressors and coral responses. With this information, managers can now prioritize areas and efforts to maximize conservation and restoration potential. This study links land-based activities to molecular responses in coral. It demonstrates that land-based activities can have an immediate impact to corals and the coral reef ecosystem. In instances where negative change is detected, it can serve as the alarm and call to action. This molecular approach, when implemented, can add a layer of information very much needed in today's coral reef managers' toolbox. When methods become more streamlined, efficient, accessible, and affordable this new tool will be able to reach remote reefs all over the globe.

3.6.2 Next Steps and Recommendations

This research was the first effort to explore molecular biomarkers expressed by corals in Laolao Bay, and with the baseline, a more extensive survey across the Bay and other reefs around Saipan and neighboring islands, investigating multiple biomarkers will be most beneficial. Downs et al. (2012) investigated 23 biomarker proteins across 6 different reefs on Guam and found that this method could be used in a diagnostic manner to identify specific stressors and facilitate appropriate management actions.

This study demonstrated that deep and shallow corals exhibited differential protein expression patterns likely tied to stressor exposure. Even deep corals can experience stress at the same levels as shallow ones. Current and future conservation efforts should consider this detail in management plans and actions. As corals at deep sites are affected by land-based sources of pollution just the same as those from shallow sites, future research should include identification of genotypes and if there are notable differences with depth and distance from shore. Current conservation efforts should focus on understanding this link further. Future studies should aim to understand the effects of LBSP on corals at deep sites. This holistic approach to coral reef management will help managers understand the problem and identify more effective solutions.

With global stressors becoming more frequent and damaging (Hughes et al. 2017), ecological monitoring alone may not be enough to confront the coral reef crisis (Bellwood et al. 2004). Biomarker diagnostic analysis should be considered a necessary layer of information for the many reefs in decline around the globe. This method should be discussed in the planning and pre-proposal stages of project development. Biomarker analysis should not replace other monitoring methods, but should be part of the coral manager's toolbox. Along with ecological monitoring and restoration, education and outreach, community involvement initiatives, land-based BMPs, biomarker analysis will add a layer of information for the much-needed management of coral reefs.

Coral managers across all levels of government and the private sector should explore all opportunities to work with stakeholders, lawmakers, other researchers, and laboratories in fine-tuning the biomarker analysis method and making this a more common coral reef monitoring option in the future. Research is generally controlled by funding agencies and focuses on "front-burner" issues. Research is excellent at identifying, describing, quantifying problems, and suggesting solutions, but falls short when attempting to implement solutions. The biomarker analysis method can be used to identify specific sources of stress, quantify coral health, and can provide information that managers can use to make real-time conservation decisions. The future of coral reefs depends on technological and diagnostic advancements – this biomarker analysis is a step in that direction.

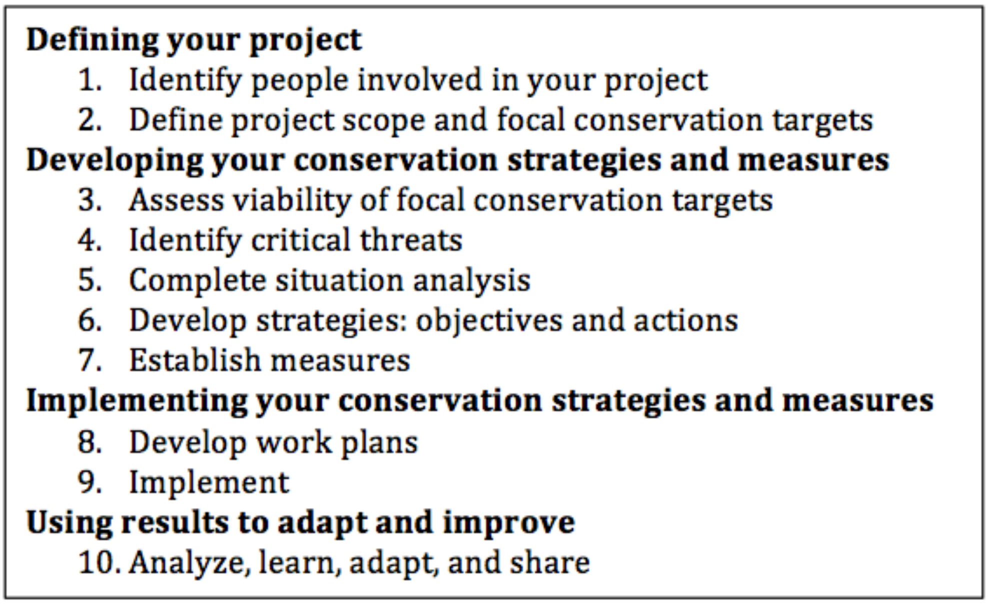
CHAPTER 4: ENHANCING CORAL REEF RESILIENCE AND RESTORATION SUCCESS: LESSONS LEARNED FROM MAUNALUA BAY, OAHU AND LAOLAO BAY, SAIPAN.

4.1 ABSTRACT

With increasing local and global threats, coral reef managers are turning to ecosystem-level restoration projects to yield greater ecologically beneficial outcomes. These projects usually require external funding and take years to complete. Communities and managers obtained funding to conduct such ecosystem-level restoration work in Laolao Bay, Saipan and Maunalua Bay, Oahu. Both projects were performed to improve marine resources by improving water and habitat quality through addressing land-based sources of pollution and invasive alien algae (specifically for Maunalua Bay). Both projects incorporated communities at different levels and underwent the conservation action plan (CAP) process. A comparison of CAP processes and ecosystem-level restoration project results were conducted and summarized. It is recommended these seven concepts are considered when planning resource restoration projects requiring strong community involvement: 1) identify all stakeholders and make conservation connections, 2) engage community members and stakeholders in the conservation planning process, 3) seek scientific support, 4) align conservation and community goals, 5) identify long-term and short-term goals, 6) align project goals, objectives, strategic actions, monitoring and success metrics, and 7) effectively communicate and disseminate information.

4.2 CONSERVATION ACTION PLANNING

Conservation Action Planning (CAP) is a powerful tool and process that The Nature Conservancy (TNC) uses to guide conservation practitioners and projects to achieve effective conservation results (TNC 2007). The CAP process helps to focus strategies into implementable, adaptable actions. This process has been used worldwide and at multiple scales. TNC Conservation Coaches are available regionally to assist practitioners and/or project participants learn and implement the CAP approach. In 2006, TNC conservation coaches hosted workshops with various groups from Hawaii and Saipan. These CAP workshops resulted in the eventual development of the Laolao Bay and Maunalua Bay CAP.



Defining your project

1. Identify people involved in your project
2. Define project scope and focal conservation targets

Developing your conservation strategies and measures

3. Assess viability of focal conservation targets
4. Identify critical threats
5. Complete situation analysis
6. Develop strategies: objectives and actions
7. Establish measures

Implementing your conservation strategies and measures

8. Develop work plans
9. Implement

Using results to adapt and improve

10. Analyze, learn, adapt, and share

Figure 4.1. The ten steps of the CAP process.

4.3 RESTORATION AND CONSERVATION IN MAUNALUA BAY

4.3.1 Conservation Action Plan Review

The resurgence in conservation activities in Maunalua Bay has been in large part a result of a community push led by Malama Maunalua, a local non-governmental organization. Malama Maunalua is a community-based stewardship organization created in 2005 to conserve and restore Maunalua Bay. Malama Maunalua facilitates conservation and restorative activities by engaging and empowering communities, and by forming strong strategic partnerships with government and non-government organizations. In 2006, and updated in 2009, Malama Maunalua in partnership with The Nature Conservancy Hawaii (TNC-H) and the National Oceanic and Atmospheric Administration (NOAA) developed the Conservation Action plan for Maunalua Bay (Maunalua Bay CAP). Malama Maunalua understood that collaborative partnerships were needed for the large-scale restorative efforts required in Maunalua Bay's watersheds and marine habitats, and adopted a partnership-based conservation model. The Maunalua Bay CAP identified 34 strategic partners from the federal and local government, NGOs, community groups, and the private sector.

Because the development of the Maunalua Bay CAP was inclusive and partnership-based, it successfully identified conservation targets, threats to those targets, and long-term conservation objectives. Key stakeholders were involved in the planning process from the very beginning and at critical steps throughout the CAP process. In the early stages of the CAP process, an emphasis to focus on land-based sources of pollution, and not focus only on fishing-related activities (and prohibitions), was identified (Davis G, personal communication, 2017). Achieving a consensus among all stakeholders was a major factor in the subsequent planning and successful implementation of the Maunalua Bay CAP.

The Maunalua Bay CAP identified three main strategies employed in Maunalua Bay: 1) reducing land-based sources of pollution through improved watershed management; 2) addressing the fisheries decline through strategic engagement and outreach to fishers; and 3) invasive alien algae removal and control. The resulting conservation targets identified were the inshore marine habitats, the fore reef areas, reef species assemblages, and restoration species of cultural importance. Polluted runoff and sedimentation, invasive marine algae, and unsustainable harvesting practices were identified as the major threats. Eight, long-term objectives were developed: the first three addressed the polluted runoff and sedimentation issue; the next three addressed invasive marine algae; the 7th addressed the unsustainable harvesting issue; and the last objective addressed community outreach and education.

The Maunalua Bay CAP indicated that monitoring progress in hitting targets is critical to their mission as it systematically measures performance of present actions. Because the CAP is a "living" document," monitoring is a critical component in adapting to change and will inform and guide future restoration and management actions. Monitoring also allows Malama Maunalua to have data on the target areas, which can be used to inform the community on the progress of the project(s). Malama Maunalua believes that strong community involvement and participation in monitoring will result in a wider awareness, and demand, for resource protection in the Bay.

4.3.2 Maunalua Bay Reef Restoration Project Outcomes

In 2009, TNC-H in partnership with Malama Maunalua, submitted an American Recovery and Reinvestment Act (ARRA) grant proposal and was awarded $3.4 million dollars to address invasive alien algae in Maunalua Bay. The three goals of the project were: to improve coral reef habitat by removing a significant section of the densest areas of invasive alien algae in the Bay; to create employment and stimulate green enterprises on Oahu; and to build sufficient community capacity in the Bay that will result in expanded and sustained local reef management efforts. Under each goal, objectives were identified which guided strategic actions. At the end of the Maunalua project, most objectives were met, or were in the process of being met.

The main goal of the restoration project was met by removing *A. amadelpha* from a total of 10.4 hectares of the Paiko reef flat (PRF). An additional 0.48 hectares of *A. amadelpha* were cleared by volunteers at six other sites in Maunalua Bay. Additionally, the removal of algae resulted in the decrease of sediments at PRF (Figure 4.2b). The other two goals of stimulating jobs and building community for sustained management were met by:

the creation of 63 direct and 97 indirect jobs (project management, labor, etc.); and by Malama Maunalua obtaining 501(c)(3) legal status and by filing its Articles of Incorporation with the State of Hawaii (TNC 2012). According to Malama Maunalua's website (http://www.malamamaunalua.org) the organization has grown since 2009, and currently has four staff, seven community *huki* leaders (algae removal coordinators), numerous interns, and a board of directors comprised of influential residents, business leaders, and politicians.

Malama Maunalua has been effective in engaging the community and building lasting relationships with stakeholders in the region. To date, over 10,000 volunteers have taken part in the restoration of Maunalua Bay. Since the completion of the Maunalua project in 2011, Malama Maunalua has continued to host regular invasive alien algae removal (*hukis*), and other education and outreach events. From 2013 – 2015, Malama Maunalua hosted an annual average of 34 *hukis* employing an average of 2,100 volunteers (http://www.malamamaunalua.org/). Malama Maunalua currently partners with 55 organizations to include businesses, schools, government agencies, community groups and received funding from 13 institutions (http://www.malamamaunalua.org/).

Malama Maunalua is excellent at developing strategic partnerships - ones that share the benefits of conservation. About the same time the Maunalua project was starting in 2009, Malama Maunalua actively recruited and supported 12 university and agency research studies in the Bay. This generated large amounts of data, which led to multiple publications and several Maunalua Bay specific science symposia. The science informed management and was presented to the broader community. Several businesses in the Maunalua Bay have permanent displays, showcasing the issues and solutions taking place in the Bay. Other strategic partners include the various farms that receive the algae and use it on their farms as fertilizer. This is a great example of "shared benefits." Instead of filling landfills, the algae are enriching the soils used to plant local produce.

4.3.3 Sediment dynamics following algal removal (Ch. 2)

The removal of *Avrainvillea amadelpha*, facilitated the flushing of fine sediment from Paiko reef flat. Over the 14 month project period, fine sediment concentrations decreased in the areas cleared of algae. The presence of the algae inhibited the flushing of fine sediment. After removal, flushing times of fine sediment was determined to be less than four years, compared to continued accumulation before removal. By completing the objective of reducing invasive algal biomass, two other objectives - restoration of coastal habitat and understanding of sediment dynamics were addressed.

On 10/5/2011, I presented findings to the Maunalua Bay community during the second Maunalua Bay Community Science Symposium. My data demonstrated that invasive algal removal was facilitating the flushing of fine sediments out of Paiko reef flat, and was met with overwhelming positive feedback. The community was delighted to hear that the hard work and all the collaborative efforts are having a positive impact on habitat and water quality in Maunalua Bay. Although only three months into my sampling, this short-term success validated the current project approach and was potentially used to motivate forward progress of the project. I have presented my research at numerous local, regional, national, and international meetings, however, this presentation to the Maunalua Bay community was the most nerve-wrecking and meaningful presentation I ever gave because it had deep connections and implications to the Maunalua Bay community present in the audience.

4.4 RESTORATION AND CONSERVATION IN LAOLAO BAY

4.4.1 Conservation Action Plan Review

Land-based sources of pollution (LBSP) were identified as a major threat having a significant negative impact on coral reef health in Laolao Bay, and the CNMI in general. During heavy rain events, storm water runoff picks up sediment, nutrients, and toxicants and delivers them to the Bay. In the Laolao Bay watershed, the un-paved road and several cleared areas, or badlands, provide the major source of sediment washed out during rain events. The Laolao Bay waters are currently listed in the CNMI 303(d) list as impaired under the Environmental Protection Agency's aquatic life use designation due to high levels of bacteria and nutrient levels. In 1998, multiple local and federal government agencies decided to take action against LBSP in Laolao Bay by revegetating the badlands or cleared areas. The CNMI marine monitoring team was subsequently formed to assess the effectiveness of the watershed work by assessing the impact to marine organisms.

The conservation action plan for Laolao Bay (Laolao CAP) was created in 2008 by the Division of Environmental Quality (DEQ), the Coastal Resource Management Office (CRM), the Division of Fish and Wildlife (DFW), and the Mariana Islands Nature Alliance (MINA) - the only non-governmental organization. The process was coordinated by the CNMI Coral Reef Initiative and facilitated by The Nature Conservancy Micronesia (TNC-M), and NOAA. The Laolao CAP process was top-down, with only two, out of 12, participants representing a NGO. No local stakeholders were a part of the process.

Thirteen threats and five targets were identified in the Laolao CAP. The conservation targets were coral, macroinvertebrates, fishes, turtles, and vegetation. The threat analysis ranked corals high and were most threatened by runoff, large-scale disturbance, and lack of herbivory. Vegetation also ranked high to threats of fire and invasive species. Nine objectives and multiple strategic actions were created to address threats and conserve targets in Laolao Bay. Three objectives addressed LBSP. One called for the reduction in turbidity at both water quality sample sites in Laolao Bay and the other two objectives addressed LBSP by revegetating badlands and reducing fires. Three other objectives were ecological in nature and called for statistically significant positive trends in the abundance of fishes, macroinvertebrates and the abundance of coral density and mean colony size. The final three objectives were enforcement and outreach in nature.

The Laolao CAP stated that an annual work plan would be created every year to prioritize the projects and to guide grant funding. The implementation of the Laolao CAP requires coordination between the CNMI Coral Reef Initiative agencies (DEQ, CRM, and DFW) due to funding issues. The Laolao CAP also identified the monitoring of marine resources as the tool to support Laolao CAP activities and document environmental change.

In 2012, an addendum and work plan were added to the Laolao CAP. Local and federal government agencies, along with the non-governmental organization Mariana Islands Nature Alliance (MINA), and a member of the press were part of the team that reviewed the original 2009 Laolao CAP and created the 2012-2013 work plan. No Laolao Bay stakeholders and/or community members were present in the process. The Laolao CAP addendum replaced the "coral" target and with "benthic habitat" and added "water quality" as a new key ecological attribute. Additionally, the CAP team revised the threat rankings by adding algal growth, diver damage, trash, and by deleting lack of herbivory, anthropogenic light sources, loss of foraging habitat, and lack of baseline data as threats.

4.4.2 Laolao Bay Road and Coastal Improvement Project Outcomes

In 2009, DEQ and CRM submitted an American Recovery and Reinvestment Act (ARRA) grant proposal and was awarded $2.6 million dollars to address water quality concerns in Laolao Bay due to land-based erosion and polluted runoff. Project objectives and strategic actions were in-line and referenced the Laolao CAP. It included: paving a section of Laolao Bay Drive; installing a ponding basin; hardening stream crossings; revegetating barren badlands; increasing public awareness; and marine ecosystem and water quality monitoring.

Upon completion of the Laolao project in July 2012, some of the objectives, as identified in the Laolao CAP addendum, were completed. Only two objectives were met as of February, 2012; wildfires were reduced to zero, and there was successful revegetation in the barren badlands. According to the Laolao CAP addendum and project summaries (DEQ 2012), over 1,600 plants representing 12 native species were planted over 14 acres of deforested areas. These activities were completed in September, 2011 with plant survival at 67%. The social marketing campaign, the three ecological objectives, improved water quality, and federal prosecutions in sea turtle crimes were all in progress – started, but not completed. The objective that called for the elimination of unsustainable beach activities was not met due to several key terms being ambiguous and undefined (DEQ 2012).

The conservation activities in Laolao Bay were and continue to be driven by the local government agencies responsible for managing the resources there (DEQ, CRM, DFW). Outside involvement has been limited to partnering government agencies and several NGOs. DEQ partners with 17 organizations, three local government agencies, four federal agencies, and three NGOs. CRM and DEQ have programs and projects that support the Laolao CAP goals and objectives. CRM is conducting two Laolao Bay specific social marketing campaigns, Our Laolao and the Laolao Bay Pride Campaign, aimed at bringing awareness to littering and sedimentation issues with land owners. The Laolao Bay Pride Campaign collaborates with the community and has provided watershed hikes to students, planted 340 native trees, conducted 500 presentations, conducted 41 campaign events, distributed 5,000 outreach materials, provided erosion training to 12 landowners and distributed 450 native trees (Younis JB, personal communication, 2018).

The Laolao Bay Road and Coastal Management Improvement Project Phase II Report (Laolao report) (Houk, et al., 2012) serves as the final report, documenting results and outcomes of the Laolao project. Because the Laolao report focused on ecological observations and metrics, the immediate assessment of Laolao project effects cannot be determined at this point. The Laolao report serves as a baseline where future change can be measured. With water quality data provided by DEQ, a comparison of turbidity values was made before and after the Laolao project. Averaged across all six water quality sample sites, turbidity values were significantly less in 2015-16 when compared those from 2011-12 (Figure 4.2a). As plants mature and hold more soil, as Laolao Bay residents become more environmentally conscious, and as the structural improvements to the road continue to reduce sediments from entering the ocean, turbidity values are expect to decrease further. Over time, comparison of ecological data with baseline data gathered from this project will elucidate if the Laolao project activities had a positive impact on marine resources.

4.4.3 The effects of watershed restoration on coral physiological health (Ch. 3)

Because molecular methods were used to quantify stress-related biomarkers in live coral, it was possible to measure the direct impacts of the Laolao project on coral physiological health. Before the Laolao project, there were no differences in expression between shallow and deep sites for all biomarkers tested. Corals were experiencing the same amount of stress, regardless of depth. There was noticeably less expression at the Tuturam and reference site for Catalase and CYP1A1. After the Laolao project, there was a noticeable decrease in the amount of SOD, Catalase, and CYP1A1 expression at deep sites, compared to shallow sites. The corals at depth, outside the reef, were not experiencing the same amount of stress as the shallow site corals. The amount of expression in corals at deep sites was similar to that at the Tuturam site. There was noticeably less expression in all biomarkers in deep corals sampled after the Laolao project when compared to deep corals sampled before the Laolao project was completed. Comparing shallow corals expression before and after the Laolao project, a slight decrease in CPY1A1 was observed. For SOD and catalase, expression was higher after the Laolao project.

Overall, the Laolao project had a positive impact on deep corals and no impact to corals at shallow sites. After the Laolao project, deep corals had lower expression when compared to shallow sites, and when compared to deep corals sampled before the Laolao project. Before the Laolao project, there was no difference in expression between shallow and deep corals. These results demonstrate that: 1) large-scale restorative work can have an immediate positive impact on coral health; 2) without intervention, LBSP negatively impacts shallow and deep corals equally over the range sampled; and 3) that immediate impact can be measured using molecular tools.

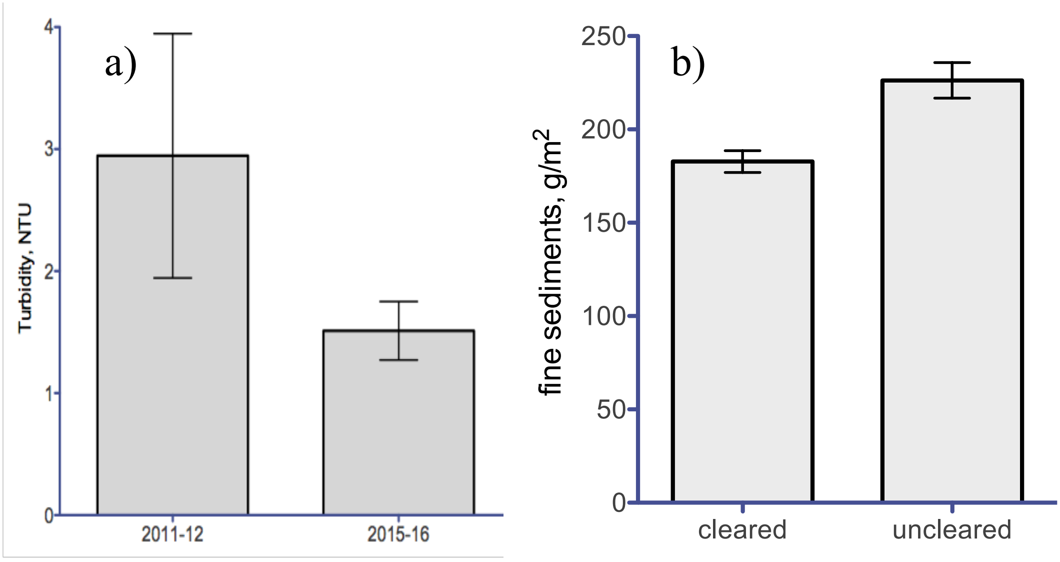


Figure 4.2. a) Turbidity values averaged across all BECQ water quality sampling sites at two time points, one before the Laolao project (2011-12) and one after (2015-16). b) Sediment concentrations in cleared and uncleared areas at Paiko reef flat in Maunalua Bay. 95% confidence intervals are shown $p < 0.05$.

4.5 DISCUSSION

The restoration of ecological systems requires an approach that incorporates science, management, and complex social components present in stakeholder communities. Human activities are responsible for most of the threats coral reefs face, and must be addressed as in finding solutions. Natural resource conservation is most successful when communities are included in the planning, implementing, and monitoring stages of a conservation project. Aligning the needs of the community with the goals of the project is ideal, but can be tricky due to incongruities and competing needs (Adams, 1998). All communities are different and may require different actions and approaches to achieve success. However, there are some common actions and activities associated with successful implementation of community-based conservation and natural resource management programs.

4.5.1 Community Engagement

One re-occurring theme in successful implementation of natural resource management projects is the ability to engage and involve the community early and throughout the entire process. The work in Maunalua Bay was initiated, maintained by NGOs and utilized a bottom-up approach. Community members representing multiple stakeholder groups were present and active in the planning and development of the Maunalua CAP. Science and inquiry were requested and used to guide decisions and address data gaps. Malama Maunalua was the main catalyst responsible for the implementation success observed. Malama Maunalua is a local NGO with a mission specific to Maunalua Bay. Government and academic organizations were also important in the process, but played a supporting role.

In Laolao Bay, the community was incorporated into the project, but only after the creation of the Laolao Bay CAP. Although the Mariana Islands Nature Alliance (MINA) was a part of the development of the Laolao CAP, they played a supporting role to local government agencies (CRM, DEQ, DFW). No other stakeholders were involved in the 2009 and 2012 planning of conservation activities in Laolao Bay. Currently CRM, through the OurLaolao and Laolao Bay Pride Campaigns, are aiming to increase awareness and build community involvement in the restoration of Laolao Bay.

4.5.2 Aligning Conservation Goals with Community Needs

Conservation planning involves the identification of threats, targets, and strategic actions to achieve desired goals, objectives, and outcomes. As mentioned, communities are different and may respond differently to recommendations developed in a CAP. To avoid incongruities, including the stakeholders early in the planning stages of CAP development will give them the opportunity to comment on target and threat identification. The development of the Maunalua CAP involved key stakeholders during the initial and critical stages of threat and target identification. Consensus was reached to address land-based sources of pollution and not to focus solely on fishing prohibitions. The rationale was that prohibiting fishing alone would not lead to the restoration of Maunalua Bay and would lead to additional conflict among users. All stakeholders agreed that the first step was to restore the conditions required for natural recovery by improving water and substrate quality by reducing sediment-laden runoff and addressing invasive algal species.

A critical step in aligning conservation goals and community needs is to ensure that project goals, objectives, and metrics are aligned, transparent, clearly defined, and make sense. The Maunalua Bay CAP identified land-based sources of pollution (LBSP) as a major threat to the overall health of Maunalua Bay. The goals and objectives were aligned with the threat. Three objectives addressed polluted runoff and sedimentation with the goals of reducing, mitigating, and improving nearshore habitats. Objectives aimed at understanding sediment transport patterns and impacts, reducing discharges, and implementing practices to other watersheds in the Maunalua Bay region were identified. Strategic actions included conducting studies, monitoring, outreach, and developing partnerships.

The Laolao Bay CAP was created to improve water quality and reduce LBSP threats to Laolao Bay. Out of nine objectives, three addressed LBSP while one addressed turbidity directly. It aimed to reduce turbidity levels below 1997 levels by 10% and 50%, by 2015 and 2018 respectively. Strategic actions to achieve this objective are: restrict vehicle access to beach; revegetate badlands; implement road improvement plan; promote the use of Crime Stoppers to report violations; and install and check answering machines daily at DFW, DEQ and CRM. Three of the strategic actions are enforcement in nature. None of the strategic actions involve monitoring or understanding the sedimentation issue, thus no mechanism was identified to monitor or understand this objective. Monitoring activities were only listed for the ecological objectives.

4.5.3 Sharing the Benefits of Conservation

When planned properly, conservation actions are almost always associated with conservation benefits. CAPs and other planning tools identify conservation outcomes that will be realized in the long term (years, decades), for example, the re-establishment of healthy coral reef assemblages, increase populations of desired fish and invertebrates, improved water quality, etc. These outcomes usually drive project actions because they have the most perceived benefits. In addition to anticipating long-term benefits and outcomes, short-term benefits and outcomes should also be considered in project planning, implementation, and information dissemination. Short-term successes help to sustain the effort needed to realize long-term benefits. It will be difficult for a community to be active in a process where the benefits are years or even decades away.

Kittinger et al. 2013, demonstrated that the Maunalua Bay project provided significant socioeconomic and cultural benefits to the Maunalua Bay community. When benefits of conservation are realized and shared, participating groups are motivated to continue to contribute to the successful conservation of resources. In Maunalua Bay, key partnerships were made with academic institutions conducting research in the Bay. Through scientific support, MM was able to address data gaps and build the cumulative knowledge of the Bay. The researchers benefit by obtaining grants, publishing results, and working in an area with a community who embraces science and conservation. In multiple instances, the science conducted in the Bay was part of a MS or PhD thesis (Murphy 2013; this study). Another example of shared benefits is the recycling of the invasive algae. MM partnered with local farms who took and used the algae as fertilizer. The algae would have otherwise been sent to a landfill for disposal. The tool initially used to bring the community together was the *huki*, or invasive algae removal volunteer events. Volunteer school, industry, and community groups removed invasive algae in regularly planned, publicized events. These events introduce the community to the threats and management solutions in the Bay. MM receives help in managing invasive algae while the volunteers learn something new while conducting an outdoor activity with others.

4.5.4 Recommendations

Conservation in communities can be challenging. Communities will always have a few individuals, stake holder groups, or even governmental agencies that are resistant to conservation. Focusing on conservation goals and targets that make sense, will be important in convincing all stakeholders that conservation is needed and is in alignment in meeting community needs. When conservation goals and objectives are consensus driven, being non-compliant will look irresponsible. For example, in the CNMI, it is looked down upon to fish using dynamite or scuba equipment. Community members will not hesitate to report these violations to the proper authorities. In this instance, conservation makes total sense, and all stakeholders involved share benefits.

Below are seven practices that should be considered when planning resource restoration projects requiring strong community involvement:

- Identify all stakeholders in the project region and identify potential conservation connections. Attempt to engage all in the process and set the stage for future partnerships. This is more critical for smaller communities where stakeholder groups and individuals are limited.
- Engage community members and encourage active participation early in the planning, implementation, and monitoring phases of the project.

- Seek scientific support. Academic, agency, or NGO scientists can be key partners and provide valuable information during all phases of a project. Additionally, they can add to the data generated at a project site, which will further guide management.
- As much as possible, conservation goals should be aligned with community goals. Conservation is “easy” when all involved share the benefits.
- Identify both long-term and short-term goals and benefits. Short-term goals and associated benefits are important as it motivates communities to remain active. It will celebrate small successes and document and guide progress.
- Project goals, objectives, strategic actions, success metrics, and monitoring metrics should be aligned. Monitoring and success metrics should be directly related to the goals and objectives.
- Communicating, reporting and information dissemination should be frequent, consistent, publically available, understandable, and presented in various forms (scientific and non-scientific publications, videos, social media posts, presentations, outreach events, etc.).

CHAPTER 5: DISCUSSION

5.1 CHOOSING THE RIGHT APPROACH

Enhancing resilience in corals for reef restoration and recovery can be approached several different and complimentary ways. The Laolao Bay project was an example of a top down, government led, project conducting land-based restoration activities to reduce erosion and sedimentation impacts on adjacent coral reefs. The Maunalua Bay project was a bottom up effort, led by non-governmental organizations, conducting in-water invasive algal removal to promote sediment flushing at Paiko reef flat. Both projects utilized the conservation action planning process and identified both conservation targets and activities.

Providing answers to key management questions supports the decision-making process and the selection of appropriate approaches. Science can describe the problems and provide corrective action options. For example, in Palau, clearing and grading coastal areas and the removal of mangroves were responsible for increased sedimentation onto the adjacent coral reef. Researchers were able to document the problem and present their findings to the villagers including chiefs, fishers and Womens' Groups, through culturally connected scientists. About six weeks later a moratorium on mangrove and upland clearing was enacted (Richmond et al, 2007).

It is important to consider site-specific information and conditions when choosing a restoration approach. Choosing between an in-water, or land-based restoration activity will depend on the site, community, financial, and scientific support. Simply applying one of the above solutions, without careful planning, will not necessarily lead to successful conservation actions and outcomes. For both Maunalua Bay and Laolao Bay, multi-million dollar grants were awarded and used to implement restoration strategies developed by previous conservation action planning activities. It is important to note that the paths leading to conservation success at Maunalua Bay and Laolao Bay are the exception, and not the norm.

Most areas in need of conservation have little to no pre-planning opportunities and are financially limited. The American Recovery and Reinvestment Act (ARRA) funded both the Maunalua Bay and Laolao Bay projects in 2009. Similar funding opportunities have not been offered since.

5.2 TRUSTING SCIENCE AND MANAGEMENT

Science and management should be used as tools to understand ecosystem problems and identify solutions that communities can use to support sustainability of natural resources. The invasive algal removal project in Maunalua Bay is a good example of how trusted science and resource management planning a led to successful conservation outcome. The main objective of the ARRA funded project was to improve habitat quality at PRF by removing the invasive alga, *Avrainvilla amadelpha,* and associated fine sediment. In 2011, I presented my sediment resuspension data from PRF to the Maunalua Bay community at the 2nd Maunalua Bay Science Symposium. My results indicated that the removal of *A. amadelpha* was having a positive impact on habitat quality – fine sediments were mobilized and flushing. Community members present at my presentation were reassured with my findings, which worked to validate the importance of the hard work and coordinated efforts performed by the Maunalua Bay community.

Six years after my data collection at PRF, extremely high rainfall and stream flows were recorded in the Niu Valley and Kuliouou Stream respectively in April 2018. After the record-breaking rain and stream flow events, Malama Maunalua volunteers visited PRF and noticed sediment plumes extending from the stream mouths out into the bay. To understand the sediment dynamics in the cleared areas at PRF, MM volunteers measured and compared pre-storm and post-storm sediment depths at 37 locations and found no statistical difference (http://www.malamamaunalua.org/malama-maunalua-studies-effects-of-severe-april-flooding-on-maunalua-bay/). Initial efforts back in 2009 to improve habitat quality were still having a positive effect at PRF. Instead of sediment accumulation, the absence of *A. amadelpha* is allowing for the continued mobilization and flushing of fine sediment.

Another example of how management resulted in realized benefits to the Saipan community was the introduction of the topshell marine snail, *Trochus niloticus.* In 1938, about 3000 individuals of *T. niloticus* were introduced to Saipan from Palau mainly for shell production (Gillette 2002). The introduced topshell snail is highly desired as food by the local population and currently has local protections in place to protect from overharvesting. In the CNMI, the current moratorium on the harvest of the topshell snail was enacted in 1981. Additionally, the Lighthouse Reef Trochus Sanctuary was established in the Saipan lagoon to provide a refuge for when the moratorium is lifted.

Good science and resource management have to contend with past failures, when trying to engage communities in the conservation process. It is easy to trust science and management, and participate in the conservation process when the process runs smoothly and when conservation benefits are realized. That is not always the case. In Hawaii, some current conservation efforts, are focused on fixing failed science and management actions. Back in the 1970s, university researchers introduced the algae *Kappaphycus* spp. in Kaneohe Bay, and *Gracillaria salicornia* in Waikiki and Kaneohe Bay, for their potential economic value. The field experiments were later abandoned and the invasive algae have since spread throughout Kaneohe Bay, and throughout Oahu and Molokai for *G. salicornia* (Russell 1992; Smith et al 2002). The overabundance of these introduced algal species are having a negative impact on coral reef health (Smith et al 2002). At the ecosystem level, invasive algae outcompete corals for space and overgrow them (Smith et al 2002). At the organismal level, dense algal mats smother the coral, reducing access to light, and create anoxic conditions (Martinez, 2012). The State of Hawaii, The Nature Conservancy of Hawaii (TNC), and the

University of Hawaii developed the first Super Sucker in 2005. It is a marine vessel equipped with a suction system used to make the removal of invasive alien algae more efficient.

Another failed attempt in Hawaii was the introduction of numerous fish species by the Hawaii State Division of Fish and Game (now the Division of Aquatic Resources). From as early as 1905 thru the early 1960s, 21 fish species were intentionally introduced to Hawaiian waters to control aquatic plants, as baitfish, and as foodfish (Randall, 1987). The peacock grouper, *Cephalopholis argus*, and bluelined snapper, *Lutjanus kasmira*, are two examples of introduced fishes that have proliferated in Hawaiian waters. Randall (1987) states that the unpopularity with fishermen is due to the potential for ciguatera and unwanted bycatch and small size for *C. argus* and *L. kasmira* respectively. Not targeted as heavily as expected, these introduced fishes were allowed to flourish and spread throughout the State. This can be problematic because *C. argus* was shown to prey upon native fish populations (Dierking 2007).

5.3 SUCCESSFUL AND SUSTAINED RESTORATION REQUIRES COMMUNITIES

In order for conservation activities to be successful, impacted communities need to “want” to conserve. Being able to communicate effectively with communities regarding the benefits of conservation using scientific data is crucial. The Maunalua Bay community was “ready” and “wanted” conservation. The community was involved in the initial planning back in 2009 and is still currently planning and conducting conservation activities. In 2009, the Kaneohe community went through a similar conservation planning process, but because the community was “not ready” to commit to conservation, activities were limited to certain land areas only (Richmond 2014 personal communication). When communities are “not ready” for conservation, and there is no consensus on goals and objectives, conservation activities are just words on paper, they are not effective, and success is difficult to achieve.

Conservation has to make sense to humans, specifically those who depend on the resources potentially impacted by conservation actions. Kareiva and Marvier (2012) conclude that “forward-looking” conservation has to consider both people and nature – “nature can prosper so long as people see conservation as something that sustains and enriches their own lives.” A majority of the resource users in the islands interact with the environment to realize some sort of recreational or monetary benefit (food or money). Fishermen, hunters, and other resource users do not interact with the resource to intentionally cause harm and damage. They do so to maintain a lifestyle of subsistence or for recreation. Conservation of resources, for future use, is in their best interest. If conservation actions require communities to give up use or access to a resource, that void needs to be filled by an alternate mechanism.

When no alternatives are in place, conservation actions become misaligned with community needs, and conservation success is limited and not sustained (Adams 1998). The island of Rota, in the CNMI, is the last place where the critically endangered Marianas Crow has a wild population. Wild populations have become extinct in Guam due to the invasive brown tree snake and other factors. To prevent further decline in populations on Guam, the Marianas Crow was federally listed as endangered in 1984. The listing had unforeseen consequences on Rota. Because the crow was not harvested as food, it was seen as a nuisance and a hindrance to local landowners (Fancy et al 1999). There was no conservation benefit to the local land owner. To prevent unwanted prohibitions on private lands by the Endangered Species Act, the crow was persecuted by local land owners (Fancy et al 1999). In 2012, the US Fish and Wildlife Service, along with local partners adopted the Marianas Crow land owner incentive plan. The plan monetized ($500 USD) land owners in conservation activities. The Service, along with partners, understood that the “endangered” federally listed status alone was not going to protect the crow. Broad acceptance and cooperation by the land-owning community was required for the current and future conservation of the crow.

The Pacific Island nation of Palau is considered to be a global leader in Marine conservation. In 2015, Palau created the sixth largest marine protected area in the world by closing off 80% of its national waters to fishing. The Honorable Tommy Remengesau, Palau President, reaffirmed to the Senate President in a letter that the Palauan people are the true beneficiaries of the law. The law allows permitted fishing in 20% of its waters for domestic use and limited export. The law has steep penalties for violators and imposes a $100 environmental impact fee to visitors that is allocated for environmental conservation and other national matters (pension fund, allocated to states, etc.). This process should be modeled by other coral reef nations worldwide. It uses science to promote management actions that are aligned with community needs that ultimately benefit the people.

5.4 CONCLUSION

In my opinion, the future of coral reefs, and natural resources in general, desperately needs to incorporate and address social issues like never attempted before. Science and management will always play an important role, but in order to implement successful, sustained conservation actions, human compliance is required. The fatal flaw in current resource management is the ignorance towards humans and the role humans play in nature. Most modern food chains and food webs depictions exclude humans. I understand that humans should be viewed somewhat differently, but shouldn’t be ignored altogether. Humans, especially in developing regions, or those struggling in developed regions, require access to resources to survive. Humans are often viewed as the problem (rightfully so in numerous examples), but should also be viewed as the solution. In Maunalua Bay and Laolao Bay conservation objectives were met, and in Maunalua Bay, sustained, due to the strong science, management, and community partnerships. It is possible to instill conservation beliefs in communities and achieve sustained conservation success. The future of coral reefs requires resilient ecological AND social systems.

REFERENCES

Adams TJ (1998). The interface between traditional and modern methods of fishery management in the Pacific Islands. Ocean Coast. Manag. 40: 127-142.

Alcala AC and Russ GR (1990). A direct test of the effects of protective management on abundance and yield of tropical marine resources. J. Conserv. Internat. Explor. Mer 46: 40-47.

Anthony KRN (2000). Enhanced particle-feeding capacity of corals on turbid reefs (Great Barrier Reef, Australia). Coral Reefs 19: 59-67.

Anthony KRN and Connolly SR (2004). Environmental limits to growth: physiological niche boundaries of corals along turbidity–light gradients. Oecologia 141:373–384.

Bellwood DR, Hughes TP, Folke C, and Nystrom M (2004). Confronting the coral reef crisis. Nature 429: 827-833.

Beukering Pv, Haider W, Wolfs E, Liu Y, Leeuw Kvd, Longland M, Sablan J, Beardmore B, Prima SD, Massey E, Cesar H, Hausfather Z (2006). The Ecoomic Value of the Coral Reefs of Saipan, Commonwealth of the Northern Mariana Islands. Department of Interior, NOAA - Technical report, 99 pp.

Brostoff WN (1989). *Avrainvillea amadelpha* (Codiales, Chlorophyta) from Oahu, Hawaii. Pacific Science, 43: 166-169.

Brown BE and Howard LS (1985). Assessing the effects of stress on corals. Advanced Marine Biology 22:1-63.

Burke L, Reytar K, Spalding M, and Perry A (2011) Reefs at Risk Revisited. Washington, D.C., World Resources Institute (WRI), The Nature Conservancy, WorldFish Center, International Coral Reef Action Network, UNEP World Conservation Monitoring Centre and Global Coral Reef Monitoring Network, 114p.

Carlton JT and Eldredge LG (2009). Marine bioinvasions of Hawaii. The introduced and cryptogenic marine and estuarine animals and plants of the Hawaiian Archipelago. Bishop Museum Bulletins in Cultural and Environmental Studies 4, 202 pp.

Cesar HSJ, and van Beukering P (2004). Economic Valuation of the Coral Reefs of Hawaii. Pacific Science 58(2): 231-242.

Cesar H, Burke L, Pet-Soede L (2003a). The economics of worldwide coral reef degradation. WWF and ICRAN.

Cheenis Pacific Company CPC (1992). Quantitative marine baseline survey. Biological resources and water quality. Bahia Laulau and Unai Laulau Kattan areas, Saipan, Mariana Islands. In: (ed. Office CCRM) Saipan, MP.

Cloud PE (1959). Geology of Saipan, Mariana Islands; Submarine topography and shoalwater ecology. Geological Survey Professional Paper, 361-445.

Conklin E and Stimson J (2004). An attempt to increase numbers of herbivorous fishes as a means of controlling populations of fleshy macroalgae on coral reefs in Kane'ohe Bay, Hawai'i. Pacific Science 58(2): 189-200.

Connell JH (1978). Diversity in Tropical Rain Forests and Coral Reefs. Science 199: 1302-1310.

Connell JH, Hughes H, and Wallace CC (1997). A 30 year study of coral abundance, recruitment, and disturbance at several scales in space and time. Ecological Monographs 67: 461-488.

Davies PS (1991). Effects of daylight variations on the energy budgets of shallow-water corals. Marine Biology 108: 137-144.

Davis G (2017). Personal communication. NOAA Pacific Islands Regional Office, Honolulu, Hawaii.

Dierking J (2007) Effects of the introduced predatory fish *Cephalopholis argus* on native reef fish populations in Hawaii. Ph.D. dissertation, Zoology Department, University of Hawaii at Manoa, Honolulu, Hawaii, USA: 115 pp.

Division of Environmental Quality (2012). Laolao Bay Road and Coastal Management Improvement Plan: Project Summary December 2012.

Division of Environmental Quality (2009). Laolao Bay Conservation Action Plan.

Downs CA, Fauth JE, Robinson CE, Curry R, Lanzendorf B, Halas JC, Halas J, Woodley CM (2005b) Cellular diagnostics and coral health: declining coral health in the Florida keys. Mar Pollut Bull 51:558–569

Downs CA, Richmond RH, Mendiola WJ, Rougee L, Ostrander G (2006). Cellular physiological effects of the M.V. Kyowa Violet grounding on the hard coral *Porites lobata*. Environ Toxicol Chem 25: 3171–3180

Downs CA, Ostrander GK, Rougee L, Rongo T, Knutson S, Williams DE, Mendioloa W, Holbrook J, and Richmond RH (2012). The Use of Cellular Diagnostics for Identifying Sub-lethal Stress in Reef Corals. Ecotoxicology 21:768-782

Dyer KR (1950). Bed sheer stresses and the sedimentation of sandy gravels. Marine Geology 13: 31-36.

Edmondson CH (1928). The ecology of a Hawaiian coral reef. Bulletin of Bernice Pauahi Bishop Museum, 45:l.

Fabricius KE (2005). Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin 50: 125-146.

Fancy SG, Lusk MR, and Grout DJ (1999). Status of the Marianas Crow Population on Rota, Mariana Islands. Micronesica 32(1): 3-10.

Friedlander AM and Ziemann DA (2003). Impact of hatchery releases on the recreational fishery for Pacific threadfin (*Polydactylus sexfilis*) in Hawaii. Fishery Bulletin 101(1): 32-43.

Gillette R (2002). Pacific Islands trochus introductions 1927–1998. South Pacific Commission, Noumea, New Caledonia.

Glynn, PW, Howard LS, Corcoran E, Freay D (1986). Preliminary Investigations into the Occurrence and Toxicity of Commercial Herbicide formulations in Reef Building Corals. In Jokiel, P.L., Richmond, R.H., and Rogers, R.A. (eds.) Coral Reef Population Biology. Hawaii Inst. of Mar. Biol. Tech. Rep. 37. Seagrant Cooperative Report UNIHI-Seagrant CR-86-01. pp. 473-485.

Golbuu Y, van Woesik R, Richmond RH, Harrison P, and Fabricius KE (2011). Marine Pollution Bulletin 62: 824–831.

Great Barrier Reef Marine Park Authority (2016). Interim Report: 2016 Coral Bleaching Event on the Great Barrier Reef. GBRMPA, Townsville.

Hodgson G (1999). A global assessment of human effects on Coral Reefs. Marine Pollution Bulletin 38(5): 345-355.

Houk P, Okano R, Iguel J, Camacho R, Benavente D, and Johnson S (2011). Laolao Bay Road and Coastal Improvement Project: Ecological and Water Quality Assessment. Phase I Report: Pre-construction condition report, including an integrated assessment of ecological change since 1991. 42 pp.

Houk P, Okano R, Iguel J, Benavente D, and Johnson S (2012). Laolao Bay Road and Coastal Improvement Project: Ecological and Water Quality Assessment. Phase II Report: Integration of water quality and ecological data to characterize coral reefs and the drivers of change since 1991. 43 pp.

Hughes TP, Kerry JT, and Wilson SK (2017). Global Warning and recurrent mass bleaching of corals. Nature 543: 373-377.

Ingersoll CG (1995). Sediment tests. In G.M. Rand (ed.) Fundamentals of aquatic toxicology: effects, environmental fate, and risk assessment, pp 231-255. Taylor and Francis, Washington DC.

Jackson JBC, Donovan MK, Cramer KL, and Lam VV (editors). (2014). Status and Trends of Caribbean Coral Reefs: 1970-2012. Global Coral Reef Monitoring Network, IUCN, Gland, Switzerland.

Johannes RE (1978). Traditional Marine Conservation Methods in Oceania and their Demise. Annual Review of Ecological Systems 9: 349-364.

Jokiel PL, Brown EK, Friedlander A, Rodgers SK, and Smith WR (2004). Hawaii Coral Reef Assessment and Monitoring Program: Spatial patterns and temporal dynamics in reef coral communities. Pacific Science 58(2):145-158.

Jokiel PL, Rodgers KS, Walsh WJ, Polhemus DA, and Wilhelm TA (2011). Marine Resource Management in the Hawaiian Archipelago: The Traditional Hawaiian System in Relation to the Western Approach. Journal of Marine Biology. doi:10.1155/2011/151682 16 pp.

Jokiel PL, Rodgers KS, Storlazzi CD, Field ME, Lager CV, Lager D (2014). Response of reef corals on a fringing reef flat to elevated suspended-sediment concentrations: Moloka'i, Hawai'i. PeerJ 2:e699 DOI 10.7717/peerj.699.

Karieva P and Marvier M (2012). What is conservation science? BioScience 62(11): 962-969.

Karlson RH (1999). Dynamics of coral communities. Boston: Kluwer Academic Publishers.
Kay, R., and Alder, J. (2005). Coastal Planning and Management. 2nd ed. Taylor & Francis, London and New York, 380pp.

Kay RC and Alder J (2005). Coastal planning and management. New York, NY: Taylor & Francis.

Ketchum BH (1950). Hydrographic factors Involved in dispersion of pollutants introduced into tidal streams Dispersion of Pollutants Introduces into Tidal streams. Journal Qf Boston Society of Civil Engineers 37, 296- 314.

Kittinger JN, Bambico TM, Minton D, Miller A, Mejia M, Kalei N, Wong B, and Glazier EW (2013). Restoring ecosystems, restoring community: socioeconomic and cultural dimensions of community-based coral reef restoration project. Reg Environ Change 16: 301-313.

Markey KL, Baird AH, Humphrey C, and Negri AP (2007). Insecticides and a fungicide affect multiple coral life stages. Marine Ecology Progress Series 330: 127-137.

Martinez JA, unpublished data.

Martinez JA, Smith CM, and Richmond RH (2012). Invasive algal mats degrade coral reef physical habitat quality. Estaurine, Coastal, and Shelf Science 99: 42-49.

Malama Maunalua (2009). Maunalua Bay Conservation Action Plan: A Community's Call to Action.

Malama Maunalua website. http://www.malamamaunalua.org/.

Minton D and Conklin E (2012). Recovery of a Hawaiian reef flat community following the removal of the invasive alien algae *Avrainvillea amadelpha* in the Paiko area of Maunalua Bay,
Hawai'i. Honolulu, Hawaii, The Nature Conservancy of Hawai'i.

Molony BW, Lenanton R, Jackson G, and Norriss J (2003). Stock enhancement as a fisheries management tool. Reviews in fish biology and fisheries 13: 409-432.

Murphy AF (2013). Characterizing Growth Patterns to Facilitate Restoration of the seagrass Halophila hawaiina. MS Thesis. Hawaii Pacific University.

Murphy JWA and Richmond RH (2016). Changes to coral health and metabolic activity under oxygen deprivation. PeerJ, 4(2), e1956–16. http://doi.org/10.7717/peerj.1956.

Myers JH, Simberloff D, Kuris AM, and Carey JR (2002). Eradication revisited: dealing with exotic species. Trends in ecology and evolution 15(8): 316-320.

Pandolfi JM, Connolly SR, Marshall DJ, and Cohen AL (2011). Projecting coral reef futures under global warming and ocean acidification. Science 333: 418-422.

Perez III K, Rodgers KS, Jokiel PL, Lager CV, and Lager DJ (2014). Effects of terrigenous sediment on settlement and survival of the reef coral *Pocillopora damicornis*. PeerJ 2:e387;DOI 10.7717/peerj.387

Peyton KA (2009). Aquatic invasive species impacts in Hawaiian soft sediment habitats. Ph.D.
dissertation. University of Hawai'i at Manoa, Honolulu.

Prescott R (2009). Wailupe and Kuliouou Watershed Assessment and Protocol Development Maunalua Bay, Hawaii. Submitted to Malama Maunalua.

Randall JE (1987). Introductions of marine fishes to the Hawaiian Islands. Bulletin of Marine Science 41(2): 490-502.

Richmond RH (2014). Personal communication. Kewalo Marine Laboratory. Hawaii

Richmond RH, Rongo T, Golbuu Y, Victor S, Idechong N, Davis G, Kostka W, Neth L, Hamnett M, and Wolanski E (2007). Watersheds and coral reefs: Conservation science, policy, and implementation. BioScience 57: 598-607.

Rinkevich B (2005). Conservation of coral reefs through active restoration measures: Recent approaches and last decade progress. Environ. Sci. Technol. 39: 4333-4342.

Rinkevich B (2006). The Coral Gardening Concept and the Use of Underwater Nurseries. 291-301.

Rodgers KS, Jokiel PL, Bird CE, Brown EK (2010). Quantifying the Condition of Hawaiian Coral Reefs. Aquatic Conserv: Mar. Freshw. Ecosyst. 20: 93-105.

Rodgers KS, Jokiel PL, Brown EK, Hau S, and Sparks R (2015). Hawai‘i Coral Reef Assessment and Monitoring Program: Over a Decade of Change in Spatial and Temporal Dynamics in Coral Reef Communities. Pacific Science. 69:1.

Rogers CS (1990). Responses of coral reefs and reef organisms to sedimentation. Marine Ecology Progress Series 62: 185–202.

Rougee L, Downs CA, Richmond RH, Ostrander GK (2006). Alteration of normal cellular profiles in the stony coral *Pocillopora damicornis* following laboratory exposure to fuel oil. Environ Toxicol Chem 25: 3181–3187.

Russ GR and Alcala AC (1989). Effects of intense fishing pressure on an assemblage of coral reef fishes. Marine Ecology Progress Series 56 (1–2): 13–27.

Russell DJ (1987). Introductions and establishment of alien marine algae. Bulletin of Marine Science 42: 641-642.

Schaffelke B, Smith JE, and Hewitt CL (2006). Introduced macroalgae – a growing concern. Journal of Applied Phycology. DOI: 10.1007/s10811-006-9074-2.

Scheffer M, Carpenter S, Foley JA, Folke C, and Walker B (2001). Catastrophic shifts in ecosystems. Nature 413: 591-596.

Selig ER and Bruno JF (2010). A Global Analysis of the Effectiveness of Marine Protected Areas in Preventing Coral Loss. PLoS ONE 5(2): e9278.

Selkoe KA, Halpern BS, Ebert CM, Franklin EC, Selig ER, Casey KS, Bruno J, and Toonen RJ (2009). A map of human impacts to a "pristine" coral reef ecosystem, the Papahanaumokuakea Marine National Monment. Coral Reefs 28: 635-650.

Shelton III AJ and Richmond RH (2016). Watershed restoration as a tool for improving coral reef resilience against climate change and other impacts. Estuarine, Coastal, and Shelf Science 183: 430-437.

Smith SV (1978). Coral reef area and the contribution of reefs to processes and resources in the world's oceans. Nature 273: 225-226.

Smith JE, Hunter CL, and Smith CM (2002). Distribution and reproductive characteristics of nonindigenous and invasive marine algae in the Hawaiian Islands. Pacific Science 56 (3): 299–315.

Sorokin YI (ed) (1993). Coral reef ecology, ecological studies 102. Springer-Verlag, Berlin.

Stimson J, Cunha T, and Philippoff J (2007). Food preferences and related behavior of the browsing sea urchin *Tripneustes gratilla* (Linnaeus) and its potential for use as a biological control agent. Marine Biology 151(5): 1761-1772.

Te FT (2001). Response of Hawaiian scleractinian corals to different levels of terrestrial and carbonate sediment. Dissertation. Department of Zoology, University of Hawaii. pp 286.

The Nature Conservancy (2007). Conservation action planning handbook. The Nature Conservancy Arlington, VA.

The Nature Conservancy, Hawaii Office (2012). Maunalua Bay Reef Restoration Report: Final Report. Prepared for NOAA Restoration Center, US Department of Commerce.

US Fish and Wildlife Service (2012). The Mariana Crow Landowner Incentive Program.

Victor S, Neth L, Golbuu Y, Wolanski E, and Richmond R (2006). Estuarine, Coastal and Shelf Science 66: 409-416.

Weber M, de Beer D, Lott C, Polercky L, Kohls K, Abed RMM, Ferdelman TG, Fabricius KE (2012). Mechanisms of damage to corals exposed to sedimentation. Proc. Natl. Acad. Sci. 109(24) E1558eE1567.

Wilkinson C (2004). Status of coral reefs of the World. Townsville: Australian Institute of Marine Science.

Wolanski E, Richmond RH, McCook L (2004). A model of the effects of land-based, human activities on the health of coral reefs in the Great Barrier Reef and in Fouha Bay, Guam, Micronesia. J Mar Sys 46: 133–144.

Wolanski E, Martinez JA, and Richmond RH (2009). Quantifying the impact of watershed urbanization on a coral reef: Maunalua Bay, Hawaii. Estuarine, Coastal and Shelf Science 84: 259–268.

Younis JB (2018). Personal communication. CNMI Bureau of Environmental Quality, Saipan.