Assessment of coral settlement distributions and environmental conditions

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Final Report

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Summary
The patterns of coral recruitment along environmental gradients in relation to coral and fish communities, in reference to historical, sedimentation, and water quality data were determined. Changes on the reef in relation to changes on the watershed were evaluated. From our evaluation of past, present and projected future condition of the coral reefs of Pelekane Bay we find that the historical reef decline has been subsiding, offering support of local action strategies including regulatory initiatives and watershed restoration. Abundance and diversity of reef fishes has increased since 1996 and coral decline has stabilized. Coral recruitment patterns show substantially lower levels in inshore waters. This is supported by manipulative lab experiments showing larval settlement blockage under very low levels of fine sediments. Results of water quality analysis and field assessment suggest no substantial change in offshore water quality from 2010 to 2014. Moreover, greater observed coral settlement offshore remained steady across years suggesting no immediate threat from land-based sedimentation. The potential threat from existing mud deposits adjacent to excellent coral reefs appears to be minimal.

Baselines have been set for 34 sites within the Kawaihae/Pelekane region that will be valuable in evaluation of changes in the future in response to further natural and anthropogenic impacts and management strategies. This highly successful project produced five peer-reviewed journal articles. Outreach components include 12 venues that reached members of science, academia, and management. All goals and objectives proposed have been met or exceeded.

1. Problem Statement

The marine environment of Pelekane Bay has been severely impacted by the construction of the neighboring Kawaihae Harbor in the 1950's and subsequent changes in land use throughout the bay's watershed. Sedimentation and other forms of land-based pollution have led to declines in water quality and coral reef ecosystem health over the last two decades (Tissot 1998). The Kohala Watershed Partnership was awarded $2.69 million from NOAA's Restoration Center as part of the American Recovery and Reinvestment Act (ARRA) of 2009 to stabilize soil and improve land use practices on the Pelekane Bay watershed. This work has been completed and various upland watershed management activities are ongoing that will reduce land-based sources of pollution into Pelekane Bay. There is a need to determine the efficacy of land restoration and reef recovery. The emerging South Kohala Conservation Action Plan (SKCAP) has identified a number of "Target" areas that will require scientific input on the condition of the reefs.

2. Goals and Objectives

A number of questions must be answered in order to (1) evaluate the effectiveness of the terrestrial watershed remediation efforts in relationship to reef recovery; (2) to understand the potential of the local marine ecosystem to recover; and (3) to understand the potential threat that existing mud deposits pose to adjacent, relatively pristine coral reef ecosystems. This project made use of an extensive existing database coupled with additional work on coral recruitment patterns to address these questions and establish a framework to evaluate the success of restoration efforts. The results of this program provide resource managers with information relevant to other watershed restoration efforts currently being planned in neighboring watersheds. All anticipated results and deliverables have been completed in accordance with the proposal work plan.

3. Management Relevance

This project addresses the following goals and objectives as described in local, state and national coral reef management documents. It addresses the Hawaiʻi's Coral Reef Strategy Objective 1: Reduce key anthropogenic threats to two priority nearshore coral reef sites by 2015 and five by 2020 using *ahupua'a* based management. The extensive database from 34 stations within Pelekane Bay is crucial to creating initial baseline data on marine coral, algal and fish communities and will serve to evaluate watershed restoration efforts for development of management strategies in the Kawaihae/Pelekane *ahupuaʻa*. It also addresses Hawaii's LAS-LBPS Goal: Reduce land-based pollution to improve coastal water quality and coral reef ecosystem function and health, Objective 1: Reduce pollutant load to surface water and groundwater through site-specific actions and best management practices. This research meets this objective by determining the pattern of recruitment as a viable indicator of recovery by examining patterns of coral recruitment along environmental gradients in relation to coral and fish communities throughout the area in reference to historical, sedimentation, and water quality data. A focus on documenting change on the reef in relation to changes on the watershed can support management strategies to improve water quality. In addition it addresses NOAA's Coral Reef Conservation Program Goal 1: Reduce pollutant loading from watersheds to priority coral reef ecosystems, Objective 1.3: Implement watershed management plans and relevant local action strategy within priority coral reef ecosystems and associated watershed to improve coral reef ecosystem resilience. This research occurred within one of the local action strategy priority regions and will add to the foundational evidence needed to develop sound management decisions.

This project is also directed at meeting some of the priority needs of the South Kohala Conservation Action Plan (SKCAP). The database and other information that we have collected as part of this project will allow us to provide the information required by the following SKCAP "Target Areas": 1.Coastal-marine Food Resources, 2. Coral Reef Ecosystems, 3. Native Reef Herbivores and 4. Native Reef Predators. Restoration of the Pelekane Bay watershed and recovery of the adjacent reef is a key element of the SKCAP discussions. This research can help meet the needs of SKCAP for a scientific assessment of the resource while laying the foundation for future assessments of the efficacy of conservation measures.

4. Project Description

This project is directed at establishing past, present and future condition for reefs of Pelekane Bay and south Kohala, Hawai'i. The PI and his associates have developed a large database on this region over the past two decades through a series of research programs in this area. This includes studies associated with the construction of the small boat harbor and coral transplantation at Kawaihae from 1996 through 1998 (Jokiel et al. 1999). In 1999, the Coral Reef Assessment and Monitoring Program (CRAMP) set up long-term permanent baseline transects off Kawaihae to determine any changes over time where monitoring continues. Rapid assessment transects in Pelekane Bay were conducted in 2002. In addition, an extensive survey of the region was undertaken to ground truth satellite images for the NOAA coral reef mapping program (2000-2008). In 2009, a collaborative project was initiated in collaboration with NMFS to evaluate the effect of sedimentation on reef fisheries (DeMartini et al. 2013). The PI in collaboration with USGS undertook a major 1-year Hawai'i Coral Reef Initiative (HCRI) project involving detailed measurement of biological and physical characteristics of the Pelekane region.

This sediment transport and water quality work (Storlazzi et al. 2012) along with the biological results (DeMaritini et al. 2013) have recently been published. We have now compiled extensive data on the biology of Pelekane Bay and South Kohala which includes growth rates of corals, rates of coral mortality, distribution and abundance of corals and fishes throughout the region in relation to sedimentation, and impact of sediment on fish recruitment.

5.1 Objective (1): To evaluate the effectiveness of the terrestrial watershed remediation efforts in relationship to reef recovery.

a) Photo Documentation

Conditions at Pelekane Bay following a January 2014 heavy rain event were assessed through photo documentation and shoreline surveys. Aerial images of the Bay and adjacent areas were obtained through helicopter surveys. Interviews with NPS rangers concerning the January storm flood and impact on the reef were conducted.

b) Data Synthesis and Resurveys

For a historical reference we synthesized a large amount of data on sedimentation and water quality. Using this data and revisiting previously established transects, we have published on 30 years of change in Pelekane Bay. Historical studies describing the Pelekane Bay coral reef communities (Chaney et al. 1977, Tissot 1998) were resurveyed using similar methodology to document changes over time (Fig. 1). Recent surveys help to determine the efficacy of land restoration and reef recovery in the watershed. Resurveys were conducted and results submitted to a peer reviewed journal that was subsequently published in PeerJ during the project period (see full article: Appendix I).

Figure 1. Study sites in Pelekane Bay surveyed in 1977, 1998, and 2012. Sites F1-8 depicts Demartini et al. 2013 sites.

Stender Y, Jokiel PL, and Rodgers KS. 2014. Thirty Years of Coral Reef Change in Relation to Coastal Construction and Increased Sedimentation at Pelekane Bay, Hawai'i. PeerJ DOI 10.7717/peerj.300**.**

Abstract: Coral reefs are being critically impacted by anthropogenic processes throughout the world. Long term monitoring is essential to the understanding of coral reef response to human impacts and the effectiveness of corrective management efforts. Here we reevaluated a valuable coral reef baseline established in Pelekane Bay, Hawai'i during 1976 and subsequently resurveyed in 1996. During this time interval substantial impacts occurred followed by extensive corrective measures. Coral and fish communities showed dramatic declines from 1977 to 1996 due to massive harbor construction and suboptimal land management practices on the watershed. More recently, corrective measures in the form of watershed stabilization and fishing regulations have been implemented. Consequently our 2012 survey reveals that coral cover since 1996 has increased slightly accompanied by a significant increase in fish abundance, diversity, and evenness. This improvement can be attributed to lower fishing pressure since 1996 due to reduced shoreline access, tighter fishing regulations and increased monitoring of legal and illegal fishing activities. Stabilization of the coral community can be attributed partially to reduced sedimentation resulting from watershed restoration that included installation of sediment check dams, control of feral ungulates, controlled grazing and replanting of native vegetation. Insight into the mechanism that removes sediment from reefs was provided by a major storm event and a tsunami that remobilized and flushed out sediment deposits. The increase in herbivorous fishes probably played a role in reducing algal competition in favor of corals. The data suggest that the precipitous reef decline in this area has been arrested and offers support for the corrective actions previously undertaken.

Summary of Findings

Results show fish assemblage abundance, richness, and diversity in Pelekane Bay has improved over the past 16 years following a severe decline between 1976 and 1996. Our data also show an increased abundance of herbivores. This pattern is supported by results of a 2005 survey by U.S. National Park Service Inventory and Monitoring Program (Beets et al. 2010). Species composition has shifted relative to the 1976 survey but remains similar to that observed in 2005. Results of the present survey are also in agreement with the findings of DeMartini et al. (2013) who demonstrated a significant positive effect of improved habitat (lower sediment accumulation and greater availability of branching corals) on the density of juvenile parrotfishes (Fig. 1). The same pattern of increasing fish abundance along a gradient of improving habitat was shown in our study as well as the study by Beets et al. (2010).

This study showed stabilization and perhaps a slight increase in coral cover since 1996 following a substantial reduction between 1976 and 1996. The increase in herbivorous fishes has likely helped the coral population by reducing algal competition in favor of corals. Since 1996 there have been substantial changes at Pelekane Bay that may explain the increases in fish populations. A public county road that formerly ran along the coastline was realigned at a higher elevation in

1996 in order to restore the shoreline to conditions that existed at the time when the historic Puʻukoholā temple was dedicated. Removal of the road limited shoreline accessibility. New rules restricted camping to Spencer Beach Park at the south end of Pelekane Bay, which resulted in, lowered fishing pressure in the study area. In addition, a new NPS visitor information center was built in 2007. The visitor center is located close to the bay with an overlook complete with telescopes that allows for constant observation of the reefs by visitors and rangers. Rangers now conduct patrols along the shoreline as part of their duty. Access to Pelekane Bay from the harbor area to the north was further restricted in 2011 due to increased harbor security under the Homeland Security Program at Kawaihae Harbor following the terrorist attack of Sept. 11, 2001. The establishment of nearby marine protected areas designated by the State of Hawaiʻi in 1998 may also have contributed to the increase in fish populations. In select regions, the West Hawaiʻi Fisheries Management Areas (FMAs) and Fisheries Replenishment Areas (FRAs) were designed to limit high take methods of fishing, create fish reserves. Marine protected areas (MPAs) act as fish refuges with research demonstrating an increase in the number and size and connectivity within and between reserves (Friedlander et al. 2010). Areas adjacent to reserves benefit as fishes move in and out of the area and "spill-over" into nearby regions (Birkeland and Friedlander 2001). The "spill-over" effect was particularly significant for resource fishes including parrotfishes in Hawaiʻi (Stamoulis and Freidlander 2012). Although fishing is still permitted by law, Pelekane Bay has developed into a de facto marine protected area due to more limited access.

A seasonal effect among the three survey periods is most likely minimal relative to inter-annual differences in the overall fish abundance. For example, inter-annual variability of recruit abundance in Hawaiʻi is greater than the seasonal variability (Walsh 1987). Lunar differences in recruitment and spawning periodicity have been reported for several species in Hawaiʻi (Walsh 1987), but the three surveys used in the present analysis were conducted on multiple days with varying moon phases within each year. The potential effect of lunar phase on overall fish abundances were averaged and not biased towards new or full moon when recruitment and spawning are reported to occur for some species.

Results of the extensive studies by Storlazzi et al. (2013) and DeMartini et al. (2013) indicated that the turbidity, sediment cover and sediment accumulation rate are highest near the sediment source (stream mouth) and decrease on the reef with increasing distance from the stream mouth. Our study is in agreement with these observations. Biotic factors show an inverse relationship to this sediment pattern with the lowest rugosity, coral cover, coral richness, fish abundance, fish diversity, and evenness increasing with distance from the stream mouth. Pelekane Bay has a long history of chronic land-based influences including sedimentation and resuspension, which has affected coral reef recovery. Substantial sediment accumulation between 1928 and 2011 has occurred in Pelekane Bay (Storlazzi et al. 2013). Comparison of bathymetry over this time period revealed that 22,489 to 37,483 m-3 of sediment was deposited that resulted in a shoaling of 0.41 to 0.61 m during this time interval. Nevertheless natural resilience of reef ecosystems can facilitate recovery (Nyström and Folke 2000). Full recovery to pre-disturbance levels may be an extended process, requiring many more decades. Even though the reefs have been damaged, our data show that further decline can be stopped and recovery can begin once stressors are reduced. Such damaged reefs may be prime candidates for restoration activities because at this point on the degradation curve a slight improvement in the environment may result in a greater improvement in coral and fish assemblages than might be observed from similar restorative effort on a mildly stressed reef. Our conclusion is that watershed restoration projects, reduced fishing pressure, and increases in marine protected areas in adjacent regions have allowed for partial recovery of fish populations since the Tissot (1998) surveys.

The community structure of the Pelekane Bay reef over the past two centuries apparently has changed in a manner that results in tolerance resistance to severe impacts including storm events and land-based sedimentation. Results of this survey show that the Pelekane Bay reef has the ability to absorb severe disturbance while continuing to maintain functional capacities. Factors that can affect reef resilience include improved water and substrate quality (Wolanski et al. 2004), herbivore abundance, stable coral cover, and species and habitat diversity (McClanahan et al. 2012). These factors have all improved since the previous survey. Recent change in the reef community of Pelekane Bay exemplified the positive effects of an integrated approach of watershed management and acute wave disturbances on mitigating local human impacts. The long-term data set that now exists for Pelekane Bay will be valuable in the future for continued assessment of reef community response to environmental change and improved management strategies. Continued monitoring and expansion of the original dataset will allow evaluation of relationships between abiotic and biotic factors. These data can be used to examine ecological trends and patterns in response to human and natural impact.

c) Statewide Monitoring Efforts

Our continued efforts in documenting the changes on the reef in relation to changes on the watershed have culminated in a publication on long-term monitoring.

Rodgers KS, Jokiel PL, Brown EK, Hau S, and Russell Sparks R. 2014. Over a Decade of Change in Spatial and Temporal Dynamics in Hawaiian Coral Reef Communities. Pacific Science Early View.

Abstract: The Hawai‘i Coral Reef Assessment and Monitoring Program (CRAMP) was established in 1999 to describe spatial and temporal variation in Hawaiian coral reef communities in relation to natural and anthropogenic factors. In this study, we analyze changes over a 14 year period (1999 to 2012) based on data from 60 permanent reef stations at 30 sites in the main Hawaiian Islands. Overall mean statewide coral cover, richness, and diversity did not vary significantly since initial surveys, although local variations in coral cover trends were detected. The greatest proportion of stations with significant declines in coral cover was found on the island of Maui (0.40) while Hawai‘i Island had the highest proportion of stations with significant increases (0.58). Trends in coral cover at some stations varied over time due to acute (e.g. crown of thorns outbreak) and chronic (e.g. sedimentation) disturbances. Stations with increasing coral cover with the potential for recovery from disturbances were identified for possible management actions in the face of future climate change. The Hawaiian archipelago, located in the center of the subtropical Pacific, has experienced a temporary reprieve of slight cooling due to a downturn of temperature since 1998 at the end of the last cycle of the Pacific Decadal Oscillation (PDO). However, temperatures have been steadily increasing over the past several decades and models predict more severe bleaching events to increase in frequency and intensity in coming decades with concomitant decline in Hawaiian corals. Trends reported in this study provide a baseline that can later be used to test this predicted decline associated with future warming.

Summary of findings in the Pelekane/Kawaihae area

This study focused on station-specific trends since CRAMP was started in 1999 (Fig. 2). Identifying stations that are improving or stable despite perceived natural and anthropogenic variations will be crucial to direct management strategies in the face of future climate change. The main Hawaiian Islands occupy a unique geographic position in an area of the north-central Pacific that has escaped major bleaching events (Burke et al. 2011) as well as rapid sea level rise (Leuliette 2012) over the past decade. The long-term trend of increasing water temperature in Hawaiian waters, however, indicates that Hawaiʻi may not be buffered indefinitely from these climatic events. In addition, projected changes in the ocean chemistry due to ocean acidification will have profound effects on reef areas globally and in Hawaiʻi unless carbon emissions are reduced substantially (Hoegh-Guldberg et al. 2007). Consequently, it is imperative that reefs be identified that appear to be more resistant and/or resilient to these perturbations. Several of the stations in this study such as many of the shallow stations on Hawaiʻi Island appear to fit these criteria and could act as source populations.

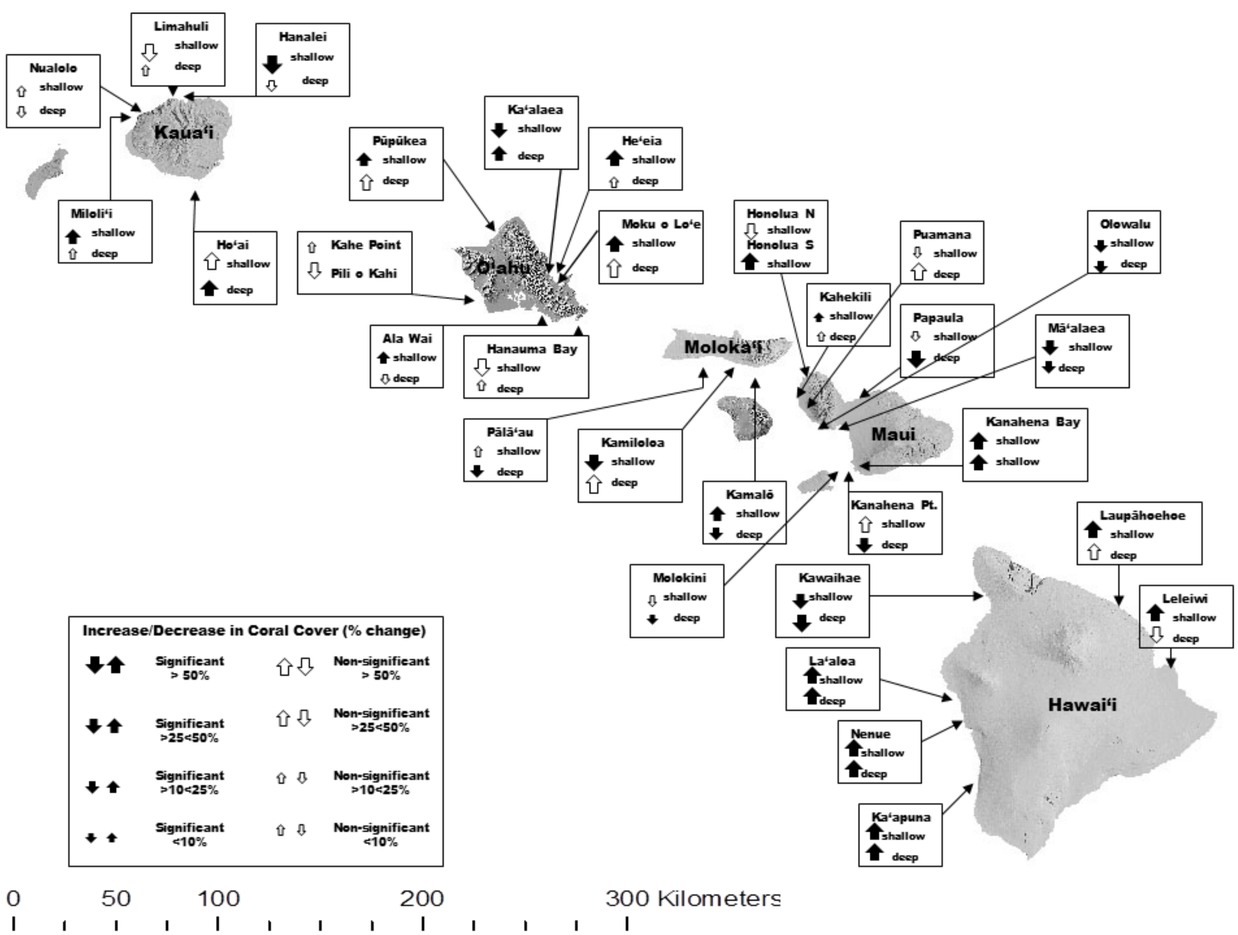

Figure 2. Map of CRAMP sites in the state of Hawaiʻi. Solid arrows indicate statistically significant trends. Size of arrows are correlated with the size of the change in coral cover. Direction of arrow indicates the direction of the change (up arrow shows increase).

Many stations on the island of Hawaiʻi experienced an overall increase in coral cover during the study period as indicated by the positive regression slopes in percent coral cover (Fig. 2). The exceptions were the two stations at Kawaihae along the northern section of the West Hawaiʻi coastline. These results are in agreement with data from the Division of Aquatic Resources (DAR) West Hawaiʻi Aquarium Project (WHAP) that has developed extensive spatial and temporal data coverage at 24 sites along the West Hawaiʻi coastline. WHAP results showed a significant decline in coral cover since 2003 at six of their seven northern sites that encompass the West Hawaiʻi coastline (Walsh et al. 2009). In addition, DAR and the Nature Conservancy found drastic declines in reef fishes and associated coral habitat when reviewing historical and recent data at sites near Kawaihae, West Hawaiʻi (Minton et al. 2012). Minton et al. (2012) found that contributing factors included a decrease in vegetation cover in the adjacent watersheds due to a reduction in rainfall over the past nine years that increased sediment deposition on nearshore reefs. Survey plots in the Pelekane Bay Watershed above the Kawaihae site also showed a decline in vegetation as drought conditions progressed (The Kohala Center 2011). Major sedimentation events occurred during periods of high rainfall (USGS 2006, 2013).

The 1999–2000 CRAMP baseline established reliable reference points to evaluate coral cover statewide over time. In addition, comparative studies at the onset (e.g. Brown 2004, Brown et al. 2004) enabled the program to examine earlier temporal data sets at a larger spatial than had been previously attempted. This present study documented the trends at individual stations and found similar levels of improving and declining reefs suggesting that overall statewide coral cover and diversity has remained relatively stable since the initial CRAMP survey. The key strategy will be focusing management efforts on the stations that have been declining in a chronic fashion. Even though many of these reefs may have already been in a degraded state when CRAMP was initiated, the current results will set a new baseline for assessing future declines and potential recovery at reefs targeted for management actions.

5.2 Objective (2): To understand the potential of the local marine ecosystem to recover.

a) Coral recruitment patterns along a sediment gradient

One of the best short-term indicators of environmental change and recovery is the pattern of coral recruitment in relation to land-derived sedimentation. Coral larvae and recruits are sensitive to sediment impacts and other anthropogenic changes in addition to natural variability. Larval production, settlement, and recruitment are crucial biological processes maintaining the population structures for the preservation of coral reefs. A major focus of this study is therefore quantifying coral settlement and environmental factors influencing coral recruitment to assess (1) early settlement patterns along environmental regimes, (2) how settlement rates may vary between years, and (3) how early settlement patterns may be related to characteristics of existing benthic habitat and community. This data will help establish information on early settlement patterns along environmental regimes, how settlement rates vary temporally, and how early settlement patterns may be related to characteristics of established communities.

Coral settlement and recruitment are crucial processes for long-term preservation and integrity of coral reef ecosystems. Successful settlement and recruitment depend upon habitat quality and environmental factors such as sedimentation, available light, salinity, temperature, substrate, surface rugosity, and current patterns. Early settlers and recruits are especially vulnerable to environmental degradation and unsuitable habitats impacted by human-induced processes. Reef habitat and water quality in Pelekane Bay has been subjected to major alteration and multiple stressors including human-induced changes in water circulation and land-based sedimentation. In our previous study, the greater number of early coral settlers was found on the offshore reef than on the inshore reef at where water is poorly circulated and murky near the stream mouth. Percentage of live tissue and growth rate of corals that are commonly found in Pelekane Bay also decreased closer to the stream mouth where water quality is not favorable. We repeated the coral settlement studies to better understand patterns of Hawaiian coral settlers, their response to human impacts and environmental conditions, and to continue monitoring as long-term information is essential to the effectiveness of corrective management effort in the South Kohala region.

Methods

The primary study area includes the Pelekane Bay and Kawaihae areas (Fig. 3). Eight stations were established at a mean depth of 1.5, 5, and 15 m. Six of these stations were established primarily in the vicinity of USGS geologic instrument locations deployed between the winter of 2010 and 2011 along the sediment gradient. These stations included five sampling sites within a radius of approximately 250 m from the instrument package. Two nearest stations to the shoreline included six and four sites. Ten of these 40 sites were established and surveyed by The Nature Conservancy in 2010. Sites were accessed from both shoreline and from a small vessel.

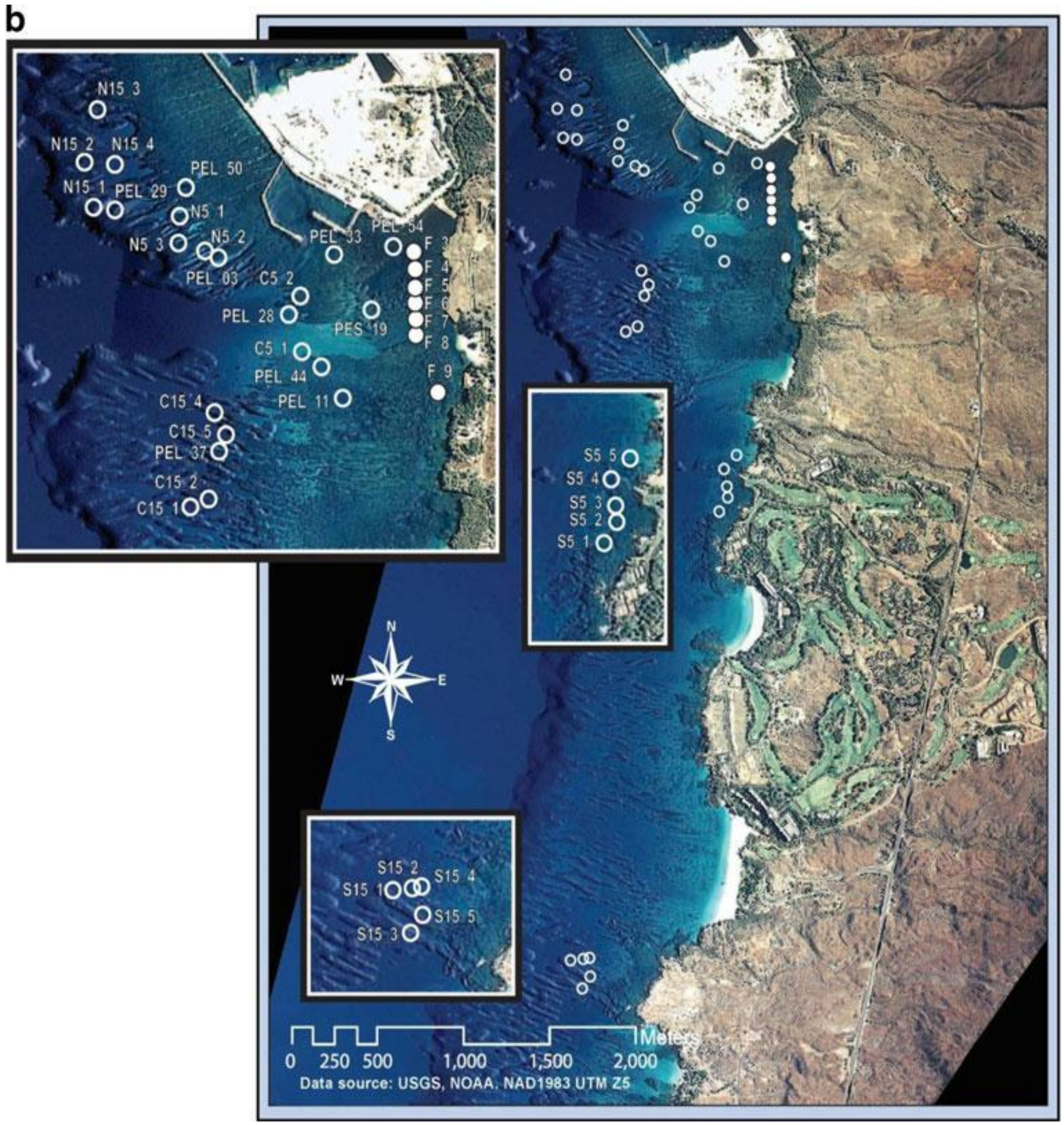

Figure 3. Map of sampling stations with detailed inset of stations within Pelekane Bay and Puakō where recruitment arrays were deployed, surveys conducted, and water quality measurements taken in 2011 and 2014.

Environmental Conditions

Sediment and water quality data were collected to define a gradient of habitat conditions upon the deployment and retrieval of settlement tiles in 2011 and again prior to and following tile deployment and removal in 2014. Water quality parameters collected in 2011 included pH, temperature, salinity (conductivity), dissolved oxygen and turbidity and Photosyntheically

Active Radiation (PAR), while PAR and turbidity were measured in 2014. Water quality parameters were measured with a multi-parameter meter YSI 6920 V2 SONDE at deployment sites above the sea floor during sample collection. PAR was measured using a portable light meter LI-COR LI-250A with an underwater quantum-sensor. Bulk sediment samples were collected manually for composition and grain size analysis at each deployment site if sediment was present. Additionally PAR and suspended solid concentration were measured at each of 37 sites in 2014. Two 1L-seawater samples were manually collected near the seafloor at each site in May and September, 2014. Samples were vacuum-filtered through pre-weighed Whatman 47mm GF/F 0.7μm glass microfiber filters immediately following sampling. Filters were then air-dried for at least a week and weighed on a Mettler Toledo X54035 microbalance on three separate days to obtain an average weight.

Coral Settlement

Settlement data were collected by using the following methods in 2011 and were replicated in the 2014 study. A set of two unglazed terracotta tiles (10 cm x 9.7 cm) was assembled and attached to a PVC post (Fig. 4). Recruitment arrays were deployed at 34 randomly selected sites stratified by depth (ranging between 1.5 and 15 m) and proximity from the stream mouth (Fig. 3) prior to the start of the summer reproductive season (June-August).

Figure 4. Unglazed terracotta tiles assembled in an array as a settlement platform at each of the 34 sampling stations.

Three arrays were placed at each sampling site along a 25-m transect in each year (n=204). To replicate the recruitment study in 2011, arrays were deployed in late April in 2014, and retrieved in September of 2014. Retrieved tiles were processed following Brown et al. (2007) to remove sediment and fleshy tissues of settled organisms by soaking tiles in 10% household bleach solution for 24 hours. Tiles were gently rinsed with flowing fresh water then air-dried for subsequent visual examination. Analysis of settlement tiles was conducted in the laboratory using a Carl Zeiss Stemi 2000-C stereomicroscope to determine the abundance of settlers and their positions on the plate surfaces. Individual coral settlers were counted and identified to genus level according to morphological characteristics of skeletons (Fig. 5). An individual was recorded as unidentified when its skeletal structure was not developed enough for positive identification. A settler, which did not follow the skeletal morphology of a known genus, was also recorded as an unidentified individual.

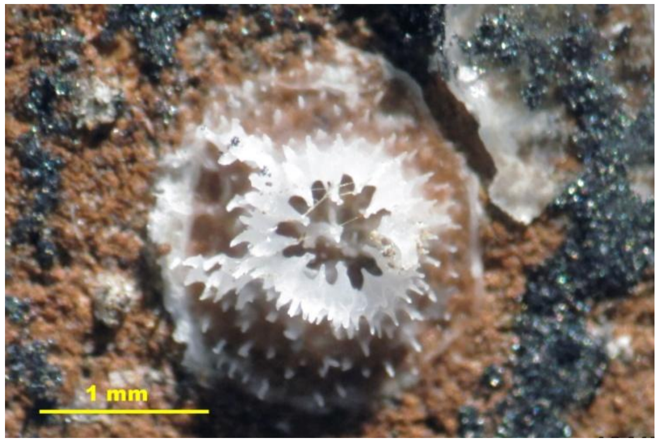

Figure 5. Coral recruit as seen under dissecting microscope.

Data Analysis

Data sets collected between 2010 and 2014 were integrated and analyzed for this study. A gradient of environmental conditions was characterized and established by use of a Principal Component Analysis (PCA) using a linear combination of correlated water quality and habitat metrics. Descriptive statistics of coral settlement were summarized using data from horizontally-oriented tile sets retrieved at 42 sites across years. Settlement data collected in 2011 and 2014 from 34 sites were statistically analyzed using a Generalized Linear Model (GLM) with the negative binomial distribution (Zuur et al. 2009) in R version 3.1.1. This was to examine the distribution pattern in relation to environmental conditions and variation between years, accounting for non-linearity and the appearance of frequent zeros in the count data. Performance of four non-linear statistical models, including a Poisson GLM (PGLM), Negative Binomial GLM (NBGLM), Zero-inflated Poisson mixture model (ZIP), and Zero-inflated NB mixture model (ZINB), were first compared to evaluate the assumption of no overdispersion (the variance and mean are equal for the Poisson distribution) and a relative importance of zero counts using values of the overdispersion parameters and Akaike Information Criterion (AIC). Settlement data from Puako (five sites of S15 in 2011 and three sites in 2014) were not included in the statistical tests as no associated environmental data for S15 sites were available and settlement arrays were either missing or had been rearranged. The spatial distribution of coral settlers was visually represented using ArcGIS 10.1.

Results

Environmental Conditions

The first three principle components explained about 77% of the variability among study sites. These sites were separated into two primary environmental regimes along the first principle component (PC1). Temperature, salinity, a light extinction coefficient, and depth were strongly correlated with PC1, which explained 43% of the variation in the environmental data collected at study sites. Temperature made the greatest contribution followed by salinity, light extinction coefficient, and depth. Turbidity, pH, and rugosity were correlated to the second principle component (PC2) accounting for 17% of the remaining variation. Turbidity was the greatest contributor in relation to PC2. Rugosity and pH correlated with the third component accounting for about 17% of the remaining variation. Sites located relatively close to the stream mouth were clustered while sites distant from the shoreline formed another cluster along PC1 and PC2. Shallow (< 2.5 m) inshore sites were generally characterized by warmer temperature, lower salinity, higher light extinction coefficient, higher turbidity, and lower pH than deeper (3-15 m) offshore sites. Sites were aggregated and will hereafter be referred as "inshore" and "offshore" sites (Table 1) based on this analysis for the remainder of this document.

Table 1. Primary sampling sites for coral settlement characterized by environmental types in Pelekane and Kawaihae area in 2011 and 2014. Geographic coordinates of sites are expressed in decimal degree (dd).

Site	Station	Environment	Latitude (dd)	Longitude (dd)
F3	C2	Inshore	20.02656	-155.82463
F4	C2	Inshore	20.02601	-155.82456
F5	C2	Inshore	20.02540	-155.82452
PEL_54	C2	Inshore	20.02673	-155.82540
PES_19	C2	Inshore	20.02432	-155.82522
PES_33	C2	Inshore	20.02647	-155.82748
F6	F	Inshore	20.02495	-155.82452
F7	F	Inshore	20.02445	-155.82447
F8	F	Inshore	20.02396	-155.82447
C15_1	C15	Offshore	20.01864	-155.83183
C15_2	C15	Offshore	20.01838	-155.83248
C15_4	C15	Offshore	20.02137	-155.83166
C15_5	C15	Offshore	20.02069	-155.83124
PEL_37	C15	Offshore	20.02016	-155.83146
C5_1	C5	Offshore	20.02335	-155.82859
C5_2	C5	Offshore	20.02453	-155.82906
PEL_11	C5	Offshore	20.02189	-155.82708
PEL_28	C5	Offshore	20.02512	-155.82868
PEL_44	C5	Offshore	20.02287	-155.82786
N15_1	N15	Offshore	20.02783	-155.83611
N15_2	N15	Offshore	20.02926	-155.83644
N15_3	N15	Offshore	20.03094	-155.83603
N15_4	N15	Offshore	20.02919	-155.83538
PEL_29	N15	Offshore	20.02775	-155.83534
N5_1	N5	Offshore	20.02761	-155.83302
N5_2	N5	Offshore	20.02654	-155.83209
N5_3	N5	Offshore	20.02628	-155.83160
PEL_03	N5	Offshore	20.02673	-155.83305

PEL_50	N5	Offshore	20.02853	-155.83280
S5_1	S5	Offshore	20.00961	-155.82716
S5_2	S5	Offshore	20.01034	-155.82672
S5_3	S5	Offshore	20.01084	-155.82675
S5_4	S5	Offshore	20.01171	-155.82694
S5_5	S5	Offshore	20.01241	-155.82624

Coral Settlement

Total number of coral settlement was 761 individuals across all existing sites between 2010, 2011, and 2014. About 75-85% of total coral settlement occurred on the bottom surface of lower tiles and edges of tiles in 2011 and 2014 across all sites (Fig. 6). In 2011 and 2014, predominant genus included Porites, Pocillopora, and Montipora. Poritids accounting for about 55 – 80% of total settlement in both inshore and offshore environments (Fig. 7).

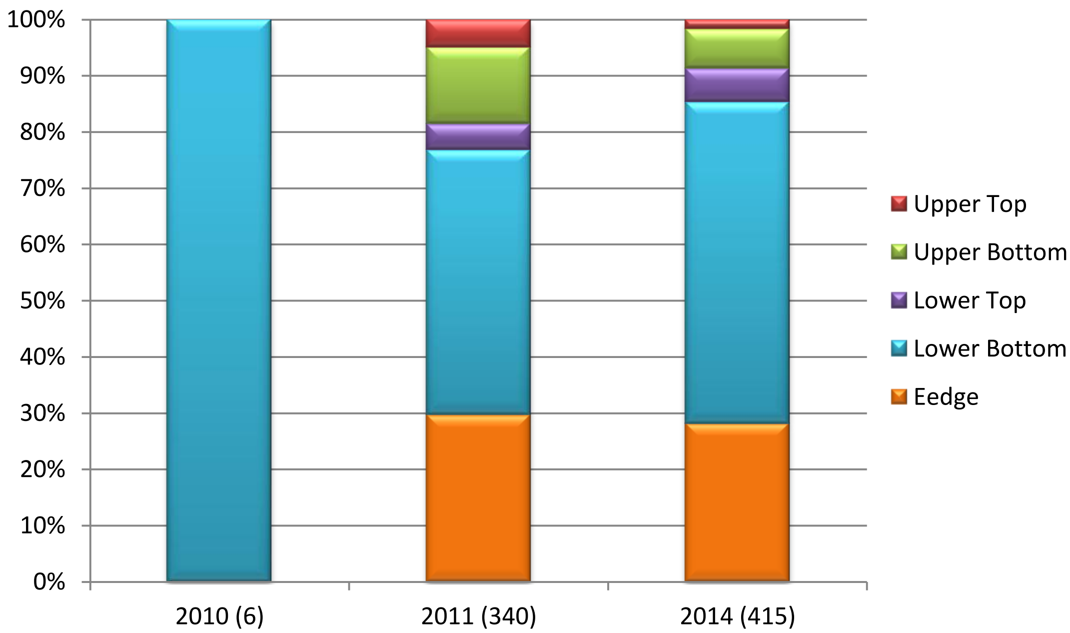

Figure 6. Proportion of settlers on different tile surfaces. Total number of settlers are indicated on the X axis in parentheses.

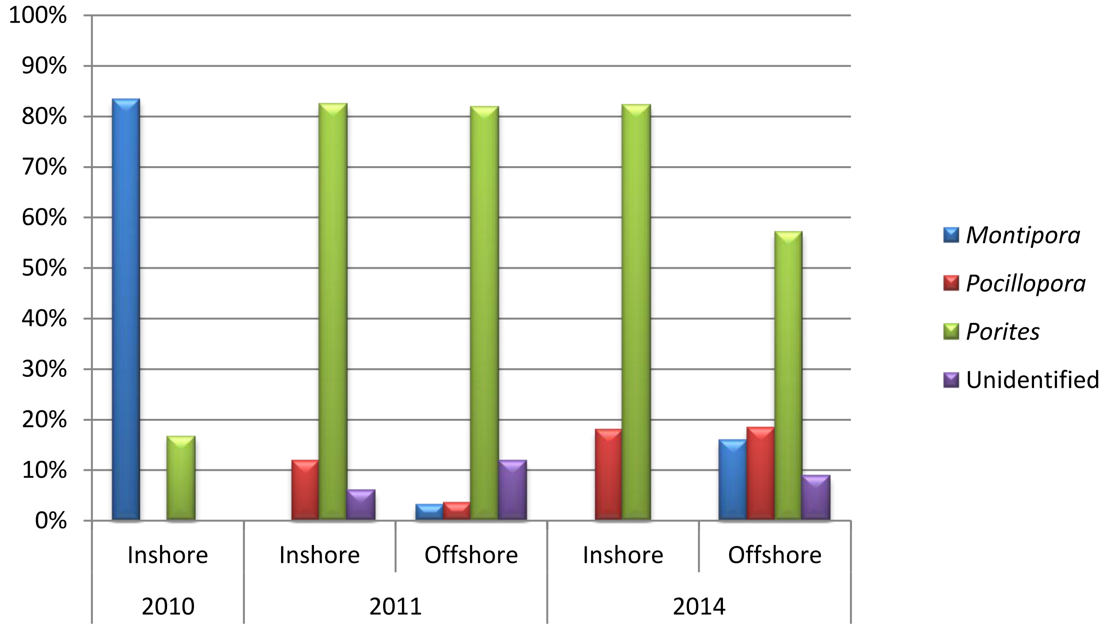

Figure 7. Proportion of settlers by genus, environment, and year.

Overall, the average coral settlement rate was 58.8 ± 62.9 s.d.m. $m^{-2}year^{-1}$ for the South Kohala region including Pelekane Bay, Kawaihae, and Puakō areas. Considerable differences in coral settlement were observed between inshore and offshore environments (Fig. 8) regardless of large Coefficient of Variation (Table 2). Total number of individuals and mean settlement were substantially less for inshore (51 and 14.3 $m^{-2}year^{-1}$) than offshore environment (710 and 78.3 $m^{-2}year^{-1}$). A small difference in total number of individuals and mean settlement was found between 2011 and 2014 (Table 3). Coefficient of Variation was similar between environmental conditions within a same year while there were some variations between 2011 and 2014 (Table 4).

Table 2. Descriptive statistics summary of coral settlement aggregated by environmental conditions. The unit of values is $m^{-2}year^{-1}$.

Environment	N	Total settlement	Min mean	Max mean	Grand Mean	CV (%)
Inshore	25	51	0.0	61.2	14.3	110
Offshore	57	710	0.0	251.7	78.3	84

Table 3. Descriptive statistics summary of coral settlement aggregated by year. The unit of values is $m^{-2}year^{-1}$.

Year	N	Total settlement	Min mean	Max mean	Grand Mean	CV (%)
2010	7	6	0.0	40.8	7.3	209

2011	39	340	0.0	251.7	52.2	123
2014	36	415	0.0	251.7	76.0	81

Table 4. Descriptive statistics summary of coral settlement aggregated by year and environmental conditions. The unit of values is m-^{2}yr-^{1}.

Year	Environment	N	Total settlement	Min mean	Max mean	Grand Mean	CV (%)
2010	Inshore	7	6	0.0	40.8	7.3	209
2011	Inshore	9	17	0.0	34.0	12.8	101
	Offshore	30	323	0.0	251.7	63.9	108
2014	Inshore	9	28	6.8	61.2	21.2	81
	Offshore	27	387	0.0	251.7	94.2	64

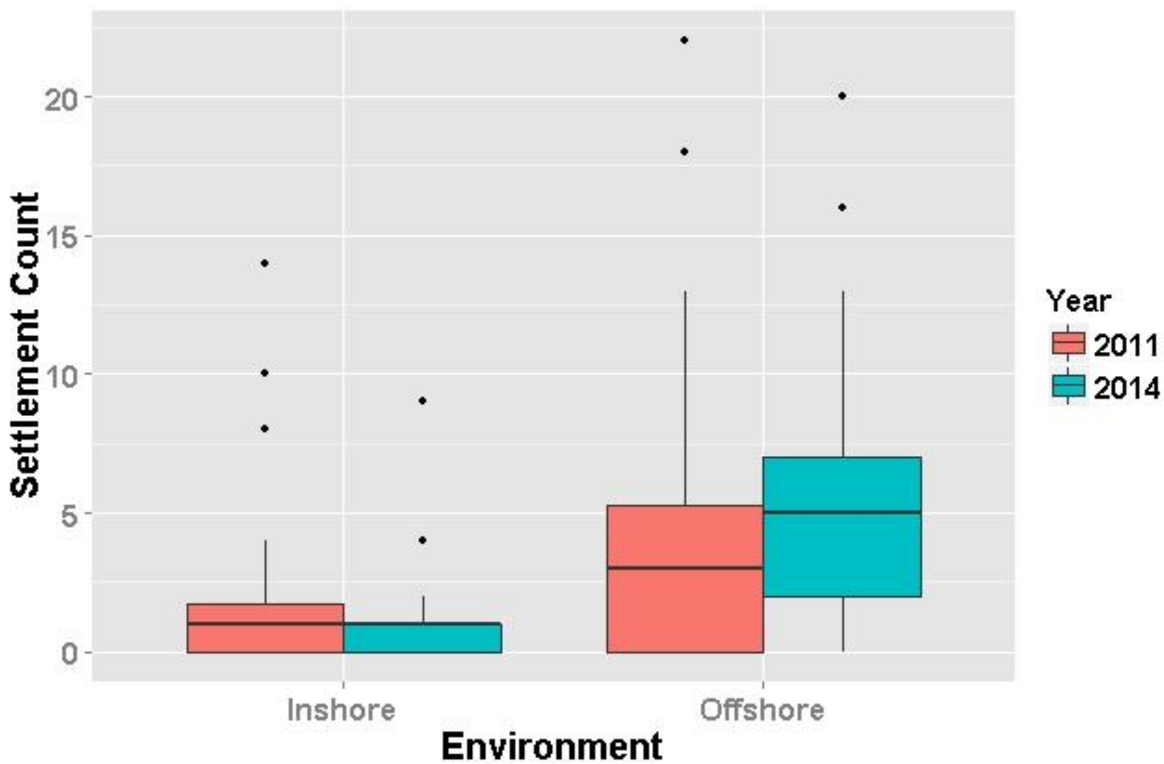

Figure 8. A boxplot of the average coral settlement count by environmental conditions and year.

While the Poisson Generalized Linear Model (PGLM) indicated a considerable overdispersion shown by the highest parameter value, a negative binomial Generalized Linear Model (NBGLM) resulted in the preferred model with the smallest Akaike Information Criterion (AIC) and overdispersion (Table 5). A likelihood ratio test also resulted in a preference of NBGLM (χ^2 = 280 (1), p < 0.0001) when compared to PGLM. Zero-inflated negative binomial Model (ZINB) indicated an improvement from Zero-inflated Poisson Model (ZIP), but did not show a substantial support for a high probability of excess zeros coming from the separate binomial distribution, different from a Poisson process. Effects of environmental regimes and year were then assessed based on NBGLM. While the effect of environmental regimes was statistically significant (χ^2 = 37.1 (1), $p < 0.0001$) the effect of year and interactions were not.

Table 5. Summary of AIC and overdispersion parameter values for a Poisson GLM (PGLM), Negative Binomial GLM (NBGLM), Zero-inflated Poisson mixture model (ZIP), and Zero-inflated NB mixture model (ZINB).

Model	AIC	Overdispersion
PGLM	1202	4.38
NBGLM	923	1.17
ZIP	1050	2.17
ZINB	923	1.24

Spatial distributions of coral settlement were similar among years 2010, 2011, and 2014 (Figs. 9, 10). Greater total settlement of individuals is observed for sites that are distant from the stream mouth than sites near a stream and away from the shoreline.

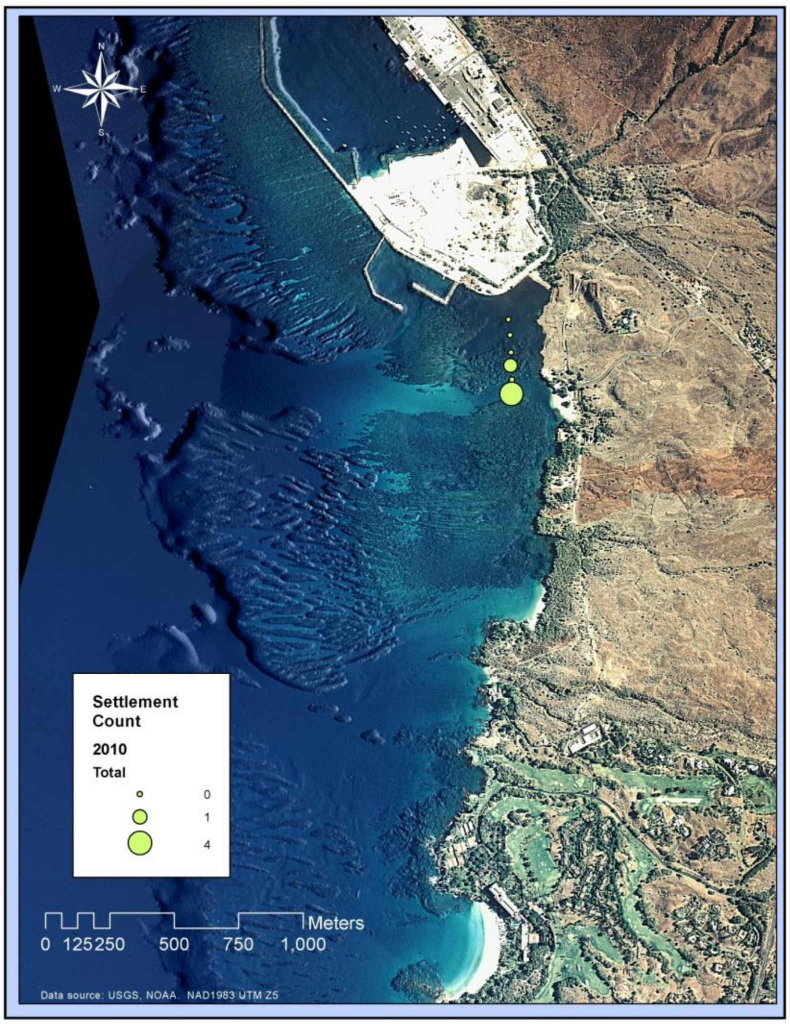

Figure 9. Total numbers of coral settlers at six sites in Pelekane Bay along a sediment gradient in 2010.

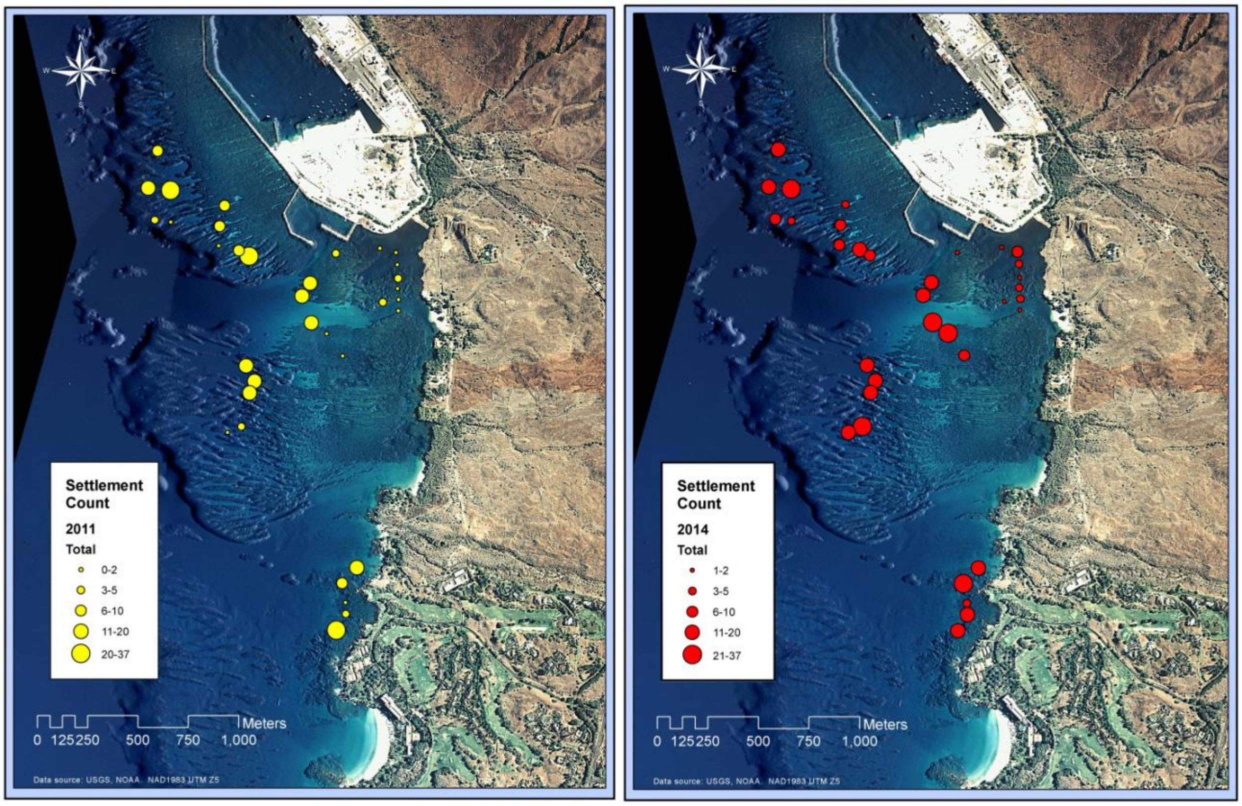

Figure 10. Total number of coral settlers at 34 sites in Kawaihae, Pelekane Bay, and Puakō in 2011 (left panel) and 2014 (right panel).

Results suggested that coral settlement is strongly affected by environmental conditions. On average, coral settlement is extremely lower in the inshore environment than the offshore environment. There is no large statistical variation between years. Although overall variability of coral settlement has been known to be typically high in time and space, there was a considerable difference between the abundance and distribution of settlers by environmental conditions and habitat characteristics.

The distribution pattern of coral settlement was comparable to the size-frequency distribution of *Porites lobate*, one of dominant species in Pelekane Bay and Kawaihae. The distribution of colony size was significantly related to surface turbidity values (Minton et al. 2011). Smaller colonies (0-5cm) were more frequent in less turbid surface water while larger colonies (5-80cm) were associated with greater turbidity (Minton et al. 2011). Colony size of *P. lobata* sampled further inshore attained >50 – 150cm (DeMartini et al. 2013). The turbidity is relatively high inshore, and can exceed a minimum value of turbidity by three orders of magnitudes (1.6 – 1525 NTU, USGS 2013) during the flood and large wave events. Although large colonies have been surviving with partial mortality in the turbid environment (DeMartini et al. 2013), very few coral settlements occurred under this condition during the present study. Survey sites with frequent small colonies coincided with settlement study sites in the offshore environment where greater settlement was observed. Observed small colonies in the offshore environment may include successful recruits of early coral settlers in addition to colonies established by asexual fragmentation and fission.

The range and average recruitment rate of the present study was similar to reported values for Waiakailio Bay and Puakō in Martin and Walsh (2014). These two DAR monitoring sites are positioned north and south of Pelekane Bay and Kawaihae. Average recruitment rates were substantially higher at Waiakailio Bay and Puakō when compared to seven other southern locations along the West Hawai‘i coast, therefore recruitment rates for Pelekane and Kawaihae should be high as well. Topography of Pelekane and Kawaihae is relatively complex, characterized by basalt pavement and rock. Fossil finger coral beds and other calcified structures on the geologic foundation provide abundance of suitable micro habitat for coral settlement. Episodic large waves observed in this area help clear accumulated sediment. Coral reef recovery is potentially rapid if sediment sources are controlled with improvements to inshore hydrodynamics.

b) Low levels of sediment can block coral recruitment

Fine red terrigenous sediments as are found in Pelekane Bay (Fig. 11) were used in laboratory experiments to determine settlement and survival rates of the Hawaiian coral *Pocillopora damicornis* planulae. These results were revisited and published in the peer reviewed journal PeerJ to better understand sediment patterns in the Pelekane area.

K. Perez III, K.S. Rodgers, P. L. Jokiel, C. Lager, D. Lager. 2014. Effects of terrigenous sediment on settlement and survival of the reef coral *Pocillopora damicornis*. PeerJ 2:e387; DOI 10.7717/peerj.387.

Abstract: Survival and settlement of *Pocillopora damicornis* larvae on hard surfaces covered with fine (<63 µm) terrigenous red clay was measured in laboratory Petri dishes. The dishes were prepared with sediment films of various thicknesses covering the bottoms. Coral larvae were incubated in the dishes for two weeks and the percent that settled on the bottom was determined. There was a statistically significant relationship between the amount of sediment and coral recruitment on the bottom, with no recruitment on surfaces having a sediment cover above 0.9 mg cm^{-2}. Experimental conditions for the delicate coral larvae were favorable in these experiments. Total survival over the two week settlement tests expressed as the sum of coral recruits and live larvae at the end of the experiment did not show a significant decline, so the major impact of the sediment was on successful settlement rather than on mortality. Larval substrate selection behavior was the primary factor in the observed result.

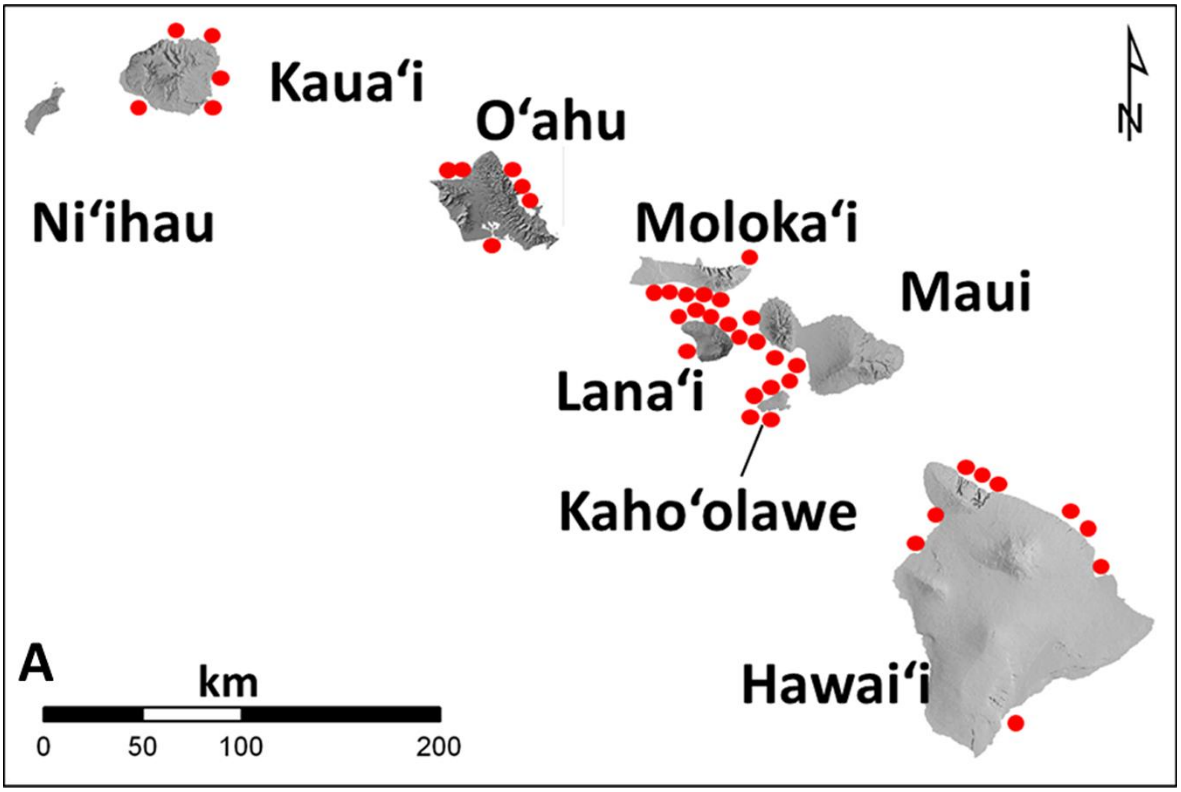

Figure 11. A. Map of the main Hawaiian Islands showing areas with heavy red mud deposits including Pelekane Bay in West Hawaiʻi.

Findings: Our laboratory results should be used with caution in applying the results to field situations. However, the value of this research is that it shows that an extremely thin film can block recruitment. For further details see Appendix IV.
In summary, the results of the present investigation support and amplify the findings of previous investigations:

• Although a variety of settling cues have been shown, it is possible that a thin film of sediment can override these cues blocking larval settlement.

• Recruitment rate of larvae in sediment experiments is very low. Te (1992) recorded 2% to 3% settlement of *Pocillopora damicornis* larvae over a two week period. Babcock & Davies (1991) report a mean of only 15% settlement in a two day experiment using larvae of the coral *Acropora millipora*.

• Larval behavior is an important factor in determining settling success and survival. Larvae will seek a suitable settlement site (Harrigan, 1972) and will find areas that are free of sediment. Hodgson (1991) conducted larvae settlement experiments on *P. damicornis* on glass plates with sediment layers of 0 to 500 mg cm^{-2}, but the sediment covering the glass settling plates was not uniform, having some areas clear of sediment. The corals were able to find and settle in open areas not covered with sediment.

• A relatively thin uniform coating of land-derived sediment can prevent coral recruitment. Hodgson (1991) reports a larval settlement threshold for *P. damicornis* of 536 mg/cm–^{2} over patchy horizontal surfaces that blocked 95% of coral settlements. Results of this study refine this cutoff to a lower value of 1 mg/cm–^{2}, for a uniform sediment film of fine muds.

c) Corals can survive and grow in highly turbid areas

Manipulative field experiments were conducted along a sediment gradient to determine how corals are affected. This research relates to recovery of marine ecosystems throughout the Hawaiian Islands. For more detailed information see Appendix V.

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 https://dx.doi.org/10.7717/peerj.699

Abstract: A long-term (10 month exposure) experiment on effects of suspended sediment on the mortality, growth, and recruitment of the reef corals *Montipora capitata* and *Porites compressa* was conducted on the shallow reef flat off south Moloka□i, Hawai□i. Corals were grown on wire platforms with attached coral recruitment tiles along a suspended solid concentration (SSC) gradient that ranged from 37 mg l−1 (inshore) to 3 mg l−1 (offshore). Natural coral reef development on the reef flat is limited to areas with SSCs less than 10 mg l−1 as previously suggested in the scientific literature. However, the experimental corals held at much higher levels of turbidity showed surprisingly good survivorship and growth. High SSCs encountered on the reef flat reduced coral recruitment by one to three orders of magnitude compared to other sites throughout Hawai□i. There was a significant correlation between the biomass of macroalgae attached to the wire growth platforms at the end of the experiment and percentage of the corals showing mortality. We conclude that lack of suitable hard substrate, macroalgal competition, and blockage of recruitment on available substratum are major factors accounting for the low natural coral coverage in areas of high turbidity. The direct impact of high turbidity on growth and mortality is of lesser importance.

Findings:

- At the end of a 10 month growth period it was apparent that the growth platforms had recruited different amounts of macroalgae. All macroalgae was removed from each platform, rinsed dried and an ash-free dry weight was determined. When total coral mortality plus partial mortality is plotted against macroalgae dry weight a significant relationship is revealed. Therefore a large amount of the mortality observed in this experiment can be attributed to competition with macroalgae rather than sediment effect.
- Likewise, coral growth was quite good in spite high turbidity. Growth was excellent in the sites at Kamiloloa that were farthest offshore.
- Coral growth at Transect H (Kamiloloa) showed a strong relationship with increasing distance from shore while transect E (Kawela) did not show a strong trend.
- Measures of coral recruitment produced the greatest surprise, with levels of coral recruitment one to three orders of magnitude lower than other reefs measured with the same technique at locations throughout the Hawaiian Islands. This result is explained by

the dramatic impact of thin layers of fine red sediment on coral larval settlement recently documented by Perez et al. (2014).

Our research on sediment levels that can block coral recruitment is highly relevant to conditions at Pelekane Bay. A thin film of sediment was shown to block coral settlement of *Pocillopora damicornis* larvae. Fine muds as were used in this experiment are found throughout Pelekane Bay's benthic habitat. This prevents coral recruits from establishing. However, the large colonies previously established are continuing to survive and grow even under these turbid conditions as were documented in our south Moloka'i study. The levels of fine sediment at Pelekane are comparable to those in south Moloka'i (Rodgers 2005). Although survivorship and growth are negatively correlated with sediment levels, increasing along a sediment gradient, corals can still survive in highly turbid waters as exist in Pelekane Bay.

5.3 Objective 3): To understand the potential threat that existing mud deposits pose to adjacent, relatively pristine coral reef ecosystems.

a) Quantification of fish community factors

Fish biomass and abundance were quantified for 57 observations (34 inshore and 23 offshore environments) to characterize the assemblage using the standard visual belt transect approach (Brock 1954; Brock 1982). A diver swam along two to five 25 m x 5 m transects (125 m^2) at each site. Species, quantity, and total length of fishes were recorded. All fishes were identified to the lowest taxon possible. The same individual quantified fishes for all samples to eliminate observer variability. Total length (TL) of fish was estimated to the nearest centimeter in the field. The estimated length was converted to biomass density estimates, metric tons per hectare (t ha^{-1}), with length-mass fitting parameters. Length estimates were converted to mass using estimated fitting parameters available from the Hawai'i Cooperative Fishery Research Unit (HCFRU) or FishBase (www.fishbase.org). If a specific fitting parameter is not available, a congener of similar shape within the genus was used.

Table 6 summarizes overall means and the Coefficient of Variation by environmental regimes. While mean biomass, abundance, and species richness were lower for inshore than the offshore environment, a variation was high within each environmental condition. Total biomass of reef fishes was found to be greater at offshore sites (809 g/m^{-2}) among 16 families than inshore environments (350 g/m^{-2}) among 19 families (Table 7). Acanthurids accounted for the highest total biomass for both inshore and offshore sites. Acanthuridae, Labridae, Mullidae, Scaridae, and Lutjanidae consisted about 85% of total biomass for inshore. About 88% of total biomass included Acanthridae, Labridae, Scaridae, Serranidae, and Lethrinidae, which includes a single species, *Monotaxis grandoculis*, in Hawai'i, in the offshore environment.

Table 6. Overall means and Coefficient of Variation by environment.

	Biomass		Abundance		Richness	
Environment	Mean	CV (%)	Mean	CV (%)	Richness	CV (%)
Inshore	11.3	99.2	64.9	84.0	12.5	39.5
Offshore	33.7	80.6	84.3	49.7	13.5	24.6

Table 7. Total biomass, means of total biomass, and Coefficient of Variation of fish by family. The sample size (n) indicates the number of transects for observed families.

Environment	Family	Total biomass (g/m^{-2})	Mean	CV (%)	n
Inshore	Acanthuridae	135.7	4.1	82.8	33
	Blenniidae	0	0.0	NA	3
	Carangidae	8.7	1.5	97.3	6
	Chaetodontidae	14.1	1.3	54.1	20
	Gobiidae	0	0.0	NA	23
	Holocentridae	0.9	0.3	66.7	3
	Labridae	35.8	1.1	91.8	33
	Lutjanidae	19.7	1.2	80.4	17
	Mugilidae	1.2	1.2	NA	1
	Mullidae	40.1	1.8	166.9	22
	Ostraciidae	0.3	0.0	222.7	17
	Pomacentridae	17.8	0.5	200.4	33
	Scaridae	66.1	2.3	155.2	29
	Serranidae	9.4	4.7	51.2	2
	Synodontidae	0.3	0.2	47.1	2
	Tetraodontidae	0.1	0.1	NA	1
Sub total		350.2			
Offshore	Acanthuridae	319.5	13.9	79.3	23
	Aulostomidae	0	0.0	NA	1
	Balistidae	11.8	1.5	63.0	8
	Blenniidae	0	0.0	NA	2
	Chaetodontidae	35.2	2.0	91.5	18
	Cirrhitidae	4.4	0.4	66.1	12
	Labridae	105.5	4.6	58.9	23
	Lethrinidae	114.8	114.8	NA	1
	Lutjanidae	0.6	0.6	NA	1
	Monacanthidae	4	4.0	NA	1
	Mullidae	28.5	1.7	69.5	17
	Ostraciidae	0.1	0.1	141.4	2
	Pomacanthidae	1.7	2.0	NA	5
	Pomacentridae	12	0.7	122.6	18
	Scaridae	84.4	5.3	172.0	16
	Serranidae	83.8	10.5	80.2	8
	Synodontidae	0.6	0.6	NA	1
	Tetraodontidae	0.6	0.2	86.6	3
	Zanclidae	1.2	1.2	NA	1
Sub total		808.7			

Grand total	1158.9

The total number of individual reef fishes was found to be greater offshore (2177) than inshore (1969) (Table 8). Scarids accounted for the highest number of individuals inshore while Labrids were the most abundant offshore (Table 8). Acanthuridae, Labridae, Mullidae, Scaridae, and Pomacentridae consisted about 91% of the total number of individuals inshore. About 93% of the total number of individuals included species from the Acanthridae, Chaetodontidae, Labridae, Pomacentridae, and Scaridae offshore.

Table 8. Total abundance. Means of total biomass, and Coefficient of Variation of fish by family. The sample size (n) indicates the number of transects conducted.

Environment	Family	Total abundance	Mean	CV (%)	n
Inshore	Acanthuridae	534	16.2	82.1	33
	Blenniidae	3	1.0	0.0	3
	Carangidae	11	1.8	63.8	6
	Chaetodontidae	45	4.3	43.4	20
	Gobiidae	72	3.1	85.8	23
	Holocentridae	3	1.0	0.0	3
	Labridae	452	13.7	84.3	33
	Lutjanidae	34	2.0	86.6	17
	Mugilidae	1	1.0	NA	1
	Mullidae	87	4.0	171.2	22
	Ostraciidae	21	1.2	45.5	17
	Pomacentridae	258	7.8	80.5	33
	Scaridae	651	22.4	99.7	29
	Serranidae	2	1.0	0.0	2
	Synodontidae	2	1.0	0.0	2
	Tetraodontidae	1	1.0	NA	1
Sub total		2177			
Offshore	Acanthuridae	1010	43.9	74.9	23
	Aulostomidae	2	2.0	NA	1
	Balistidae	9	1.1	31.4	8
	Blenniidae	2	1.0	0.0	2
	Chaetodontidae	56	3.1	57.2	18
	Cirrhitidae	26	2.2	61.7	12
	Labridae	514	22.3	62.2	23
	Lethrinidae	22	22.0	NA	1
	Lutjanidae	1	1.0	NA	1
	Monacanthidae	1	1.0	NA	1
	Mullidae	42	2.5	68.8	17
	Ostraciidae	2	1.0	95.7	2

	Pomacanthidae	7	1.4	39.1	5
	Pomacentridae	140	7.8	94.8	18
	Scaridae	115	7.2	124.8	16
	Serranidae	13	1.6	45.8	8
	Synodontidae	1	1.0	NA	1
	Tetraodontidae	5	1.7	69.3	3
	Zanclidae	1	1.0	NA	1
Sub total		1969			
Grand total		4146			

There were total of 76 species observed on all transects, and 28 of those species were present in both inshore and offshore environments. Table 9 and 10 summarize the 10 highest ranking species of fishes in total biomass and abundance inshore and offshore.

Table 9. Top 10 ranking fish species for total biomass ($g*m^{-2}$) in inshore and offshore environments.

Rank	Inshore	Offshore
1	*Acanthurus nigrofuscus*	*Acanthurus nigrofuscus*
2	*Chlorurus spilurus*	*Monotaxis grandoculis*
3	*Mulloidichthys flavolineatus*	*Cephalopholis argus*
4	*Thalassoma duperrey*	*Thalassoma duperrey*
5	*Lutjanus fulvus*	*Chlorurus spilurus*
6	*Cephalopholis argus*	*Ctenochaetus strigosus*
7	*Abudefduf abdominalis*	*Acanthurus olivaceus*
8	*Caranx melampygus*	*Acanthurus blochii*
9	*Naso lituratus*	*Chaetodon ornatissimus*
10	*Parupeneus multifasciatus*	*Acanthurus leucopareius*

Table 10. Top 10 ranking fish species for total number of individuals in inshore and offshore environments.

Rank	Inshore	Offshore
1	*Chlorurus spilurus*	*Acanthurus nigrofuscus*
2	*Acanthurus nigrofuscus*	*Thalassoma duperrey*
3	*Thalassoma duperrey*	*Ctenochaetus strigosus*
4	*Abudefduf abdominalis*	*Chlorurus spilurus*
5	*Scarus psittacus*	*Chromis vanderbilti*
6	*Gomphosus varius*	*Gomphosus varius*
7	*Gobiidae* spp.	*Oxycheilinus unifasciatus*
8	*Mulloidichthys flavolineatus*	*Stegastes marginatus*

9	*Acanthurus triostegus*	*Acanthurus blochii*
10	*Stethojulis balteata*	*Paracirrhites arcatus*

Four species were commonly shared between inshore and offshore environment within the 10 highest ranking species for both total biomass and total number of individuals. The five most frequently occurring species inshore were *Thalassoma duperrey, Acanthurus nigrofuscus, Abudefduf abdominalis, Chlorurus spilurus,* and *Scarus psittacus*, and *Thalassoma duperrey, Acanthurus nigrofuscus, Ctenochaetus strigosus, Gomphosus varius*, and *Oxycheilinus unifasciatus* in the offshore environment. While *Monotaxis grandoculis* ranked second highest for total biomass in the offshore environment, it was an uncommon transient species. Fish biomass and abundance are highly variable making the impact of land-based sedimentation on the offshore reef fish community difficult to evaluate.

b) Water Quality Analyses to Characterize Environmental Regimes

The relative difference in the extent of sedimentation and water quality was reevaluated during field operations between late April and early May 2014, incorporating water quality data collected in 2011. Water chemistry parameters were measured to characterize environmental regimes in Pelekane Bay using a multi-parameter water quality meter and data logger at the time of recruitment array deployment. Environmental variables measured at each station included temperature, pH, salinity, turbidity, and photosynthetic active radiance (PAR) at deployment sites above the sea floor during sample collection. The light extinction coefficient was calculated using PAR and depth values.

Table 11 summarizes medians and the inter quartile range of water quality variables. There were numerical differences in median temperature and salinity between inshore and offshore environments. Turbidity was highly variable inshore while it was relatively consistent in the offshore environment.

Table 11. Summary of medians for water quality variables by environmental conditions. n= number of sites. Values in parentheses indicate the inter quartile range.

Environment	n	Temperature (˚C)	Salinity (ppt)	Turbidity (NTU)	pH
Inshore	10	27.21(1.67)	34.09(0.4)	1.06(0.99)	8.17(0.13)
Offshore	25	25.36(0.30)	34.99(0.11)	0.01(0.23)	8.21(0.07)

Relatively high values of the light extinction coefficient were found in the inshore environment in both the spring and fall seasons (Fig. 12). The light extinction coefficients were more highly variable for inshore sites than across depths (3 m and 15 m) (Fig. 13). Ranges of the coefficients were distinct between inshore and offshore environments with overlap across years.

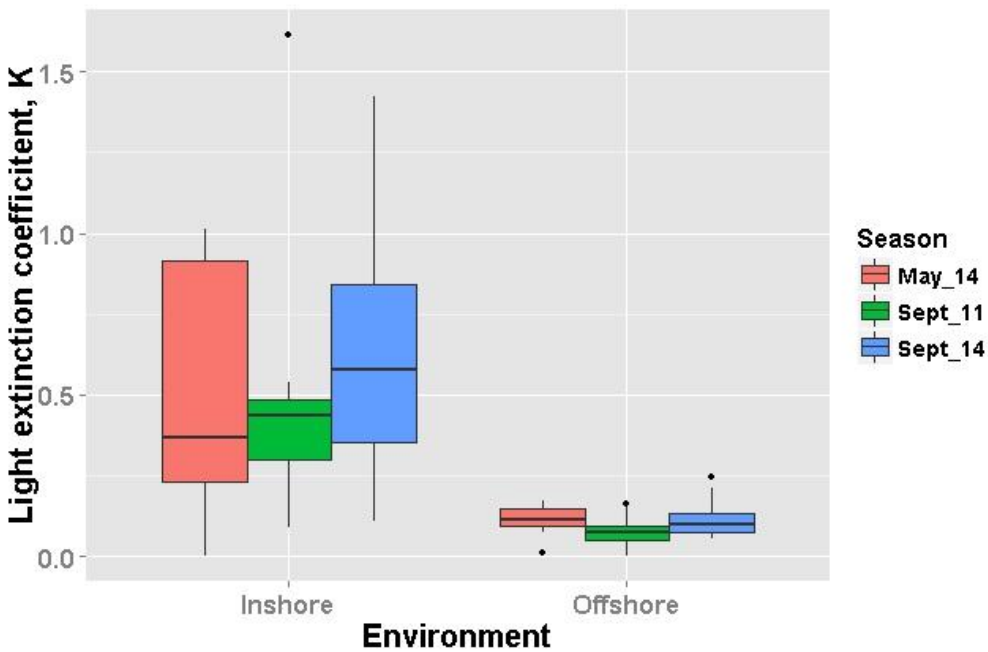

Figure12. Variations in the light extinction coefficient by environmental regimes (inshore vs. offshore).

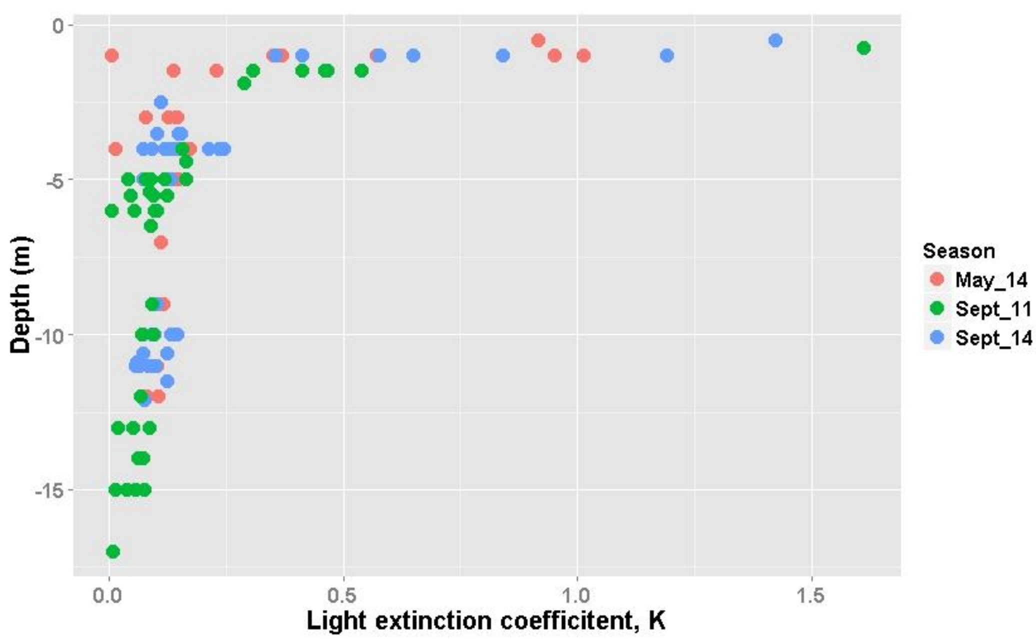

Figure 13. Distribution of the light extinction coefficient along depth.

Median Suspended solids concentration (SSC) is slightly lower offshore than inshore (Figure 14) with high variability.

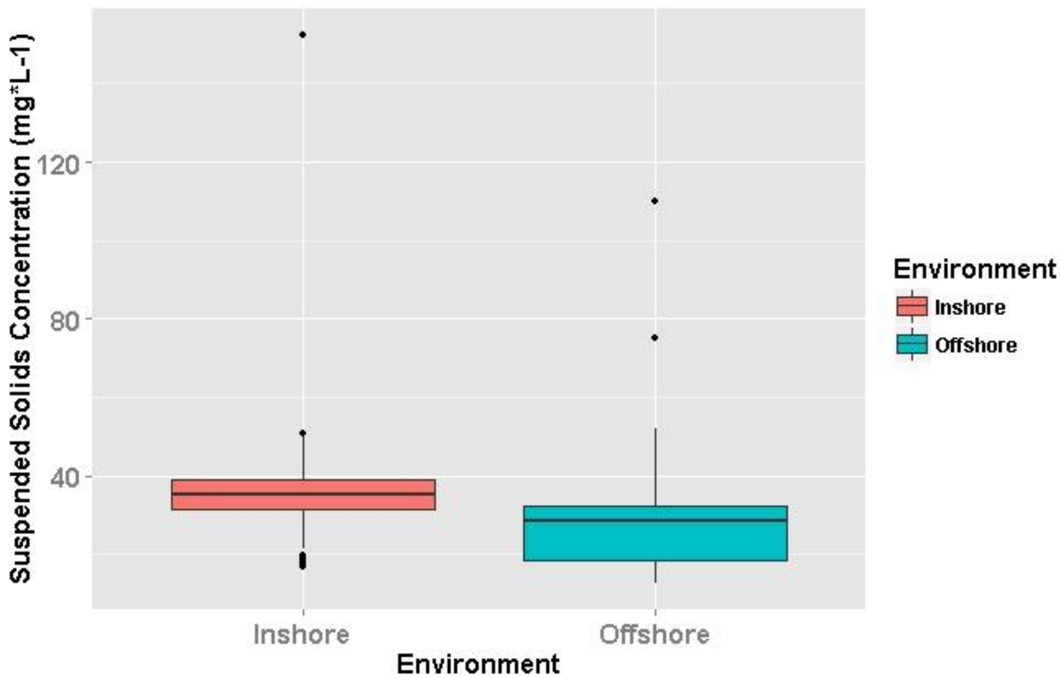

Figure 14. Suspended solids concentration by environment.

SSC appeared to be numerically lower in March and April than in June and Spring months across years. (Figure 15, Table 9).

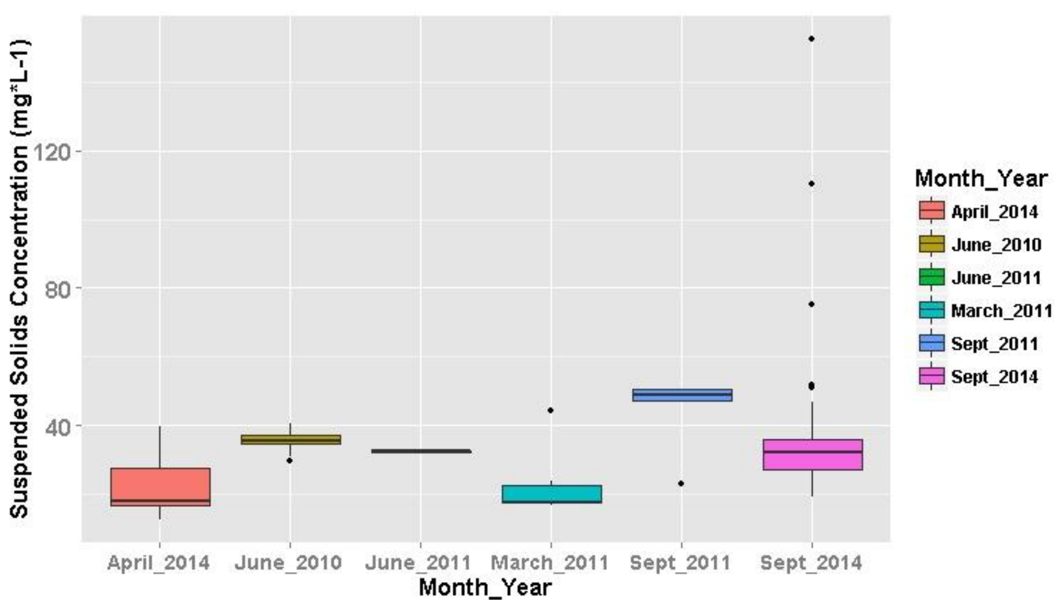

Fig. 15. Suspended solids concentration by month and year.

Table 12. Suspended Solid Concentration ($mg*L^{-1}$) by Season and Environment. N = number of sampling sites, Geometric s.d.m. = Geometric standard deviation; IQR = Inter quartile range.

Month_Year	Environment	N	Geometric mean	Geometric s.d.m.	Median	IQR
June_2010	Inshore	23	35.5	1.1	35.4	3.1
June_2011	Inshore	2	32.5	1.0	32.5	1.0
March_2011	Inshore	4	23.9	1.5	20.9	16.5
March_2011	Offshore	2	17.1	1.0	17.2	0.5
April_2014	Inshore	13	24.5	1.4	19.8	18.6
April_2014	Offshore	30	19.3	1.3	17.8	2.7
Sept_2011	Inshore	6	43.4	1.4	49.1	3.5
Sept_2014	Inshore	18	38.8	1.5	37.2	7.0
Sept_2014	Offshore	58	31.0	1.4	31.2	9.7

While there was no substantial difference in median SCC values between inshore and offshore in 2014, colors of sample filters indicated different types of suspended materials. Colors of filtered inshore samples were dark brown, indicating that suspended matter included terrigenous silt. Colors of filtered offshore samples were very pale, translucent, or clear, indicating absence of substantial amounts of silt. Suspended materials such as colloids, flocculent organic particulates and plankton likely comprised the mass of filtered offshore samples. Visual assessment of sediment samples collected during spring and fall 2014 from settlement sites suggested no substantial change in composition. The spatial extent of terrigenous mud observed during field sampling in 2014 was similar to the field assessment in 2011 and 2012. The extent of terrigenous sediment was limited to the inshore environment while carbonate sediment predominated offshore. Results of water quality analysis and field assessment suggest no substantial change in offshore water quality since 2010. Moreover, greater observed coral settlement offshore remained steady across years suggesting no immediate threat from land-based sedimentation. The potential threat from existing mud deposits adjacent to coral reefs in excellent condition appears to be minimal.

c) Benthic Habitat Map Updates

We are collaborating with the NOAA Coral Reef Ecosystem Division to update benthic habitat maps including shallow reefs in the South Kohala region. We have provided benthic imagery data from our study sites to NOAA, maps have been generated, and data are currently being analyzed.

6. Discussion

The data analyzed suggests that the precipitous reef decline in the Pelekane area has been arrested. This success offers support for actions of various local management initiatives involving fishing regulations and watershed stabilization. This long-term data set will be valuable in the future for assessing changes in biota in response to environmental change and management strategies. Continued monitoring and expansion of the original dataset allows evaluation of relationships between abiotic and biotic factors. These data can be used to examine ecological trends and patterns in response to human and natural impact. The research conducted on impacts of sedimentation on Hawaiian corals can assist in planning management strategies based on sound scientific findings.

7. Key Findings

- The existing and new data analyzed suggests changes in reef communities occurred in the last 30 years in the Pelekane area.
- Reef fish abundance and diversity increased since 1996.
- Decline of live coral cover has stabilized since 1996 following a substantial reduction between 1976 and 1996.
- Coral settlement was substantially lower inshore where there is more impact by sedimentation than at offshore reefs in both 2011 and 2014.
- No strong temporal variation was observed in coral settlement between years.
- Recent episodic seasonal large wave events demonstrate that natural processes remove accumulated sediment deposits on coral reefs to deeper offshore waters.
- Threats from mud deposits to offshore reefs that will affect habitat quality are minimal.
- Although a variety of settling cues have been shown, it is possible that a thin film of sediment can override these cues, blocking larval settlement.
- A uniform sediment film of fine muds as low as 1 mg/cm^{-2} can block recruitment.

8. Project Evaluation

Outputs (products) and Outcomes.

We produced an evaluation of past, present and projected future condition of the coral reefs of Pelekane Bay. We focused on the best short-term indicator of environmental change, which is the pattern of coral recruitment in relation to land-derived sedimentation. We measured coral recruitment during 2010-2011 and 2014 along a sediment gradient in Pelekane Bay. Although coral recruitment is highly variable from year to year the pattern of recruitment can be a good indicator of recovery. This study was directed at patterns of coral recruitment along environmental gradients in relation to coral and fish communities, in reference to a historical, sedimentation, and water quality data, however, other research surrounding sedimentation were explored. Changes on the reef in relation to changes on the watershed were evaluated. During June 2012 we successfully resurveyed the Pelekane transects (Ball 1977, Cheney et al 1977, Tissot 1998) to give us insight into changes over the past 35 years. Manipulative experiments on the impact of sediment on inshore reefs and larval settlement were conducted.

Evaluation of Success

As researchers our long term criteria of success is publication in peer reviewed journals (see citations below) followed by citation of our work. In the short term we can evaluate success by completion of the tasks, production of a final report, evaluation of the interest of managers and scientists to the project (e.g. inclusion in the State of the Reef Reports), outreach venues, successful training of a Ph.D. candidate (Ms. Yuko Stender) who will use this study as a basis of a dissertation, and finally through the acceptance and support of these efforts by the general public in programs such as the South Kohala Conservation Action Plan (SKCAP). We have accomplished all of these measures of a successful project including five articles published in 2014 in peer reviewed journals (see Appendices for full articles).

1) Stender Y., P. L. Jokiel, K. S. Rodgers. 2014. Thirty Years of Coral Reef Change in Relation to Coastal Construction and Increased Sedimentation at Pelekane Bay, Hawai‘i. PeerJ. v2013:11:960:1:0.

2) Stender Y., M. Foley, K. S. Rodgers, P. L. Jokiel, A. Singh. 2014. Evaluation of the nearshore benthic habitat, marine biota, and water quality adjacent to Kahului Commercial Harbor, Maui, Hawai‘i. UH Engineering Report pp 27.

3) Perez III K, K.S. Rodgers, P. L. Jokiel, C. Lager, D. Lager. 2014. Effects of terrigenous sediment on settlement and survival of the reef coral *Pocillopora damicornis*. PeerJ 2:e387; DOI 10.7717/peerj.387.

4) Rodgers KS, Jokiel PL, Brown EK, Hau S, and Sparks R. 2014. Hawai‘i Coral Reef Assessment and Monitoring Program: Over a Decade of Change in Spatial and Temporal Dynamics in Coral Reef Communities. Pacific Science. Early View.

5) 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 https://dx.doi.org/10.7717/peerj.699

Data management and dissemination of results

We will continue to use the data management system developed by Dr. Eric Brown early in the development of CRAMP that has now been expanded to include all NPS monitoring data and data from other sources. This data base is moving toward integration with NMFS, UH and other groups. CRAMP has and will continue to archive all data and images at NOAA’s National Ocean Data Center under the direction of Mr. Pat Caldwell as we have since 1998. Dissemination of results during this study includes the five peer reviewed journal articles listed above and attached as appendices.

Outreach

Twelve outreach venues were conducted to present research findings from this project. These conferences and meetings were well attended by students, researchers, educators, and managers in the marine community.

a. February 23, 2014 Ocean Science Meeting, Honolulu, HI. “Thirty Years of Coral Reef Change in Relation to Coastal Construction and Increased Sedimentation at Pelekane Bay, Hawai‘i.” Yuko Stender presenter

b. March 12, 2014 The 39th Albert L. Tester Memorial Symposium, Honolulu, HI. “Thirty Years of Coral Reef Change in Relation to Coastal Construction and Increased Sedimentation at Pelekane Bay, Hawai‘i.” Yuko Stender presenter

c. May 5, 2014 South Kohala Coastal Partnership Core Team Meeting, Waimea, HI, Paul Jokiel presented findings on sediment impacts.

d. July 10, 2014 Biol 403 Field Problems in Marine Biology Class PPT Presentation on watershed and reef connections Ku‘ulei Rodgers

e. July 17, 2014 Biol 403 Lecture State of the Hawai‘i’s Coral Reefs Ku‘ulei Rodgers

f. July 15 2014 Hawai‘i Conservation Conference “Response of Coral Reefs to Extreme Turbidity on the South Moloka‘i Reef Flat”. Ku‘ulei Rodgers presenter.

g. Sept 3-4, 2014. Kona Integrated Ecological Assessment Program. Kona Hawaii, King Kamehameha Hotel. “Recent Insights into Effects of Sedimentation on Kona Reefs” presentation by Paul L. Jokiel

h. Jan 23, 2015 The 23rd Hawaii Conservation Conference, Hilo, HI, August 3-6, 2015 “Assessment of Coral Settlement Distribution and Environmental Condition in Pelekane Bay, Hawai‘i” Abstract submitted by Yuko Stender

i. Jan 28, 2015 Zoology 410 Corals and Coral Reefs PPT presentation watershed/reef connection

j. February 1, 2015 UH Sea Grant Reef Talk, Kaloko-Honokohau National Park Visitor Center. Impacts of Sedimentation on the Coral Reef Community in Pelekane Bay, Hawai‘i. Yuko Stender presenter

k. Feb 24, 2015 IS 203 Windward Community College Ahupua‘a class PPT presentation Mauka/ Makai Connections. Ku‘ulei Rodgers presenter

l. March 31, 2015 Oceanography Ridge to Reef Class PPT Ridge to Reef Connections Ku‘ulei Rodgers presenter

References

Babcock, R. and Paves, D. 1991. Effects of sedimentation on settlement of *Acropora millepora*. Coral Reefs 9: 205 – 208 DOI 10.1007/BF00290423.

Ball, F. W. 1977. Benthic marine algae of the coastal waters of Puukohola Heiau National Historic Site. Tech. Report #16, Coop. National Park Resources Study Unit, Dept. of Botany, Univ. of Hawaii, Honolulu, Hawaii. 12 pp.

Beets J E, Brown EK, Friedlander A. 2010. Inventory of Marine Vertebrate Species and Fish-habitat Utilization Patterns in Coastal Waters off Four National Parks in Hawai‘i. Pacific Cooperative Studies Unit, University of Hawai‘i, Technical Report 168. Pp 60.

Birkeland C and Friedlander AM. 2001. The Importance of Fish Refuges to Reef Fish Replenishment in Hawai‘i. The Hawai‘i Audubon Society Pacific Fisheries Coalition. Honolulu, Hawai‘i.

Brock, R.E. 1982. A critique of the visual census method for assessing coral reef fish populations. *Bulletin of Marine Science* 32: 269-276

Brock, V.E. 1954. A preliminary report on a method of estimating reef fish populations. *Journal of Wildlife Management* 18: 297-308

Brown, E., Minton, D., Daniel, R., Klasner, F., Basch, L., Snyder, A., Craig, P., Dicus, G., DeVerse, K., and Jones, T. Benthic marine monitoring protocol; Pacific Island Network. Natural Resource Report NPS/PACN/NRTR-2007/002. U.S. Department of the Interior, National Park Service, Natural Resource Program Center, Fort Collins, Colorado. 367pp.

Brown, Eric. 2004. Reef coral populations: spatial and temporal differences observed on six reefs off west Maui. Ph.D. Dissertation. University of Hawaii at Manoa, Honolulu. 277 pp.

Burke, L., K. Reytar, M. Spalding, and A. Perry. 2011. Reefs at Risk Revisited. World Resources Institute, Washington D.C. 116 pp.

Chaney, D., D. Hemmes and R. Nolan. 1977. Physiography and marine fauna of inshore and intertidal areas in Puukohala Heiau National Historic Site. Tech. Report #13, Coop. National Park Resources Study Unit, Dept. of Botany, Univ. of Hawaii, Honolulu, Hawaii. 36 pp.

DeMartini, E. E., P. L. Jokiel, J. P. Beets. Y. Stender, C. Storlazzi, D. Minton, and E. Conklin 2013. Terrigenous sediment impact on coral recruitment and growth affects the use of coral habitat by recruit parrotfishes (F. Scaridae). Journal of Coastal Conservation: Planning and Management. DOI 10.1007/s11852-013-0247-2.

Harrigan, J.F. 1972. The planula larva of *Pocillopora damicornis*: lunar periodicity of swarming and substratum selection behavior. PhD thesis, University of Hawai‘i, Honolulu, 213.

Hodgson G. 1991. Sediment and the settlement of larvae of the reef coral Pocillopora damicornis. Coral Reefs 9:41–43 DOI 10.1007/BF00686720.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfi eld, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A. J., Caldeira, K. et al. 2007. Coral reefs under rapid climate change and ocean acidifi cation. Science 318 1737-1742.

Jokiel, Paul L., Evelyn F. Cox, Franklyn T. Te and Darby Irons. 1999. Mitigation of reef damage at Kawaihae Harbor through transplantation of reef corals. Final report to USFWS. 20 pp.

Jokiel, Paul L. and Ku’ulei Rodgers. 2008. Hawai‘i Coral Reef Assessment and Monitoring Program Quality Assurance Project Plan. US Environmental Protection Agency. 45 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 https://dx.doi.org/10.7717/peerj.699

Leuliette, E.W. 2012. Sea level trend map: National Oceanic and Atmospheric Administration Laboratory for Satellite Altimetry sea-level rise products, online data, accessed at http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/.

Martin,R.A. and Walsh, W.J. 2014. The West Hawai'i Coral Recruitment Project, Recruitment dynamics of scleractinian corals along the Kona Coast of the Big Island of Hawai'i. Hawai'i State, Department of Land and Natural Resources, Division of Aquatic Resources. 24p.

McClanahan TR, Donner SD, Maynard JA, MacNeil MA, and Graham NJ. 2012. Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate. PLoS ONE 7(8): e42884. doi:10.1371/journal.pone.0042884.

Minton, D., Conklin, E., Couch, C.S., Garren, M, Hardt, M.J., Amimoto, R, Pollock, K., and Wiggins, C. 2011. Survey of the Coral Reefs of Pelekane Bay. The Nature Conservancey. 54p.

Minton, D., E. Conklin, P. Weiant, and C. Wiggins. 2012. 40 Years of Decline on Puakō’s Coral Reefs - A review of Historical and Current Data (1970-2010). The Nature Conservancy. pp. 43.

Nyström, M., Folke, C., and Moberg, F. 2000. Coral reef disturbance and resilience in a human-dominated environment. Trends in Ecology & Evolution 15(10): 413-417

Rodgers KS, Jokiel PL, Brown EK, Hau S, and Sparks R. 2014. Hawai‘i Coral Reef Assessment and Monitoring Program: Over a Decade of Change in Spatial and Temporal Dynamics in Coral Reef Communities. Pacific Science. Early View.

Perez III K, K.S. Rodgers, P. L. Jokiel, C. Lager, D. Lager. 2014. Effects of terrigenous sediment on settlement and survival of the reef coral *Pocillopora damicornis*. PeerJ 2:e387; DOI 10.7717/peerj.387.

Rodgers, K. S. Evaluation of Nearshore Coral Reef Condition and Identification of Indicators in the Main Hawaiian Islands. 2005. PhD Dissertation. University of Hawai’i, Dept. of Geography. Honolulu, Hawai’i. Pp.203.

Rodgers K.S., Kido M.H., Jokiel P.L., Edmonds T., Brown E.K. 2012. Use of integrated landscape indicators to evaluate the health of linked watersheds and coral reef environments in the Hawaiian Islands. Environmental Management (DOI: 10.1007/s00267-012-9867-9).

Stender Y, P. L. Jokiel, K. S. Rodgers. 2014. Thirty Years of Coral Reef Change in Relation to Coastal Construction and Increased Sedimentation at Pelekane Bay, Hawai‘i. PeerJ. v2013:11:960:1:0

Stender Y., M. Foley, K. S. Rodgers, P. L. Jokiel, A. Singh. 2014. Evaluation of the nearshore benthic habitat, marine biota, and water quality adjacent to Kahului Commercial Harbor, Maui, Hawai‘i. UH Engineering Report pp 27.

Storlazzi, C.D., Field, M.E., Presto, M.K., Swarzenski, P.W., Logan, J.B., Reiss, T.R., Elfers, T.C., Cochran, S.A., Torresan M.E., and Chezar, H., 2012, Coastal circulation and sediment dynamics in Pelekane and Kawaihae Bays, Hawaii; measurements of waves, currents, temperature, salinity, turbidity, and geochronology; November 2010–March 2011: U.S. Geological Survey Open-File Report 2012

Te FT. 1992. Response to higher sediment loads by Pocillopora damicornis planulae. Coral Reefs 11(3):131–134 DOI 10.1007/BF00255466.

Tissot, Brian N. 1998. Changes in the marine habitat and biota of Pelekane Bay, Hawaii over a 20-year period. U.S.Fish and Wildlife Service Pacific Islands Office, Honolulu, HI. 34 pp.

U.S. Geological Survey. 2006. Geologic resource evaluation of Puʻukoholä Heiau National Historic Site, Hawaiʻi. Part II: Benthic habitat mapping. Scientific Investigations Report 2006-5254.

U.S. Geological Survey. 2013. Coastal circulation and sediment dynamics in Pelekane and Kawaihae Bays, Hawaii. Geological Survey Open-File Report 2012. 111p.

Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M. 2009. Mixed Effects Models and Extensions in Ecology with R, Statistics for Biology and Health. New York: Springer-Verlag New York 600p. DOI 10.1007/978-0-387-87458-6

Walsh WJ. 1987. Patterns of recruitment and spawning in Hawaiian reef fishes. Environmental Biology of Fishes 18(4): 257-276

Wolanski E, Richmond RH, and 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. Journal of Marine Systems 46: 133-144

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APPENDIXES

Appendix I

Stender Y, Jokiel PL, and Rodgers KS. 2014. Thirty Years of Coral Reef Change in Relation to Coastal Construction and Increased Sedimentation at Pelekane Bay, Hawaiʻi. PeerJ DOI 10.7717/peerj.300**.**

Appendix II

Rodgers KS, Jokiel PL, Brown EK, Hau S, and Russell Sparks R. 2014. Over a Decade of Change in Spatial and Temporal Dynamics in Hawaiian Coral Reef Communities. Pacific Science Early View.

Appendix III

K. Perez III, K.S. Rodgers, P. L. Jokiel, C. Lager, D. Lager. 2014. Effects of terrigenous sediment on settlement and survival of the reef coral *Pocillopora damicornis*. PeerJ 2:e387; DOI 10.7717/peerj.387.

Appendix IV

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: Molokaʻi, Hawaiʻi. PeerJ 2:e699 https://dx.doi.org/10.7717/peerj.699

Appendix V

Use of Integrated Landscape Indicators and development of Biocriteria to Evaluate the Health of Linked Watersheds and Coral Reef Environments in the Hawaiian Islands

Kuʻulei S. Rodgers, Michael H. Kido, Paul L. Jokiel, Jason S. Rodgers

PowerPoint Presentation at Hawai‘i Conservation Conference 2013

Appendix VI
Response of reef corals to extreme turbidity on the south Moloka‘i reef flat.
Ku‘ulei Rodgers and Paul L. Jokiel PowerPoint Presentation at Hawai‘i Conservation Conference 2013

Appendix VII
The 23rd Hawaii Conservation Conference, Hilo, HI, August 3-6, 2015 "Assessment of Coral Settlement Distribution and Environmental Condition in Pelekane Bay, Hawai‘i" Abstract submitted by Yuko Stender

Appendix VIII
UH Sea Grant Reef Talk, Kaloko-Honokohau National Park Visitor Center. 2015 Impacts of Sedimentation on the Coral Reef Community in Pelekane Bay, Hawai‘i. Yuko Stender presenter