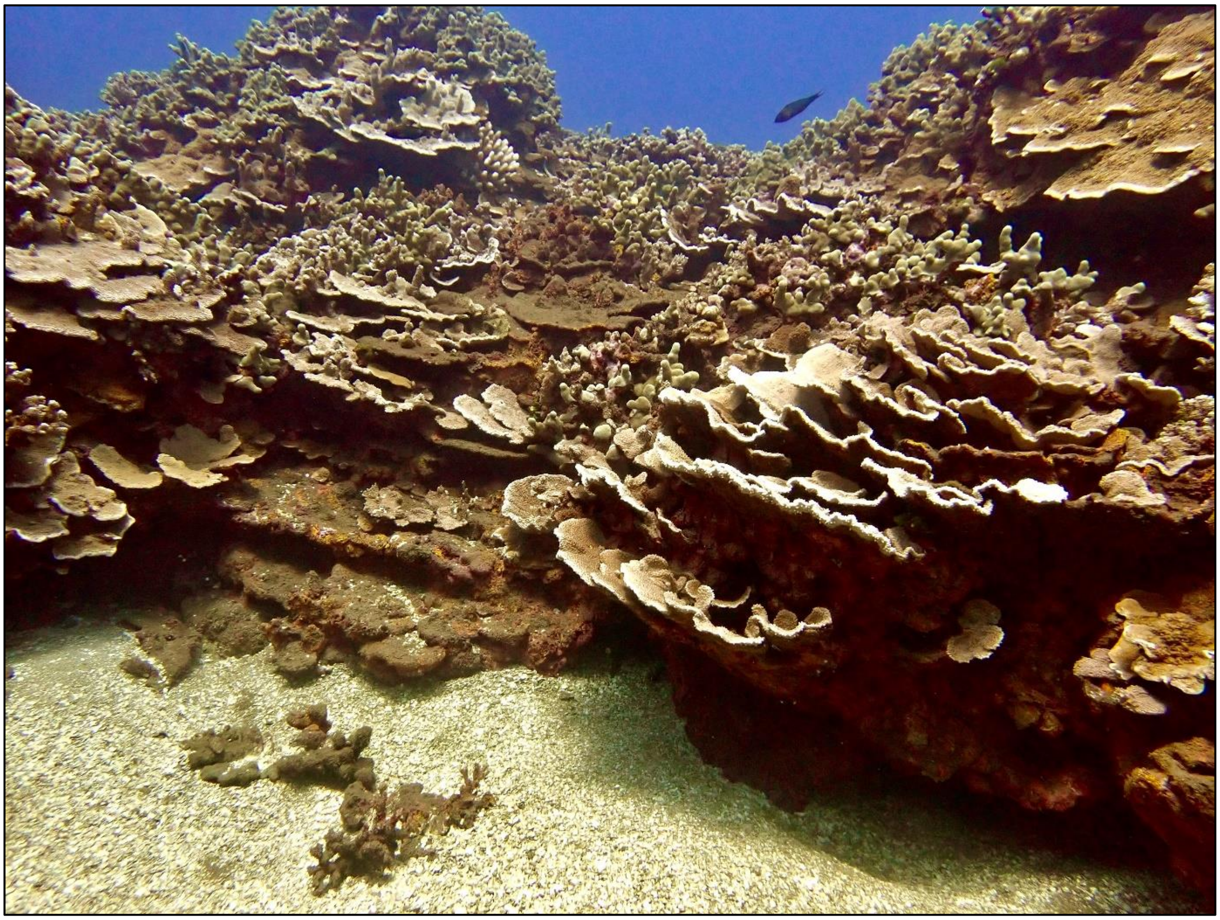
Coral Reef and Water Quality Surveys of the Keōmuku Reef Tract, Lānaʻi



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NOAA CORAL REEF CONSERVATION PROGRAM

Coral Reef and Water Quality Surveys of the Keōmuku Reef Tract, Lānaʻi

by

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List of English Common, Hawaiian, and Scientific Names of Species Included in this Report

Common Name	Hawaiian Name	Scientific Name
Ocellated coral	-	*Cyphastrea ocellina*
Mushroom coral	ʻĀkoʻakoʻa kohe	*Fungia scutaria*
Crust coral	Koʻa	*Leptastrea purpurea*
Transverse coral	-	*Leptastrea transversa*
Swelling coral	-	*Leptoseris incrustans*
Rice coral	ʻĀkoʻakoʻa	*Montipora capitata*
Branching rice corql	-	*Montipora incrassata*
Sandpaper coral	Koʻa	*Montipora patula*
Porkchop coral	-	*Pavona duerdeni*
Maldive coral		*Pavona maldivensis*
Corrugated coral	ʻĀkoʻakoʻa	*Pavona varians*
Cauliflower coral	Koʻa	*Pocillopora meandrina*
Lace coral	-	*Pocillopora damicornis*
Finger coral	Pōhaku puna	*Porites compressa*
Lobe coral	Pōhaku puna	*Porites lobata*
Lichen coral	-	*Porites lichen*
Mound coral	-	*Porites lutea*
Plate and pillar coral	-	*Porites rus*
Plate and knob coral	-	*Porites monticulosa*
Stellar coral	-	*Psammocora stellata*

Common Name	Hawaiian Name	Scientific Name
-	Limu koho	*Amansia glomerata*
-	-	*Asparagopsis* spp.
-	-	*Halimeda* spp.
-	-	*Padina* spp.

Common Name	Hawaiian Name	Scientific Name
Achilles tang	Paku'iku'i	*Acanthurus achilles*
Ringtail surgeonfish	Pualu	*Acanthurus blochii*
Eyestripe surgeonfish	Palani	*Acanthurus dussumieri*
Whitebar surgeonfish	Maikoiko	*Acanthurus leucopareius*
Goldrim surgeonfish	-	*Acanthurus nigricans*
Brown surgeonfish	Māʻiʻiʻi	*Acanthurus nigrofuscus*
Bluelined surgeonfish	Maiko	*Acanthurus nigroris*
Orangeband surgeonfish	Naʻenaʻe	*Acanthurus olivaceus*
Convict tang	Manini	*Acanthurus triostegus*

Common Name	**Hawaiian Name**	**Scientific Name**
Yellowfin surgeonfish	Pualu	*Acanthurus xanthopterus*
Smalltoothed jobfish	Wahanui	*Aphareus furca*
Green jobfish	Uku	*Aprion virescens*
Hawaiian hogfish	ʻAʻawa	*Bodianus albotaeniatus*
Bluefin trevally	ʻŌmilu	*Caranx melampygus*
Peacock grouper	Roi	*Cephalopholis argus*
Multiband butterflyfish	-	*Chaetodon multicinctus*
Ornate butterflyfish	-	*Chaetodon ornatissimus*
Fourspot butterflyfish	-	*Chaetodon quadrimaculatus*
Teardrop butterflyfish	-	*Chaetodon unimaculatus*
Milkfish	Awa	*Chanos chanos*
Cigar wrasse	Kupou	*Cheilio inermis*
Bullethead parrotfish	Uhu	*Chlorurus spilurus*
Spectacled parrotfish	Uhu ʻahuʻula	*Chlorurus perspicillatus*
Stocky hawkfish	Poʻopaʻa	*Cirrhitus pinnulatus*
Yellowstriped coris	Hilu	*Coris flavovittata*
Yellowtail coris	Hinālea ʻaki-lolo	*Coris gaimard*
Mackerel scad	ʻŌpelu	*Decapterus macarellus*
Rainbow runner	Kamanu	*Elagatis bipinnulata*
Bluestriped snapper	Taʻape	*Lutjanus kasmira*
Blacktail snapper	Toau	*Lutjanus fulvus*
Bigeye emperor	Mū	*Monotaxis grandoculis*
Paletail unicornfish	Kala lōlō	*Naso brevirostris*
Orangespine unicornfish	Umaumalei	*Naso literatus*
Ringtail wrasse	Poʻou	*Oxycheilinus unifasciatus*
Saber squirrelfish	ʻAlaʻihi	*Sargocentron spiniferum*
Tahitian squirrelfish	ʻAlaʻihi	*Sargocentron tiere*
Palenose parrotfish	Uhu	*Scarus psittacus*
Ember parrotfish	Uhu ʻeleʻele	*Scarus rubroviolaceus*
Doublespotted queenfish	Lai	*Scomberoides lysan*
Great barracuda	Kākū	*Sphyraena barracuda*
Old woman wrasse	Hinālea lauhine	*Thalassoma ballieui*
Saddle wrasse	Hinālea lau-wili	*Thalassoma duperrey*
Surge wrasse	Hou	*Thalassoma purpureum*

Note on names: Common and Hawaiian names were obtained primarily from three sources: Randall (2007) for fish, and Hoover (1998) and Bernice P. Bishop Museum for invertebrates.

Table of Contents

Cover Photo: Montipora capitata and Porites compressa dominate a deep reef area in the Keōmuku Reef Tract (Photo: The Nature Conservancy)

Summary of Findings

The coral reefs of Lānaʻi have long provided invaluable cultural and ecological benefits, but community observations and scientific surveys indicate the health of these ecosystems may be declining due to threats such as overharvest of fish, sedimentation resulting from poor land use practices and overgrazing, and climate change. While landowner- and community-initiated efforts to restore upland areas and manage other key environmental stressors are now being undertaken, these efforts are being hampered by a lack of recent data on reef resources from large sections of the Lānaʻi's reefs.

Filling this information gap would facilitate the development of effective management strategies, including as part of the State of Hawaiʻi Division of Aquatic Resources' (DAR) Holomua: Marine 30x30 Initiative to effectively manage 30% of Hawaii's marine waters by 2030. To address this need, The Nature Conservancy (TNC) assessed the benthic and reef fish assemblages on the east coast of Lānaʻi, between Halulu and Waiʻōpae Gulches, an area referred to as the Keōmuku Reef Tract. In addition, TNC gathered information on water quality and sediment to examine relationships between terrestrial inputs and coral reef condition. These assessments were specifically designed to gather information that would:

- establish baseline conditions against which future improvements due to management actions could be evaluated;
- inform terrestrial restoration activities that seek to address sediment impacts; and
- contribute to the State's Holomua: Marine 30x30 Initiative planning for marine managed areas.

Between May 12 and June 25, 2021, TNC collected fish and benthic data at 129 randomly-selected sites between 0.3 and 13 m depth within the Keōmuku Reef Tract. In addition, a comprehensive suite of water quality, benthic sediment flux and sediment composition data were collected at or near the same sites.

As on most coral reefs in Hawaiʻi, the composition of the reefs in the Keōmuku Reef Tract changed with depth. Coral cover increased and turf, macroalgae, and abiotic (mostly unconsolidated bottom) cover decreased with depth, with a clear transition occurring at approximately 2 m depth. Shallow reef areas were dominated by sediment and turf algae, covering 61.5 ± 1.8% and 22.4 ± 2.2% of the bottom, respectively. Mean coral cover was low, 7.1 ± 1.0%, but variable across the reef tract. Coral species richness was surprisingly high with 19 taxa, although most species were rare, accounting for <0.1% cover. This taxonomic richness makes the shallow reef area within the Keōmuku Reef Tract among the most diverse in the Hawaiian Islands. Resource fish (fish species most prized as food fish) abundance and biomass were lower in shallow compared to deep reef areas, and prime spawners (the largest individuals of resource species) were nearly absent from shallow reefs in the Keōmuku Reef Tract. For at least some fish species, shallow reefs appeared to serve as juvenile habitat.

Distinct shallow reef assemblages characterized by very low coral cover (0.7 ± 0.6%) were identified adjacent to Wahane Gulch, a sizeable sediment fan at the drainage of an unnamed gulch to the south of Nahoko Gulch, and the southern end of the Keōmuku Reef Tract. All three locations were shown to be or are likely to experience high sediment inputs from upland areas and are evidence of the negative effects sedimentation has on the reef assemblage in some areas of the Keōmuku Reef Tract.

Unlike the shallow reef area, the benthic assemblage on the deep reef appeared to be uniform across the Keōmuku Reef Tract, suggesting less influence from terrestrial sediment inputs. Deeper reef areas (>2 meters) within the Keōmuku Reef Tract had among the highest average coral cover in the state at 54.7 ± 3.4%, and over a fifth of the survey sites had >75% coral cover. The dominant corals species transition from sediment- and wave-tolerant species (*e.g.*, *Porites lobata*, *Pocillopora meandrina*, and *P. damicornis*) in shallower water to species commonly observed at depth on Hawaiian reefs, including *Porites compressa*, *Montipoa capitata*, and *M. patula*. Resource fish and prime spawner biomass in deep reef areas were higher than many other areas in Maui Nui, but lower than sites on Hawaiʻi island, Kahoʻolawe, and even some areas on Oʻahu, suggesting overharvesting may be occurring.

Average nearshore turbidity across the study area was 2.6 ± 5.0 s.d FNU for all sites. Onshore-offshore gradients showed up to 10 times more sediment accumulation (15,805 $g/m^2/d$ to 392 $g/m^2/d$), and three times more turbidity (8.5 FNU to 3.5 FNU) moving from 10-m to 250-m offshore. Sediment accumulation data collected 250-m offshore matched previously collected results at Lae hī of 292 $g/m^2/d$, yet accumulation rates at the same distance from shore near Waiʻōpae fishpond were 1,934 $g/m^2/d$. Shallow reef areas up to 50-m from shore experienced turbidity significantly greater than previously established thresholds for healthy coral systems, providing strong evidence of sediment stress to these habitats.

Sediment composition was dominated by calcareous marine sediments that ranged from a mean of 87.2% to 92.6%, however there were some sediment samples that were dominated by terrigenous sediments. The highest organic percentages were found near the former Keōmuku town coastal areas, in shallow depths less than 2m. Sediment composition was not linked to increases in coral bleaching observed in some areas surveyed.

Continuous turbidity measurements made over a 48-hour period at 250-m offshore of Waiʻōpae revealed that turbidity at high tides was over 10 times that at low tides, indicating that resuspension on high tides may a continuous source of stress for coral systems. Historical analysis of the 1878 survey image shows that the coastline has extended seaward up to 146m in multiple locations. With predicted sea level rise, both upland sources of sediment and also increased access to fine sediments deposited on the coastal plain may contribute to increases in sediment loads available for resuspension in the nearshore.

Specific considerations were derived from the knowledge gained from TNC's 2021 surveys and can be used to develop a monitoring effort tailored to the needs and resources for a Keōmuku Reef Tract monitoring program.

1. Introduction

The coral reefs and associated reef fishes of Lānaʻi have long provided native Hawaiian and local resident families invaluable cultural and ecological benefits, and they remain central to island life today. However, community observations and scientific surveys indicate the health of these ecosystems may be declining due to threats such as overharvesting, sedimentation resulting from poor land use practices and overgrazing, and climate change (Friedlander *et al.* 2005, Maunalei Ahupuaʻa CMMA2016). In response, community-initiated efforts to restore watersheds, or ʻahupuaʻa, and manage key stressors are beginning to link with state and federal initiatives to improve reef condition, such as the State Holomua: Marine 30x30 Initiative to effectively manage 30% of Hawai ʻi nearshore waters by 2030.

These efforts, however, are hampered by a lack of recent data on reef resources from large sections of the island's reefs. Over the past decade, reefs in Hawaiʻi have been affected by major coral bleaching events, sedimentation events, and overharvesting, which raises concerns that older data are no longer representative of the current condition and challenges confronting Lānaʻi's reefs, making it difficult to identify the areas most under threat, the areas most important to protect, and the stressors that most need to be addressed to restore or enhance the resilience of these reef resources.

While some efforts are currently underway to address these knowledge gaps (*e.g.*, Asner *et al.* 2020), few scientific investigations have been conducted on Lānaʻi's coral reef ecosystem over the past 20 years. The State of Hawaii Division of Aquatic Resources (DAR) conducts regular monitoring in and around the Mānele - Hulopoʻe Marine Life Conservation District on the south end of the island. The University of Hawaiʻi's Coral Reef Assessment and Monitoring Program examined coral distributions and condition at a long-term monitoring site at Hulopoʻe, and has four additional rapid assessment sites on the northwest side (Palaoa, Keanapapa, Kalaeāhole, and Kaʻāpahu). In 2012, the Hawaiʻi Cooperative Fishery Research Unit (HCFRU) undertook comprehensive benthic and fish assessments of the coral reef in the Maunalei ʻahupuaʻa (Friedlander *et al.* 2012). Finally, NOAA's Ecosystems Services Division (NOAA-ESD[1]), which periodically conducts reef assessments across the Hawaiian Islands, surveyed a handful of sites around Lānaʻi in 2013 and 2016 (McCoy *et al.* 2016).

Similarly, data on sediment supply, deposition, and adjoining coastal water quality have been limited to the Maunalei ʻahupuaʻa (Teneva *et al.* 2016). While it is widely acknowledged that many reef areas around the Lānaʻi are severely affected by sediment deposition from land (Falinski 2016; Lanai Planning Commission 2014; Teneva *et al.* 2016), few studies have spatially assessed the severity of the impacts or adequately described the sources.

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[1] Formerly known as CRED

Filling these spatial and temporal data gaps would facilitate development of effective strategies to improve reef condition and allow implementing organizations to assess the success of management actions over time. For example, DAR recently launched the Holomua: Marine 30x30 Initiative to effectively manage 30% of the state’s nearshore waters by 2030 by developing a network of marine managed areas (MMA) across the main Hawaiian Islands. DAR has requested additional coral reef survey work to provide critical information to ensure a science-based MMA network for Lānaʻi could meet community needs by ensuring sustainable fisheries, improving reef condition, and enhancing resilience to a changing climate.

Additional data could also benefit watershed restoration and erosion reduction efforts on the island. The Kuahiwi a Kai: Lānaʻi Watershed Conservation Program facilitates federal, state and private collaborations in conservation efforts along the Keōmuku coast of Lānaʻi. To address the issues of erosion and habitat destruction, the program is installing landscape-level, ungulate-proof fencing to manage large numbers of invasive axis deer and mouflon sheep within the program area. In addition, community-led efforts are underway to seed and plant native species and conduct sediment trapping using low-cost approached such as gabion check dams (Pūlama Lānaʻi 2022). Up-to-date information on the status of the coral reefs along the Keōmuku coast is needed to assess the effectiveness of these management actions at improving reef condition.

To address these data needs, TNC conducted assessments of the Keōmuku Reef Tract on the east coast of Lānaʻi, between Halulu and Waiʻōpae Gulches, to describe the composition and condition of the benthic and reef fish assemblages. In addition, TNC gathered information on water quality and sediment to examine relationships between terrestrial inputs and coral reef condition. These 2021 assessments were specifically designed to gather information that would:

- establish baseline conditions against which future improvements due to management actions could be evaluated;
- inform terrestrial restoration activities that seek to address sediment impacts; and
- contribute to the State’s Holomua: Marine 30x30 Initiative planning for marine managed areas.

This report describes the findings of these assessments and makes recommendations for future monitoring of coral reef responses to terrestrial restoration efforts in the ahupuaʻa adjacent to the study area.

2. Keōmuku Reef Tract

Field *et al.* (2019) used the name "Keōmuku Reef Tract" for the reef area between Kūāhua Gulch on the north and Makaīwa on the south. This approximately 13 km reef area corresponds well with TNC's survey area, and their name has been adopted for this report. The Keōmuku Reef Tract is compromised of the makai (ocean) portion of several ahupuaʻa (Figure 2.1). The upland area consists of numerous ridges, stream valleys (commonly referred to as gulches), and coastal areas that are primarily sandy beaches. These include the Maunalei, Hauola, and Kaʻa gulches, among numerous others. The 1984 USGS map in Figure 2.1 shows the place names, along with key reef, fishpond and wahi pana.

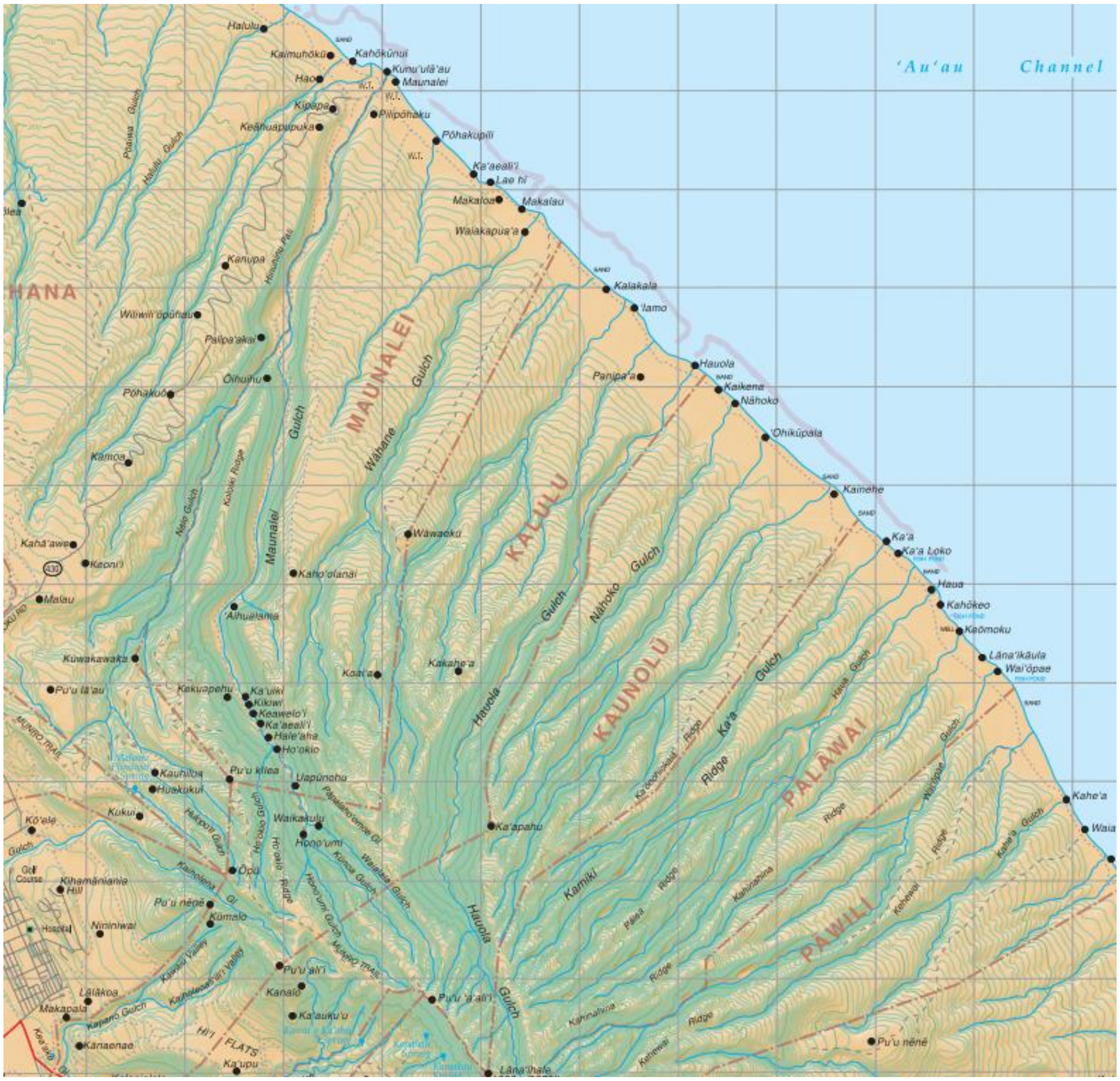

Figure 2.1. USGS 1984 Topo map with place names and ahupuaʻa boundaries (in dashed red lines)

The reef is composed of a shallow reef flat that is usually less than 500 m in width, and a forereef area that slopes into the ʻAuʻau Channel separating Lānaʻi from Maui. Previous surveys had identified a band of nearly continuous live coral cover exceeding 50% cover on the forereef (Vermeij *et al.* 2010, McCoy *et al.* 2016), although lower coral cover may have been present offshore of Maunalei Gulch (Friedlander *et al.* 2012). Field *et al.* (2019) estimated the Keōmuku Reef Tract has more than 2,100 acres of live coral (Figure 2.2).

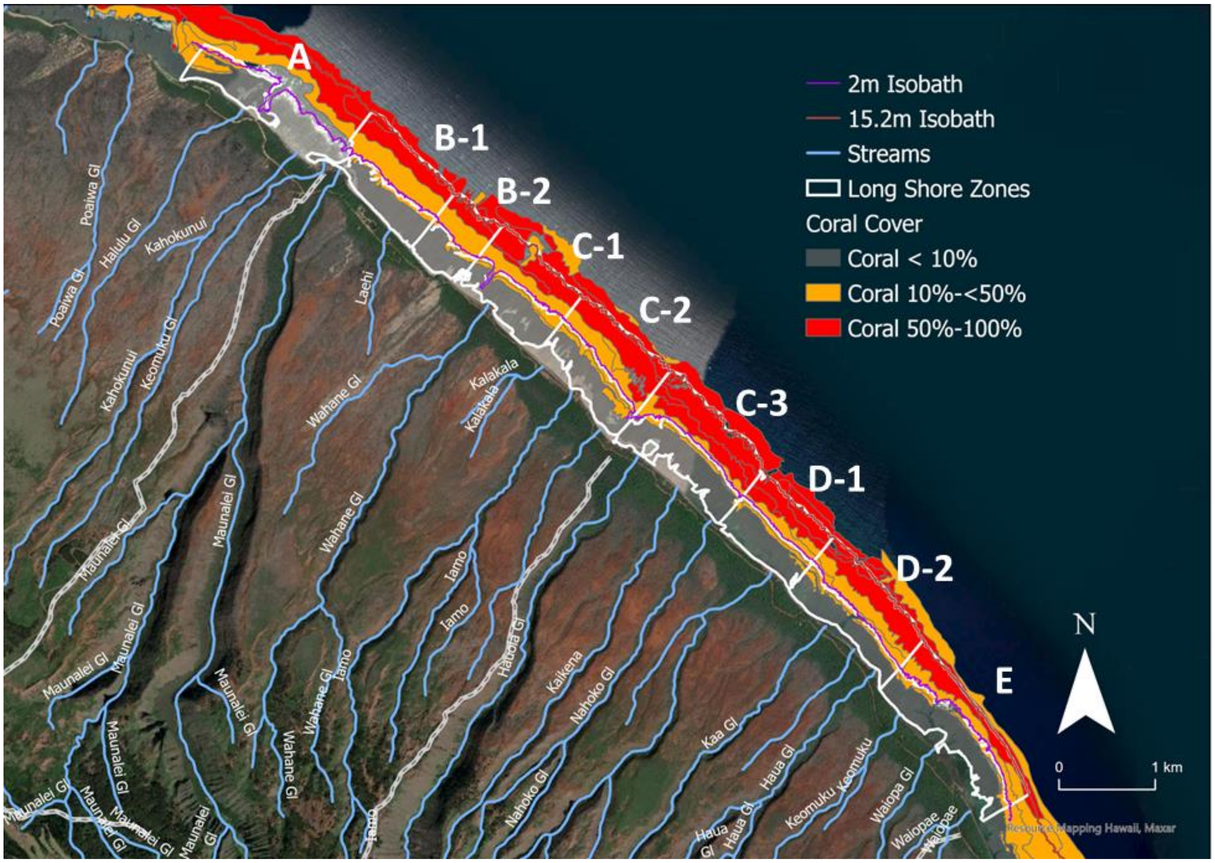

Figure 2.2 Coral cover within the Keōmuku Reef Tract derived from the 2007 NOAA benthic habitat maps. White polygons are Reef Zones (A-E) with sub-zones (*e.g.*, B-1, B-2, etc.) used in this study. See Table 2.1 for reef zone descriptions.

Ahupuaʻa on Lānaʻi are short (<10 km), and their ephemeral streams are prone to sediment-laden flash flooding. Loss of vegetation associated with historic land use practices, changing hydrologic patterns and ungulate pressure have denuded much of Lānaʻi's landscape and led to increased soil erosion. Following heavy rains, loose soil washes down the gulches into the nearshore water, increasing turbidity and transforming formerly sandy bottom shores to mud-laden benthic surfaces (Teneva *et al.* 2016). Erosion modeling has predicted spatially-variable sedimentation across the Keōmuku Reef Tract, with high sediment loads associated with Maunalei and Kaʻa gulches, and lesser loads off Wahane and Hauola gulches (Figure 2.3) (Falinski, unpublished).

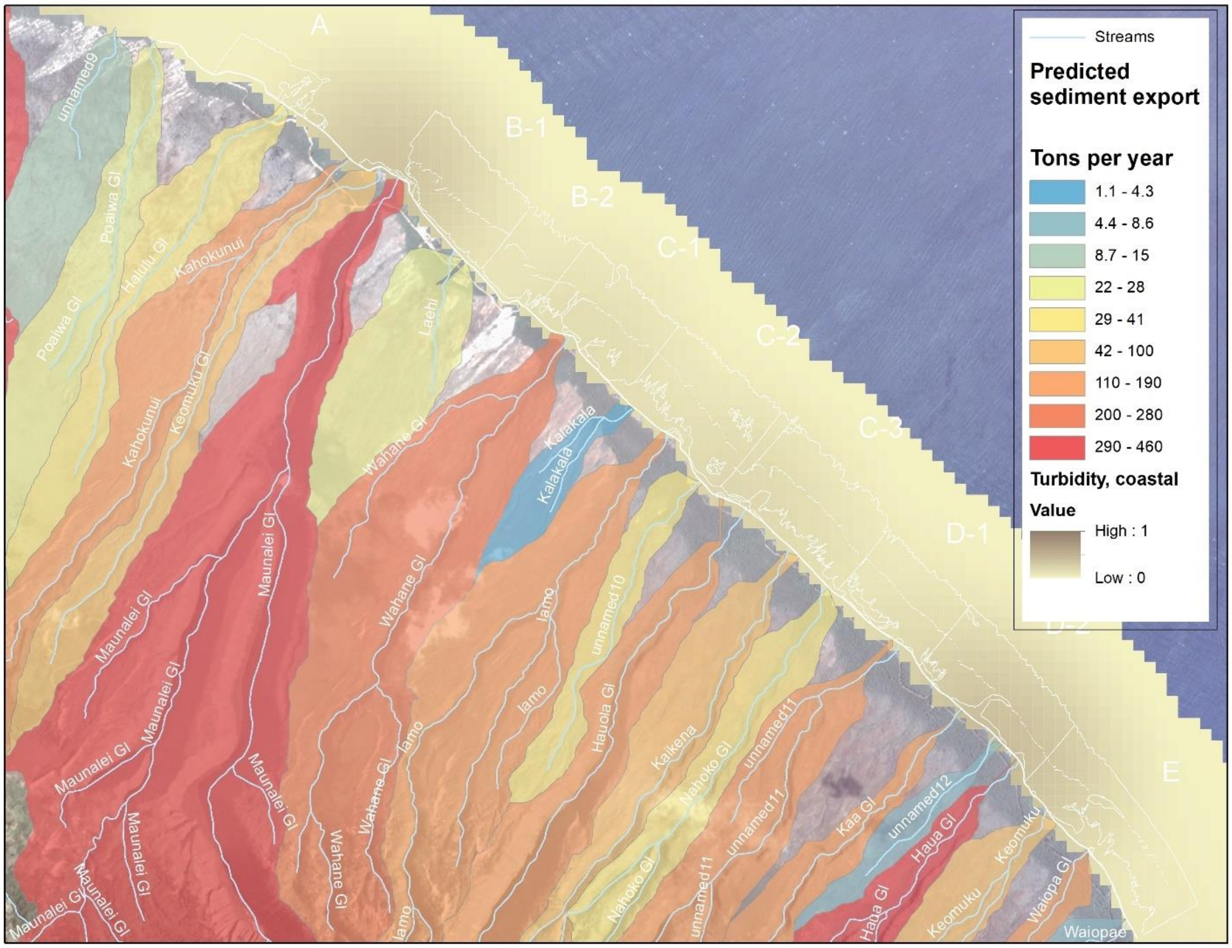

Figure 2.3. Keōmuku Reef Tract area showing the shallow nearshore area and estimates of sediment concentration from Ocean Tipping Points spatial mapping project (Falinski, unpub, 2021; Wedding *et al.* 2018). Estimates of bare areas that contribute to the model are from the 2005 C-CAP land use layer.

The coastal areas of Lānaʻi are navigated by a network of four-wheel drive roads that are within 100m of the coastline in many places. One such road runs nearly the length of the Keōmuku Reef Tract. Recent clearing of vegetation adjacent to this road has raised concerns about increased erosion due to the loss of a potentially important vegetative buffer.

To facilitate analysis and discussion of spatial patterns in this report, we divided the Keōmuku Reef Tract into five Reef Zones, labeled A through E (Table 2.1). Three of the Reef Zones were further divided into two (B-1, B-2, D-1, and D-2) or three (C-1, C-2, and C-3) sub-zones. Reef zones were delineated based on results from the erosion modeling, the presence of submarine groundwater discharges (SGD), and expert opinion. Each reef zone is briefly described in Table 2.1.

Table 2.1. The five Reef Zones (A-E) and sub-zones of the Keōmuku Reef Tract used in this report.

Reef Zone	Primary Stressor(s)	Description
A	Waves	Zone A is physically separate from Zone B by a sediment-filled break in the reef. Survey teams noted wave action was higher in Zone A compared to other zones while they were conducting surveys, and the reef was rocky and predominantly sediment free.
B	Sediment Freshwater	Zone B lies at the base of Maunalei gulch and based on aerial imagery, is within the range of its large sediment plume. The plume moves longshore in a predominantly northwest direction. The coastline's aspect changes slightly, which results in lower wave exposure than Zone A. Previous studies by Friedlander *et al.* (2012) and Teneva *et al.* (2016) were conducted within Zone B. Zone B is divided into two sub-zones: • B-1 is offshore of a sandy beach. Surveys teams reported strong currents in this area. Bottom was noticeably sediment covered. • B-2 is offshore of Lae hī, a large limestone formation sometimes referred to as White Stone, and extends southeast to the ridgeline between Maunalei and Wahane Gulches. A wide reef channel is present at the B-2 and C-1 boundary. Unlike B-1, B-2 has a submarine groundwater discharge (SGD) at the base of Lae hī.
C	Sediment Freshwater (C-3)	Zone C fronts several large gulches and the coastal four-wheel drive road approaches within 20 m of the water. The kiawe on the seaward side of the road was recently cleared, which may increase non-point sediment inputs. Survey teams noted SGDs near the boundary of Zones C and D. Zone C is divided into three sub-zones: • C-1 is centered on a large sediment discharge at the base of Wahane Gulch. • C-2 in centered on a large sediment discharge at the base of the gulch adjacent to Wahane Gulch. The southeast boundary aligns with the fenceline of Pūlama Lānaʻi's Hauola-Kehewai unit, as well as a large gap in the reef.

		• C-3 lies outside of the Hauola-Kehewai unit and fronts a series of narrow gulches, including Hauola and Nahoko Gulches. Sediment inputs and turbidity are believed to be higher than in C-1 and C-2.
D	Sediment Freshwater	Zone D fronts several small gulches. The coastal road retreats landward from its shoreline position in Zone C. Kiawe on the seaward side of the road has not been cleared, and the trees are more developed and mature compared to Zone C. Sediment models suggest Zone D should have high turbidity, especially off Kaʻa Gulch. Survey teams noted some freshwater inputs near the boundary of Zones C and D. Zone D is divided into two sub-zones: • D-1 fronts a narrow gulch whose name has not been identified. The boundary with D-2 aligns with a cut in the reef. • D-2 is at the base of Kaʻa Gulch and shows evidence of an historical fishpond. Erosion models predict high sedimentation. SGDs may present near to shore. Historically, D-2 contained a pier for loading watermelons onto boats for transport to Lahaina, Maui.
E	Sediment	Zone E has a different aspect from other reef zones, which results in less exposure and likely higher sediment resident times. A partially restored fishpond wall appears to have disrupted longshore movement of sediment. Survey teams noted considerable sediment on the reef compared to other Reef Zones. Significant sediment plumes are routinely observed offshore of Zone E. Nearshore visibility was poor; survey teams had trouble relocating deployed sediment traps. Sharks were noted outside the restored fishpond wall.

3. Methods

TNC collected sediment, fish, benthic data at 129 randomly-selected sites within the Keōmuku Reef Tract between May 12 and June 25, 2021 (Figure 3.1, Figure 3.2). All sites were between 0.3 and 13 m depth and on predominately hardbottom. Locational information (latitude/longitude) and other metadata for all survey sites has been compiled in Appendix A.

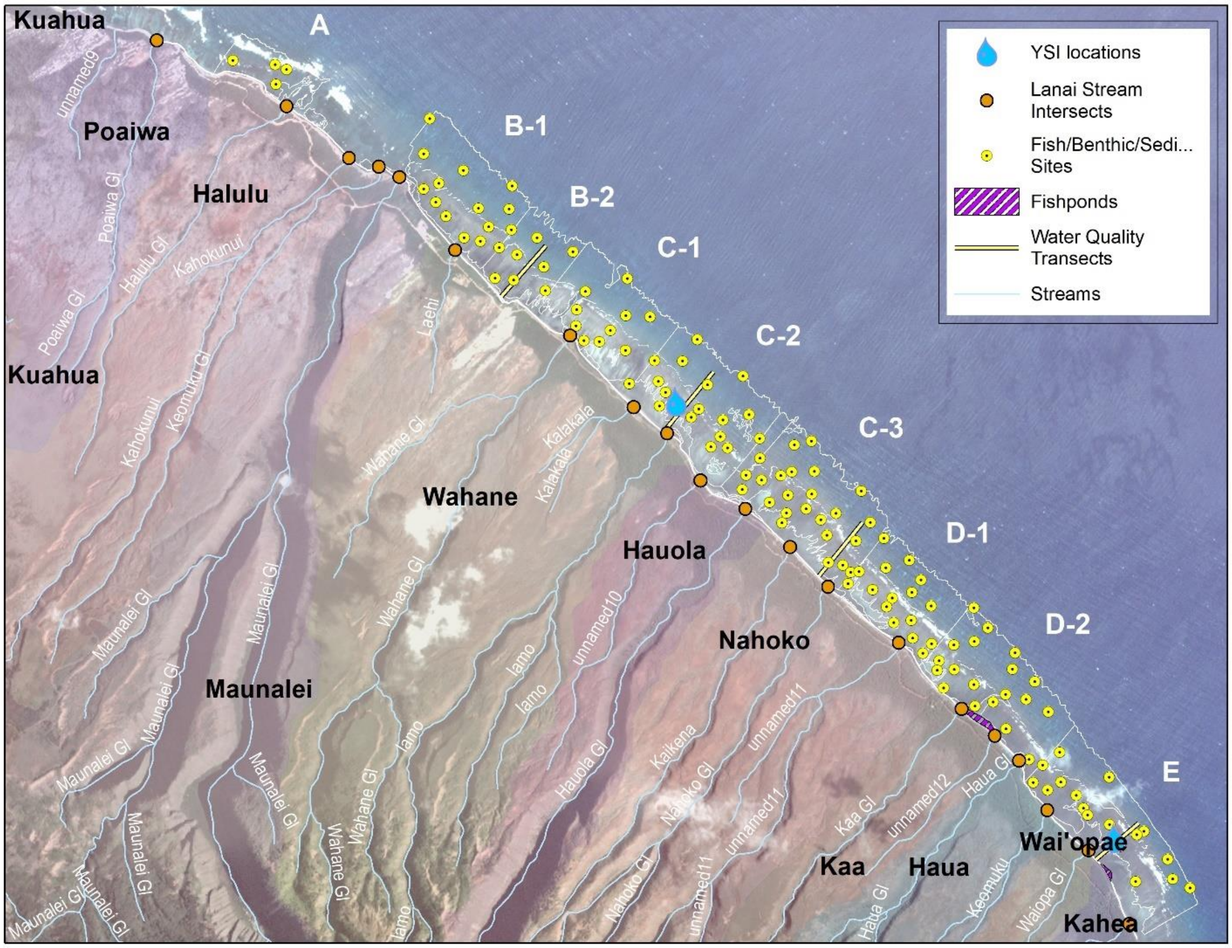

Figure 3.1. Sites surveyed by TNC in the Keōmuku Reef Tract, Lānaʻi between May 12 and June 25, 2021. Yellow lines are water quality monitoring transects sampled concurrent with the reef surveys, and yellow "drops" are sites of 48-hour water quality sensor deployments (see Section 3.1.5). Lettered boxes are the Reef Zones and sub-zones out to a 15.2m depth isobath (Table 2.1). Base imagery is from December 2021

For sites on the forereef (*i.e.*, seaward of the reef crest), survey teams navigated via small, motorized boat to each pre-selected site using a Garmin GPS unit. Once on site, surveyors using SCUBA descended directly to the bottom where they established two transect start-points approximately 10 m apart. From each start-point, surveyors deployed separate 25-m transect lines along a predetermined compass heading, resulting in two transect lines running parallel to each other. If the pre-determined compass bearing resulted in a large change in depth, the bearing was altered such that the transect followed the contour at the depth of the start point. All data collection except coral recruits (section 4.2) was conducted along one or both transect lines.

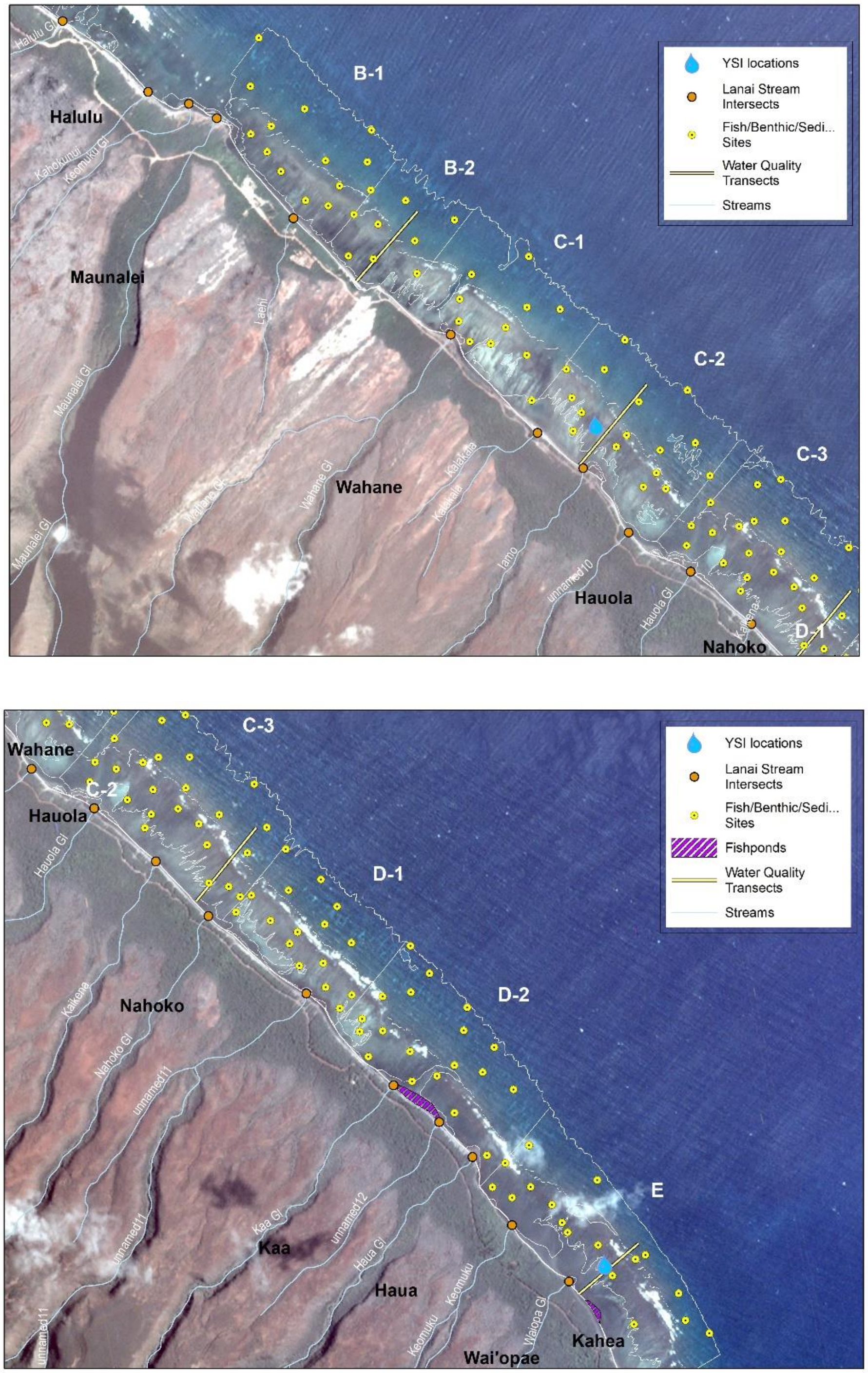

Figure 3.2. Site maps, like Figure 3.1, with focus areas on the northern and southern parts of Keomoku reef tract.

Surveyors accessed sites on the reef flat (*i.e.*, landward of the reef crest) either by snorkeling or kayaking from shore, guided by a waterproof, handheld GPS. Unlike the forereef sites, surveyors established only one transect at each shallow site, and all data collection was conducted on this line, resulting in a single fish transect being completed at each shallow reef site.

In addition to the 129 sites described above, there were four 250m-long transects established along an onshore-offshore axis at points shown in Figure 3.1. Water column measurements of water quality were taken along these transects, along with the establishment of sediment traps, as described below.

Lastly, along the length of the Keōmuku reef tract, kayak surveys were conducted with an attached water quality sonde to collect continuous water quality data across the entire study area.

All data were collected by trained and experienced scientific divers who had been calibrated to reduce surveyor variability. The specific survey methods for each type of data collected are discussed in detail below.

3.1. Sediment and Water Quality Methods

3.1.1. Spatial assessment of water column salinity and turbidity.

To understand turbidity and salinity variability in the water column across the entire study area, we used kayaks with attached physical water quality sensors to survey the coastal reef zone within the priority area. Water quality sensors (YSI Pro DSS, Xylem Inc.) took surface measurements of turbidity, dissolved oxygen, pH, salinity and temperature every minute on two transects paddled parallel to the coast at approximately 50m and 500m from shore, depending on the location of the reef. Kayak transects were conducted along the entire coastline within the Keōmuku project area over four days on a neap tide: May 17, 2021 through May 20, 2021 between 0600 and 1000, with approximately 10km of coastline surveyed each day. Wind conditions were 20-25 knot tradewinds coming from the northeast direction. Low tide was in the early morning (0600 to 1000).

3.1.2. Sediment thickness measurements.

To map the extent of sediment on the reefs on the Keōmuku reef tract, sediment thickness measurements and composition samples were co-located at the fish and benthic survey sites detailed above. At nearshore sites surveyed, sediment thickness measurements were taken at the beginning of each benthic survey transect. For these measurements, the closest area of soft sediment to each sample location was identified and a graduated fiberglass rod inserted into the sediment until hard bottom was reached or the entire length of the rod was inserted. Ten measurements of thickness (recorded to the nearest cm) were collected at each site and used to generate a site average for thickness. These measurements were collected at a subset of shallow sites (n=76).

3.1.3. Sediment composition analysis

At 115 of the 129 survey sites where benthic transects were conducted (both offshore and nearshore), sediment grab samples were collected to determine grain size, its origin (terrestrial or marine), and its organic content. Soft sediment was located near the start of the predetermined transect location and approximately 500 g wet weight of sediment was collected into Whirl-Pak bags. The samples were allowed to settle for up to 12 weeks, and then overlying water was decanted from the samples. At the sediment laboratory located at the Hawaiʻi Institute of Marine Biology, the samples were air-dried (or oven-dried to 60°C if they were originally very wet), oven-dried at 100 °C, weighed three times (dry weight), burned in a muffle furnace at 500 °C, reweighed (ash-free dry weight), and finally reburned at 1000 °C and weighed a third time (non-carbonate dry weight). The weight data were used to calculate the organic fraction of each sample, and the ratio of terrigenous (basaltic) sediment to marine (carbonate) sediment (Craft et al. 1991).

3.1.4. Sediment traps

Onshore-offshore transects were established at four key locations along the coast (Waiʻōpae, Kaʻa Gulch, and Hauola Gulch, and Lae Hī (White Stone) beach, Figure 3.2) to measure sediment accumulation over a 48 period representing resuspension in absence of a storm event. For each transect, five sediment traps (in duplicate) were deployed at 10-m, 25-m, 50-m, 100-m and 250-m from shore. Sediment traps were 5.2-cm (2.09-in) inner diameter and 15-cm in height. Prior to retrieval of the traps, water column YSI measurements were made at each trap deployment sites. The traps were capped underwater after 48 hours of soak time and retrieved. Samples were allowed to settle and decanted and filtered through Whatman 4 qualitative circles upon return to the laboratory. Filters were air dried until constant weight could be achieve over multiple days. Samples were analyzed for dry weight. Two of the sites, Hauola and Kaʻa, were missing traps for the 25-m site. Values of sediment accumulation were averaged between the two traps deployed at each distance from shore and converted to g/m^2/day for comparison with other studies.

3.1.5. Continuous water quality measurements

A water quality sonde (YSI EXO1, Xylem Inc) was deployed at 250-m offshore at Waiʻōpae on May 17, 2021 for 48 hours with the intent of measuring changes in turbidity over tidal and diurnal cycles. The sonde was deployed on a rebar stake approximately 25cm from the benthos. Data collected by the sonde included turbidity, temperature, and water depth.

3.2. **Benthic Cover**

Two methods were used to collect benthic data depending upon site-specific conditions. At most sites (124 of 129 sites), photographs of the bottom were taken every meter along one 25-m transect line using a Canon Powershot camera or equivalent in an underwater housing mounted on a PVC monopod. The white-balance of the camera was adjusted prior to photographing each transect to improve color quality. This generated 25 non-overlapping images for each survey site, with each photo covering approximately 0.8 x 0.6 m of the bottom.

Twenty randomly-selected photographs from each transect were analyzed to estimate the percent cover of coral, algae, and other benthic organisms. Photos were analyzed using CoralNet, an online repository and resource for benthic image analysis maintained by the University of California, San Diego (Beijbom *et al.* 2015). Thirty random points[2] were overlaid on each digital photograph, and the benthic component under each point was identified to the lowest possible taxonomic level, primarily individual species for coral, type of abiotic substratum (*e.g.*, sand, rubble, etc.), and at higher levels for other taxonomic groups (*e.g.*, turf, crustose coralline algae, etc.). All photographs were processed by the same analyst to reduce potential observer variability.

At five survey sites, a point intercept transect (PIT) method was used because the sites were either too shallow or visibility was too low to obtain usable photographs. At every 25-cm point along one transect, the benthic component was identified to the lowest possible taxonomic level, primarily individual species for coral, type of abiotic substratum (*e.g.*, sand, rubble, etc.), and at higher levels for other taxonomic groups (*e.g.*, turf, crustose coralline algae, etc.). This produced 100 points that were converted into percent cover per taxon. The PIT method produced comparable, but lower resolution, data to the benthic photos. However, given the low number of PITs, this discrepancy likely had little if any effect on the analysis.

3.3. **Coral Recruits**

Coral recruits were assessed at sediment trap deployment stations (see Section 3.1.4). At each station, four 0.25 m^2 quadrats were haphazardly deployed onto the bottom. Within each quadrat, all coral <5 cm in diameter were identified to species (or genera if species could not be determined) and sized to the nearest centimeter. To avoid over- or under-estimation bias, colonies were counted only if the geometric center was within the quadrat (Zuvloni *et al.* 2008)

3.4. **Benthic Topography**

The topographic complexity of the bottom at each site was measured using an index of rugosity calculated along the first 10 m of the same 25-m transect line used to collect benthic cover data.

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[2] The number of points analyzed on each photograph (30 points) and the number of photographs at each site (20 photographs) represent the lowest sampling effort necessary to achieve adequate statistical power to detect spatial and temporal differences in benthic cover.

The index was calculated by dividing the length of brass chain necessary to contour the bottom by the 10-m transect length (McCormick 1994). For this index, a value of one represents a flat surface with no topographic relief, and increasing values represent more topographically complex substratum. Rugosity was collected at all survey sites (Appendix A).

3.5. Reef Fish Abundance and Biomass

While slowly deploying the parallel 25-m transect lines, divers identified to species and sized to the nearest centimeter all fishes within and passing through a 5-m wide belt along the transect. Divers took between 10 and 15 minutes to complete a single survey. Individual fish biomass (*i.e.*, wet weight) was calculated using fish length and species-specific, size-to-weight conversion parameters from FishBase (Froese and Pauly 2010) or the HCFRU. Some species, such as eels (Family Muraenidae), cannot be reliably sized using non-intrusive visual surveys, so these species were counted but excluded from biomass estimates.

3.6. Data Management and Analysis

3.6.1. Data Handling

All fish and site data were entered into a custom Access database and checked for errors. All benthic data were downloaded from CoralNet, compiled in Excel spreadsheets, and checked for errors prior to analysis. All databases and spreadsheets supported safeguards to ensure high data quality, and reside on a secure, central TNC server that is backed up daily to an offsite location to protect against data loss.

Fish data were pooled into several groups for analysis: total (all) fish, fish family, resource fish[3] including a selected non-resource group for comparison, prime spawners, and invasive fish. Resource fish refer to fishes desirable for food, commercial activity, and/or cultural practices in Hawaiʻi (Williams *et al.* 2008), whereas the selected non-resource fish are species not routinely targeted by fishers in Hawaiʻi to a significant degree (Table 3.1). Nearly all fish species are taken by some fishers at some time in Hawaiʻi, therefore designating a fish species as either “resource” or “non-resource” is oftentimes difficult. These two groupings—resource fish and non-resource fish—are intended to represent the high and low ends of the fishing pressure continuum.

Prime spawners are individual resource fishes larger than 70% of the maximum size reported for the species in Hawaiʻi. Fishes at the high end of their size range are widely considered to be a disproportionately important component of total stock breeding potential due to their high fecundity and higher larval survival compared to smaller breeding individuals (Birkeland and Dayton 2005, Williams *et al.* 2008). In addition, fishers often preferentially target large resource fish, making prime spawner biomass a good indicator of fishing pressure.

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[3] In other TNC reports, "resource fish" may be called "target fish." The species comprising these groups are identical (see Table 3.1).

Invasive fishes included three species: *Cephalopholis argus* (peacock grouper or roi), *Lutjanus kasmira* (bluestriped snapper or ta‘ape), and *L. fulvus* (blacktail snapper or to‘au).

3.6.2. Statistical Analysis

Fish and benthic data: Standard parametric and non-parametric statistical approaches, as appropriate, were used to test for differences between Reef Zones and depth. In most cases, a multifactor ANOVA including Reef Zone and depth was used to examine summary-level variables (*e.g.*, total fish biomass, total fish abundance). Reef Zone was considered a fixed categorical factor and depth was treated as a continuous covariate. Any significant interaction term was investigated using graphical plots to assess the effect of the interaction on the interpretation of the individual factors. Given the natural variability of coral reef ecosystems, statistical significance for biological and sediment data was considered to be $p_{adj} \leq 0.05$ and marginal significance to be $0.05 < p_{adj} \leq 0.10$. Model fits were assessed by examining the distribution of model residuals, Cook's distances with values greater than 4/n as the threshold for influential data points, and leverage. Fish biomass data were (log+1)-transformed to correct skewness and improve heteroscedasticity prior to analysis. For significant factors, *post hoc* multiple comparisons were made using a Tukey correction to control the overall Type I error rate.

Sediment data: Sites were grouped into four depth categories: 0-2m, 2-5m, 5-10m and greater than 10m. Statistical analyses were conducted using R (version 3.4).

Different generalized linear statistical models were considered to identify which environmental factors were most important in influencing coral bleaching rates observed across the survey sites. Fixed factors considered were percent terrestrial origin, organic material, and grain size (silts, fines, silts plus fines, medium sands), while depth and zone were random factors. Prior to analysis, all factors were transformed using an arcsinsqrt function to reduce skewness. Because the models differed in the possible fixed factors considered, the REML was forced to be false for comparison. Models were compared by examining their AIC.

3.6.3. Comparisons with other survey efforts

Two other survey efforts have been undertaken within the Keōmuku Reef Tract. The HCFRU undertook a one-time, comprehensive benthic and fish assessment of the reef area fronting Maunalei Gulch (Friedlander *et al.* 2012) using similar transect methods to those employed in 2021. Direct comparisons were made with the HCFRU data on total fish abundance and biomass and benthic cover using data from sites in Reef Zone B. To improve comparability, the 2021 data were stratified by the same substratum categories as those used by Friedlander *et al.* (2012).

NOAA-ESD surveyed 11 sites on the forereef of the Keōmuku Reef Tract in 2013 (seven sites) and 2016 (four sites). While the benthic cover data were comparable to those collected by TNC in 2021, the NOAA-ESD surveys used stationary point counts (SPC) instead of transects to assess the fish assemblage. The use of different methods results in NOAA-ESD fish data that are not easily comparable with the data collected by TNC using belt transect. For this reason, these data are not considered in this report.

Table 3.1. Fish species comprising the seven resource species groups and the non-resource group used in this report. Groups are modified from Williams *et al.* (2008).

Resource Group	Species	
Acanthuridae (Surgeonfishes)	*Acanthurus achilles* *Acanthurus blochii* *Acanthurus dussumieri* *Acanthurus leucopareius* *Acanthurus nigroris*	*Acanthurus olivaceus* *Acanthurus triostegus* *Acanthurus xanthopterus* *Ctenochaetus* spp. *Naso* spp.
Apex	*Aphareus furca* *Aprion virescens* All Carangidae (jacks)	All Priacanthidae (big-eyes) All Sphyraenidae (barracuda)
Labridae (Wrasses)	*Bodianus albotaeniatus* *Cheilio inermis* *Coris flavovittata* *Coris gaimard*	*Iniistius* spp. *Oxycheilinus unifasciatus* *Thalassoma ballieui* *Thalassoma purpureum*
Mullidae (Goatfishes)	All	
Others	*Chanos chanos* *Cirrhitus pinnulatus*	*Monotaxis grandoculis*
Holocentridae (Redfish)	*Myripristis* spp. *Sargocentron spiniferum*	*Sargocentron tiere*
Scaridae (Parrotfishes)	All	
Non-Resource	*Acanthurus nigrofuscus* *Acanthurus nigricans* *Chaetodon multicinctus* *Chaetodon ornatissimus* *Chaetodon quadrimaculatus* *Chaetodon unimaculatus*	*Plectroglyphidodon* spp. *Stegastes* spp. All wrasses, except those listed above All hawkfishes, except *Cirrhitus pinnulatus* All triggerfishes, except planktivorous species

3.6.4. Moving Window Analysis

A Moving Window Analysis (MWA) was used to examine spatial patterns in the benthic assemblage structure along the length of the Keōmuku Reef Tract. A MWA is an exploratory technique adapted from landscape ecology to investigate spatial relationships between landscapes, and to differentiate transition boundaries within those landscapes. MWA uses a relative measure of dissimilarity between consecutive samples along an environmental gradient to identify boundaries between distinct assemblages. Dissimilarity indices are calculated between adjacent “windows” and plotted against the longshore position within the reef tract. When two “windows” are sufficiently different, a high dissimilarity value occurs, and the “spike” signifies a boundary between two potentially different assemblages.

Separate MWA analyses were conducted for shallow (<2 m) and deep (>2 m) reef areas. Only corals were used in the MWA because they have been found to yield the best signal-to-noise ratio and clearest results, especially along sediment gradients (West and van Woesik 2001, Rongo 2004, Minton *et al.* 2022). In addition, the four sites within Reef Zone A were excluded from the MWA because they were spatially isolated from the rest of the survey area by a wide sand channel and were noted as being substantially different from the rest of the Keōmuku Reef Tract by the survey teams.

Each analysis window was created by averaging across five adjacent survey sites along the length of the Keōmuku Reef Tract. For example, assuming survey sites were numbered sequentially across the reef tract, analysis windows would include the average of sites one through five ($\bar{x}_{1\text{-}5}$), two through six ($\bar{x}_{2\text{-}6}$), three through seven ($\bar{x}_{3\text{-}7}$), and so on until the end of the reef tract is reached ($\bar{x}_{(n\text{-}4)\text{-}n}$). Following guidance in West and van Woesik (2001), this window size was found to maximize the signal-to-noise ratio, and provided the clearest delineation of likely transition boundaries. Other window sizes were tested, but were rejected because the signal-to-noise ratios were lower.

A Bray-Curtis dissimilarity index was calculated for each adjacent set of windows. A dissimilarity value of 70% was used to identify two windows with low similarity, and thus a potential transition boundary between two dissimilar assemblages.

Potential transition boundaries were confirmed using a PERMANOVA with the identified assemblages identified by the MWA as the factor. Data for each assemblage included coral cover by species at all survey sites that comprised the assemblage. If the PERMANOVA found no significant difference between two assemblages, the transition boundary was determined to be “false” and the two assemblages combined into a single assemblage and re-analyzed. The process continued until no additional “false” boundaries were identified. Each assemblage was then described using all available benthic information.

3.6.5. Data Interpolations

Several maps within this report were generated using a spatial analysis technique called interpolation. This technique uses available survey data to generate a complete spatial model of the data by estimating values between the surveys data using a mathematical algorithm that considers the values of nearby data weighed by their distance. Areas with a higher density of surveys will produce more “accurate” interpolations than areas with lower survey density. Interpolation maps were generated for this report primarily to display general spatial patterns and should not be used to predict exact values at any given location. For example, an interpolation map can, with a high degree of reliability, indicate that one Reef Zone has more coral than another Reef Zone, but it should not be used to estimate the “exact” coral cover at a specific location within the Reef Zone. To estimate coral cover, amount of fish, etc., current survey data from the specific location should always be used over the interpolation maps when these data are available.

Spatial raster (interpolation) models for coral cover and coral bleaching were generated in ArcGIS Pro. An Inverse Distance Weighted (IDW) model was chosen based on the dense sample design and the interpolated surfaces being highly locally dependent (*i.e.* sites nearby are similar to each other). IDW tends to be more accurate in predicting the abundance of sessile marine organisms, especially when the distance between sampled locations is small. Interpolated surfaces were generated using the three nearest sampled locations, and a power of 3 was used to increase the weight of the nearest sampled locations and minimize the mean error between measured and predicted values.

3.6.6. Statistical Programs and Libraries

All statistical analyses were conducted in R ver. 3.6.1 (2019-07-05). Final data were exported to Microsoft Excel for graphing and figure generation. Multi-factor ANOVAs were conducted using standard linear model functions in R. All multivariate analyses were conducting using the “vegan” package, with follow-up PERMANOVA pairwise comparisons made using the “pairwise.adonis()” function developed by Pedro Martinez Arbizu. Throughout this report, means are presented as the average ± the standard error of the mean (SEM) unless otherwise stated. ANOVA and PERMANOVA summary tables have been compiled in Appendix B.

4. Results and Discussion

4.1. Sediment and Water Quality

The survey of the shallow reef waters for water column turbidity, benthic sediment characteristics and sedimentation rates indicated that the Keōmuku Reef Tract has some of the most turbid and sediment-affected waters in the Hawaiian islands. The results detailed below come from surveys conducted in the early summer, after spring rains had passed and before possible hurricane and tropical storms might deliver rainfall. Streams had been dry for multiple weeks when surveyed, so the data presented here represent baseline, non-storm conditions on typical tradewind-driven days.

4.1.1. Sediment composition and thickness

A typical benthic sediment sample was mostly calcareous in origin (86.8 ± 12.7%), with 8.9 ± 11.4% terrigenous material and 4.3 ± 1.6 % organic material (Table 4.1). Only four sites had less than 50% marine-derived calcareous material. These terrigenous-dominant sites were located in the more southerly reef zones D and E near Keōmuku and Wai‘ōpae watersheds (see Figure 3.1). The values here are similar to the percentages determined by Field et al for south shore Moloka’i’s fringing reef, where terrigenous sediments were found to be 13.3% with considerable variability across reef flat sites.

For grain size, fines and silts comprised about 15% of average sample by weight, with 10.6% fines and 4.4% silts. Sites were highly variable, with some sites having up to 74% fine sands. Fines and silts both increased with percent terrigenous material (Fines: ANOVA, F_{157}(92), $p<0.0001$), but only silts were significantly correlated with percent organic material, indicating that the organic material was very fine-grained (Table 4.2). In addition, increased silts were found at sites with deeper sediment thickness. We examined Silts, Fine and Silts+Fines separately, and found that silts were more likely to be significantly correlated with independent variables, suggesting that Silts may be the more important parameter to consider when looking at terrigenous impacts.

Areas with more complex reef topography (as quantified through rugosity measurements) were associated with high percentages of medium and coarse sand, but topographic complexity and terrigenous percentages were not correlated. This is likely because of the physical oceanographic processes that occur with reefs that have more vertical variability – pockets of less turbulent waters can retain finer sediments.

Table 4.1. Composition of sediment collected in this study.

	(N = 115)
Percent Terrigenous	
min	0.05
max	70.04
mean (sd)	8.89 (11.43)
Percent Calcareous	
min	22.1
max	96.72
mean (sd)	86.78 (12.66)
Percent Organic	
min	0.56
max	9.46
mean (sd)	4.33 (1.57)
Percent Fines	
min	0
max	74
mean (sd)	10.63 (14.18)
Percent Silts	
min	1
max	26
mean (sd)	4.43 (4.42)

Table 4.2: R-square values associated with sediment characteristics at transect sites (n=94).

	Organic %	**Terrigenous %**	**Sediment Thickness**	**Rugosity**	**Water Depth**
Fines + Silts	0.31	0.557	0.218	0.057	0.045
Silt	0.0085	0.03	0.195	0.093	0.044
Fines	0.35	0.603	0.140	0.031	0.032
Medium	0.06	0.107	0.023	0.031	0.037
Coarse	0.25	0.452	0.157	0.061	0.056
Organic %	-	0.56	0.102	0.012	0.023
Terrigenous %	0.56	-	0.121	0.003	0.001

Sediment thickness was measured at 76 survey sites, with average thickness at sites ranging between 0 and 23.3cm. Sediment thickness was highest between 200 and 400m offshore and increased steadily as distance offshore increased (Figure 4.1). The sites offshore that were highest (in red box) were closest to Waiʻōpae in the south and in front of Iamo Stream near the Hauola transect. Sediment thickness and sediment composition parameters were not well correlated, overall (Table 4.2).

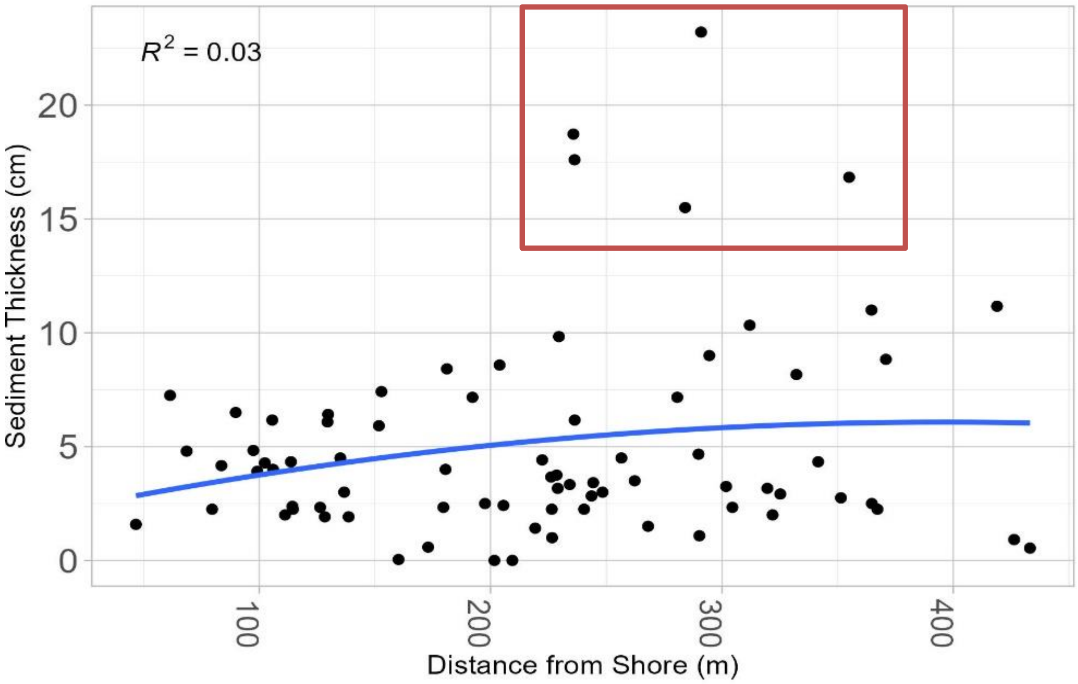


Figure 4.1. Sediment thickness compared with distance offshore. The red box shows the five highest sites located at Wai'ōpae and near Iamo stream.

However, sediment thickness was only weakly positively correlated with both percent matter and percent terrigenous (Figure 4.2) and did not have a strong relation to grain size metrics except for Medium sand. This indicates that thickness might be a quick proxy measurement for whether a sample is terrigenous or calcareous in some settings once a baseline has been established, but likely is not the right tool to measure for places with silt concentrations. In addition, when compared with water column turbidity, however, there was little relationship between averages in zones for sediment thickness and turbidity (Table 4.3).

Overall, sediment characteristics indicated siltier, more terrigenous sediments located nearshore (especially less than 25-m from shore) and in the more southern watersheds of Nahoko, Kaʻa and Waiʻōpae, which will be discussed in section 4.1.2. On Moloka'i, Storlazzi *et al.* (2010) found sediment thickness in the reef flats between 5 to 90 cm at some of the most sediment dominated locations near the shoreline. For this study on Lānaʻi, most samples were less than 10cm in thickness on the inner reef flat.

This data will be discussed further when patterns alongshore and cross shore are considered below.

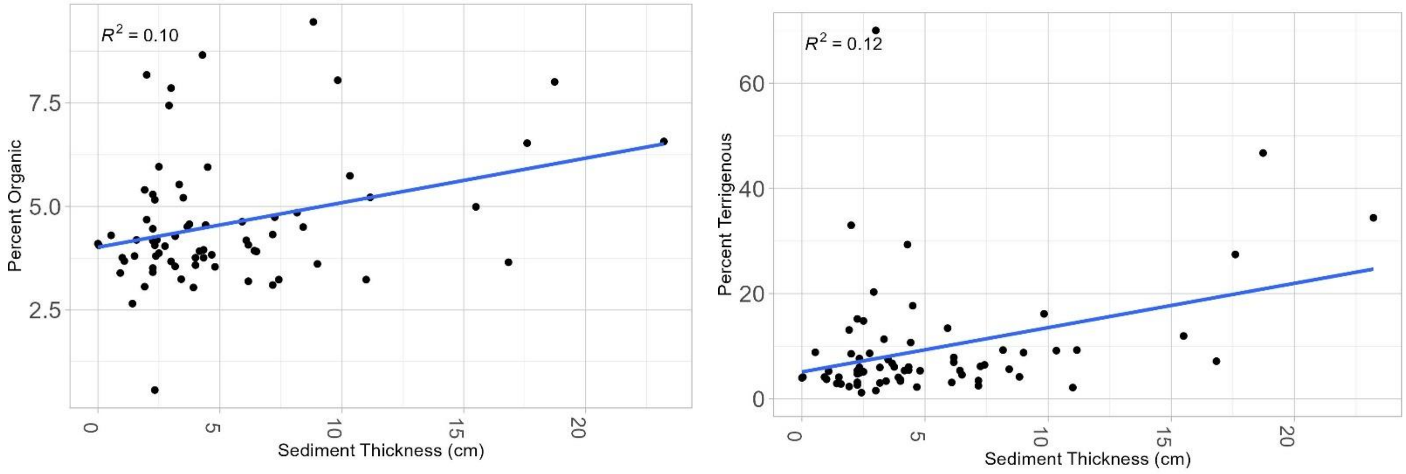


Figure 4.2. Sediment thickness compared with sediment composition parameters (left) percent organic and (right) percent terrigenous.

Sediment composition alongshore

Terrigenous-originating sediments had the highest percentages in front of three stream areas – in Zone B near the mouth of Maunalei Stream, in Zone C near Iamo Stream, and in Zone D south of Nahoko Stream (Table 4.3, Figure 4.3). The percentage of both terrigenous sediments, organic matter and silts increased as the sites were more southward. The percent calcareous predictably increased with distance from shore – demonstrating increasing marine originating sediments (Figure 4.4).

Table 4.3. Sediment characteristics alongshore. Letters represent the five longshore zones.

	Longshore Zone				
	A (N = 1)	B (N = 18)	C (N = 36)	D (N = 26)	E (N = 13)
Percent Terrigenous					
min	4.08	0.92	0.05	1.25	1.57
max	4.08	17.7	47.54	58.74	27.45
mean (sd)	4.08 (NA)	5.28 (4.39)	7.94 (9.90)	8.51 (12.38)	8.26 (6.41)
Percent Calcareous					
min	92.88	76.36	44.05	31.94	66.02
max	92.88	96.32	96.72	95.8	94.76
mean (sd)	92.88 (NA)	91.11 (5.26)	87.74 (11.09)	87.12 (13.82)	87.55 (7.44)
Percent Organic					
min	3.04	0.56	2.26	2.34	2.12
max	3.04	5.95	8.4	9.46	6.53
mean (sd)	3.04 (NA)	3.61 (1.18)	4.32 (1.49)	4.37 (1.90)	4.19 (1.31)
Percent Fines					
min	7	0	1	1	1
max	7	16	70	74	33
mean (sd)	7.00 (NA)	6.06 (5.08)	12.33 (17.42)	11.81 (16.42)	6.77 (8.95)
Percent Silts					
min	2	1	1	1	1
max	2	26	15	17	25
mean (sd)	2.00 (NA)	4.00 (5.78)	4.50 (3.67)	5.04 (4.40)	5.54 (6.72)

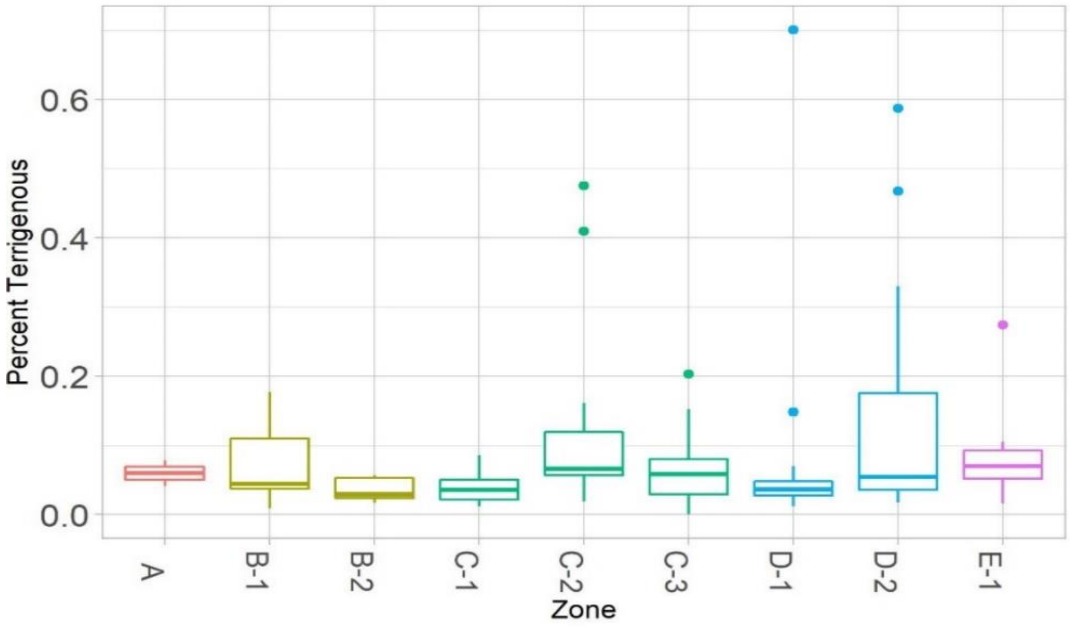


Figure 4.3. Sediment composition alongshore the Keōmuku Reef Tract, showing the increased variability in terrigenous compounds in the more southern zones adjacent to Iamo (Zone C-2) and Nahoko (Zone D-2) streams.

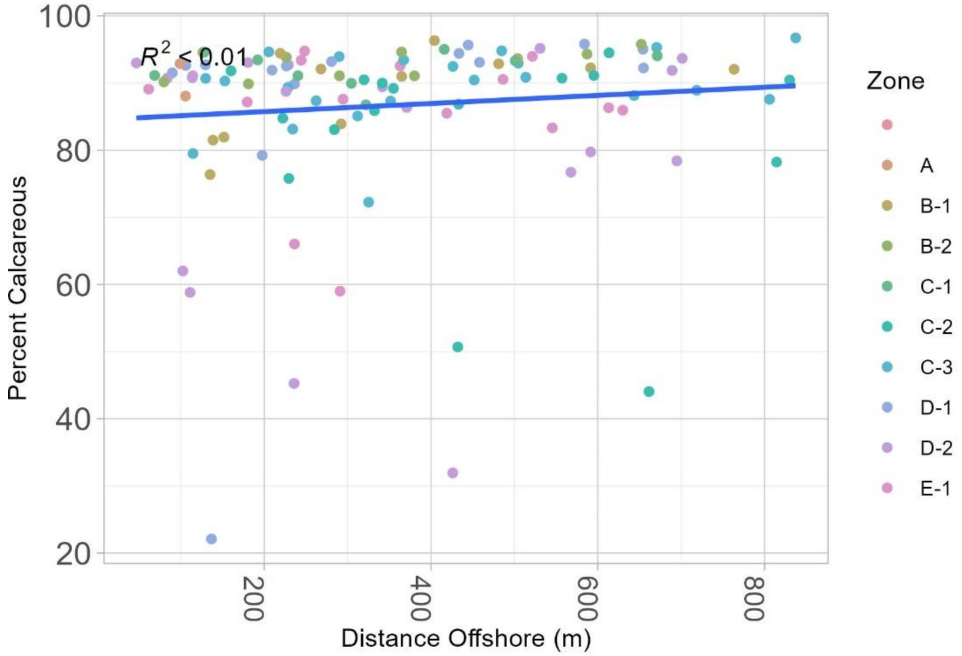


Figure 4.4. Calcareous sediments increase offshore, as organic matter decreases.

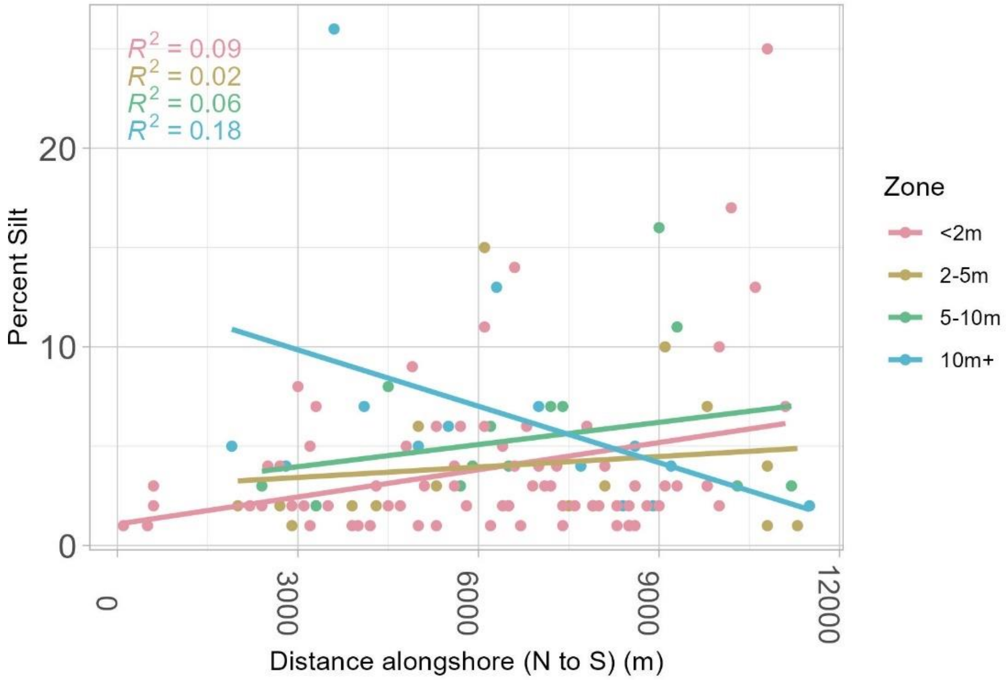


Figure 4.5. Percent silt as a function of distance from the northernmost Zone A, showing an overall increase moving south along the coast for depth categories from 0-10m.

In addition, grain size and depth were highly correlated but showed no linear correlation with distance alongshore from north to south. However, maximum values varied alongshore, with zones in the south between 9000 and 12000m alongshore (C, D, E) having larger outliers than northerly zones (A and B), indicating the presence of patches of fine-grained and terrigenous sediments (Figure 4.5)..

4.1.2. Nearshore water quality

Turbidity. Using *in situ* water quality measurements (turbidity, salinity, dissolved oxygen), the most turbid waters (greater than 50 FNUs) along the Keōmuku Reef Tract were found in front of Kaʻa Gulch, in the area adjacent to the former fishpond at the mouth of that stream. Additional high turbidity locations were at the mouths of Hauola Gulch (and the surrounding shoreline) and Maunalei Stream and surrounding Waiʻōpae fishpond. For the 653 samples measured along the coast over the four days of kayaking, the mean in water turbidity was 2.6 FNU ± 5.0 FNU, with a minimum of 0.4 FNU. Nearshore (<50m from shore) waters were much more turbid than offshore (>500m) waters for the entire coastline (Figure 4.6 a,b). Offshore, higher turbidity was found closer to the reef crest where there was more wave energy – for instance towards Maunalei point and at the southernmost point in zone E offshore of Wai'ōpae. The two highest turbidity measurements were made adjacent to former fishponds at Kaʻa and at Wai ʻōpae, both greater than 20 FNU. A summary of the data by longshore zone is presented in Table 4.3.

There were some anomalies in the kayaking data that deserved a closer look. In zone C-1, for instance, the farther offshore transect showed a stretch of about 280m of high turbidity (mean 4.17 FNU) waters in otherwise clear (<1 FNU) water. Similar plumes reaching offshore were seen near the mouth of Hauola Gulch and in front of Ka’a gulch. The area north of Maunalei Gulch had the highest offshore readings (average of 4.65 ± 1.69 FNU), even in areas that were not affected by surf. These were areas that were not sampled for benthic, fish or sediment composition because there were no hard surfaces – but the kayaking turbidity data was able to document the severity of the water clarity problem.

Table 4.4. Mean coastal water quality parameters summarized by longshore zones.

Zone	Salinity, mean (ppt)	Salinity, s.d. (ppt)	Turbidity, mean (FNU)	Turbidity, s.d. (FNU)	Temperature (deg F)	Sediment Thickness (cm)
A	34.78	0.15	1.36	0.99	75.65	4.31
B-1	34.65	0.56	1.55	1.60	74.62	2.87
B-2	34.60	0.49	1.72	1.93	75.24	5.00
C-1	34.78	0.07	1.54	1.31	74.95	3.61
C-2	34.87	0.03	1.23	0.70	75.65	6.98
C-3	34.82	0.04	1.61	2.13	75.90	3.82
D-1	34.68	0.45	0.91	1.23	75.36	3.97
D-2	34.74	0.49	2.52	12.23	74.96	5.48
E	34.82	0.18	1.49	1.47	75.10	8.40

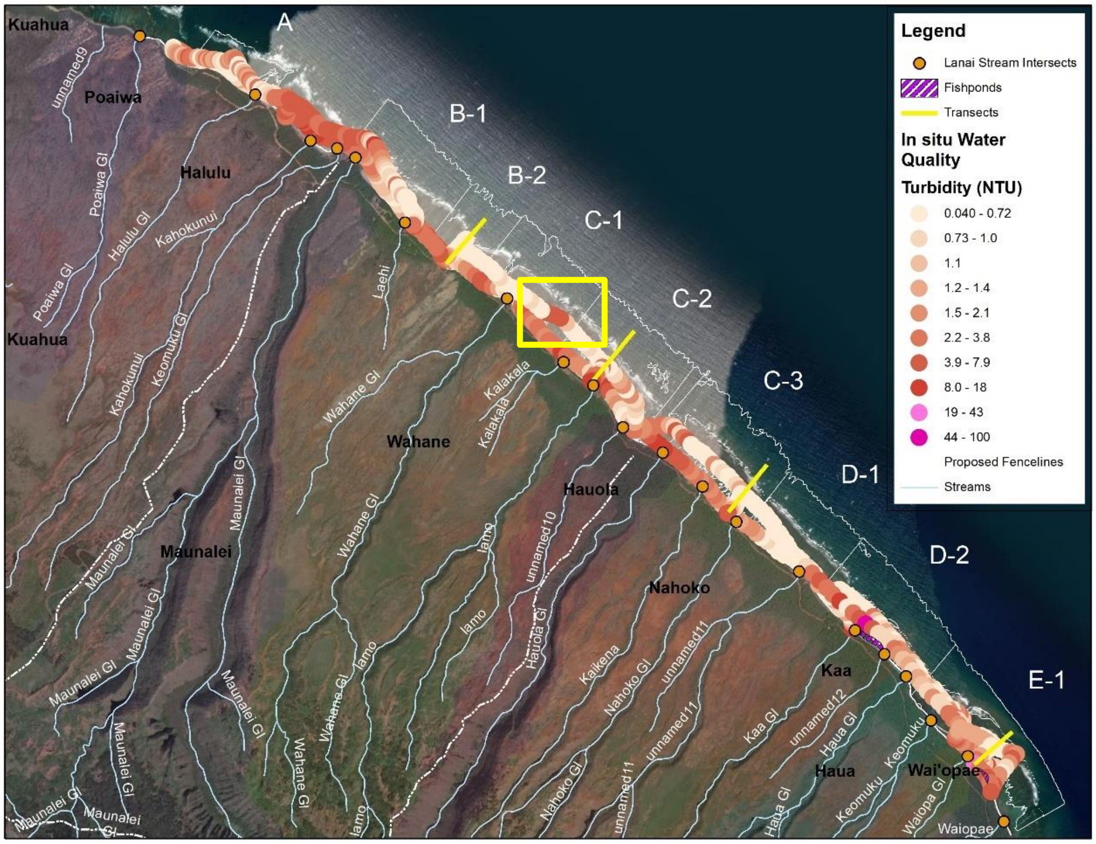


Figure 4.6a. Turbidity mapping along the Keōmuku coast showing transect parallel to shore at approximately 50 and 500m from shore, within the reef flat. The yellow box shows an area offshore of anomalous high turbidity in zone C-1. Satellite imagery confirms that this area is a plume moving offshore.

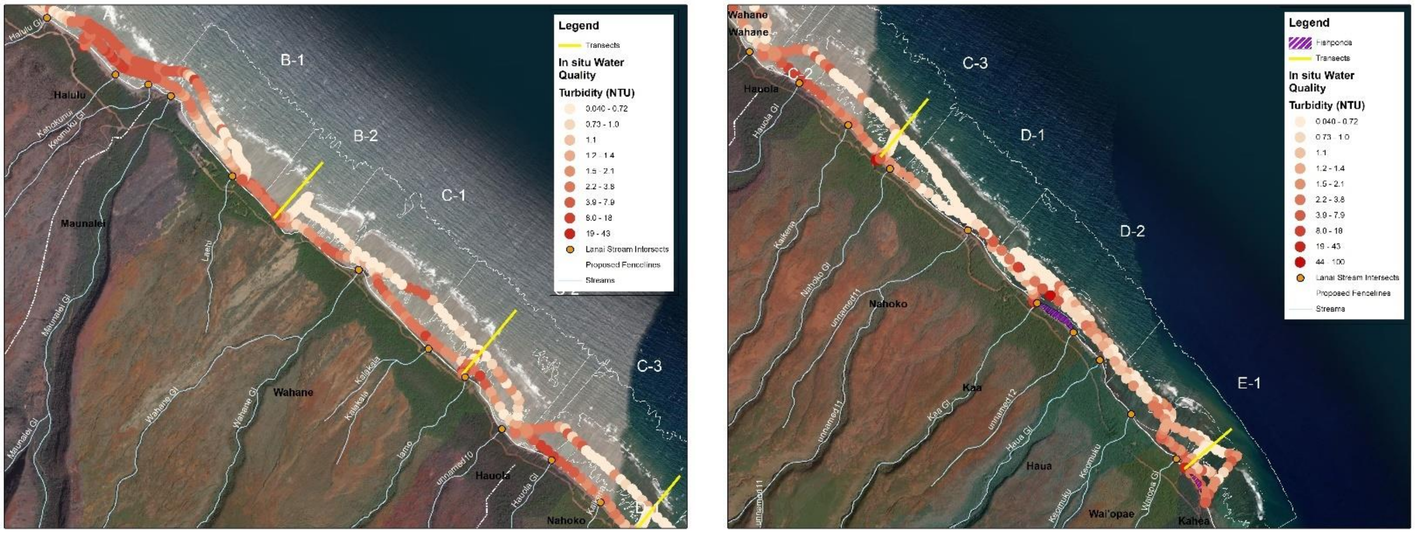


Figure 4.6b. Close-up of turbidity mapping along near (<50m) and far (>250m) transects parallel to shore.

Salinity and groundwater. The sensors used also provided information about salinity, which had surprising gradients across the coastline (Figure 4.7a,b). Areas of fresher, colder water were evident just north of White Stone (zone B-1), and this was accompanied by higher than average turbidity in the nearshore. In zones D-1 and D-2 in front of the unnamed gulch south of Nahoko, fresher, colder water were also found, but in this case coincided with an area that was comparatively clearer than the surrounding areas, with an average of 0.91 FNU compared to the overall average of 1.55 FNU. Sediment delivery and transport to the coastal zone rely on surface water pathways and coastal erosion for moving eroded soils into the water column. Since White Stone is closer to Maunalei watershed, it is possible that there are more inputs that are remaining in place to be resuspended, while still have submarine groundwater discharge due to the unique former dune geologic formation that abuts this section of coastline.

Although all of Lānaʻi is geologically a more uniform type (Lānaʻi Basalt), the small hills that are adjacent to White Stone are made of historic dunes that lend their “white” sand lithography and appearance. This is the only place on the island where this type of geologic feature can be found at scale. Historically, areas with freshwater inputs were good places to grow limu (macroalgae), and attracted juvenile fish and turtles.

There are no similar notable geologic features near the more southern Nahoko Gulch that also had evidence of freshwater inputs. It was observed, however, that this was one of the places were wetland plant species such as akulikuli (*Sesuvium portulacastrum*) were seen in the adjoining coastline. Standing water was visible alongside the road at all tides. Further investigation into the 1878 land map that was created by surveyor W.D. Alexander shows former settlements in this exact area, as well.

This might be an area that would be beneficial for future wetland restoration. The area is flat, and will be likely to be inundated in the future with predicted sea level rise.

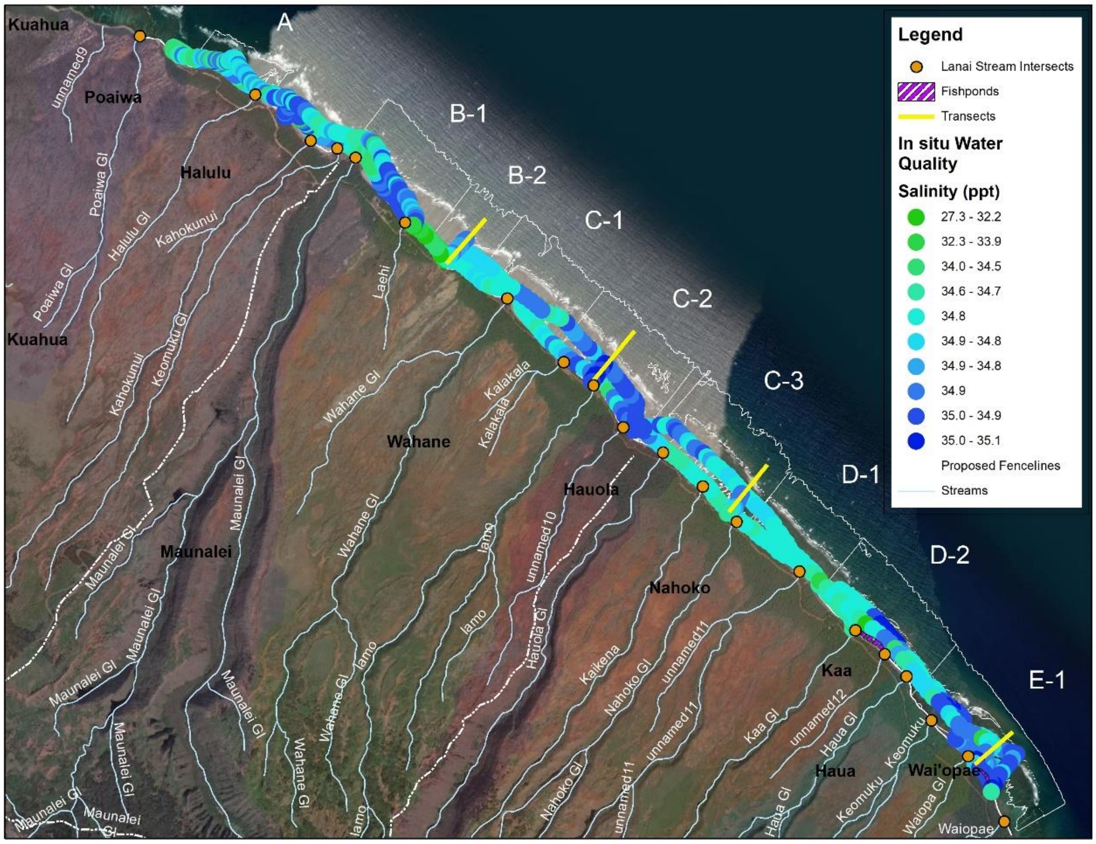


Figure 4.7a: Salinity mapping along the Keōmuku coast.

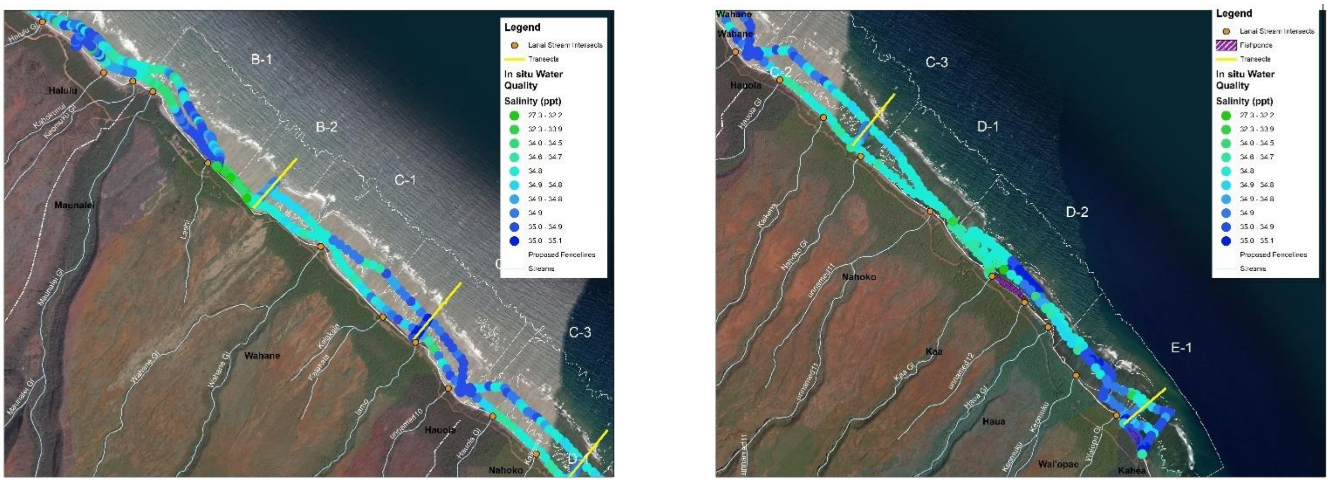


Figure 4.7b. Close up of salinity mapping along near (<50m) and far (>250m) transects parallel to shore. Green values are more freshwater.

4.1.3. Onshore-offshore gradients

As shown above poor water quality indicators such as high turbidity and terrigenous, fine sediments are more prevalent closer to shore. By using the four on-shore/offshore transect stations at 10-m, 25-m, 50-m, 100-m and 250-m offshore, these gradients were further investigated for changes in turbidity and sediment accumulation.

First, we focused on in water column turbidity on onshore-offshore transects using slow kayak-assisted turbidity measurements along the transects. Figure 4.8 shows that the in-water turbidity was highest at Waiʻōpae, reaching above 20 FNU. At all of the sites, the turbidity was highest nearshore and decreased moving offshore, with less than 1 FNU at Lae Hī and Waiʻōpae at 250-m.

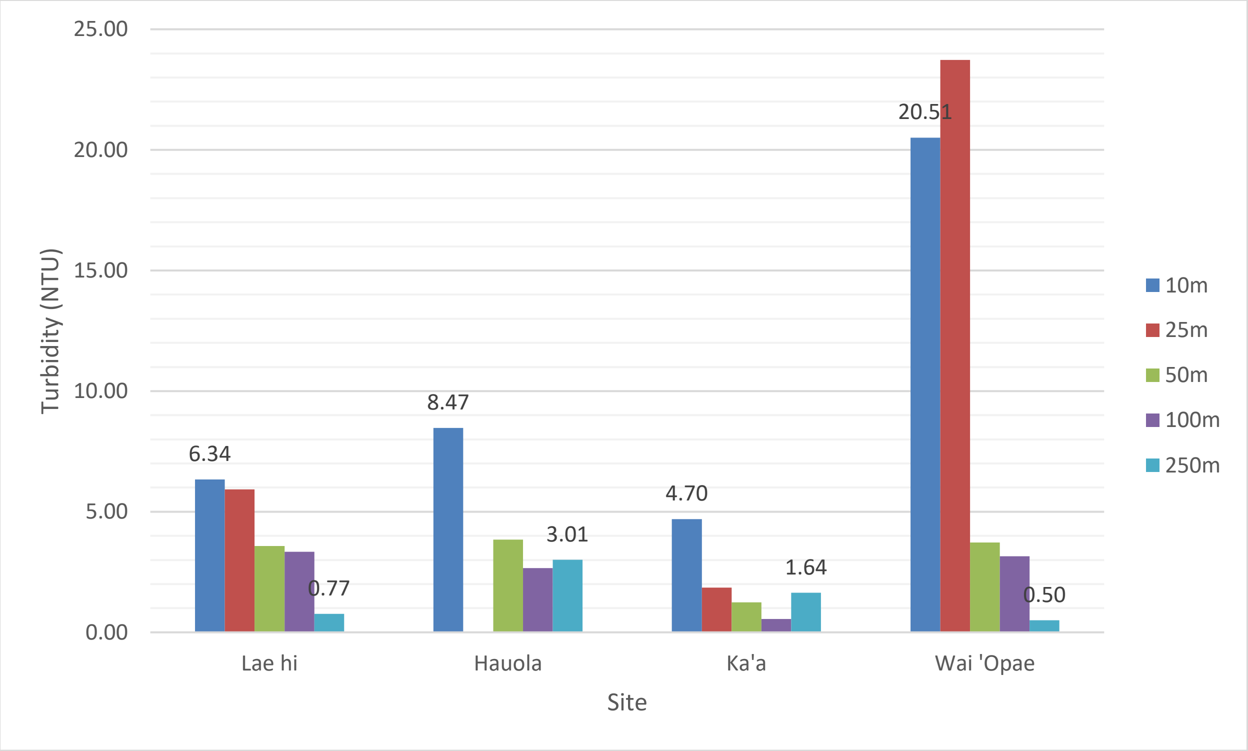


Figure 4.8. Turbidity measured at the surface at distances from shore at four transects.

The maximum sediment trap accumulation for the 10-m station at each site was 884 g/m^2/day, 15,808 g/m^2/day, 5,878 g/m^2/day and 15,280 g/m^2/day for Lae hī, Hauola, Kaʻa and Waiʻopae transects, respectively (Figure 4.9).

These very nearshore values are extraordinarily high compared to data from four similar simple sediment trap experiments on Oʻahu, Kauaʻi, Guam and Molokaʻi in the existing literature of which the highest was 2,000 g/m^2/day (Storlazzi *et al*., 2011). The values recorded here for the

250-m sites are comparable to those from a similar study conducted by Field *et al*. (2013) in Hanalei Bay, which found net sediment accumulations of 67-172 g/m^2/day.

Previous data collected along the Keōmuku Reef Tract by Teneva *et al.* (2014) was from two sites adjacent to the Lae hī transect in this study. They found much lower net accumulation rates for a 60-day study, with 346.2 g/m^2/day and 246.6 g/cm^2/day for traps that were 8-cm in diameter compared to our 5.2-cm traps set for 48 hours. Their traps were placed at approximately 250-m offshore. At 250-m at Lae hī, our results showed a comparable 291 g/m^2/day of sediment capture. This suggests that non-flood sediment accumulation rates have been consistent over the last decade, documenting persistent stress on this section of the reef tract.

The sediment trap and surface turbidity data revealed comparable on-shore/offshore patterns (Figures 4.7 and 4.8). For instance, both surface turbidity and net sediment accumulation rates were higher at Hauola compared to Kaʻa. Both also showed strong decreases with increasing distance offshore, although the decrease in net accumulation rate was much more severe than the decrease in turbidity. The height of the sediment traps (6-in, 0.15m) compared with the depth of the water (in some cases less than 2m depending on the tide), combined with the fineness of the sediments means that the traps may be more likely to capture re-suspension events than the instantaneous turbidity measurements taken. This could explain why shallow water net accumulation rates were so much higher relative to offshore values than was found with turbidiy. It is also possible that the process of deploying and retrieving the sediment traps stirred up sediment that was captured in the traps, inflating accumlation rate values.

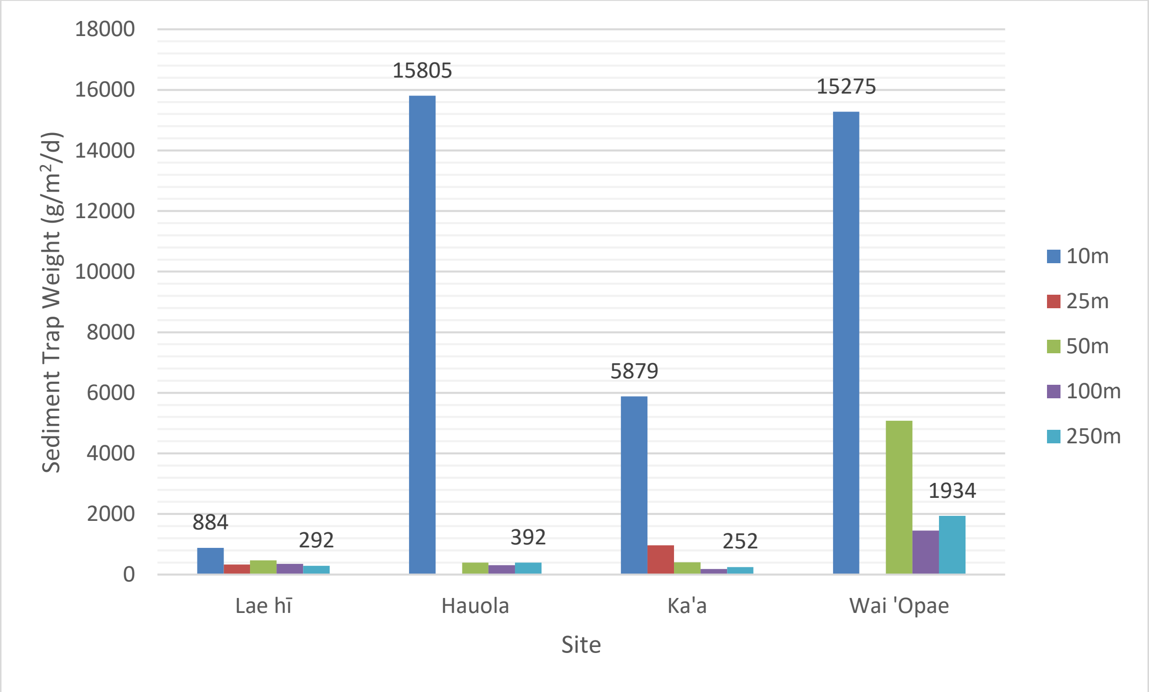


Figure 4.9: Changes in net sediment accumulation over time with distance from shore.

The turbidity mapping partially validated the InVEST Sediment model results presented in Figure 2.3, showing Maunalei Gulch as a hotspot along the coast. However the spatial resolution of the model was not correct – showing a slow dispersion to 1km offshore. Our kayaking data and sediment trap data showed that the impact were much more severe close to the coast, and fell off by 500m – while the offshore Ocean Tipping Points dispersion layer showed a slow decline to 1-km.

It was anticipated that siltier, terrigenous-originating sediments would be more prevalent in shallow nearshore depths because 1) sediments are closer to the surface runoff and coastal erosion sources, 2) reduced wave energy nearshore wouldn't flush sediments as rapidly, and 3) consistent onshore winds also tend to push and keep sediment close to shore. Table 4.5 describes sediment grain size and composition by the different depth profiles where sediments were collected.

Table 4.5. Sediment characteristics by depth.

Characteristics by depth zone	0-2m (N = 51)	2-5m (N = 15)	5-10m (N = 15)	10m+ (N = 13)
Percent Terrigenous				
min	1.18	0.92	1.25	0.05
max	70.04	10.96	58.74	16.19
mean (sd)	9.47 (11.66)	4.42 (2.90)	11.81 (17.52)	7.42 (5.45)
Percent Calcareous				
min	22.1	83.91	31.94	78.23
max	95.65	96.32	95.8	96.72
mean (sd)	86.02 (12.85)	91.61 (3.41)	83.81 (19.51)	88.84 (6.41)
Percent Organic				
min	0.56	2.12	2.26	2.52
max	9.46	6.97	9.32	5.58
mean (sd)	4.50 (1.56)	3.97 (1.34)	4.37 (2.12)	3.75 (1.09)
Percent Fines				
min	0	1	1	2
max	67	17	74	33
mean (sd)	9.14 (11.30)	4.47 (4.63)	20.07 (26.46)	15.08 (10.92)
Percent Silts				
min	1	1	2	2
max	25	15	16	26
mean (sd)	3.92 (4.09)	4.07 (3.95)	5.47 (3.89)	6.54 (6.51)

Surprisingly, the highest percentages of silts and organic materials was near the reef crest between 5-10m depth, and afterwards fell over toward the seaward facing reef slope (Figure 4.7).

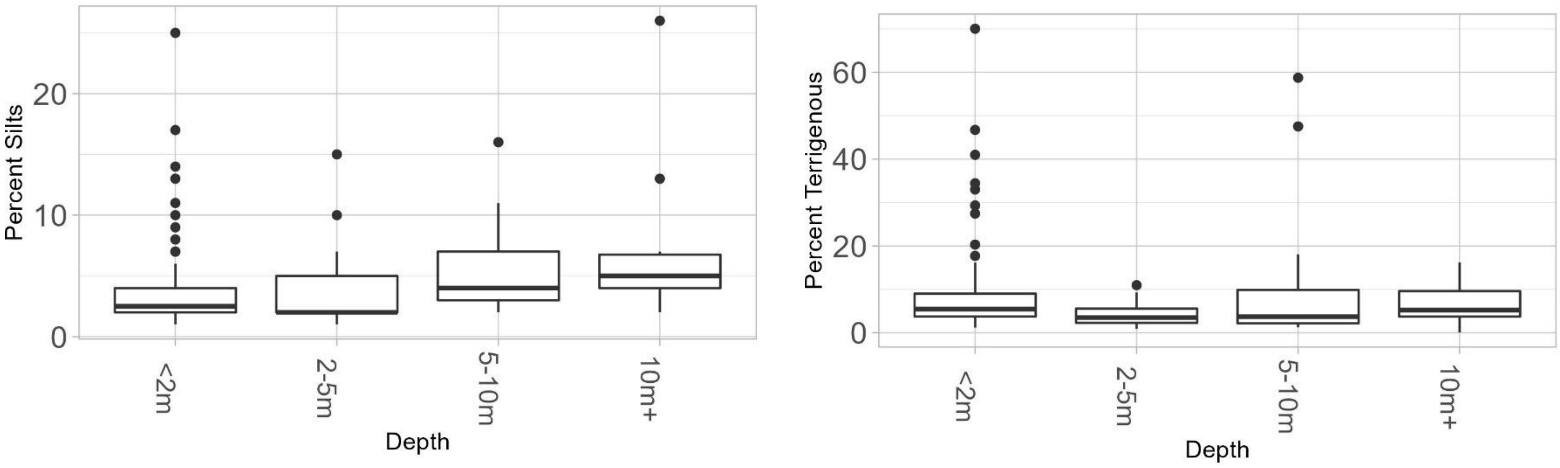


Figure 4.7. **Sediment composition as a function of depth in the shallow reef**

4.1.4. Tidal and wind-driven cycles

During the study, we observed that turbidity seemed to increase in the late afternoons, which we originally attributed to wind-driven mixing in the nearshore. The deployment of a continuous sensor at 250-m offshore at Waiʻōpae allowed us to get a more comprehensive look at what was driving nearshore turbidity. Figure 4.9 shows turbidity over time as compared to water depth. The results show a clear pattern of increases of turbidity with increases in water depth. This suggests higher tides lead to resuspension in the nearshore, increasing turbidity by ten times it's low tide values.

Interestingly, the 48-hour deployment did not show wind-driven increases in turbidity on two consecutive days. Turbidity did not begin to increase until the late afternoon when the tide began to rise. There was no delay between the rising tide and the rising turbidity, suggesting that resuspension and not mobilization by currents or other hydrographic factors, was the source of the increased turbidity.

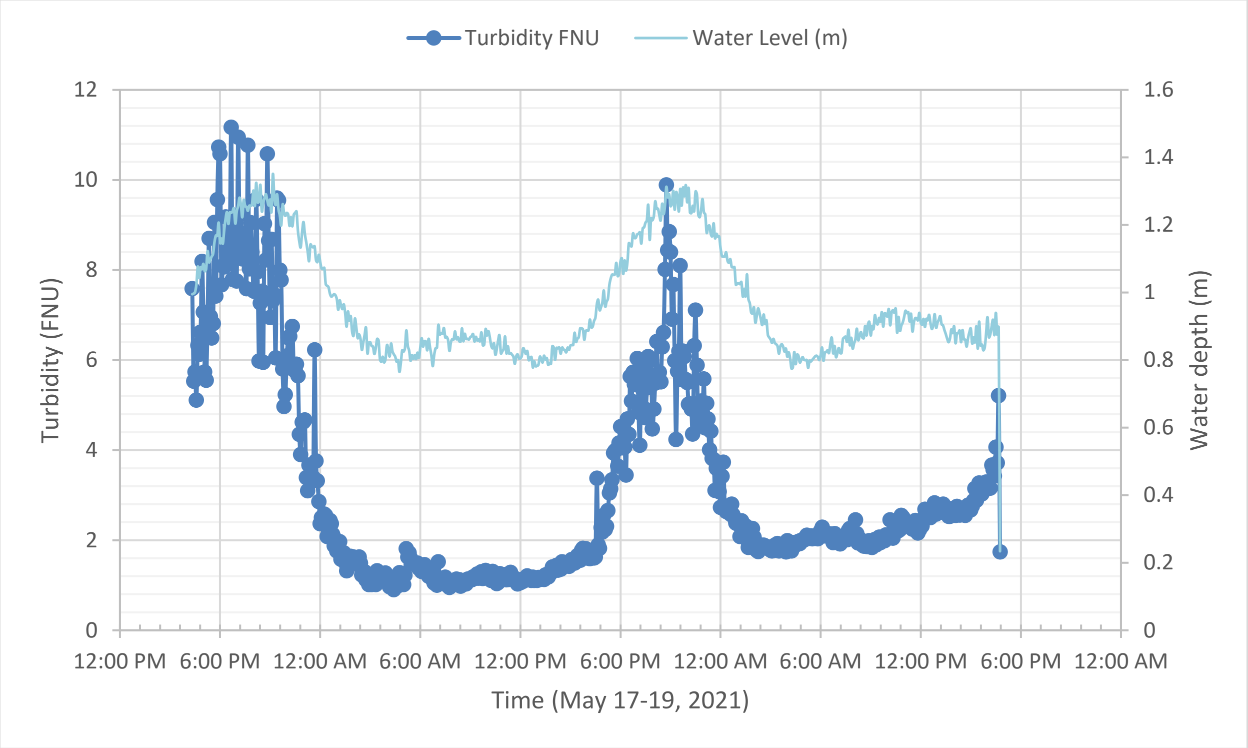


Figure 4.9. 48-hour deployment of a water quality sonde reveals patterns of turbidity and tidal cycle.

4.1.5. Historical investigations into the Keōmuku coastline

It is well known by Lānaʻi residents that the shoreline has moved seaward over the last 150 years in the Keōmoku coast. What was once a pier is today 90m inland in former Keōmoku town. When comparing the current shoreline with the historical georeferenced 1878 map, additional locations where the shoreline has shifted outward were identified. The most notable of these locations include just south of Nahoko at the unnamed stream that was identified as a "transition" point along the shore for benthic habitat in section 4.2 below. At this location, the shore currently extends 117m further onto the reef than it was did in 1878 (Figure 4.10). At Maunalei Gulch, the current shoreline extends 95m past the former shoreline. And, at another location is at the output of Iamo stream, which is coincident with the above Hauola transect – today's shoreline is 146m farther onto the reef than it was in 1878. While this study was meant to be a snapshot of turbidity and sedimentation in the coastal zone on a non-flood summer's week, looking at the 1878 map in comparison to present day allows us to consider long term accumulation. Anticipated sea level rise may mean that future scenarios would have ocean water interacting with formerly deposited fine sediments. Indeed in some locations (notably around the Leahi stream outfall), meters high banks of cut sediments were visible on the shoreline – cut away by ocean waters.

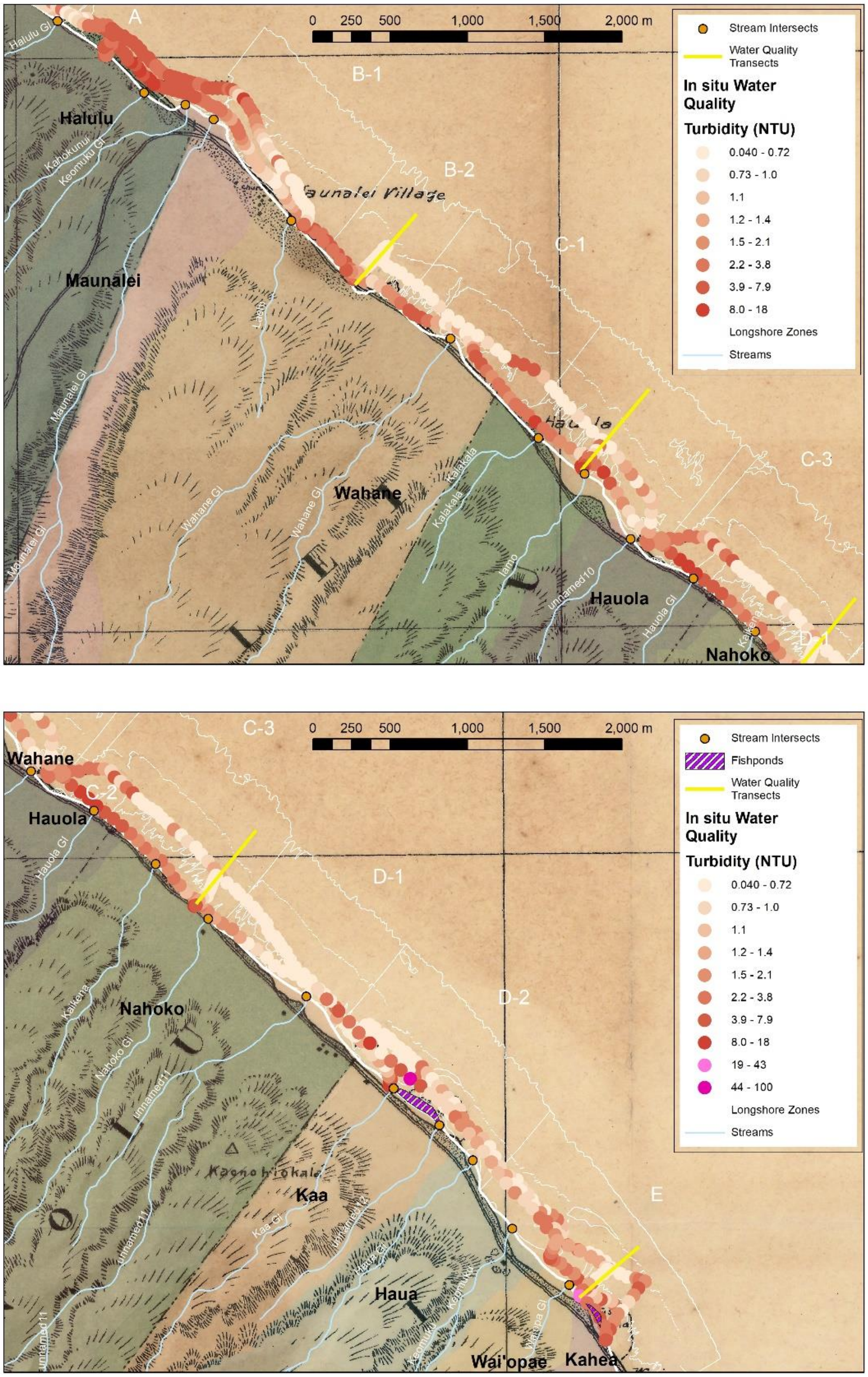


Figure 4.10 Current shoreline (white line) and stream channels (blue lines and orange dots) compared with W.D. Alexander's 1878 map of the Keōmuku coast for Maunalei to Nahoko (top) and Hauola to Wai'ōpae (bottom). The map also includes settlements (small black dots). The 2021 surface turbidity measurements conducted with kayak are also included.

4.1.6. Summary: Sedimentation and Water Quality

Sediment is among the most widespread land-based sources of pollution to shallow water photosynthetic communities such as coral reefs (Takesue and Storlazzi 2019). Sediment-driven harm to coral growth and recruitment comes from decreased access to light, poor surfaces for coral recruits to attach to, and excess organic matter in sediment which can cause bacterial overgrowth and a mucus response from corals (Jokiel *et al.* 2014). Land degradation that increases sediment inputs to the coastal zone results in poor water clarity, especially if there is limited flushing in the nearshore (Wenger 2017, Bainbridge *et al*. 2018). Successful mitigation of land-based impacts to coral reefs requires a source-to-sink framework that targets the main sources of sediments, and also incorporates an understanding of hydrodynamic transport of sediments between source and sink areas in coastal areas (Jokiel *et al*. 2011, Richmond *et al*. 2007). For this study, we found onshore-offshore gradients with locations within 10m of the coast to have turbidity and sediment deposition rates that were over ten times as much as only 250m offshore.

According to Rogers (1990), 10mg/L is the critical suspended sediment concentration (SSC) for coral reef success, above which there is a negative impact to coral growth and recruitment. Tuttle *et al*. (2021) continued to investigate the threshold question and developed a model for impact to adult corals that considered both time and concentration of the sediment threat. They found that sediment levels above 800 g/m^2/day or 80 mg/L for more than 20 days had a negative impact. While we did not take extensive suspended sediment samples for this study, Wenger *et al*. (2017) have suggested an approximate 1:1 relationship between total suspended sediment and turbidity values. For 10 mg/L that critical limit would be 10 FNU, a value that was common in the very nearshore (<25m) sites in this study. A total of 20 samples had values greater than 10 FNU. However, only in the coastal area in front of Maunalei Gulch had above-10 FNU values for turbidity past 100m offshore.

The sediment accumulation data available at four transects corroborated that the locations that would be above literature suggested thresholds were less than 25m from shore. Sediment accumulation values for the 10-m sites had a maximum of 15,800 g/m^2/day – clearly above the suggested 800 g/m^2/day limit. However at the Waiʻōpae even at 250m offshore, sediment accumulation was calculated at 1,948 g/m^2/day, and the 50-m and 100-m sites were also above the critical threshold.

Siltier, more terrigenous benthic sediment samples were most common in the most southerly zones, D and E (acknowledging that benthic sediment samples weren't taken in front of Maunalei Gulch). In these zones, turbidity and sediment depth increased offshore farther than at more northerly zones. Satellite imagery confirmed that plumes were moving offshore.

Comparison with historical imagery showed that the land had extended by up to 146m seaward from its 1878 location at the mouths of three streams: Iamo, Nahoko and Waiʻōpae – or a rate of shoreline extension of over 1m per year. Future sea level rise impacts made lead to increased coastal erosion as these sediments are accessed by coastal waters.

Continuous turbidity measurements made over a 48-hour cycle on a neap tide at 250-m offshore indicated that turbidity increased (upwards of 10FNU) with high tide. Recent studies have concluded that storm pulses may be less detrimental to reef condition than continued lower concentration turbidity (Bahr *et al*. 2020). The range of turbidity over the tidal cycle – from approximately 1.2 FNU to a peak average of 9 FNU shows that corals may be experiencing a range of conditions and sediment stress even without storm inputs. These measurements were taken one of the sites with the highest turbidity and sediment accumulation at 250-m (Wai’ōpae).

If the effects on corals from sediment are driven in large part by resuspension of sediments that were deposited during big storm events or by coastal erosion of fine alluvial plain adjacent to the coast, it can be expected that even with significant decreases in sediment erosion from upland sources, corals in the nearshore (less than 400m offshore) might still be affected for many years to come until those sediments are flushed from the system.

4.2. **Benthic Assemblage**

As with most coral reefs in Hawaiʻi, the composition of the reefs in the Keōmuku Reef Tract changed with depth. Coral cover increased and turf, macroalgae, and abiotic (mostly unconsolidated bottom) cover decreased with depth (Figure 4.12). Two meters was visually identified as the threshold at which the benthic community changed, and corresponded well with depth at which the shallow reef flat transitioned into the deeper reef slope. Nearly all (98%) survey sites within 300 meters of the shore were ≤2.0 meters depth, as were 95% of sites within 400 meters of the shore (Figure 4.13). For this reason, the reef assessment area was divided into "shallow" and "deep" reef areas for further analysis.

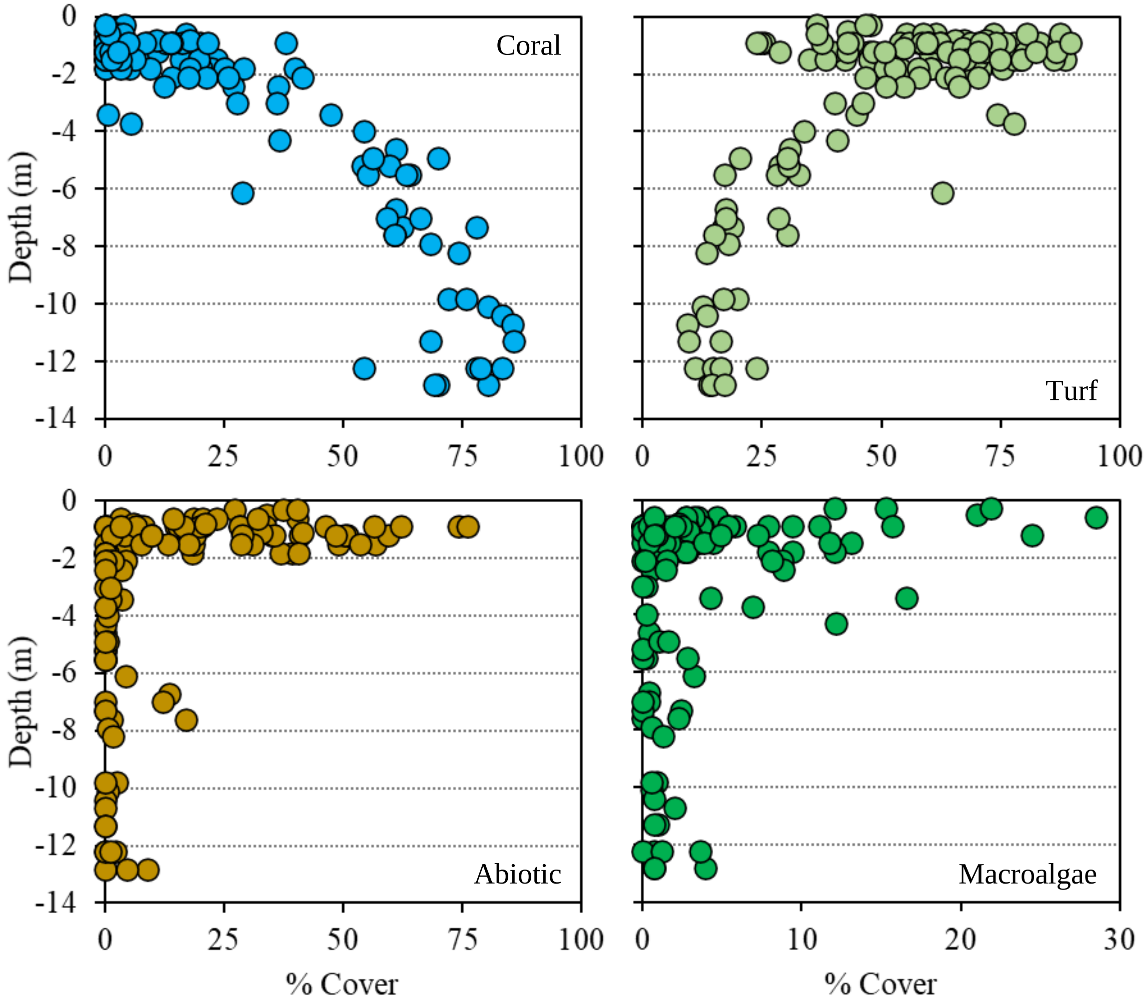


Figure 4.12. Percent cover of coral, turf, abiotic substratum (*e.g.*, sand), and macroalgae by depth within the Keōmuku Reef Tract.

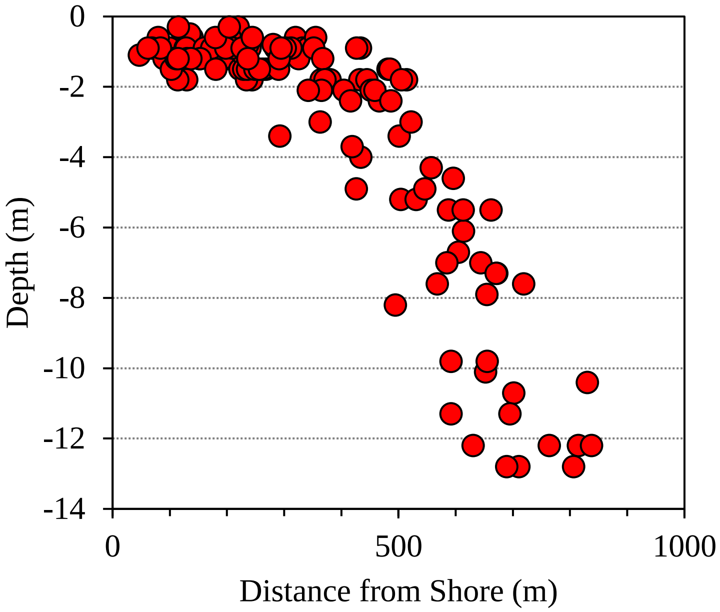


Figure 4.13. Distance from shore by depth within the Keōmuku Reef Tract.

4.2.1. Shallow Reef

Shallow reef areas (<2 meters) were dominated by sediment and turf algae (Table 4.6), covering 61.5 ± 1.8% and 22.4 ± 2.2% of the bottom, respectively. Mean coral cover was low, 7.1 ± 1.0%, but variable across the reef tract (Figure 4.14), which suggests more than one benthic assemblage might the present. Not unexpectedly, coral cover tended to be highest along the seaward perimeter of the shallow reef area, which corresponds approximately with the area immediately landward of the reef crest. Coral species richness was surprisingly high with 19 taxa, although most species were rare, accounting for <0.1% cover. This taxonomic richness makes the shallow reef area within the Keōmuku Reef Tract among the most diverse in the Hawaiian Islands. *Porites lobata* (2.9 ± 0.5%) and *Montipora capitata* (2.1 ± 0.4%) were the dominant coral species, comprising almost three-quarters of all coral cover on the shallow reef.

Macroalgae were also abundant and diverse. Individual species were difficult to identify in the benthic photographs, but at least 13 taxa were observed on the shallow reef, including *Halimeda* spp., *Padina* spp., *Asparagopsis* spp., and *Amansia glomerata*. These species tended to be fairly ubiquitous across the shallow reef area.

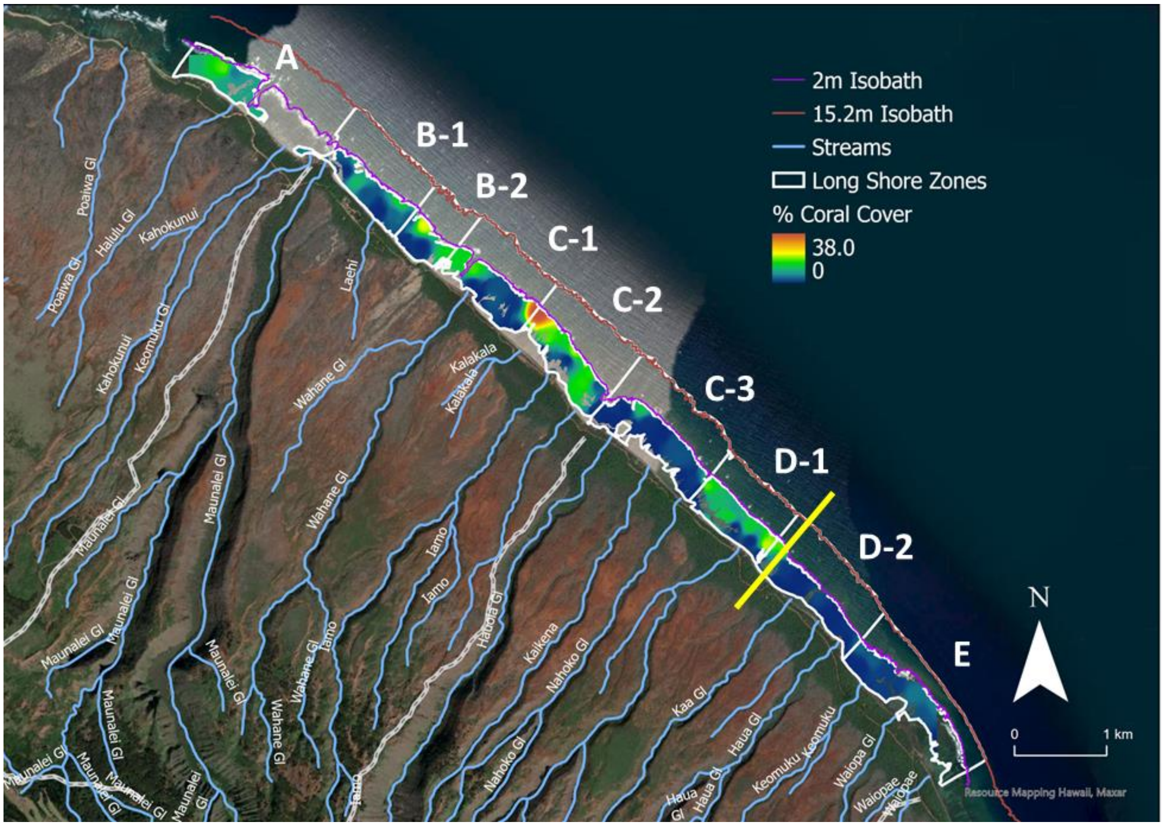


Figure 4.14. Interpolation of coral cover across the shallow reef area of the Keōmuku Reef Tract. The yellow line shows the approximate boundary between the S1/S2/S3 (to the northwest) and the S4 (to the southeast) benthic assemblages (see text for discussion).

Benthic assemblage structure did not significantly differ among Reef Zones, whether sub-zones were considered (PERMANOVA; $F_{7,77}$=1.09; p=0.353) or not (PERMANOVA; $F_{3,77}$=0.96; p=0.507). While the benthic assemblage structure did not align well with the Reef Zones identified by TNC, the MWA identified three potential transition boundaries within the shallow reef assemblage (designated a-c in Figure 4.15):

(a) A double signal near the Wahane gulch drainage at longshore distances 4,140 and 4,400 m);

(b) A single signal at the boundary of Nahoko gulch and a small gulch to the southeast at a longshore distance of 7,100 m and which roughly corresponded with the boundary between Reef Zones C and D; and

(c) A single signal aligning with a reef channel off Ka‘a gulch at a longshore distance of 8,600 m and which roughly corresponded with the boundary between Reef Zones D-1 and D-2.

Table 4.6. Mean (±SEM) percent cover of the bottom by taxa observed in shallow (<2 m) and deep (>2 m) reef areas of the Keōmuku Reef Tract during 2021 surveys.

	Shallow reef (n=82)	**Deep reef** (n=47)
Coral	7.1 ± 1.0	54.7 ± 3.4
Montipora capitata	2.1 ± 0.4	28.4 ± 3.0
Montipora patula	0.6 ± 0.1	13.3 ± 1.1
Porites lobata	2.9 ± 0.5	5.0 ± 0.9
Porites compressa	0.8 ± 0.2	4.9 ± 1.0
Pocillopora meandrina	0.4 ± 0.1	1.7 ± 0.3
Porites rus	0.1 ± 0.1	0.5 ± 0.2
Pavona varians	0.1 ± 0.1	0.4 ± 0.1
Pavona duerdeni	0.1 ± 0.1	0.4 ± 0.1
Pocillopora damicornis	0.1 ± 0.1	<0.1
Leptastrea purpurea	<0.1	<0.1
Porites lichen	<0.1	<0.1
Leptastrea transversa	<0.1	<0.1
Porites lutea	<0.1	<0.1
Cyphastrea ocellina	<0.1	<0.1
Porites monticulosa	<0.1	<0.1
Leptoseris incrustans	0	<0.1
Montipora incrassata	0	<0.1
Coral sp.	<0.1	0
Fungia scutaria	<0.1	0
Pavona maldivensis	<0.1	0
Psammocora stellata	<0.1	0
Turf	61.5 ± 1.8	31.9 ± 2.9
CCA	2.7 ± 0.5	9.2 ± 0.9
Macroalgae	4.3 ± 0.6	2.2 ± 0.5
Other	0.9 ± 0.8	0.1 ± 0.1
Cyanobacteria	1.1 ± 0.6	<0.1
Abiotic	22.4 ± 2.2	1.9 ± 0.6
Sand	21.4 ± 2.1	1.9 ± 0.5
Rubble	0.9 ± 0.2	<0.1
Recently dead coral	<0.1	<0.1
Pavement	0	<0.1

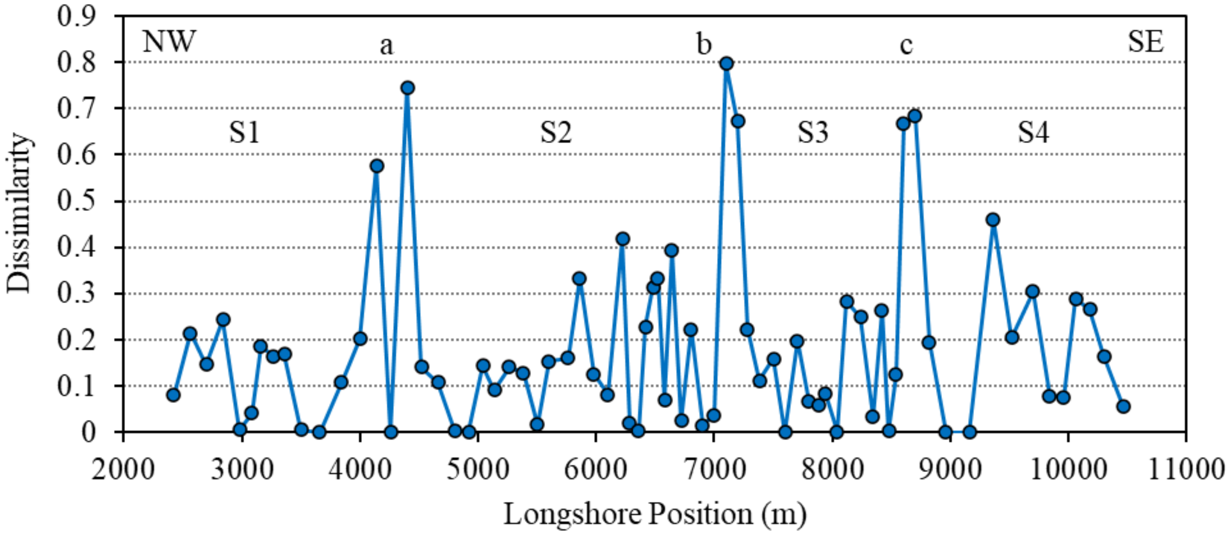


Figure 4.15. Dissimilarity between the shallow reef windows used in the MWA plotted by their longshore position. The longshore position of each window was the average position of the five assessment sites that comprised the window. Longshore position was measured from the northwest boundary of the assessment area, but sites within Reef Zone A were not included in the MWA. Letters (a, b, and c) designate transition boundaries and S1 through S4 designate potential shallow water benthic assemblages.

These transitions created four potential benthic assemblages (designated S1-S4 in the Figure 4.15). However, the PERMANOVA conducted to confirm these assemblages supported only transition boundary c at the 8,600-mark (PERMANOVA; $F_{3,60}$=1.74; p=0.024). Assemblages S1, S2, and S3 showed no pairwise differences among them, but all three were significantly different from S4. Differences between the S1/S2/S3 and S4 assemblages were driven primarily by the abundance of coral (Table 4.7). The S4 assemblage to the southeast had lower total coral cover and species richness than the S1/S2/S3 assemblage to the northwest. Otherwise, the two assemblages had similar cover of most other benthic groups (Table 4.7). The interpolation maps for coral cover (Figure 4.14) also suggest the S1/S2/S3 assemblage may be more spatially heterogeneous than the S4 assemblage, with small sections of high coral cover interspersed among reefs areas with predominately low coral cover.

Previous studies that have used MWA have used window sizes considerably smaller (on the order of 5-10 m) than those employed here. The size of the windows in the MWA averaged 452.7 ± 18.8 m and were sufficiently large that they might have been insensitive to assemblages covering small spatial scales. To investigate, a detailed examination of each transition boundary was conducted.

Examining coral cover by longshore distance (Figure 4.16) shows that all three transition boundaries identified in the MWA correspond to an area of low coral cover directly adjacent to an area of high coral cover. The first transition boundary (a in Figure 4.16) appears to encompass an approximately 700 m long region of low coral cover (0.7 ± 0.6%) bookended by areas with

Table 4.7. Mean (±SEM) percent cover of the bottom by taxa and coral species richness in the S1/S2/S3 and S4 assemblages identified by the shallow reef MWA.

	S1/S2/S3 (n=63)	S4 (n=15)
Coral	8.3 ± 1.3 (Richness: 18)	1.3 ± 0.4 (Richness: 8)
Turf	59.5 ± 2.0	66.0 ± 5.0
CCA	3.1 ± 0.7	0.9 ± 0.4
Macroalgae	4.2 ± 0.7	5.7 ± 2.2
Other	1.2 ± 1.0	<0.1
Cyanobacteria	1.4 ± 0.8	<0.1
Abiotic	22.4 ± 2.5	26.1 ± 5.1

higher coral cover (NW: 10.5 ± 3.2%; SE: 17.2 ± 7.0%). This region of low coral cover lies directly off the stream input draining Wahane Gulch, and has an obvious sediment fan extending out onto the reef flat in aerial images.

Likewise, the second transition boundary (b in Figure 4.16) also appears to encompass a short section of reef (~300 m) with low coral cover (0.3 ± 0.3) that is also sandwiched between areas of higher coral cover (NW: 8.6 ± 7.9%; SE: 9.9 ± 0.9%). This sliver of low coral cover reef lies just north of a sizable channel in the reef that appears to be a primary path for sediment moving offshore. A sizeable sediment fan at the drainage of an unnamed gulch to the south of the Nohako gulch is clearly visible in aerial images, as are numerous inputs at the base of Nahoko gulch.

The final transition boundary (c in Figure 4.16), which was confirmed by the PERMANOVA, separates the relatively high coral cover assemblage to the northwest from a uniformly low coral cover assemblage that extended approximately 1,500 m to the southeast, and comprised the remainder of the Keōmuku Reef Tract.

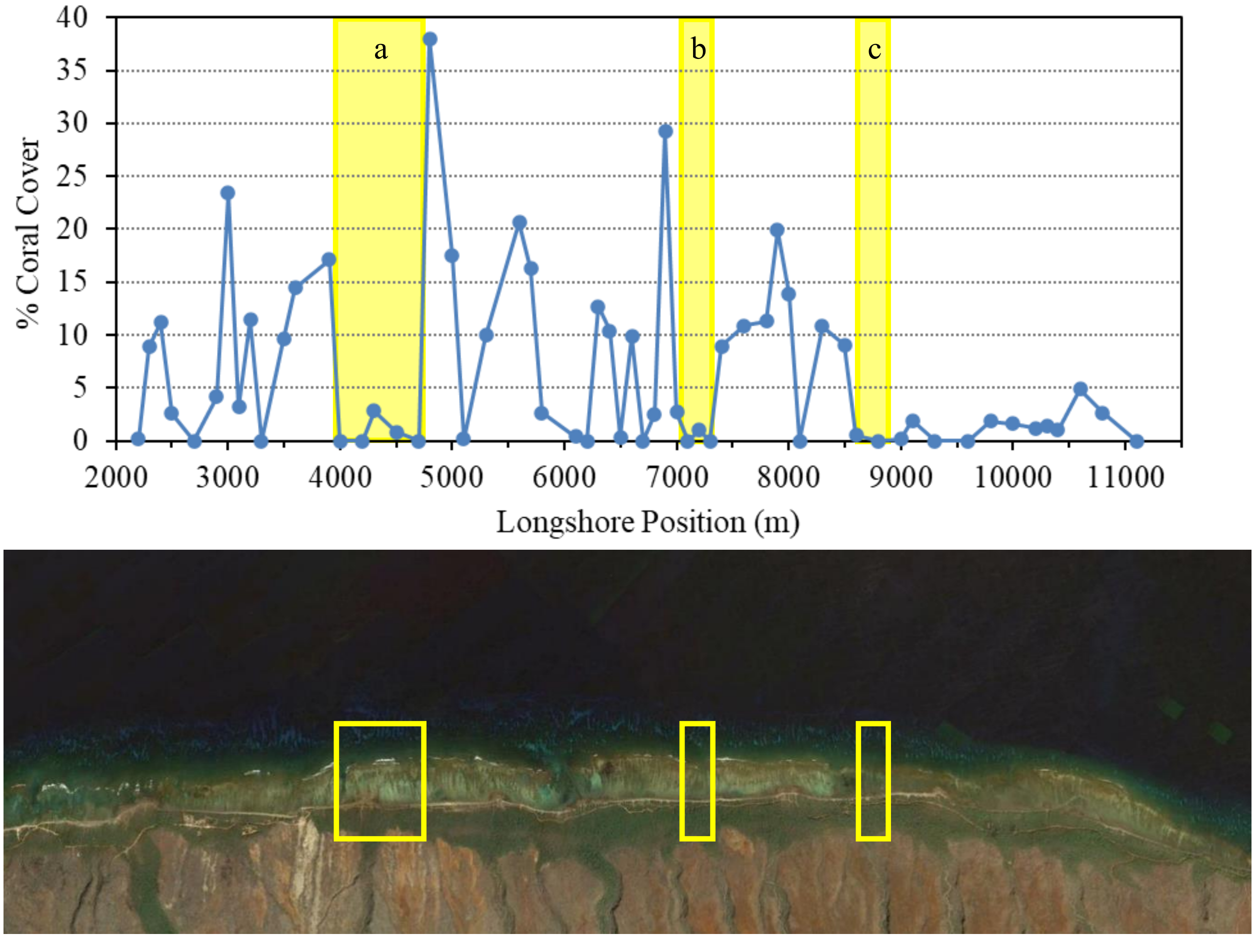


Figure 4.16. Coral cover in the shallow reef area of the Keōmuku Reef Tract. Longshore position was measured from the northwest boundary of the assessment area. Yellow boxes labeled a, b, and c correspond with the transition boundaries identified in Figure 4.15. Sites in Reef Zone A have been excluded from the figure.

4.2.2. Relationship between bleaching and sediment characteristics

The shallow reef areas of the Keōmuku Reef Tract show considerable evidence of sediment-related stress. Many coral species are sensitive to sediment. In sedimented environments, coral colonies are at risk of burial, and also must contend with reduced light due to increased water turbidity. Reef-building corals rely on photosynthetic zooxanthellae for the majority of their energetic needs, and turbid water reduces photosynthetic output.

Bleaching, which occurs when a coral loses its zooxanthellae, is a generalized stress response that is most often associated with elevated water temperature. However, many stressors can induce a bleaching response in coral, including sedimentation. Coral colonies may undergo bleaching when sediment is deposited atop them and/or when light intensity is reduced due to sediment suspended in the water column (Erftemeijer *et al.* 2012).

Coral tissue bleaching rates showed a strong depth-related pattern, and were highest within the shallow reef area (Figure 4.17). The mean coral tissue bleaching rate was 49.9 ± 4.0% in shallow areas compared to 8.9 ± 1.7% for deep reef areas. The tissue bleaching rates in the shallow reef area exceeded those reported from elsewhere in Hawaiʻi during the 2015 bleaching event (Kramer *et al.* 2016, Maynard *et al.* 2016), which is widely considered to be worst mass bleaching event in the state's history.

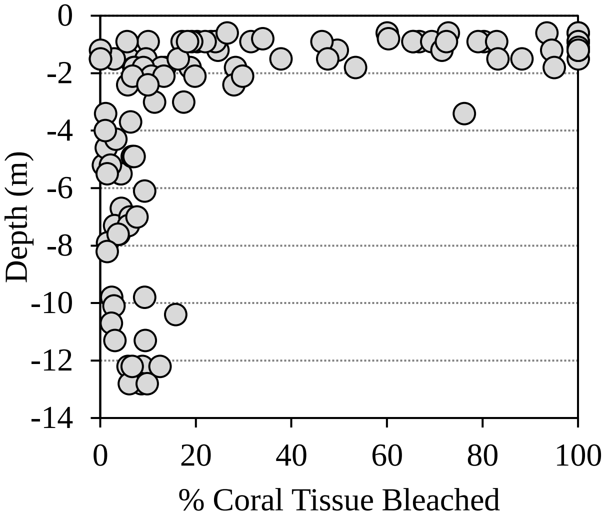


Figure 4.17. Coral tissue bleaching rate by depth within the Keōmuku Reef Tract.

Bleaching was observed across the entirety of the reef tract (Figure 4.18), which suggests it was associated with a widespread stressor. Freshwater inputs tend to have localized effects, and this does not adequately explain the extent of bleaching. Water temperatures were

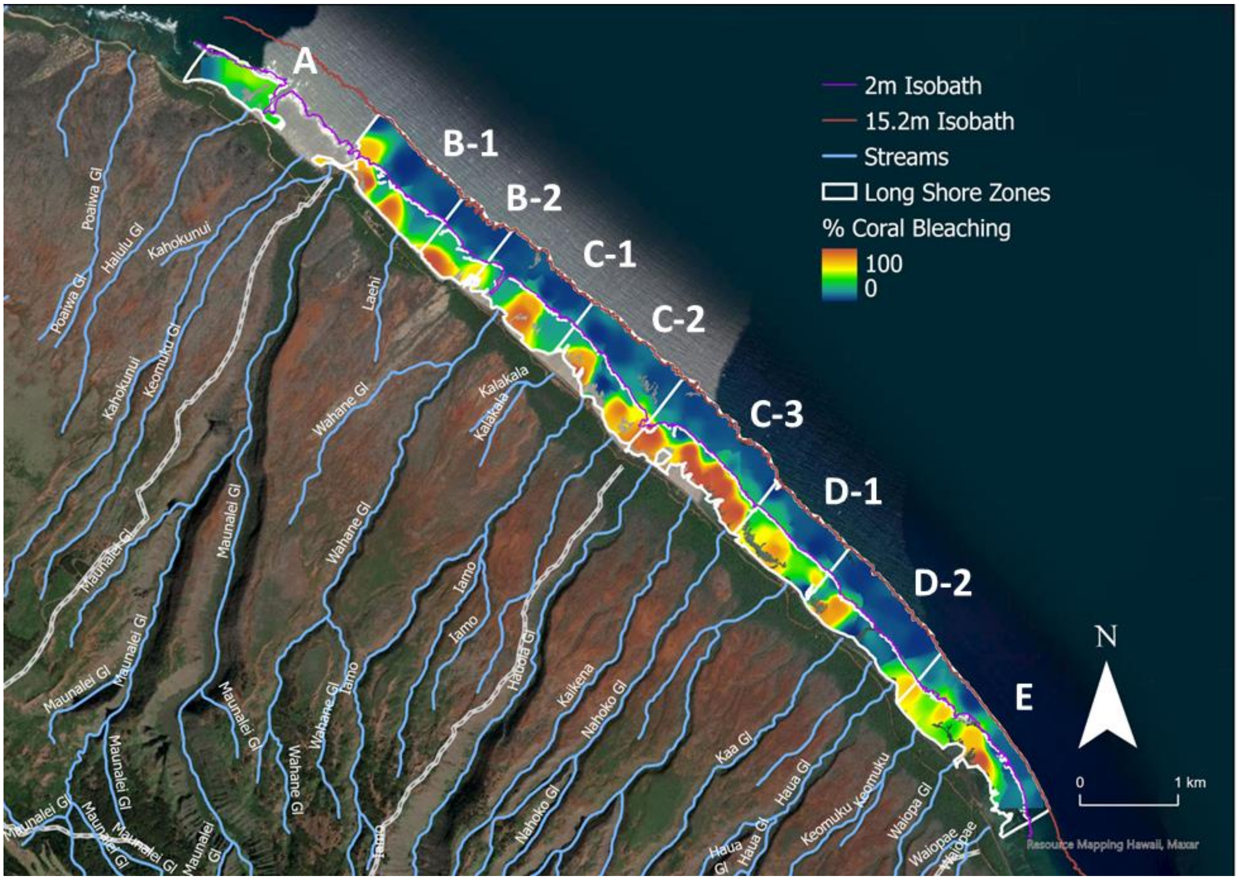


Figure 4.18. Interpolation of coral tissue bleaching rates across the Keōmuku Reef Tract.

not sufficiently elevated to result in a bleaching risk (NOAA Coral Reef Watch) around the time of TNC’s assessment, leaving sediment as the likely stressor responsible for the high coral tissue bleaching rates. Even with high bleaching rates, little coral morality was observed over the course of the survey period (May 12 to June 25, 2021); cover of recently dead coral was low across both shallow and deep reef areas (Table 4.7). Lānaʻi’s reefs lost little coral area as a result of the 2015 mass coral bleaching event (DAR 2017), suggesting these reefs may have some degree of resistance.

Sedimentation can also adversely affect coral recruitment by impairing settlement habitat, burying new recruits, or increasing energetic demands while reducing photosynthesis (Hodgson 1990, Erftemeijer *et al.* 2012, Perez *et al.* 2015). Coral recruit densities showed a significant increasing trend with distance offshore (Correlation; r=0.599; p=0.0018). No coral recruits were observed inside of 50 meters of the shore on any transect (Figure 4.19), and on the Hauola and Kaʻa transects, no recruits were observed within 100 meters of the shore. Sixty percent of coral recruits were *Pocilliopora damicornis*, a "weedy" species that has been found to be common on other sedimented reefs in Hawaiʻi (Minton *et al.* 2019).

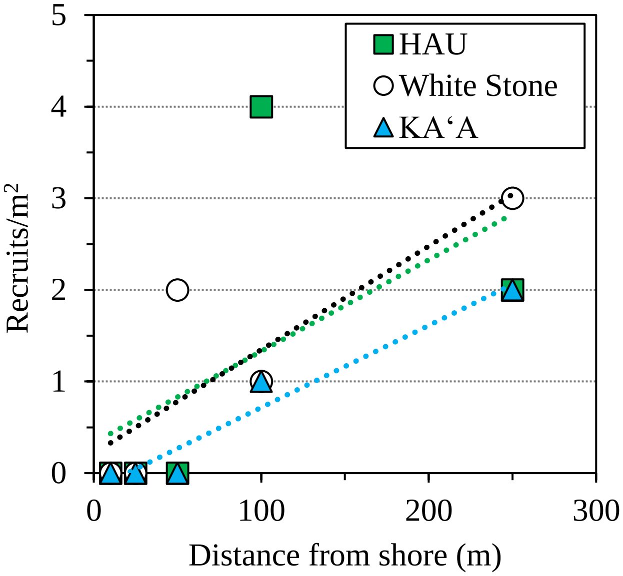


Figure 4.19. Coral recruitment by distance from shore. HAU=Hauola Gulch, White Stone= Lae hī, KAʻA=Kaʻa Gulch

The Kaʻa transect lay within the boundaries of the low coral cover assemblage off Kaʻa Gulch (see Figure 4.16). In contrast, the Lae hī and Hauola transects were within reef areas with higher coral cover that lay to either side of the low coral cover assemblage off Wahane Gulch. The Kaʻa transect had lower coral recruit densities than both the Lae hī and Hauola (Figure 4.19), suggesting recruitment limitation may be higher within this low coral cover assemblage compared to other areas on the shallow reef. Erosion models also identified Kaʻa Gulch as the source of high sediment loads on the nearshore reefs (see Figure 2.3).

Each of the different zones, with the exception of B-2, had certain sites where 100% of the corals were bleached. The overall average was 31.8%, with a standard deviation of 35.2% (Table 4.8). Bleaching strongly correlated with depth, with depth category A (<2m) having an average of 51% of corals bleached, compared to 4.5% and 7.3% in areas greater than 5m and 10m, respectively. A trend in bleaching was also seen going from north to south, with zone E near Waiʻōpae showing 42.4% of corals bleached, on average, in comparison with 29.6% in zone B. Corals nearshore and south showed the greatest impacts from bleaching.

Table 4.8. Coral bleaching in the Keōmuku Reef Tract by depth and location alongshore.

Bleaching % by depth category.	**0-2m (N = 51)**	**2-5m (N = 15)**	**5-10m (N = 15)**	**10+m (N = 13)**	**Overall**
Percent Bleached					
min	0	0.98	0.62	2.3	0
max	100	75	9.26	15.71	100
mean (sd)	51.33 (36.55)	14.14 (18.61)	4.48 (2.55)	7.25 (4.14)	31.82 (35.18)

Bleaching % by longshore zone	**A (N = 1)**	**B (N = 18)**	**C (N = 36)**	**D (N = 26)**	**E (N = 13)**
Percent Bleached					
min	94.74	0.62	0	0.98	1.39
max	94.74	100	100	100	100
mean (sd)	94.74 (NA)	29.56 (33.09)	25.33 (31.62)	34.67 (37.12)	42.40 (40.62)

Sediment characteristics, however, were not significantly correlated with coral bleaching across the reef tract. The fine and silt (combined) components were compared with percent bleached were not significant (ANOVA, F=0.67, p=0.31). The medium and coarse sand fractions were higher with higher percent bleaching. Similarly, the percent algae found on a given transect was not statistically correlated with any sediment characteristic, but instead was related to the percent coral on the transect and the depth (ANOVA, F=0.8, p=0.03).

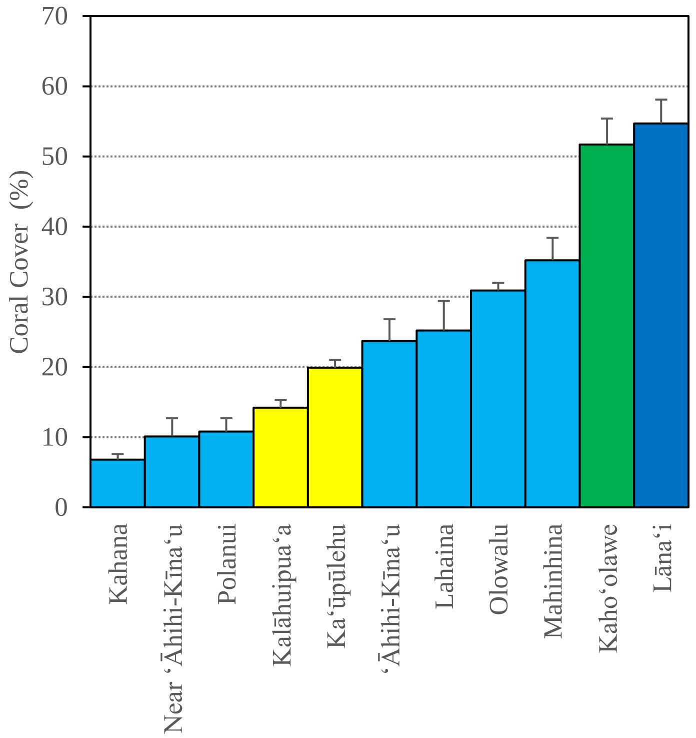
Sedimentary processes associated within nearshore coastal settings play a critical role in not only determining the occurrence and extent of coral growth (Larcombe et al., 2001; Browne et al., 2010; Morgan et al., 2016a), but also in defining turbid-zone coral community structure and long-term rates and styles of vertical reef growth (Browne et al., 2013a; Perry et al., 2013; Morgan et al., 2016b; Johnson et al., 2017). High turbidity attenuates solar irradiance more rapidly than in clear-water settings resulting in light-limited growth conditions for corals (Larcombe et al., 1995; Storlazzi et al., 2015; Fabricius et al., 2016). Coral communities that inhabit low-light conditions have of late been increasingly discussed in the context of deep-water habitats along shelf edges (e.g., Bridge et al., 2011).

4.2.3. Deep Reef

Deep reef areas (>2 meters) within the Keōmuku Reef Tract had among the highest average coral cover in the state at 54.7 ± 3.4%[4]. Over a fifth of the survey sites had >75% coral cover. For comparison, mean coral cover on 15 reef tracts on West Maui ranged from 6.8 to 35.2% cover (Figure 4.20), and these reefs were considered to have slightly above average coral cover in the state (Minton *et al.* 2020). *Monitpora capitata* was the dominant coral species in the deep reef area. *Montipora capitata* generally has an encrusting morphology, but can assume a highly complex branching form when in turbid and/or sheltered waters (*e.g.*, Kāneohe Bay, Oʻahu and Olowalu, Maui). While not specifically quantified in this analysis, the branching form was common at deep reef sites, and the dominant form at many (Minton, pers. obs.). *Montipora patula* was also common, and together, these two *Montipora* species comprised 76% of the deep reef coral cover (Table 4.6).

After corals, the next most common benthic groups were turf (31.9 ± 2.9%) and crustose coralline algae (9.2 ± 0.9%). The high cover of coral and CCA, often referred to as "reef builders" when considered together, indicates a high potential for calcium carbonate deposition, which is key to reef growth and will be an important process under climate-change-driven sea-

Figure 4.20. Comparison of coral cover within the Keōmuku Reef Tract (dark blue) and ten other locations in Maui Nui (blue bars), Hawaiʻi Island (yellow bars), and the sheltered side of Kahoʻolawe (green bar). Data from Minton *et al.* (2016a, 2016b, 2020, 2021) and Falinski *et al.* (2020).



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[4] Most coral reef survey efforts occur in forereef areas at >2 m depths. For the deep reef, comparisons can be made with this existing body of data. Given the scarcity of coral surveys at shallower depths (<2 m), similar comparisons for the shallow reef area of the Keōmuku Reef Tract were not possible.

level rise. Unlike the shallow reef area, sediment covered less than 2% of the deep reef, and when present tended to be of marine origin (see section 4.1).

Benthic assemblage structure did not significantly differ among the Reef Zones, whether sub-zones were considered (PERMANOVA; $F_{7,46}$=1.16; p=0.323) or not (PERMANOVA; $F_{3,46}$=2.04; p=0.110). Likewise, the MWA identified no transition boundaries (Figure 4.21). The coral assemblage across the entire reef tract showed >80% similarity (<20% dissimilarity) indicating no hard transitions in the composition or abundance of the coral assemblage. An interpolation map of coral cover shows a band of high coral cover extended the length of the reef tract (Figure 4.22).

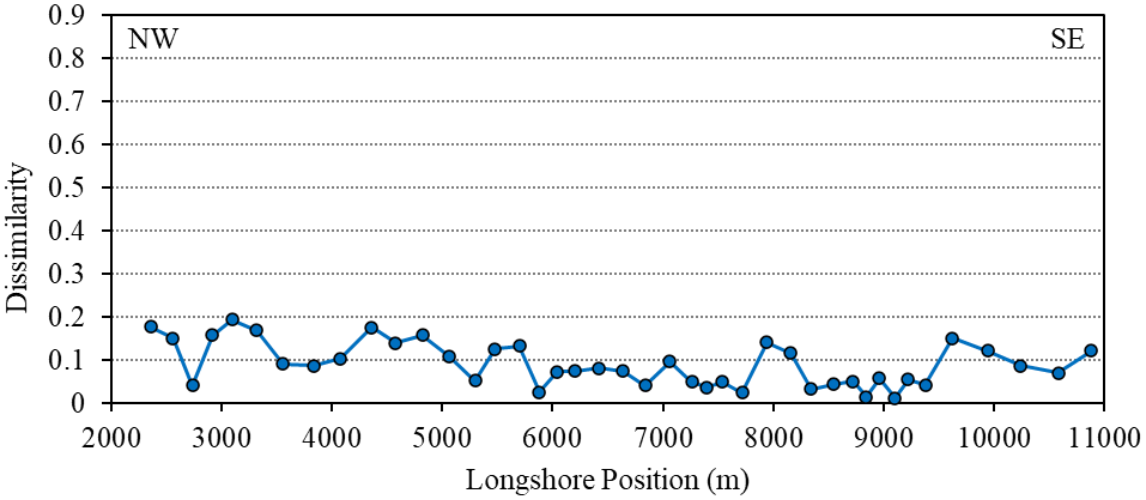


Figure 4.21. Dissimilarity between the deep reef windows used in the MWA plotted by their longshore position. The longshore position of each window was their average position of the five assessment sites that comprised the window. Longshore position was measured from the northwest boundary of the assessment area, but sites within Reef Zone A were not included in the MWA.

However, MWA is insensitive to gradual changes in community structure, so we investigated the possibility of a gradual shift in assemblage structure across the reef tract using nMDS. nMDS is an ordination technique that visualizes the similarity of survey sites based on their species abundance data. When plotted, the similarity in the assemblage structure between any two sites (*i.e.*, points in the figure) is correlated with their distance from each other in the plot. If two distinct assemblages are present, the survey sites will form two distinct clusters. If a gradual shift in assemblage structure is occurring, the survey sites will be spread across the figure and will not appear as a compact cluster. In addition, the sites will be ordered spatially. For example, if the assemblage shift is associated with depth, the survey sites will be ordered in the nMDS plot from shallowest to deepest.

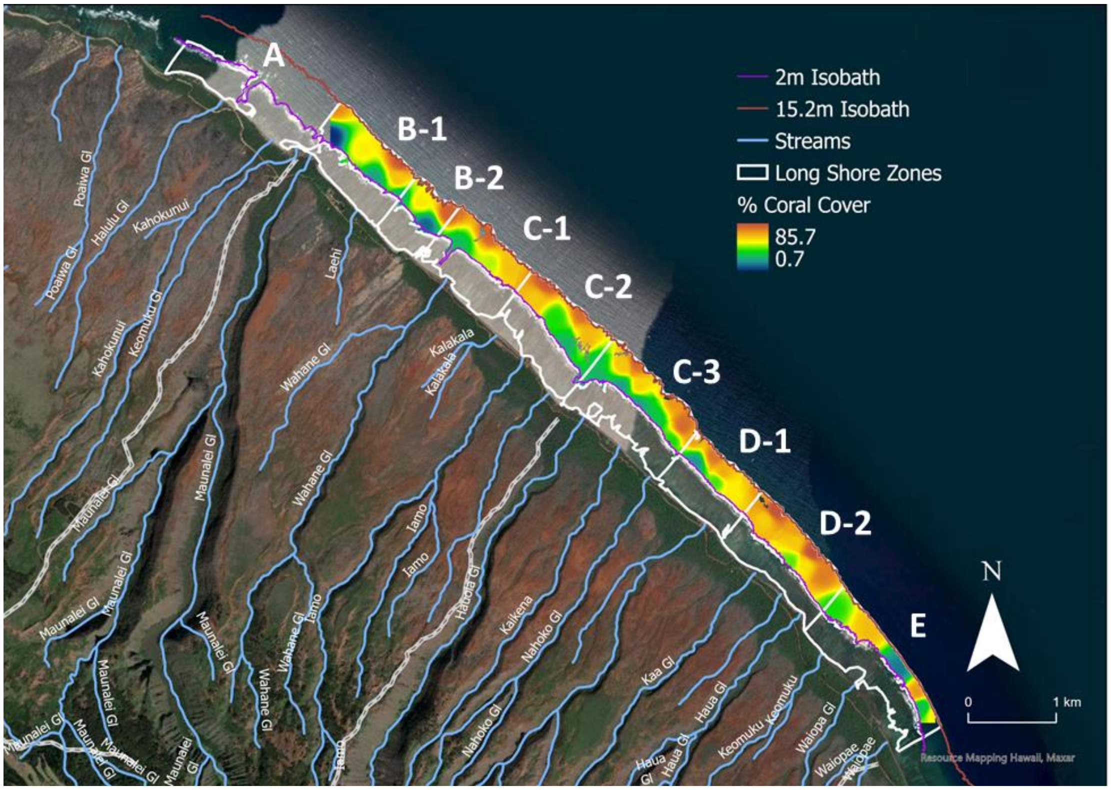
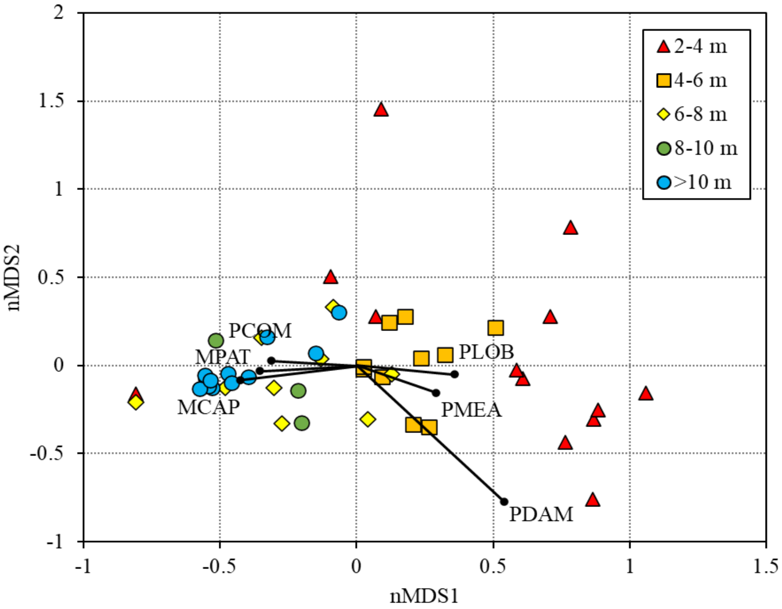


Figure 4.22. Interpolation of coral cover across the deep reef area of the Keōmuku Reef Tract.

The nMDS plot for the deep reef areas of the Keōmuku Reef Tract showed a single, elongated cluster of points (Figure 4.23), suggesting a gradual change may be occurring in the benthic assemblage. The first nMDS axis was not correlated with longshore position (Correlation; r_{46}=-0.054; p=0.717), but was significantly correlated with depth (Correlation; r_{46}=0.729; p<0.001) (Figure 4.24). The second nMDS axis was not correlated with either longshore position or depth.

Figure 4.23. nMDS plot of coral assemblage data within the Keōmuku Reef Tract. Each point represents a survey site, and the closer together any two points are in the plot, the more similar their coral assemblages. MCAP=*Montipora capitata*, MPAT=*M. patula*, PDAM=*Pocillopora damicornis*, PMEA=*P. meandrina*, PCOM=*Porites compressa*, PLOB=*P. lobata*.



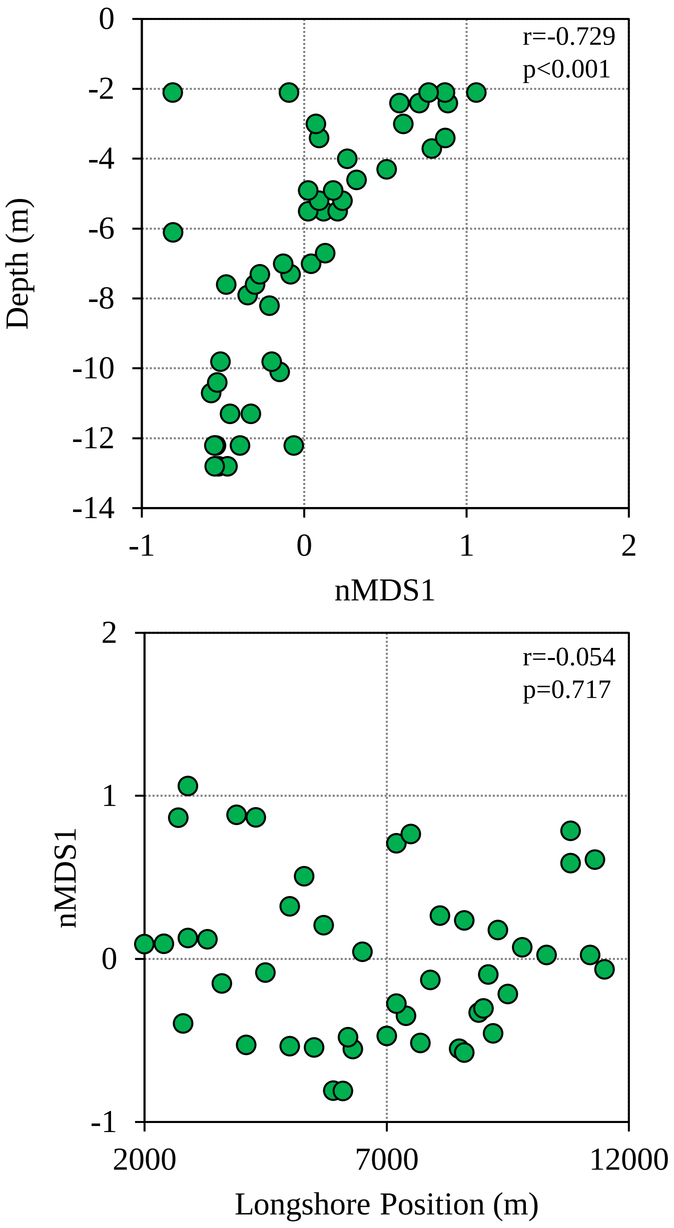


Figure 4.24. The first nMDS axis (nMDS1) vs. depth and longshore position for deep reef areas.

This indicates that the deep reef gradually shifts from an assemblage dominated by *Porites lobata*, *Pocillopora meandrina*, and *P. damicornis* in shallower regions towards an assemblage dominated by *Montipora capitata*, *M. patuala*, and *Porites compressa* in deeper waters (Figure 4.25). Shifts in the coral community composition are expected; similar changes in species composition (*e.g.*, from *P. lobata* on shallow reefs to *P. compressa* at depth) occur frequently on Maui (Minton *et al.* 2020) and Hawai‘i Island (Minton *et al.* 2012, Minton *et al.* 2017, Falinski *et al.* 2021).

The nMDS also indicates that deep reef sites tended to be similar to each other regardless of their longshore position. This is shown by the tight clustering of the sites greater than 10 m in depth in the nMDS (Figure 4.23). In contrast, middle depth sites (2-6 m) are considerably more heterogenous in their assemblage structure, as shown by their wide spread in the nMDS plot. This is not particularly surprising as these sites are closest to shore and likely more exposed to both sediment and wave stressors due to proximity and depth. These locations are also at the transition of the reef from reef flat to reef crest to forereef and likely had higher structural and habitat heterogeneity than shallower (<2 m) or deeper (>6 m) areas.

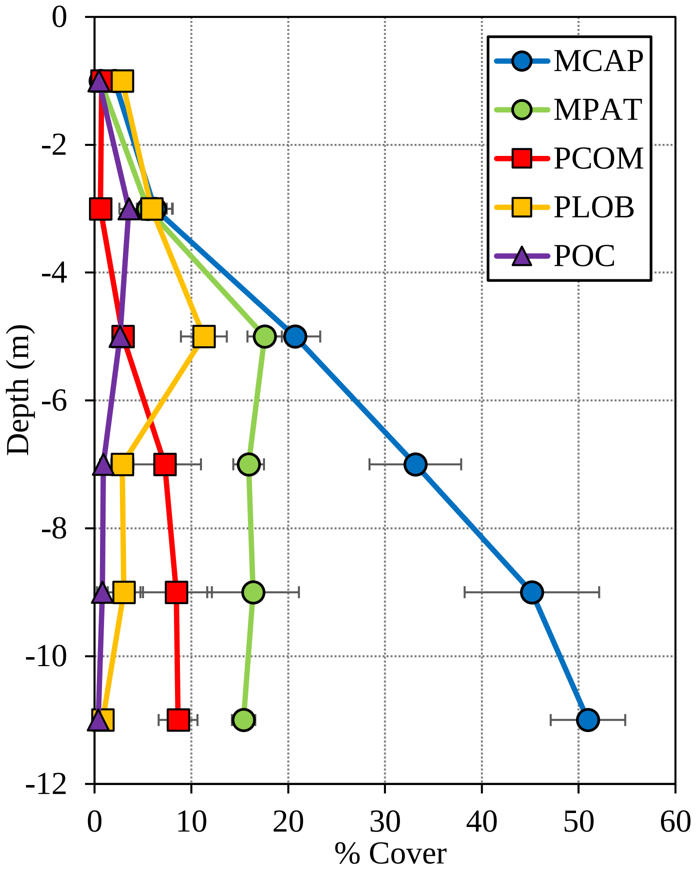


Figure 4.25. Mean (±SEM) percent cover of the dominant coral taxa vs depth. Data are the mean cover of each taxon within sequential 2-m depth bins (0 to 2 m, 2 to 4 m, …, >10 m). MCAP=*Montipora capitata*, MPAT=*M. patula*, PCOM=*Porites compressa*, PLOB=*P. lobata*, POC=*Pocillopora* spp.

4.2.4. Benthic Assemblage from 2012 to 2021

Benthic assemblage information was available from surveys conducted by HCFRU along the reef areas fronting Manualei Gulch (Friedlander *et al.* 2012). The 2012 benthic cover data were summarized by reef structural categories, such as aggregate reef, spur and groove, pavement, etc. To facilitate comparison, TNC's 2021 data were summarized similarly using the 2007 NOAA benthic habitat maps (Table 4.9). Only sites found in Zone B were used, which limited the number of sites for comparison, however, enough data were available to compare benthic cover in pavement and aggregate reefs. Pavement areas corresponded roughly with the shallow reef area and aggregate reef with the deep reef area.

Pavement areas of the Maunalei reef appear to have changed little since 2012. However, aggregate reefs have nearly five-fold more coral cover in 2021 than in 2012. Cover of turf was also greater in 2021, but may not be different depending on the variability in the 2012 data.

Monitpora capitata, *Porites compressa*, *M. patula*, and *P. lobata* were the four most abundant corals in 2012. The same four corals continued to dominate the Maunalei reef in 2021, although their relative dominance was different and depended upon the structural category. NOAA-ESD data were also available for four aggregate reef sites fronting Maunalei Gulch and were surveyed in either 2013 (three sites) or 2016 (one site). Benthic cover data for the NOAA-ESD sites were limited and extremely variable, so few conclusions can be drawn from them except that in 2013 coral cover was more similar to that observed in 2021 than in 2012. Finally, two haphazardly-selected sites (10 m depth) near Maunalei Gulch were surveyed by Vermeij *et al.* (2010) in 2007, and both had high coral cover (59.9 and 72.6%).

Table 4.9. Mean (±SEM) percent cover of coral, CCA, macroalgae, and turf in pavement and aggregate reef areas off Maunalei, Lānaʻi in 2012, 2013/2016, and 2021. Data for 2012 were from Friedlander *et al.* (2012) and did not include estimates of variability. The 2013 and 2016 data for aggregate reefs were obtained from NOAA-ESD.

	Pavement		**Aggregate Reef**			
Benthic Group	**2012 (n=7)**	**2021 (n=8)**	**2012 (n=76)**	**2013 (n=3)**	**2016 (n=1)**	**2021 (n=12)**
Coral	2	4.2 ± 2.1	7	27.2 ± 8.9	76.2	33.8 ± 8.8
CCA	3	0.8 ± 0.4	11	3.6 ± 2.7	1	9.8 ± 1.8
Macroalgae	5	5.4 ± 3.1	3	17.1 ± 18.7	0.3	4.7 ± 1.7
Turf	41	46.1 ± 5.7	32	52.4 ± 19.2	22.5	46.3 ± 7.3

Reconciling these estimates of coral cover off Maunalei Gulch are difficult. Both the 2012 and TNC's 2021 survey efforts used random sampling designs and had sufficiently large sample sizes that the estimates should be robust. While montiporids are among the fastest growing genera of coral in Hawaiʻi (Minton 2015), a decade of optimal growth is still unlikely to account for the difference observed between the 2012 and 2021 assessments. The handful of additional sites in 2007, 2013, and 2016 all found higher coral cover than Friedlander *et al.* (2012), but might simply serve to illustrate the variability in coral cover on the Maunalei reef around that time period. These datasets illustrate the importance of having current, up to date survey data that has been collected with a sufficient amount of survey effort to account for the reef's spatial variability.

4.2.5. Summary: Benthic Assemblage

The shallow reef areas of the Keōmuku Reef Tract appear to be a mosaic of heavily impacted benthic assemblages. The most significant stressor is likely sediment, inputted primarily from the intermittent streams that drain highly eroded gulches. Sediment impacted areas have low coral cover, extremely high coral tissue bleaching rates, and impaired coral recruitment. Sediment and sediment-entrained turf cover the majority of the bottom, creating conditions that are not conducive to coral settle, growth and survival. When coral species are present, they are sediment tolerant or weedy species, and reminiscent of the species found in other areas of the state that suffer from high sedimentation (*e.g.*, Pelekane Bay).

However, as poor as these sediment-impacted assemblages might be, a few areas of the reef flat appear to be in considerably better condition. These areas have higher coral cover and species richness, higher coral recruit densities, and lower bleaching rates than the "impaired" areas of the reef flat. While certainly still impaired by sediment, these “nice” reef flat areas may represent remnants of the historical coral reef flat community and should be indicative of what might be attainable if sedimentation can be addressed, and recovery is allowed to occur.

Finally, the findings of this assessment indicate that finer-scale sampling of the benthic community would be beneficial to better understanding the composition and ecological dynamics at play within the reef flat community. Greater resolution of "impaired" and "nice" benthic assemblages would also be beneficial to organizations wishing to monitor reef health in relationship to sediment mitigation. Areas of "nice" reef could serve as reference areas and assist with identifying realistic recovery targets. See Section 5 for more monitoring considerations.

The deep reef areas of the Keōmuku Reef Tract appear to be a single benthic assemble characterized by exceptionally high coral cover and high species diversity. The benthic assemblage shows a strong depth-related gradient in coral species composition. The dominant corals species transition from sediment- and wave-tolerant species (*e.g.*, *Porites lobata*, *Pocillopora meandrina*, and *P. damicornis*) to species commonly observed at depth on Hawaiian reefs, including *Porites compressa*, branching forms of *Montipoa capitata*, and *M. patula*. Unlike on the shallow reef, sediment does not appear to be a significant stressor, especially in deeper areas. However, given the complexities of climate change effects, it’s plausible that changes in sea level, storm frequency and intensity, and ocean acidity could alter nearshore sediment dynamics and shift the spatial patterns of sedimentation on the Keōmuku Reef Tract.

4.3. **Fish Assemblage**

A total of 112 taxa representing 27 families of fish were observed within the Keōmuku Reef Tract. Surgeonfishes (Acanthuridae), wrasses (Labridae), and parrotfishes (Scaridae) were numerically the most abundant, accounting for ~82% of all observed individuals (Table 4.10). Surgeonfishes, and parrotfishes contributed the most to the total fish biomass and accounted for over 71% of fish biomass. These fish families are typically well-represented on reefs in Hawaiʻi, and they're relative dominance in the Keōmuku Reef Tract is consistent with many reefs across the state. For a complete list of fish species observed, see Appendix C

Similar to the benthic assemblage, the reef fish assemblage varied with depth. Shallow reef areas had lower average abundance, biomass, and species richness compared to deep reef areas (Figure 4.26), although the relationship was considerably weaker for fish than the benthic assemblage. This was especially apparent for total fish biomass, where deep reef areas frequently had low biomass values (Figure 4.26) However, unlike coral cover, reef fish abundance, biomass, and richness peaked at middle depths, between approximately two and six meters, before declining sharply in deeper reef areas. These locations are at the transition of the reef from reef flat to reef crest to forereef and likely had higher structural and habitat heterogeneity than shallower (<2 m) or deeper (>6 m) areas. Structural and habitat heterogeneity is often correlated high fish abundance and species richness.

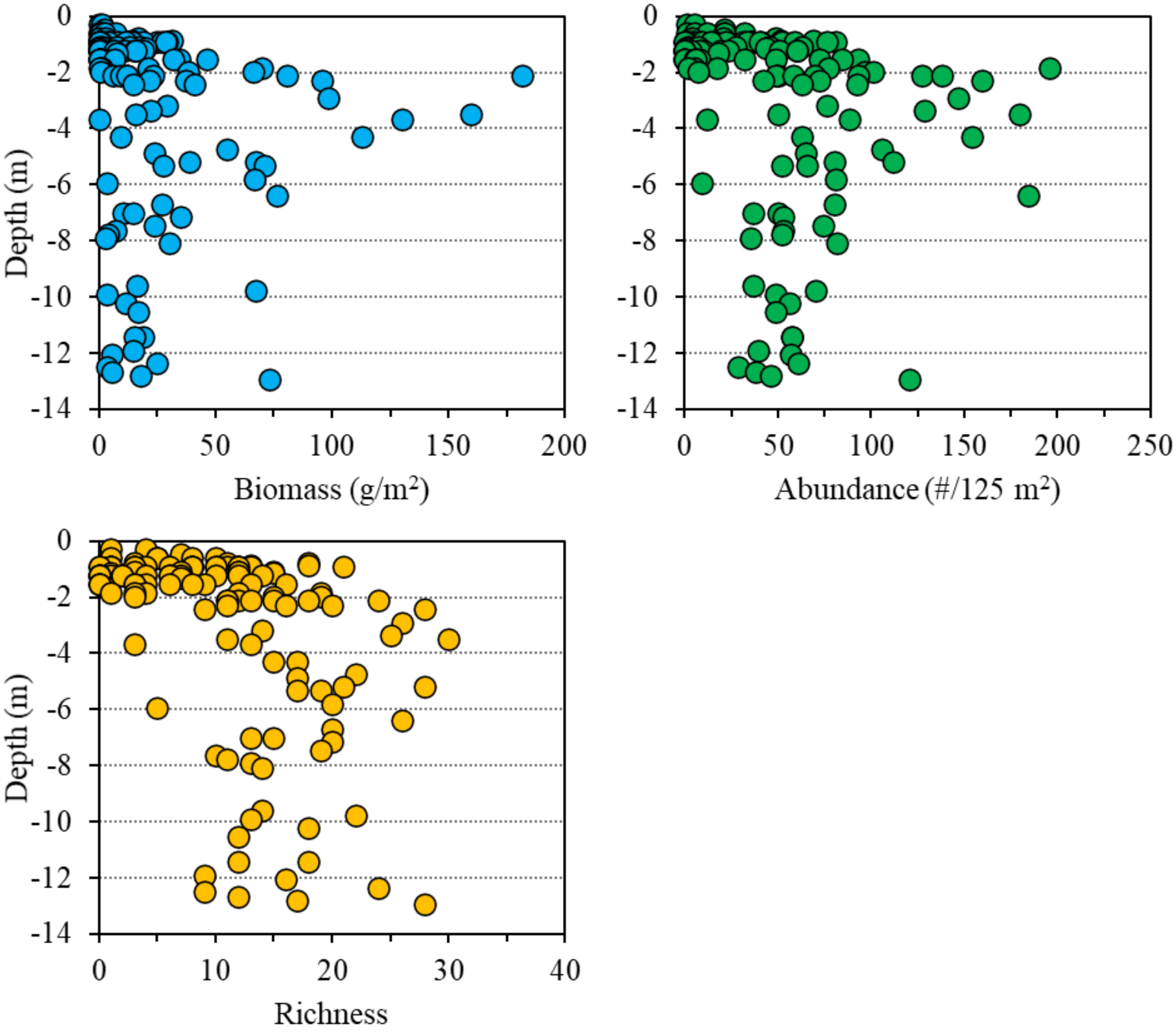


Figure 4.26. Total fish biomass, abundance and fish species richness per site by depth within the Keōmuku Reef Tract.

Total fish biomass (ANOVA; $F_{3,117}$ =2.72 p=0.048) and abundance differed by Reef Zone (ANOVA; $F_{3,117}$ =2.75; p=0.046). Follow-up pair-wise comparisons showed Zone E had significantly higher biomass and abundance than Zone C (Figure 4.27). The difference between the two zones was driven primarily by the surgeonfishes and parrotfishes, which accounted for

Table 4.10. Average abundance (#/125 m^2) and biomass (g/m^2) (±SEM) of fish by family within the Keōmuku Reef Tract (KRT) in 2021. Families are arranged by decreasing biomass.

	Abundance			**Biomass**		
Fish Family	**KRT**	**Shallow**	**Deep**	**KRT**	**Shallow**	**Deep**
Surgeonfish (Acanthuridae)	21.3 ± 2.1	11.5 ± 1.8	38.4 ± 3.9	9.7 ± 1.6	4.9 ± 0.9	18.3 ± 3.9
Parrotfish (Scaridae)	7.3 ± 1.3	6.7 ± 2.0	8.8 ± 1.5	5.4 ± 1.0	2.0 ± 0.6	11.5 ± 2.3
Wrasses (Labridae)	10.4 ± 0.7	7.8 ± 0.9	14.6 ± 1.0	1.4 ± 0.1	1.0 ± 0.1	2.2 ± 0.3
Groupers (Serranidae)	0.2 ± 0.1	0 ± 0	0.5 ± 0.1	0.9 ± 0.2	0.1 ± 0.1	2.3 ± 0.5
Snappers (Lutjanidae)	0.6 ± 0.1	0.6 ± 0.2	0.5 ± 0.2	0.7 ± 0.2	0.6 ± 0.2	0.9 ± 0.4
Goatfish (Mullidae)	1.0 ± 0.1	0.9 ± 0.2	1.3 ± 0.2	0.6 ± 0.1	0.6 ± 0.2	0.6 ± 0.2
Damselfish (Pomacentridae)	4.1 ± 0.7	1.7 ± 0.3	8.1 ± 1.6	0.6 ± 0.1	0.4 ± 0.1	0.9 ± 0.2
Triggerfish (Balistidae)	0.3 ± 0.1	0.1 ± 0.1	0.8 ± 0.4	0.6 ± 0.2	0.1 ± 0.1	1.4 ± 0.6
Butterflyfish (Chaetodontidae)	0.7 ± 0.1	0.3 ± 0.1	1.5 ± 0.2	0.4 ± 0.1	0.1 ± 0.1	1.1 ± 0.2
Chubs (Kyphosidae)	<0.1	<0.1	0.1 ± 0.1	0.3 ± 0.1	0.2 ± 0.2	0.5 ± 0.2
Emperors (Lethrinidae)	<0.1	0	0.1 ± 0.1	0.2 ± 0.1	0	0.6 ± 0.4
Filefish (Monacanthidae)	<0.1	0	0.1 ± 0.1	0.1 ± 0.1	0	0.3 ± 0.2
Jacks (Carangidae)	0.1 ± 0.1	0	0.2 ± 0.1	0.1 ± 0.1	0	0.2 ± 0.1
Squirrelfish (Holocentridae)	0.1 ± 0.1	<0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Pufferfish (Tetraodontidae)	0.4 ± 0.1	0.3 ± 0.1	0.6 ± 0.1	<0.1	<0.1	0.1 ± 0.1
Hawkfish (Cirrhitidae)	0.4 ± 0.1	<0.1	1.0 ± 0.2	<0.1	<0.1	0.1 ± 0.1
Needlefishes (Belonidae)	0.1 ± 0.1	0	0.4 ± 0.3	<0.1	0	<0.1
Blennies (Blenniidae)	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	<0.1	<0.1	<0.1
Angelfish (Pomacanthidae)	<0.1	0	0.1 ± 0.1	<0.1	0	<0.1
Boxfish (Ostraciidae)	<0.1	<0.1	0.1 ± 0.1	<0.1	<0.1	<0.1
Gobies (Gobiidae)	0.2 ± 0.1	0.4 ± 0.1	0	<0.1	<0.1	0
Trumpetfish (Aulostomidae)	<0.1	0	<0.1	<0.1	0	<0.1

	Abundance			Biomass		
Fish Family	**KRT**	**Shallow**	**Deep**	**KRT**	**Shallow**	**Deep**
Lizardfish (Synodontidae)	<0.1	<0.1	0	<0.1	<0.1	0
Cornetfish (Fistulariidae)	<0.1	0	<0.1	<0.1	0	<0.1
Barracudas (Sphyraenidae)	<0.1	<0.1	0	<0.1	<0.1	0
Requiem sharks (Carcharhinidae)	<0.1	0	<0.1	<0.1	0	<0.1
Eels (Muraenidae)	<0.1	<0.1	0	**	**	**
TOTAL	**47.6 ± 3.8**	**30.4 ± 3.9**	**77.7 ± 6.1**	**21.2 ± 2.8**	**9.9 ± 1.7**	**41.1 ± 6.2**

**=biomass for species was not estimated

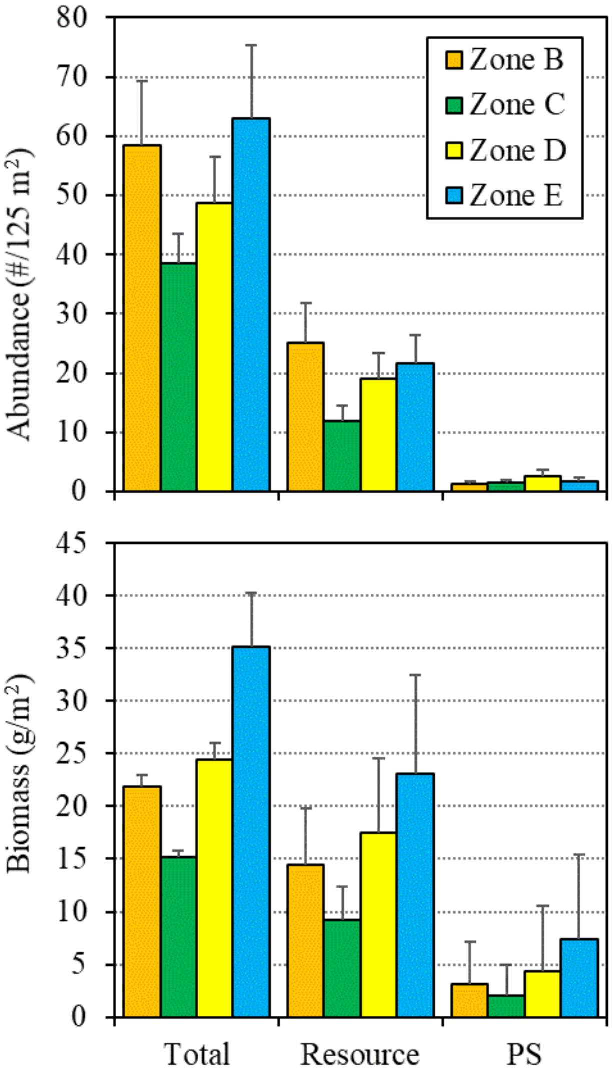
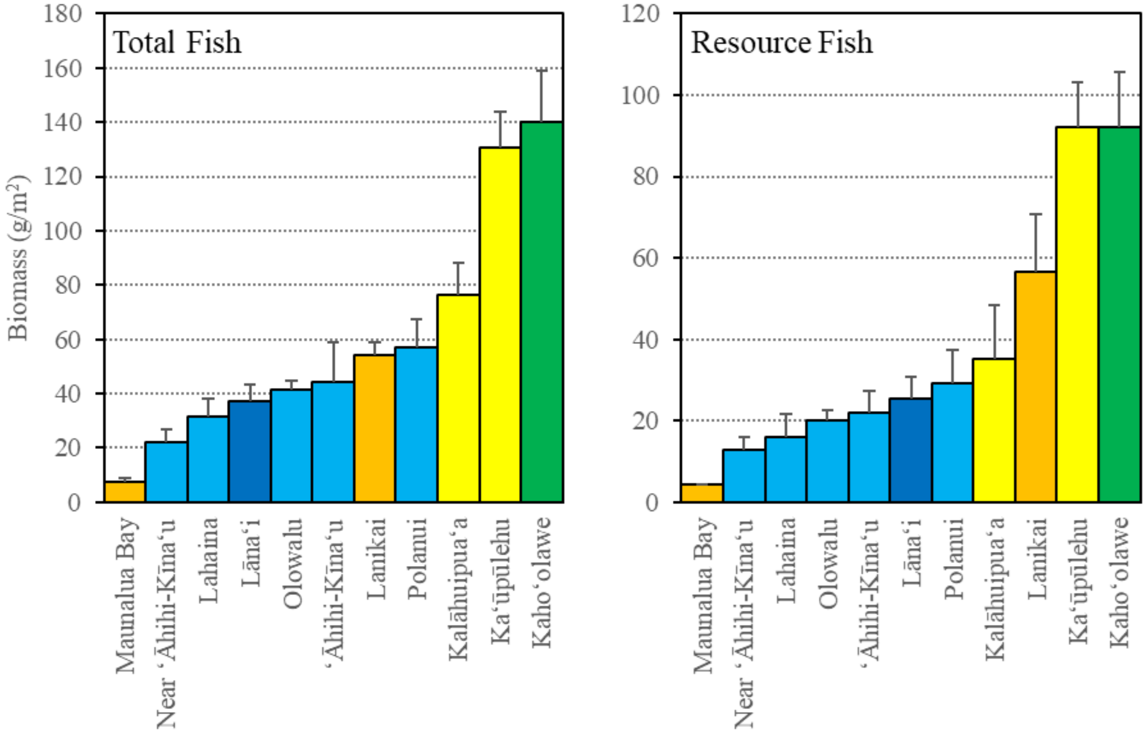


Figure 4.27. Abundance (top) and biomass (bottom) of total fish, resource fish, and prime spawners (PS) in Reef Zones B-E.

over 73% of the difference in biomass and over 77% of the difference in abundance. Given both of these families are important resource fish groups, it was not surprising that total resource fish biomass (ANOVA; $F_{3,117}$ =4.12; p=0.008) and abundance (ANOVA; $F_{3,117}$ =2.25; p=0.086) also differed among Reef Zones. However, in addition to Zone E having higher resource fish biomass than Zone C, pairwise comparisons also showed Zone C had significantly lower biomass and abundance than Zone B (Figure 4.27). Finally, primes spawners showed no difference among Reef Zones (Figure 4.27).

Total fish biomass across the Keōmuku Reef Tract was 21.2 ± 2.8 g/m^2, which was surprisingly low when compared to other reefs in the state. However, most reef surveys in Hawai‘i do not include shallow reef areas (<3 m), which typically have lower reef fish abundance and biomass. Limiting the comparison to reef areas >3 m almost doubles the mean total fish biomass across the Keōmuku Reef Tract to 37.2 ± 6.2 g/m^2, and brings it more in line with other reef areas on Maui (Figure 4.28). However, given the generally good habitat condition of the deep reef area, fish biomass was still surprisingly low. Potential reasons for this are explored more below.



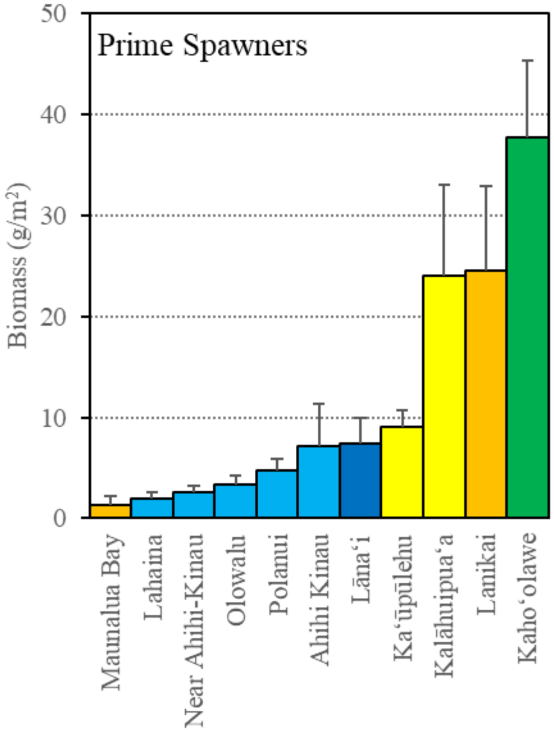


Figure 4.28. Comparison of total fish, resource fish, and prime spawner biomass (g/m^2) within the Keōmuku Reef Tract (dark blue) and ten other locations on Oʻahu (orange bars), Maui nui (blue bars), Hawaiʻi Island (yellow bars), and Kahoʻolawe (green bar). Data from Minton *et al.* (2014, 2015, 2016a, 2016b, 2020, 2021) and Falinski *et al.* (2020).

4.3.1. Resource Fish

Resource fish[5] biomass and abundance were greater in deep compared to shallow reef areas, with the highest abundance and biomass at middle depths (Figure 4.29). Resource fish biomass on deep reefs was 28.8 ± 5.7 g/m^2 compared 5.5 ± 1.2 g/m^2 on shallow reefs. Similarly, abundance was 26.3 ± 3.6 individuals/125 m^2 on deep reefs areas, compared to 12.0 ± 2.3 individuals/125 m^2 in shallow areas. Resource fish were also patchily distributed in the shallow reef area; nearly 30% of the shallow reef sites had no resource fish, compared to resource fish present at all deep reef sites.

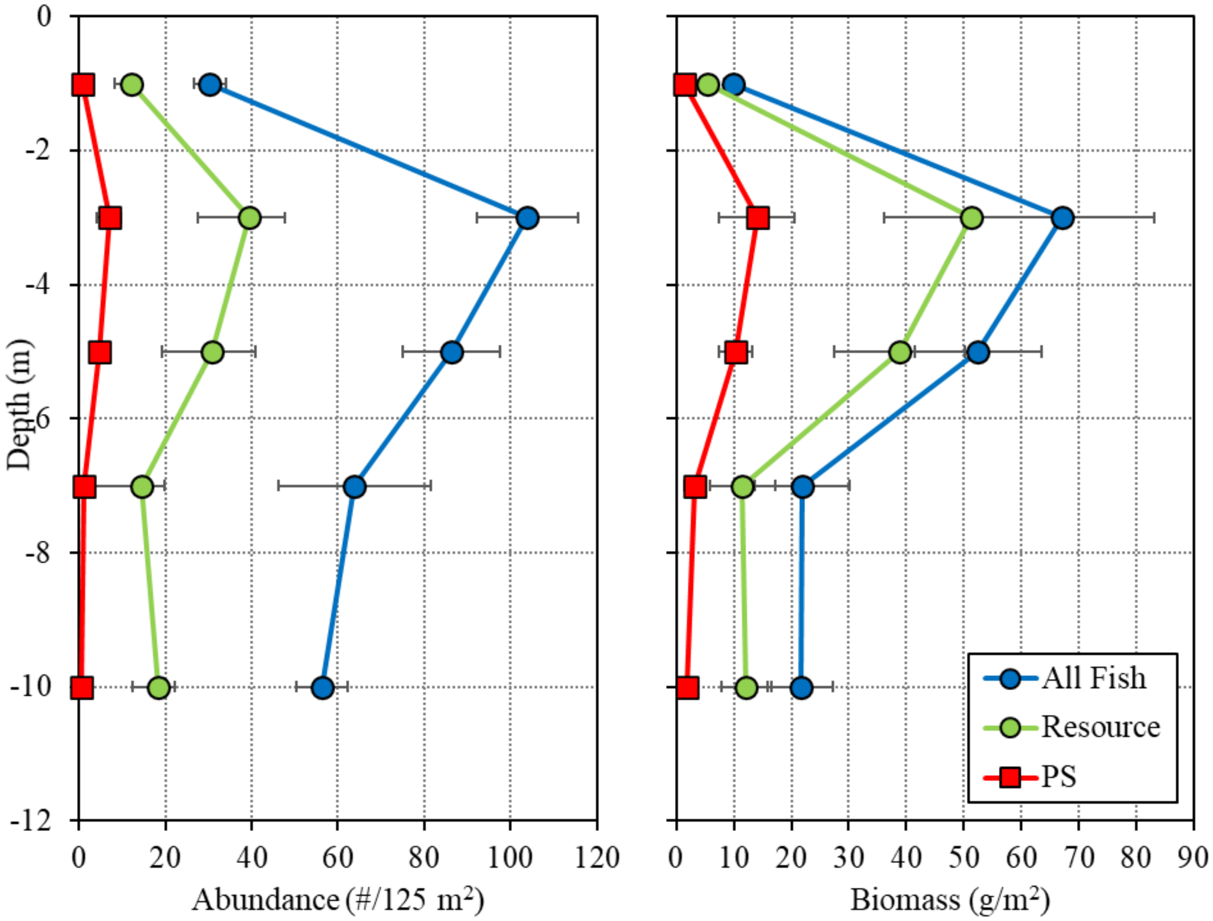


Figure 4.29. Total fish, resource fish, and prime spawner abundance (#/125 m^2) and biomass (g/m^2) by depth on the Keōmuku Reef Tract in 2021.

At both depths, resource fish biomass was dominated by surgeonfishes and parrotfishes (Figure 4.30), which comprised 85% and 91% of the biomass at shallow and deep sites, respectively. On shallow reefs areas, goatfish had the third most biomass, and along with surgeonfish and

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[5] See Table 4.1 for species included in this group.

parrotfish, accounted for 98% of the resource fish biomass. In contrast, the remaining resource fish biomass on deep reefs was more diverse, divided among wrasses, goatfish, apex predators, and other resource fish. The relative dominance of goatfish on shallow reef areas was likely associated with the high cover of sediment, over which many goatfish species forage.

Among apex predators, only a single juvenile *Sphyraena barracuda* (barracuda) was observed on the shallow reef, while four species of apex predator, totaling 22 individuals, were found at depth, including *Caranx melampygus* (bluefin trevally or ʻōmilu), *Decapterus macarellus* (mackeral scad or ʻōpelu), *Elagatis bipinnulata* (rainbow runner), and *Scomberoides lysan* (doublespotted queenfish).

Resource fish biomass in the Keōmuku Reef Tract was higher than many other areas in Maui Nui (Figure 4.28), but below sites on Hawaiʻi Island, Kahoʻolawe, and even some areas on Oʻahu. This low resource fish biomass suggests fishing may be an impact. Examining the ratio of resource fish to non-resource fish (R:NR) can shed light on fishing pressure. Areas with high fishing pressure should have a lower R:NR ratio than areas with relatively lower fishing pressure because harvest of resource fish will lower their biomass while leaving non-resource fish biomass unaltered (Minton *et al.* 2020). The R:NR ratio for the deep reef area in the Keōmuku Reef Tract was 4.1 ± 0.9, which was below the average for West Maui (4.7), and was consistent with West Maui sites considered to have moderate to moderate-low fishing pressure (Minton *et al.* 2020).

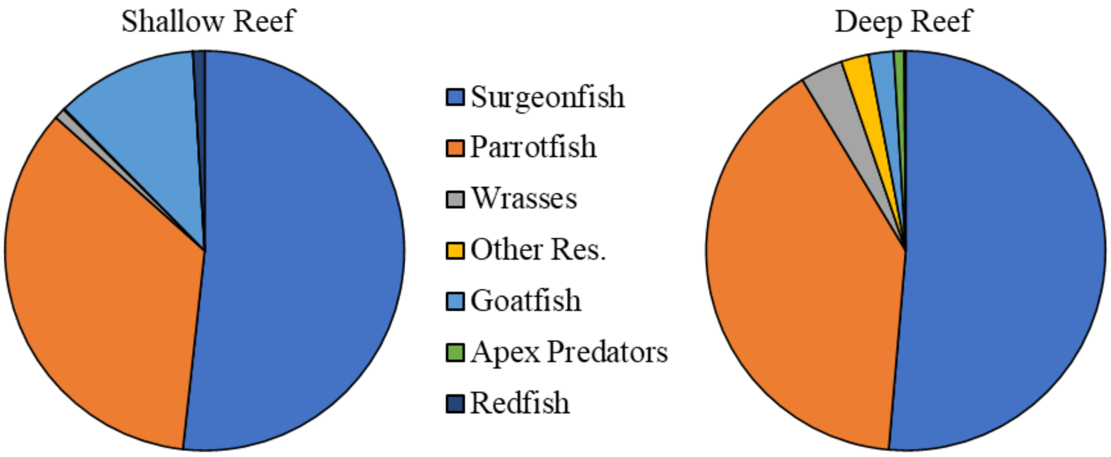

Figure 4.30. Composition (% of biomass) of resource fish on shallow and deep reefs within the Keōmuku Reef Tract in 2021.

4.3.2. Fish Size and Prime Spawners

Fish size is an informative demographic parameter that has direct implications on an individual's survival and reproductive success. The size-frequency distribution (*i.e.*, percentage of fishes found in different size classes) can provide insights into a fish population's health, how it uses a particular habitat, and the stressors that may be impact it.

Sufficient data were available to examine the size-frequency distributions of five species within the Keōmuku Reef Tract. These species included three resource (*Acanthurus blochii*, *Chlorurus spilurus*, and *Scarus psittacus*) and two non-resource (*A. nigrofuscus* and *Thalassoma duperrey*) species.

Three of the species showed differential use of the shallow and deep reef areas. *Chlorurus spilurus* and *A. blochii* tended toward smaller sizes in the shallow compared deep reef areas (Figure 4.31), suggesting the shallow reef might be serving as juvenile habitat. For *A. blochii*, no individuals <14 cm in length were observed in the deep reef area. In contrast, individuals of the non-resource species *A. nigrofuscus* tended to be larger in the shallows, although considerable overlap was present in the shallow and deep size-frequency distributions (Figure 4.31).

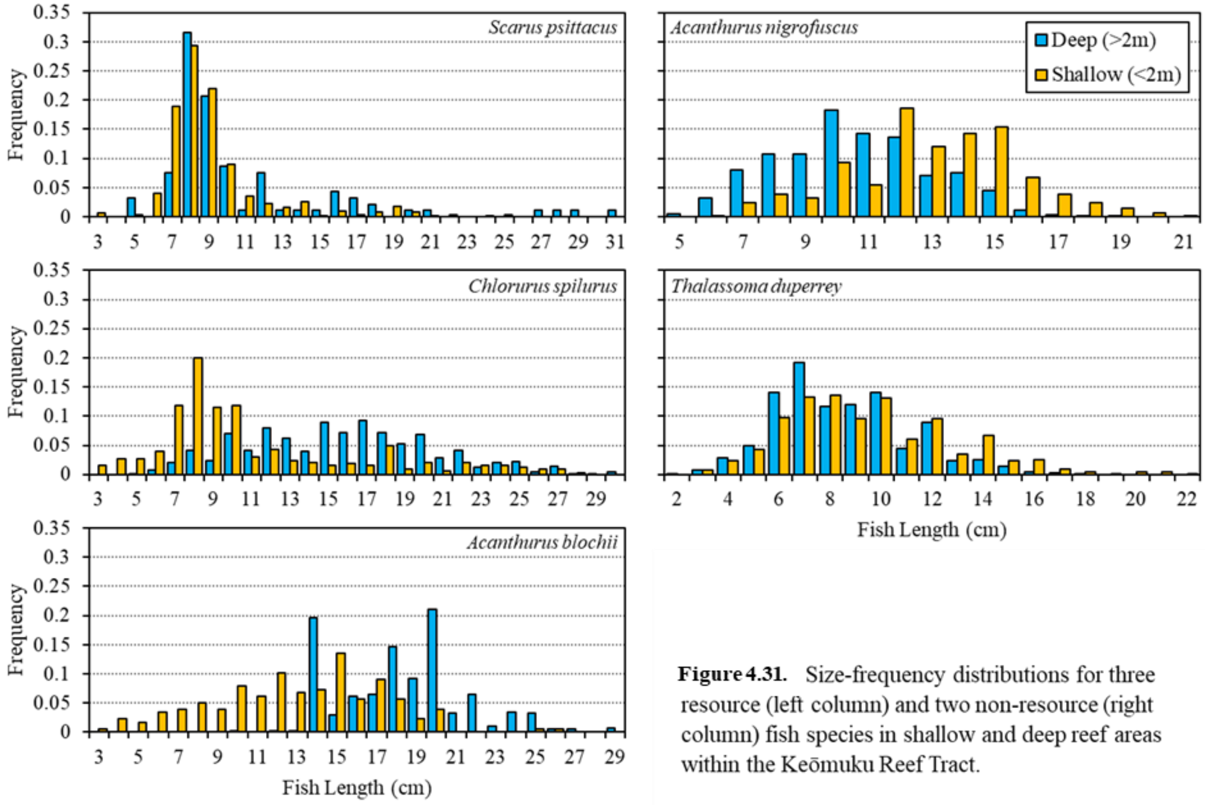

Figure 4.31. Size-frequency distributions for three resource (left column) and two non-resource (right column) fish species in shallow and deep reef areas within the Keōmuku Reef Tract.

Both of the non-resource fish size-frequency distributions appeared to be normally distributed compared to the distributions for the three resource species. Resource species had right-skewed distributions, meaning that the bulk of the individuals were of smaller sizes and the number of large individuals was low, creating what is commonly referred to as a "tail" extending to the right of the figure (Figure 4.31). This indicates that large sizes are proportionately less common than smaller-sizes for the resource species, which can sometimes be indicative of a fishing effect. A right-skewed distribution may be particularly problematic if the vast majority of individuals within the population are below the size at maturity. For the two non-resource species, from approximately 74-92% of the population were above the size at maturity (Table 4.11), whereas resource fish species had between 8-46% of their individuals larger than the size at maturity.

Prime spawners are individual resource fishes larger than 70% of the maximum size reported for the species in Hawaiʻi. These individuals are widely thought to be ecologically important, and fishers often preferentially target then, making prime spawner biomass a good indicator of fishing impacts.

In the shallow reef areas of the Keōmuku Reef Tract, prime spawners were absent from nearly 70% of the survey sites, and averaged less than one individual per transect (0.9 ± 0.2 individuals/125 m^2). Prime spawners of ten species were observed, and their abundance was split evenly between three families: surgeonfish, parrotfish, and goatfish. Average prime spawner biomass was low, averaging only 1.4 ± 0.3 g/m^2.

In deep reef areas, prime spawners were absent form 30% of the survey sites, but were more than twice as abundant (3.3 ± 1.0 individuals/125 m^2), and had four times the biomass (7.3 ± 2.1 g/m^2) as in the shallow reef area. Similar to resource species, prime spawner abundance and biomass was greatest at middle depths (Figure 4.29). Deep reef prime spawners consisted of 17 species, but unlike shallow reef areas, over 70% of the prime spawners were surgeonfish and an additional 17% were parrotfish. Large individuals of other resource fish groups (*e.g.*, apex predators, redfish, etc.) were rarely observed on the Keōmuku Reef Tract.

Table 4.11. Percentage of individuals above the size at maturity for three resource and two non-resource fish species within the Keōmuku Reef Tract in 2021.

Species	Size at Maturity	% Mature
Resource		
Acanthurus blochii	~22 cm[a]	29
Chlorurus spilurus	~15 cm[b]	46
Scarus psittacus	~15 cm[b]	8
Non-resource		
A. nigrofuscus	~10 cm[c]	74
Thalassoma duperrey	~6 cm[d]	92

[a] Pardee *et al.* (2022)
[b] HCRFU (2008)
[c] Hart and Russ (1996)
[d] Ross (1982)

As with resource fish, prime spawner biomass in the Keōmuku Reef Tract was comparable to many other areas in Maui Nui (Figure 4.28), but again, was below sites on Hawai‘i Island, Kaho‘olawe, and O‘ahu. Even with prime spawner biomass higher than most areas on Maui, and similar to the ‘Āhihi-Kīna‘u MLCD, the Keōmuku Reef Tract shows evidence of moderate fishing pressure.

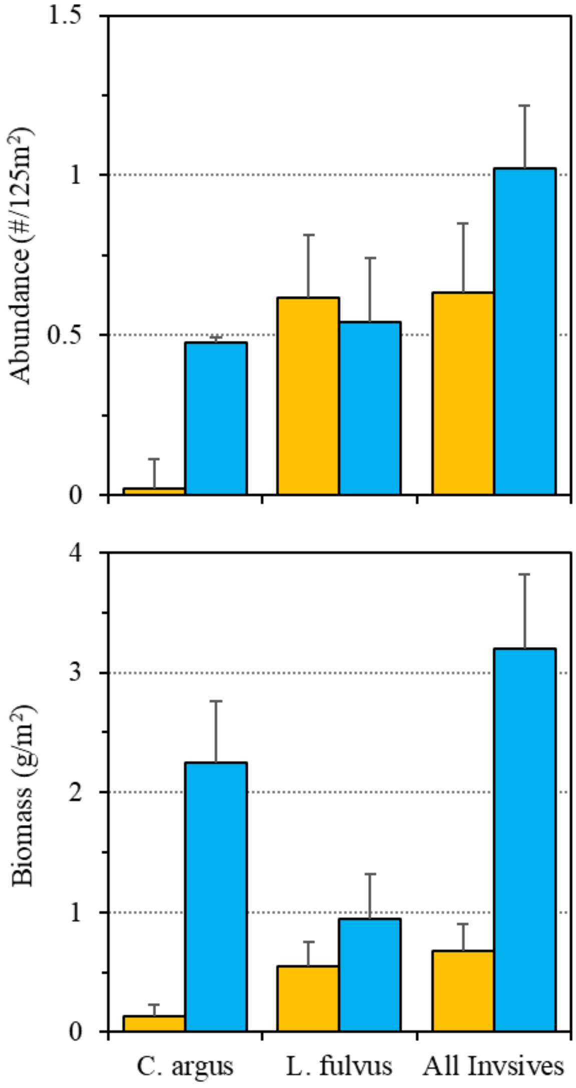

Figure 4.32. Mean (±SEM) abundance and biomass of invasive fish species in shallow (gold bars) and deep (blue bars) areas of the Keōmuku Reef Tract in 2021.

4.3.3. Invasive Species

Three invasive fish species intentionally introduced to Hawai‘i between 1955 and 1961 successfully established permanent populations, and within 15 years had spread throughout the Main Hawaiian Islands. Currently, *Lutjanus kasmira* (bluestriped snapper or ta‘ape) is found throughout the Hawaiian Archipelago, and *Cephalopholis argus* (peacock grouper or roi) occurs at all islands south of French Frigate Shoals (Gaither *et al.* 2012). Both species have demonstrated good dispersal ability. *Lutjanus fulvus* (blacktail snapper or to‘au) is currently restricted to the Main Hawaiian Islands, and its low population growth in Hawai‘i may be inhibiting its ability to spread more widely across the archipelago.

Only two invasive fish species were observed within the Keōmuku Reef Tract: *C. argus* and *L. fulvus*. Interestingly, *L. kasmira*, which tends to be common on many Hawaiian reefs, was absent. Invasive fish were present at only 40% of the survey sites.

Invasive fish abundance did not differ between shallow and deep reef areas (t-test; t_{109}=1.53; p=0.129), but biomass was significantly higher in deep reef areas (t-test; t_{65}=4.82; p<0.001). The abundance and biomass of *L. fulvus* was similar between the reef areas (Figure 4.32), so differences were driven primarily by *C. argus*.

4.3.4. Fish Assemblage from 2012 to 2021

Fish assemblage data were available from HCFRU surveys conducted along the reef area fronting Manualei Gulch (Friedlander *et al.* 2012). The HCFRU data were summarized by reef structural categories, such as aggregate reef, spur and groove, pavement, etc., but locational data were available for the sites, allowing us to use GIS to estimate the depth of each HCFRU survey location. Therefore, two possible comparisons could be made: 1) by shallow and deep reef areas, as used in this report, and 2) by structural categories, as used in the HCRFU report. Benthic structure category for all 2021 survey sites (Zone B only) were determined using available NOAA benthic habitat maps. Enough data were available to compare total fish abundance and biomass in pavement and aggregate reefs. Based on NOAA habitat maps, pavement areas correlate with the shallow reef area and aggregate reef areas correlate with the deep reef area.

Shallow reef areas and pavement areas of the Maunalei reef appear to have changed little since 2012 (Figure 4.33). However, deep reef areas and aggregate reefs had over three-times more fish biomass in 2012 than in 2021, an opposite pattern to that observed for the benthic assemblage (see Section 4.2.4). While biomass was higher in 2012, total abundance did not significantly differ, which suggests more large fish were in the deep reef/aggregate reef fish assemblage in 2012 than presently. This could result from either 1) larger individuals being present in 2012 or 2) larger bodied species were present in 2012 compared to 2021.

Species-specific data were limited from 2012, but a list of the nine most common species (by biomass) was available (Table 4.12). Five of the nine most common species in 2012 were also common in 2021. The parrotfish *Chlorurus spilurus* had the high biomass in both years. Missing from 2012's top nine in 2021 were:

- *C. perspicillatus* - #2 in 2012 but not observed in 2021
- *Naso lituratus* - #5 in 2012 and #19 in 2021
- *Acanthurus leucopareius* - #8 in 2012 and #45 in 2021
- *A. triostegus* - # 9 in 2012 #18 in 2021

These species were replaced by *N. brevirostris*, *A. blochii*, *A. dussumieri*, and *Cephalopholis argus*. These four species are not noticeably smaller than the one's they replaced in the top nine, and arguably they are, on average, larger-bodied species than the four in the 2012 list. While the fish assemblage off Maunalei Gulch appears have undergone at least some shift in the species composition, sufficient similarity between the fish 2012 and 2021 fish assemblage to suggest that species changes alone are not adequate to the explain the large decline in fish biomass on this reef.

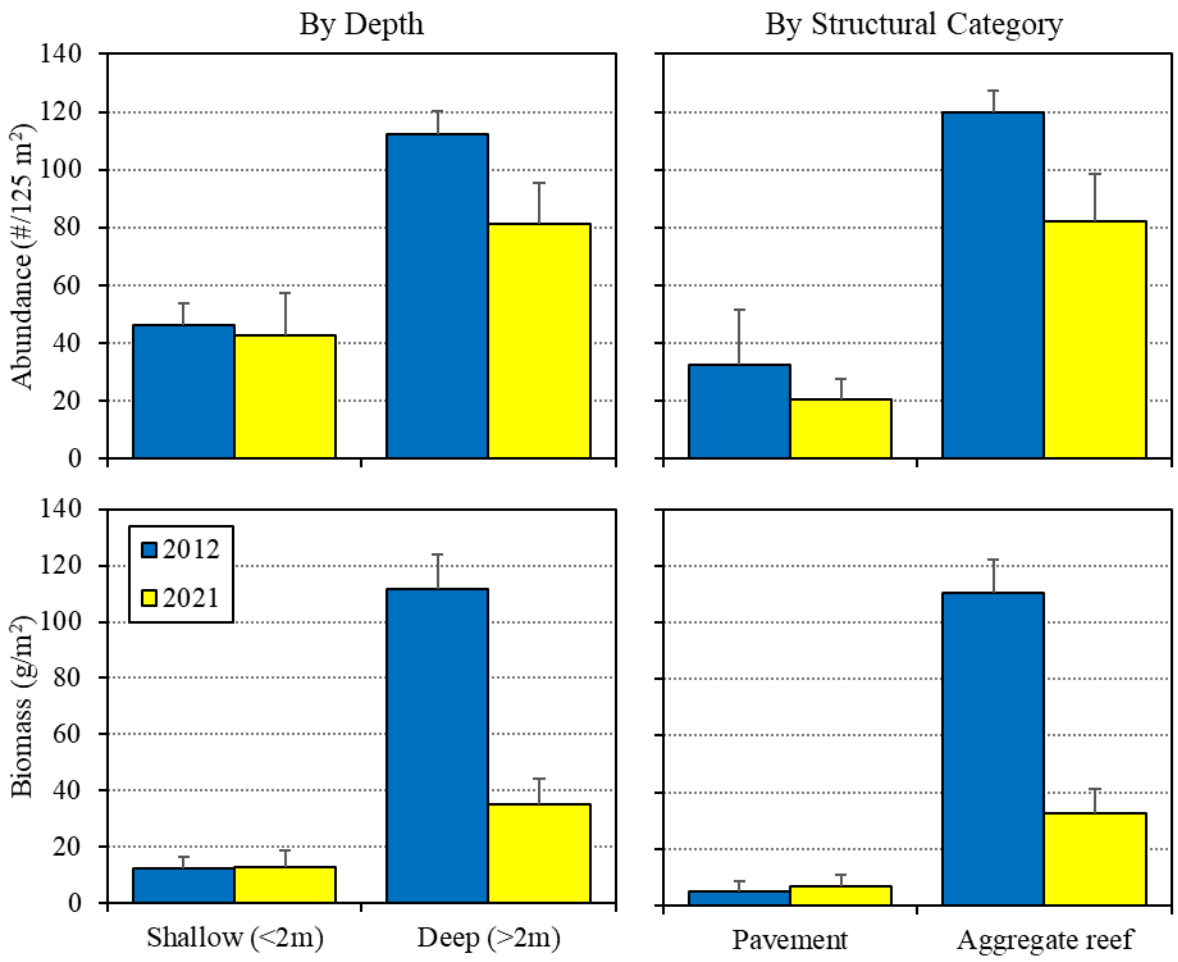

Figure 4.33. Mean (±SEM) total fish abundance and biomass by depth (shallow vs. deep reef areas) and structural category (pavement vs. aggregate reef) off Maunalei, Lānaʻi in 2012 and 2021. Data for 2012 are from Friedlander *et al.* (2012).

4.3.5. Summary: Fish Assemblage

Given what appears to be good quality habitat in the deep reef areas of the Keōmuku Reef Tract, the reef fish assemblage has surprisingly low biomass and species richness. Fish biomass is comparable to many areas on West Maui, and various metrics indicate the Keōmuku Reef Tract is likely experiencing moderate to moderate-light fishing pressure, which is greater than might be expected based on its relatively remote location. Whether the current state of the reef fish assemblage can be fully attributed to fishing pressure alone or is instead a combination of fishing pressure and other stressors is not clear from this study. The available historical data from the reef fronting Maunalei suggest that the shallow reef populations have had consistently low biomass for at least a decade, whereas the deeper reef areas have undergone substantial declines in recent years.

Table 4.12. Nine most common fish species (by biomass) observed off Maunalei Gulch in 2012 and 2021 in order of decreasing biomass. Data for 2012 are from Friedlander *et al.* (2012). Species in both lists are color coded to illustrate their relative position in in 2012 and 2021.

2012	2021
Chlorurus spilurus	*Chlorurus spilurus*
Chlorurus perspicillatus	*Acanthurus nigrofuscus*
Acanthurus nigrofuscus	*Naso brevirostris*
Scarus psittacus	*Acanthurus blochii*
Naso lituratus	*Scarus rubroviolaceus*
Scarus rubroviolaceus	*Scarus psittacus*
Thalassoma duperrey	*Acanthurus dussumieri*
Acanthurus leucopareius	*Cephalopholis argus*
Acanthurus triostegus	*Thalassoma duperrey*

Shallow reef areas have low fish abundance and biomass, but appear to be used as juvenile habitat for several resource species, including *Chlorurus spilurus* and *Acanthurus blochii*. Shallow reef areas are clearly affected by terrestrial-derived sedimentation (See Section 4.1), which likely has reduced the value of these reefs as habitat for fish. While the research on this topic is still new, some studies have shown that juvenile fish populations are impacted by high turbidity and soft sediments, similar to when areas are dredged (Wenger *et al*., 2017; Bainbridge *et al*. 2018).

This raises important demographic questions about the importance of the shallow reef area in the Keōmuku Reef Tract to the larger reef assemblage; specifically, are the reef flats the primary juvenile habitat for the Keōmuku Reef Tract reef fish population, and has the decline in shallow reef condition created a recruitment limitation that has resulted in a lower fish abundance and biomass than would ordinarily be expected? Many reef fish species do not migrate large distances (Green *et al.* 2015), especially over deep water; thus, the reef assemblage within the Keōmuku Reef Tract area is unlikely to have high rates of juvenile and adult immigration from other islands in Maui Nui. In addition, modeling of larval dispersal in Maui Nui indicates that reef areas in Keōmuku Reef Tract are primarily self-seeding (Storlazzi *et al.* 2017), which further raises the importance of high-quality, juvenile habitat for this reef fish assemblage.

Sedimentation effects on fish are generally indirect, coming through habitat-mediated pathways such as changes in prey abundance and/or composition, loss of three-dimensional structure, reductions in the quality of juvenile habitat, etc. These qualities are difficult to assess without targeted scientific study, but deep reef areas appear to be good quality reef fish habitat that are experiencing relatively minor sediment-related effects. This alone would raise legitimate questions about whether reducing upland erosion will produce large increases in fish abundance or biomass. However, it appears shallow reef habitat, which currently shows evidence of considerable sediment stress, may be important juvenile habitat for at least some fish species within the Keōmuku Reef Tract. These shallow reef areas are likely to benefit from reductions in sedimentation, which may increase their quality as juvenile habitat, and thus provide benefits to the adult populations that inhabit the deep reef areas.

5. Monitoring Considerations

Considerations for monitoring are provided based on the information collected and analyzed by TNC in 2021. This study was designed to describe the spatial distribution of benthic organisms and reef fish on the Keōmuku Reef Tract and to provide information on sediment and water quality on the reef flat. The information obtained in 2021 was relatively coarse in its spatial resolution and represents a one-time snapshot of the biological, physical, and chemical condition of the Keōmuku Reef Tract.

TNC's study could be considered a first step in the development of a long-term monitoring program for the Keōmuku Reef Tract. Unless this assessment is repeated in the future, the findings from this study are likely not ideally suited to be used as baseline information within a monitoring program[6], but they provide useful information that can aid the development of a robust monitoring program.

Both general and specific considerations are provided below. General considerations apply broadly to the design and implementation of any monitoring program. The specific considerations were derived from the knowledge gained from TNC's 2021 surveys, and can be used to develop a monitoring effort specifically tailored to the needs and resources of a Keōmuku Reef Tract monitoring program.

5.1. General Recommendations

To develop a rigorous monitoring program that assesses the effectiveness of management actions requires:

1. *Clearly defined objectives (and goals) for the monitoring.*

   Defining the objectives of a monitoring program is likely the most critical step of its development because the objectives are the foundation onto which every action conducted by the program will be built. Most comprehensive monitoring programs will have multiple objectives to address specific goals for the program. The objectives should be categorized and assigned a priority order. Compiling, integrating, and reconciling the monitoring objectives of the many stakeholders and partners invested in the condition and future of the Keōmuku Reef Tract was beyond the purview of the work reported here, so proposing specific monitoring questions, parameters of interest, and monitoring methods and designs would be premature. For example, an objective to demonstrate a reduction in sediment input

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[6] The 2021 surveys were designed to assess patterns in the reef assemblage across a large spatial area. This spatial area is likely to be different from that incorporated in a targeted Keōmuku Reef Tract monitoring program. Likewise, TNC's sampling design used random site selection to ensure an unbiased examination of the entire reef area. Long-term monitoring will likely benefit form a substantially different study design (*e.g.,* fixed stations). However, if these assessments were to be repeated in the future, the 2021 data would serve as a robust baseline for comparison

from Maunalei Gulch onto the reef would require fundamentally different monitoring questions, data needs, data collection, analysis and reporting than an objective to demonstrate an improvement on the condition of benthic organisms.

Objectives should also identify the intended use of the information and the audience. This will shape the type of data collected, its analysis, and presentation, and will dictate the level of certainty required. Higher certainty generally requires greater investment in data collection and analysis, which usually leads to higher programmatic costs. Objectives should be developed for data management, and timely analysis and reporting. Finally, the monitoring program should include *adaptive monitoring* objectives, necessitating periodic review of the monitoring program to ensure it is meeting its objectives. This should not be confused with *adaptive management*, which is the change in a management program (*e.g.*, switching erosion control measures) that maybe be triggered if monitoring demonstrates the current approaches are ineffective. Ideally, the monitoring program should inform but be separated from the adaptive management decision-making process because this process almost always requires consideration of information that is outside scope of the monitoring program (*e.g.*, social, political, and/or financial considerations).

2. *Specific questions that are measurable, achievable, linked to the goals/objectives (i.e., relevant), and time-bound.*

Objectives are generally broad statements describing the goals of the monitoring program. However, the monitoring program should be designed around specific and detailed questions. The more specific and relevant the monitoring question, the more likely the program will meet its objective. SMART questions are likely to facilitate the development of a robust monitoring program and should be Specific, Measurable, Achievable, Relevant, and Time-bound. For example, “Has sediment decreased?” is not a SMART question. A “SMARTer” question might be, “Has turbidity on the reef adjacent to Maunalei Gulch improved by at least 25% after 10 years?”

SMART questions should be formulated by technical experts and people familiar with the natural system to be monitored. The 2021 surveys of Keōmuku Reef Tract should be valuable when developing SMART, monitoring-related questions because it has generated site-specific information on relevant parameters that can provide insight into their spatial patterns relative to point sources of terrestrial inputs, variability, and their relationship to broad concepts such as “reef condition.”

3. *A broad understanding of the spatial and temporal dynamics of the natural system under investigation, especially its variability.*

The primary purpose of any monitoring program is to detect change in a parameter from an initial state. The ability to detect change is directly influenced by the amount of variability in a given parameter, where the more variable the parameter, the more difficult it is to detect if that parameter has actually changed. For example, if parrotfish biomass natural varies between 7 and 10 g/m^2 between survey years[7] and a monitoring location increase in biomass from 8 to 30 g/m^2, it is easy to conclude that parrotfish biomass has increase at the location. However, it parrotfish biomass varies between 7 and 40 g/m^2 from year to year, it would be unclear if a similar increase is a “real” increase or simply variability within it’s natural range.

Variability in natural systems can be partitioned into different types of variability, of which variability through space and variability through time are generally the two most significant. Understanding both spatial and temporal variability are important when deciding where, when, and how frequently to collect data. Without a good understanding of variability, any monitoring effort risks not having sufficient analytical power to detect meaningful change. The 2021 Keōmuku Reef Tract surveys will be invaluable when assessing spatial variability. The data collected by TNC can be used to estimate the spatial variability for all parameters collected (*e.g.*, abundance by species, sediment depth, coral cover, etc.). In addition, these data can be combined with previous studies, such as Friedlander *et al.* (2012) to generate a crude estimate of temporal variability for relevant parameters. A Keōmuku Reef Tract monitoring program should be developed in coordination with a statistician experienced in measuring, characterizing, and sampling variability in marine ecosystems.

4. *Realistic consideration of resources.*

When monitoring, it is almost always better to do a few things well, than many things poorly. Data collected using imprecise methods or with insufficient replication to overcome the variability of the system, and/or inadequate analysis and reporting will fail to answer the program’s monitoring questions and result in no or incorrect adaptive management decisions, increasing the risk of failure of the management action.

In addition, long-term monitoring, as its name implies, must continue for many years or decades to meet its objective(s). This creates unique funding challenges and requires the monitoring program be designed for flexibility and adaptability.

Funding long-term monitoring is difficult, so understanding the resources available and being realistic about what can be accomplished is critical. Funding and staffing to conduct long-term sampling, analysis, and reporting can be easily underestimated. To counter these challenges, a monitoring program should have a “modular” design with a few core questions and data collection needs that can be achieved with minimal funding or staff. Secondary questions and/or additional data can then be included in the program as resources permit (or be cut from the program if future funding necessitates).

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[7] Ideally, as determined from multiple years of baseline data from the location, but this can also be determined from examining similar data from similar locations.

5.2. **Specific Considerations for the Keōmuku Reef Tract**

Monitoring objectives are the most important step in the development of a monitoring program. They will guide the development of SMART questions, which in turn will shape the design of the monitoring effort and the collection, analysis, and reporting of information. Objectives should be ordered by their importance in the likelihood the program will not be able to complete them all. This should be done through a process involving the appropriate decision makers (*e.g.*, whoever will be using the information from the monitoring program to make decisions about the management actions) and in consultation with stakeholders and technical experts.

Restoration actions upland from the Keōmuku Reef Tract are attempting to reduce soil erosion and sediment transport onto the nearshore coral reefs. Detecting reductions in sediment discharge and/or accumulation on the reef flat would be appropriate objectives for long-term monitoring. A sediment reduction objective could provide direct evidence of the effectiveness of upland restoration efforts, and data collected to address one or more well-conceived SMART questions associated with that objective could provide considerable insight into the effectiveness of specific management actions and/or locations (*e.g.*, specific questions could be targeted for specific gulches). However, a sediment reduction objective would not provide information on the benefits of sediment reduction to reef organisms, and additional objectives would be necessary if this is determined to be important. Based on the findings of the 2021 study, biological objectives targeting the shallow reef area of the Keōmuku Reef Tract are more likely to document benefits associated with sediment reduction than ones targeting the deep reef area.

Once SMART questions have been developed, appropriate parameters to measure should be carefully selected. Most questions will likely have more than one potential parameter that could be used to assess it. When selecting parameters, their variability, measurability, ease of collection (including the safety of the field team), and resource costs (*e.g.*, equipment, staffing, etc.) should be considered. Parameters that have high variability, such as turbidity, will generally require more replication than parameters with low variability to achieve a desired level of analytical power to detect change. This may result in higher resource costs. Tidal and diurnal wind forcing were found to have an outsized effect on nearshore turbidity, while storm events seemed to drive large scale patterns of sedimentation – indicating that imagery (drone or satellite) taken at post-flood and during the same tide and time of day might be the best for a long-term monitoring program to look at changes in water clarity. Some example parameters are summarized in Table 5.1.

Parameter variability will be the primary factor that affects where, when and how frequently data should be collected. Generally, in long-term monitoring, temporal variability is more important than spatial variability. Specific sampling designs can be implemented to greatly reduce spatial variability (*e.g.*, fixed sampling locations) and somewhat reduce temporal variability (*e.g.*, sampling at the same time of year or under the same conditions such as after a rain event).

TNC’s 2021 reef assessment does not quantify temporal variability on the Keōmuku Reef Tract. Therefore, a Keōmuku Reef Tract monitoring program should consider “oversampling” initially (*e.g.*, the first 1-5 years) to estimate temporally variability. Afterwards, sampling frequency can be adjusted as necessary to achieve the needed level of replication to obtain the desired analytical power. While expert opinion or temporal data from other similar locations may also be valuable, especially initially, site-specific information should be obtained in the early years of the monitoring program.

Finally, a long-term monitoring program whose objective is assessing the effectiveness of a management action will be interested in attributing any observed change to its activities. Natural systems are affected by many factors beyond the management action, so reference sites are crucial for distinguishing the effects of the management activities from other local (*e.g.*, fishing), regional (*e.g.*, coral recruitment), and global factors (*e.g.*, climate change). The 2021 reef surveys have identified considerable spatial variability in shallow reef condition. This heterogeneity may be useful when selecting reference locations. For example, monitoring locations placed near to a sediment discharge may be complemented by reference locations in adjacent shallow reef areas that experience considerably less sediment stress.

While TNC's reef surveys have captured broad spatial patterns on the shallow reef, selecting reference locations will likely require higher-resolution spatial sampling than was completed in this assessment. Once specific monitoring objectives and SMART questions have been developed, it would be beneficial to conduct a targeted, high-resolution assessment of reef areas to identified suitable reference locations for any parameters of interest. Fortunately, the range of parameters investigated and the resolution of the 2021 surveys are sufficient to allow any additional work to be targeted at specific areas of the reef.

Finally, the benthic assemblages found in these shallow reef areas experiencing less sediment stress may represent remnants of the historical coral reef flat community and may be indicative of what might be attainable if sedimentation can be addressed, and recovery is allowed to occur. These areas may help define recovery targets.

Table 5.1. Six example parameters that could be measured as part of a Keōmuku Reef Tract monitoring program, their variability, the effort necessary to obtain (which is usually correlated with cost), and the expected time horizon for change. The time horizon is measured from the point of full implementation of management actions in the Keōmuku Reef Tract. The (?) included with some entries for variability indicates uncertainty with the variability estimate.

	Variability	**Effort**	**Time horizon**	**Notes**
Example sediment parameters				
Sediment depth	Spatial: medium to high Temporal: medium (?)	Low	Years to decades	Requires little equipment or specialized training.
Turbidity	Spatial: high Temporal: high	Low	Years	Requires specialized equipment and some training.
Terrigenous composition	Spatial: medium to high Temporal: low (?)	High	Years to decades	Requires considerable specialized equipment, “laboratory” space, and training.
Example biological parameters				
Coral cover	Spatial: medium to high Temporal: low (?)	Medium	Decades	Some methods allow for data collection in the water. Requires considerable expertise/training.
Coral bleaching rate	Spatial: medium to high Temporal: medium (?)	Medium	Years to decades	Hawai‘i Eyes of the Reef program may provide sufficient training for data collection by citizen scientists.
Density of coral recruits	Spatial: medium to high Temporal: medium (?)	High	Years to decades	Requires considerable expertise/training.

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8. Appendix A. Site Metadata

Reef zone and sub-zone (A-E), depth category, latitude, longitude, depth and rugosity for all sites surveyed in the Keōmuku Reef Tract in 2021.

Site	Zone	Depth Category	Lat.	Long.	Depth	Rug.
2021-LANA-002	E-1	Deep (>2m)	20.84562925	-156.8142993	12.2	1.95
2021-LANA-003	E-1	Deep (>2m)	20.850267	-156.818211	2.4	1.49
2021-LANA-005	E-1	Deep (>2m)	20.84798136	-156.816179	4.9	1.49
2021-LANA-007	E-1	Deep (>2m)	20.85467857	-156.8211342	5.5	1.59
2021-LANA-009	E-1	Deep (>2m)	20.84640712	-156.8157696	3	1.53
2021-LANA-011	D-1	Deep (>2m)	20.86874204	-156.8362416	4	1.47
2021-LANA-013	E-1	Deep (>2m)	20.85676661	-156.8253516	3	1.95
2021-LANA-016	D-2	Deep (>2m)	20.86852921	-156.83257	12.8	1.72
2021-LANA-023	C-3	Shallow (<2m)	20.879748	-156.84809	1.8	1.28
2021-LANA-024	D-2	Deep (>2m)	20.86108095	-156.8281814	4.9	1.71
2021-LANA-031	D-1	Deep (>2m)	20.87246914	-156.8380838	9.8	1.53
2021-LANA-032	D-2	Deep (>2m)	20.86486911	-156.8290793	11.3	1.58
2021-LANA-033	C-3	Deep (>2m)	20.88219841	-156.8463798	12.2	1.88
2021-LANA-034	D-1	Deep (>2m)	20.87087237	-156.8371009	7	1.4
2021-LANA-036	C-3	Deep (>2m)	20.87810857	-156.8421451	12.8	1.65
2021-LANA-037	D-2	Deep (>2m)	20.8635318	-156.8293214	7.6	1.6
2021-LANA-038	D-2	Deep (>2m)	20.86689106	-156.8314087	10.7	1.65
2021-LANA-039	C-3	Deep (>2m)	20.87556435	-156.8414074	7.3	1.51
2021-LANA-041	C-3	Deep (>2m)	20.87974316	-156.8461384	7	1.8
2021-LANA-042	D-1	Deep (>2m)	20.87186432	-156.8401143	2.1	1.49
2021-LANA-043	C-3	Deep (>2m)	20.88190468	-156.8478486	7.6	1.79
2021-LANA-044	D-2	Deep (>2m)	20.861505	-156.8299349	2.1	1.42
2021-LANA-045	C-3	Shallow (<2m)	20.87634497	-156.8443513	1.8	1.33
2021-LANA-046	D-2	Deep (>2m)	20.86581229	-156.8325819	5.2	1.81
2021-LANA-047	D-2	Deep (>2m)	20.86251695	-156.8274365	11.3	1.69
2021-LANA-050	D-2	Deep (>2m)	20.86003486	-156.8262735	8.2	1.57
2021-LANA-051	D-1	Deep (>2m)	20.87427318	-156.840239	7.9	1.66
2021-LANA-054	D-1	Shallow (<2m)	20.869853	-156.837891	1.8	1.42
2021-LANA-055	C-3	Shallow (<2m)	20.877921	-156.846415	1.5	1.4
2021-LANA-058	C-3	Deep (>2m)	20.874081	-156.842645	2.4	1.38
2021-LANA-059	B-1	Deep (>2m)	20.9044659	-156.8760446	5.2	1.58
2021-LANA-062	B-2	Deep (>2m)	20.89779409	-156.8666947	10.1	1.74
2021-LANA-064	C-1	Deep (>2m)	20.89256809	-156.8622166	3.4	1.51
2021-LANA-065	C-1	Deep (>2m)	20.89556026	-156.8620448	12.8	1.5

Site	Zone	Depth Category	Lat.	Long.	Depth	Rug.
2021-LANA-068	B-1	Shallow (<2m)	20.899622	-156.871954	1.5	1.49
2021-LANA-069	B-1	Deep (>2m)	20.9012916	-156.8721419	6.7	1.58
2021-LANA-070	B-2	Deep (>2m)	20.89896389	-156.8697515	5.5	1.79
2021-LANA-071	B-1	Deep (>2m)	20.90138933	-156.8747631	2.1	1.43
2021-LANA-072	B-2	Shallow (<2m)	20.89658742	-156.8692077	1.8	1.61
2021-LANA-073	C-1	Deep (>2m)	20.89242722	-156.8601233	7.3	2.01
2021-LANA-075	B-1	Deep (>2m)	20.90584689	-156.8794266	3.4	1.88
2021-LANA-077	B-1	Deep (>2m)	20.90870529	-156.8788673	9.8	1.71
2021-LANA-078	B-1	Deep (>2m)	20.90316276	-156.8718428	12.2	1.55
2021-LANA-079	C-1	Deep (>2m)	20.89455125	-156.8656645	2.4	1.43
2021-LANA-082	C-2	Deep (>2m)	20.88754313	-156.8521892	12.2	1.6
2021-LANA-087	C-3	Deep (>2m)	20.88087556	-156.8508243	2.1	1.6
2021-LANA-088	C-2	Deep (>2m)	20.88440262	-156.8517269	5.5	1.48
2021-LANA-089	C-2	Shallow (<2m)	20.88401128	-156.8539526	1.8	1.53
2021-LANA-092	C-2	Deep (>2m)	20.88882861	-156.8573862	4.6	1.67
2021-LANA-096	C-2	Deep (>2m)	20.88688461	-156.8552574	4.3	1.4
2021-LANA-099	C-2	Deep (>2m)	20.88247647	-156.8508328	6.1	1.7
2021-LANA-100	C-2	Deep (>2m)	20.89055399	-156.8560672	10.4	1.7
2021-LANA-502	E-1	Deep (>2m)	20.85001854	-156.8188264	3.7	1.72
2021-LANA-503	E-1	Shallow (<2m)	20.85222366	-156.823365	1.5	1.2
2021-LANA-504	E-1	Shallow (<2m)	20.85087586	-156.8211352	0.9	1.34
2021-LANA-505	E-1	Shallow (<2m)	20.84907092	-156.8202733	1.2	1.47
2021-LANA-507	E-1	Shallow (<2m)	20.846218	-156.818972	0.3	1.08
2021-LANA-508	E-1	Shallow (<2m)	20.85326484	-156.8239777	1.2	1.42
2021-LANA-550	D-1	Shallow (<2m)	20.87011172	-156.8412599	0.8	1.33
2021-LANA-551	C-3	Shallow (<2m)	20.87835153	-156.8523714	1.2	1.15
2021-LANA-552	D-1	Shallow (<2m)	20.87063645	-156.843392	1.2	1.11
2021-LANA-554	C-3	Shallow (<2m)	20.87951857	-156.8520531	1.5	1.24
2021-LANA-555	D-2	Shallow (<2m)	20.85871715	-156.8299635	1.2	1.25
2021-LANA-556	D-2	Shallow (<2m)	20.86059456	-156.8325821	1.5	1.24
2021-LANA-557	C-3	Shallow (<2m)	20.8778506	-156.8484508	1.2	1.1
2021-LANA-558	C-3	Shallow (<2m)	20.87562534	-156.8490038	0.3	1.12
2021-LANA-559	C-3	Shallow (<2m)	20.87641587	-156.8485922	0.6	1.3
2021-LANA-562	C-3	Shallow (<2m)	20.87153758	-156.8431257	1.8	1.29
2021-LANA-563	D-1	Shallow (<2m)	20.86617466	-156.83788	1.2	1.16
2021-LANA-566	D-2	Shallow (<2m)	20.8635702	-156.8343536	1.5	1.21
2021-LANA-567	E-1	Shallow (<2m)	20.854342	-156.827673	0.9	1.29
2021-LANA-570	C-3	Shallow (<2m)	20.87909797	-156.8507287	1.5	1.06
2021-LANA-572	D-2	Shallow (<2m)	20.86233968	-156.8326798	1.5	1.15
2021-LANA-573	D-2	Shallow (<2m)	20.86207737	-156.8352665	1.1	1.1

Site	Zone	Depth Category	Lat.	Long.	Depth	Rug.
2021-LANA-574	C-3	Shallow (<2m)	20.87212541	-156.8438155	1.1	1.45
2021-LANA-575	D-1	Shallow (<2m)	20.86569149	-156.8362555	0.9	1.29
2021-LANA-576	D-1	Shallow (<2m)	20.86743865	-156.839494	1.8	1.22
2021-LANA-577	E-1	Shallow (<2m)	20.85371926	-156.8264578	1.2	1.15
2021-LANA-578	C-3	Shallow (<2m)	20.8767248	-156.8469155	0.9	1.12
2021-LANA-579	D-1	Shallow (<2m)	20.86942745	-156.8395824	0.9	1.23
2021-LANA-580	C-3	Shallow (<2m)	20.87581998	-156.8456447	1.2	1.35
2021-LANA-581	C-3	Shallow (<2m)	20.8794449	-156.8490501	0.9	1.43
2021-LANA-584	E-1	Shallow (<2m)	20.85433476	-156.825294	1.5	1.51
2021-LANA-585	C-3	Shallow (<2m)	20.87729168	-156.8500604	0.9	1.12
2021-LANA-586	C-3	Shallow (<2m)	20.8745786	-156.8451381	0.9	1.21
2021-LANA-587	D-2	Shallow (<2m)	20.86089619	-156.8310278	0.9	1.36
2021-LANA-588	E-1	Shallow (<2m)	20.85574323	-156.82685	0.6	1.2
2021-LANA-589	D-1	Shallow (<2m)	20.86873545	-156.8400805	0.9	1.2
2021-LANA-590	D-2	Shallow (<2m)	20.86429382	-156.8356329	1.5	1.22
2021-LANA-591	D-1	Shallow (<2m)	20.87159298	-156.8424284	0.8	1.3
2021-LANA-592	D-1	Shallow (<2m)	20.86492768	-156.8370114	1.2	1.19
2021-LANA-594	D-1	Shallow (<2m)	20.86758613	-156.8380022	0.9	1.4
2021-LANA-596	C-3	Shallow (<2m)	20.87236886	-156.8450601	1.2	1.14
2021-LANA-597	D-2	Shallow (<2m)	20.86557818	-156.8343298	1.8	1.28
2021-LANA-598	E-1	Shallow (<2m)	20.851645	-156.823028	0.6	1.22
2021-LANA-599	D-2	Shallow (<2m)	20.856213	-156.827991	0.9	1.44
2021-LANA-600	C-2	Shallow (<2m)	20.88522033	-156.8594049	0.9	1.18
2021-LANA-601	C-2	Shallow (<2m)	20.88185919	-156.8550438	1.5	1.4
2021-LANA-604	C-2	Shallow (<2m)	20.88424531	-156.8567026	1.5	1.38
2021-LANA-605	C-2	Shallow (<2m)	20.88719671	-156.8594676	0.6	1.55
2021-LANA-607	C-2	Shallow (<2m)	20.88267342	-156.8542028	0.9	1.5
2021-LANA-608	C-2	Shallow (<2m)	20.88629208	-156.8588678	0.9	1.21
2021-LANA-613	C-2	Shallow (<2m)	20.88493326	-156.8560319	0.9	1.39
2021-LANA-616	C-2	Shallow (<2m)	20.88173604	-156.8536154	0.6	1.14
2021-LANA-650	C-2	Shallow (<2m)	20.88888012	-156.8597884	0.9	1.16
2021-LANA-651	B-2	Shallow (<2m)	20.89760233	-156.8715121	1.8	1.7
2021-LANA-652	B-1	Shallow (<2m)	20.89904269	-156.8760531	0.5	1.2
2021-LANA-654	C-1	Shallow (<2m)	20.89310621	-156.8664393	0.9	1.15
2021-LANA-655	B-2	Shallow (<2m)	20.89573162	-156.8734059	0.6	1.11
2021-LANA-657	C-1	Shallow (<2m)	20.89178903	-156.8665163	1.2	1.12
2021-LANA-658	B-2	Shallow (<2m)	20.89555186	-156.8718351	0.8	1.19
2021-LANA-659	B-2	Shallow (<2m)	20.89818337	-156.8730162	0.9	1.31
2021-LANA-660	B-1	Shallow (<2m)	20.903025	-156.8794581	0.9	1.37
2021-LANA-661	C-1	Shallow (<2m)	20.89139342	-156.8635674	0.9	1.14

Site	Zone	Depth Category	Lat.	Long.	Depth	Rug.
2021-LANA-664	B-1	Deep (>2m)	20.89989506	-156.8739109	2.1	1.41
2021-LANA-667	B-1	Shallow (<2m)	20.9007958	-156.8775849	0.6	1.33
2021-LANA-668	C-1	Shallow (<2m)	20.88974154	-156.8622734	0.9	1.05
2021-LANA-669	B-1	Shallow (<2m)	20.901946	-156.878446	1.2	1.71
2021-LANA-670	B-1	Shallow (<2m)	20.89872349	-156.8746438	0.3	1.21
2021-LANA-690	B-1	Shallow (<2m)	20.903465	-156.87816	1.5	1.31
2021-LANA-692	B-2	Shallow (<2m)	20.894655	-156.869113	0.9	1.37
2021-LANA-696	D-2	Shallow (<2m)	20.863548	-156.835796	1.8	1.38
2021-LANA-697	C-1	Shallow (<2m)	20.88706	-156.861988	0.9	1.2
2021-LANA-698	C-1	Shallow (<2m)	20.890463	-156.864517	1.2	1.43
2021-LANA-699	C-1	Shallow (<2m)	20.890586	-156.865846	0.9	1.07
2021-LANA-700	A	Shallow (<2m)	20.91323538	-156.8921143	1.2	1.4
2021-LANA-704	A	Shallow (<2m)	20.91283524	-156.8911335	1.8	1.05
2021-LANA-705	A	Shallow (<2m)	20.91164954	-156.892074	0.9	1.38
2021-LANA-711	A	Shallow (<2m)	20.91362284	-156.8957545	0.9	1.1

9. Appendix B. ANOVA/PERMANOVA Results

Table B.1. PERMANOVA of percent cover by benthic groups for Reef Zones B through E (no sub-zones) in the shallow reef area.

```
           Df SumsOfSqs  MeanSqs F.Model      R2 Pr(>F)
Reef_Zone1  3    0.1796 0.059859 0.92147 0.03601  0.507
Residuals  74    4.8070 0.064960         0.96399
Total      77    4.9866                  1.00000
```

Table B.2. PERMANOVA of percent cover by benthic groups for Reef Zones B through E (includes sub-zones) in the shallow reef area.

```
           Df SumsOfSqs  MeanSqs F.Model      R2 Pr(>F)
Reef_Zone2  7    0.4893 0.069900   1.088 0.09812  0.353
Residuals  70    4.4973 0.064247         0.90188
Total      77    4.9866                  1.00000
```

Table B.3. PERMANOVA results for shallow reef coral assemblages identified by the MWA analysis.

```
          Df SumsOfSqs MeanSqs F.Model      R2 Pr(>F)
MWA_cat    3    1.5835 0.52785  1.7404 0.08391  0.024 *
Residuals 57   17.2879 0.30330         0.91609
Total     60   18.8714                 1.00000
---

     pairs   F.Model         R2 p.value p.adjusted sig
1 S1 vs S2 1.0040179 0.02641873   0.396      1.000
2 S1 vs S3 0.5892147 0.01991316   0.763      1.000
3 S1 vs S4 3.1273054 0.11118397   0.003      0.018 **
4 S2 vs S3 0.7415105 0.02264741   0.594      1.000
5 S2 vs S4 2.6282243 0.08581053   0.014      0.084 *
6 S3 vs S4 3.2867622 0.14114295   0.008      0.048 **
```

Table B.4. PERMANOVA of percent cover by benthic groups for Reef Zones B through E (no sub-zones) in the deep reef area.

```
           Df SumsOfSqs  MeanSqs F.Model      R2 Pr(>F)
Reef_Zone1  3   0.37365 0.124550  2.0354 0.12435  0.110
Residuals  43   2.63124 0.061192         0.87565
Total      46   3.00489                  1.00000
```

Table B.5. PERMANOVA of percent cover by benthic groups for Reef Zones B through E (includes sub-zones) in the deep reef area.

```
           Df SumsOfSqs  MeanSqs F.Model      R2 Pr(>F)
Reef_Zone2  7   0.51923 0.074175  1.1638 0.17279  0.323
Residuals  39   2.48567 0.063735         0.82721
Total      46   3.00489                  1.00000
```

Table B.6. ANOVA of total fish biomass for Reef Zones B through E (includes sub-zones) by depth category (shallow vs deep).

```
                Df Sum Sq Mean Sq F value    Pr(>F)
Zone             3   2.33   0.777   2.721    0.0476
Depth_Cat        1  15.70  15.703  55.023  2.06e-11
Zone:Depth_Cat   3   0.56   0.186   0.653    0.5827
Residuals      117  33.39   0.285

           diff          lwr       upr     p adj
C-B -0.25437898 -0.609535806 0.1007778 0.2480353
D-B -0.09946583 -0.478298331 0.2793667 0.9028882
E-B  0.13233932 -0.317286936 0.5819656 0.8690889
D-C  0.15491315 -0.150709321 0.4605356 0.5514340
E-C  0.38671830 -0.003223749 0.7766604 0.0527971 *
E-D  0.23180516 -0.179816633 0.6434269 0.4602179
```

Table B.7. ANOVA of total fish abundance for Reef Zones B through E (includes sub-zones) by depth category (shallow vs deep).

```
                Df Sum Sq Mean Sq F value    Pr(>F)
Zone             3  0.685   0.228   2.753    0.0457
Depth_Cat        1  3.984   3.984  48.064  2.41e-10
Zone:Depth_Cat   3  0.517   0.172   2.079    0.1068
Residuals      117  9.699   0.083

           diff         lwr        upr     p adj
C-B -0.15841355 -0.34982726 0.03300017 0.1415451
D-B -0.07644156 -0.28061540 0.12773229 0.7634776
E-B  0.03633155 -0.20599698 0.27866008 0.9796542
D-C  0.08197199 -0.08274491 0.24668889 0.5666482
E-C  0.19474510 -0.01541630 0.40490650 0.0797870 *
E-D  0.11277311 -0.10907270 0.33461892 0.5490249
```

Table B.8. ANOVA of resource fish biomass for Reef Zones B through E (includes sub-zones) by depth category (shallow vs deep).

```
                Df Sum Sq Mean Sq F value   Pr(>F)
Zone             3   3.43   1.142   4.116  0.00815
Depth_Cat        1  11.97  11.974  43.164 1.46e-09
Zone:Depth_Cat   3   1.32   0.440   1.587  0.19633
Residuals      117  32.46   0.277

$Zone
          diff         lwr       upr     p adj
C-B -0.3188633 -0.66901951 0.0312930 0.0879371 *
D-B -0.1217789 -0.49527744 0.2517197 0.8304515
E-B  0.1422005 -0.30109502 0.5854961 0.8371866
D-C  0.1970844 -0.10423495 0.4984037 0.3258723
E-C  0.4610638  0.07661209 0.8455155 0.0118416 **
E-D  0.2639794 -0.14184679 0.6698056 0.3307594
```

Table B.9. ANOVA of resource fish abundance for Reef Zones B through E (includes sub-zones) by depth category (shallow vs deep).

```
                Df Sum Sq Mean Sq F value  Pr(>F)
Zone             3  0.209  0.0697   2.254 0.08569
Depth_Cat        1  0.333  0.3328  10.760 0.00137
Zone:Depth_Cat   3  0.106  0.0353   1.142 0.33514
Residuals      117  3.619  0.0309


$Zone
           diff         lwr        upr     p adj
C-B -0.10626738 -0.22318592 0.01065116 0.0888568 *
D-B -0.04874805 -0.17346068 0.07596458 0.7388016
E-B -0.02885561 -0.17687374 0.11916251 0.9570175
D-C  0.05751933 -0.04309237 0.15813103 0.4467640
E-C  0.07741176 -0.05095816 0.20578169 0.3987218
E-D  0.01989244 -0.11561451 0.15539939 0.9808550
```

Table B.10. ANOVA of prime spawner biomass for Reef Zones B through E (includes sub-zones) by depth category (shallow vs deep).

```
                Df Sum Sq Mean Sq F value   Pr(>F)
Zone             3  0.714   0.238   1.345    0.263
Depth_Cat        1  3.687   3.687  20.841 1.24e-05
```

```
Zone:Depth_Cat   3  1.282   0.427   2.415    0.070
Residuals      117 20.698   0.177
```

Table B.11. ANOVA of prime spawner abundance for Reef Zones B through E (includes sub-zones) by depth category (shallow vs deep).

```
                Df  Sum Sq  Mean Sq F value  Pr(>F)
Zone             3 0.00187 0.000625   0.509 0.67675
Depth_Cat        1 0.01145 0.011445   9.329 0.00279
Zone:Depth_Cat   3 0.00632 0.002107   1.717 0.16728
Residuals      117 0.14354 0.001227
```

10.Appendix C. Fish Species by Reef Area

Fish species observed the shallow and deep reef areas within the Keōmuku Reef Tract in 2021. Values in the columns are the rank based on biomass, with 1 being the species contributing the most to the total fish biomass. The top 10 species have been highlighted in green. X=no biomass calculated for the species.

Longshore_	**KRT**	**Shallow**	**Deep**
Acanthurus blochii	1	3	1
Chlorurus spilurus	2	11	2
Acanthurus nigrofuscus	3	2	3
Scarus rubroviolaceus	4	1	4
Naso unicornis	5	9	5
Cephalopholis argus	6	16	6
Thalassoma duperrey	7		7
Naso brevirostris	8	17	8
Lutjanus fulvus	9	23	9
Scarus psittacus	10	4	10
Naso lituratus	11	8	11
Acanthurus triostegus	12	40	12
Melichthys niger	13		13
Acanthurus dussumieri	14	38	14
Parupeneus multifasciatus	15	46	15
Chaetodon ornatissimus	16	7	16
Monotaxis grandoculis	17	5	17
Kyphosus sp.	18	15	18
Abudefduf sordidus	19	22	19
Ctenochaetus strigosus	20	37	20
Oxycheilinus unifasciatus	21		21
Abudefduf vaigiensis	22		22
Gomphosus varius	23		23
Mulloidichthys flavolineatus	24	10	24
Acanthurus leucopareius	25	12	25
Acanthurus xanthopterus	26		
Stegastes marginatus	27		27
Bodianus albotaeniatus	28	19	28
Cantherhines sandwichiensis	29	6	29
Stethojulis balteata	30		30
Mulloidichthys vanicolensis	31		31

Caranx melampygus	32	34	32
Naso hexacanthus	33	20	33
Plectroglyphidodon johnstonianus	34		34
Melichthys vidua	35		35
Coris gaimard	36		36
Chaetodon lunula	37		37
Chaetodon unimaculatus	38	42	38
Thalassoma ballieui	39	57	39
Myripristis berndti	40		40
Chaetodon lunulatus	41		41
Chaetodon auriga	42		42
Thalassoma purpureum	43		43
Calotomus carolinus	44	14	44
Chaetodon multicinctus	45	26	45
Acanthurus olivaceus	46	31	46
Zebrasoma flavescens	47		47
Paracirrhites arcatus	48		48
Sufflamen bursa	49	39	49
Canthigaster jactator	50	56	50
Kyphosus hawaiiensis	51		51
Cantherhines dumerilii	52	33	52
Neoniphon sammara	53	51	53
Parupeneus cyclostomus	54		54
Parupeneus insularis	55		55
Canthigaster amboinensis	56	18	56
Ctenochaetus hawaiiensis	57	28	57
Scomberoides lysan	58	62	58
Zebrasoma veliferum	59	29	59
Abudefduf abdominalis	60		60
Chromis ovalis	61		61
Kyphosus sandwicensis	62		62
Myripristis kuntee	63	13	63
Rhinecanthus rectangulus	64		64
Chromis vanderbilti	65	25	65
Thalassoma trilobatum	66		66
Paracirrhites forsteri	67		67
Halichoeres ornatissimus	68	24	68
Scarus sp.	69		69
Forcipiger longirostris	70	35	70

Tylosurus crocodilus	71		71
Acanthurus nigricans	72		72
Cirrhitus pinnulatus	73	44	73
Cirripectes vanderbilti	74	41	74
Centropyge potteri	75		75
Ostracion meleagris	76		76
Chaetodon lineolatus	77	55	77
Chaetodon ephippium	78	43	78
Acanthurus achilles	79	30	79
Chromis hanui	80	27	80
Plectroglyphidodon imparipennis	81		81
Chaetodon miliaris	82	63	82
Thalassoma lutescens	83		83
Forcipiger flavissimus	84		84
Parupeneus porphyreus	85		85
Thalassoma quinquevittatum	86		86
Dascyllus albisella	87		87
Anampses cuvier	88	64	88
Sufflamen fraenatus	89		89
Asterropteryx semipunctatus	90		90
Cirrhitops fasciatus	91	65	91
Labroides phthirophagus	92	45	92
Aulostomus chinensis	93	21	
Synodus sp.	94	32	
Pseudocheilinus octotaenia	95	36	
Pseudocheilinus tetrataenia	96	47	
Fistularia commersonii	97	48	
Chromis agilis	98	49	
Oxycheilinus bimaculatus	99	50	
Sphyraena barracuda	100	52	
Pseudojuloides cerasinus	101	53	
Gobiidae sp.	102	54	
Cheilio inermis	103	58	
Macropharyngodon geoffroy	104	59	
Carcharhinus amblyrhynchos	105	60	
Plagiotremus goslinei	106	61	
Decapterus macarellus	X		X
Elagatis bipinnulata	X		X
Gymnothorax eurostus	X	X	

Gymnothorax flavimarginatus	X	X	
Gymnothorax meleagris	X	X	
Gymnothorax sp.	X	X	

11. Appendix D: Sediment export model

One published sediment export model was included as a layer in the Ocean Tipping Points dataset (Wedding et al, 2018). Using the InVEST SDR sediment export model, Falinski (2016) estimated sediment loads using a modified RUSLE equation for the Hawaiian islands. For this project, we redid the model, this time eliminating slopes greater than 40 degrees from contributing to the overall export. It has been shown that steeply sloped areas are poorly predicted by RUSLE based models. In addition, we created smaller subwatershed using ArcHydro that were more focused on the study area. Since 2015 when the original model was created, updated values that more accurately represent Hawaiʻi mesic and dryland forest cover have also been created, and those values were used.

Recent work has shown that increasingly flashy storm events would possibly increase the rainfall erosion estimates, and 2021's 500-year flood events were some of the largest seen in nearby Kīhei. As such, we can expect an annual model like the InVEST SDR to do poorly at predicting year over year sediment export. The new results with the updated slope parameters are presented below as a guide. Figure D-1 shows the total export amounts highlighting Maunalei watershed, the largest watershed in the region, followed by Wahane and Iamo watersheds. Figure D-2 shows the possible hotspots indicated by the specific sediment yield in tons per km^2. Figure D-2 shows Ka'a Gulch, in addition to the smaller gulch Kahokunui, as having the highest yield by area. These results more closely match the nearshore turbidity patterns observed. In this case, compared to the 2016 model results, there were not significant differences in pattern of sedimentation due to the updated model parameters.

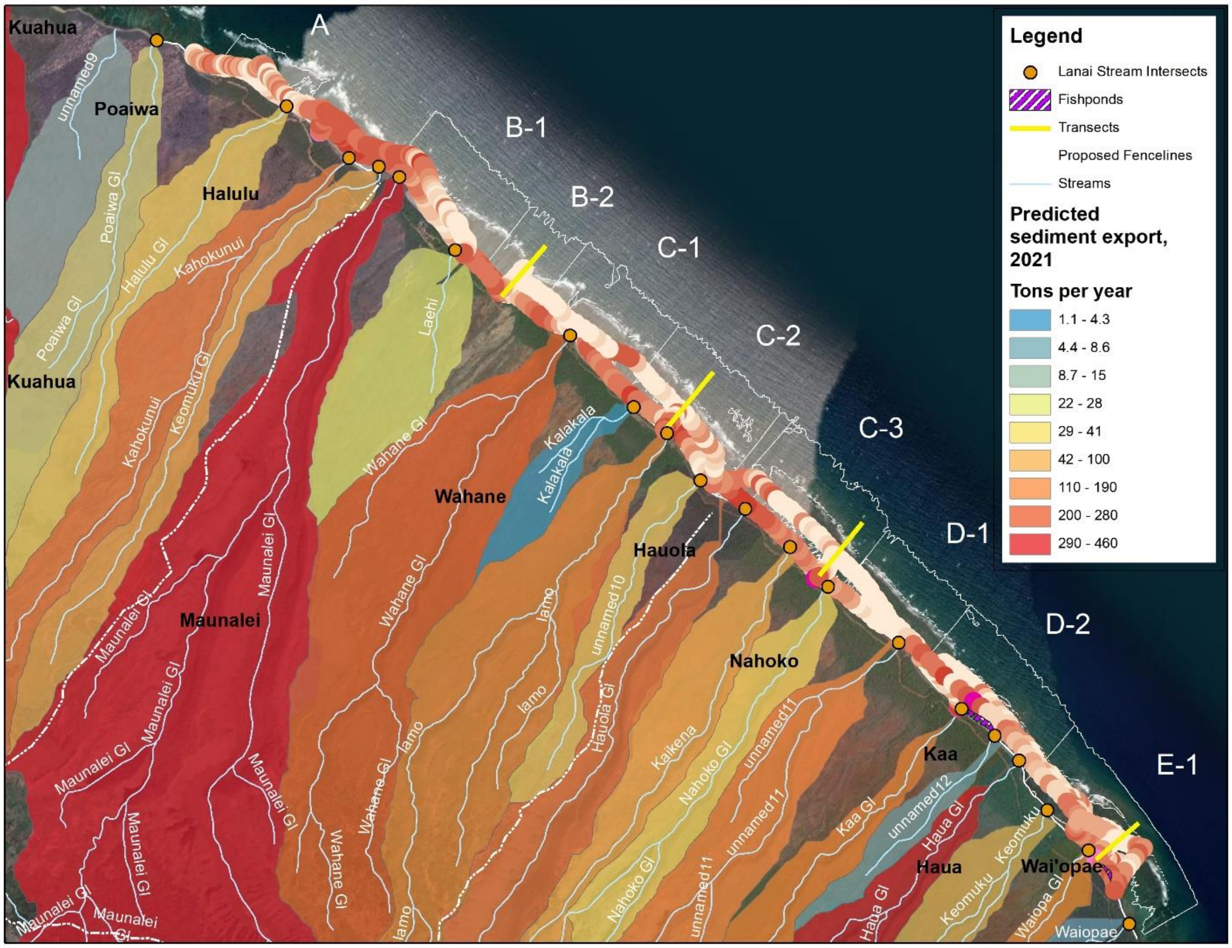

Figure D-1. InVEST SDR results showing total annual sediment export predictions.

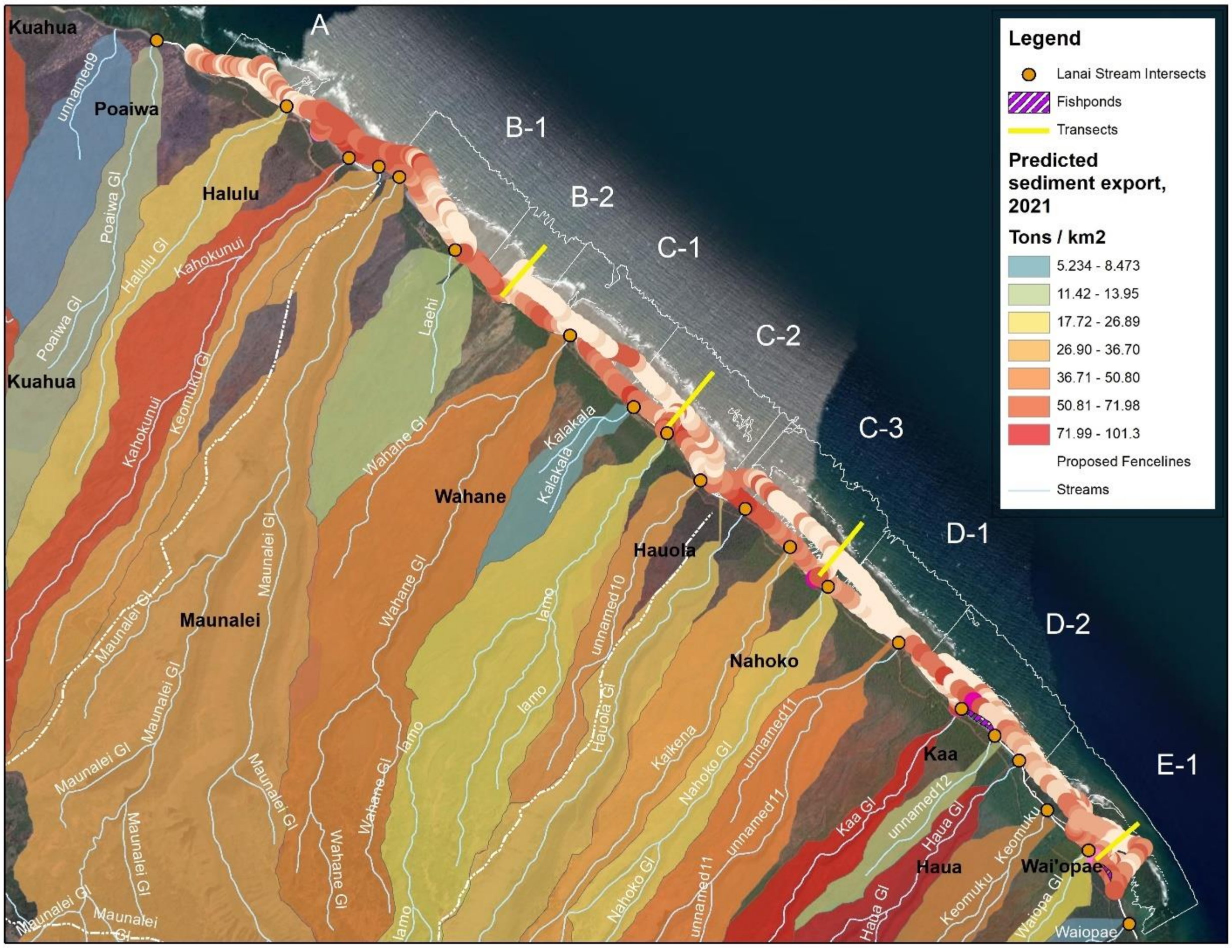

Figure D-2: Sediment export per unit area for the Keōmuku region, as estimated by a modified InVEST SDR model.