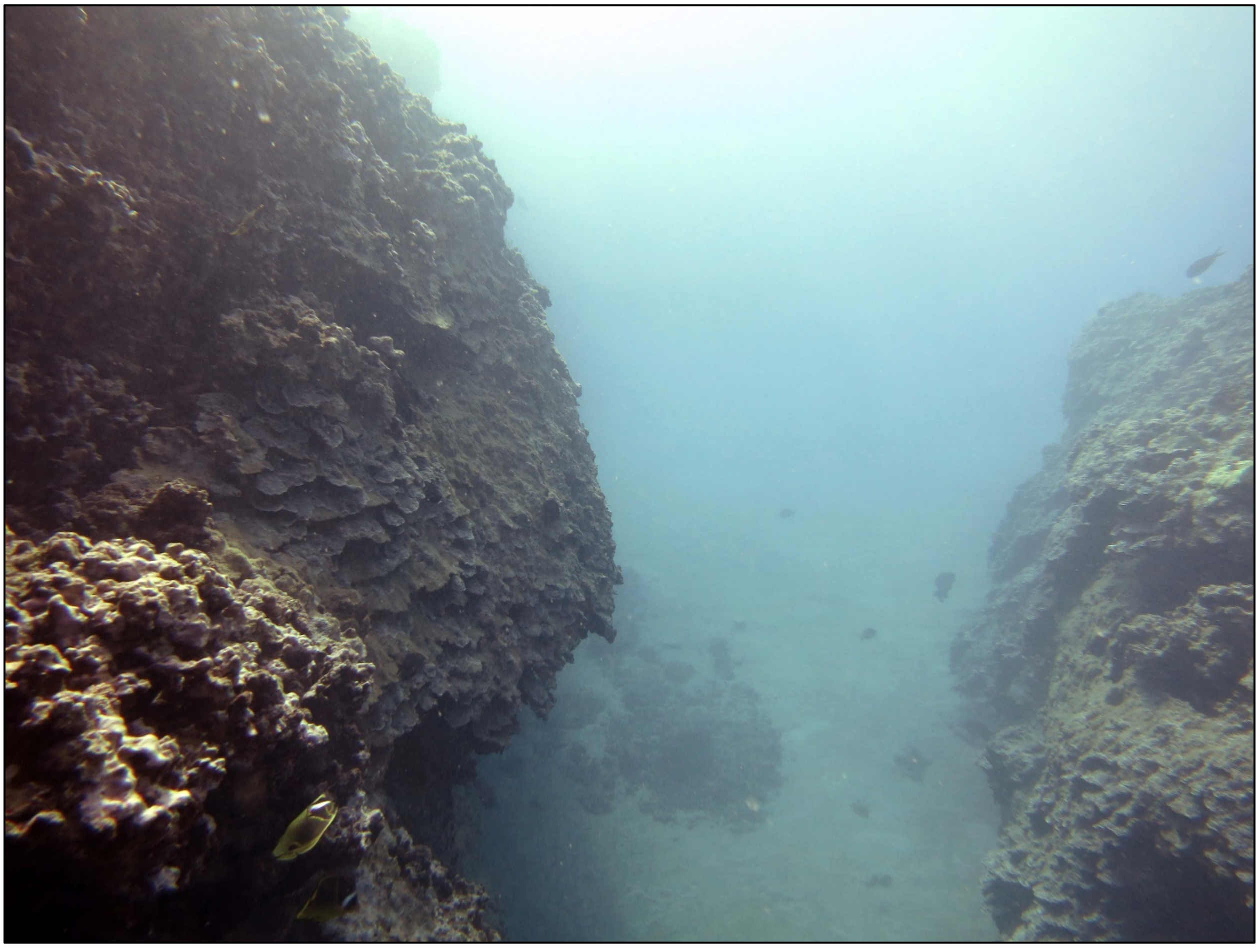
Evaluating Coral Reef Recovery to Improve Reef Resilience Planning Along the West Coast of Hawaiʻi Island



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Evaluating Coral Reef Recovery to Improve Reef Resilience Planning Along the West Coast of Hawai‘i Island

by

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Cover Photo: Coral canyons at the ʻŌhaiʻula deep sites in 2017

1.0 Executive Summary

Coral reef resilience is the capacity of a reef to resist and/or recover from degradation and maintain provisions of ecosystem functions and services. Resilience-based management involves the application of resilience theory and tools to deliver ecosystem-based management outcomes into the future and can include assessing spatial variation in resilience potential and then using these results to target and tailor actions to preserve or restore the resilience of reefs. Such assessments generally involve measuring or assessing resilience indicators across several sites and producing an aggregate score that expresses resilience potential for each site relative to the site with the highest assessed resilience potential.

In the fall of 2015 and 2016, The Nature Conservancy (TNC) with its partners assessed the relative resilience potential of twenty reef location along West Hawaiʻi Island. Ongoing at the start of the 2015 surveys, West Hawaiʻi was undergoing a mass coral bleaching event that affected nearly all coral species and extended to sites as deep as 15 m. Follow up surveys in 2016 documented considerable coral mortality. In 2017, TNC and its partners returned to the same reef locations and repeated surveys conducted in prior years. The 2017 study had two objectives: 1) assess the condition of the previously-surveyed reef areas two years after the 2015 mass bleaching event, and 2) evaluate the condition at the locations in 2017 relative to the 2015 rankings to assess the performance of the 2015 reef resilience analysis.

Twenty-five coral species were identified during the 2017 surveys with *Porites lobata* (lobe coral) and *P. compressa* (finger coral) accounting for over 93% of all coral observations. Coral cover did not decrease between 2016 and 2017, holding steady at 18.5 ± 1.4%, but was significantly lower than that in 2015 (25.5 ± 1.6%). Disease prevalence has dropped each year since 2015 and continues to be low (2.5 ± 0.4%), but with generally greater prevalence at the southern end of the survey area. Five coral diseases (*Porites* Growth Anomalies, *Porites* Tissue Loss Syndrome, *Montipora* Growth Anomalies, *Pocillopora* Tissue Loss Syndrome and *Porites* Trematodiasis) and two other conditions (algal overgrowth and bleaching) were identified. Algal overgrowth was the most prevalent disease/condition affecting corals on West Hawaiʻi.

A total of 133 species of reef fish in 25 families were observed in 2017. The families Acanthuridae (surgeonfishes), Balistidae (triggerfishes), and Scaridae (parrotfishes) contributed the most to total fish biomass. Herbivores accounted for over half of all the total fish biomass, whereas apex predators were rarely observed. Total fish biomass was 45.4 ± 7.2 g/m^2, which was significantly lower than observed in 2016 (71.1 ± 9.8 g/m^2) and 2015 (79.6 ± 4.6 g/m^2). This decline is likely associated with elevated fish biomass in 2015 and 2016 due to a large fish recruitment in 2014 followed by a gradual return to pre-2014 biomass levels.

Using two years of post-bleaching information, we assessed the performance of the 2015 resilience rankings at predicting resistance to bleaching (the recovery component of resilience can only be assessed after allowing several years for recovery to take place). The 2015 rankings were generally not correlated with indicators that described the ability of a reef to resist a thermal stress event and recover from adverse effects, suggesting the rankings did not perform as intended. However, deeper investigations suggest that the rankings were successful at differentiating sites at the top and bottom of the ranking. Two sites at each depth consistently performed well in the annual rankings calculated from 2015 to 2017. Likewise, three sites at each depth consistently performed poorly in each year, suggesting the rankings effectively identify sites with high and low relative resilience. When resilience indicators for these sites were examined, they showed a trend toward overperforming (high ranking sites) or underperforming (low ranking sites) relative to other locations; for example, bleaching resistance in 2017 at the top two sites was 98.6 ± 0.65% compared to 90.1 ± 2.5% for the middle sites, and 83.9 ± 5.1% for the bottom three sites. In addition, using rankings derived from multiple-years of surveys many help to illuminate patterns obscured by the natural variability of these reef systems, and may provide additional insight into the resilience of West Hawai‘i’s coral reefs and their response the 2015 mass coral bleaching event.

This project highlights the value of collecting data across a range of sites when conducting reef resilience assessments. By returning to reefs that experienced a significant thermal stress event, we have been able to assess the performance of our original rankings. While the approach did not perform entirely as expected for predicting resistance and the initial stages of recovery, it still produced valuable results that can contribute to improved management of reefs on West Hawai‘i. And while insufficient time has passed to allow for recovery, it is encouraging that coral cover has stabilized in 2017 and coral health improved, with the reefs of West Hawai‘i avoiding longer-term declines in coral cover and health that can often follow severe bleaching events.

2.0 Introduction

The west coast of Hawaiʻi Island contains one of the longest contiguous coral reef systems in the main Hawaiian Islands. These biodiverse reefs are home to culturally- and economically-significant species[1], mitigate wave and storm impacts, and provide recreational and other economic benefits to the residents of the state (Cesar and van Beukering 2004). Due to their interconnectedness, island communities will acutely feel any degradation of the nearshore coral reefs and supporting the resilience of these marine ecosystems is a goal within many management plans for West Hawai'i and is regularly mentioned by stakeholders.

Coral reef resilience is the capacity of a reef to resist and/or recover from degradation and maintain provisions of ecosystem functions and services (Mumby *et al.* 2007). This is especially important within the context of climate change, under which global stressors including rising ocean water temperature and acidification are exerting increasing stress on coral reef ecosystems worldwide and contributing to reef degradation and loss.

Resilience-based management involves the application of resilience theory and tools to deliver ecosystem-based management outcomes into the future (Chapin *et al.* 2009). Generally, this involves examining indicators/processes thought to make reefs more resistant to thermal events (*e.g.*, temperature resistance, etc.) and better able to recover from any adverse effects (*e.g.*, recruitment, etc.). This information is then used to target and tailor actions to preserve or restore the resilience of reefs (Weeks and Jupiter 2013, Maynard *et al.* 2015). Such assessments have been recommended by coral reef scientists, managers, and leading conservation organizations (Maynard *et al.* 2015, Anthony *et al.* 2015, McClanahan *et al.* 2012, Graham *et al.* 2013). Typically, the assessments involve measuring or assessing resilience indicators across several sites and producing an aggregate score that expresses resilience potential for each site relative to the site with the highest assessed resilience potential.

This type of guidance would be valuable in Hawaiʻi because the frequency of adverse "warm water events" and associated coral bleaching are expected to increase. Warm water conditions sufficient to trigger coral bleaching events are expected to occur annually in Hawaiʻi by the middle of the century (van Hooidonk *et al.* 2014). Given the slow natural recovery rates for most coral species, frequent and repeated bleaching events would likely decrease coral cover and alter species composition, creating cascade effects through the coral reef ecosystem that likely would reduce fish species abundance and alter fish assemblage composition (Garpe *et al.* 2006, Bellwood *et al.* 2016).

In October 2015, The Nature Conservancy (TNC) with partners at the Hawaiʻi Division of Aquatic Resources (DAR), NOAA's Coral Reef Ecosystems Division (NOAA CRED), and community organizations in West Hawaiʻi assessed the relative resilience potential of 20 reef locations within priority areas of South Kohala and North Kona along the west coast of Hawaiʻi Island. At the time these surveys were conducted, a prolonged period of warm, calm weather had resulted in elevated sea water temperatures and the onset of widespread coral bleaching on

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[1] Nearly a quarter of the coral and fish species in Hawaiʻi are endemic (*i.e.*, can only be found in the Hawaiian Islands).

West Hawai‘i reefs (Kramer *et al.* 2016, Maynard *et al.* 2016), which lasted from September through December 2015 and peaked between October 22-25, 2015 (NOAA CRW 2016). Sea temperatures were above the bleaching threshold (Degree Heating Weeks = 4 °C-weeks) for two months (NOAA CRW 2016), a level of thermal stress unprecedented in Hawai’i. TNC’s research team documented severe, widespread bleaching in nearly all coral species and down to depths of at least 15 m (Maynard *et al.* 2016). Bleaching susceptibility varied widely across taxa, with lobate species such as *Porites lobata* showing less bleaching than branching forms such as *Pocillopora meandrina* (Maynard *et al.* 2016). Due to its severity and duration, the bleaching caused significant coral mortality (Kramer *et al.* 2016, Minton *et al.* 2018a), the long-term consequences of which remain unclear but are the subject of ongoing research, including the study presented here.

In 2016, TNC and its partners returned to the same reef locations and repeated the reef resilience and bleaching surveys conducted in the prior year and documented significant coral mortality, but also noted hopeful signs that recovery potential existed or that recovery may be underway (Minton *et al.* 2018a). In addition, evidence was found suggesting ecological dynamics such a recruitment may play a larger role in reef resilience compared to “static” indicators such as coral cover. Linkages were also identified between local environmental stressors and site resilience.

TNC returned to these locations in 2017, two years following the mass coral bleaching event, to again document the condition and recovery of these reefs. These new data are also intended to allow for deeper exploration of the effectiveness of the resilience rankings developed in 2015. This report will describe the results of the 2017 surveys and build upon pre-existing information to assess the current condition and trajectory of these 20 West Hawai‘i reef locations.

3.0 Methods

Survey methods have been described previously (Maynard *et al.* 2016, Minton *et al.* 2018a), and are summarized here. The purpose of these methods was to collect information to 1) assess the general condition of the marine resources at a site, and 2) collect specific reef resilience indicators that could be used to create and evaluate a relative ranking of the sites reflective of their resilience to the effects of climate change.

Numerous reef resilience indicators proposed in the scientific literature were examined by McClanahan *et al.* (2012) and ranked based on their perceived importance, scientific evidence supporting their linkage to resilience, and their feasibility of measurement. Eleven indicators were selected from this assessment by a suite of Hawai‘i coral reef scientists and managers for investigation at West Hawai‘i (Maynard *et al.* 2016). Seven biological indicators, including six identified by McClanahan *et al.* (2012) (coral cover, coral diversity, coral recruitment, bleaching resistance, macroalgae cover, and herbivorous fish biomass) and rugosity[2], were used to create an aggregate resilience score and ranking. The remaining five indicators (temperature variability, nutrients, sedimentation, physical human impacts, and fishing pressure) were used to investigate linkages between these environmental indicators and site resilience, which has been discussed elsewhere (Minton *et al.* 2018a) and will not be included in this report.

3.1 Locations and Sites

The NOAA Coral Reef Conservation Program, NOAA Habitat Blueprint, and Sentinel Site Program have an overlapping Focus Area on the west side of Hawai’i Island (hereafter West Hawai‘i). These programs have consolidated their efforts to gather information and provide support for effective management of this area. This Focus Area also overlaps with, and is supported by, the NOAA Hawaiian Islands Humpback Whale National Marine Sanctuary, and is a focus of the NOAA National Marine Fisheries West Hawai‘i Integrated Ecosystems Assessment Project.

In 2015, reef resilience was assessed at twenty locations selected in consultation with DAR, extending from North Kona to South Kohala Districts of West Hawai‘i (Figure 1). Eighteen locations were spaced approximately ~2.5 kilometers apart within the Focus Area using ArcGIS and should be representative of the full range of the area’s ecological and physical conditions. At the request of the DAR, two additional locations south of the Focus Area (Honokohau and Keahou) were also surveyed. In addition, seven of the selected locations overlapped with existing DAR West Hawai‘i monitoring sites (Figure 1). At each location, a shallow (5-7 m) and deep (12-15 m) site were surveyed. Location metadata are provided in Appendix A.

While not generally part of a typical resilience assessment, we returned in 2016 to these locations to repeat the reef resilience surveys. The 2015 mass bleaching event presented a unique opportunity to examine the response of West Hawai‘i’s reefs to the event and evaluate the short-term predictive potential of the 2015 reef resilience assessment (*i.e.*, the “resistance” component

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[2] Benthic rugosity is often correlated with abundance and diversity of associated species, especially fish (Friedlander and Parrish 1998).

of resilience, as evidenced by indicators such as coral mortality, etc.). Site photos, field notes, and compass bearings collected in 2015 were used to realign transects for re-surveying in 2016, and stainless steel pins were installed at the start and end of each transect to permanently mark them for future resurveys. Transects at locations that overlapped with existing DAR-West Hawaiʻi monitoring sites needed to be offset approximately 100 m from the original 2015 location to avoid interference with DAR's long-term monitoring effort. Because we could not resurvey the exact same sections of reef from 2015 to 2016, additional spatial variability was likely introduced into 2015 to 2016 comparisons that is not present when comparing the 2016 and 2017 data collected along the permanent transects installed in 2016. However, an analysis (Minton *et al.* 2018a) showed the effects of the bleaching event were much larger than the variability introduced from the spatial shift in transect position, and that the shifting of transects introduced no systematic bias into the findings.

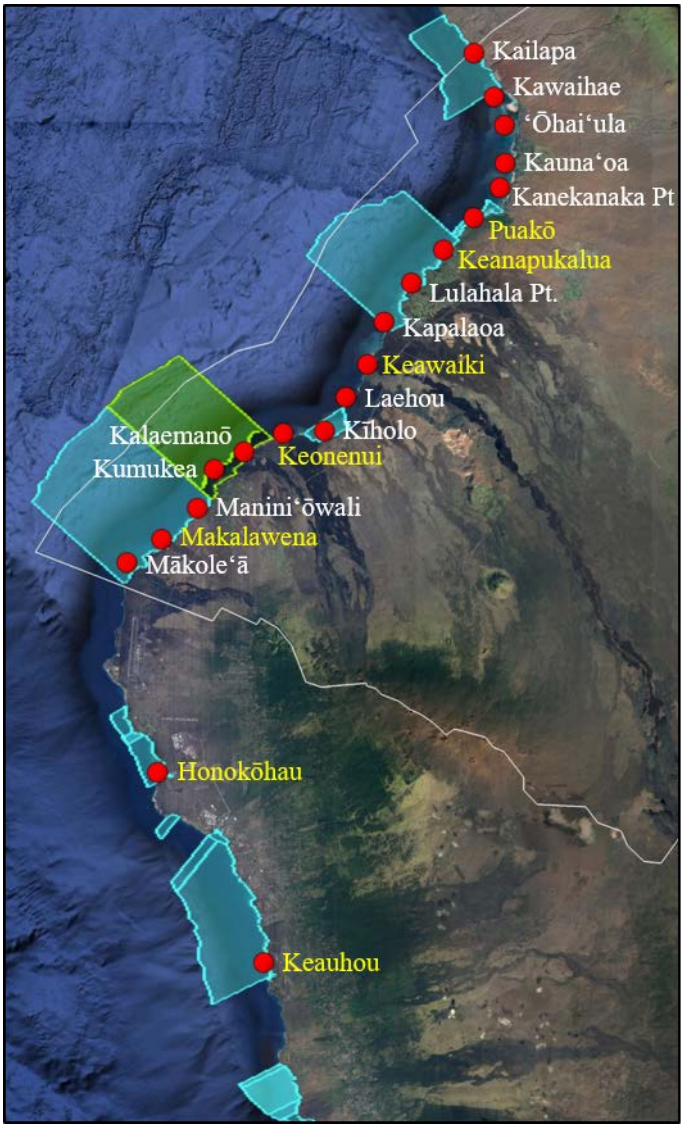

Figure 1. Map of survey locations, at which a shallow and deep site was surveyed. The white line is the boundary of the NOAA's West Hawaiʻi Focus Area. Blue polygons are State of Hawaiʻi Fishery Management Areas (FMAs) and Fishery Replenishment Areas (FRA). Both FMAs and FRAs have additional fishing restrictions compared to "open" areas. The green polygon is the Kaʻūpūlehu Marine Reserve. Two survey location (Kumukea and Kalaemanō) are within the nearshore section of the Marine Reserve, which was closed to all fishing on July 29, 2016. Prior to closure, the Kaʻūpūlehu Marine Reserve was an FRA. Locations highlighted in yellow overlap with DAR West Hawaiʻi Monitoring sites. See text for additional discussion.

3.2 Field Assessments

At all locations, we conducted comprehensive assessments to document spatial patterns of species abundance, biomass and condition. Surveys were conducted along all or part of three replicate 25-m transect lines laid out consecutively within the defined depth ranges at shallow and deep sites. An intervening space of ~10 m was left between the end of one transect and the start of the next. Assessments were

Table 1. Summary of field survey methods. All surveys were conducted along all or part of each 25-m transect line (three replicate transects/site). See Appendix B for a more-detailed description of each method.

Data Type	**Location**	**Method**
Coral Health	0-10 m (1 m-wide belt)	All coral colonies were counted and identified to species. Each colony was inspected for signs of known diseases and other conditions (e.g., bleaching, algal overgrowth, etc.). The prevalence of each condition was calculated separately for each site and by species, as appropriate.
Coral Juveniles	0-10 m (1 m-wide belt)	All coral colonies ≤5 cm in diameter (longest dimension) whose geometric center lay within a 0.5 x 0.5 m quadrat were counted and identified to the lowest taxonomic level. Four quadrats were haphazardly spaced ~2 m apart within the coral health belt transect.
Rugosity	0-10 m	A rugosity index was calculated by dividing the length of brass chain required to contour the bottom by the 10 m transect length. For this index, a value of one represents a flat surface with no relief, and increasing values represent more topographically complex substratum.
Benthic Cover	0-25 m	Photographs of the bottom were taken at every meter using a Canon G12 or S110 camera mounted on a 0.8 m long PVC monopod, generating 25 images/transect. Twenty randomly-selected photographs from each transect were analyzed using the online tool Coralnet to estimate benthic cover. The benthic component under each of thirty randomly distributed points was identified to the lowest possible taxonomic level. Due to lower taxonomic resolution in the 2015 survey data, when inter-annual comparisons were made, data were aggregated into four major benthic categories: corals, macroalgae, coralline algae, and other substrata.
Fish abundance and Size	0-25 m (5 m-wide belt)	All fish within or passing through a 5-m wide belt were identified to species and sized into 5-cm bins (*i.e.*, 0-5 cm, >5-10 cm, >10-15 cm, etc.). The weight of each fish in grams was calculated using standard weight-length relationships and using coefficients sourced from FishBase, the USGS Hawaiʻi Cooperative Fishery Research Unit and NOAA's Coral Reef Ecosystem Program. Only herbivorous fish biomass was used in the resilience assessment.

conducted by a three- or four-person team, comprised of surveyors who were trained and calibrated to reduce observer variability and produce relevant and credible data. The method for each survey type is summarized in Table 1, with a more-detailed description in Appendix B.

3.3 Analysis

All fish and site data were entered into a custom Access database and checked for errors. All benthic data were compiled and verified in either Excel spreadsheets (benthic cover) or using the R statistical package (coral health) prior to analysis. All databases and spreadsheets support safeguards to ensure high data quality, and they reside on a secure, central TNC server that is backed up daily to an offsite location to protect against data loss.

Reef Condition

The benthic assemblage was characterized by percent cover by benthic type/group (*e.g.*, all coral, all macroalgae, abiotic, etc.), and where there existed sufficient taxonomic resolution, to species (*e.g.*, coral). Overall coral health was examined using disease (DZ) and compromised health (COMP) condition prevalence, calculated as follows:

$$\text{Prev} = \frac{\text{\# of colonies with at least 1 type of DZ or COMP}}{\text{\# of total colonies}}$$

The prevalence of each condition for all coral or for individual coral genera was calculated as follows:

$$\text{Prev}_{(\text{DZ or COMP})} = \frac{\text{\# of colonies with a specific DZ or COMP}}{\text{\# of total colonies or \# of colonies of a given genus}}$$

Fish survey data were pooled into two groups: all fish and by trophic group. A 5-level trophic designation was used, including: herbivores (primary), piscivores (secondary), other carnivores (secondary), planktivores (secondary), and apex predators (tertiary). Trophic designations for each species were obtained primarily from FishBase (Froese and Pauly 2011), or from species-specific literature if Hawaiian populations were known to vary from the larger species.

All means are presented as the average ± the standard error of the mean (SEM) unless otherwise stated. Standard parametric and non-parametric statistical approaches, as appropriate, were used to test for differences between depth and among years. Analyses were conducted using R version 3.4.2 (2017-09-28).

Resilience Rankings

For each biological indicator, data were averaged across the three transects at each site and normalized to a unidirectional scale of 0-1 by dividing by the maximum value for the variable among all 20 sites within the depth strata. To ensure that high scores always inferred higher relative resilience potential, normalized scores were inverted for macroalgae cover and coral disease[3]. All indicators were equally weighted. Resilience scores were calculated by averaging the normalized indicator scores for each site, after which these aggregated scores were also normalized. Sites were then ordered by score and ranked from 1 (highest rank) to 20 (lowest

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[3] In contrast to other biological indicators, lower amounts of coral disease and macroalgal cover are considered to be representative of “better” reef condition.

rank). These rankings express the resilience of all sites as relative to the site with the highest score, *i.e.*, the final normalized scores ranged from 0-1 and represented decimal percentages of the site with the highest score (1.00). Separate resilience scores were calculated for shallow and deep sites. “Qualitative” classifications for resilience scores were defined as follows:

High → Final Score $\geq \bar{x} + 1$ standard deviation (sd)
Medium-high → $\bar{x} + 1$ sd > Final Score $\geq \bar{x}$
Medium-low → $\bar{x}$ > Final Score $\geq \bar{x} - 1$ sd
Low → $\bar{x} - 1$ sd > Final Score

Average ranks were also generated using data from 2015-2017 by averaging normalized scores across the years prior to aggregating and normalizing again prior to ordering and ranking from 1 to 20. To determine the potential range of these ranks, upper and lower rankings were determined by adding or subtracting the standard deviation of the normalize indicator score prior to aggregating, normalizing, and ordering.

We measured deviance between annual rankings using absolute cumulative change in position (hereafter, change score), which was calculated as the summation of the absolute differences between the two annual rankings. A low change score indicated the annual rankings from one year were similar to those of the other year. The minimum change score possible was 0 (all rankings stayed the same) and the maximum possible change score was 181. If the revised rankings were re-assigned at random (*e.g.*, using no data from the indicators), the average change score follows a normal distribution with a mean and standard deviation of 131 ± 18.

4.0 Results and Discussion

4.1 Reef Condition: Two Years Post-bleaching

Turf algae was the most common benthic cover type among the twenty West Hawaiʻi locations, averaging 63.7 ± 1.3% cover (Table 2). Mean coral cover across the survey area was 18.5 ± 1.4%, with no significant difference between shallow (19.9 ± 2.3%) and deep (17.1 ± 2.2%) sites (t-test; T_{34}=1.03, p=0.307). Twenty-five coral species were identified, and *Porites lobata* (lobe coral) and *P. compressa* (finger coral) were the most abundant, accounting for over 93% of all coral observations. *P. monticulosa* (plate and knob coral) and *Montipora capitata* (rice coral) were next most abundant, but each accounted for only about 2% of all coral observations. Other coral species were rarely encountered.

Average coral disease prevalence across the survey area continued to be low overall (2.5 ± 0.4%), about half that observed in 2015 (5.9 ± 0.6%) (Maynard *et al.* 2016) and 2016 (4.4 ± 0.6%) (Minton *et al*. 2018). Keonenui had the highest disease prevalence, 8.0% and 10.2% at shallow and deep sites respectively. Disease prevalence at Keonenui was higher than that observed in 2015 and 2016, when Kalaemanō, the site adjacent to Keonenui had the highest disease prevalence among the 20 locations. Persistent elevated disease prevalence appears to be a feature along this specific section of the West Hawaiʻi Coast (Couch *et al.* 2014), but reason for this are not clear. Overall disease prevalence did not significantly vary between shallow (2.8 ± 0.5%) and deep (2.2 ± 0.6%) sites (t-test, T_{38}=0.71, p=0.481).

Five coral diseases were identified (most to least prevalent): *Porites* Growth Anomalies (PorGA), *Porites* Tissue Loss Syndrome (PorTLS), *Montipora* Growth Anomalies (MonGA), *Pocillopora* Tissue Loss Syndrome (PocTLS) and *Porites* Trematodiasis (PorTrem) (Table 3). PorGA occurred at 88% of sites with *Porites* and affected 2.7 ± 0.5% of *Porites* colonies.

In addition to the five diseases, two other conditions were common: algal overgrowth (ALOG) and bleaching. ALOG, primarily caused by red filamentous turf algae, was the most prevalent disease/condition affecting corals on West Hawaiʻi with 10.7 ± 1.5% of all colonies displaying the condition. Bleaching prevalence in 2017 was 10.0 ± 1.5%, which was double that observed in 2016 (5.1 ± 0.9%), but far less than that observed during the mass bleaching in 2015 (64.2 ± 2.7%). Prevalence of bleaching varied among species, with only a small percentage of *Porites lobata* and *P. compressa* colonies affected (Table 4). In contrast, nearly half of all *Montipora capitata* colonies were bleached, with over a quarter severely bleached (>50% of the colony bleached). This general pattern is consistent with the expected response based on each species genera-specific bleaching susceptibility (Swain *et al.* 2016).

Coral cover at our twenty West Hawaiʻi reef locations significantly decreased between 2015 and 2016 (Minton *et al.* 2018a), but coral cover did not change between 2016 and 2017 (Figure 2) (Paired t-test, T_{39}=0.57, p=0.568). That coral cover did not continue to decline in 2017, and disease rates were low, suggest reef condition has stabilized following the initial adverse effects of the 2015 mass coral bleaching event.

Table 2. Average percent cover of major benthic groups/species. An * indicates the species was observed during the coral health surveys, but not during the benthic cover surveys.

	West Hawai‘i	**SHALLOW**	**DEEP**
Coral	18.5 ± 1.4	19.9 ± 2.3	17.1 ± 2.2
Porites lobata	13.7 ± 1.2	17.7 ± 2.1	9.8 ± 2.1
Porites compressa	3.5 ± 1.0	1.3 ± 0.6	5.7 ± 1.2
Porites monticulosa	0.4 ± 0.6	<0.1	0.9 ± 0.6
Montipora capitata	0.3 ± 0.1	0.1 ± 0.1	0.5 ± 0.1
Pavona varians	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.1
Porites rus	0.1 ± 0.1	0.2 ± 0.3	<0.1
Montipora patula	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Porites lutea	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Pavona duerdeni	0.1 ± 0.1	0.1 ± 0.1	<0.1
Pocillopora meandrina	<0.1	0.1 ± 0.1	<0.1
Leptastrea purpurea	<0.1	*	<0.1
Porites bernardi	<0.1	<0.1	<0.1
Fungia scutaria	<0.1	*	<0.1
Psammocora nierstraszi	<0.1	*	<0.1
Montipora flabellata	*	0	*
Pavona maldivensis	*	*	*
Cyphastrea ocellina	*	*	*
Leptastrea bewickensis	*	*	*
Leptastrea transversa	*	0	*
Montipora incrassata	*	*	*
Pocillopora damicornis	*	*	*
Porites evermanni/lutea	*	*	*
Porites brighami	*	*	*
Psammocora haimeana	*	*	0
Psammocora stellata	*	*	*
Turf	63.7 ± 1.3	66.8 ± 2.3	60.6 ± 2.2
CCA	7.7 ± 1.3	6.5 ± 1.6	9.0 ± 1.7
Cyanobacteria	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1
Other	<0.1	<0.1	<0.1
Macroalgae	<0.1	<0.1	<0.1
Abiotic	9.8 ± 2.3	6.5 ± 1.5	13 ± 2.7
Sand	7.2 ± 0	5.8 ± 0.1	8.6 ± 0.1
Rubble	2.4 ± 1	0.6 ± 0.2	4.3 ± 1.1
Recently Dead Coral	0.1 ± 0	0.1 ± 0.1	0.1 ± 0.1
Pavement	<0.1	<0.1	<0.1

Table 3. Prevalence of disease and other conditions by location and depth, with locations arranged from the most northerly (top) to the most southerly (bottom). Values are average percentage of the three transects surveyed at each depth (all values are %). Disease is total prevalence of all diseases and conditions except bleaching (% of colonies). The other five diseases are prevalence for the described genera (% of *Porites*/*Montipora*/*Pocillopora* colonies). Bleaching is the percent of colonies fully- or partially-bleached. Severe bleaching is the percent of colonies with >50% loss of pigmentation. See text for definitions of the disease abbreviations.

	Shallow									Deep								
Site	Disease	PorGA	MonGA	PorTLS	PocTLS	Por Trem	ALOG	Bleach	Sev. Bleach	Disease	PorGA	MonGA	PorTLS	PocTLS	Por Trem	ALOG	Bleach	Sev. Bleach
Kailapa	0.6	0.6	0	0	0	0	19.3	0.4	0.4	0.5	0.8	0	0	0	0	11.3	1	0.3
Kawaihae	1.6	2.4	0	0	0	0	14.2	0.8	0.1	0	0	0	0	0	0	8.3	9.5	3.1
‘Ōhai‘ula	0	0	0	0	0	0	5	23	4.7	0	0	0	0	0	0	12.5	34	4.3
Kauna‘oa	3.7	4.3	0	0	0	0	21.4	21.1	1.2	2.4	0.7	0	0	1.1	0	30	19.4	3.3
Kanekanaka Pt.	4.8	4.5	0	0	0	0	13.1	4.9	0	0	0	0	0	0	0	21.1	3.9	0
Puakō	4.6	4.9	0	0	0	0	5.1	0	0	0.3	0.3	0	0	0	0	8.6	0	0
Keanapukalua	0.8	0.4	0	0	0.7	0.4	3.3	18.4	4.3	2	1.8	0	0	0.9	1.3	14.5	17.4	2.7
Lulahala Pt.	2.4	2.3	0	0	0.4	0.5	2.2	8.9	6	1.5	1.4	0	0	0.4	1	16.6	25.1	9.2
Kapalaoa	1.5	2.3	0	0	0	0.6	21.6	20.1	2.6	2.2	2.5	0	0	0.6	0.7	14.6	22.5	9
Keawaiki	0.4	0.6	0	0	0	0	11.7	1.3	0	0.4	0.4	0	0	0.1	0	8.6	6.3	1.4
Laehou	3.4	3.3	0	0	0.8	0.1	3.7	1.3	1.3	3	2.7	0	0	0.8	0	5	2.5	1.7
Kīholo	0.5	0.6	0	0	0	0	6	10.8	3	0.2	0.4	0	0	0	0	2.7	35.2	19
Kalaemanō	1	1.1	0	0	0	0.3	0	8.2	3.2	0	0	0	0	0	0	2.3	8.3	5.9
Keonenui	8	12.7	0.5	3.3	0.6	0	4.6	8.3	5.9	10.2	12.4	0	0	0.8	0	5.2	9.6	3.8
Kumukea	2.1	2.3	0	0	0.2	0	3.1	1.9	1.6	0.4	0.4	0	0	0	0.3	1.1	13.7	10.9
Manini‘ōwali	8.5	8.5	0	0	0.4	0	5.4	0.6	0.4	3.4	3	0	0	0.6	0	5.4	4.1	2.9
Makalawena	2.5	3.2	0	0	0	1.4	1.4	17.4	2.8	5.1	5.8	0	0	0	0	4	2.1	1.1
Mākole‘ā	3.8	3.1	0	0	0.5	0.2	3.8	6	3.7	4.3	5.1	1	0	0.1	0.4	6.4	5.5	4.4
Honokōhau	2.5	2.9	0	0	0.6	0.5	15.7	11.6	2.5	3.7	2.8	0	0	1	3.8	43	13.6	1.8
Keauhou	2.7	3.2	0	0	0	0	10.8	0.6	0	5	5.6	0	0	0	0	36	0.6	0

Table 4. Percent of colonies of the eight most common coral species (>100 colonies) that were bleached (any amount of paling/bleaching) and severely bleached (>50% of the colony bleached).

Species	**Total Colonies**	**% Bleached**	**% Sev. Bleached**
Porites lobata	12,196	0.6	0.1
Porites compressa	3355	3.7	0.3
Montipora capitata	1595	48.2	27.9
Pavona varians	1149	23.7	3.7
Montipora patula	777	26.1	8.5
Porites monticulosa	242	39.7	2.1
Pavona duerdeni	139	28.1	3.6
Pocillopora meandrina	125	30.4	15.2

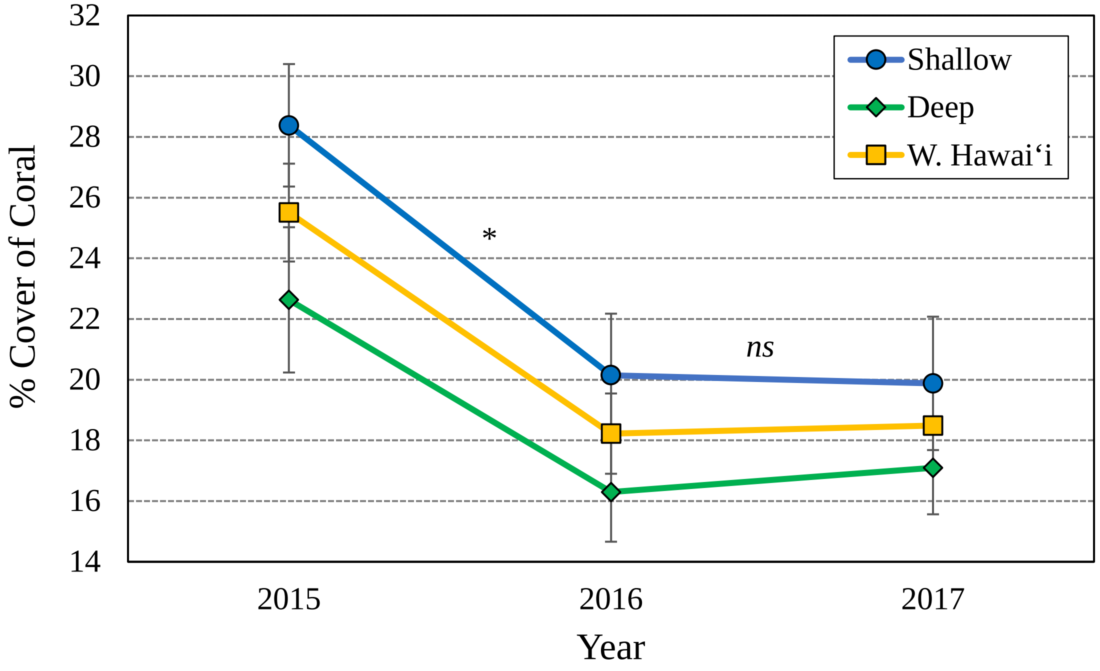

Figure 2. Percent coral cover at 20 reef locations along West Hawai‘i Island (orange squares). Each location contained a shallow (blue circle) and deep (green diamond) survey site. *=change was significant at p=0.05; ns=change not significant.

While coral did not change, coral density increased from 2016 to 2017 from 12.9 ± 1.2 colonies/m^2 to 16.9 ± 1.6 colonies/m^2 (Paired t-test, T_{39}=3.85, p<0.001). Taken together, these data suggest that the number of "small" colonies[4] increased across the survey area. This could be a sampling artifact that often arises after colonies experience partial mortality; with passing time colonies that have under partial mortality become increasingly difficult to identify, resulting in the counting of more smaller colonies that previously would have been identified as a single colony. Alternatively, while total colony densities were higher in 2017 compared to 2016, the density of juvenile corals decreased from 26.2 ± 1.9 juvenile colonies/m^2 to 22.6 ± 1.7 juvenile colonies/m^2 (Paired t-test, T_{39}=2.06, p=0.046). This continues a trend of declining juvenile colonies from 2015, but it is unclear if this is due to reduced recruitment or colonies growing larger in diameter and thus no longer being captured in the juvenile survey. Colony size data collected in the 2017 surveys show nearly three-quarters of the juvenile colonies were <3 cm in diameter (16.5 ± 1.4 colonies/m^2), suggesting recent recruitment to the area has been strong. Size data for juvenile colonies were not collected in 2015 or 2016, preventing comparisons to these time periods.

We observed 133 species of reef fish in 25 families across the survey area in 2017. Total fish biomass was 45.4 ± 7.2 g/m^2 and varied from a low of 14.9 ± 4.2 g/m^2 (Kawaihae) to a high of 171.9 ± 46.2 g/m^2 (Puakō). Total fish biomass at the Puakō deep site was 2.5-times greater than the site with the next highest biomass (Keauhou). This was similar to that in 2016, suggesting the high fish biomass at Puakō may be feature of the location, and not simply an artifact of the naturally high variability of coral reef fish assemblages. Variability among the sites, especially the deep sites, was high and total fish biomass did not significantly differ between depths (t-test; T_{34}=0.61, p=0.547).

As on many reefs in the main Hawaiian Islands, the families Acanthuridae (surgeonfishes), Balistidae (triggerfish) and Scaridae (parrotfishes) contributed the most to total fish biomass, 40.3%, 17.4%, and 14.1% of the total, respectively (Table 5). Herbivores accounted for 54% of the total fish biomass on West Hawaiʻi (Figure 3), while apex predators accounted for <1% and were rarely observed, appearing on less than 4% of the transects.

Total fish biomass across the survey area has declined since 2015 (Figure 4). While this decline appears to be precipitous, additional context is important to fully interpret the trend. Long-term declines in reef fish populations have been documented for some West Hawaiʻi reefs (Minton *et al.* 2012, 2015, 2018b,Walsh *et al.* 2013), but the decline observed from 2015 to 2017 is likely associated with a large fish recruitment event in 2014 (Talbot 2014, Minton *et al.* 2017, 2018b). This recruitment event substantially increased the abundance and biomass of the reef fish assemblage relative to pre-2014 levels, likely creating an unsustainable surplus of individuals. Based on fish biomass data collected with similar methods at numerous West Hawaiʻi island sites since 2010[5], total fish biomass for West Hawaiʻi reefs prior to the 2014 recruitment event was estimated at 47.2 ± 1.9 g/m^2, consistent with the 2017 estimate reported here.

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[4] Coral heath surveys, from which the colonies densities are derived, examined all colonies >5 cm in diameter. Smaller colonies (>0 to 5 cm) were considered juvenile corals and enumerated separately.

[5] Data from Kaʻūpūlehu 2009, 2010, and 2011 (Minton *et al.* 2014), Kaʻūpūlehu-Kīholo 2012 and 2013 (Minton *et al.* 2015), Puakō 2014 (TNC unpub.), Pelekane-Kawaihae 2010 (Minton *et al.* 2012), Kailua Kona, Waialea Bay,

Table 5. Fish biomass by family (g/m^2) averaged over all West Hawaiʻi survey locations and by depth. Biomass was not estimated for Muraenidae (eels) due to challenges associated with accurately sizing these fish.

Family	West Hawaiʻi	Shallow	Deep
Acanthuridae	18.3 ± 1.7	19.7 ± 2.1	16.9 ± 2.7
Balistidae	7.9 ± 2.1	6.6 ± 1.0	9.3 ± 4.1
Scaridae	6.4 ± 1.0	7.9 ± 1.1	4.9 ± 1.6
Labridae	2.8 ± 0.2	2.3 ± 0.2	3.2 ± 0.4
Chaetodontidae	1.4 ± 0.2	1.5 ± 0.2	1.3 ± 0.2
Serranidae	1.4 ± 0.3	0.5 ± 0.2	2.3 ± 0.5
Mullidae	1.3 ± 0.3	1.0 ± 0.2	1.6 ± 0.5
Pomacentridae	1.3 ± 0.4	0.9 ± 0.2	1.3 ± 0.5
Holocentridae	1.3 ± 0.5	0.2 ± 0.1	2.3 ± 1.0
Lethrinidae	1.0 ± 0.4	1.1 ± 0.6	0.9 ± 0.4
Lutjanidae	1.0 ± 0.4	0.4 ± 0.3	1.5 ± 0.7
Zanclidae	0.3 ± 0.1	0.1 ± 0.1	0.5 ± 0.2
Kyphosidae	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.2
Aulostomidae	0.2 ± 0.1	0.3 ± 0.2	0.1 ± 0.0
Tetraodontidae	0.2 ± 0.1	0.1 ± 0.0	0.3 ± 0.2
Cirrhitidae	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
Diodontidae	0.1 ± 0.1	0.2 ± 0.2	0.0 ± 0.0
Monacanthidae	0.1 ± 0.1	0.2 ± 0.2	0.0 ± 0.0
Pomacanthidae	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0
Carangidae	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Ostraciidae	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Blenniidae	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Scorpaenidae	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Apogonidae	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Muraenidae	present	present	present
Grand Total	**45.4 ± 7.2**	**43.9 ± 5.9**	**46.9 ± 13.1**

TNC and its partners have collected a robust baseline assessment of fish populations at Kaʻūpūlehu, Hawaiʻi (see Minton *et al.* 2018b). The Kaʻūpūlehu survey area overlaps several reef resilience locations, and a sufficient number of surveys sites exist within 150 m of the Keonenui reef resilience location and across multiple years, to allow for a reasonable baseline condition to be assembled for this location (Figure 5). This nearly 10-year baseline shows a

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and South Kohala locations around 2004 (data courtesy of USGS), and Kaloko-Honokau 2005 (data courtesy of USGS).

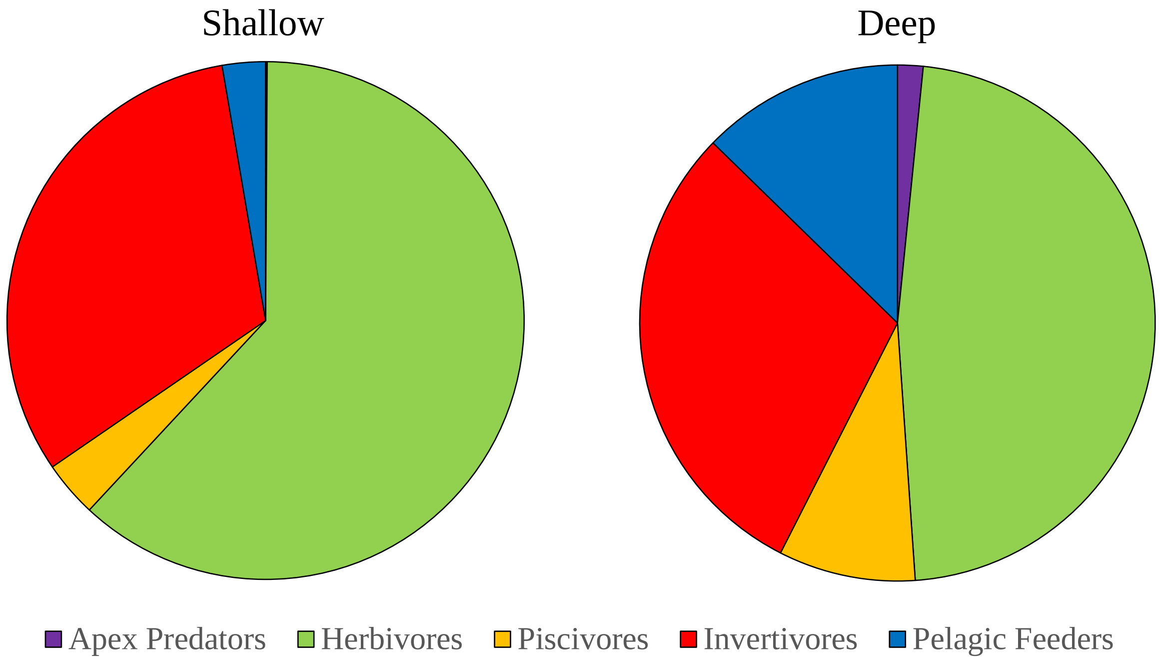

Figure 3. Trophic structure at shallow and deep sites along West Hawai‘i in 2017.

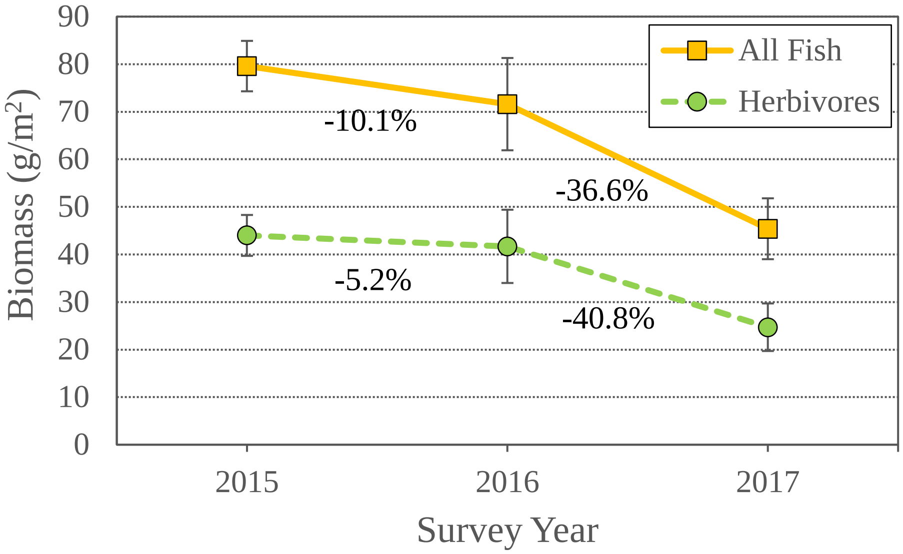

Figure 4. Total fish and herbivorous fish biomass across at 20 locations in the West Hawai‘i reef resilience survey area from 2015-2017. Numbers are the relative decline in biomass between survey years.

“spike” in total fish biomass in 2015, corresponding with the atypically large coral reef fish recruitment event in 2014. As with other fish populations in West Hawai‘i, Keonenui now appears to be returning to pre-2014 biomass levels. At this point, we believe it likely that the decline in fish biomass found across all reef resilience survey locations since 2015 is due to this same phenomenon and is not a decline associated with the coral loss from the 2015 bleaching event. However, future survey efforts will be needed to definitively address this question. Herbivorous fish biomass is one of our seven biological indicators used to develop the ref resilience rank. Similar to total fish biomass, herbivore biomass has declined since 2015 (Figure 4). The annual rate of decline was similar for both herbivores and all fish, suggesting no disproportionate effect on herbivore biomass relative to the other fishes. As with total fish, the decline in herbivorous fish is likely associate with a gradual relaxation following the unusually large reef fish recruitment event in 2014. Neither total fish (t-test; T_{34}=0.61, p=0.547) nor herbivorous fish (t-test; T_{34}=1.71, p=0.630) biomass significantly differed between depths.

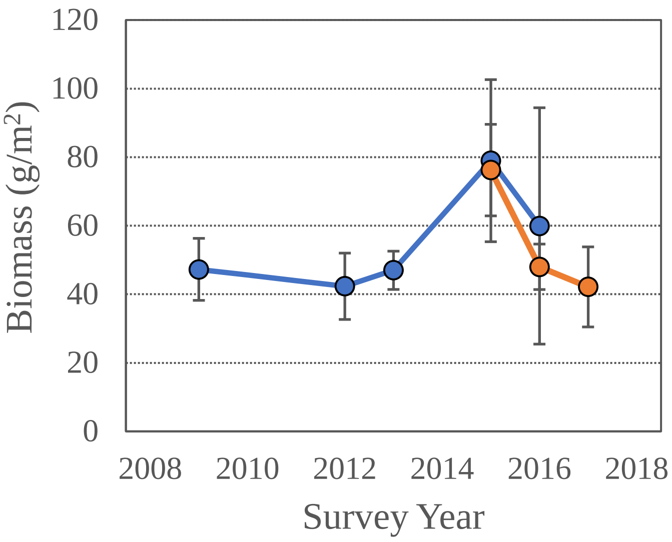

Figure 5. Change in total fish biomass (g/m^2) at Keonenui, Hawai‘i from 2009 to 2016. Blue circles are data from Minton *et al.* (2014, 2015, 2018) and include all survey sites within 150 m radius of the Keonenui location. Orange circles are from reef resilience surveys conducted at Keonenui, with values from 2015 from Maynard *et al.* (2016), 2016 from Minton *et al.* (2018b), and 2016 from this report.

4.2 Revisiting 2015 Reef Resilience Rankings

In 2015, TNC developed resilience rankings for the 20 locations in West Hawai‘i. These ranking were intended to order sites by resilience potential, from most resilient (rank 1) to least resilient (rank 20). The 2015 mass coral bleaching on West Hawai‘i has provided a unique opportunity to assess the performance of these rankings.

Sites ranked as most resilient should experience fewer and/or recover more quickly from adverse effects from the stressor event. While too little time has passed from the 2015 thermal stress event to evaluate recovery (which can be expected to take several years), our combined 2016 and 2017 surveys allow us to evaluate resistance, manifest through signs such as lower coral mortality from the 2015 bleaching event, higher bleaching resistance, lower disease prevalence, and fewer changes in the benthic assemblage structure following the 2015 bleaching event compared to less resilient sites. We found little correlation between the 2015 resilience rankings and seven variables that are indicative of resistance to thermal stress (Table 6). Only one variable (benthic assemblage similarity between 2015 and 2016) showed a statistically

Table 6. Correlations (r) of indicators of resistance and recovery with the 2015 reef resilience rankings for 20 shallow and deep on West Hawai‘i. ns=not significant, *=p<0.05, **=p<0.001

	Shallow	**Deep**	**Hypothesis**
Resistance			
Bleaching resistance (2016)	-0.381^{ns}	-0.290^{ns}	(-) correlation
Bleaching resistance (2017)	-0.292^{ns}	-0.019^{ns}	(-) correlation
Δ coral cover, relative (2015-2016)	0.084^{ns}	-0.331^{ns}	(-) correlation
Δ coral colony density, relative (2015-2016)	-0.008^{ns}	-0.259^{ns}	(-) correlation
disease prevalence (2016)	-0.140^{ns}	-0.195^{ns}	(+) correlation
disease prevalence (2017)	-0.105^{ns}	0.103^{ns}	(+) correlation
Benthic assemblage similarity (2015-2016)	-0.015^{ns}	0.452*	(-) correlation
Recovery			
Δ coral cover, relative (2016-2017)	-0.086^{ns}	0.001^{ns}	(-) correlation
Δ coral colony density, relative (2016-2017)	0.177^{ns}	-0.033^{ns}	(-) correlation
Coral juvenile density (2016)	-0.682**	-0.387^{ns}	(-) correlation
Coral juvenile density (2017)	-0.427*	-0.056^{ns}	(-) correlation
Herbivorous fish biomass (2016)	0.213^{ns}	-0.104^{ns}	(-) correlation
Herbivorous fish biomass (2017)	-0.205^{ns}	-0.165^{ns}	(-) correlation

significant relationship, but that relationship was the opposite of what was expected (*i.e.*, positive instead of negative).

While the two-year recovery period is not long enough for much recovery to have occurred, we can also look for the initial evidence of recovery at a site, expecting more resilient sites to undergo faster recovery as indicated by signs such as high coral settlement/recruitment, the presence of suitable settlement habitat, and the presence of processes that would promote settlement (*e.g.*, herbivorous fish). The 2015 resilience rankings were significantly correlated with juvenile densities at shallow sites, both in 2016 and 2017, but not with other variables that would be indicative of recovery (Table 6).

Although it is difficult to assess recovery only two years post-bleaching, the overall poor correlation of our 2015 rankings with the suite of variables intended to describe features of both resistance and recovery suggests our method is not performing as expected. Minton *et al.* (2018a) noted that rankings calculated using the 2016 survey data varied considerably from those calculated in 2015, but that there was some consistency in sites that scored at the top and bottom of the rankings. For example, both Laehou and Kumukea were the top ranked sites regardless of whether 2015 or 2016 data were used to generate the rankings (Minton *et al.* 2018a). It is possible that our approach to ranking sites may be able to distinguish sites at the extremes, but may not have sufficient sensitivity to reliably sort sites in the middle, an idea that will be explored in more detail in the next section.

4.3 2017 Reef Resilience Rankings

Reef Resilience scores for each location were recalculated using the 2017 survey data. Normalized resilience scores for shallow sites ranged from 0.69 to 1.00 (Table 7). Two sites were classified as having high relative resilience, nine with medium-high resilience, six with medium-low resilience, and three with low resilience. With a few exceptions, resilience rankings at the shallow sites in 2017 changed considerably from both 2015 and 2016, as indicated by change scores of 94 and 116, respectively. Notably, Laehou continued to be the top ranked shallow water site. The largest drop in ranking was 11 positions (Maniniʻōwali), from seven in 2016 to eighteen in 2017, while the greatest rise was 14 (Kalaemanō), from twenty in 2016 to two in 2017. Reasons for these jumps are not clear, but warrant further investigation.

Table 7. Resilience assessment results for shallow (5-7 m) reef areas along the West Hawaiʻi coastline. Colors correspond to the resilience category: high (green), medium-high (yellow), medium-low (orange), low (red). Rankings and ranking categories for 2015 are from Maynard *et al.* (2016) and for 2016 from Minton *et al.* (2018).

Site Name	Raw Score	Norm. Score	2017	2016	2015
Laehou	0.819	1	1	1	1
Kalaemanō	0.793	0.969	2	20	11
Kīholo	0.741	0.905	3	11	3
Kailapa	0.734	0.896	4	14	14
Kumukea	0.725	0.885	5	2	2
Puakō	0.722	0.882	6	12	20
Keawaiki	0.716	0.874	7	3	6
Kapalaoa	0.714	0.872	8	9	16
Keanapukalua	0.711	0.867	9	8	9
Keauhou	0.704	0.860	10	13	13
Lulahala Pt.	0.682	0.832	11	16	10
Makalawena	0.668	0.815	12	5	7
Keonenui	0.642	0.784	13	4	8
Kawaihae	0.636	0.777	14	18	15
Mākoleʻā	0.621	0.758	15	6	4
ʻŌhaiʻula	0.620	0.757	16	19	18
Honokōhau	0.616	0.752	17	15	17
Maniniʻōwali	0.607	0.741	18	7	5
Kanekanaka Pt.	0.580	0.708	19	17	19
Kaunaʻoa	0.565	0.689	20	10	12

Normalized resilience scores for deep sites ranged from 0.49 to 1.00 (Table 8). Two sites were classified as having high relative resilience, only three with medium-high resilience, ten with medium-low resilience, and five with low resilience. Resilience rankings at the deep sites also changed considerably between 2017 and both 2015 and 2016, as indicated by change scores of 86 and 126, respectively. The largest drop in ranking was 18 positions (Keonenui), from top rank in 2016 to nineteen in 2017, while the greatest rise was 16 (Kanekanaka Pt.), from nineteen in 2016 to three in 2017. Most disturbing, however, is the large shift of sites from the high and medium-high categories to the medium-low and low categories. Since 2015, the number of sites categorized as having low resilience has steadily increased from three to five.

The large change in resilience ranks among years raises concerns about the effectiveness of this approach to consistently and meaningfully differentiate resilience potential among these reef biological assemblages at sites are altered by stressors, the high change scores found among our

Table 8. Resilience assessment results for deep (10-12 m) reef areas along the West Hawaiʻi coastline. Colors correspond to the resilience category: high (green), medium-high (yellow), medium-low (orange), low (red). Rankings and ranking categories for 2015 are from Maynard *et al.* (2016) and for 2016 from Minton *et al.* (2018

Site Name	Raw Score	Norm. Score	2017	2016	2015
Puakō	0.890	1	1	3	3
Laehou	0.737	0.828	2	7	1
Kanekanaka Pt.	0.701	0.787	3	19	16
Kumukea	0.692	0.777	4	5	4
Kailapa	0.675	0.758	5	14	9
Kalaemanō	0.669	0.752	6	16	15
Keanapukalua	0.639	0.718	7	2	13
Honokōhau	0.636	0.714	8	18	8
Kīholo	0.616	0.692	9	6	2
ʻŌhaiʻula	0.613	0.689	10	13	7
Makalawena	0.604	0.678	11	10	5
Maniniʻōwali	0.602	0.676	12	9	11
Lulahala Pt.	0.587	0.659	13	20	20
Kaunaʻoa	0.576	0.647	14	12	6
Keawaiki	0.565	0.634	15	8	14
Keauhou	0.555	0.623	16	15	12
Kapalaoa	0.517	0.580	17	11	19
Kawaihae	0.464	0.521	18	17	18
Keonenui	0.456	0.513	19	1	17
Mākoleʻā	0.440	0.494	20	4	10

sites. While resilience rankings should be expected to change relative to each other as the survey years makes it problematic to distinguish if these changes reflect meaningful shifts in resilience potential or are the result of essentially random[6] shifts associated with natural variability at the sites. What is reassuring, however, is that we observed some general consistency among sites positioned at the two extremes of the rankings (*e.g.*, shallow sites Laehou and Kumukea routinely scored well among years, whereas Kanekanaka Pt. generally scored poorly), suggesting that it may be possible to consistently identify sites with the highest and lowest resilience, even if it is not possible to reliably and meaningfully order sites in the middle. This issue may be relieved to some extent by averaging the normalized score over multiple years, accounting for annual variability (Table 9) and allowing us to assess the general resilience potential of a site. Rankings developed from multi-year data make clear that several sites can consistently be classified as having high or low resilience. Unfortunately, the rankings derived from the average normalized scores do not improve the relationship between the rankings and the suite of variables intended to describe features of resilience (see section 4.2 for discussion of the

Table 9. Average resilience rankings (2015-2017) for shallow and deep reef areas along the West Hawai‘i coastline. Range was the highest and lowest rankings when accounting for annual variability in the normalized scores used to derive the mean rank (see methods). Data for 2015 are from Maynard *et al.* (2016) and for 2016 from Minton *et al.* (2018a).

Mean (Range)	Shallow Sites	Deep Sites	Mean (Range)
1 (1)	Laehou	Puakō	1 (1-2)
2 (2)	Kumukea	Laehou	2 (1-2)
3 (3-4)	Keawaiki	Kumukea	3 (3-5)
4 (3-11)	Kīholo	Kīholo	4 (4-7)
5 (5-6)	Keanapukalua	Keanapukalua	5 (5-10)
6 (3-10)	Makalawena	Makalawena	6 (4-6)
7 (5-8)	Mākole‘ā	Kailapa	7 (7-10)
8 (7-9)	Keonenui	Manini‘ōwali	8 (5-13)
9 (8-9)	Kailapa	‘Ōhai‘ula	9 (6-15)
10 (5-15)	Manini‘ōwali	Kauna‘oa	10 (8-14)
11 (10-11)	Kapalaoa	Keonenui	11 (3-18)
12 (12)	Keauhou	Honokōhau	12 (7-16)
13 (13-14)	Lulahala Pt.	Mākole‘ā	13 (12-13)
14 (7-17)	Kalaemanō	Keawaiki	14 (9-14)
15 (14-16)	Kauna‘oa	Kanekanaka Pt.	15 (11-15)
16 (13-19)	Puakō	Kalaemanō	16 (8-19)
17 (15-18)	Kawaihae	Keauhou	17 (11-18)
18 (18-19)	Honokōhau	Kapalaoa	18 (16-18)
19 (16-20)	‘Ōhai‘ula	Lulahala Pt.	19 (17-20)
20 (17-20)	Kanekanaka Pt.	Kawaihae	20 (19-20)

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[6] A random change score would follow a normal distribution with and mean and standard deviation of 131 ± 18.

indicators). However, when looking at just the top and bottom ranked sites with the two depth strata, a trend emerges with the top two locations outscoring the remaining sites for most of the resilience variables, while the bottom three sites tend to underperform. For example, bleaching resistance in 2017 at the top two sites was 98.6 ± 0.65% compared to 90.1 ± 2.5% for the middle sites, and 83.9 ± 5.1% for the bottom three sites.

These findings are complicated somewhat by the spatial shift in the position of the transects between 2015 and 2016/2017 (see methods). However, Minton *et al.* (2018a) showed the temporal changes of the reef community at our 20 locations appeared to be unidirectional (toward a "worse" condition) and of a magnitude sufficiently large to "drown" out any spatial variability that may have been introduced. Consistency in the sites occupying the high and low end of the rankings suggest that factors other than random variability added as a result of the shift in transect lines are responsible for this pattern of change observed within the rankings from year-to-year.

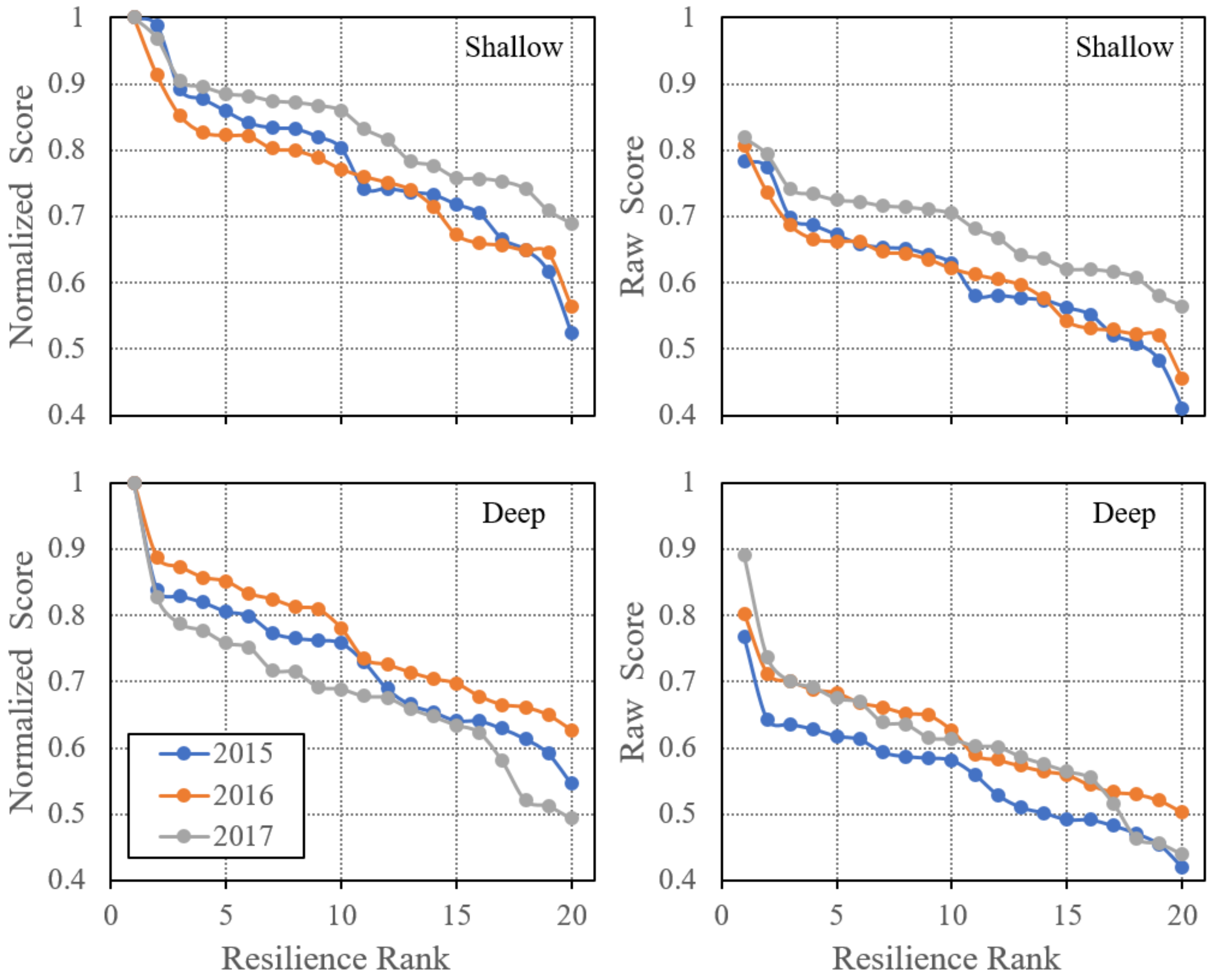

Figure 6. Normalized and raw resilience scores for 20 locations along West Hawai'i from 2015 to 2016. Data for 2015 are from Maynard *et al.* (2016) and for 2016 from Minton *et al.* (2018a).

While the change in the rankings of the sites from year-to-year raises concerns about how effectively the rankings can be used to improve management actions, the approach may provide insights into the resilience of West Hawaiʻi's coral reefs and their response the 2015 mass coral bleaching event. Examining the normalized scores directly (Figure 6) shows a generally linear relationship along the middle values of the range, but non-linear trends at the extremes. Given the variability in indicator scores, the relatively flat, linear slope would contribute to the large change in relative rankings among these middle-ranked sites. Examining annual raw scores may also provide insight into annual changes among the sites. For example, the raw score for top-ranked shallow sites has changed little from 2015-2017, whereas the raw score for top-ranked deep sites has increased every year, contributing to the change in the number of sites that fall into medium-low and low resilience categories. This change in deep sites suggests that some reef areas, specifically ones with high resilience ranks, are improving more relative to other sites, and, perhaps of more concern, that sites ranked with low resilience potential have worsened since 2016. Finally, the range of the scores may also provide some insight, although given the inherent nature of multi-factor indices, further investigation would be needed to before drawing conclusions.

Given this, resilience rankings appear to provide some meaningful resolution among sites at the extremes (most and least resilient categories), but seem to have little power to differentiate among the bulk of sites in the middle, at least in these early years post-bleaching. While the rankings appear to have some limitations, the ability to reliably and consistently identify sites with high and low resilience and potentially track these through time using raw scores has considerable value to managers.

Most efforts to develop resilience rankings involve a single round of surveys, which make it difficult to assess the performance of the approach. Our analysis highlights the value of collecting multiple years of reef resilience data at the 20 West Hawaiʻi locations. By returning to reefs that experienced a significant thermal stress event, we have been able to assess the performance of our rankings within a resilience framework (*i.e.,* resistance and recovery). While the approach did not perform entirely as expected, it still produced valuable results that should contribute to improved management of reefs on West Hawaiʻi.

In addition, the data collected could be used to refine, and perhaps improve, the method. For example, indicators that comprise the index were incorporated with equal weighting. The data collected at the sites in subsequent years could be used to inform a weighting process that would improve the performance of the rankings, which could then be assessed with future data from West Hawaiʻi or another Hawaiian Island (*e.g.,* TNC has recently completed resilience surveys in leeward Maui).

Finally, our surveys extend only two years post-bleaching, a length of time insufficient to capture significant recovery on West Hawaiʻi's reefs. In future years, TNC or other researchers should return to the 20 locations and repeat the suite of data collection. Doing this will allow us to better understand the process of recovery, as it relates to resilience generally and the resilience ranking process specifically.

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Appendix A.

Twenty locations (shallow and deep survey sites) originally surveyed in 2015 and repeated in 2016 and 2017. See Minton *et al.* (2018) for additional discussion of realignment and installation of the 2016 transect. Sites in the same "Cluster" experience similar environmental stressor regimes, as originally described by Minton *et al.* (2018). The three clusters lie along a gradient of stress with Cluster B having the fewest stressors (primarily aquarium fishing), followed by Cluster A (primarily non-fishing), followed by Cluster C (both non-fishing and fishing).

#	Location	Survey Site Lat./Long.	Cluster	Notes
1	Kailapa	S: (20.05962, -155.84837) D: (20.05939, -155.84876)	A	North Kohala FRA
2	Kawaihae	S: (20.03571, -155.83661) D: (20.03566, -155.83714)	A	Near harbor
3	ʻŌhaiʻula	S: (20.02049, -155.82993) D: (20.0204, -155.8312)	A	Offshore of Pelekane Bay (sediment)
4	Kaunaʻoa	S: (20.00066, -155.82893) D: (19.99986, -155.83092)	C	Near golf course
5	Kanekanaka Pt.	S: (19.98635, -155.83212) D: (19.98668, -155.8338)	A	FRA
6	Puakō	S: (19.96976, -155.84755) D: (19.97007, -155.84764)	C	Puakō Bay and Puakō Reef FMA; near residential development; DAR Long-term Monitoring Site
7	Keanapukalua	S: (19.95174, -155.86589) D: (19.95194, -155.86681)	A	Puakō-Anaehoomalu FRA / Netting Restricted Area; near golf course; DAR Long-term Monitoring Site
8	Lulahala Pt.	S: (19.93455, -155.88426) D: (19.93513, -155.88478)	C	Puakō-Anaehoomalu FRA / Netting Restricted Area; near golf course
9	Kapalaoa	S: (19.91363, -155.89874) D: (19.91402, -155.9006)	A	Puakō-Anaehoomalu FRA / Netting Restricted Area
10	Keawaiki	S: (19.89031, -155.90777) D: (19.89013, -155.91025)	B	DAR Long-term Monitoring Site
11	Laehou	S: (19.87313, -155.92201) D: (19.87344, -155.92252)	B	
12	Kīholo	S: (19.85513, -155.93415) D: (19.85527, -155.93479)	B	Kīholo Bay FMA
13	Kalaemanō	S: (19.85339, -155.95826)		

#	Location	Survey Site Lat./Long.	Cluster	Notes
		D: (19.85392, -155.95844)		
14	Keonenui	S: (19.843, -155.98045) D: (19.84298, -155.98122)	C	Kaʻūpūlehu Marine Reserve; near residential development; DAR Long-term Monitoring Site
15	Kumukea	S: (19.83415, -155.9976) D: (19.83444, -155.99803)	A	Kaʻūpūlehu Marine Reserve; near hotel/resort
16	Maniniʻōwali	S: (19.81315, -156.00703) D: (19.81344, -156.00761)	B	Kikaua Pt- Mākoleʻā Netting Restricted Area
17	Makalawena	S: (19.79692, -156.0268) D: (19.79738, -156.02708)	B	Kikaua Pt- Mākoleʻā Netting Restricted Area; DAR Long-term Monitoring Site
18	Mākoleʻā	S: (19.78396, -156.04752) D: (19.78407, -156.048)	B	
19	Honokōhau	S: (19.6722, -156.03036) D: (19.6719, -156.03117)	A	Kaloko-Honokōhau FRA / Netting Restricted Area; near harbor; DAR Long-term Monitoring Site
20	Keauhou	S: (19.5684, -155.96903) D: (19.56838, -155.96933)	C	Kailua-Keauhou FRA; near golf course; DAR Long-term Monitoring Site

Appendix B.

Survey Methods

Coral Health

Coral health and disease surveys were conducted along the first 10 m of each transect line. All coral colonies within a 1-m wide belt were identified to species and enumerated. The condition of each colony was assessed, and any signs of diseases (*i.e.*, growth anomalies, Trematodiasis, and tissue loss syndrome) and/or compromised health (*i.e.*, algal overgrowth, discoloration, bleaching or paling, physical damage, gastropod predation and crown-of-thorns predation) were noted.

Coral health was examined using disease prevalence, calculated as follows:

$$\text{Prev} = \frac{\text{\# of colonies with at least 1 type of DZ or COMP}}{\text{\# of total colonies}}$$

The prevalence of each condition for all coral or for individual species was calculated as follows:

$$\text{Prev}_{(\text{DZ or COMP})} = \frac{\text{\# of colonies with a specific DZ or COMP}}{\text{\# of total colonies or \# of colonies of a species}}$$

Juvenile Corals

All coral colonies ≤5 cm in diameter (longest dimension) whose geometric center lay within a 0.5 x 0.5 m quadrat were counted and identified to the lowest taxonomic level. Four quadrats were haphazardly spaced ~2 m apart within the first 10 m of each transect, corresponding with coral health belt transect.

Benthic Topography (Rugosity)

The topographic complexity of the bottom at each site was estimated using an index of rugosity calculated along the first 10 meters of each transect by dividing the length of brass chain required 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.

Benthic Cover

At each survey site, photographs of the bottom were taken every meter along each 25-m transect line using a Canon Powershot camera or equivalent mounted on a 0.8-m PVC monopod. This generated 25 images for each survey site, with each photo covering approximately 0.8 x 0.6 m of the bottom. A 5-cm scale bar marked in 1-cm increments was included in all photographs.

Twenty randomly-selected photographs from each transect were analyzed to estimate the percent cover of coral, algae, and other benthic organisms present. As needed, selected photographs were imported into Adobe Photoshop CS5 where their color, contrast, and tone were auto-balanced to improve photo quality prior to analysis. Photos were analyzed using Coralnet, an online repository and resource for benthic images analysis maintained by the University of California San Diego (Beijbom *et al.* 2015). Thirty random points were overlaid on each digital photograph, and the benthic component under each point was identified to the lowest possible taxonomic level, primarily individual coral species, algae at higher taxonomic resolution (*e.g.*, red, green, brown, turf, and crustose coralline, but sometimes genera), and abiotic substratum type. All photographs were processed by the same analyst to reduce potential observer variability. Once completed, the raw point data from each photograph was combined to calculate the percent cover of each benthic component for the survey site.

Coral Reef Fish Abundance and Biomass

While slowly deploying the parallel 25-m transect lines, the surveyor identified to species and sized into 5-cm bins (*i.e.*, 0-5 cm, >5-10 cm, >10-15 cm, etc.) all fish within or passing through a 5-m wide belt along the transect. Each transect took between 10 and 15 minutes to complete. Individual fish biomass (=wet weight) was calculated using the mean length of the size bin and size-to-weight conversion parameters from FishBase (Froese and Pauly 2010), the USGS Hawai‘i Cooperative Fishery Research Unit (HCFRU), and NOAA’s Coral Reef Ecosystems Program. All fish surveys were conducted by trained and calibrated divers to reduce surveyor variability.