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Assessing the Resilience of Leeward Maui Reefs to Help Design a Resilient Managed Area Network

Jeffrey Maynard*, Eric Conklin*, Dwayne Minton, Gareth J. Williams, Dieter Tracey, Russell Amimoto, Harry Lynch, Ryan Carr, Julia Rose, Russell Sparks, Emily Fielding, Roxie Sylva, Darla White

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Summary

Assessing the Resilience of Leeward Maui Reefs to Help Design a Resilient Managed Area Network

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Introduction and objectives — As the need for healthy reefs increases, Hawaiʻi finds the condition of its marine ecosystems in decline. Coral cover has decreased at many locations, especially near the island of Maui. On the coral reefs of Maui, coral diseases have become more prevalent, and nearshore fisheries have declined by > 75% over the past century. These trends predate the state's first truly statewide mass bleaching event in 2015 that affected almost all of the Hawaiian Islands. While it is too early to know the long-term effects of these events, Hawaiʻi is taking action to address this new threat and reverse the declining condition of coral reefs. At the 2016 World Conservation Congress, Hawaiʻi's Governor David Ige announced an ambitious plan to effectively manage 30% of Hawaiʻi's nearshore waters by 2030. To meet this goal, Hawaiʻi's Division of Aquatic Resources (DAR) has initiated a process to develop a statewide network of marine managed areas, and has indicated that reefs along the west coast of Hawaiʻi Island (West Hawaiʻi) and the leeward shore of Maui are priority locations in which to start the design and implementation of this network. To ensure long-term ecosystem sustainability and resilience, the network's design must consider climate change effects.

While discussing the need to support resilience, managers and scientists working in Maui have expressed frustration about the lack of data on reef condition and relative resilience. Partners have also expressed frustration with the challenges of making management decisions to meet conservation goals with inadequate information on how best to prioritize locations and actions. The Nature Conservancy and Hawaiʻi DAR team conceptualized this project to fill these vital knowledge gaps and inform near- and long-term management of the coral reefs of Maui.

Our project team assessed the relative resilience of reef sites at two depths along areas of West and South-West Maui ('leeward Maui') in March of 2018. The surveys were conducted as a collaborative effort with DAR, The Nature Conservancy, and community organizations. This report presents findings from meeting these project objectives: 1) assess benthic cover comparisons among sites and depths, 2) complete resilience assessment including relative resilience and rankings for two depths, 3) conduct analyses that determine the primary drivers of differences in resilience between sites, and 4) develop a framework for using the resilience analysis outputs to identify and prioritize potential management actions to support the resilience of coral reefs in Maui.

Results

<u>Benthic Cover</u>: Average coral cover for the shallow (3-7 m) reef sites was 27.64 + 16.23%. Average coral cover for the deep (8-13 m) reef sites was 34.44+22.97%. In total, 24 coral species were observed, considering recruits (i.e. <5 cm) and larger corals combined). Macroalgae cover was <0.5% at all shallow reef sites except Pali Tunnel, where macroalgae cover was 0.61%. Macroalgae cover was <0.5% at all deep reef sites except Puamana, where macroalgae cover was 0.78%. Crustose Coralline Algae (CCA) cover ranged from 0-49% (average: 5+9.18%) at the shallow reef sites. At the deep reef sites, CCA cover ranged from 0-27% (average: 5+6.94%). Turf algae cover ranged from 19-89% (average: 54+17.49%) at shallow reef sites. Turf algae ranged from 16-81% (average: 46+17.28%) at the deep reef sites.

Relative resilience: The resilience indicators included were coral cover, coral diversity, coral recruitment, reef builder ratio, coral disease, rugosity, and herbivorous fish biomass. The resilience assessment compared within rather than among depths.

Shallow – Normalized resilience scores ranged from 0.44-1.00. Five sites were assessed as having high relative resilience, 10 medium-high, 12 medium-low, and 4 low. The five sites with high relative resilience were Keālia, Kihei North, Ulua Beach Park, Molokini, and Honolua North; except for Honolua North these sites are all south-east of Māʻalaea nd near Kihei (Fig. S1). The four sites with low relative resilience are Olowalu CRAMP, Kalama Park, Maluaka Point, and Awalua; these sites are south of Kihei (Kalama Park and Maluaka Point) and near and north-west of Māʻalaea (Olowalu CRAMP and Awalua).

Deep – Normalized resilience scores ranged from 0.53-1. Four sites were assessed as having high relative resilience, 6 medium-high, 6 medium-low, and 4 low. The four sites with high relative resilience were Keālia, Molokini, Kalama Park, and Pali Tunnel; these are near Māʻalaea (Pali Tunnel), near Kihei (Keālia and Kalama Park), and south of Kihei (Molokini, Fig. S1). The four sites with low relative resilience are Maluaka Point, Māʻalaea CRAMP, Puamana and Olowalu North; these are just north-west of Māʻalaea (Puamana and Olowalu North), just east of Māʻalaea (Māʻalaea North), and south of Kihei (Maluaka Point).

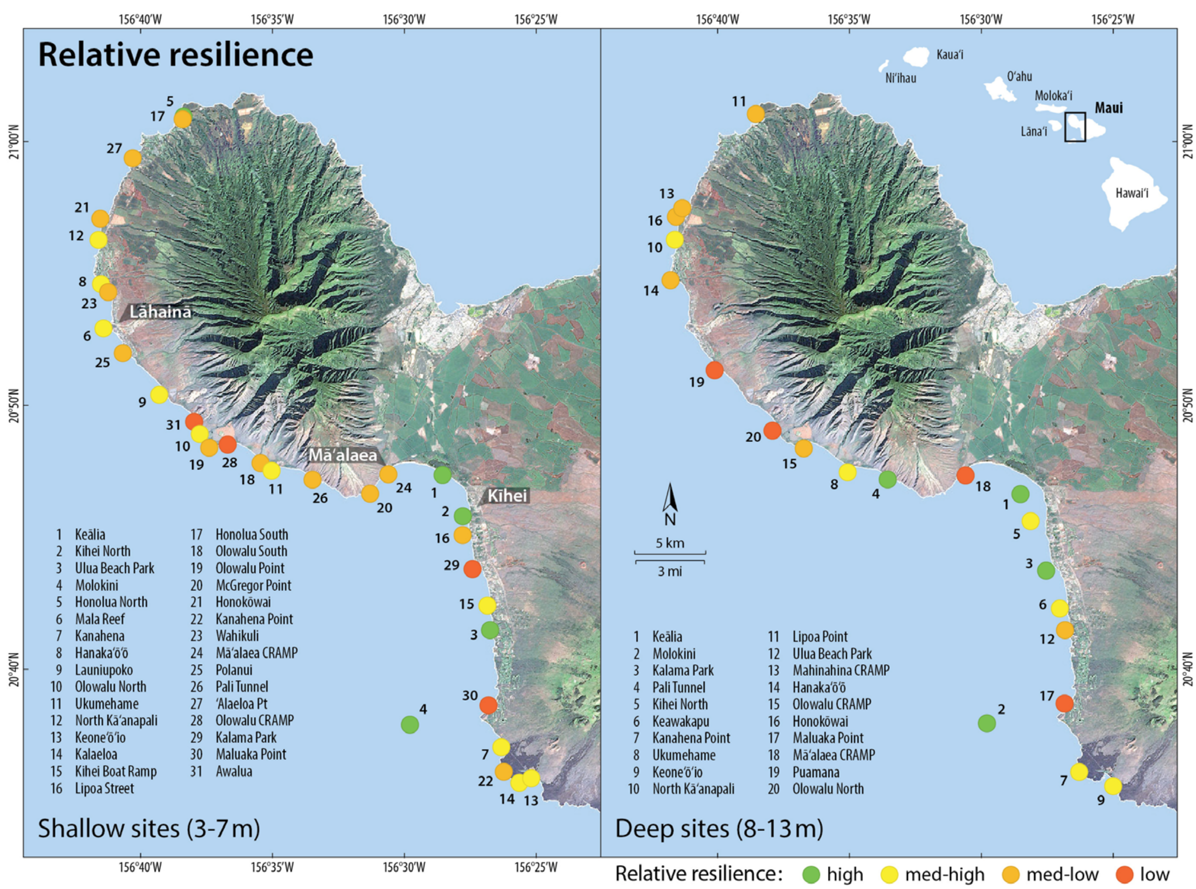

Figure S1. Resilience assessment results for shallow (3-7 m) and deep (8-13 m) reef areas along Leeward Maui. For both shallow and deep, the numbers next to the site marker represent the resilience rank. Relative classifications for resilience scores and resilience indicator scores are as follows: high (final scores that are >1 sd above average (avg), medium-high (<avg+1sd and >avg), medium-low (<avg and >avg-1sd), and low (<avg-1sd).

Resilience drivers: We examined whether high scores for some indicators are consistently associated with high resilience (and low scores for some indicators with low resilience) using a CAP analysis. Across the shallow reef sites of Maui, higher resilience correlated most strongly with higher coral cover and a higher reef-builder ratio. In contrast, 'low' resilience sites were negatively correlated with the majority of the resilience indicators (i.e., low resilience sites have low scores for all or nearly all indicators). Across the deep sites, 'high' resilience sites were correlated most strongly with a higher reef builder ratio and higher coral cover, as was the case for shallow sites. 'Medium-high' and 'medium-low' resilience, in addition to two of the 'high' resilience sites (Pali Tunnel and Kalama Park), were also characterized by higher coral diversity and higher herbivore biomass. 'Low' resilience deep sites showed tight clustering and were most strongly characterized as having lower reef-builder ratio, lower coral cover, lower coral diversity and lower herbivore biomass.

Potential management actions: To identify management opportunities that could support resilience at survey locations, data on anthropogenic stress were compiled from a collaboration with the Ocean Tipping Points Project. Data layers on stress used in our analyses include: total effluent, nitrogen flux, phosphorus flux, sedimentation and fishing. Stressor intensity varied along the leeward coast of Maui, with nutrient-related stressors concentrated near Lahaina, Kihei, coastal development between Maʻalaea and Kihei, and fishing pressure high along most of the coastline.

The anthropogenic stress data were then combined with the scores for relative resilience and individual resilience indicators. Criteria were then set to identify management opportunities and reef areas where such actions would support resilience.

Four types of potential conservation actions were identified for sites with high and medium-high relative resilience (Figure S2):

*Prioritize **C**onservation* – These sites have medium-high or high relative resilience and are not currently within marine managed areas. Shallow sites that met these criteria are Keālia, Kihei North, Ulua Beach Park, Molokini, Honolua North. Deep sites that met these criteria are Keālia, Molokini, Kalama Park, and Pali Tunnel.

*Manage **W**ater quality* – These sites have medium-high or high relative resilience and greater of total effluent, phosphorus or nitrogen flux than the leeward Maui average + 1 sd. Shallow sites that met these criteria are Hanakaʻōʻō and Kihei Boat Ramp. Deep sites that met these criteria are Kalama Park and Keawakapu.

*Reduce **S**edimentation* – These sites have medium-high or high relative resilience and greater sedimentation levels than the leeward Maui average + 1 sd. Shallow sites that met these criteria are Honolua North and Mala Reef. There are no deep sites that met these criteria.

*Monitor **F**ishing Pressure* – These sites have medium-high or high relative resilience and total fishing catch is greater than the leeward Maui average +1 sd. Shallow sites that met these criteria are Keālia, Hanakaʻōʻō, Olowalu North, and North Kāʻanapali. The deep site that met these criteria is North Kāʻanapali.

The decision-support framework presented here should be seen as an example for how assessments of resilience can be combined with information on stressors related to human activities to guide discussions among managers. Managers will have access to a range of additional information that will guide discussions and decisions related to spatial planning.

The overarching recommendation from this project team is that management effort will have the greatest long-term benefit if stressors are addressed at sites with relatively high resilience. Available information on stressors related to human activities can help in deciding which actions will be most effective in supporting resilience.

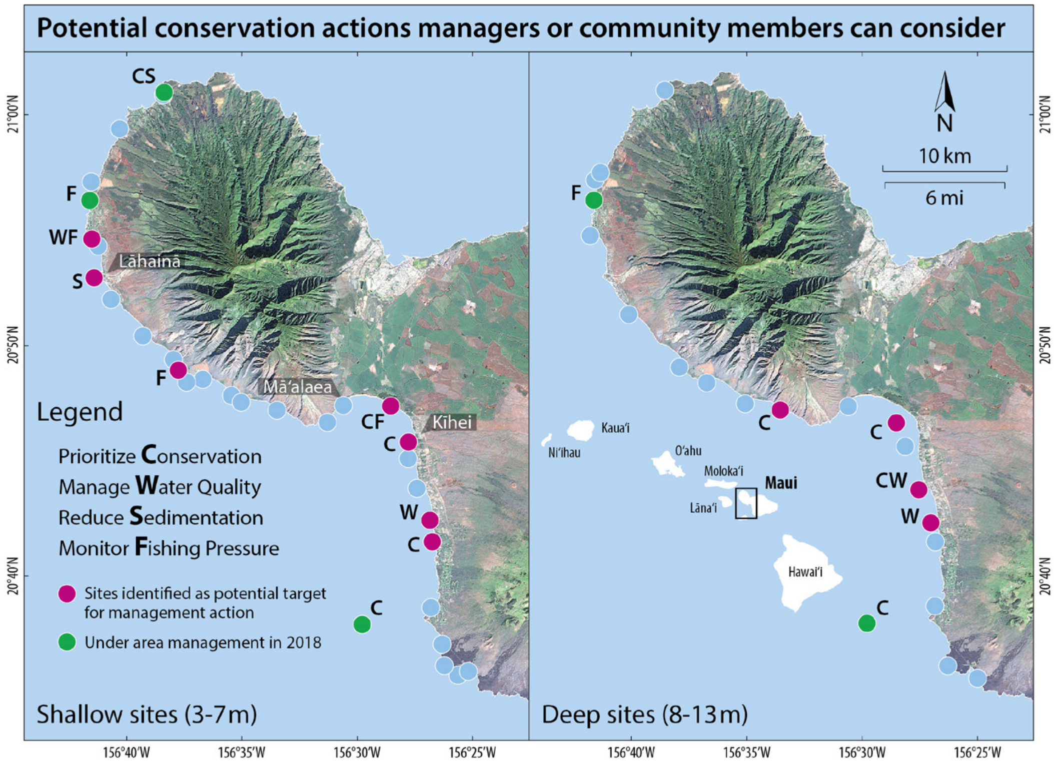

Figure S2. Sites identified as potential targets for management actions that support resilience to climate change.

Next steps

<u>Education and Outreach</u>: The information within this report will be used to develop outreach material that can be shared with community members to explain project results and promote resilience-based management. An outreach presentation will also be developed that explains how the project results can inform planning for the 30 x 30 initiative, and then shared with policymakers, managers and community members.

<u>Designing a Resilient Managed Area Network</u>: Our team will attempt to raise funds from CRCP and other project partners to expand on the resilience assessment completed under this project. We aim to combine data collected under this project with data collected by DAR and other partners from other reef sites in Leeward Maui, and then re-assess resilience to climate change. Combining datasets would enable us to generate spatially continuous data for relative resilience in Leeward Maui that is based on ~5 times more survey sites than was possible under this project. Manager partners at Hawaii DAR that worked closely with us on this project are strongly requesting this next step be completed in the coming year.

Acknowledgments: Financial support for this applied research was provided by the NOAA Coral Reef Conservation Program, matched by contributions from SymbioSeas and the Harold K.L. Castle Foundation. The Hawai'i Division of Aquatic Resources (DAR) helped design the study and supported the fieldwork. The contents of this report are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the U.S. Government.

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Introduction

Hawai'i depends on its coral reefs for shoreline protection, food, cultural value, and economic contributions. Unfortunately, as the need for healthy reefs increases, Hawai'i finds the condition of its marine ecosystems in decline (Rodgers et al. 2015). Coral cover has decreased at many locations (Minton et al. 2014, Rodgers et al. 2015), especially near the island of Maui. On the coral reefs of Maui, coral diseases have become more prevalent, and nearshore fisheries have declined by > 75% over the past century (Kittinger et al. 2011).

These trends predate the state's first widespread mass bleaching event in 2014 that primarily affected O'ahu (Minton et al. 2015), and then was followed by the first truly statewide mass bleaching event in 2015 that affected almost all of the Hawaiian islands. While it is too early to know the long-term effects of these events, Hawai'i is taking action to address this new threat and reverse the declining condition of coral reefs. At the 2016 World Conservation Congress, Hawai'i's Governor David Ige announced an ambitious plan to effectively manage 30% of Hawai'i's nearshore waters by 2030. To meet this goal, Hawai'i's Division of Aquatic Resources (DAR) has initiated a process to develop a statewide network of marine managed areas, and has indicated that reefs along the west coast of Hawai'i Island (West Hawai'i) and the leeward shore of Maui are priority locations in which to start the design and implementation of this network. To ensure long-term ecosystem sustainability and resilience, the network's design must consider climate change effects. The network planning process presents an unprecedented opportunity in Hawai'i to incorporate climate change resilience principles directly into the State's management actions at broad spatial scales.

Coral reef resilience is the capacity of a reef to resist or recover from degradation and maintain provision of ecosystem goods and services (Mumby et al. 2007). Resilience-based management (RBM) has been developed to overcome the challenges of supporting ecosystem resilience in this era of rapid change (Bestelmeyer and Briske 2012). RBM involves the application of resilience theory and tools to deliver ecosystem-based management outcomes into the future (Chapin et al. 2009). RBM of coral reefs can include assessing spatial variation in resilience and then targeting and tailoring appropriate actions to preserve or restore the resilience of reefs. Such assessments have been strongly recommended by coral reef ecology experts and leading conservation organizations (Maynard et al. 2015; Anthony et al. 2015; McClanahan et al. 2012; Graham et al. 2013). The assessments involve measuring or assessing resilience indicators (e.g., coral disease, coral recruitment and herbivorous fish biomass) and producing an aggregate score that expresses resilience for all sites as relative to the site with the highest (assessed) resilience (see Maynard et al. 2017 for guidance). Assessments of resilience can explicitly assist managers in making targeted decisions, as has been the case in West Hawai'i where the results of a 2015 resilience assessment are guiding current discussions around future management decisions (Maynard et al., 2015; Weeks & Jupiter, 2013).

While discussing the need to support resilience, managers and scientists both express frustration about the lack of data on reef condition and relative resilience. The DAR (part of the Hawai'i Department of Land and Natural Resources - DLNR) and other local conservation agencies or organizations have conducted surveys of many coral reefs in the West and South-West Maui area. However, many reefs have not been surveyed, and surveys at permanent survey sites were not designed to assess relative differences in resilience among sites. Partners have also expressed frustration with the challenges of making management decisions to meet conservation goals with inadequate information on how best to prioritize locations and actions. The Nature Conservancy and Hawai‘i DAR team conceptualized this project to fill these vital knowledge gaps and inform near- and long-term management of the coral reefs of Maui.

Our project team assessed the relative resilience of reef sites at two depths along areas of West and South-West Maui (‘leeward Maui’) in March of 2018. The surveys were conducted as a collaborative effort with DAR, The Nature Conservancy, and community organizations. This report presents findings from: benthic cover surveys, the resilience assessment including relative resilience and rankings for two depths, an analysis that determines the primary drivers of differences in resilience between sites, and a framework for using the resilience analysis outputs to identify and prioritize potential management actions to support the resilience of coral reefs in Maui.

Study Objectives

Obj. 1. Benthic Cover – Assess the percentage cover of major benthic groups, including stony corals, macroalgae, turf algae, coralline algae, and other.

Obj. 2. Relative Resilience – Assess the relative resilience of coral reefs at two depths and compare resilience among survey sites.

Obj. 3. Resilience Drivers – Determine the primary drivers of differences in resilience between sites.

Obj. 4. Conservation Action Options – Identify and prioritize potential conservation actions to support coral reef resilience.

Methods

Field surveys were conducted at shallow (3-7 m) and deep (8-13 m) areas at 31 shallow and 20 deep sites of the fringing reefs of leeward Maui in March of 2018. The sites surveyed by our 3-4 diver team represent the full range of ecological settings and physical conditions as well as roughly even spatial coverage of leeward Maui. Methods used to meet all of the study objectives are described below.

Obj. 1. Benthic Cover – Photographs of the bottom were taken every meter along three 25 m transect lines at each survey site using a Canon G12 or S110 camera mounted on a 0.8 m long PVC monopod. This generated 75 images for each depth at each survey site, with each photo covering approximately 0.8 x 0.6 m of the benthos. 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 image analysis maintained by the University of California, San Diego (Beijbom et al. 2015). Thirty random points[1] were overlaid on each digital photograph, and the benthic component under each point was

1 The number of points analyzed on each photograph (30 points) and the number of photographs along each transect (20 photographs) were selected after determining that these values represented the optimal effort to achieve the greatest power to detect statistical differences.

identified to the lowest possible taxonomic level. Once completed, the raw point data from each photograph was combined to calculate the percent cover of each major benthic category for the survey site, including: corals, macroalgae, turf algae, coralline algae and 'other' (i.e., soft corals and other, rubble, sand, and other unconsolidated substrate).

Obj. 2. Relative Resilience – The resilience indicators included were coral cover, coral diversity, coral recruitment, reef builder ratio, coral disease, rugosity, and herbivorous fish biomass. These indicators were selected from among those reviewed for perceived importance and scientific evidence within McClanahan et al. (2012) and six of these seven (exception: coral cover) were used within the Commonwealth of the Northern Mariana Islands (CNMI) and five of the seven within the West Hawaiʻi Island resilience assessments (Maynard et al. 2015, Maynard et al. 2016). Temperature variability and macroalgae cover, though examined, was not included as there is almost no variation in warm season temperature variability (Heron et al. 2016) or macroalgae cover (<1% cover at all sites) among the surveyed sites. The resilience indicators were all assessed in the field. Methods for assessment or measurement of each of the resilience indicators are described in Table 1.

The resilience assessment compared within rather than among depths; i.e., data for the two depths were not aggregated and shallow was not compared to deep or vice versa. Once data were collected or calculated (i.e., reef builder ratio) for each indicator, values for each variable were normalized to a uni-directional scale of 0-1 by dividing by the maximum value for the variable among all sites within a depth within the stratum (i.e., 31 for shallow, and 20 for deep). To ensure that high scores always infer higher relative resilience, normalized scores were inverted for coral disease. All indicators were equally weighted. Resilience scores were calculated by averaging the normalized indicator scores for each site and then those site averages were normalized. This expresses resilience of all sites as relative to the site with the highest score. The final resilience scores range from 0-1 and represent decimal percentages of the site with the highest score (1.00). Relative classifications for resilience scores are as follows: high (final scores that are greater than 1 sd above average), medium-high (<avg+1sd and >avg), medium-low (<avg and >avg-1sd), and low (<avg-1sd). Resilience rankings and relative classifications, as well as scores for each resilience indicator and relative classifications for these, are all shown within tables and maps in the Results.

Obj. 3. Resilience Drivers – Understanding which variables most influence differences in resilience is also valuable information that can be gained from resilience assessments. This is because the indicators most influencing rankings are: 1) the most important to include in monitoring programs, and 2) may reveal the types of management actions that would benefit the greatest number of sites. Indicators with the greatest variability most drive differences in the resilience rankings. We plotted the average + 1 standard deviation and maximum and minimum values for the final resilience scores and for the normalized values of the resilience indicators for both depths. We compared the range of values among the indicators for each depth and identify which indicators have highest and lowest range and variability.

We also used a canonical analysis of principal coordinates (CAP) (Anderson and Willis 2003) to examine which indicators were driving differences in resilience across the four relative classifications (low, med-low, med-high, and high) at each depth. The CAP was based on a Euclidean distance matrix. Variables that might be responsible for group differences are investigated by calculating the multiple correlations of canonical ordination axes with the original indicator variables (Anderson 2008).

Table 1. Field survey methods for resilience indicators.

Variable name (unit)	Methods
Coral cover (%)	Average percent of points classified as corals among the three 25-m benthic cover transects (20 photos analyzed for each transect using CPCe).
Coral diversity (unitless)	The inverse of Simpson's index of diversity, which is based on the frequency each species was observed and the species richness. The resultant value ranges from 0-1 and assesses the probability two species selected at random from the sampled community will be different, so higher percentages equate to higher diversity. The formula for Simpson's index is $D = (\Sigma\ n(n-1))/(N(N-1)$, where n = the total number of organisms of a particular species, and N = the total number of organisms of all species observed.
Coral recruitment (#/m^2)	Average density of corals with a colony diameter <5 cm within 12 assessed quadrats (0.25 m^2); we assess new recruits, so we exclude massive and encrusting colonies that commonly have parts of larger colonies that are <5 cm (e.g., *Porites rus*) or which may have undergone partial mortality.
Coral disease (%)	Percent of colonies surveyed affected by any type of disease at time of surveys ('disease prevalence').
Reef Builder Ratio	Ratio of calcifying species (stony corals and CCA) to non-calcifying species (turf and macroalgae)
Herbivorous fish biomass (g/m^2)	Divers estimated herbivorous fish biomass along three replicate transects. For each transect, divers slowly deployed a 25 m transect line while identifying to species and sizing 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 each of two transects. Divers took between 10 and 15 minutes to complete each fish transect. The weight of each fish in grams was then calculated using standard weight-length relationships (WLRs). The coefficients used were sourced from NOAA's Coral Reef Ecosystem Program (Weijerman et al. 2013). Species were classified as herbivores using NOAA CREP classifications (all functional group designations for herbivores were combined).
Rugosity	Calculated along the first 10 meters of each 25 m 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 relief, and increasing values represent more topographically complex substrate.

Obj. 4. Conservation Action Options – To identify management opportunities that could support resilience at survey locations, data on anthropogenic stress were compiled from a collaboration with the Ocean Tipping Points Project, summarized in Wedding and Lecky et al. (2018). Data layers on stress used in the analyses include: Total effluent, Nitrogen flux, Phosphorus flux, Sedimentation, Nearshore development, and Total fishing. The anthropogenic stress data were combined with the scores for relative resilience and individual resilience indicators. Criteria were then set to identify management opportunities and reef areas where such actions would support resilience. The criteria are named below by the type of potential management opportunity.

*Prioritize **C**onservation* – These sites have medium-high or high relative resilience and are not currently within marine managed areas.

*Manage **W**ater quality* – These sites have medium-high or high relative resilience and greater total effluent, phosphorus or nitrogen flux than the leeward Maui average + 1 sd.

*Reduce **S**edimentation* – These sites have medium-high or high relative resilience and greater sedimentation levels than the leeward Maui average + 1 sd.

*Monitor **F**ishing Pressure* – These sites have medium-high or high relative resilience and total fishing catch is greater than the leeward Maui average +1 sd.

Results

Obj. 1. Benthic Cover

Coral – Average coral cover for the shallow (3-7 m) reef sites was 27.64+16.23%. Coral cover was highest for the shallow reef sites at Keālia (64%), and also >50% at Mala Reef (57%) and Kīhei North (50%). Coral cover was lowest for the shallow reef sites at Awalua (2%) and <5% at Kalaeloa (3%), Kanahena Point (3) and Olowalu CRAMP (5%).

Average coral cover for the deep (8-13 m) reef sites was 34.44+22.97%. Coral cover was highest for the deep reef sites at Molokini (80%), and also >50% at Kalama Park (70%). Coral cover was lowest for the deep reef sites at Puamana (3%) and <5% at Olowalu North (4%), Maʻalaea CRAMP (4%) and Līpoa Point (5%).

Macroalgae – Macroalgae cover was <0.5% at all shallow reef sites except Pali Tunnel, where macroalgae cover was 0.61%. Macroalgae cover was <0.5% at all deep reef sites except Puamana, where macroalgae cover was 0.78%.

Crustose coralline algae (CCA) – CCA cover ranged from 0-49% (average – 5+9.18%) at the shallow reef sites. CCA cover was <1% at 17 of the 31 shallow survey sites, and was >15% at two sites – Kanahena Point (16%) and Kalaeloa (49%). At the deep reef sites, CCA cover ranged from 0-27% (average – 5+6.94%). CCA cover was <1% at 5 of the 20 deep survey sites, and was >15% at Keawakapu (19%) and Kanahena Point (27%).

Turf algae – Turf algae cover ranged from 19-89% (average – 54+17.49%) at shallow reef sites. Turf algae cover was <20% at Keālia (20%) and Kihei North (19%), and >60% at 10 of 31 shallow survey sites, and ≥80% at Kanahena Point (80%), Māʻalaea CRAMP (83%), and Olowalu CRAMP (89%). Turf algae ranged from 16-81% (average – 46+17.28%) at the deep reef sites. Turf algae cover was <20% at Keālia (16%) and Molokini (16%), and >60% at Keoneʻōʻio (67%), Līpoa Point (81%), and Māʻalaea CRAMP (80%).

Average cover (n=3 transects) of stony corals, macroalgae, crustose coralline algae, turf algae and other is shown for shallow and deep survey sites in Table 2.

In total, 24 coral species were observed, considering recruits (i.e. <5 cm) and larger corals combined). A coral species list is presented within Table 3.

Table 2. Percent cover of major benthic groups for the shallow (3-7 m) and deep (8-13 m) survey sites. Values have been rounded to the nearest whole number. 'Other' includes other invertebrates as well as rubble and other unconsolidated substrate. See Figure 1 for survey site locations.

Shallow (3-7 m) Site	Coral (%)	Macroalgae (%)	CCA (%)	Turf Algae (%)	Other (%)
Honolua North	27	0	3	67	3
Honolua South	17	0	4	76	3
ʻAlaeloa Pt	12	0	13	75	0
Honokōwai	20	0	10	56	14
North Kāʻanapali	38	0	3	57	2
Hanakaʻōʻō	41	0	3	40	16
Mala Reef	57	0	1	41	1
Polanui	21	0	1	68	10
Launiupoko	22	0	1	65	12
Olowalu North	26	0	1	50	23
Olowalu CRAMP	5	0	1	89	5
Olowalu South	29	0	0	66	5
Ukumehame	37	0	5	51	7
Pali Tunnel	6	1	1	77	16
McGregor Point	27	0	8	59	5
Māʻalaea CRAMP	6	0	0	83	10
Keālia	64	0	1	20	16
Kihei North	50	0	9	19	23
Lipoa Street	37	0	0	39	25
Kalama Park	39	0	3	43	15
Kihei Boat Ramp	30	0	4	50	17
Ulua Beach Park	29	0	1	47	23
Maluaka Point	31	0	1	50	18
Kanahena	44	0	1	31	24
Kanahena Point	3	0	16	80	1
Kalaeloa	3	0	49	47	0
Keoneʻōʻio	28	0	3	57	12
Molokini	49	0	0	33	17
Wahikuli	19	0	1	54	25
Olowalu Point	36	0	1	54	9
Awalua	2	0	0	46	52

Deep (7-13 m) Site	Coral (%)	Macroalgae (%)	CCA (%)	Turf Algae (%)	Other (%)
Hanakaʻōʻō	46	0	8	42	4
Honokōwai	37	0	6	50	7
Kalama Park	70	0	2	24	4
Kanahena Point	15	0	27	50	9
Keālia	73	0	8	16	3
Keawakapu	39	0	19	41	1
Keoneʻōʻio	15	0	2	67	17
Kihei North	39	0	4	26	30
Lipoa Point	5	0	2	81	12
Māʻalaea CRAMP	4	0	0	80	15
Mahinahina CRAMP	45	0	3	46	6
Maluaka Point	39	0	5	46	10
Molokini	80	0	2	16	2
North Kāʻanapali	39	0	1	50	10
Olowalu CRAMP	32	0	2	43	22
Olowalu North	4	0	0	54	42
Pali Tunnel	41	0	14	44	1
Puamana	3	1	0	50	46
Ukumehame	44	0	4	48	3
Ulua Beach Park	19	0	1	46	35

Table 3. Coral species (24) observed at survey sites in leeward Maui during 2018.

Coral Species		
Cyphastrea ocellina	*Pavona duerdeni*	*Porites compressa*
Fungia scutaria	*Pavona maldivensis*	*Porites evermani*
Leptastrea bewickensis	*Pavona varians*	*Porites lobata*
Leptastrea incrusta	*Pocillopoa damicornis*	*Porites monticulosa*
Leptastrea purpurea	*Pocillopora eydouxi*	*Porites rus*
Montipora capitata	*Pocillopora meandrina*	*Psammocora haimeana*
Montipora flabellata	*Porites bernardi*	*Psammocora nierstraszi*
Montipora patula	*Porites brighami*	*Psammocora stellata*

Obj. 2. Relative resilience

Shallow – Normalized resilience scores ranged from 0.44-1.00. Five sites were assessed as having high relative resilience, 10 medium-high, 12 medium-low, and 4 low. The five sites with high relative resilience were Keālia, Kihei North, Ulua Beach Park, Molokini, and Honolua North; except for Honolua North these sites are all south-east of Mā‘alaea nd near Kihei (Fig. 1). The four sites with low relative resilience are Olowalu CRAMP, Kalama Park, Maluaka Point, and Awalua; these sites are south of Kihei (Kalama Park and Maluaka Point) and near and north-west of Mā‘alaea (Olowalu CRAMP and Awalua). Normalized values and relative classes (low-high) for each resilience indicator are shown within Tables A1.3-A1.5.

Deep – Normalized resilience scores ranged from 0.53-1. Four sites were assessed as having high relative resilience, 6 medium-high, 6 medium-low, and 4 low. The four sites with high relative resilience were Keālia, Molokini, Kalama Park, and Pali Tunnel; these are near Mā‘alaea (Pali Tunnel), near Kihei (Keālia and Kalama Park), and south of Kihei (Molokini, Fig. 1). The four sites with low relative resilience are Maluaka Point, Mā‘alaea CRAMP, Puamana and Olowalu North; these are just north-west of Mā‘alaea (Puamana and Olowalu North), just east of Mā‘alaea (Mā‘alaea North), and south of Kihei (Maluaka Point). Normalized values and relative classes (low-high) for each resilience indicator are shown within Tables A1.6-A1.8.

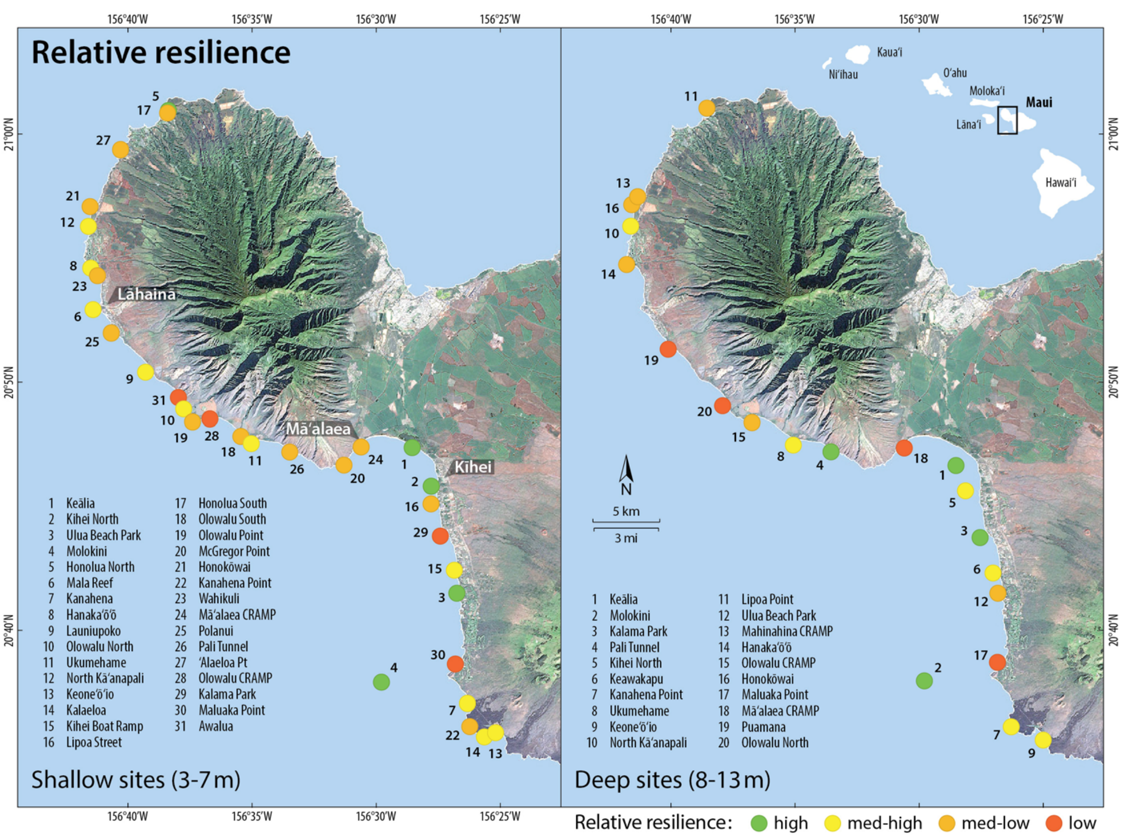

Figure 1. Resilience assessment results for shallow (3-7 m) and deep (8-13 m) reef areas along leeward Maui. For both shallow and deep, the numbers next to the site marker represent the resilience rank. Relative classifications for resilience scores and resilience indicator scores are as follows: high (final scores that are >1 sd above average (avg)), medium-high (<avg+1sd and >avg), medium-low (<avg and >avg-1sd), and low (<avg-1sd). >1 sd above average (avg), medium-high (<avg+1sd and >avg), medium-low (<avg and >avg-1sd), and low (<avg-1sd).

Obj. 3. Resilience drivers

Coral cover, reef builder ratio, and herbivorous fish biomass were the indicators with the greatest range of values and greatest variability. These indicators are greater drivers of differences among the sites in resilience scores than coral disease, coral diversity and rugosity, which have far lower relative variability (Fig. 2).

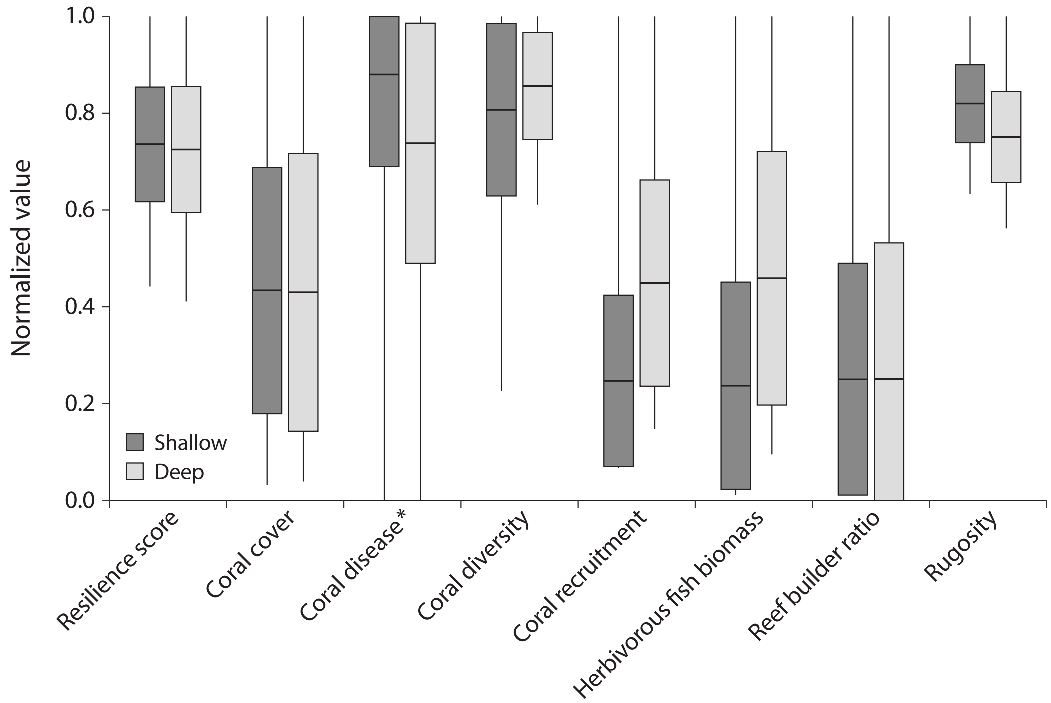

Figure 2. Distribution of normalized values for the resilience scores and for the resilience indicators. Mid-lines represent average values, the tops and bottoms of the boxes represent 1 sd and the whiskers denote the min and max values of the data range.

It was possible that high resilience sites could have this classification as a result of having high scores for different indicators and low resilience sites could have low scores for different indicators. We examined whether high scores for some indicators are consistently associated with high resilience (and low scores for some indicators with low resilience) using a CAP analysis.

Shallow – Across the shallow reef sites of Maui, higher resilience correlated most strongly with higher coral cover and a higher reef-builder ratio (Fig. 3, along CAP axis 1). Rugosity and high herbivore biomass also contributed to the separation of resilience groupings, although not as strongly (Fig. 3, along CAP axis 1). All these resilience indicators decreased in value moving along CAP axis 1 (to the right) from 'high' to 'medium-high' to 'medium' resilience. Higher coral disease also appeared to correlate with 'medium-low' resilience, separating these sites from the 'high' and 'medium-high' resilience locations (Fig. 3, along CAP axis 2). In contrast, 'low' resilience sites were negatively correlated with the majority of these resilience indicators, although two sites (Kalama Park and Maluaka Point) appeared to correlate positively with coral recruitment, however the correlation was weak (Fig. 3, along CAP axis 2).

Deep – Across the deep reef sites of Maui, 'high' resilience sites were again correlated most strongly with a higher reef builder ratio and higher coral cover (Fig. 3, along CAP axis 1).

'Medium-high' and 'medium-low' resilience, in addition to two of the 'high' resilience sites (Pali Tunnel and Kalama Park), were characterized by higher coral diversity and higher herbivore biomass (along CAP axis 2). 'Low' resilience deep sites showed tight clustering and were most strongly characterized as having lower reef-builder ratio, lower coral cover, lower coral diversity and lower herbivore biomass (Fig. 3).

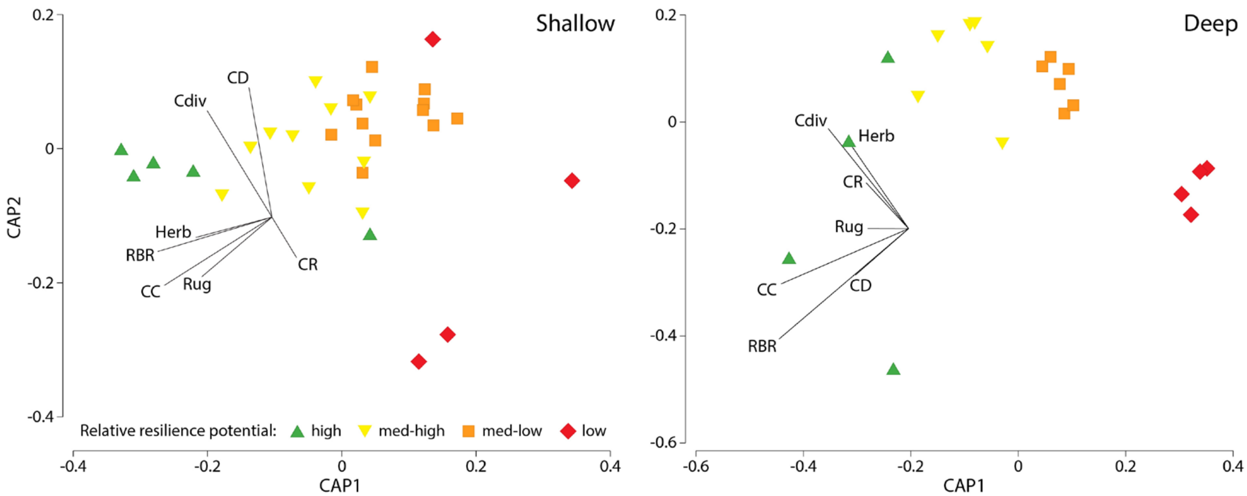

Figure 3. Canonical analysis of principal coordinates showing the relative contribution of the seven resilience indicators (overlaid as vectors) to overall resilience of shallow and deep reef sites in leeward Maui. Codes for indicators are: CC, coral cover; CR, coral recruitment; Cdiv, coral diversity; RBR, reef builder ratio; CD, coral disease; Rug, rugosity; Herb, herbivorous fish biomass. For the shallow reef sites, squared canonical correlation value (δ^2) of the first and second ordination axes equal 0.685 and 0.311, respectively. For the deep reef sites, squared canonical correlation value (δ^2) of the first and second ordination axes equal 0.952 and 0.523, respectively.

Obj. 4. Conservation Action Options

Reducing local stressors to support resistance and recovery

Local management efforts alone cannot mitigate the effects of large-scale events such as mass coral bleaching (Selig and Bruno 2010; Hughes et al. 2017). However, evidence suggests that they can, in some cases, support recovery following disturbance and may support resistant coral assemblages (West and Salm 2003; McClanahan et al. 2012). Maintaining good water quality and reducing coastal pollutants has been suggested to increase corals' thermal resistance. High sediment and nutrient loads can compromise coral recovery, decrease coral growth rates, increase coral disease and bleaching, and increase algal growth (Fabricius 2005). Yet, many factors affect coral sensitivity to sediments and nutrients (e.g., size of particle, nutrient type, intensity, duration and frequency of exposure), thus impacts will be context-specific, based on local ecological and oceanographic conditions.

This project sought to help managers target actions that reduce local stressors to support resistance and recovery of coral reefs in leeward Maui. The decision-support framework we developed targets actions to high resilience rather than low resilience sites. The next section explains that rationale, and then our methods follow.

Rationale for targeting management actions to high resilience sites

Our project team developed a model to examine the effect of management on the probability different types of reefs will be healthy by constraining exposure, sensitivity and recovery using realistic low and high values (Maynard et al. in review). We express management gains as an increase in the probability that a reef will be healthy if managed. We use this model to determine which management strategies maximize the number of healthy reefs in a system.

Under anticipated future disturbance frequencies, a different strategy is optimal than was the case in the past. Under historically observed disturbance regimes, differences in exposure to disturbance mattered less since most reefs had time to recover between disturbances. Consequently, management gains were greatest if all efforts were allocated to high exposure sites with high resilience. However, for coral reefs exposed to disturbance events more than once per decade (annual probability > 0.1), the greatest gains from management are always achieved by managing the reefs with the lowest exposure rates. For reefs with comparable exposure regimes, management gains are greatest for the reefs with highest resilience (Fig. 4). The coral reefs of leeward Maui are assumed here to have comparable future exposure regimes (van Hooidonk et al. 2016). This project team developed downscaled projections of future coral bleaching conditions – all of the reefs of leeward Maui were projected to experience annual severe bleaching within a few years of 2040 (van Hooidonk et al. 2016). The results of our model suggest a near universal rule is that coral reef management will deliver the greatest benefits when directed to high-resilience reefs. Preferentially protecting the low exposure, high resilience climate winners yields an order of magnitude greater management gain than putting all management resources into protecting the high exposure, low resilience climate losers. For this reason, having medium-high or high relative resilience (based on our analysis) is the key criteria set to identify potential targets for management actions in leeward Maui.

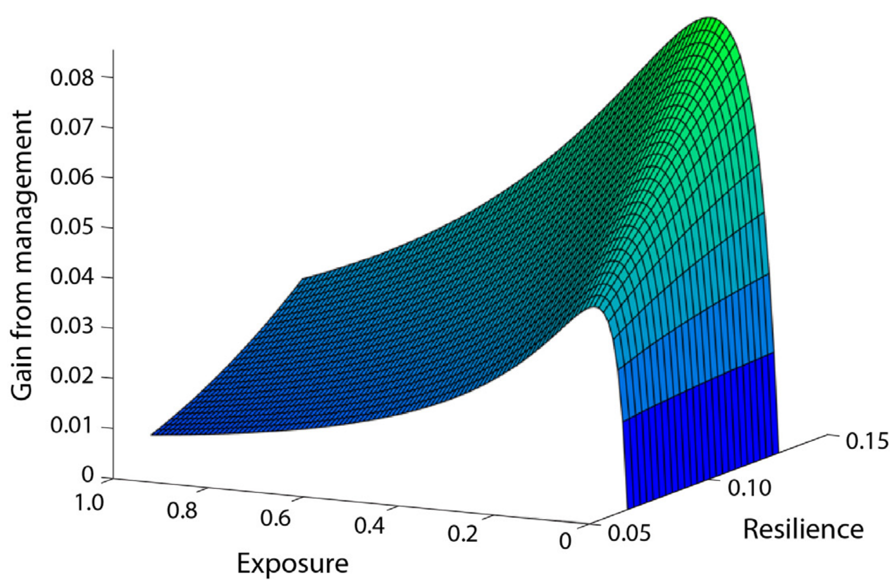

Figure 4. Gain from management for the range of values set for exposure and resilience. Once at least one disturbance occurs per decade (0.1 on exposure scale) management gains are always greatest for any set of sites by managing the highest resilience sites. Here, ‘management gain’ is the difference in the number of healthy sites as a result of management.

Potential conservation actions managers or community members can consider

To identify management opportunities that could support resilience at survey locations, data on anthropogenic stress were compiled from a collaboration with the Ocean Tipping Points Project. Data layers on stress used in the analyses presented here include: total effluent, nitrogen flux, phosphorus flux, nearshore development, sedimentation and fishing (Figure 5). Methods for the generation of the anthropogenic stress data layers are described in detail within Wedding and Lecky et al. (2018). Stressor intensity varied along the leeward coast of Maui, with nutrient-related stressors concentrated near Lahaina, Kihei, coastal development between Maʻalaea and Kihei, and fishing pressure high along most of the coastline.

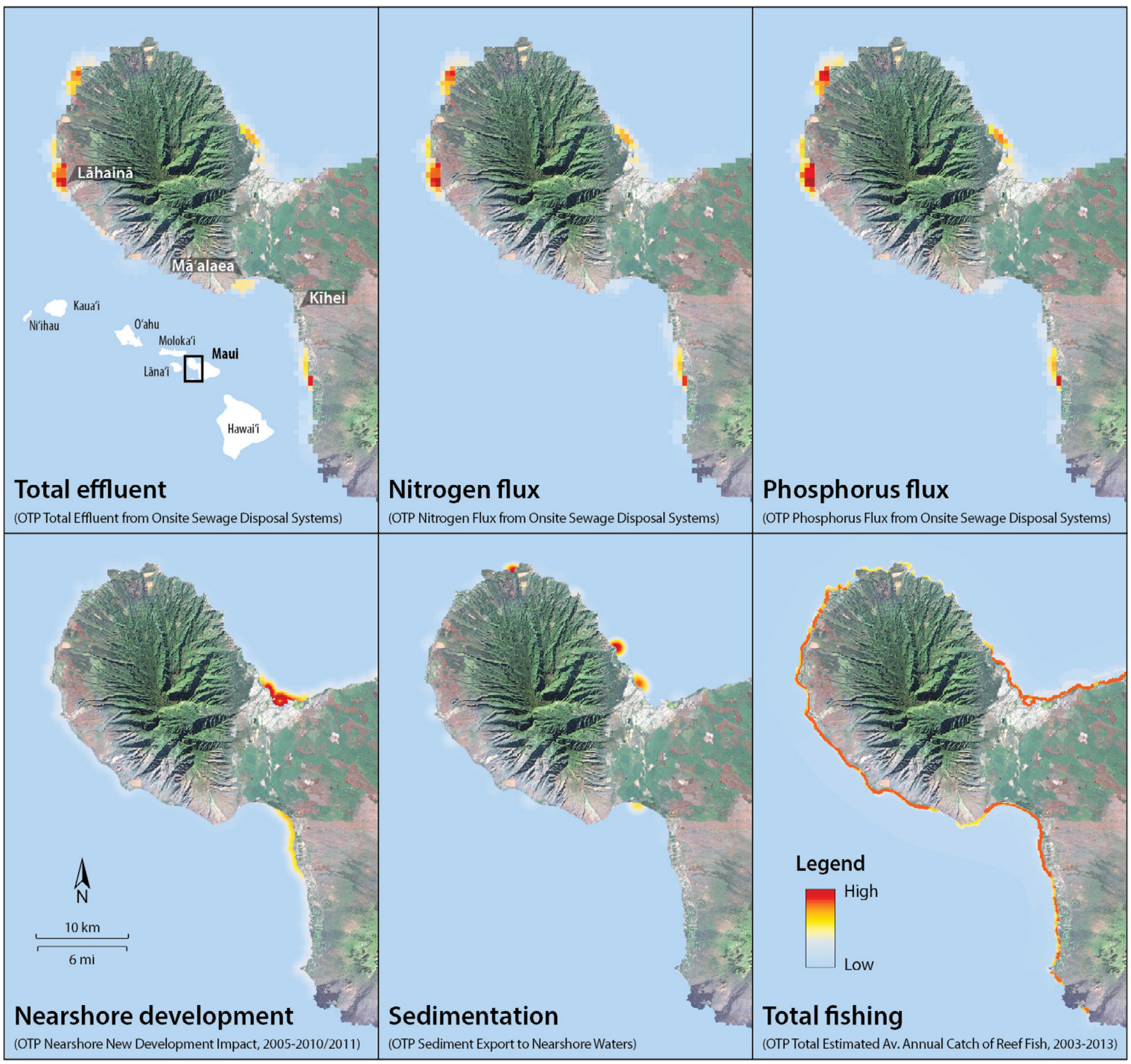

Figure 5. Anthropogenic stressors in leeward Maui, compiled by team members working on the Ocean Tipping Points project (reviewed in Wedding and Lecky 2018).

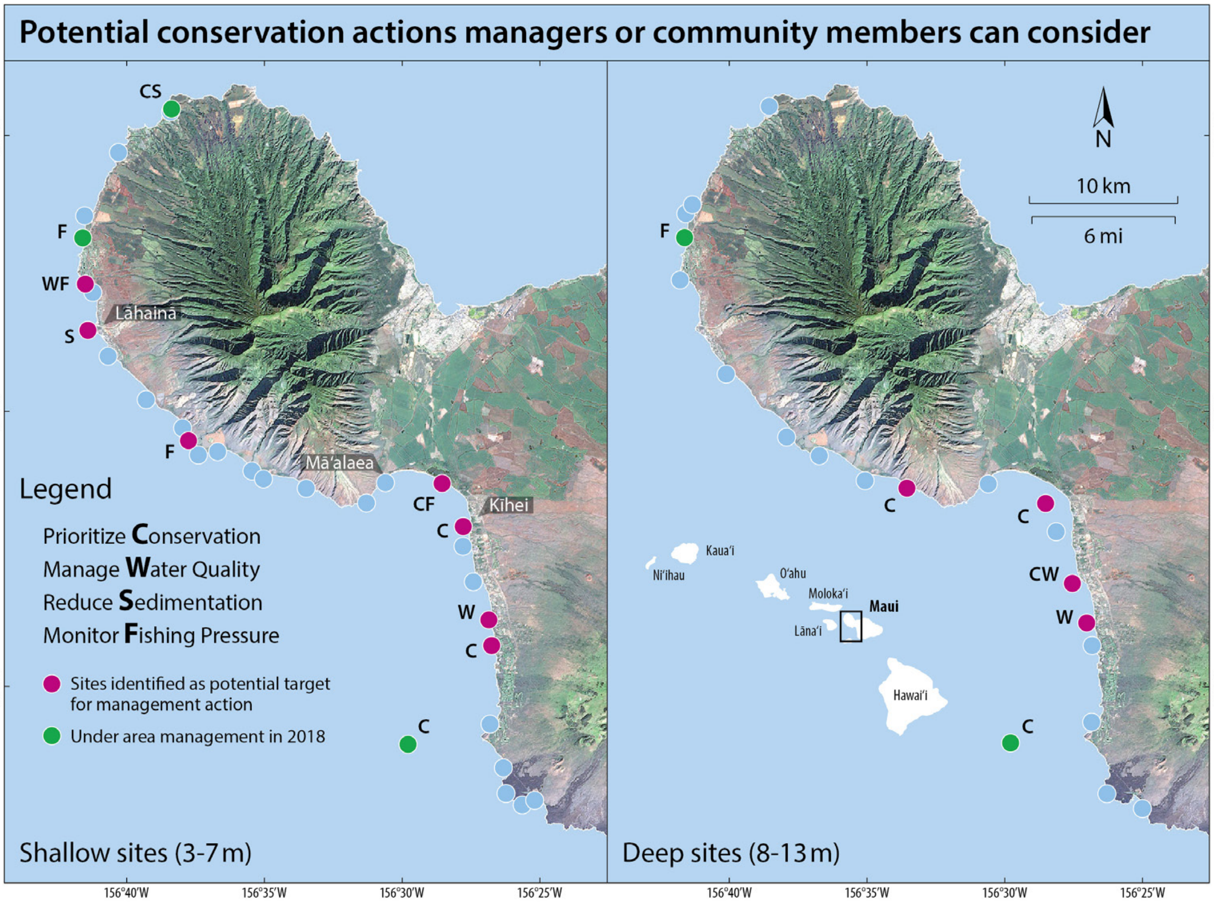

Figure 6. Sites identified as potential targets for management actions that support resilience to climate change.

The anthropogenic stress data were then combined with the scores for relative resilience and individual resilience indicators. Criteria were then set to identify management opportunities and reef areas where such actions would support resilience.

Four types of potential conservation actions were identified for sites with high and medium relative resilience (Figure 6):

Prioritize ***C****onservation* – These sites have medium-high or high relative resilience and are not currently within marine managed areas. Shallow sites that met these criteria are Keālia, Kihei North, Ulua Beach Park, Molokini, Honolua North. Deep sites that met these criteria are Keālia, Molokini, Kalama Park, and Pali Tunnel (Fig. 6).

Manage ***W****ater quality* – These sites have medium-high or high relative resilience and greater of total effluent, phosphorus or nitrogen flux than the leeward Maui average + 1 sd. Shallow sites that met these criteria are Hanakaʻōʻō and Kihei Boat Ramp. Deep sites that met these criteria are Kalama Park and Keawakapu (Fig. 6).

Reduce ***S****edimentation* – These sites have medium-high or high relative resilience and greater sedimentation levels than the leeward Maui average + 1 sd. Shallow sites that met these criteria are Honolua North and Mala Reef (Fig. 6). There are no deep sites that met these criteria.

*Monitor **F**ishing Pressure* – These sites have medium-high or high relative resilience and total fishing catch is greater than the leeward Maui average +1 sd. Shallow sites that met these criteria are Keālia, Hanakaʻōʻō, Olowalu North, and North Kāʻanapali. The deep site that met these criteria is North Kāʻanapali (Fig. 6).

The decision-support framework presented here should be seen as an example for how assessments of resilience can be combined with information on stressors related to human activities to guide discussions among managers. Managers will have access to a range of additional information that will guide discussions and decisions related to spatial planning.

The overarching recommendation from this project team related to our example framework is that management effort will have the greatest long-term benefit if stressors are addressed at sites with relatively high resilience. Available information on stressors related to human activities can help in deciding which actions will be most effective in supporting resilience.

Next Steps

All of the following are next steps the project team is planning for the year that follows publication of this Tech Memo.

Education and Outreach:

The information within this report will be used to develop outreach material that can be shared with community members to explain project results and promote resilience-based management.

An outreach presentation will be developed that explains how the project results can inform planning for the 30 x 30 initiative, and then shared with policymakers, managers and community members.

Use of project results to inform 30 by 30 initiative:

Already underway: All raw and normalized data for indicators, and the raw and final resilience scores, rankings and relative (low to high) classes for resilience has been shared among all project partners as an ArcGIS layer package. This ensures that data from this project can be used within future spatial management plans for Maui under the 30 by 30 initiative (see also just below). Our team will ensure all our project partners have access to the layer package and will raise awareness of the layer package among the scientific and management community at meetings and upcoming conference symposia. The spatial data layer package will help our team work with Maui reef stakeholders to identify areas and actions to include in marine managed area network design.

High priority future work requiring further funding: Further to our plans described just above, our team will attempt to raise funds from CRCP and other project partners to expand on the resilience assessment completed under this project. We aim to combine data collected under this project with data collected by DAR and other partners from other reef sites in Leeward Maui. DAR does not collect coral recruitment, coral disease or rugosity information. We will use spatial interpolation of those data collected under this project for the deep and shallow survey sites to create a spatially contiguous dataset for those variables for all of Leeward Maui. We will then extract values for recruitment, disease and rugosity for the ~200 other sites for which all of the other resilience indicators are available (from the HIMARC dataset, which includes data collected by Hawaii DAR and NOAA's Ecosystem Sciences Division). The data extracted from our interpolated datasets will be combined with data In the HIMARC dataset to assess relative resilience among ~200 sites in Leeward Maui. Interpolating those results will enable us to generate spatially contiguous data for relative resilience in Leeward Maui that is based on ~200 reef survey sites; i.e., a resilience map could be made that includes all of the recent reef survey data available for the region. Manager partners at Hawaii DAR that worked closely with us on this project are strongly requesting this next step be completed in the coming year.

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Appendix 1 – Site coordinates, resilience summary tables, and resilience indicator maps

Contents

Table A1.1. Survey site coordinates for shallow (3-7 m). All sites were surveyed between March 12 and 23, 2018.

Site Name	Depth	Resilience Rank	Latitude	Longitude
KeāliaKeālia	Shallow	1	20.789	-156.476
Kihei North	Shallow	2	20.763	-156.463
Ulua Beach Park	Shallow	3	20.691	-156.446
Molokini	Shallow	4	20.631	-156.496
Honolua North	Shallow	5	21.016	-156.639
Mala Reef	Shallow	6	20.882	-156.690
Kanahena	Shallow	7	20.617	-156.439
Hanakaoʻo	Shallow	8	20.910	-156.692
Laniopoko	Shallow	9	20.840	-156.655
Olowalu North	Shallow	10	20.815	-156.629
Ukumehame	Shallow	11	20.792	-156.584
North Kāʻanapali	Shallow	12	20.938	-156.693
Keoneʻoʻio	Shallow	13	20.598	-156.420
Kʻ Alaeloa	Shallow	14	20.595	-156.427
Kihei Boat Ramp	Shallow	15	20.707	-156.447
Lipoa Street	Shallow	16	20.751	-156.463
Honolua South	Shallow	17	21.014	-156.640
Olowalu South	Shallow	18	20.797	-156.591
Olowalu Point	Shallow	19	20.806	-156.623
McGregor Point	Shallow	20	20.777	-156.522
Honokōwai	Shallow	21	20.951	-156.692
Kanahena Point	Shallow	22	20.602	-156.437
Wahikuli	Shallow	23	20.905	-156.687
MāʻalaeaMaʻalaea CRAMP	Shallow	24	20.790	-156.510
Polanui	Shallow	25	20.866	-156.678
Pali Tunnel	Shallow	26	20.786	-156.558
ʻAlaeloa Pt	Shallow	27	20.989	-156.672
Olowalu CRAMP	Shallow	28	20.808	-156.612
Kalama Park	Shallow	29	20.730	-156.457
Maluaka Point	Shallow	30	20.644	-156.447
Awalua	Shallow	31	20.823	-156.633

Table A1.2. Survey site coordinates for deep (8-13 m). All sites were surveyed between March 12 and 23, 2018.

Site Name	Depth	Resilience Rank	Latitude	Longitude
KeāliaKeālia	Deep	1	20.777	-156.475
Molokini	Deep	2	20.632	-156.496
Kalama Park	Deep	3	20.729	-156.459
Pali Tunnel	Deep	4	20.786	-156.559
Kihei North	Deep	5	20.760	-156.469
Keawakapu	Deep	6	20.705	-156.450
Kanahena Point	Deep	7	20.602	-156.438
Ukumehame	Deep	8	20.791	-156.584
Keone'o'io	Deep	9	20.593	-156.417
North Kāʻanapali	Deep	10	20.938	-156.694
Lipoa Point	Deep	11	21.017	-156.643
Ulua Beach Park	Deep	12	20.691	-156.447
Mahinahina CRAMP	Deep	13	20.958	-156.689
Hanakao'o	Deep	14	20.912	-156.696
Olowalu CRAMP	Deep	15	20.806	-156.612
Honokōwai	Deep	16	20.952	-156.693
Maluaka Point	Deep	17	20.645	-156.447
MāʻalaeaMaʻalaea CRAMP	Deep	18	20.789	-156.510
Puamana	Deep	19	20.855	-156.669
Olowalu North	Deep	20	20.817	-156.632

Table A1.3. Normalized scores for all resilience indicators, raw and final resilience scores, and site rankings for the shallow (3-7 m) survey sites. Relative classifications for resilience scores and resilience indicator scores are as follows: high (final scores that are >1 sd above average (avg)), medium-high (<avg+1sd and >avg), medium-low (<avg and >avg-1sd), and low (<avg-1sd). Absolute values for all indicators, and the ranges of absolute values corresponding with each relative class (low-high), are shown in Tables A1.4 and A1.5.

Site Name	Rank	Resilience Final Score	Resilience Raw Score	Coral Cover (%)	Coral Diversity	Coral Recruit. (#/m^2)	Reef Builder Ratio	Coral Disease (%)	Rugosity	Herb. Fish Biomass (g/m^2)
Keālia	1	1.00	0.71	1.00	0.20	0.89	0.98	0.83	1.00	0.09
Kihei North	2	0.93	0.66	0.78	0.13	0.73	1.00	0.94	0.86	0.20
Ulua Beach Park	3	0.90	0.64	0.46	1.00	0.65	0.20	0.95	0.90	0.30
Molokini	4	0.88	0.63	0.77	0.20	0.83	0.53	0.90	0.84	0.35
Honolua North	5	0.88	0.63	0.42	0.14	0.96	0.14	0.97	0.76	1.00
Mala Reef	6	0.83	0.59	0.89	0.16	0.86	0.44	0.96	0.80	0.01
Kanahena	7	0.81	0.58	0.69	0.34	0.83	0.44	0.78	0.89	0.10
Hanakaʻōʻō	8	0.81	0.58	0.65	0.21	0.90	0.33	0.91	0.91	0.15
Launiupoko	9	0.81	0.58	0.35	0.25	0.74	0.11	0.94	0.82	0.84
Olowalu North	10	0.79	0.57	0.41	0.62	0.66	0.16	0.91	0.86	0.35
Ukumehame	11	0.78	0.56	0.57	0.22	0.94	0.25	0.95	0.92	0.07
North Kāʻanapali	12	0.77	0.55	0.59	0.07	0.93	0.22	0.84	0.76	0.42
Keoneʻōʻio	13	0.75	0.54	0.43	0.32	1.00	0.18	0.93	0.84	0.06
Kalaeloa	14	0.74	0.53	0.05	0.12	0.90	0.36	0.99	0.89	0.38
Kihei Boat Ramp	15	0.74	0.52	0.48	0.27	0.79	0.21	0.85	0.90	0.17
Lipoa Street	16	0.73	0.52	0.58	0.07	0.70	0.46	0.96	0.83	0.05
Honolua South	17	0.72	0.51	0.27	0.28	0.89	0.09	0.99	0.75	0.32
Olowalu South	18	0.72	0.51	0.45	0.25	0.82	0.13	0.97	0.76	0.19
Olowalu Point	19	0.71	0.51	0.57	0.27	0.75	0.21	0.85	0.75	0.16
McGregor Point	20	0.71	0.51	0.42	0.23	0.87	0.18	0.83	0.88	0.14
Honokōwai	21	0.71	0.51	0.32	0.20	0.93	0.17	0.93	0.76	0.23
Kanahena Point	22	0.71	0.51	0.05	0.26	1.00	0.07	1.00	0.83	0.34
Wahikuli	23	0.66	0.47	0.30	0.21	0.79	0.11	0.96	0.81	0.09
Māʻalaea CRAMP	24	0.64	0.46	0.10	0.46	0.77	0.03	0.98	0.63	0.21
Polanui	25	0.63	0.45	0.33	0.17	0.89	0.10	0.79	0.82	0.05
Pali Tunnel	26	0.63	0.45	0.09	0.22	0.83	0.03	0.94	0.75	0.27
ʻAlaeloa Pt	27	0.62	0.44	0.19	0.13	0.91	0.10	0.89	0.76	0.12
Olowalu CRAMP	28	0.61	0.43	0.08	0.13	1.00	0.02	1.00	0.68	0.13
Kalama Park	29	0.60	0.43	0.62	0.23	0.76	0.30	0.00	0.89	0.18
Maluaka Point	30	0.55	0.39	0.49	0.13	0.26	0.21	0.51	0.86	0.28
Awalua	31	0.44	0.32	0.03	0.16	0.23	0.01	1.00	0.68	0.09

Table A1.4. Relative classifications for resilience indicator scores are per Table A1.3. The absolute values for each indicator for the shallow survey sites corresponding with each relative class (low-high) is shown and color-graded.

	Coral Cover (%)	Coral Diversity	Coral Recruitment (#/m^2)	Reef Builder Ratio	Coral Disease (%)	Rugosity	Herbivorous Fish Biomass (g/m^2)
Low	<11.41	<0.52	<4.83	<0.04	NA	<1.32	<2.23
Medium-Low	>11.41 and <27.64	>0.52 and <0.66	>4.83 and <17.10	>0.04 and <0.83	>0 and <4.36	>1.32 and <1.46	>2.23 and <22.98
Medium-High	>27.64 and <43.87	>0.66 and <0.81	>17.10 and <29.37	>0.83 and <1.62	>4.36 and <11.23	>1.46 and <1.60	>22.98and <43.73
High	>43.87	>0.81	>29.37	>1.62	>11.23	>1.60	>43.73

Table A1.5. Absolute values and relative classes (low-high) for each resilience indicator for the shallow survey sites.

Site Name	Resilience Rank	Coral Cover (%)	Coral Diversity	Coral Recruitment (#/m^2)	Reef Builder Ratio	Coral Disease (%)	Rugosity	Herbivorous Fish Biomass (g/m^2)
Keālia	1	63.75	0.73	14.00	3.25	6.08	1.78	8.95
Kihei North	2	49.57	0.60	9.33	3.31	2.20	1.54	19.09
Ulua Beach Park	3	29.47	0.54	69.33	0.67	1.63	1.60	29.26
Molokini	4	49.15	0.68	13.67	1.77	3.46	1.50	33.51
Honolua North	5	26.62	0.79	9.67	0.45	0.94	1.36	97.01
Mala Reef	6	56.97	0.71	11.33	1.45	1.56	1.43	1.04
Kanahena	7	44.18	0.68	23.33	1.46	8.08	1.58	9.65
Hanakaʻōʻō	8	41.43	0.74	14.67	1.10	3.17	1.62	14.24
Launiupoko	9	22.15	0.61	17.50	0.35	2.28	1.46	81.72
Olowalu North	10	26.20	0.54	42.67	0.53	3.30	1.53	34.33
Ukumehame	11	36.62	0.77	15.00	0.81	1.71	1.64	7.10
North Kāʻanapali	12	37.55	0.77	5.00	0.72	5.72	1.35	41.07
Keoneʻōʻio	13	27.66	0.82	22.33	0.60	2.50	1.50	5.98
Kalaeloa	14	3.40	0.74	8.00	1.18	0.54	1.59	36.67
Kihei Boat Ramp	15	30.36	0.65	18.67	0.70	5.40	1.61	16.49
Lipoa Street	16	36.68	0.57	4.67	1.51	1.48	1.49	4.90
Honolua South	17	17.45	0.73	19.33	0.30	0.29	1.33	30.56
Olowalu South	18	28.60	0.68	17.00	0.44	1.06	1.35	18.88
Olowalu Point	19	36.21	0.62	18.67	0.70	5.52	1.34	15.49
McGregor Point	20	27.01	0.72	15.67	0.60	6.19	1.57	13.97
Honokōwai	21	20.12	0.76	14.00	0.58	2.41	1.36	22.57
Kanahena Point	22	3.11	0.82	18.00	0.24	0.00	1.47	32.58
Wahikuli	23	19.34	0.65	14.33	0.36	1.34	1.45	8.65
Māʻalaea CRAMP	24	6.44	0.64	32.00	0.09	0.57	1.13	20.11
Polanui	25	21.33	0.74	12.00	0.33	7.70	1.46	4.65
Pali Tunnel	26	5.77	0.68	15.00	0.09	2.09	1.34	26.19
ʻAlaeloa Pt	27	11.85	0.75	9.33	0.33	4.02	1.36	11.80
Olowalu CRAMP	28	5.03	0.82	9.33	0.07	0.00	1.21	12.77
Kalama Park	29	39.34	0.63	16.00	0.99	36.19	1.59	17.32
Maluaka Point	30	31.41	0.21	9.00	0.69	17.73	1.54	26.71
Awalua	31	2.03	0.19	11.33	0.03	0.00	1.22	9.04

Table A1.6. Normalized scores for all resilience indicators, raw and final resilience scores, and site rankings for the deep (8-13 m) survey sites. Relative classifications for resilience scores and resilience indicator scores are per Table A1.3. Absolute values for all indicators, and the ranges of absolute values corresponding with each relative class (low-high), are shown in Tables A1.7 and A1.8.

Site Name	Rank	Resilience Final Score	Resilience Raw Score	Coral Cover (%)	Coral Diversity	Coral Recruit. (#/m^2)	Reef Builder Ratio	Coral Disease (%)	Rugosity	Herb. Fish Biomass (g/m^2)
Keālia	1	1.00	0.78	0.91	0.59	0.96	0.95	0.95	0.84	0.24
Molokini	2	0.90	0.69	1.00	0.15	0.68	1.00	0.87	0.77	0.40
Kalama Park	3	0.89	0.69	0.88	0.35	0.87	0.57	0.85	0.79	0.55
Pali Tunnel	4	0.86	0.66	0.52	0.72	0.92	0.24	0.91	0.76	0.57
Kihei North	5	0.82	0.63	0.49	0.55	0.94	0.34	0.90	0.70	0.52
Keawakapu	6	0.81	0.63	0.48	0.53	0.92	0.27	0.56	0.78	0.86
Kanahena Point	7	0.78	0.60	0.18	1.00	0.89	0.17	0.97	0.80	0.20
Ukumehame	8	0.76	0.59	0.55	0.48	0.89	0.20	0.39	0.75	0.90
Keone'ō'io	9	0.76	0.59	0.18	0.48	0.81	0.05	0.97	0.65	1.00
North Kā'anapali	10	0.74	0.57	0.48	0.41	0.96	0.15	0.78	0.83	0.37
Lipoa Point	11	0.71	0.55	0.06	0.78	0.87	0.02	0.73	0.70	0.67
Ulua Beach Park	12	0.69	0.54	0.23	0.51	0.81	0.08	0.70	0.75	0.66
Mahinahina CRAMP	13	0.66	0.51	0.57	0.28	1.00	0.20	0.52	0.80	0.23
Hanaka'ō'ō	14	0.65	0.50	0.58	0.25	0.92	0.25	0.52	0.77	0.23
Olowalu CRAMP	15	0.65	0.50	0.40	0.17	0.82	0.15	0.73	0.73	0.50
Honokōwai	16	0.63	0.49	0.46	0.23	1.00	0.17	0.60	0.75	0.20
Maluaka Point	17	0.56	0.44	0.48	0.43	0.83	0.18	0.00	1.00	0.14
Mā'alaea CRAMP	18	0.56	0.43	0.05	0.43	0.64	0.01	0.88	0.58	0.45
Puamana	19	0.55	0.42	0.04	0.37	0.61	0.01	1.00	0.56	0.38
Olowalu North	20	0.53	0.41	0.05	0.29	0.79	0.02	0.92	0.71	0.09

Table A1.7. Relative classifications for resilience indicator scores are per Table A1.3. The absolute values for each indicator for the deep survey sites corresponding with each relative class (low-high) is shown and color-graded.

	Coral Cover (%)	Coral Diversity	Coral Recruitment (#/m^2)	Reef Builder Ratio	Coral Disease (%)	Rugosity	Herbivorous Fish Biomass (g/m^2)
Low	<11.47	<0.60	<11.80	NA	<0.06	<1.33	<6.58
Medium-Low	>11.47 and < 34.44	>0.60 and <0.69	>11.80 and <22.44	>0 and <1.32	>0.06 and <1.24	>1.33 and <1.52	>6.58 and <15.36
Medium-High	>34.44 and <57.41	>0.69 and <0.78	>22.44 and <33.08	>1.32 and <2.79	>1.24 and <2.41	>1.52 and <1.71	>15.36 and <24.15
High	>57.41	>0.78	>33.08	>2.79	>2.41	>1.71	>24.15

Table A1.8. Absolute values and relative classes (low-high) for each resilience indicator for the deep survey sites.

Site Name	Resilience Rank	Coral Cover (%)	Coral Diversity	Coral Recruitment (#/m^2)	Reef Builder Ratio	Coral Disease (%)	Rugosity	Herbivorous Fish Biomass (g/m^2)
Keālia	1	72.51	0.78	29.33	4.98	0.25	1.70	7.92
Molokini	2	80.09	0.55	7.33	5.25	0.61	1.55	13.34
Kalama Park	3	70.40	0.70	17.33	2.99	0.72	1.59	18.41
Pali Tunnel	4	41.25	0.74	36.00	1.28	0.41	1.54	19.01
Kihei North	5	39.17	0.76	27.33	1.81	0.46	1.41	17.53
Keawakapu	6	38.60	0.74	26.33	1.39	2.07	1.58	28.92
Kanahena Point	7	14.76	0.72	50.00	0.88	0.13	1.62	6.69
Ukumehame	8	43.94	0.72	24.00	1.03	2.88	1.51	30.18
Keone'ō'io	9	14.78	0.66	24.00	0.25	0.16	1.32	33.47
North Kā'anapali	10	38.51	0.78	20.67	0.79	1.02	1.69	12.35
Lipoa Point	11	4.63	0.71	39.00	0.08	1.28	1.42	22.58
Ulua Beach Park	12	18.65	0.66	25.67	0.43	1.44	1.52	22.25
Mahinahina CRAMP	13	45.37	0.81	14.00	1.07	2.25	1.62	7.68
Hanaka'ō'ō	14	46.44	0.75	12.33	1.31	2.27	1.56	7.67
Olowalu CRAMP	15	32.28	0.66	8.33	0.81	1.26	1.48	16.81
Honokōwai	16	37.12	0.81	11.67	0.87	1.89	1.51	6.78
Maluaka Point	17	38.55	0.67	21.33	0.94	4.73	2.02	4.65
Mā'alaea CRAMP	18	4.19	0.52	21.50	0.06	0.57	1.16	15.13
Puamana	19	3.13	0.49	18.33	0.06	0.00	1.14	12.68
Olowalu North	20	4.34	0.64	14.33	0.08	0.37	1.44	3.18

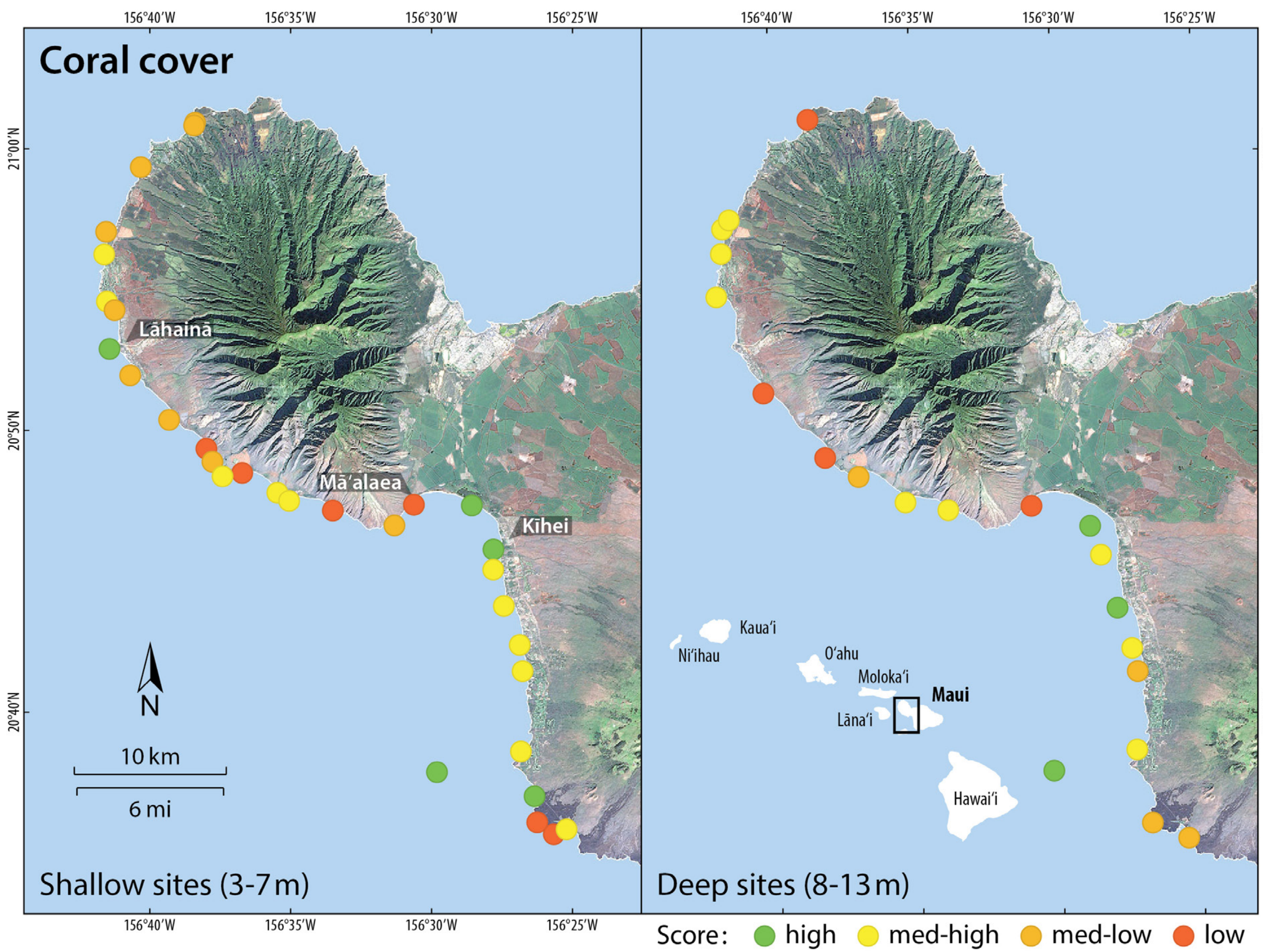

Figure A1.1. Map of relative classes for all survey sites for the resilience indicator 'coral cover'. The range in coral cover that corresponds with each relative class is shown for the shallow reef sites in Table A1.4 and deep reef sites in Table A1.7.

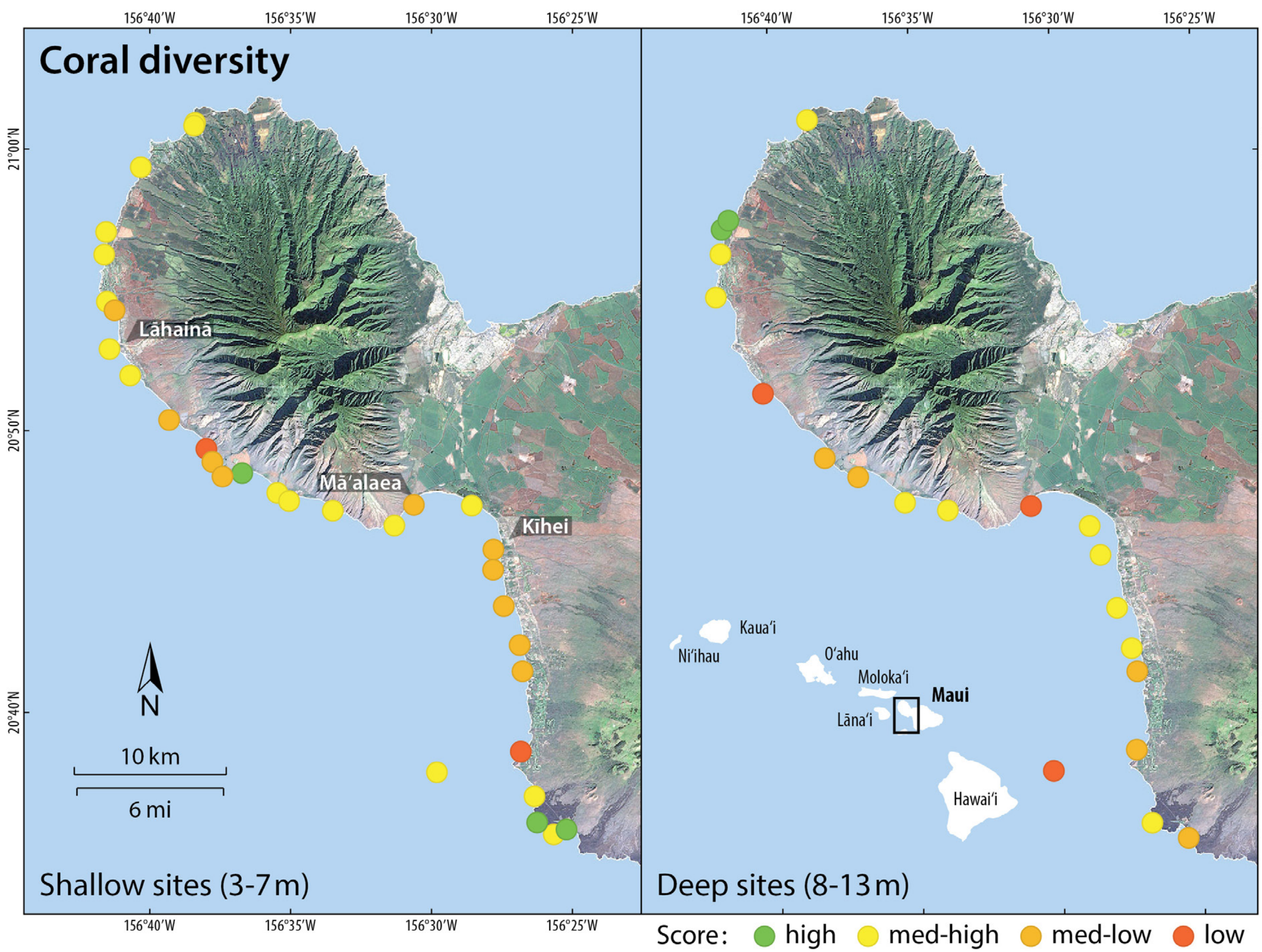

Figure A1.2. Map of relative classes for all survey sites for the resilience indicator 'coral diversity'. The range in coral diversity that corresponds with each relative class is shown for the shallow reef sites in Table A1.4 and deep reef sites in Table A1.7.

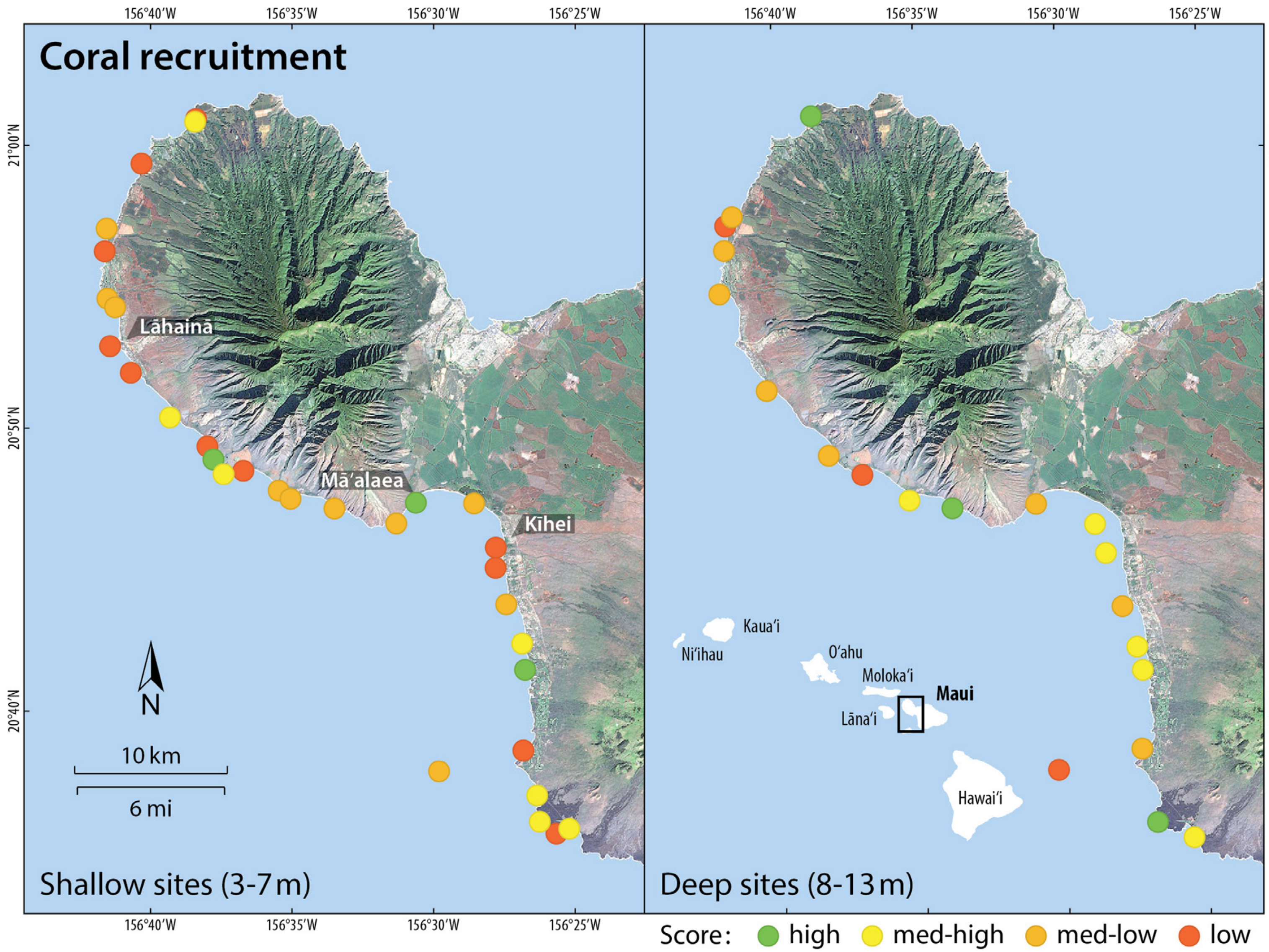

Figure A1.3. Map of relative classes for all survey sites for the resilience indicator 'coral recruitment'. The range in coral recruitment that corresponds with each relative class is shown for the shallow reef sites in Table A1.4 and deep reef sites in Table A1.7.

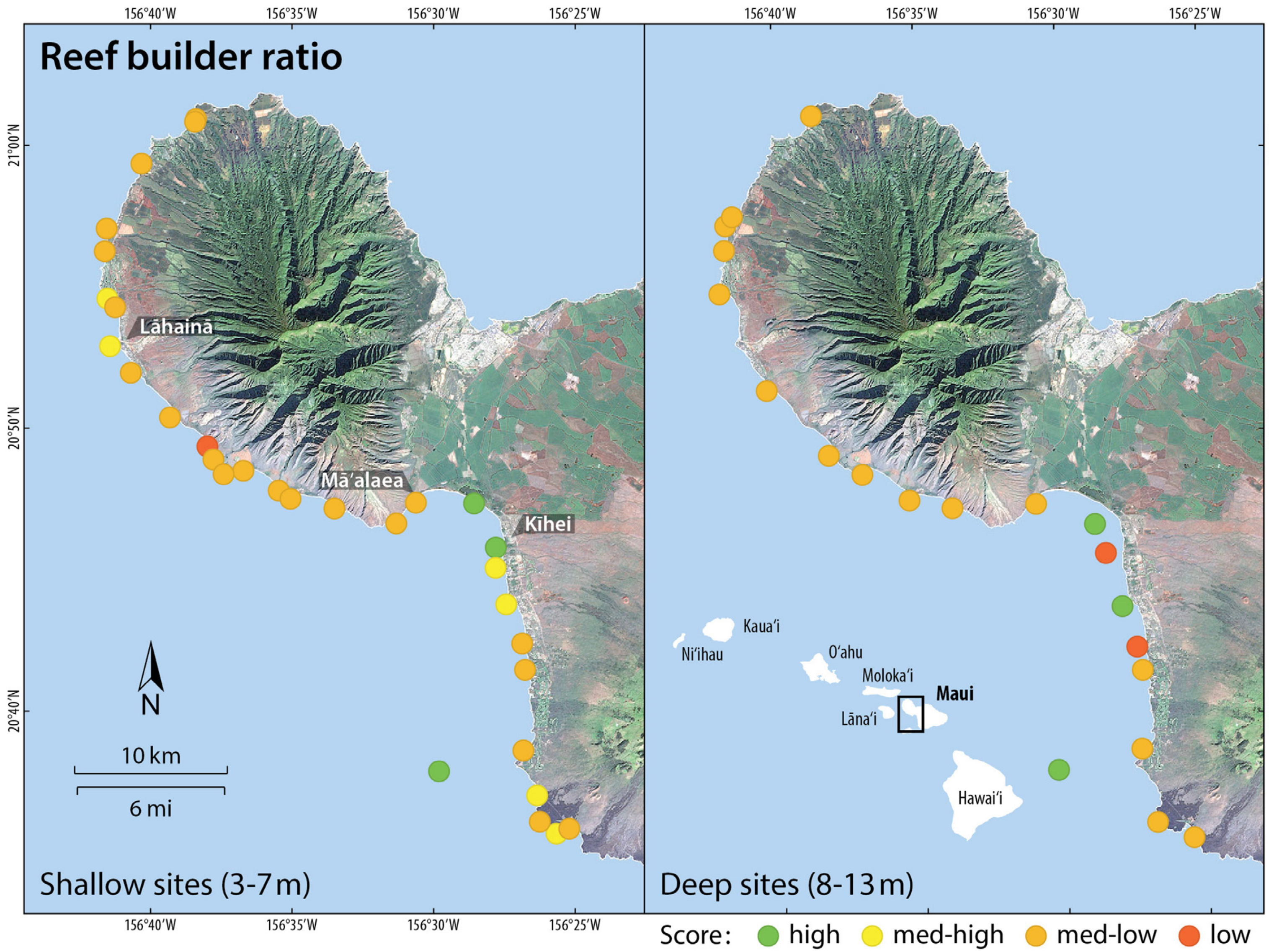

Figure A1.4. Map of relative classes for all survey sites for the resilience indicator 'reef builder ratio'. The range in reef builder ratio that corresponds with each relative class is shown for the shallow reef sites in Table A1.4 and deep reef sites in Table A1.7.

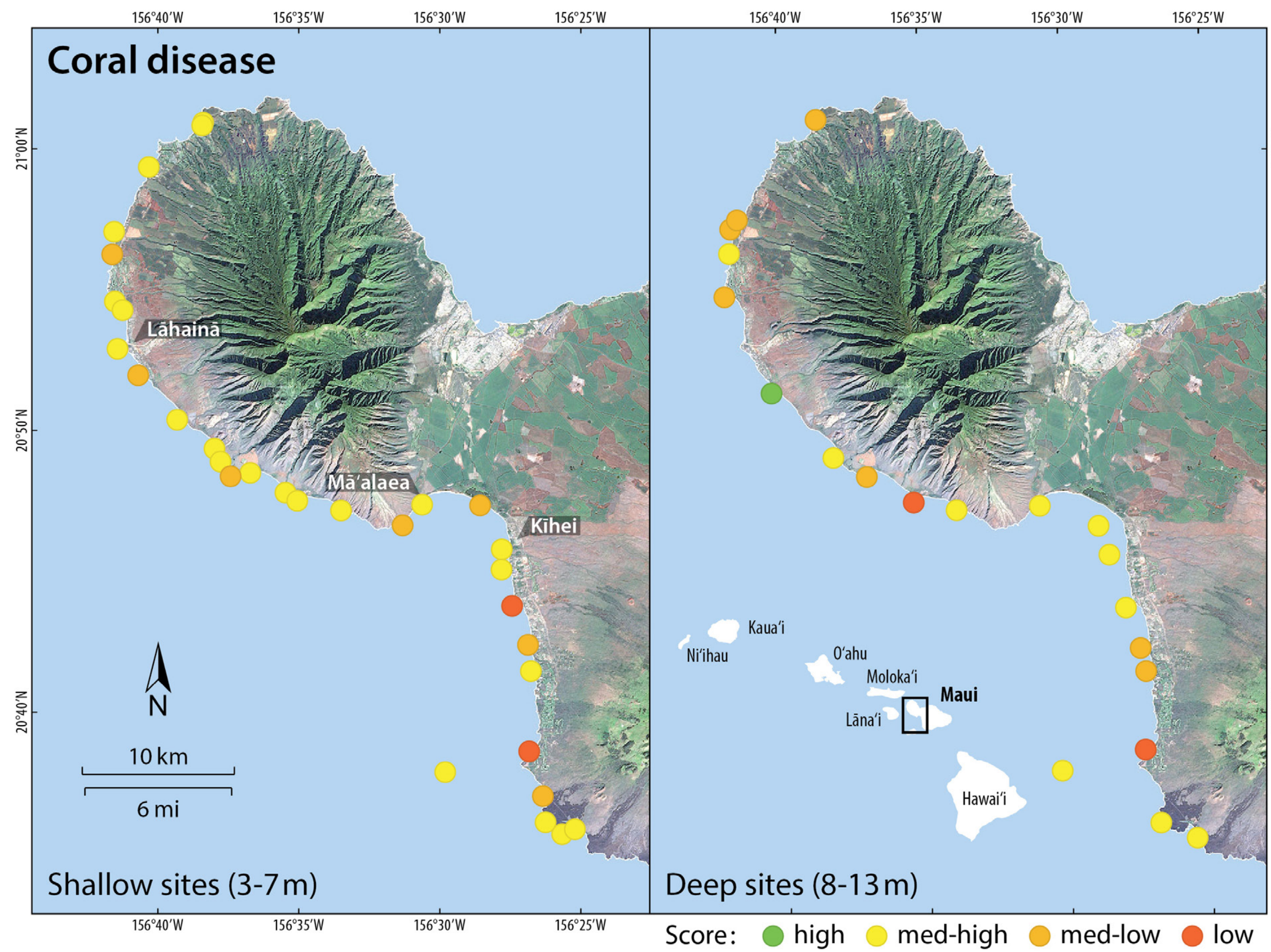

Figure A1.5. Map of relative classes for all survey sites for the resilience indicator 'coral disease'. The range in coral disease that corresponds with each relative class is shown for the shallow reef sites in Table A1.4 and deep reef sites in Table A1.7.

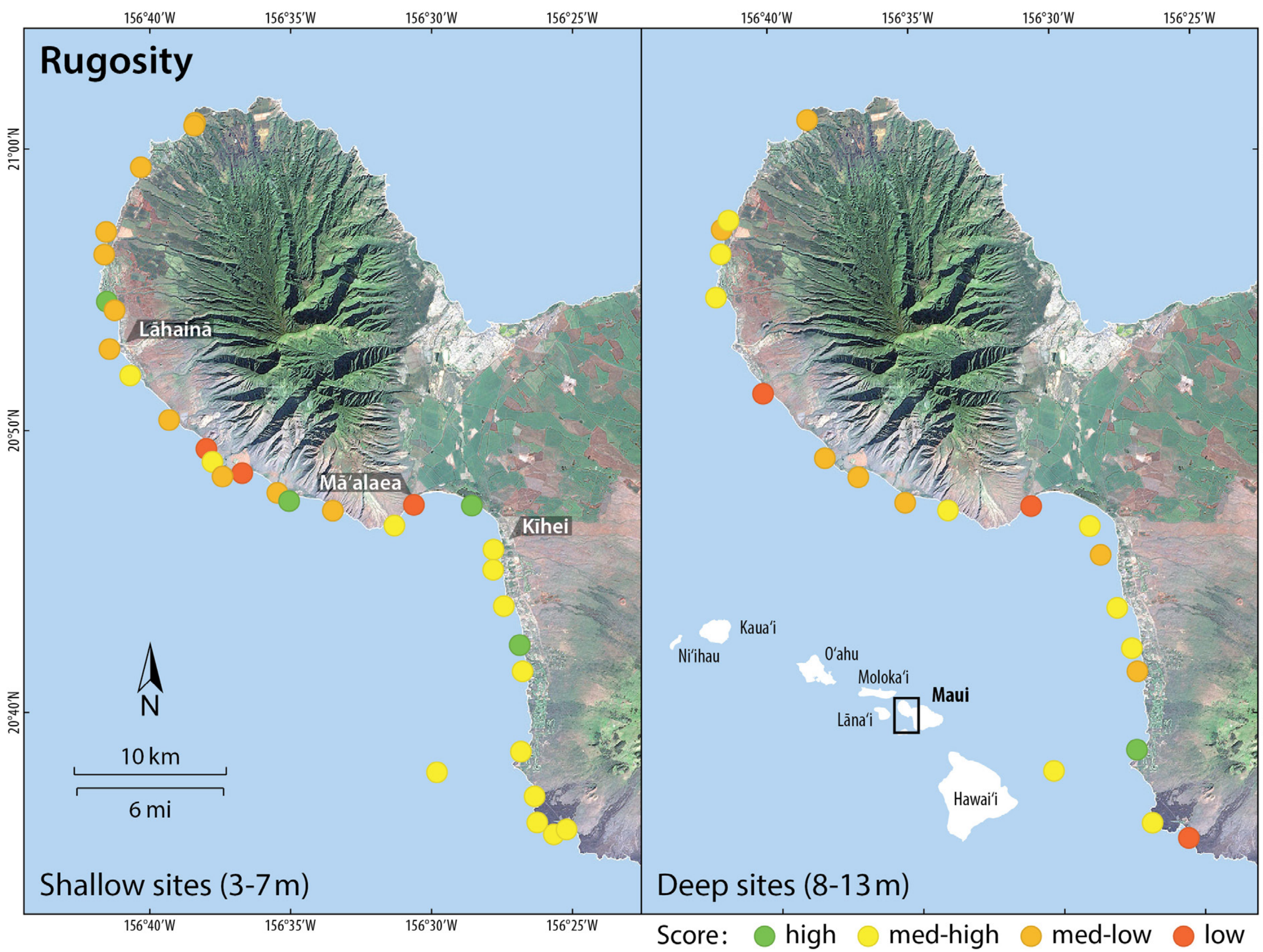

Figure A1.6. Map of relative classes for all survey sites for the resilience indicator 'rugosity'. The range in rugosity that corresponds with each relative class is shown for the shallow reef sites in Table A1.4 and deep reef sites in Table A1.7.

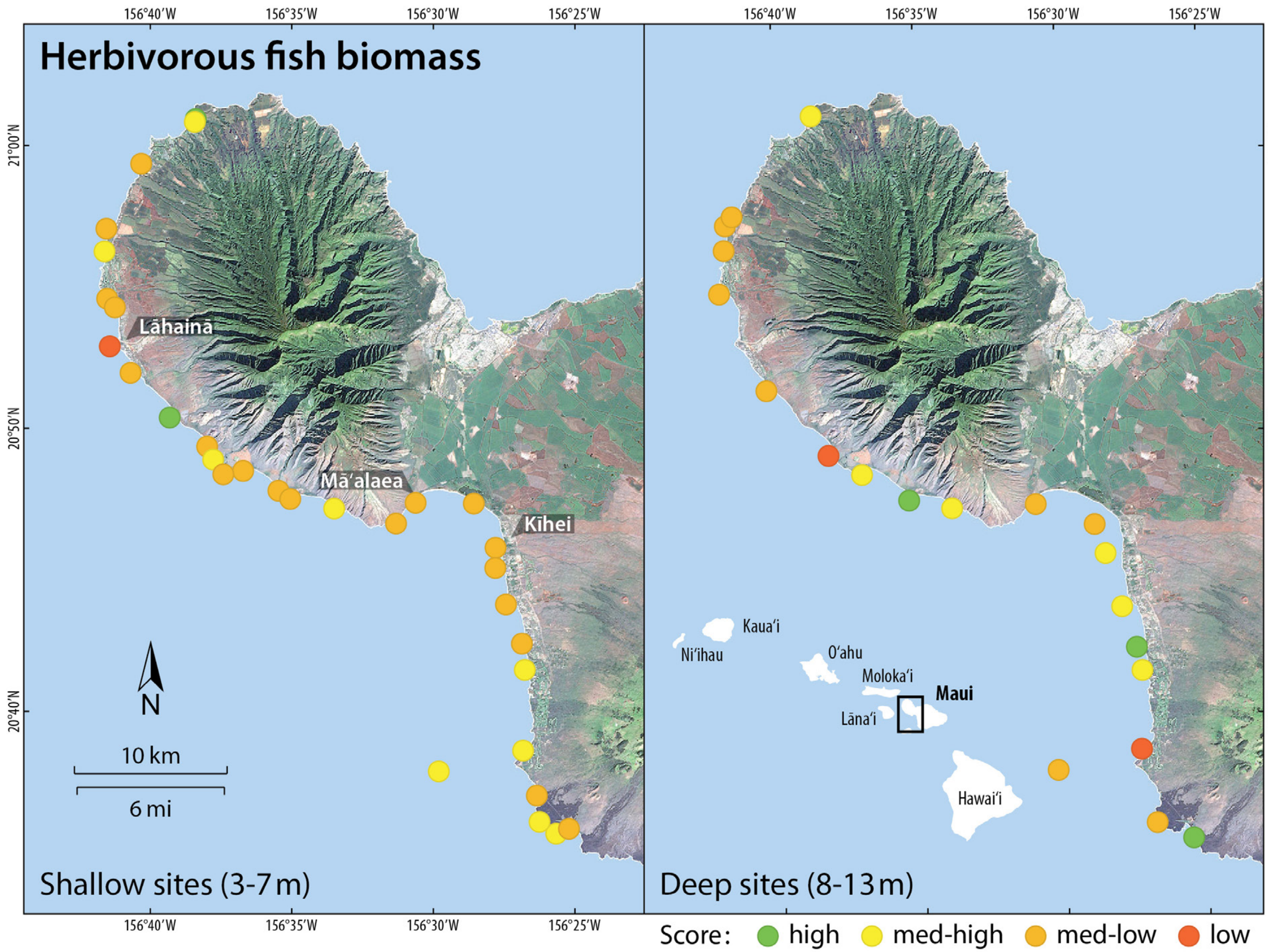

Figure A1.7. Map of relative classes for all survey sites for the resilience indicator 'herbivorous fish biomass'. The range in herbivorous fish biomass that corresponds with each relative class is shown for the shallow reef sites in Table A1.4 and deep reef sites in Table A1.7.