USING ARCMAPS TO SELECT SITES FOR CLIMATE-RESILIENT CORAL RESTORATION IN MANALUA BAY, HAWAI‘I

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Abstract

Coral reefs have been identified as a potential natural solution for reducing the risks of climate-related coastal flooding and erosion. Healthy coral reef ecosystems serve as the first line of coastal defense by providing protection from wave energy, flooding, and damage from storms, all of which have increased due to climate change. Coral reefs also offer ecosystem services by supporting marine life and economies, and are able to self-recover after disturbance. This research used environmental data to conduct weighted and non-weighted site selection analyses in ArcMaps to identify the most suitable sites for a climate-resilient coral reef restoration project. In this project, called Restore with Resilience, 4,000 climate-resilient coral nubbins are to be planted in Maunalua Bay, Hawaiʻi. Results indicate that there are several suitable regions for coral restoration in Maunalua Bay. Restoration of corals with thermal resilience in Maunalua Bay is expected to enhance coral cover in the bay for the benefit of biodiversity, local stakeholders, and coastal resilience.

Contents

Introduction

Coastal regions are home to nearly 40% of the world's population (Ferrario et al., 2014) and most of the world's megacities (Neumann et al., 2015). Coasts are particularly vulnerable to the impacts of climate change, including flood disasters from sea level rise and increasing storm intensity (Temmerman et al., 2013). Coral reefs have been identified as a potential natural solution for reducing the risks of climate-related coastal flooding and erosion (Sutton-Grier et al., 2015). Healthy coral reef ecosystems serve as the first line of coastal defense by providing protection from wave energy, flooding, and damage from storms (Beck et al., 2018).

The conventional response to flood risks is to build dikes, embankments, and seawalls. Such built infrastructure is significantly more expensive (Ferrario et al., 2014) and oftentimes, less effective in avoiding flooding damages in coastal zones compared to conserving and restoring coastal ecosystems such as coral reefs (Sutton-Grier, et al., 2018). By dissipating up to 97% of wave energy, coral reefs can significantly reduce coastal erosion and flooding (Ferrario et al., 2014). Coral reefs are able to self-recover after disturbance (Sutton-Grier et al., 2015) and have fewer negative consequences than built infrastructure. For example, seawalls are known to accelerate shoreline erosion and destroy beaches (Fletcher, 2017).

A study projecting the coastal hazards of the island of Maui found that the presence of coral reefs reduced wave-driven high-water levels and the inland extent of flooding (Storlazzi et al., 2017), suggesting that conserving coral reef ecosystems is critical for coastal protection. A report on sea level rise and climate vulnerability in Hawai‘i predicts that climate change could lead to events of 5 feet of passive flooding in low-lying areas that are hydrologically connected to the ocean in Maunalua Bay (Hawai‘i Climate Change Mitigation and Adaptation Commission, 2017). Restoring the reefs of Maunalua Bay could enhance coastal resilience in the face of climate change.

Traditional Hawaiian wisdom considers corals to be an *akua*, a deity, symbolizing the beginning of life (Gregg et al., 2015). Our modern understanding is quite similar; coral reefs play an integral role in supporting marine biodiversity. Occurring in less than 1 percent of the ocean, they provide habitat for almost twenty-five percent of all fish species (National Oceanic and Atmospheric Administration, 2020). Coral reefs also provide livelihoods to coastal communities by supporting fishing and recreational tourism economies. Each year, they contribute an estimated $360 million to the Hawaiian economy (Cesar et al., 2004), $3.4 billion to the US economy (Brander, et al., 2013), and between $25 and $30 billion to the global economy (Samonte-Tan, 2008).

Corals are especially vulnerable to the effects of climate change. Warming ocean temperatures and ocean acidification threaten reef biodiversity and trigger coral bleaching events (Hughes et al., 2017). By 2050, it is predicted that 98% of the world's reefs will sustain annual bleaching (Heron et al., 2016). Mortality associated with bleaching events can negatively impact ecosystem function, leading to loss of coral cover and shifts in community structure. Since the 1980s, mass coral bleaching events have increased in frequency and severity, including unprecedented coral bleaching events in the Hawaiian Islands (Couch et al., 2017). Studies comparing mortality rates in coral communities in Hawaiʻi and elsewhere in the Indo-Pacific during bleaching events suggest that there has been some level of acclimatization and improved resilience to heat stress (Couch et al., 2017; Coles et al., 2018).

In response to the ecosystem services offered by corals, concerns about the fate of coral reefs under climate change, and the demonstrated ability for some corals to acclimatize to shifts in ocean temperatures and chemistry, researchers in the Gates Coral Lab at the Hawaiʻi Institute of Marine Biology (HIMB) are pioneering a human-assisted evolution approach to coral conservation. Assisted-evolution is intended to allow corals to adapt to climate change conditions at a pace that aligns more closely with the current climate change trajectories (van Oppen et al., 2015).

HIMB is partnering with Mālama Maunalua, the National Oceanic and Atmospheric Administration (NOAA), and the State of Hawaiʻi's Division of Aquatic Resources (DAR) to implement the Restore with Resilience program and outplant thermally resilient corals in three pilot locations around the Island of Oʻahu: Maunalua Bay, Kāneʻohe Bay, and on the South Shore near the Daniel K. Inouye International Airport (Restore with Resilience, 2019). The Restore with Resilience project aims to restore coral reefs through the selective propagation of stress-resistant coral stocks to enhance biodiversity, benefit local stakeholders, and improve coastal protection (Restore with Resilience, 2019). Mālama Maunalua, a non-profit based in East Honolulu, Hawaiʻi, is the lead partner for the Maunalua Bay restoration efforts.

Coral reef restoration in Maunalua Bay is scheduled to begin in mid-2021. It will utilize corals of opportunity, which include fragments of reefs that have broken off due to natural or human-caused disturbances (NOAA, 2016). These corals of opportunity will be collected in Maunalua Bay and placed on a centrally located underwater nursery platform that will serve as a transition station. Sections of the corals of opportunity will be brought to the HIMB lab, where their resilience to climate change conditions will be tested. The most resilient corals will be identified and with the help of community volunteers, brought from the nursery platform to shore, and fragmented into 4,000 "nubbins", which are small pieces of coral. Those nubbins will be brought back again to the nursery platform to re-acclimate before being out-planted in the restoration sites in Maunalua Bay.

The success of climate-resilient coral restoration is dependent on the locations in which the corals are re-planted. As previously explained, corals are sensitive to environmental conditions, and restoration sites must be suitable across various criteria. This paper explores the site selection process through which abiotic and biotic parameters necessary for coral survival were identified and scored to develop a weighted site-selection analysis in ArcMaps. This analysis has identified the top ten restoration sites in Maunalua Bay where restored corals have the highest chances of survival.

Methods

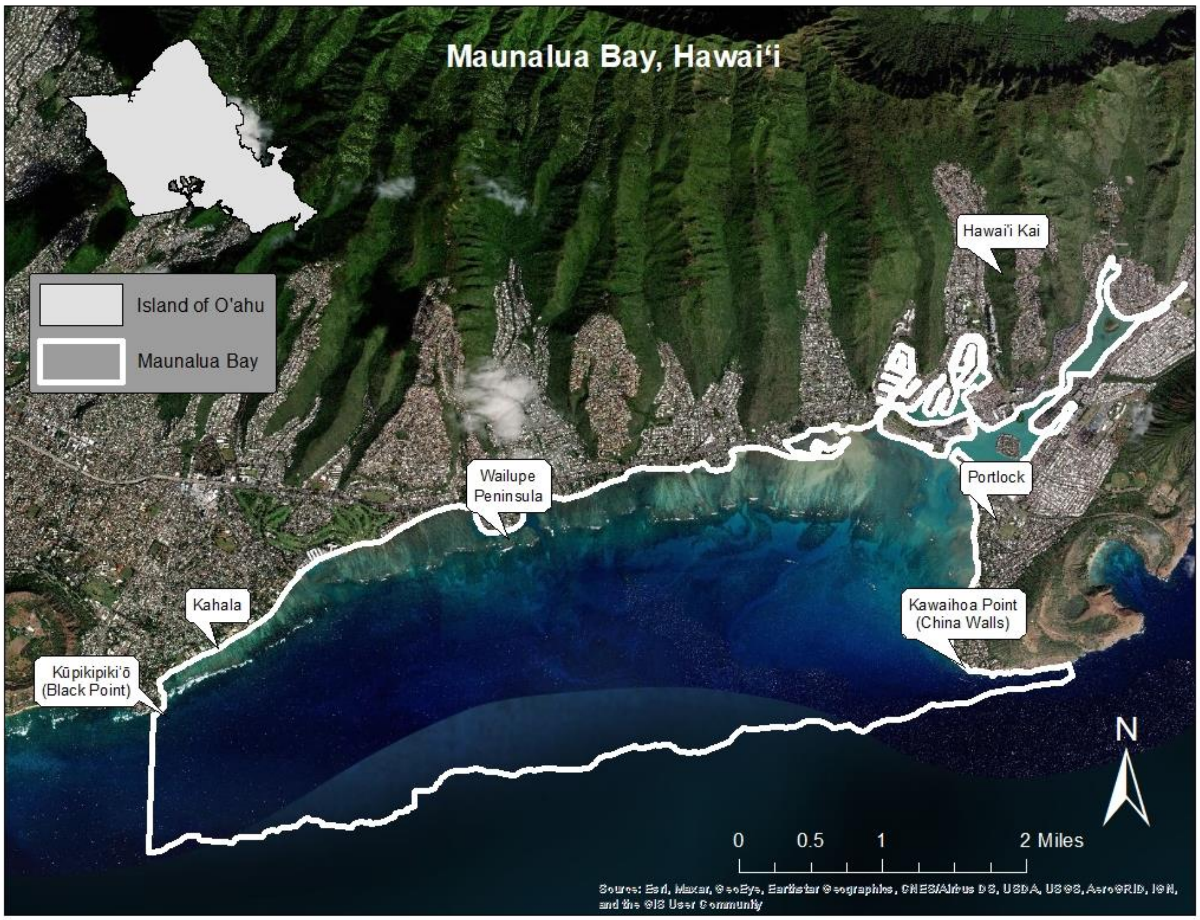
Study Area

The study area of Maunalua Bay is defined as the area between the eastern side of Kūpikipikiʻō (Black Point) to Kawaihoa Point (China Walls), with a northern boundary of the Oʻahu coastline and a southern boundary of the 40-meter depth bathymetry line (Figure 1). Maunalua Bay is approximately eight miles long and 28 square miles in area (Atkinson, 2007). Prior to the 1960s, the region was largely undeveloped with human use centered around fisheries. Seasonal wetlands and human-made fishponds lined the coastline (Wolanski et al., 2009). Surveys of the reef flat from the 1920s describe patchy coral cover averaging 3% across the bay, with up to 50% in some sites in the western most part of the bay (Pollock, 1928). Observations in 2008 demonstrated that most of the historic reef patches had died and coral cover across the bay had decreased with coral cover ranging from approximately 5% over most of the reef slope and a maximum of 19% cover at several locations in the bay (Wolanski et al., 2009).

The urbanization of Maunalua Bay began in the 1960s, starting with the dredging of two navigation channels in the bay, followed by extensive commercial and residential development

(Wolanski et al., 2009). Nearly 50,000 people reside in East Honolulu surrounding Maunalua Bay (U.S. Census Bureau, 2010). The extreme urbanization has led to increases in nonpoint source pollution and non-native species introductions most notably of macroalgae, which have impacted the ecological health of the bay and the associated ecosystem services provided by coral reefs (Atkinson, 2007).

Figure 1: Maunalua Bay, Hawai'i. The white line depicts the border of the study area. The southern border of the map is defined by the 35-meter depth contour line.



Data Collection and Preparation

To determine the most suitable locations for climate-resilient coral restoration in Maunalua Bay, available data on the historic and present conditions of the bay were compiled and formatted in Esri's ArcMap software, version 10.8.1 (ESRI, 2020). Available parameters fell into six data categories: water chemistry, other water quality measures, benthic conditions, coral cover, habitat health, and accessibility (Table 1). Coral experts[1] and the academic literature were consulted to identify the ideal range for coral restoration of each of the parameters included in the site selection analysis.

Data was prepared for analysis in ArcMaps by converting vector data to raster. In raster format, each pixel can be assigned an integer value based on what that pixel—a specific location on the grid, or map—contains (i.e. benthic cover or depth, depending on the layer). Field data with sample points were interpolated using the Inverse-distance Weighted (IDW) Interpolation tool in the Spatial Analyst toolbox of ArcToolbox. Interpolation creates a new raster grid in which each pixel is assigned an integer value that is computed by averaging the values of the nearby sample points (Tomlin, 2000). Interpolation helps understand the circumstances of areas in which data points are not available. However, it is important to note that interpolation is useful but imperfect due to nature of making spatial inferences using available data.

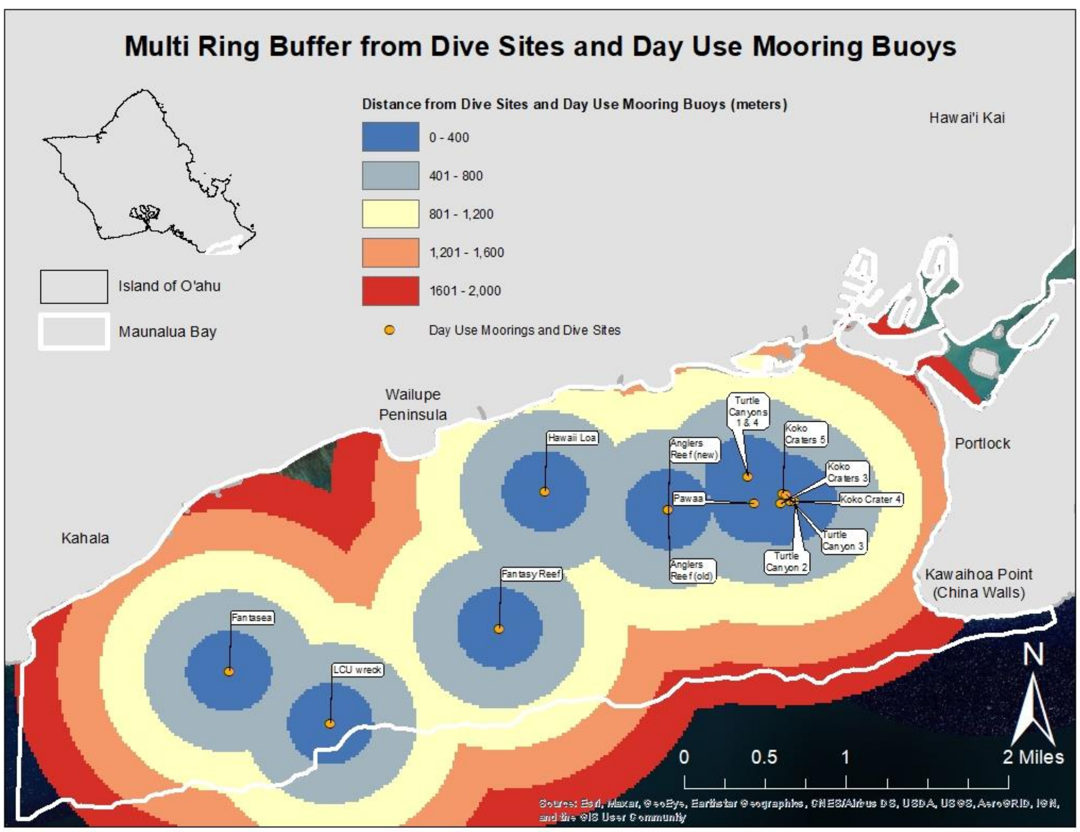
[1] Carlo Caruso, Crawford Drury, and Kira Hughes (Gates Coral Lab, HIMB); Chip Fletcher (University of Hawai‘i at Manoa); Alan Friedlander (University of Hawai‘i at Manoa); Bob Richmond (University of Hawai‘i at Manoa); Claire Lewis (University of Hawai‘i at Manoa); Megan Donahue (University of Hawai‘i at Manoa); Gator Halpern (Coral Vita); Eric Conklin (The Nature Conservancy of Hawai‘i); Kim Falinski (The Nature Conservancy of Hawai‘i); Flo La Valle and Katie Lubarsky (Scripps Institution of Oceanography); Paula Moehlenkamp (University of Hawai‘i at Manoa)

Table 1: Data categories, parameters, and sources for the site selection analysis.

Data Category	Parameter	Source
Water Chemistry	Temperature (°C)	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
	Dissolved oxygen (percent)	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
	Turbidity (NTU)	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
	pH	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
	Salinity (psu)	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
	Natural log of nitrate plus nitrite (ug/L)	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
	Total phosphorus (ug/L)	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
	Chlorophyll a (ug/L)	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
Other Water Quality Measures	Proximity to know high energy areas (meters)	Mālama Maunalua, 2017; Storlazzi et al., 2010
	Proximity to submarine groundwater discharge (SGD) sites (meters)	Lubarsky et al., 2018; Richardson et al., 2015
	Proximity to non-point source pollutants (meters)	Mālama Maunalua, 2017
Benthic Conditions	Depth	Mālama Maunalua, 2017; Donovan et al., 2018; Storlazzi et al. 2010; Presto et al. 2012; University of Hawai‘i and NOAA, 2014; University of Hawai‘i at Mānoa and The Nature Conservancy, 2020; The Nature Conservancy, 2012
	Benthic cover (predictive)	NOAA National Centers for Coastal Ocean Science (NCCOS), 2007
Coral Cover	Coral cover (predictive)	Franklin et al., 2013
	Existing coral cover (percent)	Friedlander, 2008; Donovan et al., 2018; University of Hawai‘i and NOAA, 2014; University of Hawai‘i at Mānoa and The Nature Conservancy, 2020; The Nature Conservancy, 2012 *(see CoralNet analysis box)**
	Coral cover (historic)	AECOS, Inc., 1979; NOAA, 1990
Habitat Health	Presence of Invasive Alien Algae (IAA)	DAR, 2016
	Herbivorous fish biomass	Donovan, et al., 2018, Friedlander et al., 2010, The Nature Conservancy, 2014
Accessibility	Distance from nursery platform (meters)	Mālama Maunalua, 2020
	Distance from Dive Sites / Day Mooring Buoys (meters)	Mālama Maunalua, 2017; University of Hawai‘i and NOAA, 2014
	Distance from public beach access points (meters)	Mālama Maunalua, 2017
	Proximity to wave breaks	ArcMap World Imagery Basemap

Layers that measure the proximity to certain features, such as the layers in the accessibility category, were prepared using the Multi Ring Buffer tool within the Analysis Tools toolbox of ArcToolbox. The Multi Ring Buffer tool allows one to create multiple zones within specified distances away from the input shapefile point. For example, the Multi Ring Buffer tool was used to create a series of 400-meter bands measuring the distance from dive sites and day use mooring buoys (Figure 2). Then, the Feature to Raster tool was used to convert the Multi Ring Buffer output from vector to raster format. Using the Reclassify tool within the Spatial Analyst toolbox in ArcToolbox, those bands measuring the distances were scored from one to five with scores of five for the zone closest to the dive sites and day use mooring buoys, and scores of one for the zones furthest away.

Figure 2: 400-meter bands buffered out from dive sites and day use mooring buoys using the Multi Ring Buffer tool. This is an example of how the layers measuring proximity to features were treated in the analysis.



The remaining layers that did not need to be interpolated or buffered were converted from vector to raster using the Feature to Raster, Point to Raster, and Polygon to Raster tools, which are all found in the Conversion Tools toolbox of ArcToolbox. Details for each data layer are described in Tables 1A through 6A in the Appendix.

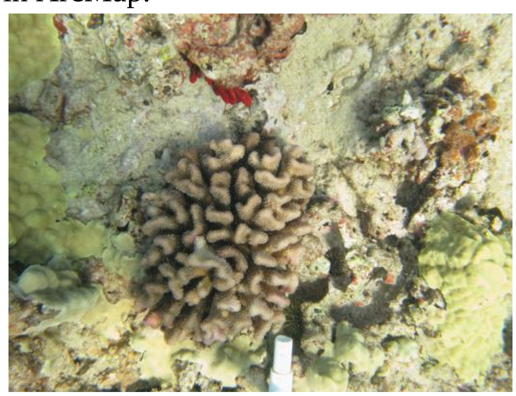
Data Analysis

Each layer was then scored to prepare for the weighted site selection analysis. For each parameter, data values were classified using the Reclassify tool within the Spatial Analyst toolbox in ArcToolbox to break the entire range of values into five levels, using Natural Breaks (Jenks), Quantile, and Manual classification, depending on the layer.

Value levels of each parameter were scored with one representing poor conditions for coral restoration and five representing ideal conditions (Figure 3). Color symbology was streamlined so that in each map, the color red represents scores of one, orange represents scores of two, yellow represents scores of three, light blue represents scores of four, and dark blue represents scores of five. Scores of one represent conditions that are not preferable for coral restoration and scores of five represent conditions that are preferable.

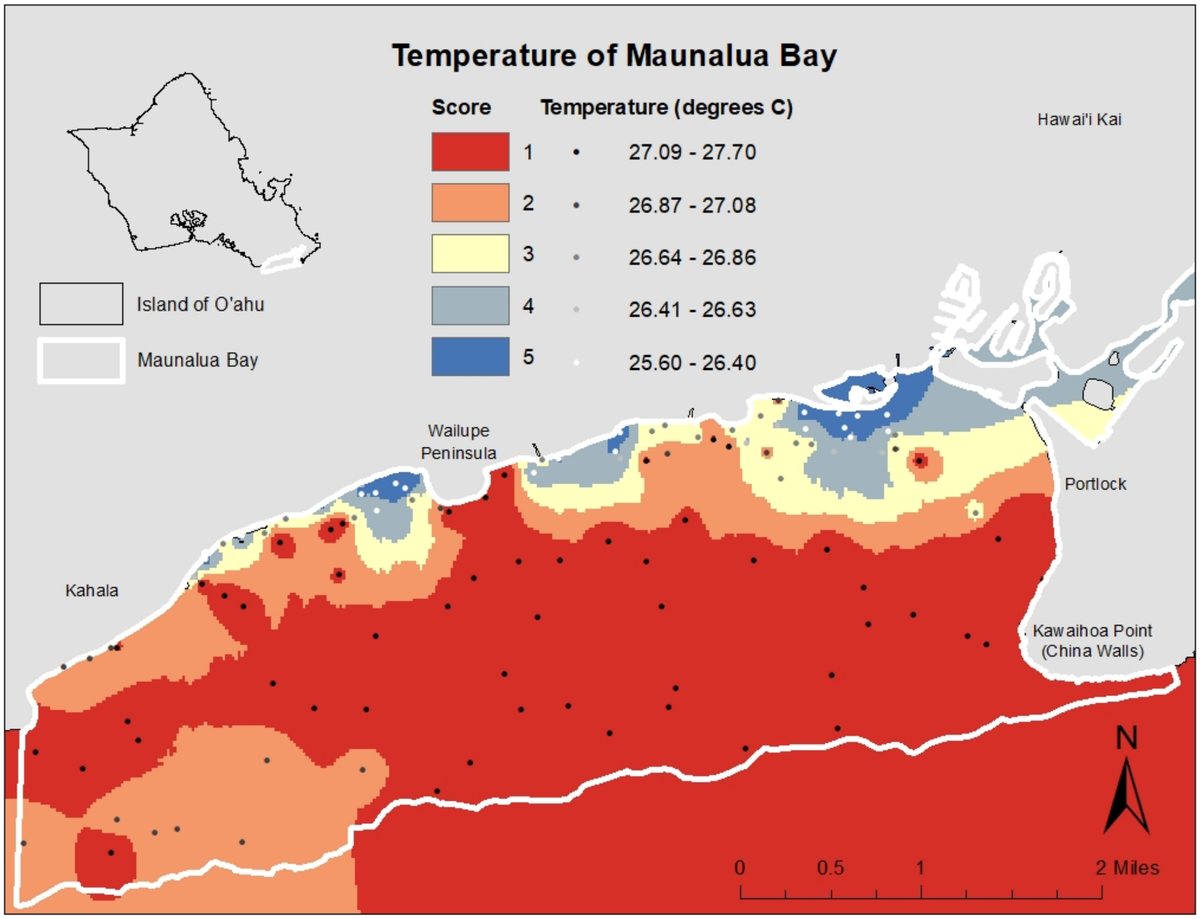
CoralNet Analysis:

A photo dataset containing benthic photos taken in 2012 along transects at sample points in Maunalua Bay was shared by Eric Conklin of The Nature Conservancy of Hawaiʻi. To prepare the data, Excel was used to randomly select 5 photos titles from each site. In CoralNet (coralnet.ucsd.edu), an open-source resource for benthic image analysis (CoralNet, 2020), 30 points for each photo were randomly assigned. Each point was manually identified as being coral, sand, silt, pavement, rock, crustose coralline algae, unknown macroalgae, and unknown. CoralNet calculated percent cover for each photo. Percent coral cover for each of the 5 photos per site was averaged and the data were converted to shapefile points in ArcMap.



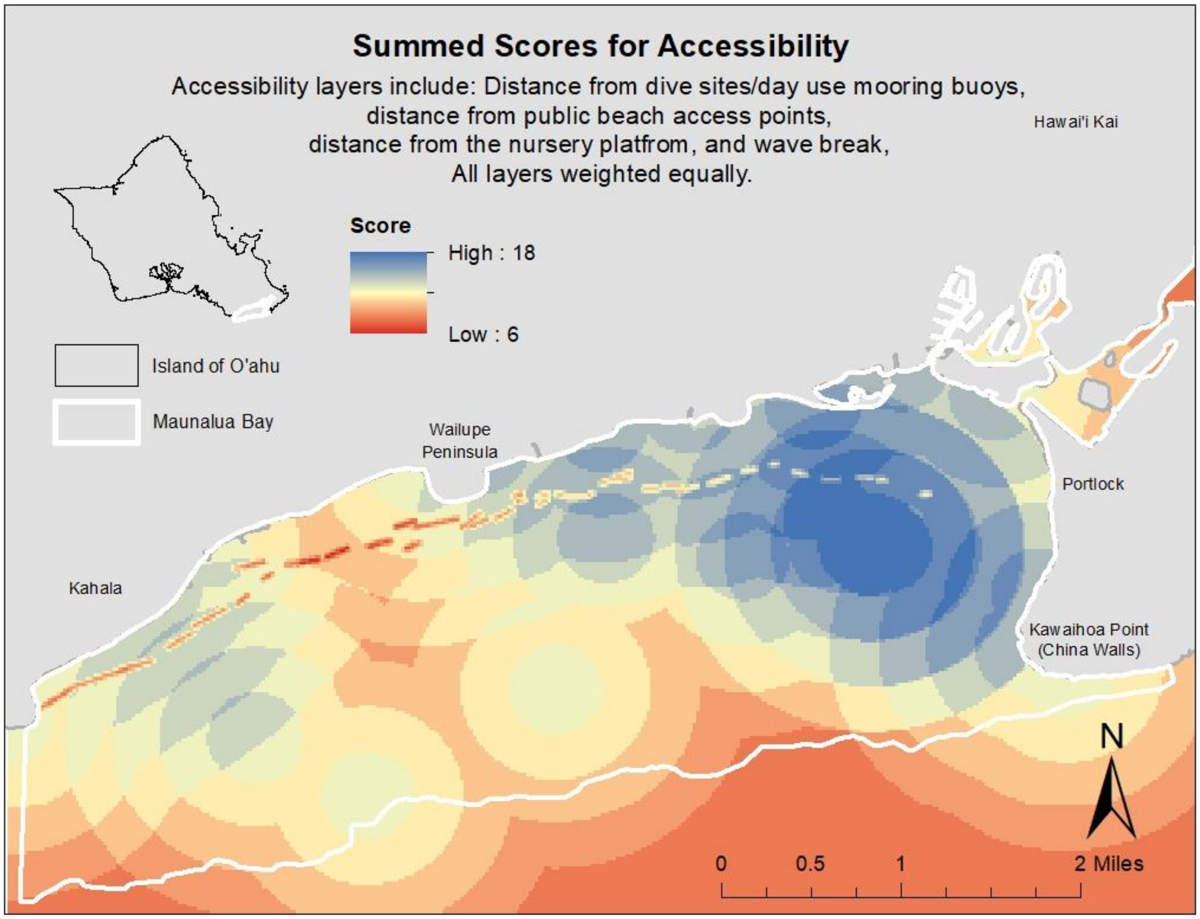
Benthic photo by Eric Conklin, The Nature Conservancy, Hawaiʻi.

Figure 3: Map of scored interpolated temperature data for Maunalua Bay. This is an example of how each data layer is treated.



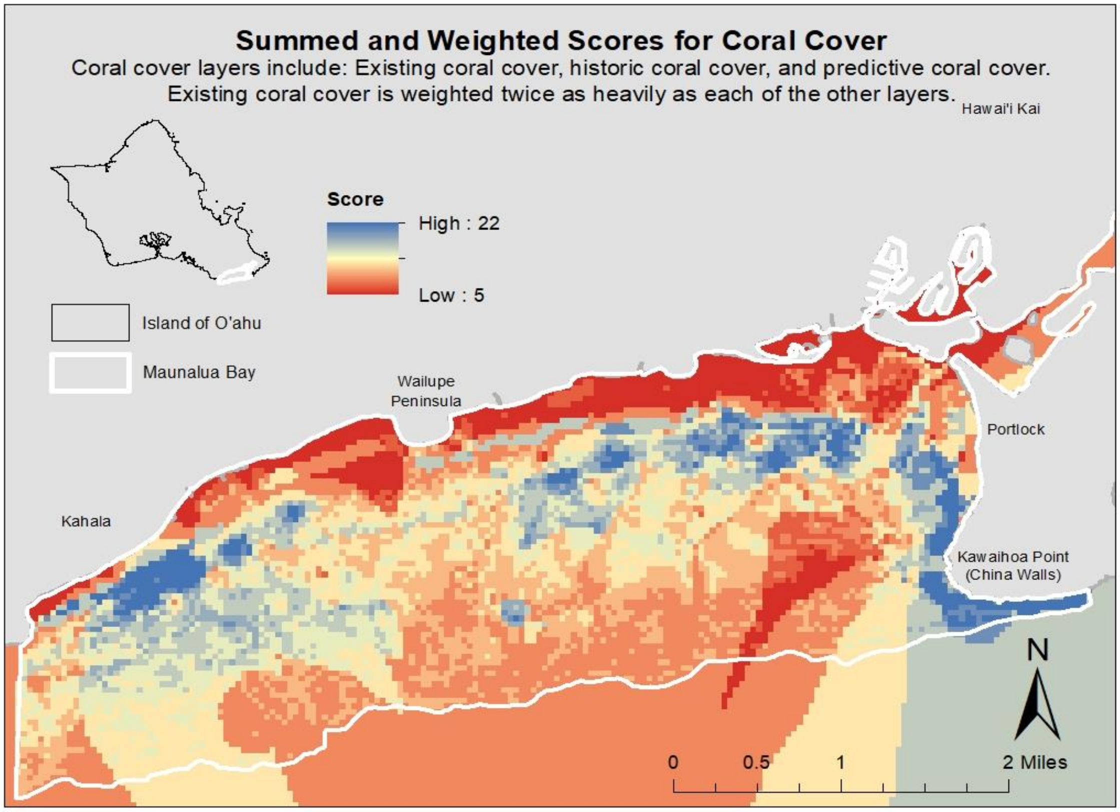
Scored layers were generated for each data layer within each category. Using the Raster Calculator tool within the Spatial Analyst Tools toolbox in ArcToolbox, scored layers within each data category were summed to derive a total score for each data category. This created un-weighted summary score layers, in which each scored layer carries the same weight in the score.

Figure 4: Map of the summed scores for the accessibility category. Similar summed maps were created using Raster Calculator for each data category as referenced in Tables 1.



To account for the importance of coral cover, hard substrate, and accessibility for coral restoration, additional scored layers in which those layers are weighted were created with Raster Calculator. By using a multiplication factor of two and summing the layers, weighted summary score layers were created (Figure 5). The layers containing the scores for current coral cover, benthic cover with hard substrate, and the accessibility layer with the locations of the wave breaks were deemed the most important criteria in discussions with the HIMB team and were weighted. Site size was also highlighted as a criterion for site selection, with each site having a minimum size requirement of 135 square meters. Each raster pixel is over 3,000 square meters in size, already meeting the criteria.

Figure 5: The summed and weighted layer for coral cover, in which existing coral cover is weighted twice as heavily as the other coral cover layers.



All summed category layers were combined using Raster Calculator. The output of the Raster Calculator tool were four maps (Figures 6-9). Two maps show the summed scores of all the unweighted layers, one with deep water preference and the other with shallow water preference. The other two maps show the summed scores of the weighted layers, also separated by depth preference. The split between nearshore and offshore sites is to provide a range of depths for the purpose of HIMB's research and to also ensure that community engagement in the restoration efforts and monitoring is possible. Community volunteers of Mālama Maunalua will be able to access the nearshore sites by walking, swimming, or paddling from public access points on the shore, surfers will be able to observe restoration sites just off the reef crest, and commercial dive operators will be able to monitor the restoration sites near day use mooring buoys and dive sites.

Figure 6: Scores of summed layers. All layers were weighted equally. This map uses the depth layer that favors depths of less than 10 meters.

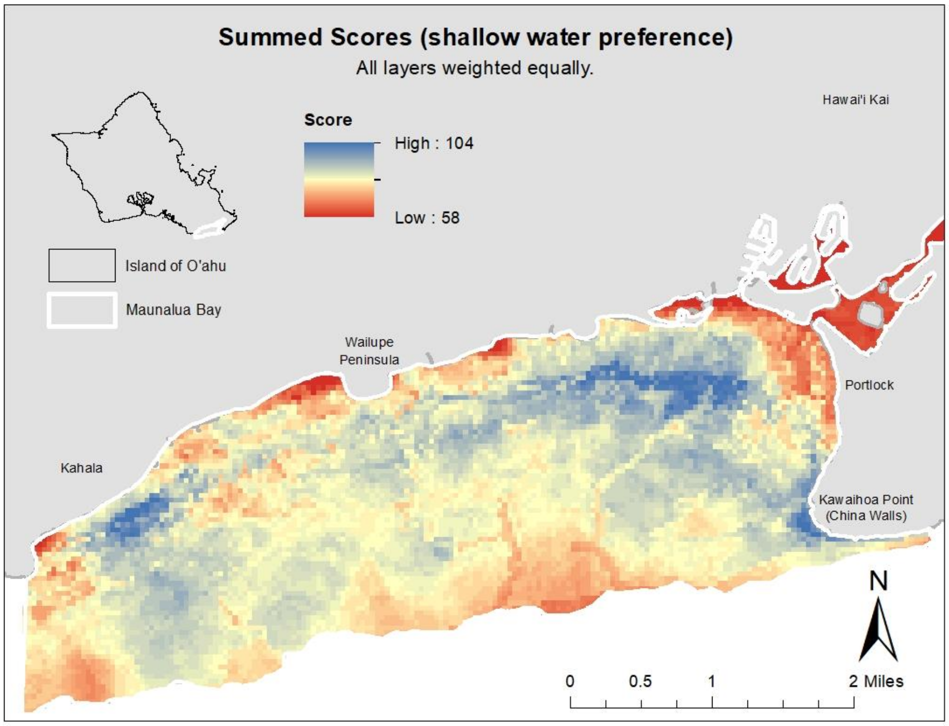


Figure 7: Scores of summed layers. All layers were weighted equally. This map uses the depth layer that favors depths of 10 meters and deeper.

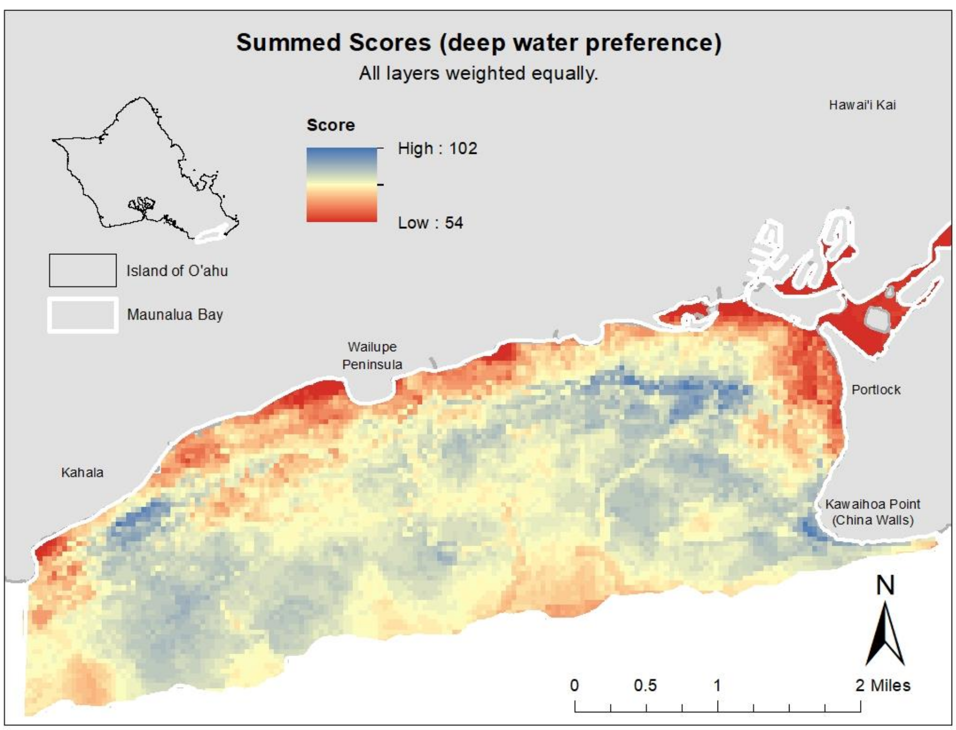


Figure 8: Scores of summed and weighted layers. Layers containing scores for existing coral cover, hard substrate, and the wave break weighted twice as heavily as all other layers. This map uses the depth layer that favors depths of less than 10 meters.

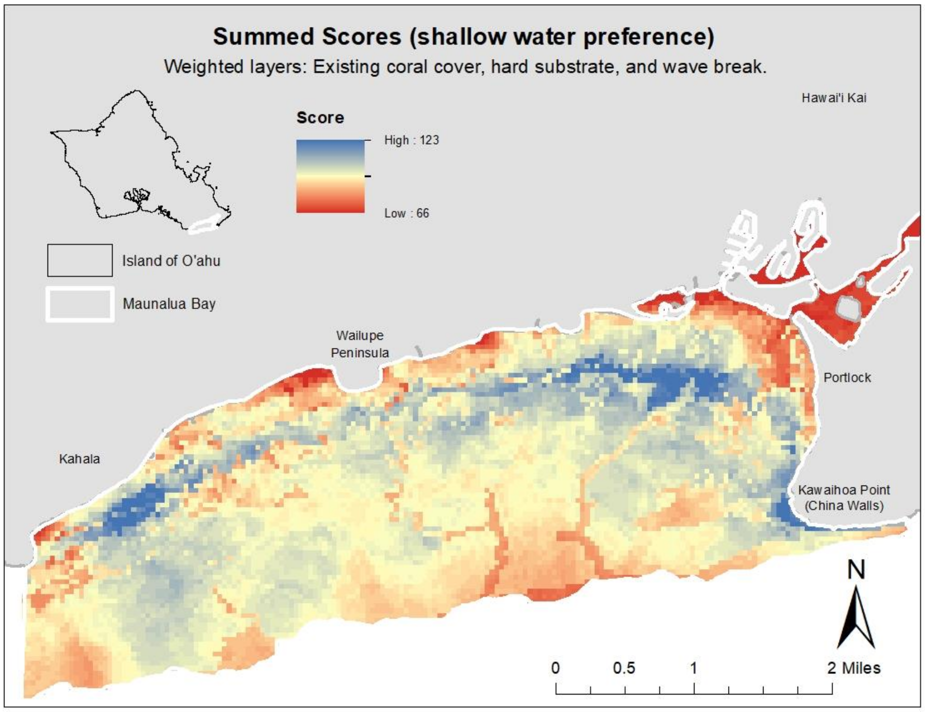
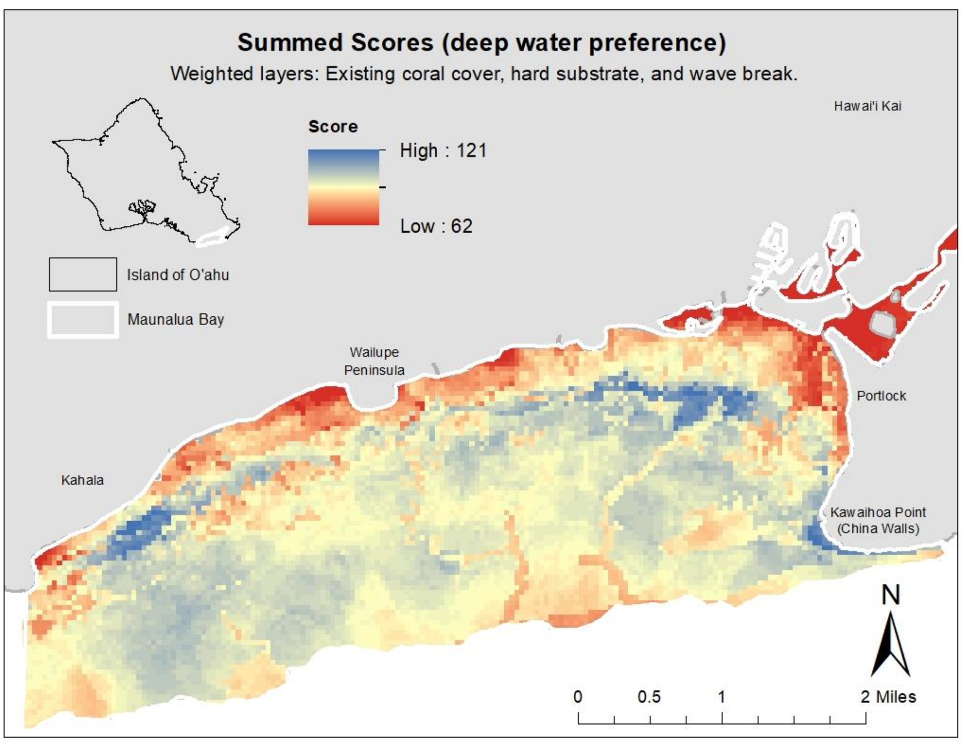


Figure 9: Scores of summed and weighted layers. Layers containing scores for existing coral cover, hard substrate, and the wave break weighted twice as heavily as all other layers. This map uses the depth layer that favors depths of 10 meters and deeper.



Finally, the Reclassify tool was used to classify the summed scores using the Equal Interval classification to generate a final scored map with ten classes total. Ten classes were used to more accurately display the pixels with the highest scores. (Figures 10-13).

Figure 10: The final scored map for site suitability for climate-resilient coral restoration in Maunalua Bay. Scores of ten, in bright blue, indicate the most suitable sites for restoration and scores of one, in red, indicate the least suitable locations. All layers were weighted equally. This map uses the depth layer that favors depths less than 10 meters.

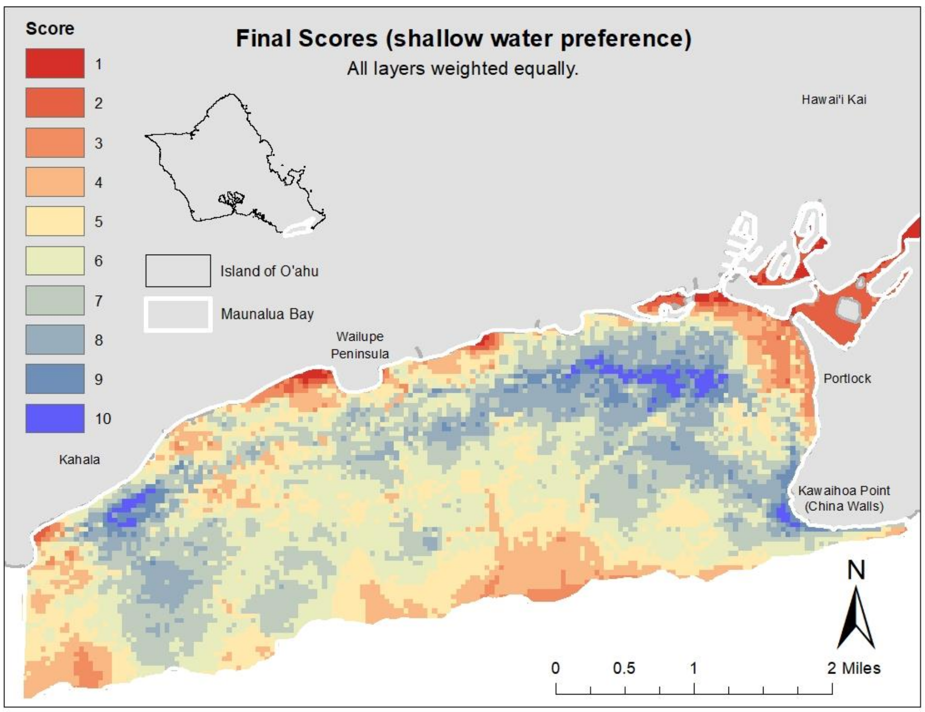


Figure 11: The final scored map for site suitability for climate-resilient coral restoration in Maunalua Bay. Scores of ten, in bright blue, indicate the most suitable sites for restoration and scores of one, in red, indicate the least suitable locations. All layers were weighted equally. This map uses the depth layer that favors depths of 10 meters and deeper.

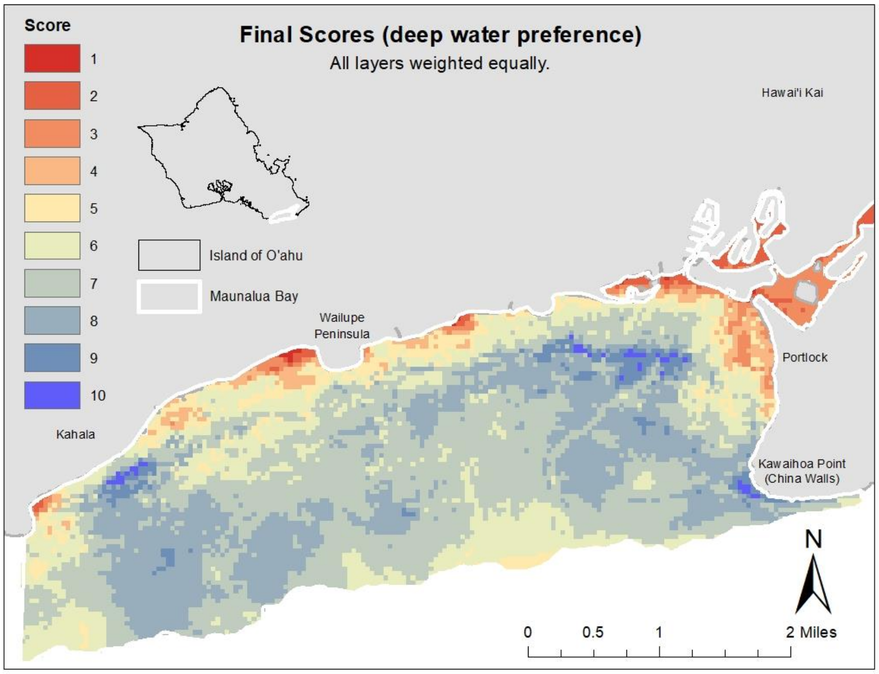


Figure 12: The final scored map for site suitability for climate-resilient coral restoration in Maunalua Bay. Scores of ten, in bright blue, indicate the most suitable sites for restoration and scores of one, in red, indicate the least suitable locations. Layers containing scores for existing coral cover, hard substrate, and the wave break weighted twice as heavily as all other layers. This map uses the depth layer that favors depths less than 10 meters.

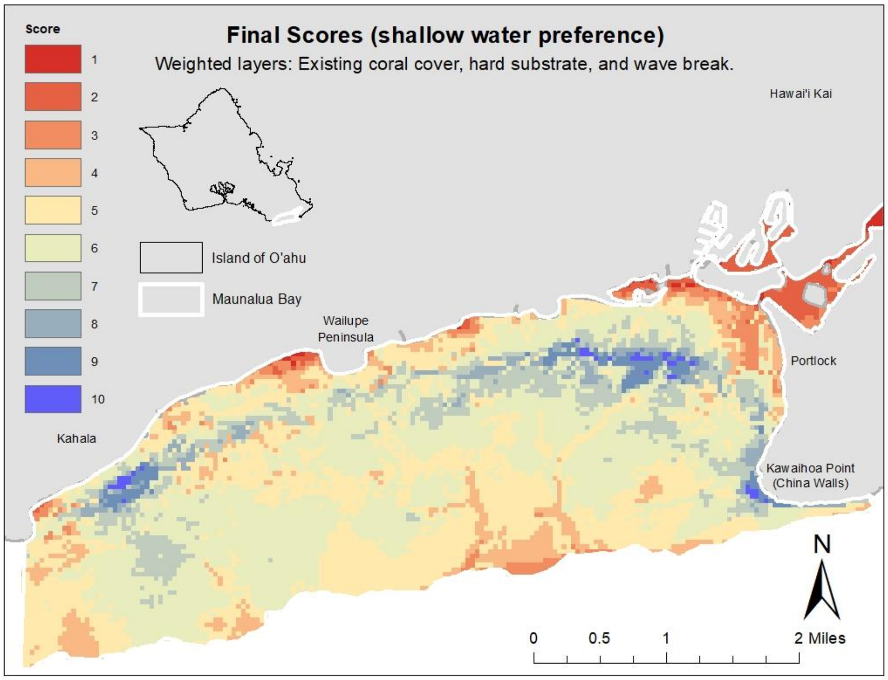
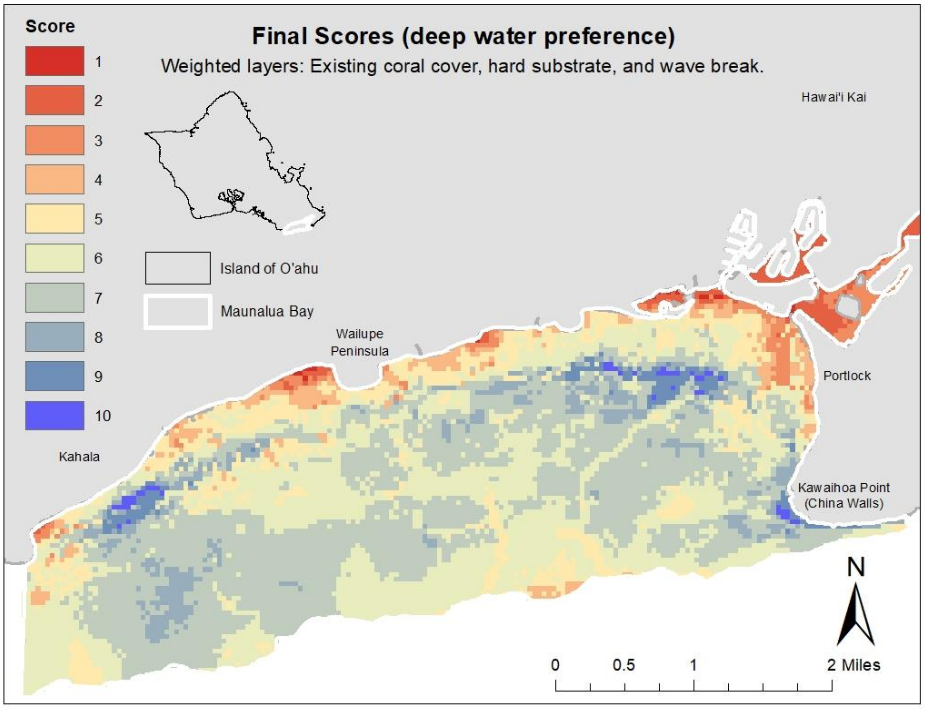


Figure 13: The final scored map for site suitability for climate-resilient coral restoration in Maunalua Bay. Scores of ten, in bright blue, indicate the most suitable sites for restoration and scores of one, in red, indicate the least suitable locations. Layers containing scores for existing coral cover, hard substrate, and the wave break weighted twice as heavily as all other layers. This map uses the depth layer that favors depths of 10 meters and deeper.



Results

The most suitable locations for coral restoration in Maunalua Bay were identified through the unweighted and weighted site selection analyses. The final scored maps demonstrate the most suitable areas for coral reef restoration in Maunalua Bay. When comparing the results of the pixels with scores of ten in each of the four analyses, there are minimal differences in the locations of the pixels between each of the analyses. Despite using different layers that favored shallow and deep waters differently, the results of the analyses did not demonstrate a noticeable difference in the distribution of pixels that received a score of ten for shallow and deep preferences.

Several regions of the bay consistently received the highest possible score of ten in every analysis (Figure 14). One of the locations is a 675-meter strip of pixels surrounding the reef crest, ranging 150-500 meters off Hunakai beach in Kahala (Figure 15). Another region with many pixels that received a score of ten begins 500 meters off the shoreline of the western edge of the Niu Peninsula and continues on both sides of the reef crest off the coast of Paikō Beach, to 900 meters offshore from Maunalua Bay Beach Park (Figure 16). There are several pixels at the Turtle Canyon dive sites that also received scores of ten. The final region to receive a cluster of pixels with scores of ten is the area ranging between 50 meters to 230 meters offshore between Koko Kai Beach and Kawaihoa Point (China Walls) (Figure 17).

These site suitability recommendations will be used by Mālama Maunalua and HIMB in the implementation stage of the Restore with Resilience project, in which 4,000 nubbins of climate-resilient coral will be planted in Maunalua Bay.

Figure 14: The pixels that received scores of ten in any of the four analyses are shown in blue. The nursery platform is shown in yellow.

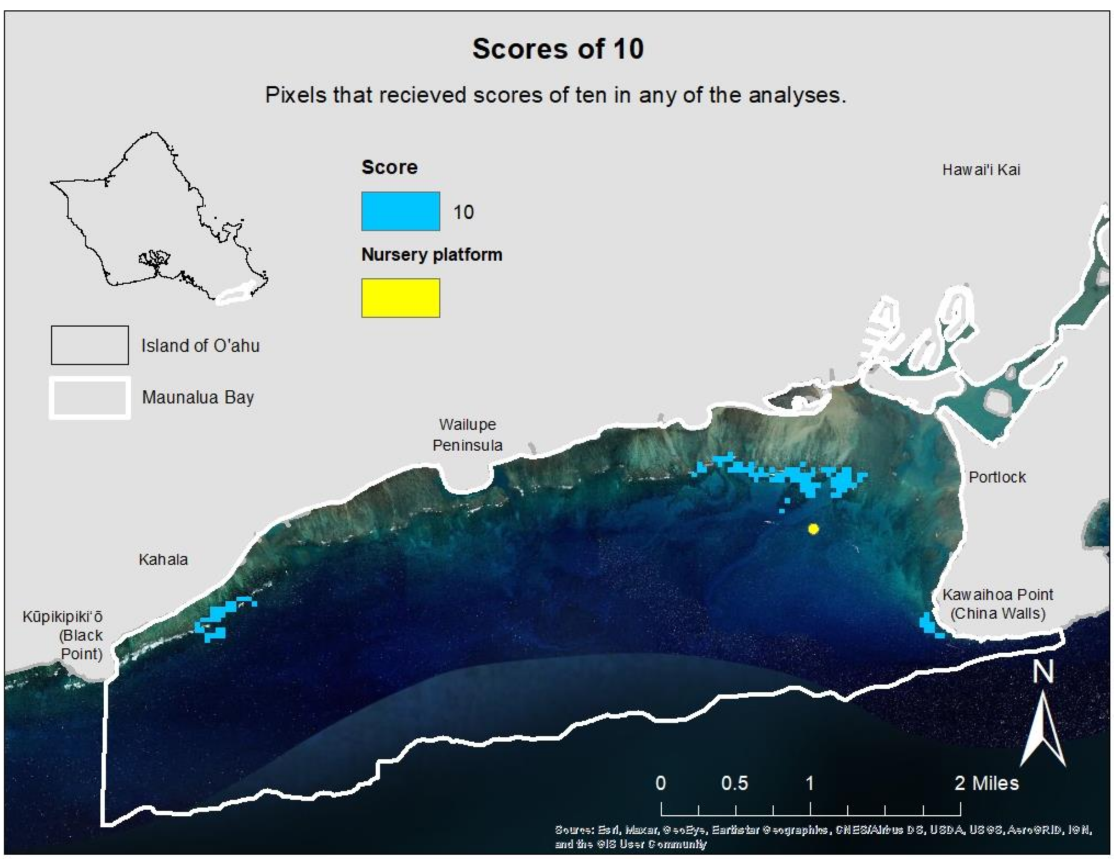


Figure 15: The cluster of pixels off the coast of Kahala that received scores on ten any of the four analyses are shown in blue.

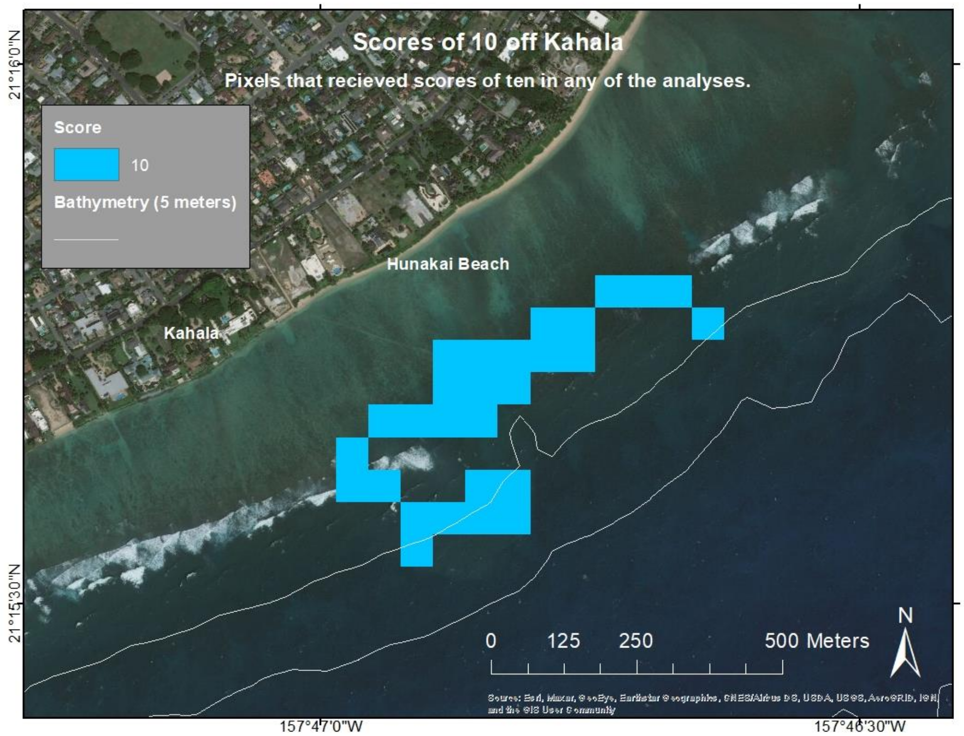


Figure 16: The cluster of pixels off the coast of Paikō Beach that received scores on ten any of the four analyses are shown in blue.

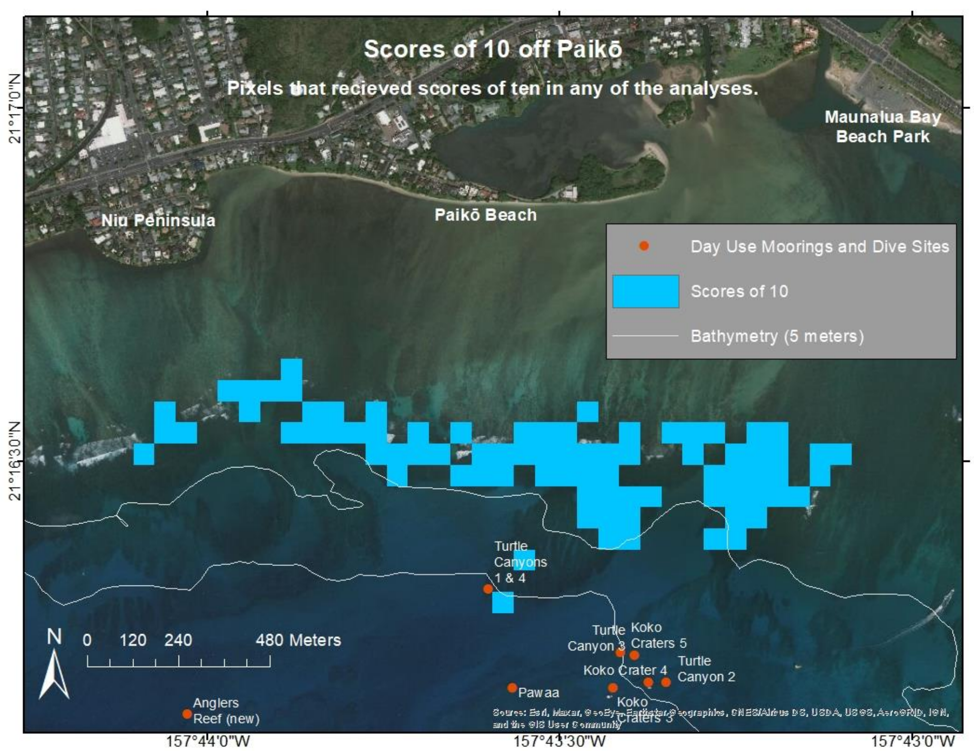
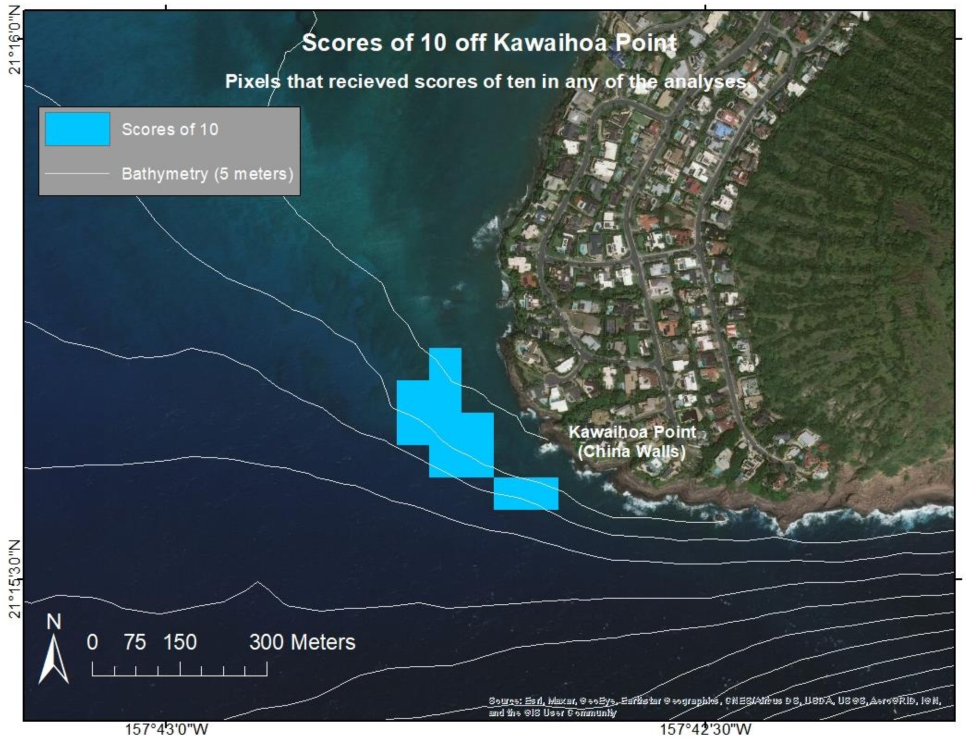


Figure 17: The cluster of pixels off the coast of Kawaihoa Point (China Walls) that received scores on ten any of the four analyses are shown in blue.



Discussion

The minimal differences between the locations of pixels that received scores of ten in each of the analyses suggests that those areas received high scores in each of the individual layers. This is likely why the weighting of the layers containing existing coral cover, hard substrate, and the location of the wave break along the reef crest did not alter the regions in which pixels scored the highest in the analyses.

While the author is grateful to have had access to a wide historic and spatial range of data for this site-selection analysis, it is important to note that there are areas of Maunalua Bay where there are data gaps. For example, few studies have sampled in the region of the bay off Wailupe Peninsula. Very little data has been collected beyond the 15-meter depth contour line. Most studies sampled in the east side of the bay, between Paikō Beach and Portlock. Using interpolation to fill data gaps is a useful technique for inferring the status of the whole bay, but it is a more accurate tool when more data points are available to interpolate from.

Considering multiple criteria using all available data can help inform site selection for coral reef restoration projects. Planting corals in areas with existing coral cover, healthy habitat, limited water quality issues, hard substrate, and of a suitable depth may make a difference in the survival of outplanted corals. Considering accessibility of sites is also important for the logistical success of the restoration project, as well as the economic and cultural benefits that come from engaging local surfers, dive operations, and community volunteers in the outplanting and monitoring of the restored coral reefs. These site selection methods developed in this study will be included in a guidebook to be shared with other communities interested in coral reef restoration. These methods can be scaled to support restoration decision-making in other regions in which healthy coral reefs can benefit coastal ecosystems and communities.

Acknowledgements

Thank you to Mālama Maunalua and HIMB for the opportunity to lead the site selection process for the Maunalua Bay location of the Restore with Resilience project. Thank you to the scientists and coral restorations specialists, especially to Dr. Pam Weiant and Doug Harper of Mālama Maunalua, for your guidance and assistance on this project. Thank you to Mālama Maunalua, the Yale Institute of Biospheric Studies, and the Hixon Center for Urban Ecology at the Yale School of the Environment for funding this research.

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Appendix

See following pages.

Table 1A: Water Chemistry Parameters, scoring classifications, GIS methods, and data sources for the water quality category of the site selection process. Scores of 1 are assigned to the least favorable conditions for coral restoration and scores of 5 are assigned to areas that are most favorable.

Data Category	Parameter	Value from data	Score	GIS methods	Data Source
Water Chemistry	Temperature (° C)	27.09 - 27.7	1	IDW interpolation, Natural breaks (jenks) classification, Reclassify into scores	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
		26.87 - 27.08	2		
		26.64 - 26.86	3		
		26.41 - 26.63	4		
		25.6 - 26.4	5		
	Dissolved oxygen (percent)	47.30 - 68.20	1	IDW interpolation, Natural breaks (jenks) classification, Reclassify into scores	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
		68.21 - 83.90	2		
		83.91 - 96.10	3		
		96.11 - 105.90	4		
		105.91 - 132.40	5		
	Turbidity (NTU)	4.77 - 45.94	1	IDW interpolation, Quantile classification, Reclassify into scores	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
		2.69 - 4.76	2		
		1.30 - 2.68	3		
		0.27 - 1.29	4		
		0.07 - 0.26	5		
	pH	7.78 - 7.91	1	IDW interpolation, Quantile classification, Reclassify into scores	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
		7.91 - 7.95	2		
		7.95 - 7.98	3		
		7.98 - 8.01	4		
		8.01 - 8.05	5		
	Salinity (psu)	0-25	1	IDW interpolation, Manual classification, Reclassify into scores	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
		25-29	2		
		29 - 31	3		
		31 - 33	4		
		33 - 35.06	5		
	Natural log of nitrate plus nitrite (ug/L)	2.92 - 7.8	1	IDW interpolation, Natural breaks (jenks) classification, Reclassify into scores	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
		1.51 - 2.91	2		
		0.93 - 1.5	3		
		0.38 - 0.92	4		
		0 - 0.37	5		
	Total Phosphorus (ug/L)	55.45 - 129.88	1	IDW interpolation, Natural breaks (jenks) classification, Reclassify into scores	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
		27.54 - 55.44	2		
		16.28 - 27.53	3		
		10.4 - 16.27	4		
		5 - 10.39	5		
	Chlorophyll-a (ug/L)	2.18 - 6.94	1	IDW interpolation, Natural breaks (jenks) classification, Reclassify into scores	University of Hawai‘i at Mānoa and The Nature Conservancy, 2020
		1.06 - 2.17	2		
		0.68 - 1.05	3		
		0.33 - 0.67	4		
		0.02 - 0.32	5		

Table 2A: Other Water Quality Meastures Parameters, scoring classifications, GIS methods, and data sources for the water quality category of the site selection process. Scores of 1 are assigned to the least favorable conditions for coral restoration and scores of 5 are assigned to areas that are most favorable.

Data Category	Parameter	Value from data	Score	GIS methods	Data Source
Other Water Quality Measures	Proximity to areas of high flow (meters)	600 +	1	Create polygons, Multi Ring Buffer, Polygon to Raster, Reclassify into scores	Mālama Maunalua, 2017; Storlazzi et al., 2010
		401 - 600	2		
		201 - 400	3		
		101 - 200	4		
		0 - 100	5		
	Proximity to submarine groundwater discharge (SDG) sites (meters)	0 - 50 m	1	Multi Ring Buffer, Polygon to Raster, Reclassify into scores	Lubarsky et al., 2018; Richardson et al., 2015
		50 - 100 m	2		
		100 - 150 m	3		
		150 - 200 m	4		
		200 - 250 m	5		
	Proximity to non-point source pollutants (meters)	0-50 m	1	Multi Ring Buffer, Polygon to Raster, Reclassify into scores	Mālama Maunalua, 2017
		50-100m	2		
		100-150m	3		
		150-200m	4		
		200-250m	5		

Table 3A: Benthic Conditions Parameters, scoring classifications, GIS methods, and data sources for the benthic conditions category of the site selection process. Scores of 1 are assigned to the least favorable conditions for coral restoration and scores of 5 are assigned to areas that are most favorable.

Data Category	Parameter	Value from data	Score	GIS methods	Data Source
Benthic Conditions	Depth (meters) - nearshore site preference	-15 - -32	1	IDW interpolation, Manual classification, Reclassify into scores	Mālama Maunalua, 2017; Donovan et al., 2018; Storlazzi et al. 2010; Presto et al. 2012; University of Hawaiʻi and NOAA, 2014; University of Hawaiʻi at Mānoa and The Nature Conservancy, 2020; The Nature Conservancy, 2012
		-10 - -15	2		
		-6 - -10	3		
		-6 - -3	4		
		-3 - 0	5		
	Depth (meters) - offshore site preference	-3 - 0	1	IDW interpolation, Manual classification, Reclassify into scores	Mālama Maunalua, 2017; Donovan et al., 2018; Storlazzi et al. 2010; Presto et al. 2012; University of Hawaiʻi and NOAA, 2014; University of Hawaiʻi at Mānoa and The Nature Conservancy, 2020; The Nature Conservancy, 2012
		-6 - -3	2		
		-6 - -10	3		
		-10 - -15	4		
		-15- -32	5		
	Benthic Cover - coral cover and hard substrate (predictive)	other	1	Reclassify into scores	NOAA National Centers for Coastal Ocean Science (NCCOS), 2007
		coral, CCA, aggregate reef, fore reef, and reef crest minus macroalgae	5		
	Benthic Cover (predictive)	Land	NoData	Reclassify into scores	NOAA National Centers for Coastal Ocean Science (NCCOS), 2007
		Artificial	1		
		Unknown	1		
		Sand	1		
		Mud	1		
		Pavement with san	3		
		Rubble	3		
		Rock/Boulder	4		
		Pavement (uncolor	4		
		Aggregate reef	5		

Table 4A: Coral Cover Parameters, scoring classifications, GIS methods, and data sources for the coral cover category of the site selection process. Scores of 1 are assigned to the least favorable conditions for coral restoration and scores of 5 are assigned to areas that are most favorable.

Data Category	Parameter	Value from data	Score	GIS methods	Data Source
Coral Cover	Existing Coral Cover (percent)	0-1	1	IDW interpolation, Manual classification, Reclassify into scores	Friedlander, 2008; Donovan et al., 2018; University of Hawaiʻi and NOAA, 2014; University of Hawaiʻi at Mānoa and The Nature Conservancy, 2020; The Nature Conservancy, 2012 (*see CoralNet box)
		1-5	2		
		5-10	3		
		10-15	4		
		15-43.29	5		
	Historic Coral Cover	No	1	Create polygons, Polygon to Raster, Reclassify into scores	NOAA, 1990
		Yes	5		
	Historic Coral Cover (percent)	-1, 0, and NoData	1	Create polygons, Polygon to Raster, Reclassify into scores	AECOS, Inc., 1979
		1	2		
		5	3		
		15	4		
		30-45	5		
	Predictive Coral Cover (values based on Raster Calculator outputs)	0.02	1	Raster Calculator to sum layers for all species from predictive coral cover study, Reclassify into scores, Natural breaks (jenks) classification	Franklin et al., 2013
		0.04	2		
		0.07	3		
		0.11	4		
		0.22	5		

Table 5A: Accessibility Parameters, scoring classifications, GIS methods, and data sources for the coral cover category of the site selection process. Scores of 1 are assigned to the least favorable conditions for coral restoration and scores of 5 are assigned to areas that are most favorable.

Data Category	Parameter	Value from data	Score	GIS methods	Data Source
Accessibility	Distance from Dive Sites / Day Mooring Buoys (meters)	> 1600	1	Multi Ring Buffer, Polygon to Raster, Reclassify into scores	Mālama Maunalua, 2017; University of Hawaiʻi and NOAA, 2014
		1200 - 1600	2		
		800 - 1200	3		
		400 - 800	4		
		0- 400	5		
	Distance from public beach access points (meters)	> 1600	1	Multi Ring Buffer, Polygon to Raster, Reclassify into scores	Mālama Maunalua, 2017
		1200 - 1600	2		
		800 - 1200	3		
		400 - 800	4		
		0- 400	5		
	Distance from nursery platform (meters)	> 1600	1	Create polygon, Multi Ring Buffer, Feature to Raster, Reclassify into scores	Mālama Maunalua, 2020
		1200 - 1600	2		
		800 - 1200	3		
		400 - 800	4		
		0- 400	5		
	Distance from wave breaks (meters)	0-10	1	Create polylines, Multi Ring Buffer, Polygon to Raster, Reclassify into scores	ArcMap World Imagery Basemap
		10-20	2		
		20-30	3		
		30-40	4		
		40-50	5		

Table 6A: Habitat Health Parameters, scoring classifications, GIS methods, and data sources for the habitat health category of the site selection process. Scores of 1 are assigned to the least favorable conditions for coral restoration and scores of 5 are assigned to areas that are most favorable.

Data Category	Parameter	Value from data	Score	GIS methods	Data Source
Habitat Health	Presence of IAA (based on scores of 0-3 assigned by DAR)	2-3	1	IDW interpolation, Manual classification, Reclassify into scores	DAR, 2008
		1-2	2		
		0.50-1	3		
		0.25-0.50	4		
		0-0.25	5		
	Presence of IAA (based on scores of 0-3 assigned by DAR)	5-8	1	IDW interpolation, Manual classification, Reclassify into scores	DAR, 2016
		4-5	2		
		3-4	3		
		2-3	4		
		1-2	5		
	Herbivorous fish biomass (grams per square meter)	0 - 1	1	IDW interpolation, Manual classification, Reclassify into scores	Donovan, et al., 2018, Friedlander, 2008; The Nature Conservancy, 2012
		1 - 2	2		
		2 - 8	3		
		8 - 15	4		
		15 - 40	5		