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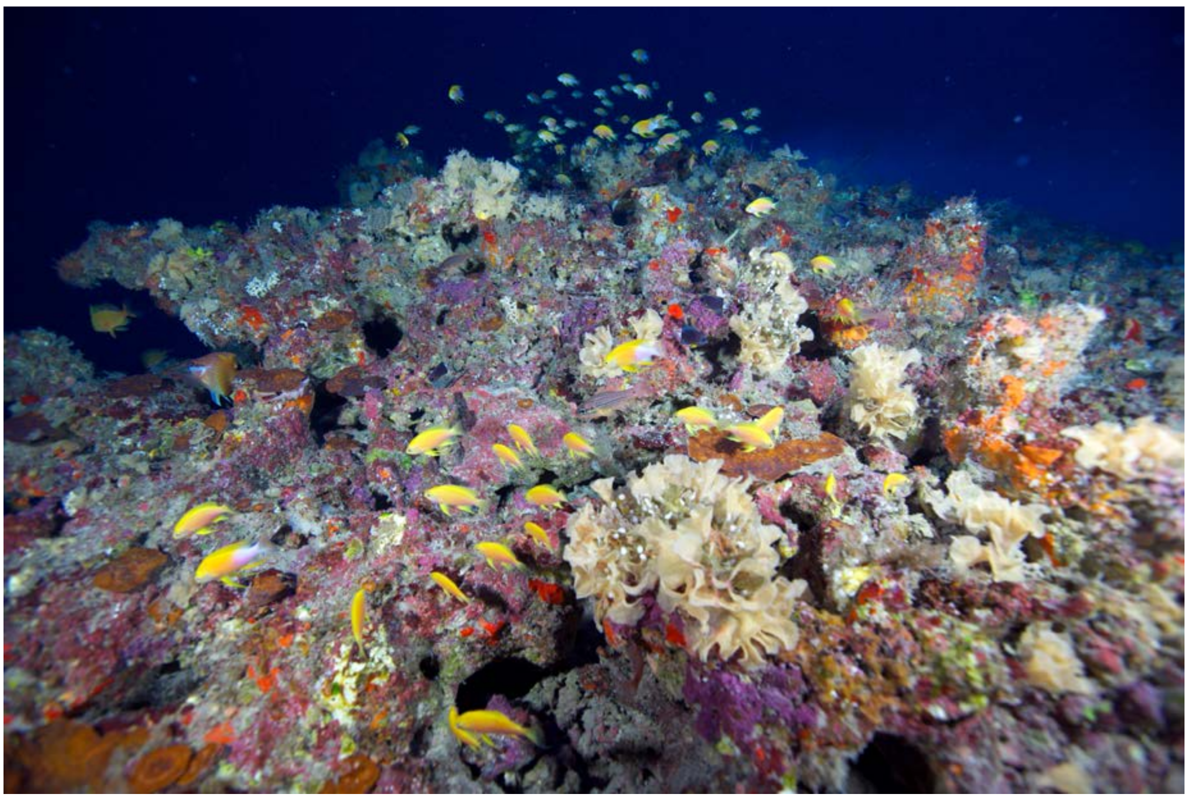
Acoustic Characterization of Mesophotic Coral Reef Ecosystems of West Hawai‘i



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Cover: Photograph of mesophotic coral and associated biota at a depth of 111 m near Kawaihae, Hawai‘i, courtesy of Association for Marine Exploration.

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Acoustic Characterization of Mesophotic Coral Reef Ecosystems of West Hawai‘i

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ABSTRACT

Coral reef habitats in Hawai‘i are common in shallow waters and extend into mesophotic depths (30-150 m). However, habitat monitoring efforts have been concentrated in depths constrained by safe dive limits of 0-30 m. Mesophotic coral ecosystems (MCEs), located in depths of 30-150 m, are important components of the coral reef ecosystem, but only a small number of surveys have been conducted in these depths. Data for these deep-water habitats are essential for evaluating and monitoring their health and resilience. Classifying benthic habitats in mesophotic depths is challenging due to dive safety limits and water penetration capabilities of remote sensing options, such as satellite imagery and Light Detection and Ranging (LiDAR). The results of this effort show that acoustic data can be used to provide detailed substrate and biological cover maps that include mesophotic coral ecosystems. Here we employ a combination of principal component analyses and unsupervised classification techniques to derive six substrate and five biological cover classes from multi-beam acoustic data, which are validated by optical seafloor imagery to create a complete benthic habitat map for the West Hawai‘i Habitat Focus Area (WHHFA). Our results show that the overall accuracy of the benthic habitat maps is 59% for substrate classification and 61% for biological cover classification. Accuracy was higher for the following individual classes; 76% Complex Reef, 86% Sand, and 88% Coral. These habitat maps are the first within the WHHFA to incorporate mesophotic data and provide important information for evaluating and managing the coral reef ecosystem as a whole.

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LIST OF ABBREVIATIONS

BTM	Benthic Terrain Modeler
CRAMP	Coral Reef Assessment and Monitoring Program
CRCP	Coral Reef Conservation Program
CREP	Coral Reef Ecology Program
DAR	Division of Aquatic Resources
EFH	Essential Fish Habitat
GPS	Geographic Positioning System
HIHWNM	Hawaiian Islands Humpback Whale National Marine Sanctuary
HIMB	Hawai‘i Institute of Marine Biology
HMRG	Hawai‘i Mapping Research Group
LiDAR	Light Detection and Ranging
MCES	Mesophotic Coral Ecosystem
MMU	Minimum Mapping Unit
MPA	Marine Protected Area
NOAA	National Oceanic and Atmospheric Administration
PCA	Principal Component Analysis
TNC	The Nature Conservancy
TOAD	Tethered Optical Assessment Device
USACE	US Army Corps of Engineers
USGS	US Geological Survey
WHHFA	West Hawai‘i Habitat Focus Area

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The U.S. National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program (CRCP) is tasked to protect, conserve, and restore the nation's coral reefs by maintaining healthy ecosystem function. Over the past 20 years, the condition of marine resources in Hawaiian waters around the populated southern islands has declined (Friedlander et al. 2008). The need for assessment and monitoring of coral reef ecosystems is important, as the effects of anthropogenic activities and climate change continue to threaten these communities, jeopardizing the ecosystem goods and services these systems provide.

The CRCP recognizes three key priority threats to coral reef ecosystems; fishing, land-based sources of pollution, and climate change. To address these issues, the CRCP, in cooperation with the State of Hawaiʻi, selected priority sites in Hawaiʻi, for ridge-to-reef management implementation (Fig. 1). The NOAA Habitat Blueprint provides a framework for management of long-term habitat focus areas and includes the CRCP priority site within the West Hawaiʻi Habitat Focus Area (WHHFA). The WHHFA compliments the CRCP priority site goals and objectives, and together they work to achieve aligned goals and objectives. The WHHFA was designated in an effort to decrease habitat loss and degradation and to encourage larger conservation activities through collaboration and efficient use of limited resources.

Many coral reef mapping projects have taken place within the WHHFA with efforts concentrated in water depths of 0–30 m, using a combination of satellite imagery, sonar bathymetry, and optical validation images (i.e., ground truth images). These projects provided shallow-water benthic habitat maps, one of the primary tools used to assess resources and implement management strategies by providing essential characterization of the seascape (Cochran et al., 2007; Coyne et al., 2003). These efforts have helped to identify threats within the WHHFA that are degrading the shallow coral reefs and include climate change, eutrophication, and sedimentation.

Reducing the impact of land-based threats, from sedimentation and pollution, is critically important to the health and resilience of the coral reef ecosystem. When coral reefs are degraded, macroalgae can become the dominant biological cover. Coral recovery is suppressed, as coral larvae require a hard substrate on which to settle (Birrell et al., 2005). Additionally, the low structural complexity of degraded coral reef habitat can sustain only a fraction of the biological productivity of a healthy reef decreasing fishery yields and biodiversity (Rogers et al., 2014).Yet, even if an acceptable substrate is available, recruitment of new corals is undermined as they are overgrown by the faster growing algae (Dixson et al., 2014). Suitable recruitment substrates may be found in deeper water, where reduced light limits algal growth and the increased distance from land reduces the harmful impacts of sedimentation and eutrophication. Under these favorable environmental conditions, certain corals normally found in shallow waters may recruit and successfully grow in waters as deep as 70 m creating a mesophotic coral ecosystem (MCE).

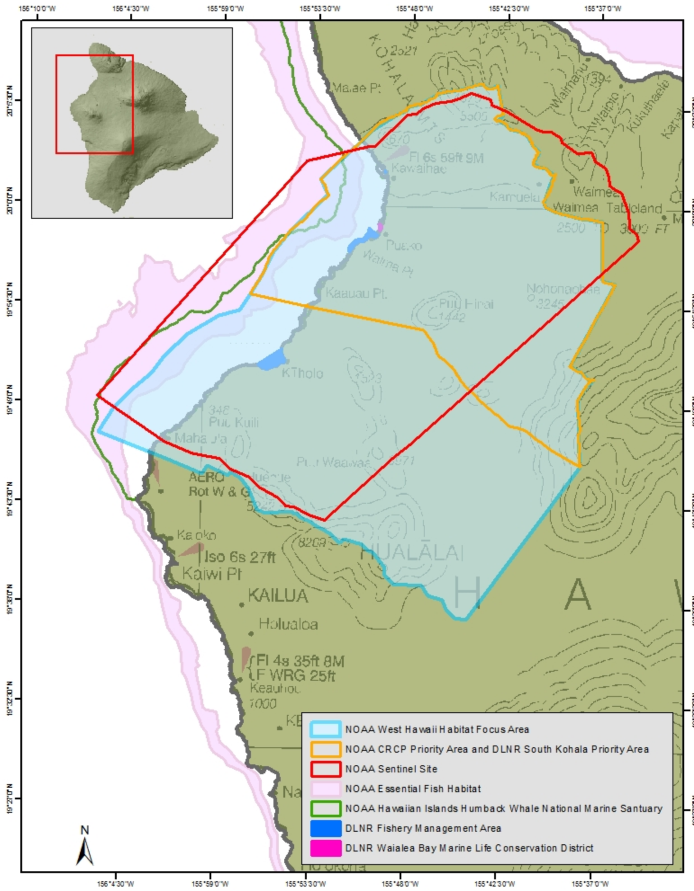

Figure 1.--Habitat mapping study area location (in blue) within the West Hawai‘i Habitat Focus Area. Also shown are the boundaries for the NOAA CRCP priority site and other managed areas in west Hawai‘i.

MCE are found at depths from 30 to150 m and are inhabited by many corals, fishes, macroalgae, and sponges. The upper MCE (30-70 m) is an extension of the shallow-water coral reef ecosystem and is dominated by shallow-water species (Kahng et al., 2014). These ecosystems are naturally buffered from some of the threats that shallow corals face as they are in cooler, deeper waters and are typically further from shorelines where anthropogenic and land-based impacts are most prominent (Baker et al., 2016). MCEs may help us quantify the impacts shallow reef systems are experiencing and potentially serve as control sites for reef health and resilience if their community compositions are similar enough to shallow water reefs.

However, MCEs are difficult to study, as they are beyond the reach of recreational scuba (40 m) and expensive to survey with submersible vehicles. Despite these limitations, the study of MCEs has increased over the past decade. In Hawai‘i, the extent of these deep coral habitats has been documented using a combination of submersibles, remotely operated vehicles, and mixed-gas scuba and rebreather diving. Mesophotic corals between depths of 50-90 m were found to cover tens of km^2 (Pyle et al., 2016). These areas are the most expansive MCEs ever recorded. However, much is still unknown about these unique coral habitats.

To evaluate and monitor the condition of Hawai‘i’s coral reef ecosystems, the NOAA Pacific Islands Fisheries Science Center’s (PIFSC) Coral Reef Ecosystem Program (CREP) is tasked with producing comprehensive, seamless maps of all coral reef habitats in Hawai‘i and throughout the Pacific. Using a combination of acoustic and optical mapping survey techniques, the CREP produces benthic habitat maps that characterize seafloor bathymetry, substrate, and coral cover.

The foundation of benthic substrate maps are high-resolution acoustic bathymetry data that provide information about the depth and topography of underwater terrain. In deep water, benthic substrate maps are created from acoustic bathymetric survey. Using shipboard multi-beam echo sounders, high-resolution bathymetry data, essential for substrate map production, are collected. However, navigational hazards in shallow coastal waters inhibit acoustic data collection. In shallow water, bathymetry can be acquired using aerial bathymetric Light Detection and Range (LiDAR) systems (Irish et al., 2000). The combination of acoustic data and LiDAR can provide continuous bathymetric coverage from the shoreline to deep ocean depths (Costa et al., 2009). Bathymetric LiDAR and multi-beam data exist for most of the main Hawaiian Islands and provide nearly continuous high-resolution bathymetry data.

To complement bathymetry, acoustic data are commonly used to derive geomorphological characteristics of the seafloor (Wright et al., 2012b; Lucieer et al., 2013; Pickrill and Todd, 2003). These characteristics provide a measure of the complexity of the seafloor morphology, which is closely tied to fish abundance (Rogers et al., 2014) and species richness (Grigg, 1994; Walker et al., 2009). Geomorphological characteristics derived from acoustic data (e.g., slope, curvature and rugosity) offer additional spatial and complexity information that contribute to the production of benthic substrate maps.

Although acoustic data provide a wealth of information about the seafloor structure and complexity, biological cover cannot be directly identified. To produce a benthic habitat map, *in situ* validation data is necessary. Validation is achieved most commonly by a photograph or video of the seafloor collected by a diver, underwater vehicle, or sled that is spatially referenced to the bathymetric data. Satellite imagery has been used successfully to delineate seafloor characteristics (Watkins, 2015), but increased light absorption with depth limits the use of these images to areas shallower than 20-m deep. Regardless of depth, validation data are crucial to identify the biological cover of the seafloor. Validation images are analyzed to identify specific attributes of the seafloor structure and composition using a defined classification scheme. The classification scheme is developed based on knowledge of the substrate and biological cover within the area being mapped.

Here we apply a technique to derive benthic habitat from acoustic bathymetry and validation imagery. This work extends efforts to map shallow water habitat by encompassing the entire coral reef ecosystem, including the mesophotic zone within the WHHFA.

MATERIALS AND METHODS

Study Area

The island of Hawai'i is the southernmost island of the Hawaiian archipelago. It is also the youngest and largest island with a land area of nearly 10,500 km^2 and ongoing volcanic activity. Topographically the island is dominated by a series of shield volcanoes, with Mauna Kea and Mauna Loa reaching a maximum elevation over 4,000 m.

Pacific trade winds from the northeast are prevalent from May through September, with ocean wind speeds of 10–20 m/s and periods of light and variable wind conditions from October through April that disrupt the trade wind flow. In west Hawaiʻi, Mauna Kea impedes the flow of trade winds creating the warmest and driest leeward weather conditions in the main Hawaiian Islands, with an average annual rainfall of less than 0.18 m compared to the windward side of the island that receives up to 7.5 m annually (WRCC, 1985).

In the lee of Mauna Kea, west Hawaiʻi ocean conditions near shore are calm, and surface mixing is reduced creating a drastic surface temperature difference of up to 4° C in contrast to the rough seas of the Alenuihaha Channel that separates the island of Hawaiʻi from Maui.

The warm, dry conditions of west Hawaiʻi are exacerbated by periodic El Niño conditions. In 2015, a strong El Niño event brought record high temperatures to Hawaiʻi that caused elevated ocean surface temperatures for 18 consecutive weeks. The State of Hawaiʻi Division of Aquatic Resources (DAR) reported severe thermal stress in West Hawaiʻi causing 38–92% of all coral colonies to bleach, with the most severe bleaching occurring within the CRCP priority site where 55–99% coral loss was recorded (DAR, 2016). This event, coupled with ongoing land-based sources of pollution from the west Hawaiʻi watershed, places increasing pressure on the coral reef ecosystem, highlighting the importance of conservation efforts in west Hawaiʻi where important cultural resources are located, and endemic, endangered, and threatened species inhabit the longest contiguous coral reef in the state.

The WHHFA extends from the slopes of Mauna Kea to the western shoreline and beyond, to three nautical miles offshore, encompassing an area of 1540 km^2, including 230 km^2 of marine habitat (Fig. 1). The marine habitat within the WHHFA includes shallow and mesophotic coral reef ecosystems as well as the shallow portion of the Essential Fish Habitat (EFH) for Hawaiʻi bottom fish (< 400-m depth).

Data Collection

Acoustic Data

These data can be derived in various ways from single-beam and multi-beam sonar, LiDAR, and satellite imagery. Within the WHHFA, high-resolution multi-beam and LiDAR coverage existed, but many bathymetric gaps remained. These gaps were covered during a multi-beam survey conducted by the CREP team in 2012. The new multi-beam bathymetry data were processed and integrated with existing sonar and LiDAR data sets maintained by the University of Hawai‘i, Hawai‘i Mapping Research Group (HMRG) to produce a high-resolution (5 m grid) bathymetry synthesis for the entire WHHFA seafloor.

Validation Data

Optical validation of the seafloor structure and biological cover is a critical component in characterizing benthic habitat. Optical validation allows possible statistical correlations to be developed between benthic structure and benthic cover from bathymetric data. This is achieved by photographing the seafloor with a diver-operated camera or a tethered camera system operated from a small boat.

Within the WHHFA, numerous collaborations were leveraged to facilitate the integration and collection of validation data to provide accurate benthic habitat maps that can support ecosystem-based coral reef resource management and conservation efforts. Data providers included the NOAA National Centers for Coastal Ocean Science Biogeography Branch, The Nature Conservancy (TNC), US Army Corps of Engineers (USACE), State of Hawaii Division of Aquatic Resources (DAR) and the Hawai‘i Institute of Marine Biology’s (HIMB) Coral Reef Assessment and Monitoring Program (CRAMP) (Fig. 2)

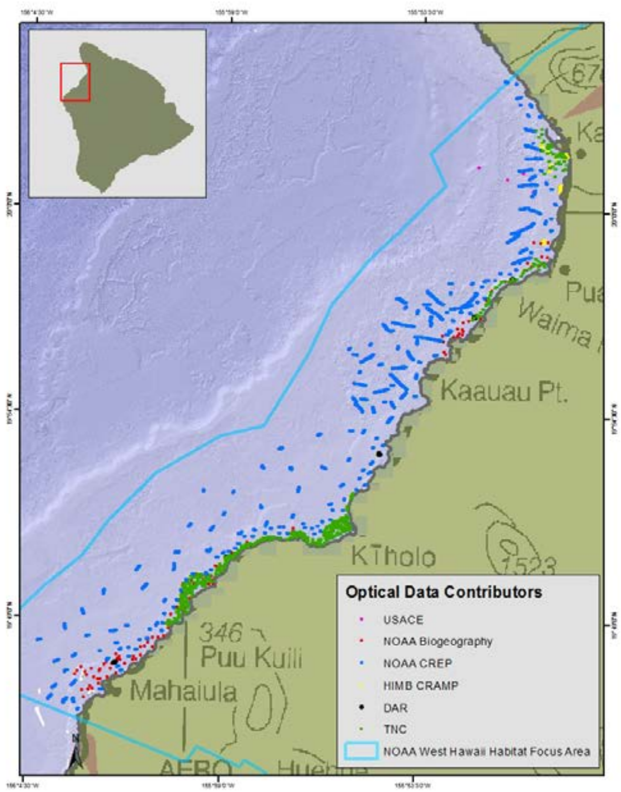

Figure 2.--Location of optical data collected by CREP and contributed by partners within the WHHFA.

In addition to this imagery, shallow-water habitat maps from the NOAA Biogeography Branch and the U.S. Geological Survey (USGS) were used as additional validation resources. In 2003, the NOAA Biogeography Branch produced a benthic habitat map to assess, inventory and monitor coral reef ecosystems along the West Hawaiʻi coastline to approximately 30-m depths (Coyne et al., 2003). In 2007, the USGS produced a benthic habitat map for the Puʻukoholā Heiau National Historic Site (Cochran et al., 2007) to evaluate the geologic resources offshore to approximately 30 m depths. Both maps were produced using a combination of satellite imagery and optical validation data. The USGS maps also incorporated bathymetry data. These maps provided a useful validation of seafloor characteristics in shallow-water areas where optical data were not available. In areas where the two maps overlapped, and two or more substrate or biological cover types were present, the dominant coverage type was used.

All existing validation data were concentrated in water depths of 30 m or less, covering just 13% of the WHHFA seafloor area. To validate seafloor characteristics in deeper water, additional seafloor imagery was collected in 2012 and 2015 by CREP. These surveys were conducted aboard the Pacific Island Fisheries Science Center (PIFSC) R/V *AHI*, the Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNM) R/V *Koholā*, and the Nature Conservancy's (TNC) R/V *Kākū*. The team used a Towed Optical Assessment Device (TOAD) camera sled (Fig. 3) and a drop camera system (Fig. 4) to collect data from 30 m to 150 m depths. Survey sites were selected using a stratified random survey design.

Figure 3.--Towed Optical Assessment Device (TOAD) camera sled being deployed from a small research vessel.

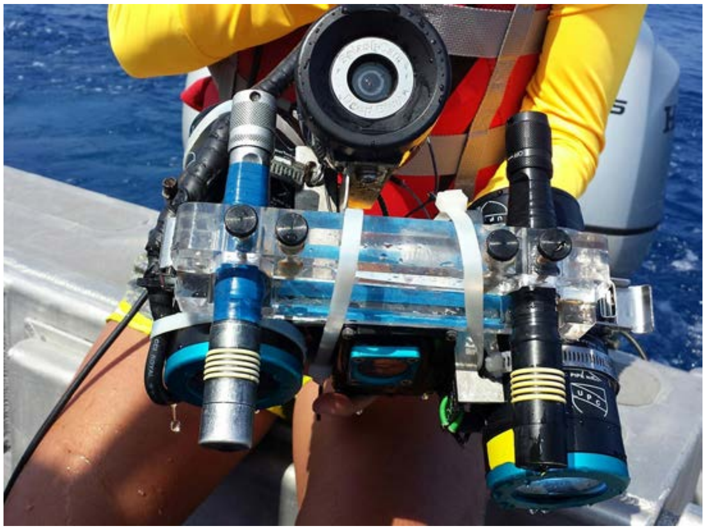

Figure 4.--Drop camera system designed and implemented during the 2015 field mission.

The TOAD camera sled is equipped with a forward-angled low-light color video camera and a downward-facing digital still camera. A pair of parallel lasers provided a scale reference in still images. The sled is also outfitted with an altimeter, a pressure (depth) sensor, and a fluxgate compass. The TOAD was deployed on a cable using a pot-hauler. A live-feed video monitor displayed the position of the sled relative to the seafloor which allowed the operator to raise and lower the sled to avoid obstacles. Still imagery was collected at 10-second intervals. A serial cable was connected to a Garmin Global Positioning system (GPS) to provide position of the vessel, and Hypack 2014 hydrographic software was used to record position data (from the GPS) and time to calculate the layback position of the sled.

Due to challenges faced in field operations, a drop camera system was constructed and implemented for the final five days of data collection in 2015. The drop camera system consisted of a forward-angled low-light video camera and a downward-facing GoPro Hero 3+ still camera. A pair of parallel lasers provided a scale reference in still images. A live-feed video display was used to monitor the position of the sled relative to the seafloor, and video data were recorded to digital files using a digital video recorder. Still imagery was collected at 10-second intervals. A hand-held Garmin 76Cx GPS unit was used to record the position of the vessel. Vessel movement was kept to a minimum (1 knot) to maintain a vertical angle on the umbilical cable to reduce position error as layback corrections were not applied to these data.

Data Processing and Analysis

Validation Image Classification

A total of 9,139 optical validation images were collected in the field and contributed by partners. All images were processed and classified at CREP by trained seafloor image analysts. As seafloor images were obtained from several sources, collection methods varied among data sets. Due to these differences, the seafloor coverage captured in photographs varied as well. For example, in some images, large structures such as individual patch reefs were visible, while in others only a small area of the seafloor was captured. Due to this discrepancy between image data sets, the standard classification scheme used by CREP, USGS, or the NOAA Biogeography Branch was not feasible. To resolve this, a hybrid classification scheme was developed to identify eight dominant substrate types based on minimum observable features, and all imagery was classified using this scheme (Table 1).

In addition to substrate, six biological cover classifications were defined based on the CREP classification scheme developed in 2011 (Table 2). These classifications are closely related to the habitat definitions used by the NOAA Biogeography Branch (Cochran et al., 2007). The USGS scheme designates major structures only.

To determine the dominant substrate and biological cover classification, each image was assigned 10 random points across the image using Coral Point Count with Excel extensions (Kohler and Gill, 2006) software. An analyst classified each point using the schemes outlined above for substrate type and biological cover. The percent cover for each substrate type and biological cover identified within the classified image was calculated. The highest percent cover dictated the dominant substrate and cover for each image. For example, if an image was 70% coral cover and 30% macroalgae cover, the image was considered 50–90% Coral. These image classifications are used to validate and correct the ArcGIS automated delineation of habitat classes.

Table 1.--Hybrid substrate classification scheme and definitions developed to standardize the analysis of seafloor imagery from several sources (USGS, NOAA Biogeography, NOAA CREP) using different collection methods.

Hybrid Substrate Classification Scheme	Definition	USGS Scheme	NOAA Biogeography Scheme	NOAA CREP 2011 Scheme
COMPLEX REEF:	50% or more Hard Bottom or Rock and NOT Rubble, Boulder or Pavement category	Aggregate Reef, Aggregated Patch Reef, Individual Patch Reef, Spur and Groove	Aggregate Reef, Aggregated Patch Reef, Individual Patch Reef, Spur and Groove	Hard bottom or Rock
PAVEMENT:	50% or more Hard Bottom or Rock and dominant biological cover consisting of Coralline Algae or Turf Algae	Volcanic Pavement with Sand Channels, Volcanic Pavement with 10–50% Rocks/Boulders, Volcanic Pavement	Pavement, Pavement w/Sand Channels, Scattered Coral/Rock	Hard bottom or Rock with 50% or more Coralline Algae or Turf Algae
MIXED SUBSTRATE:	Less than 50% of any combination of substrates	None	None	None
RUBBLE (> 2 mm and < 25 cm):	50% or more Rubble	Reef Rubble	Rubble	Rubble
BOULDER (> 25 cm):	50% or more Boulder	Volcanic Pavement w/ > 50% Rocks/Boulders	Rock/Boulder	Boulder
SAND (≥ 1/16 mm and < 2 mm):	50% or more Sand	Sand	Sand	Sand
MUD < 16 mm:	50% or more Mud	Mud	Mud	Mud
MAN-MADE:	50% or more Man-made	Artificial	Artificial	Man-Made

Table 2.--Definition for six classes of dominant biological cover.

Biological Cover Classification Scheme	CREP Definition	NOAA Biogeography Definition
CORAL	Hard coral that contribute to persistent, 3D structure of coral reef.	Hardened substrate of unspecified relief formed by the deposition of calcium carbonate by reef building corals.
CORALLINE ALGAE	Crustose coralline algae includes any calcified, hard, non-segmented, encrusting or branched, red (includes shades of pink, purple etc.) alga.	Any combination of numerous species of encrusting or coralline algae.
TURF ALGAE	Turf algae include many species of red, green, and brown algae and cyanobacteria. These occur in mixed algal assemblages that are typically short (<2 cm height) and often contain filamentous rather than fleshy algae.	Not designated as a distinct classification.
MACROALGAE	Macroalgae with a structure that can be seen in photos and video (unlike turf algae that may be invisible or appear as fine fuzz). This group includes numerous morphologies.	Any combination of numerous species of red, green, or brown macroalgae.
UNCOLONIZED	No living cover on the substrate. This only occurs when the underlying substrate is mud or sand or unconsolidated. Any hard substrate will be rapidly colonized, even if it is not possible to see the colonizer, as in the case of invisible turf algae.	Flat, low relief, solid carbonate rock that is often covered by a thin sand veneer. Surface often has sparse coverage of macroalgae, hard coral, zoanthids and other sessile invertebrates that does not obscure the underlying surface.
UNCLASSIFIED	Low image quality, shadow or other obstruction that inhibits proper classification	Bottom type uninterpretable due to turbidity, cloud cover, water depth or other interference.

Seafloor Complexity Analysis

Surface complexity layers are important components of a benthic structure data set. Bathymetric data can be used to derive seafloor characteristics that define structure for benthic organisms. To characterize the complexity of the seafloor, the Benthic Terrain Modeler (BTM) (Wright et al., 2012a) in ArcGIS 10.3 software was used to derive a series of surface complexity layers from a 5 m grid bathymetry synthesis. Eight surface complexity layers (mean depth, standard deviation of depth, curvature, plan curvature, profile curvature, rugosity, slope, and slope of slope) were produced (Fig. 5).

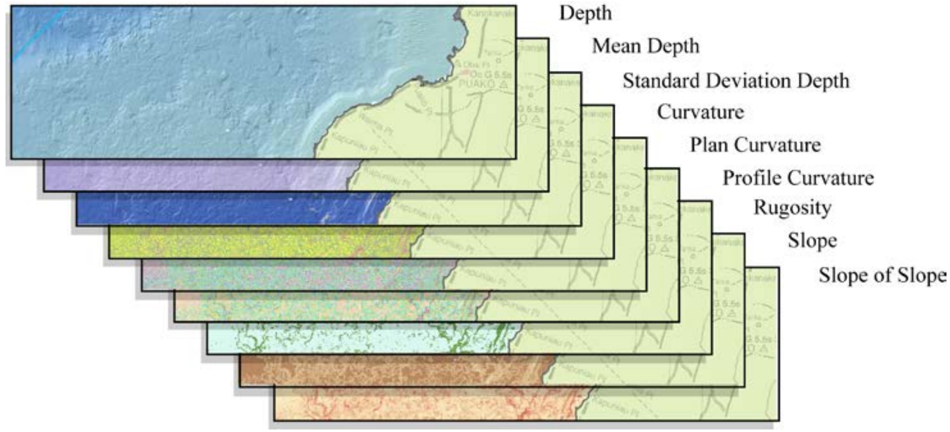

Figure 5.--Bathymetry synthesis (depth) and eight surface complexity layers (mean depth, standard deviation of depth, curvature, plan curvature, profile curvature, rugosity, slope and slope of slope) derived from the bathymetry synthesis.

The three-dimensional complexity of the seafloor is a vital driver of the distribution and abundance of marine organisms (Pittman and Brown 2011). Surface complexity layers can be analyzed together with bathymetry data to emphasize variation and identify strong patterns within the data set (Costa 2013). One method used to achieve this is Principal Component Analysis (PCA).

A PCA, using ENVI 5.3 software, was performed on the bathymetry synthesis and eight complexity surface layers to remove highly correlated data. Bathymetry and complexity surfaces were used in this analysis because previous studies have demonstrated useful application of these data for characterizing coral reef ecosystems in the US Caribbean (Pittman et al, 2007 Costa 2013). The PCA is also useful in determining which complexity layers are contributing the most variance. The PCA performed transformed the 9-band bathymetry and complexity surface image into nine principal components. In this analysis, the first three components described 99% of the data variability. The complexity surfaces that contributed the most variance were bathymetry and mean depth. Using the bathymetry alone would have provided only 50% of the variance. By including the complexity surfaces, we can determine where the variance lies within the data and retain those components. The rugosity surface contributed minimally to the overall variance but was maintained to capture the finer variance among biological cover classes (Table 3). Contributions from the remaining complexity surfaces were nearer or equal to zero. The bathymetry, mean depth, and rugosity principal components are thus considered the most important for classifying benthic habitat and were retained for use in the benthic classification process.

Table 3.--The percent of variance contributed by each of the complexity surfaces to each principal component (PC).

Principal Component	Bathymetry	Mean Depth	Standard Deviation Depth	Curvature	Plan Curve	Profile Curve	Rugosity	Slope	Slope of Slope	Accumulated % of Variance
1	**50.04**	49.90	0.02	0.04	0.00	0.00	0.00	0.00	0.00	99.8965
2	49.94	**50.03**	0.00	0.03	0.00	0.00	0.00	0.00	0.00	99.946
3	0.00	0.00	0.15	0.01	1.10	0.05	**92.36**	6.32	0.00	99.9736

Benthic Habitat Maps

Manual delineation of benthic habitats over large areas like the WHHFA can be very time consuming and is particularly difficult in deep water due to the sparsity of validation data. Fortunately, ArcGIS provides a tool to automate this process to reduce time and user bias introduced during manual delineation of habitat areas. The Iso Cluster Unsupervised Classification tool was used to classify the three-band PCA image into distinct classes or clusters. This tool computes the minimum Euclidean distance when assigning each cell to a cluster. Initially, an arbitrary mean is assigned by the software for each cluster defined by the user. Each cell is then assigned to the closest mean. New means are recalculated for a cluster based on the attribute distance of cells in the cluster after the first iteration. This process is repeated until all unknown data are grouped into a cluster or the maximum iteration is reached. Once delineated, this image was converted to a polygon shapefile. Polygons smaller than the minimum mapping unit (MMU) of 100 m^2 were merged with neighboring polygons that shared the longest common border. This MMU was chosen to be consistent with smallest MMU used in the adjacent shallow-water habitat maps. This process produced a delineated image of cell clusters with similar characteristics.

To verify the accuracy of the automated delineation, the classified optical validation points were overlaid onto the delineated image to confirm or correct the dominant substrate and biological cover composition of the seafloor at a given location. The number of images used to validate a given polygon varied due to data availability and size of the polygon. In cases where multiple validation data were available but conflicted within a polygon, the majority ruled. A minimum of 5 images were used to determine the classification for each polygon. The delineated polygon classifications were manually corrected or modified if they disagreed with the optical validation points. When optical validation points were absent, the USGS and NOAA Biogeography Branch benthic habitat maps were used as validation. For areas where no validation data existed, the polygon was considered unclassified. This process created verified substrate and biological cover maps for the WHHFA.

RESULTS

The substrate and biological cover maps created through this project are thematic in nature (Fig. 6). They depict the distribution of seafloor characteristics across geographic space. The accuracy of the maps is highly dependent upon the validation imagery. Uncertainties in geographic position, image classification, and changes in habitat over the timespan of data collection may have introduced conflicts in the data.

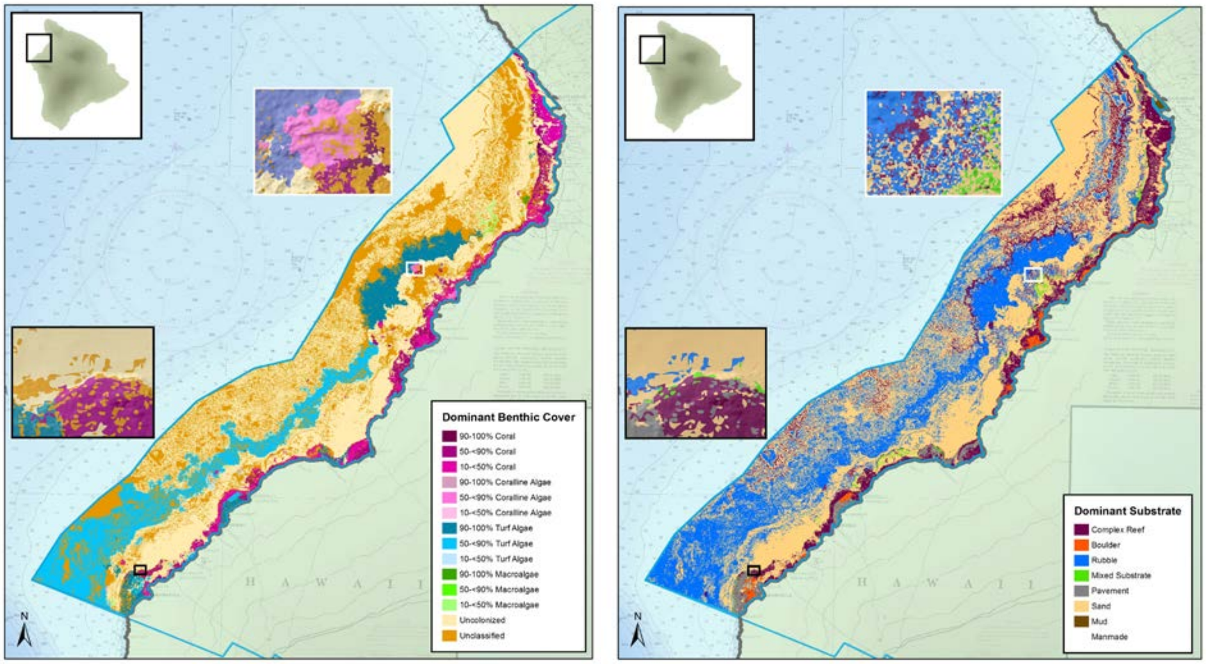

Figure 6.--Benthic habitat maps depicting dominant biological cover (left) and dominant substrate (right).

To assess the thematic accuracy, a subset of optical validation points was set aside after the image classification process was complete. This subset of points was selected using a stratified random process to ensure all seafloor classes were included and that validation points for each class were well distributed across geographic space. Validation points from the classified imagery were selected for substrate classes (n = 219) and weighted for the larger area covered by sand substrate. A separate set of validation points were selected for the biological cover classes (n = 187) and weighted for the larger area covered by uncolonized cover.

Each subset of validation points was overlaid onto the final habitat map. Values from the map were extracted to the validation point spreadsheet, and an error matrix (Story and Congalton, 1986) was generated to determine overall accuracy, Producer's accuracy, and User's accuracy for substrate (Table 4) and biological cover (Table 5).

Overall accuracy, which is the probability for a randomly selected location in the map to be correctly classified, was slightly better for biological cover at 61% versus structure at 59%. User's accuracy, a measure of reliability, which is the conditional probability that an area specifically classified in the map is also classified as the same category in the validation data. Low values signify that the area for the classification is overestimated. User's accuracy values were high for mixed and sand substrate classifications (100% and 83%, respectively) and for macroalgae cover (80%). For the remaining substrate and cover classes, the user's accuracy was low (44–73% and 29–59%, respectively), suggesting that polygons were assigned to the wrong classes, and that this effect was less pronounced for biological cover classes or that errors were introduced in scale selection or position accuracy. Producer's accuracy measures how well the classification aligned with the test pixels, where low values indicate classes that are underestimated in the map. Producer's accuracy was high for sand substrate (86%) and coral (88%) and uncolonized (81%) cover. Mixed and boulder substrates had high omission, which is expected due to the relatively low occurrence of these substrates.

Table 4.--Confusion matrix showing map accuracy values for substrate classes

		Ground Truth							
		Complex	Pavement	Mixed	Rubble	Sand	Boulder	Total	User's Accuracy
As Mapped	Complex	19	11	18	2	3	13	66	28.78%
	Pavement	4	8	3	0	2	5	22	36.36%
	Mixed	0	0	1	0	0	0	1	100%
	Rubble	0	0	0	16	9	2	27	59.25%
	Sand	2	5	2	7	86	1	103	83.49%
	Boulder	0	0	0	0	0	0	0	0%
Total		25	24	24	25	100	21	219	
Producer's Accuarcy		76%	33%	4%	64%	86%	0%		

Diagonal Sum:	130
Overall Accuracy:	59%
Kappa Coefficient:	0.44

Table 5.--Confusion matrix showing map accuracy values for Biological Cover classes

		Ground Truth						
		Coral	Coralline Algae	Turf Algae	Macroalgae	Uncolonized	Total	User's Accuracy
As Mapped	Coral	23	7	11	0	10	51	45.09%
	Coralline Algae	0	5	1	0	1	7	71.42%
	Turf Algae	2	4	11	3	5	25	44.00%
	Macroalgae	0	0	0	4	1	5	80.00%
	Uncolonized	1	5	2	19	72	99	72.72%
Total		26	21	25	26	89	187	
Producer's Accuracy		88.46%	24.81%	44.00%	15.38%	81.90%		

Diaganol Sum:	115
Overall Accuracy:	61%
Kappa Coefficient:	0.44

DISCUSSION AND CONCLUSION

Acoustic-derived benthic substrate maps provide crucial information about the extent and composition of coral reef ecosystems, especially in depths beyond the limits of recreational scuba and aerial remote sensing techniques. The WHHFA contains a large seafloor area with most data collection efforts concentrated in shallow depths (< 30 m), which make up less than one quarter of the marine environment in this area. This study filled bathymetry and validation data gaps to produce a continuous benthic habitat map for the entire WHHFA including deep-water MCES's, which are an important component of the coral reef ecosystem.

Although every effort was made by the CREP to collect as much data as possible, the deep-water imagery makes up less than 50% of the total data collected. The sparsity of deep-water data makes it difficult to bridge spatial gaps between data sets. In addition, the shallow-water data collection spans a longer time period, from 2005 to 2015, which may introduce temporal or seasonal differences between data sets. This combination of factors may have impacted the thematic accuracy of the final benthic habitat maps.

However, it is promising that this approach, using only high-resolution bathymetry and optical validation data, has potential to improve characterization of deep-water habitats where data options and availability are limited. At depths greater than ~30 m, the water column obscures remote sensing capabilities, and *in situ* observations become more expensive and time-consuming with greater depth. One option—although not currently available within the WHHFA—is backscatter, a derivative of multi-beam sonar data. Backscatter can be processed to predict seafloor impedance, roughness, and sediment grain size. Used in conjunction with high-resolution bathymetry and optical validation data, substrate classification of deeper water benthic habitats can be improved (Che Hasan et al., 2014)

With the continued advances in airborne image collection (LiDAR, Satellite, Drone, etc.) and in-water photography, the accuracy and detail of benthic habitat maps for shallow waters will continue to improve. However, with the severity of impacts shallow-water corals are facing across the Pacific, extending survey capabilities into deeper waters will be increasingly important to identify and monitor areas where shallow-water species extend into mesophotic coral ecosystems (Bongaerts et al., 2017; Pyle et al., 2016; Rooney et al., 2010).
Within the WHHFA, coral covers 17.10 km^2 (7.4%) of the seafloor, and 0.97 km^2 (5.7%) of that coral rich area is deeper than 30 m. This distribution highlights the importance of protecting and properly managing coral in deeper waters because mounting stress from climate change and human activities may further shift the distribution of coral cover to mesophotic depths where these impacts are dampened (Bongaerts et al., 2010). Current research is beginning to illustrate that the extent and diversity of mesophotic reefs is much greater than previously thought (Pyle et al., 2016) and that the shallow portion of mesophotic coral reefs (30–60 m depths) offer habitat for shallow-water marine organisms (Kahng et al., 2014). Coral coverage within this area of the mesophotic is dominated by shallow-water coral including; *Pocillopora meandrina*, *Pocillopora damicornis*, *Montipora capitata,* and *Porites lobata*. One species, *Montipora capitata,* dominates coral cover down to 75 m depth (Rooney et al., 2010). The upper MCE may provide a critical opportunity for refuge when shallow reef ecosystems are heavily impacted or destroyed.
Without details of the seafloor habitat, resource managers, policy makers, and stakeholders are poorly equipped to protect and manage marine habitats. By providing a baseline characterization of the benthic seascape and habitats throughout the WHHFA, the data and maps created have the potential to facilitate development of actionable policies, plans, and management practices, ensuring healthy fish and coral populations and improved fisheries.

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