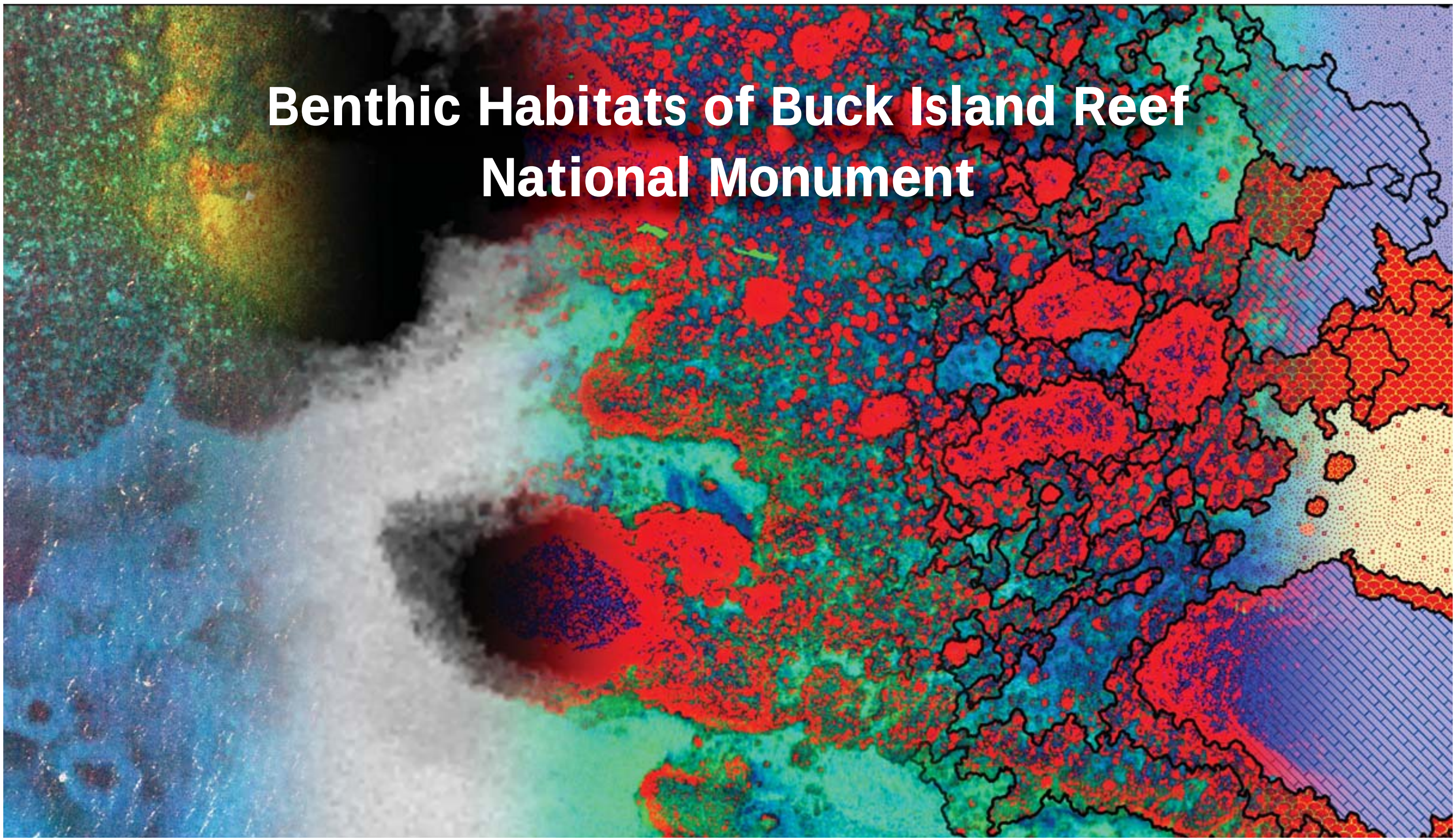

Benthic Habitats of Buck Island Reef National Monument

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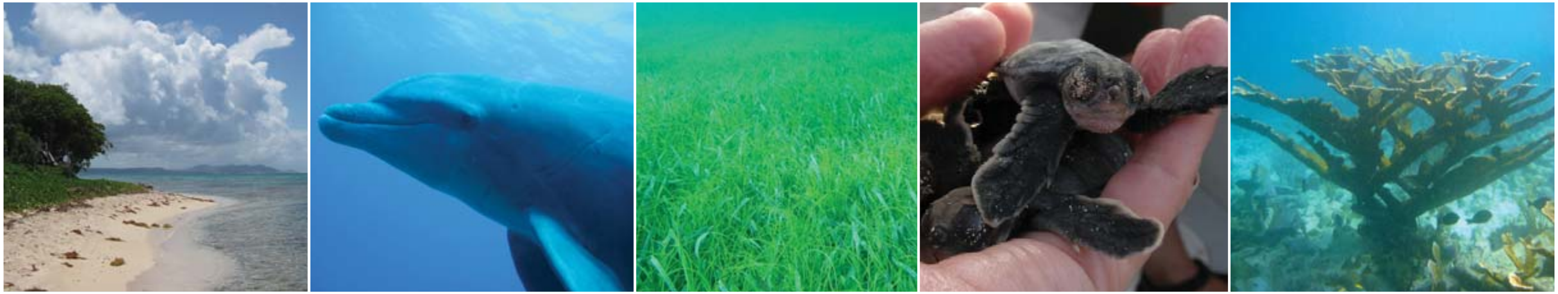

January 2012

NOAA TECHNICAL MEMORANDUM NOS NCCOS 142

NOAA NCCOS Center for Coastal Monitoring and Assessment

Acknowledgements

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Benthic Habitats of Buck Island Reef National Monument

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ABOUT THIS DOCUMENT

This report describes the creation and assessment of a shallow (0 ≤50 m), moderate (50 ≤1,000 m) and deep-water (1,000 ≤1,830 m) benthic habitat map for the Buck Island Reef National Monument (BIRNM) north of St. Croix in the U.S. Virgin Islands. The objective of this effort, conducted by NOAA's Center for Coastal Monitoring and Assessment's Biogeography Branch in partnership with the U.S. National Park Service (NPS), was to provide spatially-explicit information describing the benthic habitat types and live coral cover present in the full extent of BIRNM's boundaries. The three resulting habitat maps, generated using a combination of semi-automated classification and visual interpretation techniques, represent the first digital maps of the moderate and deep-water areas inside the Monument.

This report consists of three primary components: 1) a description of the classification scheme used to categorize the different seafloor habitats, 2) a discussion of the techniques used to create the habitat map, and 3) an assessment of the shallow-water habitat map's thematic accuracies. These habitat maps will be used by the U.S. National Park Service and other local partners for planning research and monitoring activities, and will support the management and conservation of St. Croix's BIRNM.

This work is part of NOAA Coral Reef Conservation Program's national coral reef ecosystem integrated mapping and monitoring studies throughout the U.S. Caribbean (Monaco et al., 2001).

For more information on this effort please visit:
http://ccma.nos.noaa.gov/ecosystems/coralreef/stcroix.aspx

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EXECUTIVE SUMMARY

Underwater photograph of Staghorn Coral (*Acropora cervicornis*), which is listed as “threatened” under the Endangered Species Act.

NOAA’s Center for Coastal Monitoring and Assessment’s Biogeography Branch has mapped and characterized large portions of the coral reef ecosystems inside the U.S. coastal and territorial waters, including the U.S. Caribbean. The complementary protocols used in these efforts have enabled scientists and managers to quantitatively compare different marine ecosystems in tropical U.S. waters. The Biogeography Branch used these same general protocols to generate three seamless habitat maps of the Bank/Shelf (i.e., from 0 ≤50 meters) and the Bank/Shelf Escarpment (i.e., from 50 ≤1,000 meters and from 1,000 ≤ 1,830 meters) inside Buck Island Reef National Monument (BIRNM). While this mapping effort marks the fourth time that the shallow-water habitats of BIRNM have been mapped, it is the first time habitats deeper than 30 meters (m) have been characterized. Consequently, this habitat map provides information on the distribution of mesophotic and deep-water coral reef ecosystems and serves as a spatial baseline for monitoring change in the Monument.

A benthic habitat map was developed for approximately 74.3 km^2 or 98% of the BIRNM using a combination of semi-automated and manual classification methods. The remaining 2% was not mapped due to lack of imagery in the western part of the Monument at depths ranging from 1,000 to 1,400 meters. Habitats were interpreted from orthophotographs, LiDAR (Light Detection and Ranging) imagery and four different types of MBES (Multibeam Echosounder) imagery. Three minimum mapping units (MMUs) (100, 1,000 and 5,000 m^2) were used because of the wide range of depths present in the Monument. The majority of the area that was characterized was deeper than 30 m on the *Bank/Shelf Escarpment*. This escarpment area was dominated by uncolonized sand which transitioned to mud as depth increased. Bedrock was exposed in some areas of the escarpment, where steep slopes prevented sediment deposition. Mesophotic corals were seen in the underwater video, but were too sparsely distributed to be reliably mapped from the source imagery. Habitats on the *Bank/Shelf* were much more variable than those seen on the *Bank/Shelf Escarpment*. The majority of this shelf area was comprised of coral reef and hardbottom habitat dominated by various forms of turf, fleshy, coralline or filamentous algae. Even though algae was the dominant biological cover type, nearly a quarter (24.3%) of the Monument’s *Bank/Shelf* benthos hosted a cover of 10%-<50% live coral.

In total, 198 unique combinations of habitat classes describing the geography, geology and biology of the seafloor were identified from the three types of imagery listed above. No thematic accuracy assessment was conducted for areas deeper than about 50 meters, most of which was located in the Bank/Shelf Escarpment. The thematic accuracy of classes in waters shallower than approximately 50 meters ranged from 81.4% to 94.4%. These thematic accuracies are similar to those reported for other NOAA benthic habitat mapping efforts in St. John (>80%), the Main Eight Hawaiian Islands (>84.0%) and the Republic of Palau (>80.0%). These digital maps products can be used with confidence by scientists and resource managers for a multitude of different applications, including structuring monitoring programs, supporting management decisions, and establishing and managing marine conservation areas. The final deliverables for this project, including the benthic habitat maps, source imagery and in situ field data, are available to the public on a NOAA Biogeography Branch website (http://ccma.nos.noaa.gov/ecosystems/coralreef/stcroix.aspx) and through an interactive, web-based map application (http://ccma.nos.noaa.gov/explorer/biomapper/biomapper.html?id=BUIS).

This report documents the process and methods used to create the shallow to deep-water benthic habitat maps for BIRNM. Chapter 1 provides a short introduction to BIRNM, including its history, marine life and ongoing research activities. Chapter 2 describes the benthic habitat classification scheme used to partition the different habitats into ecologically relevant groups. Chapter 3 explains the steps required to create a benthic habitat map using a combination of semi-automated and visual classification techniques. Chapter 4 details the steps used in the accuracy assessment and reports on the thematic accuracy of the final shallow-water map. Chapter 5 summarizes the type and abundance of each habitat class found inside BIRNM, how these habitats compare to past habitat maps and outlines how these new habitat maps may be used to inform future management activities.

Seagrass (*Thalassia testudinum*) habitat in BIRNM.

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CHAPTER 1: INTRODUCTION

1.1. DESCRIPTION OF BUCK ISLAND REEF NATIONAL MONUMENT

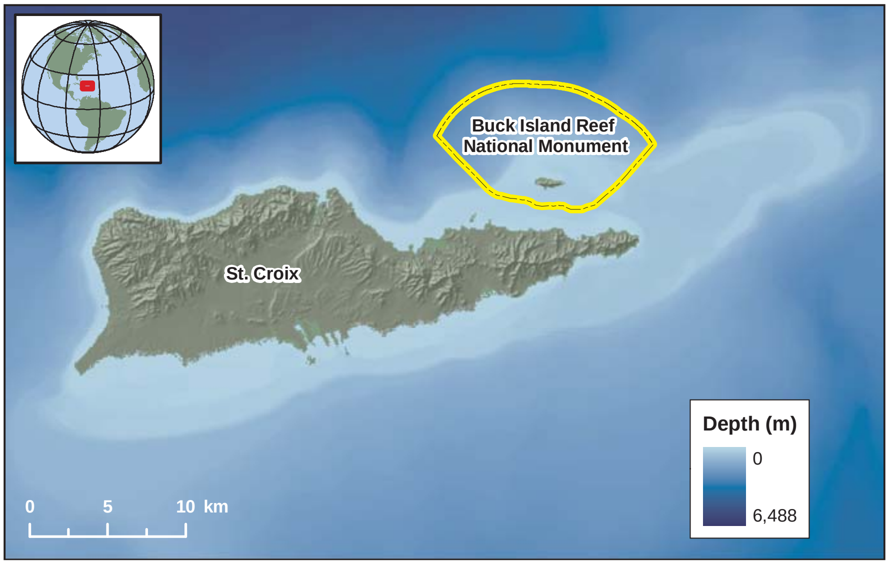

Figure 1.1. Location of BIRNM north of St. Croix in the U.S. Virgin Islands. The monument's boundaries are denoted by the yellow and black dashed line.

Buck Island Reef National Monument (BIRNM) is located on the northeastern shelf of St. Croix, in the U.S. Virgin Islands (USVI) (Figure 1.1). The monument is managed by the U.S. National Park Service (NPS) and was originally designated in 1961 by Presidential Proclamation 3443. This proclamation preserved Buck Island and the surrounding seafloor, which at that time included "one of the finest marine gardens in the Caribbean Sea" (NPS, 2011). The original Monument encompassed approximately 3.56 km^2 of area (including Buck Island). Fishing was prohibited in the eastern part of the Monument, making parts of BIRNM area one of the first no-take marine reserves in the Caribbean region. In 1975, the 1962 boundaries were modified slightly by Presidential Proclamation 4346, but it was not until 2001 that the Monument was greatly expanded to its current boundaries. Also at that time, new regulations were enacted making the entire Monument a no-take and restricted anchoring zone. These modifications resulted in a 10-fold increase in protection of shallow water (< 30 m) hardbottom and sand habitat types and a seven-fold increase for seagrasses when compared with the 1962 Monument (Pittman et al. 2008; Kendall et al. 2004). The southern and eastern boundary of the Monument adjoins the East End Marine Park, a multi-use MPA established in 2003 and managed by the U.S. Virgin Islands Government.

1.2. WHY MAP BIRNM?

The mosaic of coral reef, seagrass and sand habitats in BIRNM are home to a diversity of marine organisms, including Hawksbill Turtles (*Eretmochelys imbricata*), Elkhorn Coral (*Acropora palmata*) and Staghorn Coral (*Acropora cervicornis*), all of which are federally protected under the Endangered Species Act (NOAA OPR, 2011). In addition to providing habitat for a variety of species, these marine resources also provide valuable ecosystem services to the local community, including shoreline protection, fisheries replenishment, recreation, and tourism (Rothenberger et al. 2008). However, coral reef ecosystems in St. Croix and throughout the U.S. Caribbean are under increasing pressure from environmental and anthropogenic stressors that threaten them (Bythell et al. 1993; Catanzaro et al. 2002; Rogers and Beets, 2001; Jeffrey et al. 2005; Rothenberger et al. 2008; Pittman et al. 2008). In order to better evaluate and address these threats, a baseline understanding and periodic evaluation of the benthic communities and associated living marine resources is needed by scientists and resource managers. Habitat maps, in particular, are an integral component to this process, as they support an effective ecosystem-based approaches to management. Habitat maps provide a spatially explicit representation of benthic structure and biological cover. The spatial products developed for this project will: (1) inform local NPS managers as to the existing distribution of resources, (2) provide a baseline for future comparative efforts, (3) help locate sensitive marine communities, and (4) guide monitoring efforts and prioritize management actions. Furthermore, benthic habitat maps can help understand the ecological patterns and processes across the seascape. Recent research in seascape ecology has demonstrated that the spatial arrangement of habitat types and the composition of the seascape mosaic can help explain faunal distribution patterns (Pittman et al. 2007a; Kendall et al. 2011). When linked to behavioral data such as fish movement pathways, benthic habitat maps provide new insights into the ecology of individual animals (Hitt et al. 2011).

Given the importance of habitat maps, NOAA's Center for Coastal Monitoring and Assessment's (CCMA) Biogeography Branch (BB) developed the analytical protocols used for mapping benthic habitats throughout all U.S.

Figure 1.2. This map denotes areas in the U.S. Caribbean where habitats on the seafloor have been characterized.

jurisdictions, states, and territories, including the U.S. Caribbean (Kendall et al. 2001) (Figure 1.2). These protocols enable scientists and managers to quantitatively compare marine ecosystems throughout the U.S. The BB used these same general protocols to generate seamless habitat maps of the shallow-water, moderate-depth and deep-water ecosystems inside the BIRNM boundaries (Figure 1.3). Habitats were divided into these three depth bins because no one sensor was capable of mapping the wide range of depths present in the Monument. The habitat maps in these three depth bins provide spatially-explicit information describing the geomorphological structure, biological cover and live coral cover present inside BIRNM's present boundaries. The shallow-water map developed during this project is the fourth time habitats shallower than 30 m have been characterized inside the Monument. However, the moderate and deep-water maps developed during this project were the first of their kind, as previous mapping efforts were only able to characterize habitats shallower than 30 m using aerial orthophotos. Thus, these two new habitat maps filled an important knowledge gap by providing critical baseline information about mesophotic coral reef ecosystems inside the Monument. In addition to filling information gaps about mesophotic corals, the products developed during this project also filled knowledge gaps about the depth and topography of the seafloor. Sensors used in previous mapping efforts were not designed to collect bathymetric (i.e., depth) information. New sensors, specifically LiDAR and MBES, were used to collect this information and to meet this management need. The topographic information derived from the depth imagery can also be used to develop robust spatially explicit models of species distributions and assemblage diversity (Pittman et al. 2007b, Pittman et al. 2009, Pittman and Brown 2011) as well as be used to forecast species responses to environmental changes, such as reef flattening, over time (Pittman et al. in press).

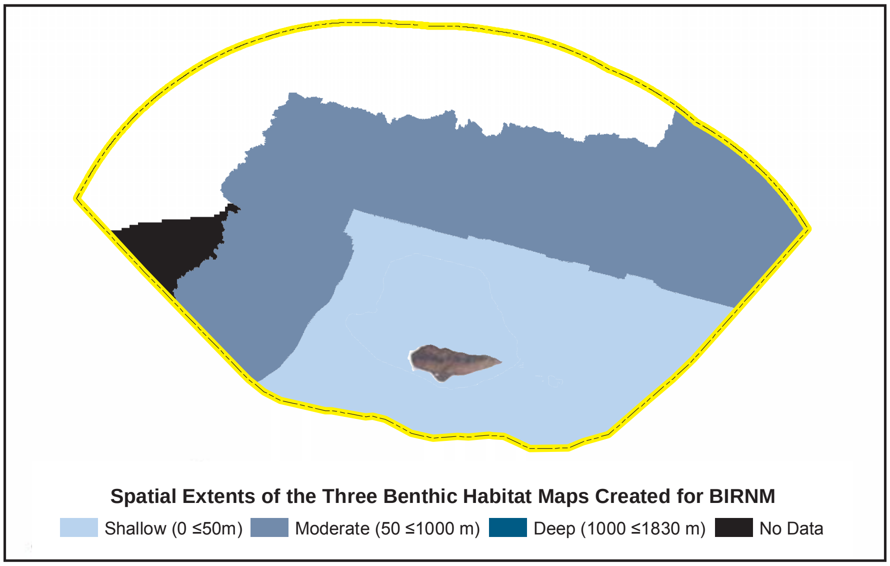

Figure 1.3. The spatial extents of the three benthic habitat maps created for BIRNM. In total, 23.7 km^2 of shallow-water, 31.1 km^2 of moderate-depth and 19.3 km^2 of deep-water benthic habitats were characterized. A 1.9 km^2 area inside BIRNM was not characterized due to a lack of seafloor imagery. An accuracy assessment was only conducted for the shallow-water habitat map.

The bathymetry and habitat maps created by BB represent two products in a suite of deliverables designed to support the management of BIRNM. In particular, these products include:

- GIS files of benthic habitats
- A classification manual
- Description of the methods used to create the habitat maps
- Bathymetry
- Source datasets, including orthophotos, LiDAR and MBES imagery
- Ground validation field data
- Accuracy assessment field data

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CHAPTER 2: BENTHIC HABITAT CLASSIFICATION SCHEME

2.1. CLASSIFICATION SCHEME

A habitat classification scheme allows scientists to systematically group habitat types based on common ecological characteristics. The initial task in any mapping effort is to develop a classification scheme by clearly identifying and defining discrete habitat classes. This scheme is subsequently used to guide the delineation and attribution of polygons during the mapping process. Consequently, it is critical for map users to have an understanding of the classification system, its structure and its definitions. This understanding allows users to decide on the appropriate uses for, and limitations of, the habitat map.


Photograph of the Great Star Coral (*Montastraea cavernosa*).

The BIRNM habitat classification scheme defines benthic communities based on five primary coral reef ecosystem attributes: 1) broad geographic zone, 2) geomorphological structure, 3) percent hardbottom, 4) dominant biological cover, and 5) amount of live coral cover. Habitat features are described by varying levels of detail (i.e., major and minor categories nested within them), so users can refine the information depicted by the habitat map to best suit their research or management needs. In total, 198 unique combinations of zone, major structure, detailed structure, percent hardbottom, major cover, percent cover and live coral cover were identified from the aerial orthophotos, LiDAR and acoustic imagery.

2.1.1. Comparison to Previous BB Classification Scheme

Many factors were considered when developing the BIRNM habitat classification scheme. These factors included: (1) how it would dovetail with existing classification schemes for marine habitats, particularly in deep-water (>50 m); (2) what limitations were associated with the source imagery; (3) how best to create a habitat map from multiple imagery sources (i.e., two aerial optical and four acoustic sensors) with six different spatial resolutions; (4) what would be an appropriate minimum mapping unit (MMU); and (5) how much quantitative *in situ* underwater video would be needed to create a habitat map.

To simplify this process, the habitat classification scheme implemented in BIRNM was based on the classification scheme developed by NOAA to map shallow-water (≤ 30 m) and moderate depth (≤ 50 m) benthic habitats around St. John in the U.S. Virgin Islands (Zitello et al. 2009; Costa et al. 2009). Specifically, the geographic zones, major and detailed geomorphological structure and biological cover types were the same for both habitat maps (Table 2.1), although some habitat types were present in BIRNM were not present in St. John and vice versa. Also, the BIRNM habitat map had three different MMUs (i.e., 100 m^2, 1,000 m^2 and 5,000 m^2) due to the different spatial resolutions of the source imagery, whereas the St. John maps only had one MMU (1,000 m^2).

While the map classifications created for BIRNM are similar to the maps created for St. John in 2009, they are different from the benthic habitat map created in 2001 by NOAA for all of St. Croix (Kendall et al. 2001). The primary differences between NOAA's 2001 and 2011 habitat maps include: (1) the separation of biological cover from habitat structure; (2) a fourfold decrease in the size of the MMU in shallow-waters; (3) the addition of more detailed structure classes due to the higher resolution of the source imagery and much smaller geographic scope of the map project; and (4) the addition of two new map attributes called *Percent Hardbottom* and *Percent Live Coral Cover*. *Percent Live Coral Cover* describes the amount of live coral cover within a habitat feature at a fine spatial scale (i.e., at the scale of the ground validation videos and photos). These new attributes are related because *Percent Live Coral Cover* refers only to the hardbottom component of any mapped polygon (and not to the entire polygon itself). For instance, an attribution of 50% ≤ 70% hardbottom and 10% ≤ 50% live coral indicates that 50% ≤ 70% of that polygon is colonized by 10% ≤ 50% live coral. The remainder (30% ≤ 50%) of that

Table 2.1. The classification scheme used to classify benthic habitats in Buck Island Reef National Monument in 2011. This classification scheme was modeled after the one used in St. John in 2009 (Zitello et al. 2009; Costa et al. 2009). Classes with a line through them were not present in BIRNM. Classes that are underlined were merged into another class (e.g., Coralline Algae was included in the Algae class). Classes in italics were present in the BIRNM habitat maps, but not in St. John habitat maps.

GEOGRAPHIC ZONE	GEOMORPHOLOGICAL STRUCTURE		BIOLOGICAL COVER
Back Reef	Coral Reef and Hardbottom (Hard)		Major Cover
Bank/Shelf	Aggregate Reef		Algae
Bank/Shelf Escarpment	Aggregated Patch Reefs		Coralline Algae
Channel	Individual Patch Reef		Live Coral
~~Dredged~~	Pavement		Mangrove
Fore Reef	Pavement with Sand Channels		No Cover
Lagoon	*Reef Rubble*	Percent Hard	Seagrass
Land	Rhodoliths	0% ≤ 10%	Unclassified
Reef Crest	Rhodoliths with Scattered Coral & Rock	10% ≤ 30%	Unknown
Reef Flat	Rock/Boulder	30% ≤ 50%	Percent Major Cover
Salt Pond	~~Spur and Groove~~	50% ≤ 70%	10% ≤ 50%
Shoreline Intertidal	Unknown	70% ≤ 90%	50% ≤ 90%
	Unconsolidated Sediment (Soft)	90% - 100%	90% ≤ 100%
	Mud	N/A	N/A
	Sand	Unknown	Unknown
	Sand with Scattered Coral and Rock		Percent Coral Cover
	Unknown		0% ≤ 10%
	Other Delineations		10% ≤ 50%
	Artificial		~~50% ≤ 90%~~
	Land		~~90% ≤ 100%~~
	Unknown		N/A
			Unknown

polygon is colonized by < 10% live coral. In addition to the 2001 NOAA habitat map, Kendall and Miller, 2008 also produced a habitat map for BIRNM at a finer scale (i.e., MMU = 100 m^2) from the same imagery used in 2001. This finer scale map was compared to the new NOAA 2011 map in the Discussion section of this report.

2.1.2. Geographic Zones

Eleven distinct and non-overlapping geographic zone types were mapped by visually interpreting aerial and acoustic imagery. Zone refers to each benthic community's geographic location. It does not address a polygon's substrate or biological cover types. For example, the zone *Lagoon* is often located adjacent to the zone *Shoreline Intertidal*. However, neither *Lagoon* nor *Shoreline Intertidal* zone types describe the structural or biological habitat within them. Additionally, the location of particular zone types may change depending on whether the system is a barrier reef, fringing reef or when no emergent reef crest is present (Figures 2.1, 2.2 and 2.3, respectively). Habitats or features with areas smaller than the MMUs (100 m^2, 1,000 m^2 and 5,000 m^2) were not considered. A brief description of each geographic zone is provided in the following text.

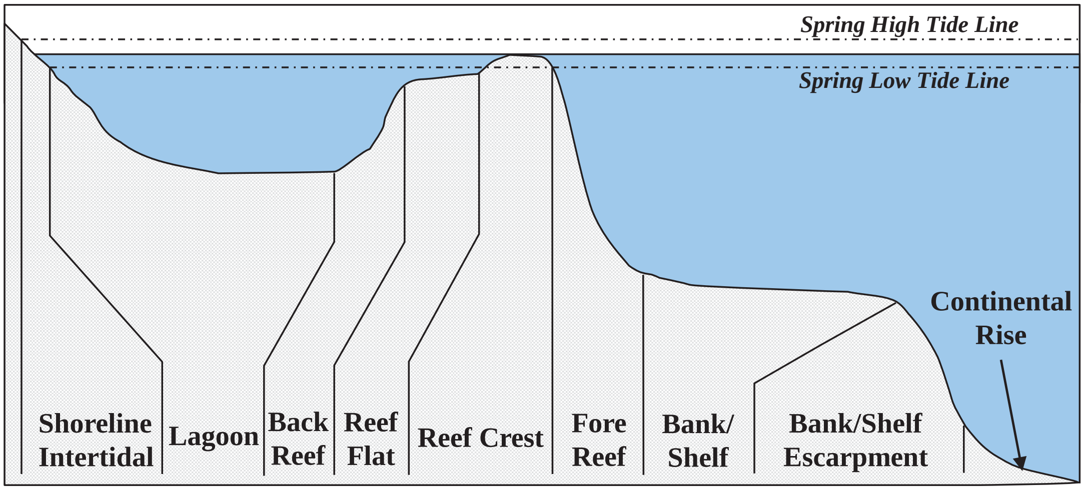

Figure 2.1. Cross-section of zone types when a barrier reef is present. The reef is separated from the shore by a relatively wide, deep lagoon.

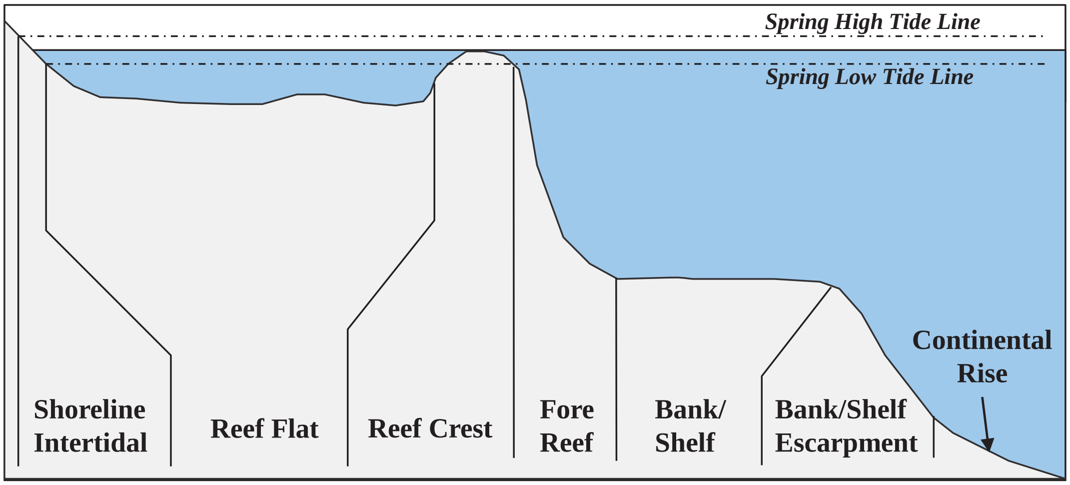

Figure 2.2. Cross-section of zone types when a fringing reef is present. The reef platform is continuous with the shore.

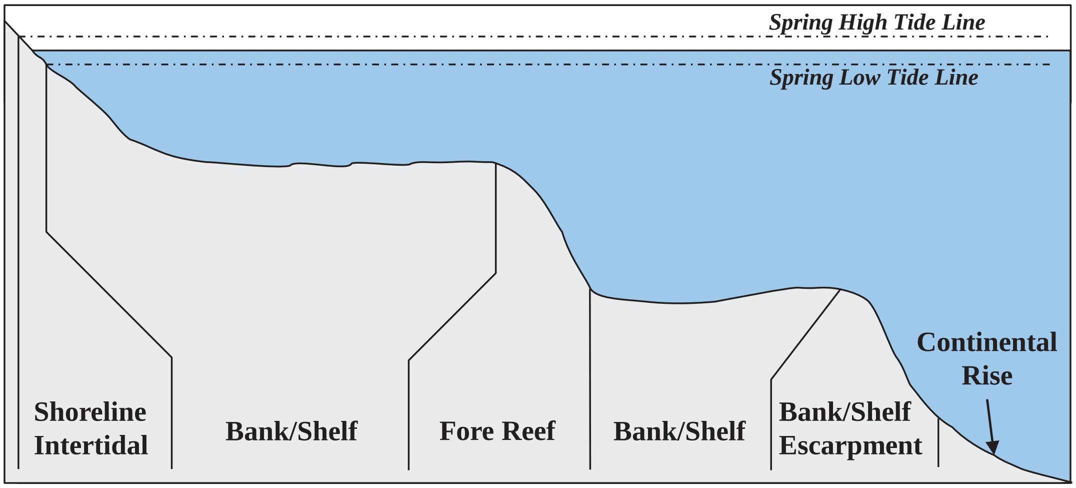

Figure 2.3. Cross-section of zone types when no emergent reef crest is present.

Back Reef
Area landward of a *Reef Crest* that slopes downward towards the seaward edge of a *Lagoon* floor or *Bank/Shelf*. This zone is present only when a *Reef Crest* exists (Figure 2.4a).

Bank/Shelf
Deeper water area (relative to the shallow water in a lagoon) extending offshore from the seaward edge of the *Fore Reef* or shoreline to the beginning of the escarpment where the insular shelf drops off into deep, oceanic water. If no *Reef Crest* is present, the *Bank/Shelf* is the flattened platform between the *Fore Reef* and deep open ocean waters or between the Shoreline Intertidal zone and open ocean (Figure 2.4b).

Bank/Shelf Escarpment
The edge of the bank/shelf where depth increases rapidly into deep oceanic water. This zone begins at approximately 30 meters, near the depth limit of features visible in aerial orthophotographs. This zone extends well into depths exceeding those that can be seen on aerial orthophotographs, or LiDAR and is intended to capture the transition from the bank/shelf to deep waters of the open ocean (Figure 2.4b).

Channel
Naturally occurring channels that cut across several different zones (Figure 2.4c).

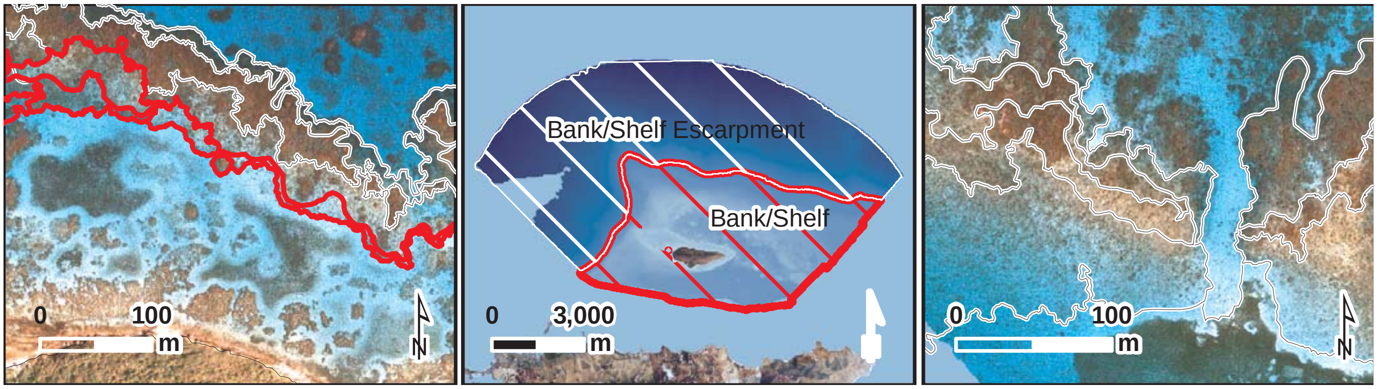

Figure 2.4. (a) The red polygon outlines an example of the geographic zone, *Back Reef*, north of Buck Island; (b) The red and white hatched polygons outline examples of the geographic zones, *Bank/Shelf* and *Bank/Shelf Escarpment* respectively, inside BIRNM; and (c) The red polygon outlines an example of the geographic zone, *Channel*, west of Buck Island.

Dredged
Area in which natural geomorphology is disrupted or altered by excavation or dredging. This geographic zone is not present in Buck Island Reef National Monument.

Fore Reef
Area along the seaward edge of the *Reef Crest* that slopes into deeper water to the landward edge of the *Bank/Shelf* platform. Features not associated with an emergent *Reef Crest* (but still having a seaward-facing slope that is significantly greater than the slope of the *Bank/Shelf*) are also designated as *Fore Reef* (Figure 2.5a).

Lagoon
Shallow area (relative to the deeper water of the *Bank/Shelf*) between the *Shoreline Intertidal* zone and the *Back Reef* of a reef or a barrier island. This zone is typically protected from the high-energy waves commonly experienced on the *Bank/Shelf* and *Reef Crest* zones (Figure 2.5b).

Land
Terrestrial features at or above the spring high tide line. Shoreline delineations describing the boundary between land and submerged zones are established at the wrack line where possible or the wet line at the time of imagery acquisition (Figure 2.5c). The wrack line is a line of organic and/or anthropogenic debris (above the mean high tide line) that has been deposited by the highest tides.

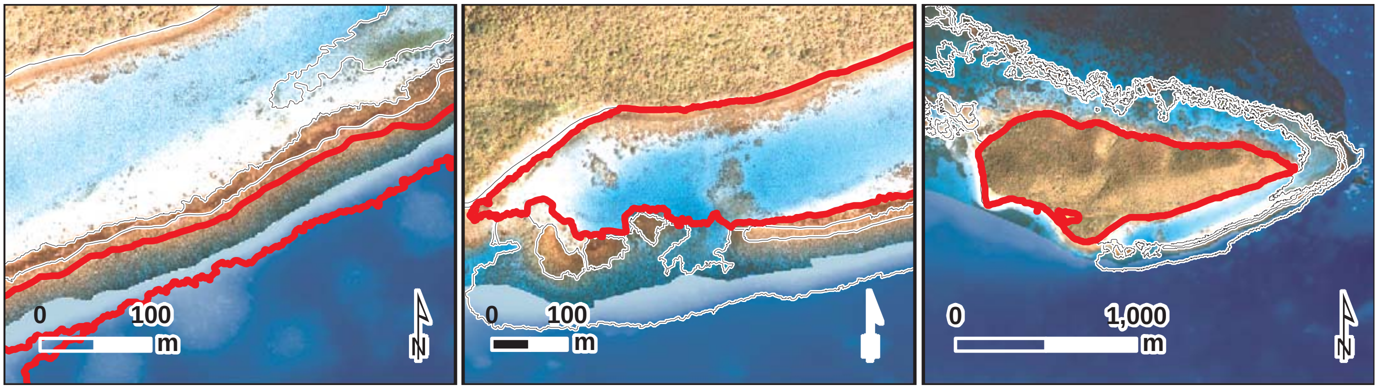

Figure 2.5. (a) The red polygon outlines an example of the geographic zone, *Fore Reef*, south of Buck Island; (b) The red polygon outlines an example of the geographic zone, *Lagoon*, south of Buck Island; and (c) The red polygon outlines an example of the geographic zone, *Land*, inside BIRNM.

Reef Crest

The flattened, emergent (especially during low tides) or nearly emergent segment of a reef. This zone of high wave energy lies between the *Fore Reef* and *Back Reef* or *Reef Flat* zones. Breaking waves are often visible in overhead imagery at the seaward edge of this zone (Figure 2.6a).

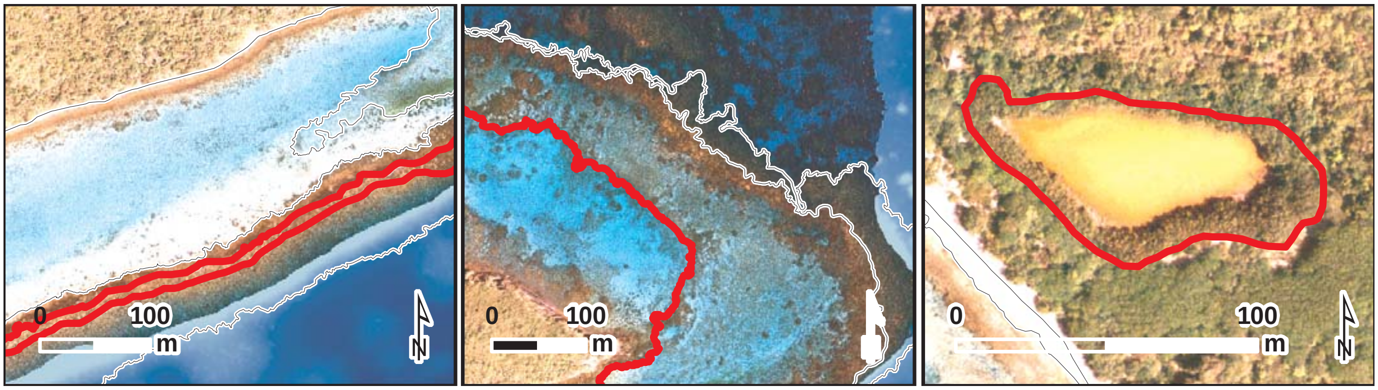

Figure 2.6. (a) The red polygon outlines an example of the geographic zone, *Reef Crest*, south of Buck Island; (b) The red polygon outlines an example of the geographic zone, *Reef Flat*, north and east of Buck Island; and (c) The red polygon outlines an example of the geographic zone, *Salt Pond*, on Buck Island.

Reef Flat

Shallow, semi-exposed area with little relief between the *Shoreline Intertidal* zone and the *Reef Crest*. This broad, flat area often exists immediately landward of a *Reef Crest* and may extend to the shoreline or drop into a *Back Reef*. This zone is protected from the high-energy waves commonly experienced on the *Bank/ Shelf* and *Reef Crest* zones (Figure 2.6b).

Salt Pond

Enclosed area immediately landward of the shoreline with a permanent or intermittent flooding regime of saline to hypersaline waters (Figure 2.6c).

Shoreline Intertidal

Area between the spring high tide line (or landward edge of emergent vegetation when present) and lowest spring tide level at the land/sea interface. Emergent segments of barrier reefs are excluded from this zone (see *Reef Crest*). Typically, this zone is narrow due to the small tidal range and steep slopes in the U.S. Caribbean (Figure 2.7).

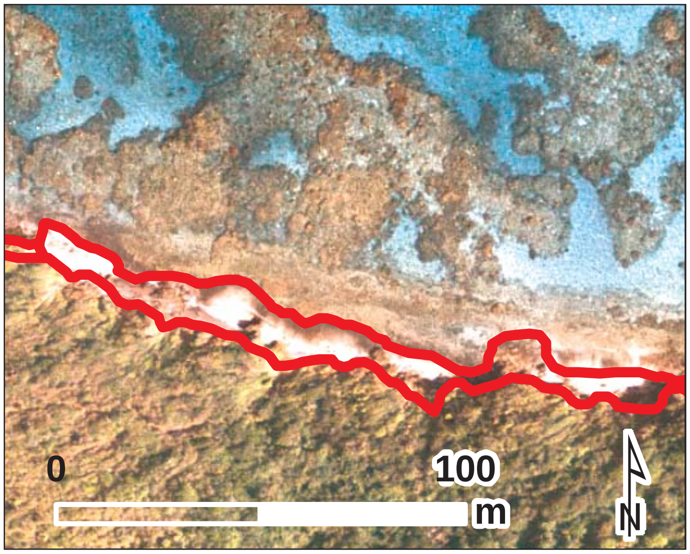

Figure 2.7. The red polygon outlines an example of the geographic zone, *Shoreline Intertidal,* north of Buck Island.

2.1.3. Geomorphological Structure Types

Thirteen distinct and non-overlapping geomorphological structure types were mapped by interpreting aerial orthophotos, LiDAR and acoustic imagery. Geomorphological structure refers to a feature's dominant physical composition and does not address geographic location (e.g., in a *Lagoon*). Structure types are defined in a collapsible hierarchy ranging from three major classes (*Coral Reef and Hardbottom, Unconsolidated Sediment*, and *Other Delineations*), to thirteen detailed classes (*Aggregate Reef, Aggregated Patch Reefs, Individual Patch Reef, Pavement, Pavement with Sand Channels, Reef Rubble, Rhodoliths, Rhodoliths with Scattered Coral and Rock, Rock/Boulder, Spur and Groove, Mud, Sand, Sand with Scattered Coral and Rock, Artificial, Land* and *Unknown*). Habitats or features with areas smaller than the MMU were not considered. The MMU was 100 m^2, 1,000 m^2 and 5,000 m^2 for habitat maps produced for the shallow-water (0 m ≤ 50 m), moderate-depth (>50 m <1,000 m) and deep-water (≥ 1,830 m) respectively.

Coral Reef and Hardbottom

Coral reef and Hardbottom habitats are areas on the seafloor with solid substrates, including bedrock, boulders and/or the deposition of calcium carbonate by reef building organisms. Substrates typically have no sediment cover, but a thin veneer (i.e., several millimeters to a few centimeters) of sand or mud may be present at times. Detailed structure classes include *Aggregate Reef, Aggregated Patch Reefs, Individual Patch Reef, Pavement, Pavement with Sand Channels, Reef Rubble, Rhodoliths, Rhodoliths with Scattered Coral and Rock, Rock/ Boulder* and *Spur and Groove.*

Aggregate Reef

Continuous, high-relief coral formation of variable shapes lacking sand channels of *Spur and Groove*. Includes linear coral formations that are oriented parallel to the shelf edge (Figure 2.8).

Figure 2.8. The black polygon outlines an example of the detailed structure type, *Aggregate Reef*, around Buck Island as seen in aerial orthophotos and acoustic imagery (left). The underwater photographs (middle and right) depict examples of aggregate reef in BIRNM.

Aggregated Patch Reefs

Aggregated Patch Reefs have the same defining characteristics as an *Individual Patch Reef*. However, this class refers to clustered patch reefs that cover ≥ 10% of the entire polygon, but are too small (less than the MMU) or are too close together to map individually. Where aggregated patch reefs share sand halos, the halo is included in the polygon (Figure 2.9). If the density of small or aggregated coral heads is <10% of the entire polygon, this structure type is described as *Sand with Scattered Coral and Rock*.

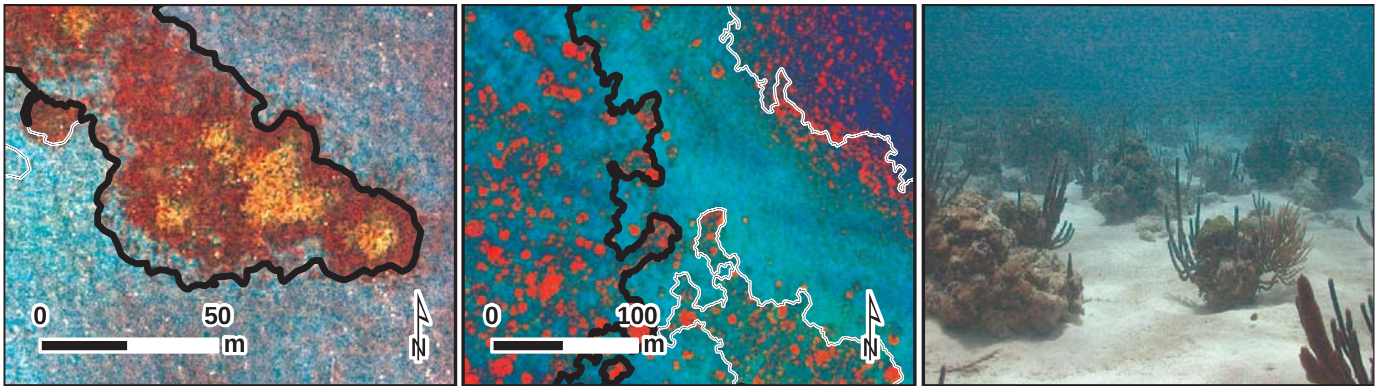

Figure 2.9. The black polygons outline examples of the detailed structure type, *Aggregated Patch Reefs*, around Buck Island as seen in aerial orthophotos (left) and acoustic imagery (middle). The underwater photograph (right) depicts an example of aggregated patch reefs in BIRNM.

Individual Patch Reef

Individual patch reefs are coral formations that are surrounded by bare sand, seagrass or other habitats , which isolate them from other coral formations. They do not have an organized structural axis relative to the shoreline or the contours of the shelf edge. They are characterized by a roughly circular or oblong shape with a vertical relief of one meter or more in relation to the surrounding seafloor (Figure 2.10). *Individual Patch Reefs* are larger than or equal to the MMU.

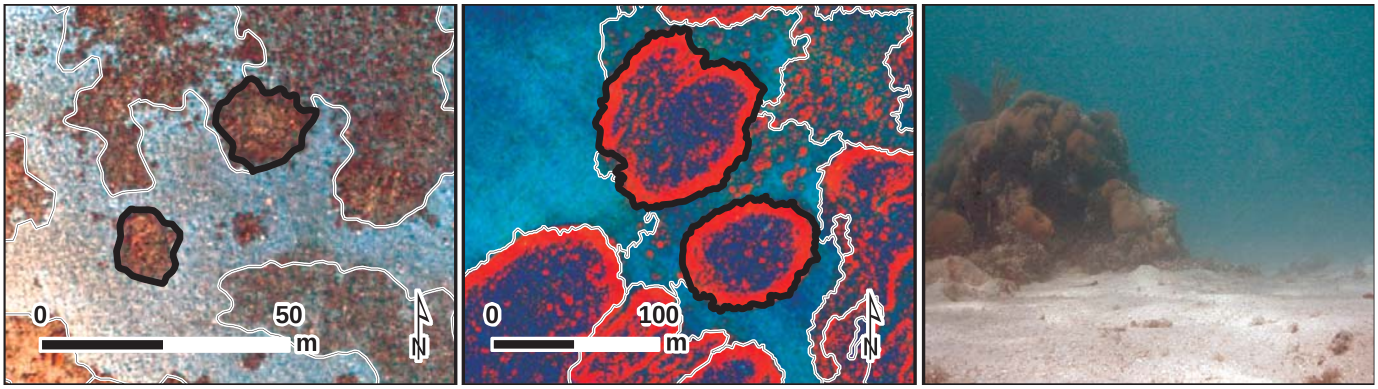

Figure 2.10. The black polygons outline examples of the detailed structure type, *Individual Patch Reef*, around Buck Island as seen in aerial orthophotos (left) and acoustic imagery (middle). The underwater photograph (right) depicts an example of an individual patch reef in BIRNM.

Pavement

Flat, low-relief or sloping solid carbonate rock with little or no fine-scale rugosity that is covered with algae, hard coral, gorgonians, zooanthids or other sessile vertebrates that are dense enough to partially obscure the underlying surface. On less colonized *Pavement* features, rock may be covered by a thin sand veneer or turf algae (Figure 2.11).

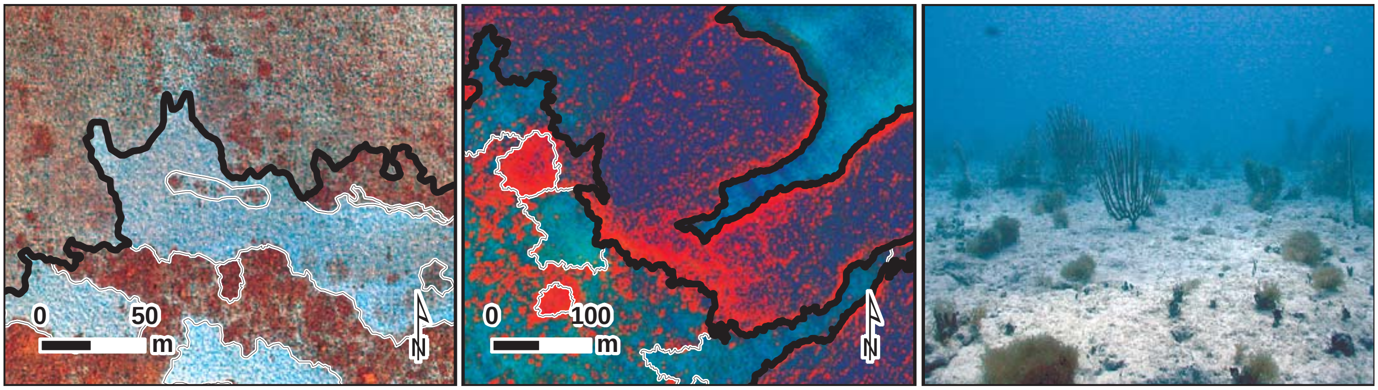

Figure 2.11. The black polygons outline examples of the detailed structure type, *Pavement*, around Buck Island as seen in aerial orthophotos (left) and acoustic imagery (middle). The underwater photograph (right) depicts an example of pavement in BIRNM.

Pavement with Sand Channels

Pavement with Sand Channels have the same defining characteristics as *Pavement*, in addition to having periodic sand/surge channels oriented perpendicular to the *Bank/Shelf Escarpment*. The sand/surge channels of this feature have low vertical relief and are typically erosional in origin. This habitat type occurs in areas exposed to moderate wave surge such as the *Bank/Shelf* zone (Figure 2.12).

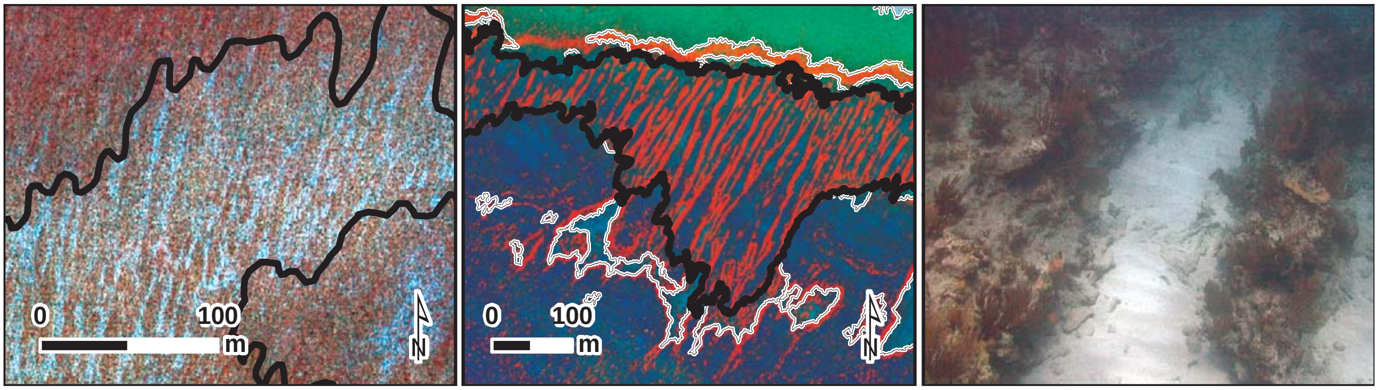

Figure 2.12. The black polygons outline examples of the detailed structure type, *Pavement with Sand Channels*, around Buck Island as seen in aerial orthophotos (left) and acoustic imagery (middle). The underwater photograph (right) depicts an example of pavement with sand channels in BIRNM.

Reef Rubble

Dead, unstable coral rubble often colonized with filamentous or other macroalgae. This habitat often occurs landward of well developed reef formations in the *Reef Crest, Back Reef* or *Reef Flat* zones. Less often, *Reef Rubble* can occur in low density aggregations on broad offshore sand areas (Figure 2.13).

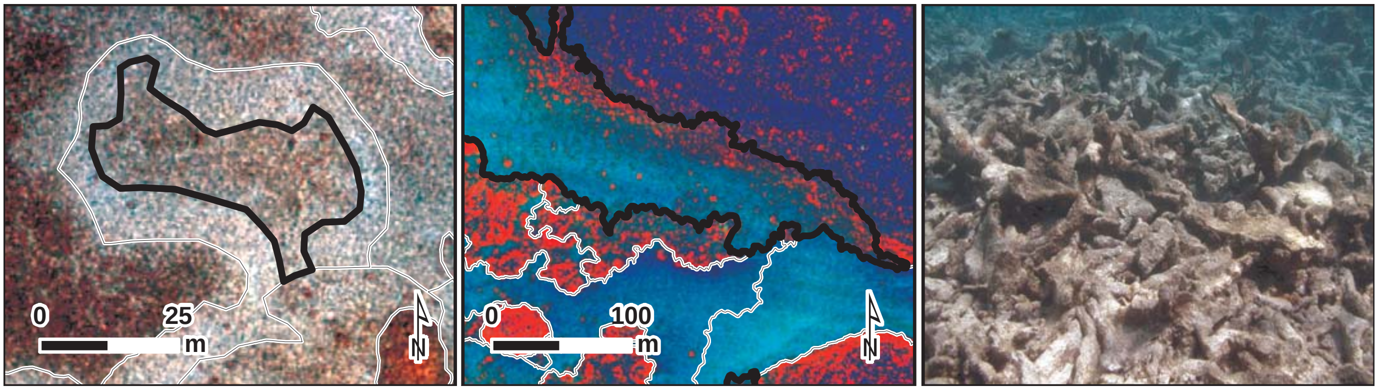

Figure 2.13. The black polygons outline examples of the detailed structure type, *Reef Rubble*, around Buck Island as seen in aerial orthophotos (left) and acoustic imagery (middle). The underwater photograph (right) depicts an example of reef rubble in BIRNM.

Rhodoliths

Areas on the seafloor that are covered by ≥ 10% rhodoliths. Rhodoliths are cylindrical, discoidal, or irregular shaped calcareous nodules averaging approximately 6 cm in diameter (Foster, 2001). These unattached nodules are colonized by successive layers of coralline red algae, and are commonly found in offshore topographic depressions (Figure 2.14). Since rhodoliths are unattached to the seafloor and mobile, their distributions can change quantifiably from year to year.

Figure 2.14. The black polygon outlines an example of the detailed structure type, *Rhodoliths*, around Buck Island as seen in acoustic imagery (left). The underwater photographs (middle and right) depict examples of rhodoliths in BIRNM.

Rhodoliths with Scattered Coral and Rock

Areas on the seafloor where ≥ 10% of the entire polygon is covered by rhodoliths, and < 10% of the entire polygon is covered by scattered rocks or isolated coral heads that are too small to be delineated individually (Figure 2.15). If the density of the rocks and/or coral heads is ≥ 10% of the entire polygon's area, then the structure type is described as *Aggregated Patch Reefs*.

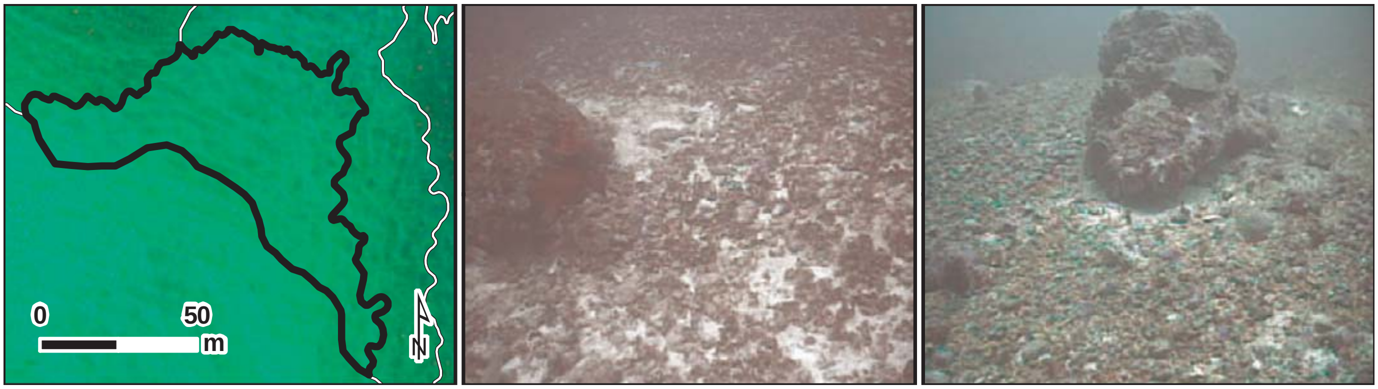

Figure 2.15. The black polygon outlines an example of the detailed structure type, *Rhodoliths with Scattered Coral and Rock*, around Buck Island as seen in acoustic imagery (left). The underwater photographs (middle and right) depict examples of rhodoliths with scattered coral and rock in BIRNM.

Rock/Boulder

Aggregation of solid carbonate blocks extending offshore from the island bedrock or loose carbonate fragments that have been detached and transported from their native beds (Figure 2.16). Individual boulders range in diameter from 0.25-3 m as defined by the Wentworth scale (Wentworth, 1922).

Figure 2.16. The black polygons outline examples of the detailed structure type, *Rock/Boulder*, around Buck Island as seen in aerial orthophotos (left). The underwater photographs (middle and right) depict examples of rock/boulder in the shallow and deep-water areas of BIRNM, respectively.

Spur and Groove

Structure having alternating sand and coral formations that are oriented perpendicular to the shore or reef crest. The coral formations (spurs) of this feature typically have a high vertical relief (approximately 1 meter or more) relative to pavement with sand channels and are separated from each other by 1-5 meters of sand or hardbottom (grooves), although the height and width of these elements may vary considerably. This habitat type typically occurs in the *Fore Reef* or *Bank/Shelf Escarpment* zone. This detailed structure type is not present in Buck Island Reef National Monument and consequently, does not appear in the 2001 and 2011 habitat maps.

Unconsolidated Sediment

Areas on the seafloor consisting of small particles (<0.25 m) with less than 50% cover of large stable substrate. Detailed structure classes include: *Mud, Sand* and *Sand with Scattered Coral and Rock*.

Mud

Fine sediment often associated with river discharge and build-up of organic material in areas sheltered from high-energy waves and currents (Figure 2.17). Particle sizes range from < 1/256 - 1/16 mm (Wentworth, 1922).

Figure 2.17. The black polygon outlines an example of the detailed structure type, *Mud*, on Buck Island as seen in aerial orthophotos (left). The photographs (middle and right) depict examples of mud in the shallow and deep-water areas of BIRNM, respectively.

Sand

Coarse sediment typically found in areas exposed to currents or wave energy (Figure 2.18). Particle sizes range from 1/16–256 mm, including pebbles and cobbles (Wentworth, 1922).

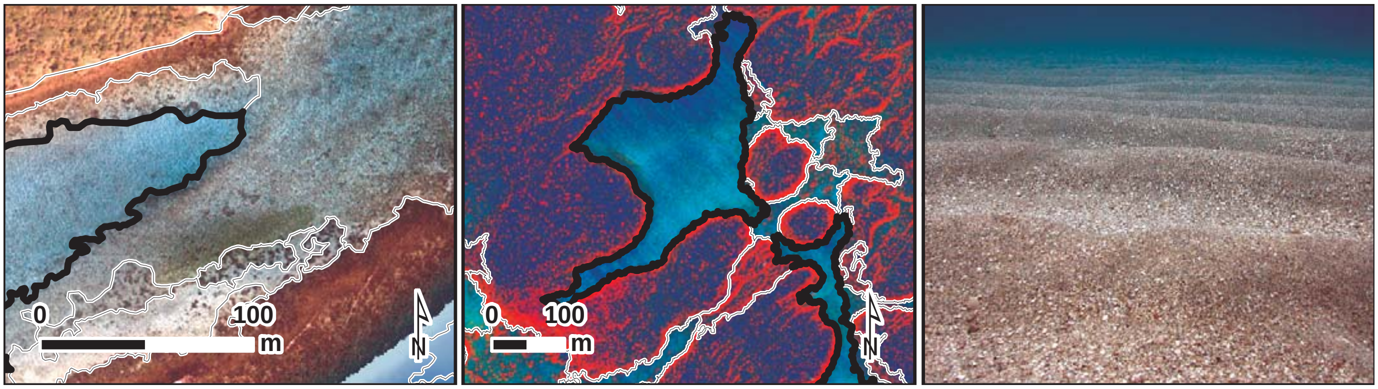

Figure 2.18. The black polygons outline examples of the detailed structure type, *Sand*, around Buck Island as seen in aerial orthophotos (left) and acoustic imagery (middle). The underwater photograph (right) depicts an example of sand in BIRNM.

Sand with Scattered Coral and Rock

Areas where ≥10% of the entire polygon is covered by sand and <10% of the entire polygon is covered by scattered rocks or small, isolated coral heads that are too small to be delineated individually (Figure 2.19). If the density of small coral heads is ≥10% of the entire polygon, this structure type is described as *Aggregated Patch Reefs*.

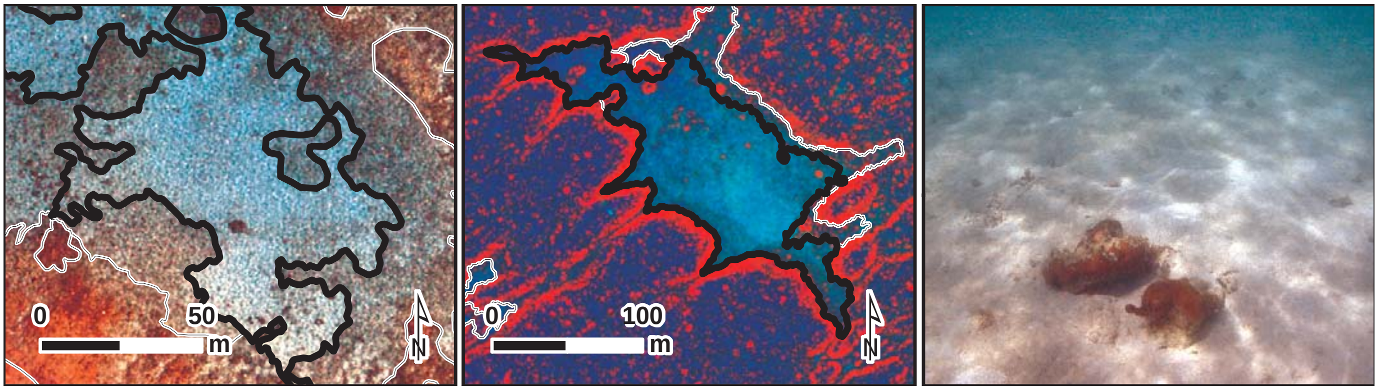

Figure 2.19. The black polygons outline examples of the detailed structure type, *Sand with Scattered Coral and Rock*, around Buck Island as seen in aerial orthophotos (left) and acoustic imagery (middle). The underwater photograph (right) depicts an example of sand with scattered coral and rock in BIRNM.

Other Delineations

Any other type of structure not classified as *Coral Reef and Hardbottom* or *Unconsolidated Sediment*. Usually related to the terrestrial environment and/or anthropogenic activity. Detailed structure classes include *Land* and *Artificial*.

Artificial

Man-made habitats such as submerged wrecks, large piers, submerged portions of rip-rap jetties, and the shoreline of islands created from dredge spoil (Figure 2.20).

Land

Terrestrial features at or above the spring high tide line (Figure 2.21).

Unknown

Major and/or detailed structure that is indistinguishable in the aerial orthophotos or LiDAR imagery due to water depth, turbidity, cloud cover, wave action, sun glint or other interference with the optical signature of the seafloor; it also may be indistinguishable in the acoustic imagery due to noise in the bathymetry and/or backscatter or other interference with the acoustic signature of the seafloor.

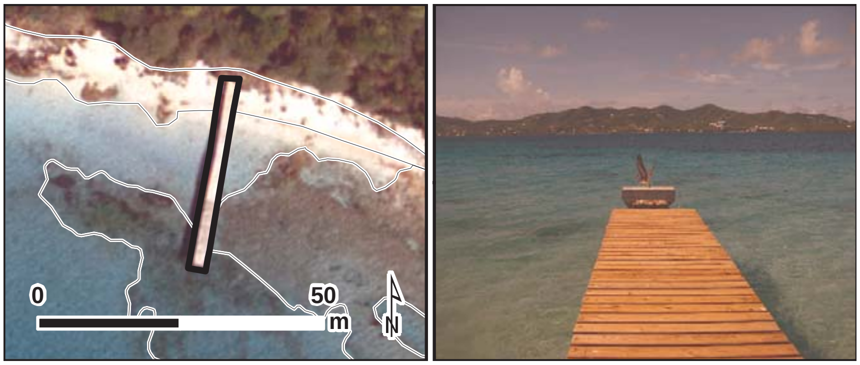

Figure 2.20. The black polygon outlines an example of the detailed structure type, *Artificial*, as seen in aerial orthophotos (left). The photograph (right) was taken looking south from the pier on Buck Island.

Figure 2.21. The black polygon outlines an example of the detailed structure type, *Land*, as seen in aerial orthophotos (left). The photograph (right) was taken from the western side of Buck Island.

2.1.4. Biological Cover Classes

Fifteen unique (i.e., major plus detailed) biological cover classes were mapped by interpreting aerial orthophotos, LiDAR and acoustic imagery. Biological cover denotes the dominant biological component colonizing the surface of the feature. It does not describe the location (e.g., on the *Bank/Shelf* or in a *Lagoon*) or structure (e.g., *Sand*) of the feature. Habitat features smaller than the MMUs were not considered. Five major cover types were identified from the aerial and acoustic imagery (i.e., *Algae, Mangrove, No Cover, Seagrass* and *Unclassified*) and combined with three modifiers describing the distribution of the dominant cover within the polygon (i.e., 10%≤50%, 50%≤90%, and 90%-100%). It is important to note that this modifier represents a measure of patchiness of the biological cover at the scale of delineation. It does not denote the density of organisms at the scale of the ground validation videos and photos. For example, a seagrass bed can be described as covering 90%-100% of a given polygon, but may have sparse densities of shoots when observed in the ground validation videos and photos. Figure 2.22 illustrates how patchiness was used to assign a biological percent cover.

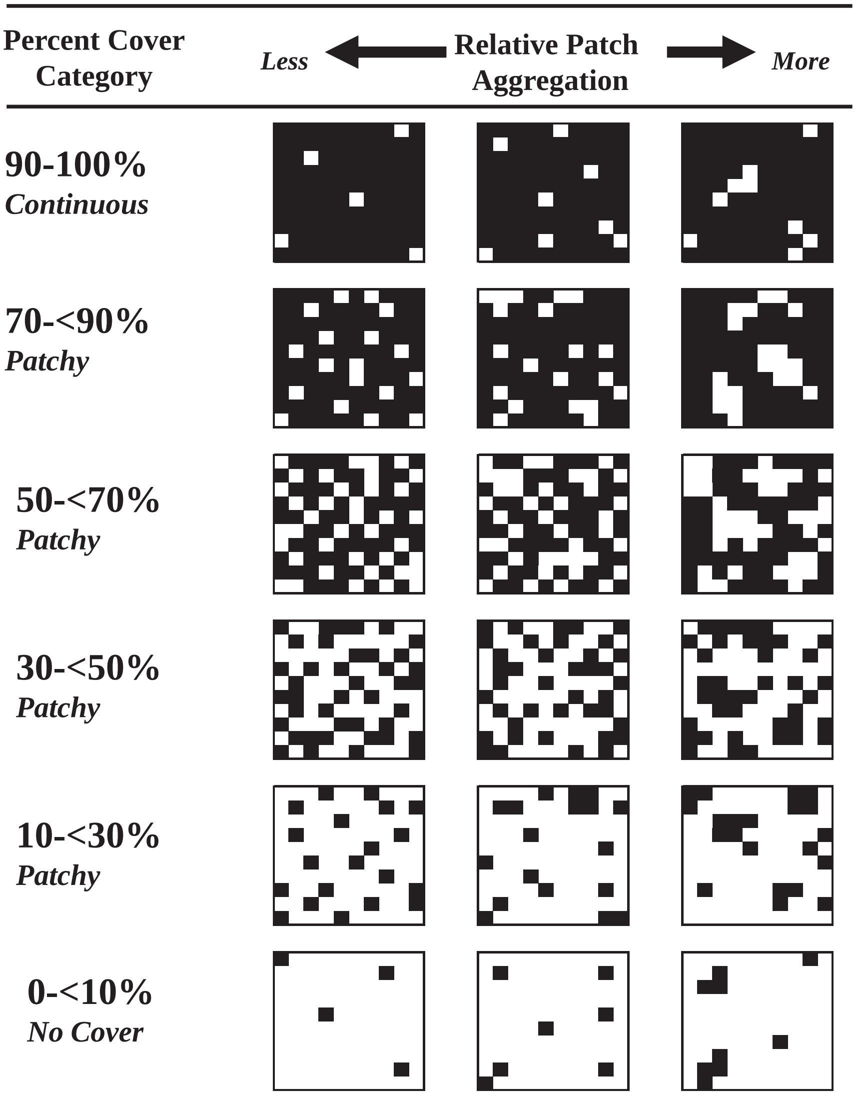

Figure 2.22. This chart outlines the process used to visually estimate patchiness when assigning a percent hardbottom and percent biological cover value to a polygon. Note that the 18 large squares are the size of a minimum mapping unit (MMU).

Major Cover

Algae

Substrates with 10% or greater distribution of any combination of numerous species of red, green, or brown algae. May be turf, fleshy, coralline or filamentous species. Occurs throughout many zones, especially on hardbottoms with low coral densities and soft bottoms in deeper waters on the *Bank/Shelf* zone (Figure 2.23).

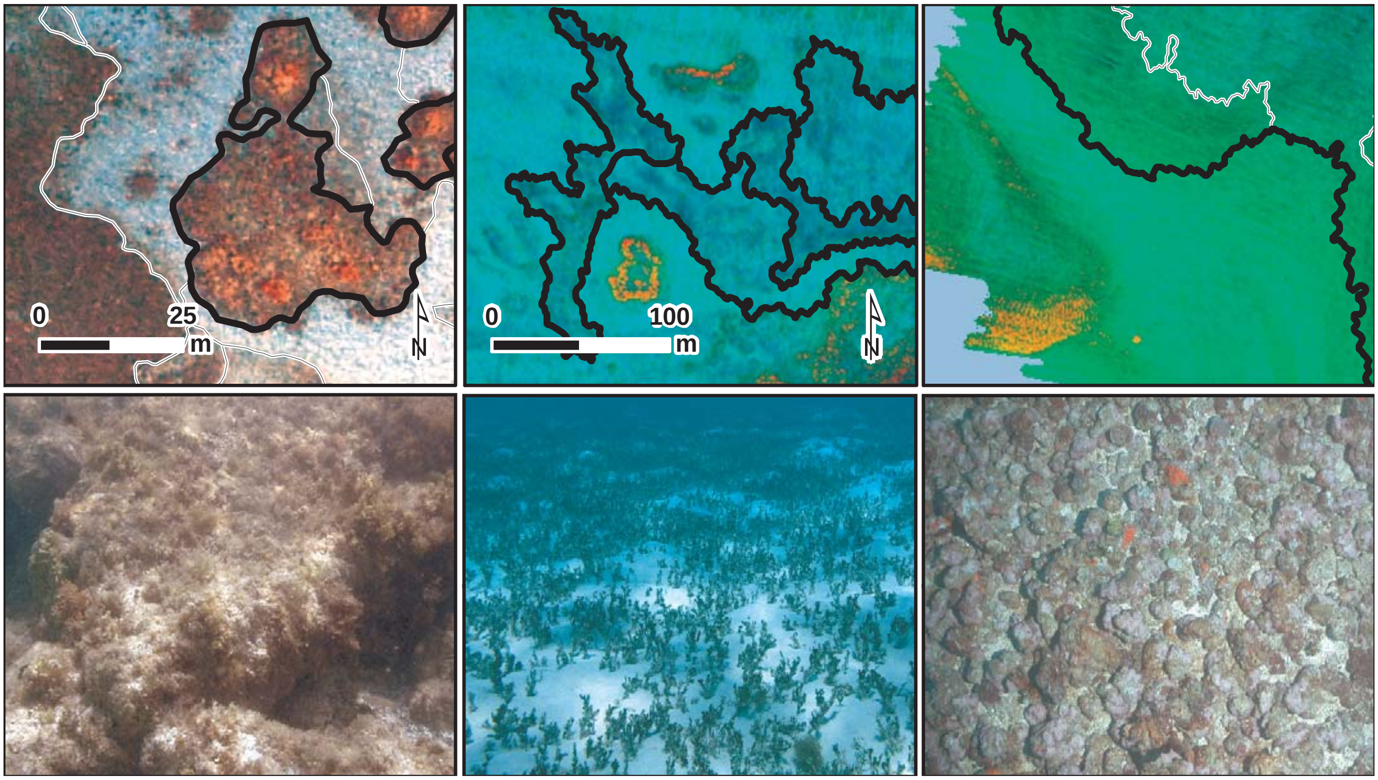

Figure 2.23. The black polygons in the maps (top) depict examples of the biological cover type, *Algae*, as seen in the aerial orthophotos and acoustic images. The underwater photographs (below) depict examples of algal habitat (i.e., turf algae, macroalgae, and coralline algae, respectively) in BIRNM.

Live Coral

Substrates colonized with 10% or greater live reef building corals and other organisms including scleractinian corals (e.g., *Acropora sp.*) and octocorals (e.g., *Briareum sp.*) (Figure 2.24).

Figure 2.24. The black polygon in the maps depict an example of the biological cover type, *Live Coral*, as seen in the LiDAR relative reflectance (left) and aerial orthophotos (middle). The underwater photograph (right) depicts examples of a habitat dominated by live soft corals in BIRNM.

Mangrove

This habitat is comprised of semi-permanently, seasonally or tidally flooded coastal areas occupied by any species of mangrove (Figure 2.25). Mangrove trees are halophytes; plants that thrive in and are especially adapted to salty conditions. In the U.S. Caribbean, there are three species of mangrove trees: red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), and white mangrove (*Laguncularia racemosa*); another tree, buttonwood (*Conocarpus erectus*) is often associated with the mangrove formation. Red mangrove grows at the water's edge and in the tidal zone. Black mangrove and white mangrove grow further inland in areas where flooding occurs only during the highest tides. This habitat type is usually found in the *Shoreline Intertidal* zone.

Figure 2.25. The black polygons outline examples of the biological cover type, *Mangrove* (left). The photographs (center and right) depict examples of mangrove habitat on Buck Island.

No Cover

Substrates not covered with a minimum of 10% of any of biological cover type. This habitat is usually associated with *Mud* or *Sand*. Overall, *No Cover* is estimated at 90%-100% of the bottom with the possibility of some very low density biological cover (Figure 2.26).

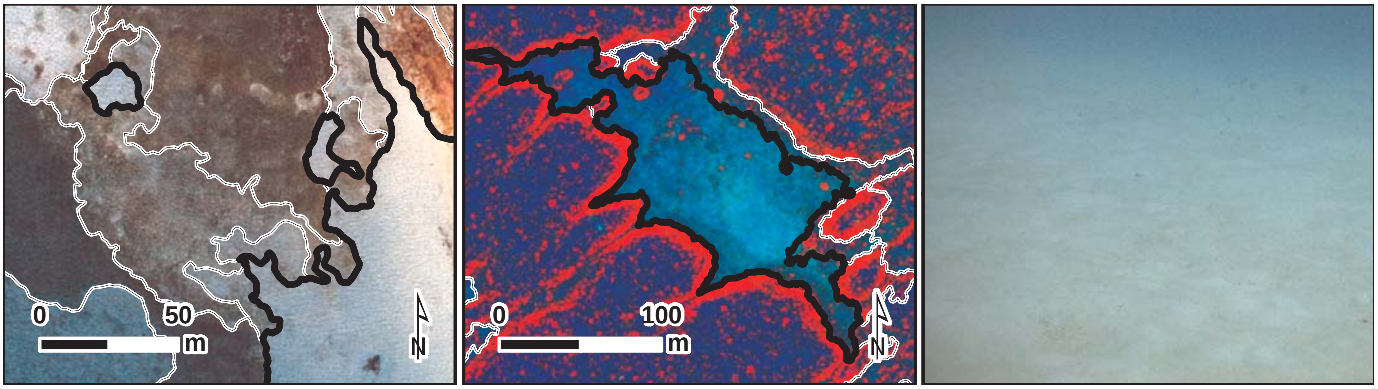

Figure 2.26. The black polygons in the maps depict examples of the biological cover type, *No Cover*, as seen in the aerial orthophotos (left) and acoustic images (middle). The underwater photograph (right) depicts an example of an area on the seafloor colonized by little or no biological organisms in BIRNM.

Seagrass

Habitat dominated by any single species of seagrass (e.g., *Syringodium* sp., *Thalassia* sp., *Halophila* sp.) or a combination of several seagrass species (Figure 2.27).

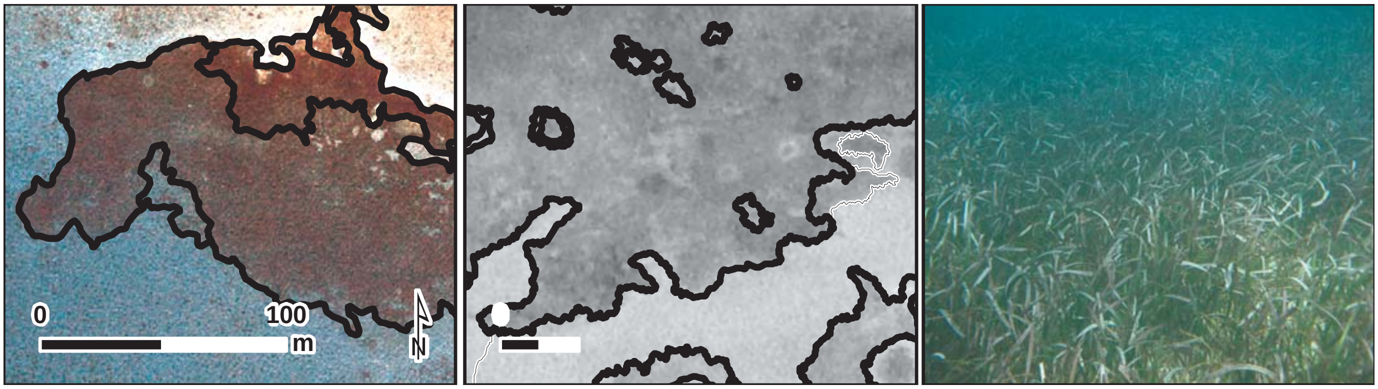

Figure 2.27. The black polygons in the maps depict examples of the biological cover type, *Seagrass*, as seen in the aerial orthophotos (left) and LiDAR relative reflectivity images (middle). The underwater photograph (right) depicts an example of seagrass habitats in BIRNM.

Unclassified

A different biological cover type, such as upland, deciduous forest, that is not included in this habitat classification scheme dominates the area. Most often used on polygons defined as *Land* with terrestrial vegetation.

Unknown

Biological cover that is indistinguishable in the aerial orthophotos or LiDAR imagery due to water depth, turbidity, cloud cover, wave action, sun glint or other interference with the optical signature of the seafloor; it also may be indistinguishable in the acoustic imagery due to noise in the bathymetry and/or backscatter or other interference with the acoustic signature of the seafloor.

Percent Major Cover

10% ≤ 50%

Discontinuous cover of the major biological type with breaks in coverage that are too diffuse to delineate or result in isolated patches of a different dominant biological cover that are too small to be mapped as a different feature (i.e., smaller than the MMU). Overall cover of the major biological type is estimated at 10% ≤ 50% of the polygon feature (Figure 2.28).

50% ≤ 90%

Discontinuous cover of the major biological type with breaks in coverage that are too diffuse to delineate or result in isolated patches of a different dominant biological cover that are too small to be mapped as a different feature (i.e., smaller than the MMU). Overall cover of the major biological type is estimated at 50% ≤ 90% of the polygon feature (Figure 2.28).

90% - 100%

Major biological cover type covering 90% or greater of the substrate. May include areas of 10% or less of the total area that are too small to be mapped independently (i.e., smaller than the MMU; Figure 2.28).

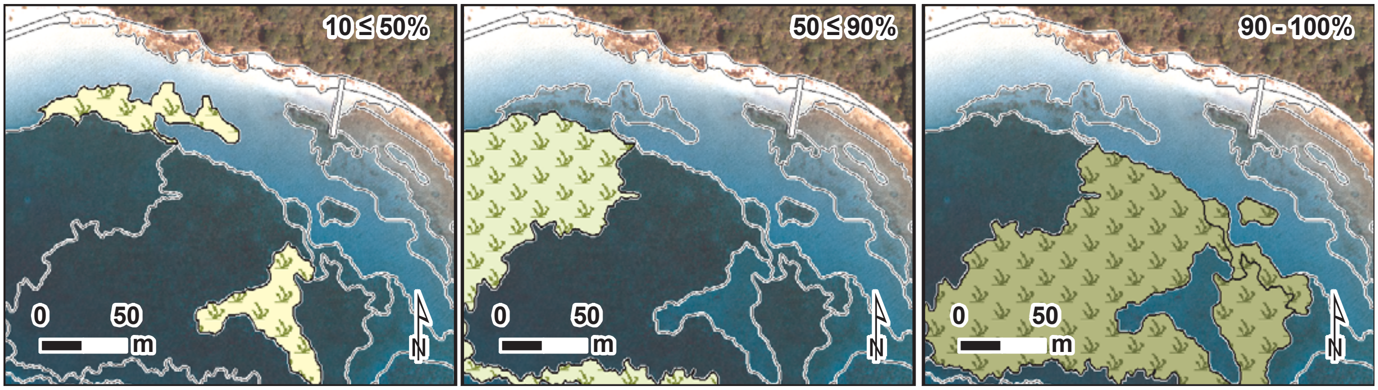

Figure 2.28. The symbolized polygons in the maps have: 10% ≤ 50% (left), 50% ≤ 90% (middle) and 90% - 100% (right) of their area covered by seagrass, respectively.

Not Applicable (N/A)
An estimate of percent cover is not appropriate for this particular major biological cover class (e.g., for *Land* polygons). Regularly accompanies the use of Unclassified as the major biological cover.

Unknown
Percent estimate of the biological cover that is indistinguishable in the aerial orthophotos or LiDAR imagery due to water depth, turbidity, cloud cover, wave action, sun glint or other interference with the optical signature of the seafloor; it also maybe indistinguishable in the acoustic imagery due to noise in the bathymetry and/or backscatter or other interference with the acoustic signature of the seafloor.

2.1.5 Live Coral Cover Classes

Four distinct and non-overlapping percent live coral classes were mapped by interpreting aerial orthophotos, LiDAR and acoustic imagery. This attribute is an additional biological cover modifier denoting the abundance live coral (both scleractinian and octocorals; Figure 2.29), even when it was not the dominant cover type within a polygon. In order to provide resource managers with additional information about corals, four range classes were used (i.e., *0%≤10%, 10%≤50%, 50%≤90%,* and *90%-100%*). Habitat features were classified into these range classes based on the amount of combined scleractinian and octocoral present in a polygon. Scleractinian coral and octocorals were combined because they could not be reliable separated in the remotely sensed imagery.


Figure 2.29. Both scleractinian and octocorals are included when estimating live coral cover. BIRNM hosts several species of scleractinian corals, including *Acropora palmata* (left) and several types of octocorals including sea rods (*Gorgoniidae*; right).

Live coral cover describes the percent coral cover on hardbottom features at a fine spatial scale (i.e., at the scale of the ground validation videos and photos). It is important to note that this metric is different from percent biological cover, which denotes the patchiness of biological organisms at the scale of the habitat feature. Due to these varying scales of interpretation, the percent biological cover and percent live coral cover modifiers are not additive, and in many cases, they will sum to greater than 100%. For instance, an aggregate reef can have continuous (90%-100%) cover of algae at the polygon scale, as well as 10%-50% density of coral at the diver scale.

0% ≤ 10%
Live coral cover of less than 10% of hardbottom substrate at diver scale (Figure 2.30a, 2.30b).

10% ≤ 50%
Live coral cover between 10% and 50% of hardbottom substrate at diver scale (Figure 2.30c).

50% ≤ 90%
Live coral cover between 50% and 90% of hardbottom substrate at diver scale. No Figure is provided because this class was not present in the area that was mapped in BIRNM.

Figure 2.30. (a) and (b) Examples of live coral cover in the 0% ≤ 10% range; and (c) an example of live coral cover in the 10% ≤ 50% range.

90% - 100%

Continuous live coral consisting of 90% or greater cover of the hardbottom substrate at diver scale. No Figure is provided because this class was not present in the area that was mapped in BIRNM.

Unknown

Percent estimate of coral cover that is indistinguishable in the aerial orthophotos or LiDAR imagery due to water depth, turbidity, cloud cover, wave action, sun glint or other interference with the aerial signature of the seafloor; it also maybe indistinguishable in the acoustic imagery due to noise in the bathymetry and/or backscatter or other interference with the acoustic signature of the seafloor.

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CHAPTER 3: METHODS

3.1. GENERAL MAPPING APPROACH

NOAA's approach to habitat mapping of the marine environments in BIRNM was a six-step process:

1. Imagery Acquisition – The first step in map creation was the acquisition and processing of high-resolution remotely sensed imagery. Aerial orthophotographs, LiDAR and acoustic data were collected to map close to the full geographic extent of BIRNM.
2. Habitat Boundary Delineation – A draft benthic habitat map was generated using edge-detection algorithms to delineate habitat features clearly visible in the orthophotographs, LiDAR and acoustic remotely sensed imagery.
3. Ground Validation (GV) – Habitat features in the map with representative or with unknown spectral or acoustic signatures were explored using underwater cameras. This was used to identify unknown habitats and to confirm that the signature of known habitats remained consistent throughout the study area. Initial maps were then edited to generate a second draft map for BIRNM.
4. Expert Review – The second draft map was reviewed online by local marine biologists, scientists and resource managers to qualitatively assess the shallow-water map's thematic accuracy.
5. Accuracy Assessment (AA) – After incorporating comments made during the expert review, thematic accuracy of the draft shallow-water habitat map was assessed using a random stratified sampling plan. No quantitative accuracy assessment was conducted for the moderate and deep water habitat maps.
6. Final Product Creation – A final benthic habitat map for BIRNM was generated by correcting inaccuracies identified during the accuracy assessment and edge-match the shallow, moderate and deep-water maps.

3.2. REMOTELY SENSED IMAGERY

3.2.1. The Sensors

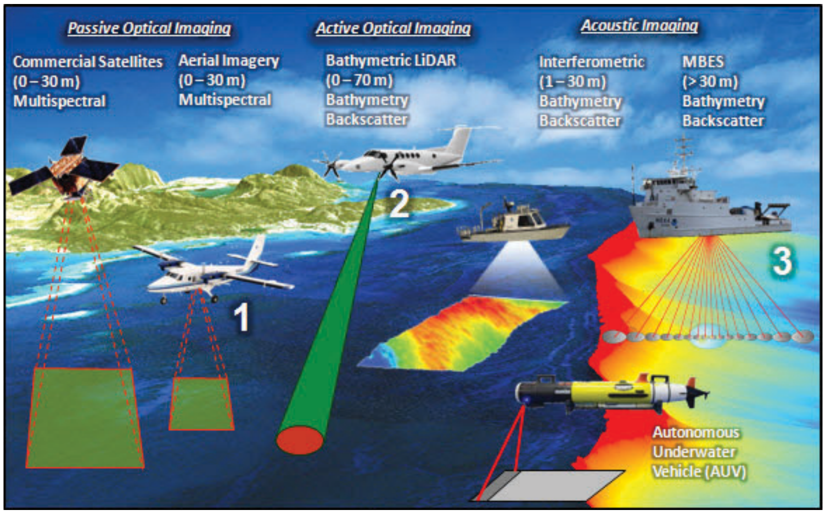


Figure 3.1. Diagram illustrating the various sensors used to map shallow-water to deep-water benthic habitats. For this mapping effort, three types of technologies were used: (1) a passive optical aerial sensor, (2) a LiDAR sensor, and (3) MBES sensors. The imagery produced by these sensors were integrated to produce a seamless habitat map from shoreline to approximately 1,830 m.

Three types of technology and six sensors were used to map 98% of BIRNM (Figure 3.1). The remaining 2% of the Monument was not mapped because the data collected in this deep area was originally meant to support earthquake modeling, and not habitat mapping (Figure 3.2). The technologies used for mapping include: (1) a passive optical aerial sensor, (2) a Light Detection and Ranging (LiDAR) sensor, and (3) four Multibeam Echosounder (MBES) Sound Navigation and Ranging (SoNAR) sensors. Passive optical sensors produce photographs of the area below the camera by measuring and recording sunlight (in the visible spectrum) that reflects off the land and seafloor (Figure 3.2). Unlike passive optical sensors, LiDAR sensors actively pulse light to measure the depth (i.e., bathymetry) and the reflectivity (i.e., intensity) of the seafloor. Similarly, MBES are active sensors which emit sound (instead of laser light) to measure the depth (i.e., bathymetry) and physical properties (i.e., intensity) of the seafloor (Figure 3.2). The resulting seafloor images (i.e., bathymetry and intensity) are valuable tools for natural resource managers and researchers because they provide baseline information on the location, extent and physical composition of seafloor habitats.

3.2.2. Acquisition and Processing of Remotely Sensed Imagery

Aerial Orthophotography

The imagery used to create a benthic habitat map of BIRNM was collected by several different federal agencies, private companies and academic institutions over the course of seven years (Figure 3.3; Table 3.1). The U.S. Army Corps of Engineers (USACE) collected aerial orthophotos for select areas in the U.S. Caribbean from

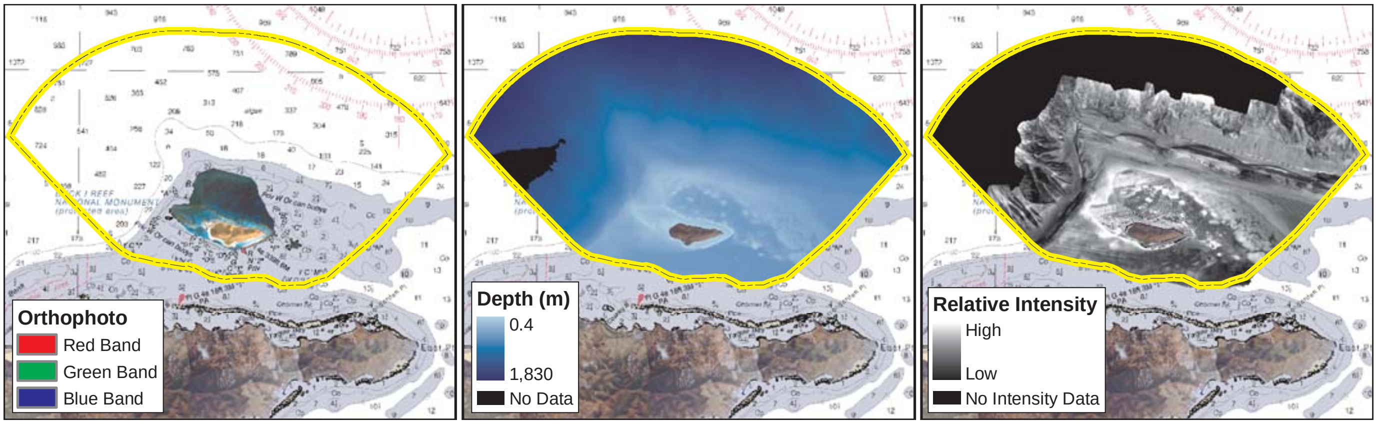


Figure 3.2. These maps depict the aerial orthophoto imagery (left), MBES and LiDAR bathymetry (middle) and MBES and LiDAR intensity (right) used to delineate and characterize the benthic habitats inside BIRNM.

November 2006 through March 2007 using a Leica ADS40 digital sensor (Briere and Suggs, 2008). The aerial orthophotos used to create a habitat map of BIRNM (i.e., blocks 17064-G5 and 17064-G6) were collected on 10/17/2007. Each orthophoto was acquired at 0.35 x 0.35 meter resolution. Leica Ground Processing Workshop (GPRO) software version 3.1.1 was used to extract the raw un-rectified imagery. For each block, a least squares bundle adjustment was performed using automatically generated tie points, ground control point measurements and control point coordinates. Each block was orthographically rectified using digital elevation models to correct the imagery for relief displacement. The horizontal positional accuracy of the orthoimagery was assessed using independently collected photo control points. The imagery met the American Society of Photogrammetry and Remote Sensing Class I Standards (FGDC, 1998) at 1:24,000 scale, which translates into a root mean square

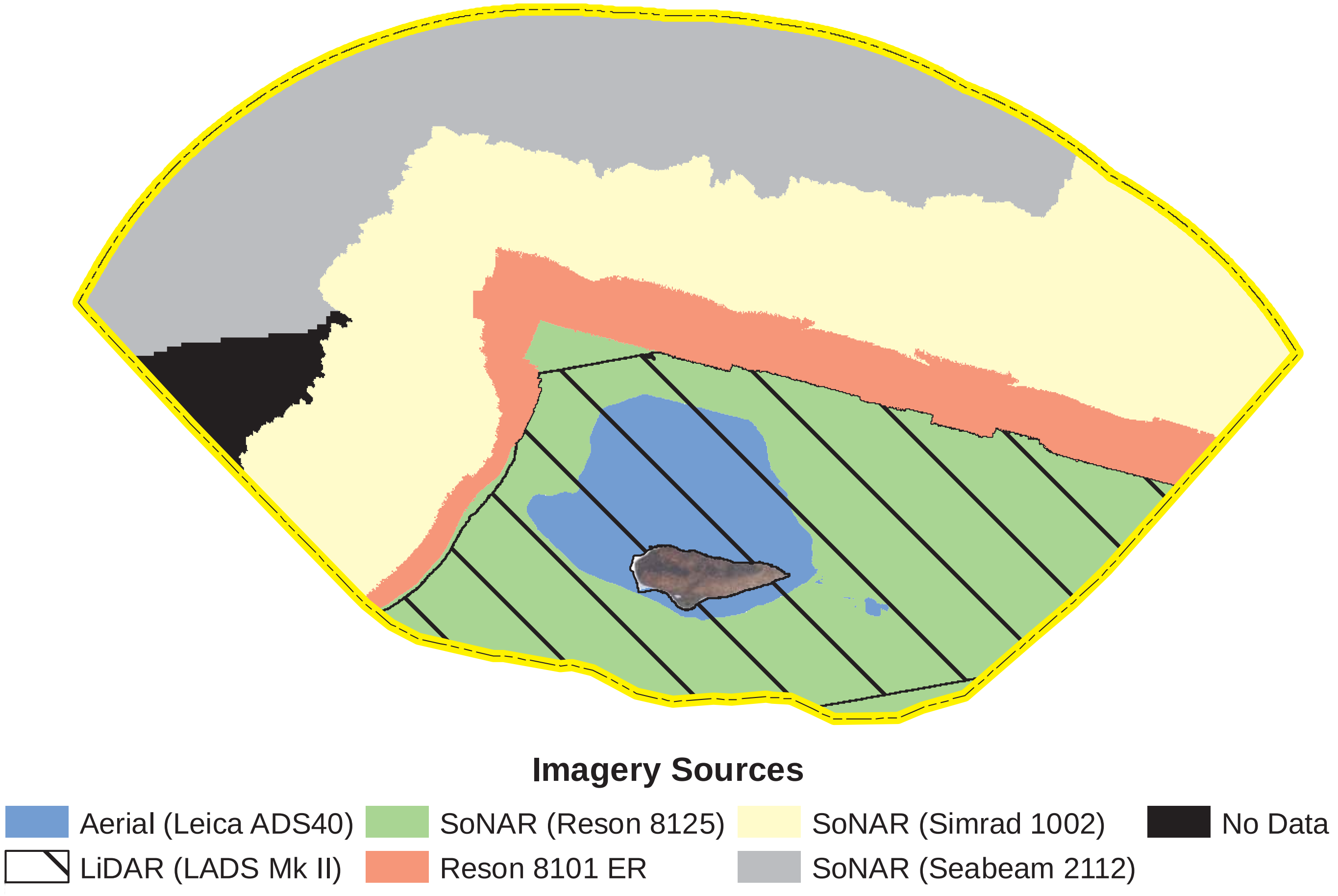


Figure 3.3. A benthic habitat map was created for the area inside BIRNM using two different optical sensors and four different acoustic sensors. This figure denotes the area that was mapped using each sensor inside BIRNM.

Table 3.1. Six different sensors were used to produce a habitat map BIRNM because of the wide depth ranges encompassed by the Monument. The types and spatial resolutions of the acquired imagery differed among sensors. The amount of area mapped and characterized by each sensor within BIRNM is also listed.

TYPE	SENSOR	TYPE OF IMAGERY PRODUCED	YEAR ACQUIRED	DATES ACQUIRED	NATIVE SPATIAL RESOLUTION (m)	AREA MAPPED WITHIN BIRNM (km²)	AREA CHARACTERIZED WITHIN BIRNM (km²)
Passive Optical	Leica ADS40	Orthophotos	2007	10/17	0.35	27.24	4.81
LiDAR	LADS Mk II	Bathymetry, Relative Reflectivity	2011	02/21 - 02/22	3	24.46	23.71
SoNAR MBES	Reson 8125	Bathymetry, Backscatter	2010	04/09 - 04/30	1	18.9	18.9
SoNAR MBES	Reson 8101 ER	Bathymetry, Backscatter	2004	02/18 - 03/05	5	8.88	6.85
SoNAR MBES	Simrad 1002	Bathymetry, Backscatter	2006	03/21 - 04/02	10	31.13	24.28
SoNAR MBES	Seabeam 2112	Bathymetry	2006	05/03 - 05/19	50	52.73	19.29
No Data			-	-	-	1.9	1.9

error of approximately ± 5 m. The final true-color orthophotos were received as 8-bit GeoTiff files (.tif) in the North American Datum 1983 (NAD 83) State Plane Puerto Rico and U.S. Virgin Islands Zone coordinate system. Originally, this orthoimagery was collected to provide the USACE with current digital orthophotos to support regulatory, land management and acquisition, planning, engineering and habitat restoration projects. This orthoimagery was also used for this mapping effort because it met this project's spatial resolution and accuracy requirements.

LiDAR Imagery

Fugro LADS, in collaboration with the BB, the University of New Hampshire and the NPS, acquired laser bathymetry and relative seafloor reflectivity in BIRNM from 2/21 to 2/22/2011. LiDAR data were acquired for depths between 0.2 m and 49 m using a Laser Airborne Depth Sounder (LADS) Mark II Airborne System. The survey was flown at ground speeds between 140 and 175 knots and at altitudes between 1200 and 2200 feet, so that survey activities could continue below low cloud ceilings. Environmental factors such as wind strength and direction, water clarity and depth also influenced the area of data acquisition on a daily basis. The airborne survey achieved 3x3 m spot spacings. Raw data were logged using the Tenix LADS Airborne System and converted using the LADS Mk II Ground System. Soundings were positioned relative to the NAD83 Universal Transverse Mercator Zone 20 North (UTM 20 N) horizontal coordinate system and to the Mean Lower Low Water (MLLW) vertical tidal coordinate system. The bathymetry and relative reflectivity products were created using CARIS HIPS and SIPS, CARIS Base Editor and proprietary LADS software. The relative reflectivity surface was corrected for changes in gain, and energy lost at the air/water interface, in the water column, from optical filtering and due to the receiver field of view (Collins et al. 2007). The bathymetry surface was corrected for sensor offsets, latency, roll, pitch, yaw and the influence of tides. The LiDAR survey was conducted to meet International Hydrographic Organization (IHO) Order 1 uncertainty standards (IHO, 2008), which is ± 5 meters plus 5% of depth for horizontal uncertainty and ± the square root of $[0.52 + (0.013 * \text{depth})^2]$ for vertical uncertainty. These equations translate into a maximum of approximately ± 7.5 m and ± 0.81 m of horizontal and vertical uncertainty, respectively. The final bathymetry and relative reflectivity surfaces were received as 32-bit GeoTiff files. This LiDAR imagery was collected not only to support the characterization of benthic habitats within BIRNM, but also to support on-going benthic habitat mapping research by the University of New Hampshire, the BB and Fugro LADS.

MBES Imagery

Acoustic imagery was acquired inside the BIRNM boundaries on four separate missions between 2004 and 2010. The primary goal of these missions was to map the seafloor to better understand the geology and biology of the benthic environment. The first mission was conducted by NOAA's BB from 2/18 to 3/5/2004 using a pole-mounted 240 kHz Reson Seabat 8101 Extended Range MBES (Monaco and Rooney, 2004). Depths between 12 and 317 m were surveyed, producing a 5x5 m bathymetry and 0.5x0.5 m backscatter surfaces. A second mission was conducted by NOAA's BB from 3/21 to 4/2/2006 using a hull-mounted 95 kHz Simrad 1002 MBES (Battista and Stecher, 2006). Depths between 16 and 1,000 m were surveyed, producing a 10x10 m bathymetry and 3x3 m backscatter surface. The third mission was conducted by the United States Geological Survey (USGS) from 5/3 to 5/19/2006 using a hull-mounted 12 kHz SeaBeam 2112 MBES (ten Brink et al. 2006). Depths between 11 and 4,670 m were surveyed, producing a 50x50 m bathymetry surface. No backscatter surface was produced.

The last mission was conducted by NOAA's BB from 4/9 to 4/30/2010 using a pole-mounted 455 kHz Reson Seabat 8125 MBES (Battista and Lazar, 2010). Depths between 5 and 50 m were surveyed, producing a 1x1 m bathymetry and 1x1 m backscatter surface. For complete descriptions of these MBES mapping missions, please see the data acquisition and processing reports referenced above (i.e., Monaco and Rooney, 2004; Battista and Stecher, 2006; ten Brink et al. 2006; Battista and Lazar, 2010).

For all the surveys, soundings were positioned relative to the same horizontal coordinate system (NAD83 UTM 20 N) and to the same vertical coordinate system (MLLW). Each bathymetry surface was corrected for sensor offsets, latency, roll, pitch, yaw, static draft, the influence of tides and the changing speed of sound in the water column using CARIS HIPS and SIPS software. The 2010 NOAA survey was conducted to meet IHO Order 1 uncertainty standards (IHO, 2008), which translates into a maximum of approximately ± 7.5 m and ± 0.82 m of horizontal and vertical uncertainty, respectively. The 2006 NOAA survey and the USGS survey were conducted to meet IHO Order 2 uncertainty standards, which is ± 20 meters plus 10% of depth for horizontal uncertainty and ± the square root of $[1.0^2 + (0.023 * \text{depth})^2]$ for vertical uncertainty. For the 2006 NOAA survey, these equations translate into a maximum of approximately ± 120 m and ± 23 m of horizontal and vertical uncertainty, respectively. For the USGS survey conducted in BIRNM, these equations translate into a maximum of approximately ± 203 m and ± 42 m of horizontal and vertical uncertainty, respectively. The 2004 NOAA survey did not meet any of the IHO standards due to noise introduced into the data by oscillation of the pole-mount and SoNAR head. For the 2004, 2006 and 2010 NOAA surveys, backscatter surfaces were geometrically corrected for navigation attitude, transducer attitude and slant range distortion and radiometrically corrected for changes in acquisition gains, power levels, pulse widths, local seafloor slope and ensonification areas using Geocoder software (Fonseca and Calder, 2005). All the intensity rasters were converted from decibels to relative 8-bit (0 – 255) values, since none of the MBES systems were calibrated. The final bathymetry and backscatter surfaces were exported as 32-bit GeoTiff files.

3.2.3. Post Processing Of Remotely Sensed Imagery

Additional image processing steps were needed before benthic habitats could be delineated from the different remotely sensed images. The primary purpose of these steps was to standardize the: (1) geographic extent, (2) format, (3) coordinate system, and (4) in some cases, the spatial resolution of the different images. These steps improved the quality and consistency of the imagery, often making the process of imagery integration and habitat delineation/characterization less time consuming and more thematically accurate. The first step in this process was to standardize the geographic extents of the images by clipping each image to the boundaries of the BIRNM and saving them in the same GeoTiff format. Next, the aerial orthophotos were reprojected into the NAD 83 UTM 20 N coordinate system using the "Reproject" tool in ArcGIS. This reprojection was done to standardize the horizontal coordinate systems of the different images. After these steps, all the images had the same format, coordinate system and geographic extents, ensuring their positioning was as consistent as possible. Lastly, the 2004 NOAA bathymetric surface was downsampled from 5x5 to 10x10 m and the 2011 LiDAR reflectivity surface was upsampled from 3x3 to 1x1 m using the "Resample" function in ArcGIS. The 2004 MBES surface was resampled to a coarser spatial resolution to reduce the visibility of noise in the imagery. The 2011 LiDAR surface was resampled to a finer spatial resolution to match the spatially coincident 2010 MBES imagery. Resampling these surfaces reduced the number of different spatial resolutions that needed to be accounted for from six to four (i.e., 0.35x0.35, 1x1, 10x10 and 50x50 m). The three MMUs used in this mapping effort were then chosen based on these spatial resolutions.

Applying Radiometric Corrections to Orthophotos

The optical signature of the seafloor is confounded by changes in environmental conditions because light attenuates (due to absorption and scattering) as it passes through the atmosphere and the water column (Figure 3.4). This attenuation means that a habitat in one location and/or at one depth will look different than that same habitat at a different location and/or deeper depth (e.g., algae at 5 m will look different than algae at 20 m). Such variability decreases the ability of an algorithm or visual interpreter to discriminate among habitat types, and hinders the consistent and accurate characterization of orthophotography (Mumby et al. 1998). To mitigate this potential source of confusion, the orthophotos were radiometrically corrected for changing water column conditions before being analyzed and interpreted. They were not atmospherically corrected because both images were acquired on the same day (10/17/2007), over a small area (27 km^2) and at the same, low altitudes (8,700 feet), minimizing the spatial and temporal variability of the ambient atmospheric conditions. The orthophotos were corrected for changes in the water column using the Lyzenga method (Lyzenga, 1978, Mumby and Edwards, 2000). The derived coefficients were then applied to both orthophotos using ArcGIS's raster calculator to normalize the images for changing conditions in the water column (Equation 1):

Depth Invariant Red Band = [natural log red band] - (9.59254284400669 * [natural log blue band]

Depth Invariant Green Band = [natural log green band] - (1.64151463264319 * [natural log blue band)

Depth Invariant Blue Band = [natural log blue band] - (0.609193472975495 * [natural log green band

Once the orthophotos were water column corrected, they were then color balanced and mosaiced using ENVI software. This final, water column corrected, color balanced mosaic was then used to delineate and characterize areas inside BIRNM that lacked acoustic imagery and that did not yet have LiDAR imagery (Figure 3.5). The final LiDAR imagery was delivered after the final orthophoto mosaic had been created.

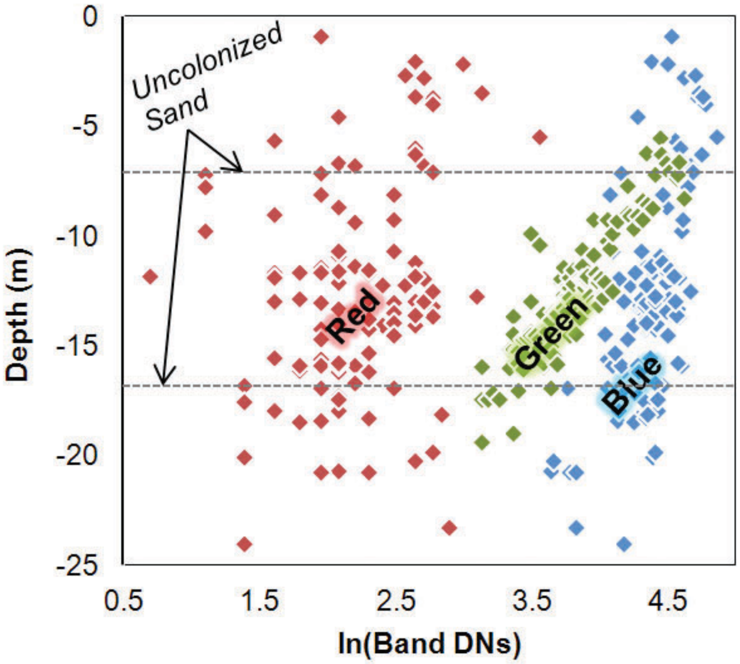


Figure 3.4. This graph illustrates how light attenuates due to scattering and absorption in the water column. Depths (in meters) are on the y-axis, and the natural log (ln) of each band's digital numbers (DNs) are on the x-axis. The horizontal lines are an example of how the same habitat (e.g., uncolonized sand) can look different at deeper depths as red, green and blue light attenuate at different rates in the water column.

Creating Derivative Surfaces from Bathymetry

Bathymetry provides valuable information for developing benthic habitat maps. In addition to depth, bathymetry can also be used to derive information about the seafloor's topography and physical structure (e.g., slope). This topographic information can be used to describe and characterize the structural complexity of the seafloor, enabling its classification into different geomorphological structure types. To extract this important topographic information, a suite of eight morphometrics were derived from each of the four bathymetric surfaces (for a total of 32 images), to characterize the complexity and structure of the seafloor. These metrics specifically included: (1) mean depth, (2) standard deviation of depth, (3) curvature, (4) plan curvature, (5) profile curvature, (6) rugosity, (7) slope, and (8) slope of slope. These eight metrics were included in the classification process because previous studies demonstrated their utility for classifying coral reef habitats (Costa and Battista, In Review) and for predicting the abundance and distribution of corals in the U.S. Caribbean (Pittman et al. 2009). These metrics are described in more detail in Table 3.2. These eight complexity surfaces

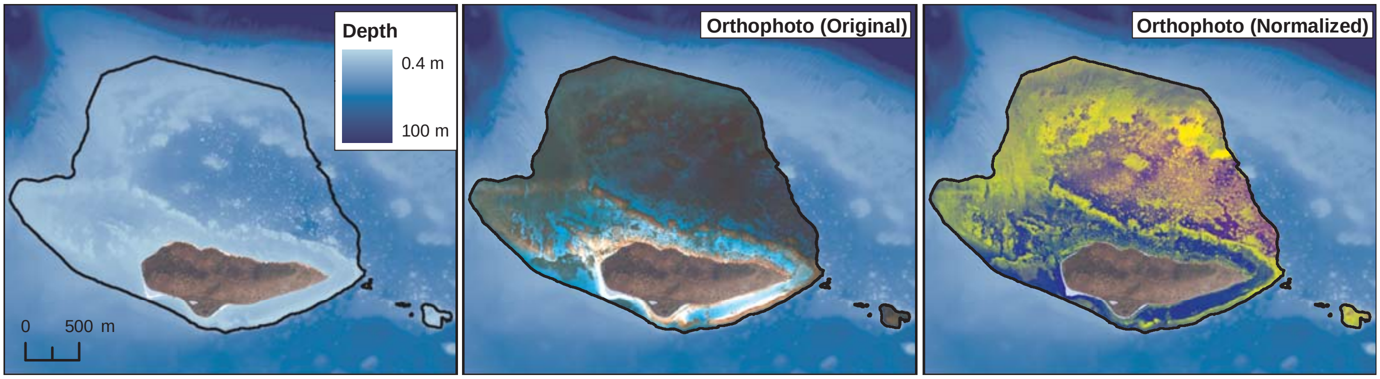
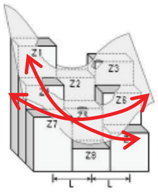
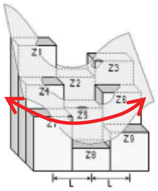
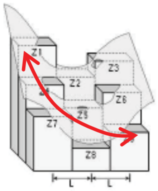
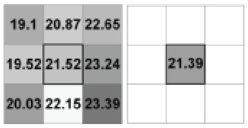
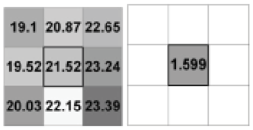
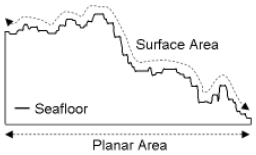
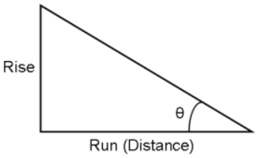
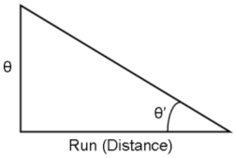


Figure 3.5. The orthophotographs were corrected for changing water column conditions before being used to characterize benthic habitats in BIRNM. The map (left) denotes depth changes around Buck Island, with the black polygon denoting the extent of the orthoimagery used in this mapping effort. The map (middle) shows the orthophotos before being water column corrected. The map (right) shows these same orthophotos after the Lyzenga correction coefficients were applied to normalize the images for changing water column conditions, most notably depth.

Table 3.2. Descriptions of the morphometrics used to characterize the complexity of the seafloor in and around BIRNM. The GIS tools used to derive these metrics from the MBES bathymetry surface are also included in the table below.

		UNIT	DESCRIPTION	TOOL
		1/100 z units – = concave + = convex	Rate of change in curvature across the surface highlighting ridges, crests and valleys (3 x 3 cell neighborhood)	Curvature function in ArcGIS 3D Analyst
		1/100 z units – = concave + = convex	Curvature of the surface perpendicular to the slope direction (3 x 3 cell neighborhood)	Plan curvature function in ArcGIS 3D Analyst
		1/100 z units – = convex + = concave	Curvature of the surface in the direction (3 x 3 cell neighborhood)	Profile curvature function in ArcGIS 3D Analyst
		Meters	Average water depth (3 x 3 cell neighborhood)	Focal statistic function in ArcGIS Spatial Analyst
		Meters	Dispersion of water depth values about the mean (3 x 3 cell neighborhood)	Focal statistic function in ArcGIS Spatial Analyst
		Ratio value	Ratio of surface area to planar area (3 x 3 cell neighborhood)	Rugosity function in the Benthic Terrain Modeler toolbox (Jenness 2002, 2004; Wright et al., 2005)
		Degrees	Maximum rate of change in slope between cell and 8 neighbors (3 x 3 cell neighborhood)	ArcGIS Spatial Analyst's slope function
		Degrees of degrees	Maximum rate of maximum slope change between cell and eight neighbors (3 x 3 cell neighborhood)	ArcGIS Spatial Analyst's slope function

were subsequently rendered, stacked and exported to create one image for each survey with several different bands (i.e., each band representing a specific metric). These images were then transformed into their first three principal components using the "Principal Components Analysis" (PCA) (Mather 2004; Lillesand and Kiefer, 2000) function in ENVI 4.7. This transformation reduced the dimensionality of each dataset by removing information that was redundant across the different bands. However, specific complexity metrics were not removed in their entirety because each metric explained significant amounts of variance in at least one of three the principal components. The resulting three band PCA images contained primarily information that uniquely described the complexity and structure of the seafloor. Each of these three bands were converted from 16-bit, floating point values and rendered to 8-bit, integer values, so that they could be imported into ENVI EX 4.7.

3.3 HABITAT FEATURE DELINEATION AND CLASSIFICATION

Historically, shallow-water coral reef habitat mapping has been conducted via heads-up digitizing and interpretation of high-resolution (≤ 4x4 m) imagery (Kendall et al. 2001, Battista et al. 2007, Zitello et al. 2009). This approach has several advantages and disadvantages. Its advantages include being able to ignore noise in the source imagery, and develop benthic habitat maps at multiple spatial scales with high thematic resolutions (i.e., up to 30 unique habitat classes) and high (i.e., > 85%) overall thematic accuracies (Kendall et al. 2001; Coyne et al. 2003, Battista et al. 2007; Battista et al. 2007^2; Prada et al. 2008). Its disadvantages include being time consuming and subjective because the habitat map's spatial and thematic accuracy depends on the knowledge and skill of the cartographer. The Biogeography Branch has sought to address some of these disadvantages in more recent maps (Costa et al. 2009) by automating the processes of delineating and attributing habitat features, an approach that has been further evaluated and refined in BIRNM. The semi-automated approach hybridizes object- and pixel-based classification techniques to extract and attribute benthic habitat features. Manual edits were made to the map where the cartographer disagreed with the semi-automated approach's interpretation. While this approach has potential to improve the efficiency with which habitat maps are made, more research is needed to improve the reliable classification of specific habitats, and further reduce the amount of manual editing that is needed.

This semi-automated habitat delineation and characterization process was broken into five corresponding regions (with three different MMUs) based upon the spatial extents and spatial resolutions of the sensors used to map the BIRNM. These regions are referred to as: "Aerial," "Shallow," "Moderate Shelf," "Moderate" and "Deep" for the remainder of this report. "Aerial" refers to the area inside BIRNM that was classified using aerial orthophotography. The "Shallow," "Moderate Shelf," "Moderate," and "Deep" regions were classified using LiDAR reflectivity and Reson 8125, Reson 8101, Simrad 1002 and Seabeam 2112 imagery, respectively. For both the Shallow and Aerial survey regions, this semi-automated approach was employed effectively to classify an area containing nearly 25 km^2 of seafloor habitat. The Deep, Moderate, and Moderate Shelf survey regions were also delineated in an automated fashion, but the polygons were manually interpreted and classified due to reduced image quality, a relative paucity of ground validation information, and the much coarser MMUs used in these areas. Figure 3.6 illustrates the general progression from imagery to habitat map for the shallow, moderate and deep-water areas.

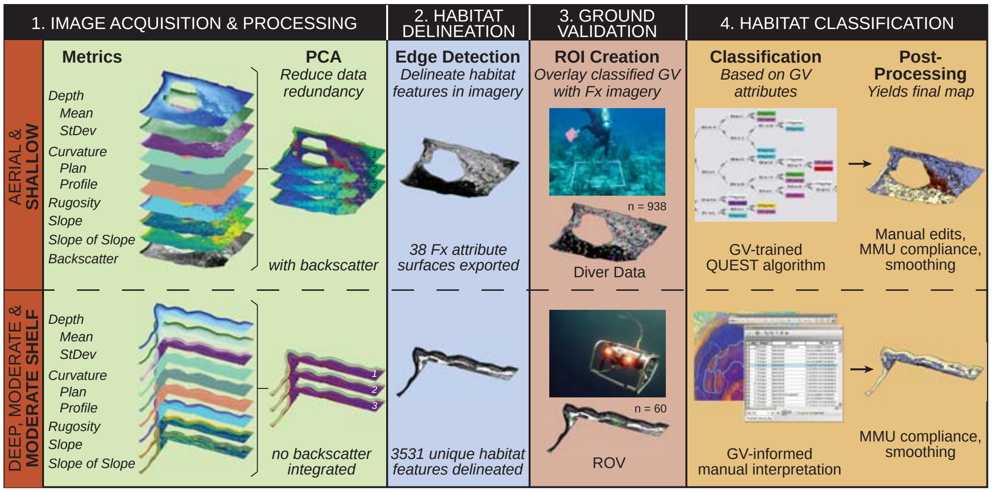


Figure 3.6. Diagram illustrating the semi-automated and manual processes used to create the Aerial and Shallow habitat maps (top), as well as the Moderate Shelf, Moderate and Deep habitat maps (bottom).

3.3.1. Habitat Delineation

Habitat features on the seafloor were identified and extracted using the ENVI Zoom 4.8 Feature Extraction (Fx) Module. This module uses edge detection algorithms to detect and delineate objects in a single image or in a suite of spatially coincident images. The Fx input imagery varied by survey area (Table 3.3), but included at a minimum an orthophoto mosaic or MBES PCA image, both of which are described in section 3.2.2. The Fx module also allows the user to ingest ancillary data along with the primary imagery source. LiDAR reflectance was used as an ancillary dataset to delineate habitats in the shallow-water area (Figure 3.7). For the Aerial survey area, a standard deviation surface of the water column-corrected bands served as an ancillary dataset. In both cases, the ancillary imagery improved contrast between habitat types, allowing Fx to more effectively distinguish heterogeneous habitats from more homogenous objects.

Table 3.3. Input images used to delineate unique habitat features using ENVI Fx.

FEATURE EXTRACTION (Fx) PARAMETERS						
	INPUT		SEGMENTATION PARAMETERS		OUTPUT	
Survey Area	**Input Imagery Source**	**Ancillary Data**	**Scale Level**	**Merge Level**	**Fx Objects**	**Fx Attributes**
Aerial	Water column-corrected color-balanced mosaic	Standard deviation of water column-corrected bands	50.0	99.0	26,409	38
Shallow	MBES (Backscatter-Integrated) PCA	LiDAR Reflectance	58.0	98.5	105,340	38
Moderate Shelf	MBES PCA	None	5.0	78.0	3,531	N/A
Moderate	MBES PCA	None	0.0	98.0	1,010	N/A
Deep	MBES PCA	None	45.0	77.6	642	N/A

Fx defines an object as a region of interest with unique spatial, spectral (brightness and color), and/or textural characteristics that make it spectrally or acoustically distinct from its surroundings (ITT VIS, 2008a). There are three steps involved in extracting discrete objects from an image (or images). Specifically, these include: (1) segmenting the image(s), (2) merging smaller segments into larger objects, and (3) computing spatial, spectral, textual and custom attributes for each object. The first two steps are interactive, allowing the user to adjust the input parameters in such a way that the segmentation captures the features in which they are most interested based on predetermined MMUs and habitat classes (defined in chapter 2). In particular, step 1 allows the user to alter the "scale level" of the edge detection algorithm to determine the size of the objects to be extracted. Choosing a higher scale level (>75), which is unitless, causes a smaller number of larger segments to be defined, while choosing a lower scale level (<25) causes a greater number of smaller segments to be defined (ITT VIS, 2008b). Step 2 allows the user to alter the "merge level" of the algorithm and to merge smaller segments into larger objects. Choosing a higher merge level (>75), which is also unitless, causes segments with faded edges to be merged, while choosing a lower merge level (<25) preserves more of these features with faded edges (ITT VIS, 2008b; Robinson et al, 2002). In step

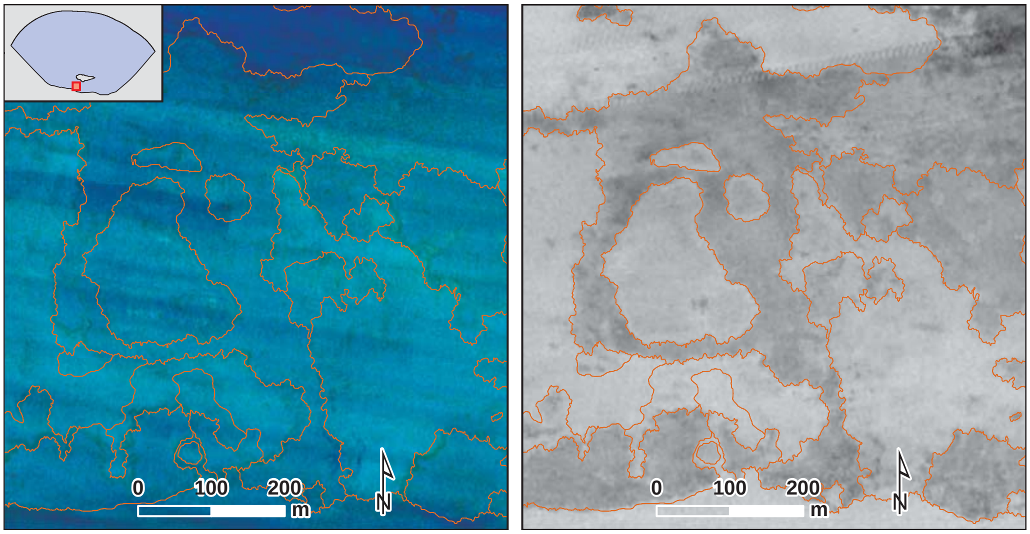


Figure 3.7. In Buck Channel, the acoustic PCA imagery (left) revealed few distinct habitat types. The LiDAR reflectance dataset (right) more clearly identified different habitat types, including a mosaic of seagrass beds (darker grey) and sand and pavement (lighter areas). Consequently cartographers integrated this reflectance surface as ancillary data in the Fx workflow.

3, ENVI Fx computes 14 spatial metrics, 4 textual metrics, 1 band ratio metric, 3 hue, saturation and intensity (HSI) metrics and 4 spectral metrics (for each input band) for each distinct object. These metrics will be referred to hereafter as “Fx object attributes,” and are described in more detail in Table 3.4 and Table 3.5. The user may then export all of the objects and their associated spatial, textual, HSI, ratio and spectral attributes as a single ESRI shapefile.

Using this workflow, discrete habitat features in each survey area were identified and delineated from the Fx input imagery. The final habitat features were exported from ENVI Zoom as ArcGIS shapefiles (Figure 3.8) with attribute tables containing Fx object attributes for each segment. For the Shallow and Aerial regions, each of the 38 resulting spatial, textual, HSI, ratio and spectral metrics were converted to rasters using a custom ArcGIS

Table 3.4. Descriptions of the spatial metrics calculated by ENVI Fx for each habitat polygon identified during the edge-detection process (ITT VIS, 2008b).

ATTRIBUTE	DESCRIPTION	FORMULA
AREA	Total area of the polygon, minus the area of the holes. Values are in map units.	-
LENGTH	The combined length of all boundaries of the polygon, including the boundaries of the holes. This is different than the MAXAXISLEN attribute. Values are in map units.	-
COMPACT	A shape measure that indicates the compactness of the polygon. A circle is the most compact shape with a value of 1 / pi. The compactness value of a square is 1 / 2(sqrt(pi)).	= Sqrt (4 * AREA / pi) / outer contour length
CONVEXITY	Polygons are either convex or concave. This attribute measures the convexity of the polygon. The convexity value for a convex polygon with no holes is 1.0, while the value for a concave polygon is less than 1.0.	= length of convex hull / LENGTH
SOLIDITY	A shape measure that compares the area of the polygon to the area of a convex hull surrounding the polygon. The solidity value for a convex polygon with no holes is 1.0, and the value for a concave polygon is less than 1.0.	= AREA / area of convex hull
ROUNDNESS	A shape measure that compares the area of the polygon to the square of the maximum diameter of the polygon. The “maximum diameter” is the length of the major axis of an oriented bounding box enclosing the polygon. Circle = 1 and square = 4/pi.	= 4 * (AREA) / (pi * MAXAXISLEN^2)
FORMFACTOR	A shape measure that compares the area of the polygon to the square of the total perimeter. The form factor value of a circle is 1, and the value of a square is pi / 4.	= 4 * pi * (AREA) / (total perimeter)^2
ELONGATION	A shape measure that indicates the ratio of the major axis of the polygon to the minor axis of the polygon. The major and minor axes are derived from an oriented bounding box containing the polygon. Square = 1 and Rectangle > 1.	= MAXAXISLEN / MINAXISLEN
RECT_FIT	A shape measure that indicates how well the shape is described by a rectangle. This attribute compares the area of the polygon to the area of the oriented bounding box enclosing the polygon. Rectangle = 1 and non-rectangle < 1.	= AREA / (MAXAXISLEN * MINAXISLEN)
MAINDIR	The angle subtended by the major axis of the polygon and the x-axis in degrees. The main direction value ranges from 0 to 180 degrees. 90 degrees is North/South, and 0 to 180 degrees is East/West.	-
MAJAXOSLEN	The length of the major axis of an oriented bounding box enclosing the polygon. Values are map units of the pixel size. If the image is not georeferenced, then pixel units are reported.	-
MINAXISLEN	The length of the minor axis of an oriented bounding box enclosing the polygon. Values are map units of the pixel size. If the image is not georeferenced, then pixel units are reported.	-
NUMHOLES	The number of holes in the polygon. Integer value.	-
HOLESOLRAT	The ratio of the total area of the polygon to the area of the outer contour of the polygon. The hole solid ratio value for a polygon with no holes is 1.0.	= AREA / outer contour area

Model Builder script, then stacked into composite images for each survey area. These multiband datasets were intersected with ground validation data to provide the foundation for the automated classification. For the Moderate Shelf, Moderate and Deep regions, the Fx object attributes were removed and the polygons were classified manually. First however, the available ground validation data was classified in the spatial context of the newly-generated Fx objects.

3.3.2. Ground Validation Classification

Extensive ground validation (GV) is needed to create high-quality benthic habitat maps because it enhances the accuracy of habitat attribution and (to a lesser degree) habitat delineation. Typically this effort is planned using a draft map (Zitello et al. 2009, Whitall et al. 2011), which increases the efficiency with which field scientists can accomplish two main objectives:

1. Explore the habitats present at unknown remote sensing signatures;
2. Verify that habitats correlated with particular remote sensing signatures remain consistent across the mapped area

A specific mission for ground validation was not conducted in BIRNM because the Biogeography Branch had already adequately sampled the benthos, employing divers in support of the Caribbean Coral Reef Ecosystem Monitoring Program (CCREMP) and deploying remotely operated vehicles (ROV's) in conjunction with the deeper hydrographic surveys. So effectually the mapping was carried out using existing habitat classification data in place of a more traditional GV mission. Later, during the accuracy assessment portion of this effort, a small number of additional GV points were selected and classified in areas that were inadequately defined in previous field work.

The GV data was collected over the course of seven years (2005-2011), using three methodologies:

1. ROV transects
2. Diver transects
3. Drop camera sites

ROV Transects

Using ROV's deployed off the NOAA ship *Nancy Foster*, the Biogeography Branch and partnering institutions conducted five habitat characterization transects from 2/1/05-2/12/05 and seven more from 3/21/06-4/2/06 that fell within BIRNM waters. In 2005, ROV sampling efforts were concentrated

Table 3.5. Descriptions of the textual, ratio, hue saturation and intensity (HSI), and spectral metrics calculated by ENVI Fx for each habitat polygon identified during the edge-detection process (ITT VIS, 2008b).

	ATTRIBUTE	DESCRIPTION
Textual	TX_RANGE	Average data range of the pixels comprising the region inside the kernel. A kernel is an array of pixels used to constrain an operation to a subset of pixels.
	TX_MEAN	Average value of the pixels comprising the region inside the kernel.
	TX_VARIANCE	Average variance of the pixels comprising the region inside the kernel.
	TX_ENTROPY	Average entropy value of the pixels comprising the region inside the kernel. ENVI Zoom computes entropy, in part, from the Max Bins in Histogram preference.
Ratio	BANDRATIO	"Values range from -1.0 to 1.0.ENVI Zoom computes a normalized band ratio between two bands, using the following equation: (B2 - B1) / (B2 + B1 + eps), where eps is a small number to avoid division by zero."
H S I	HUE	Hue is often used as a color filter and is measured in degrees from 0 to 360. A value of 0 is red, 120 is green, and 240 is blue.
	SATURATION	Saturation is often used as a color filter and is measured in floating-point values that range from 0 to 1.0.
	INTENSITY	Intensity often provides a better measure of brightness than using the AVGBAND_x spectral attribute. Intensity is measured in floating-point values from 0 to 1.0.
Spectral	MINBAND_X	Minimum value of the pixels comprising the region in band x.
	MAXBAND_X	Maximum value of the pixels comprising the region in band x.
	AVGBAND_X	Average value of the pixels comprising the region in band x.
	STDBAND_X	Standard deviation value of the pixels comprising the region in band x.

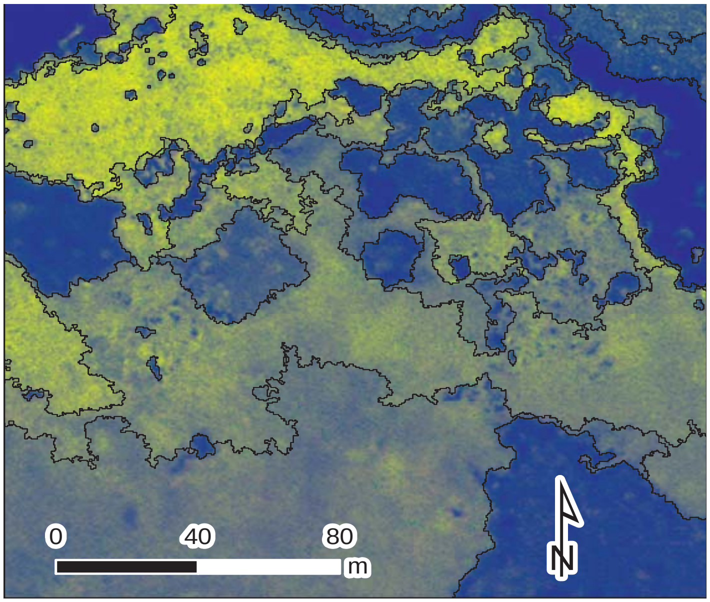


Figure 3.8. This image depicts a subset of habitat objects that were identified, delineated, and attributed by ENVI Fx, and then exported as an ESRI shapefile.

along the deepest areas of the Bank/Shelf and Bank/Shelf Escarpment zones (Figure 3.9). This area was surveyed by the *Nancy Foster* in 2004, and GV transects were systematically placed across the mapped area so as to include as many benthic habitat features and transition zones (as visually identified in the MBES imagery) as possible (Menza et al. 2007). The 2006 transects explored the benthos of the escarpment at depths of 500-850 m (Figure 3.9), and were selected in a similar manner as in 2004. This time the field scientists relied on spatially-coincident MBES data collected during the same field mission to identify benthic areas of interest (Battista and Stecher 2006).

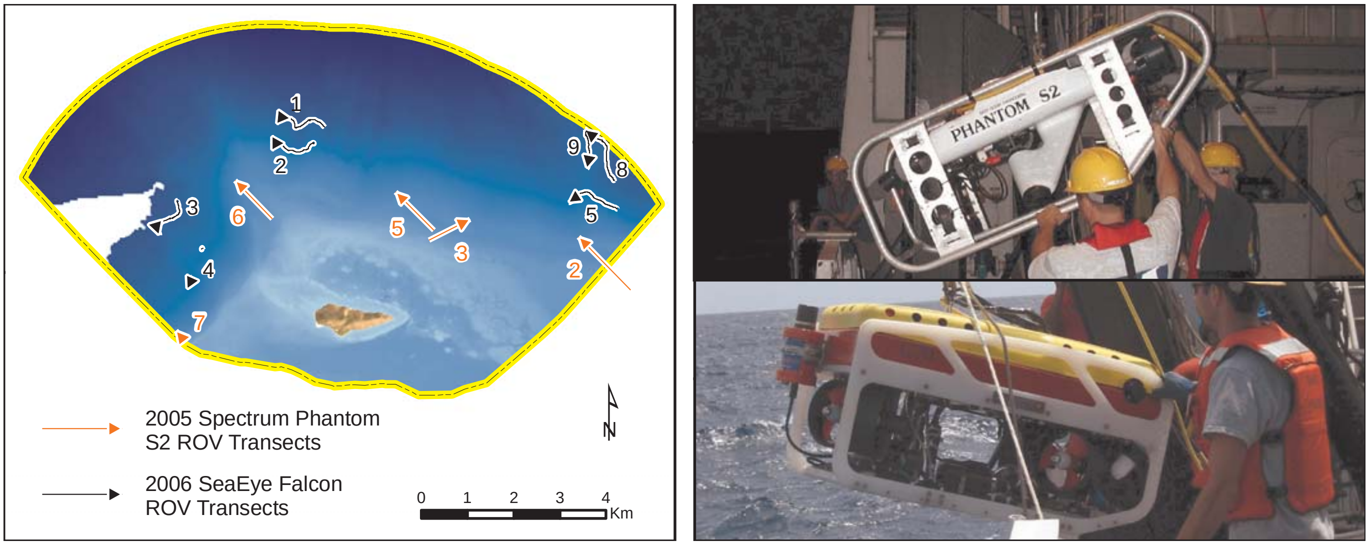


Figure 3.9. In 2005, the Spectrum Phantom S2 ROV (top right) collected underwater video and high resolution photographs of the seafloor along 5 transects (left) within BIRNM. These datasets were used for ground validation in the Moderate and Deep survey areas of this mapping effort. In 2006, the SeaEye Falcon ROV (bottom right) collected similar underwater imagery along 7 transects (left) within BIRNM. These datasets were used for ground validation in the Moderate Shelf, Moderate and Deep-water regions of BIRNM.

While researchers employed a Spectrum Phantom S2 ROV in 2005 and a SeaEye Falcon ROV in 2006, the sampling methodologies were identical in most relevant aspects. Both systems collected georeferenced underwater video and photographs using comparable video cameras and high-resolution digital still cameras mounted to the ROV frames. High-powered strobe lights mounted on both the Phantom ROV in 2005 and Falcon ROV in 2006. Video data were collected throughout each transect, and still photos were collected every 30 seconds. The forward-facing video camera was pointed at a 45 degree downward angle to give ROV pilots a view of upcoming obstacles and researchers a view of the benthic habitat. The ROV's height above the substrate and speed were approximately 2 m and 1 m/s, respectively. The ROV pilots attempted to keep the ROV height and speed constant in order to standardize the field of view and spatial resolution of interpretations. Still photo images were acquired using a downward-facing camera. A transducer attached to the ROV and an acoustic receiver (suspended into the water column off the side of the ship) were used to determine the ROV's relative position to the ship. The ROV's absolute geographic position was estimated using this relative position along with the shipboard GPS. The positional accuracy was estimated to be within +/- 5 m in 2005 (Menza et al. 2005) and 2006. Using this positional information (along with the videos and photos), each Fx polygon through which an ROV passed was classified using the current habitat scheme (Figure 3.10). Habitat transitions evident in the ROV video but missed by the Fx segmentation were also noted.

SCUBA Diver Transects

Since 2001, BB divers have collected data on shallow-water fish and benthic habitats in BIRNM. This diver data was used to classify benthic habitats in the Aerial and Shallow-water areas (Table 3.6). If the transect's position, underwater photos and habitat data did not agree, the transect was removed from further analysis.

Divers have maintained a fairly consistent set of field methods for quantifying benthic habitats at monitoring transects over the past ten years (Pittman et al. 2008). Transect starting points are selected according to a stratified random sampling plan based on the major geomorphological structure present in each study area. Boat drivers navigate to these locations using shipboard Garmin GPS. Divers are deployed to characterize a 25 m transect that follows a predetermined, random bearing. Before swimming the transect, divers typically capture at least two panoramic underwater still photographs on each side of the transect. For the 2010 sites, one diver also swam the length of the transect while recording oblique video two to three meters above the seafloor. Five one m^2 quadrats are randomly placed at five meter intervals along the 25 transect. At each quadrat, divers estimate and record two variables that are important for the BIRNM mapping effort (Pittman et al. 2008):

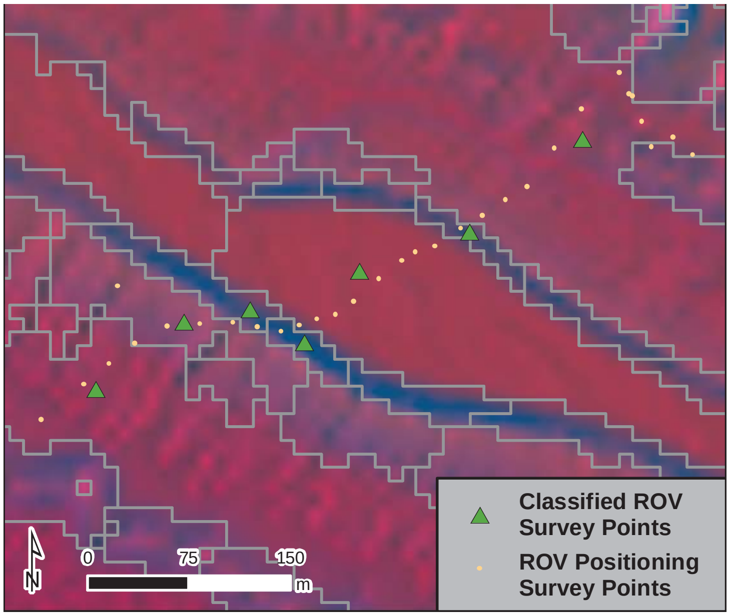


Figure 3.10. In order to streamline the deeper survey areas' manual classification, ROI's were developed by viewing the underwater imagery while tracking the system's positioning over MBES imagery. For each polygon that the ROV intersected, an ROI (green triangle) with habitat qualifiers adherent to the NOAA classification scheme was created.

1. Abiotic footprint (the quadrat's percent cover of sand, hardbottom, etc)
2. Biotic footprint (the quadrat's percent cover of seagrass, coral, algae, etc)

Despite the abundance of information that can be derived from each of the 1,715 classified habitat quadrats within the mapped area, these techniques weren't explicitly developed to support fine-scale benthic mapping. Consequently, a great deal of post-processing was required to shape the data into functional ROI's with habitat modifiers that aligned well with the current classification scheme.

Table 3.6. GV information for the Moderate Shelf, Moderate and Deep areas was collected using two ROVs. GV information for the Aerial and Shallow areas was collected using a drop camera, and was selected from the SCUBA diver data using a predetermined criteria. This criteria assessed the uncertainty associated with a diver transect's position based on whether the habitat type described in the diver data, underwater photos and source imagery was the same.

GV DATA COLLECTION METHODS							
Type	**Year**	**Mission Dates**	**Transects w/in BIRNM**	**GV Quadrats w/in BIRNM**	**GV Quadrats Employed**	**Photos**	**Videos**
ROV	2005	02/01 - 02/12	5	-	-	X	X
	2006	03/21 - 04/02	7	-	-	X	X
SCUBA Divers	2007	10/08 - 10/17	51	255	204	X	
	2008	03/10 - 03/19	63	335	234	X	
	2008	10/20 - 10/29	60	300	206	X	
	2009	03/02 - 02/13	53	265	212	X	
	2009	10/27 - 11/06	45	225	172	X	
	2010	10/18 - 10/29	63	335	260	X	X
Drop Camera	2011	08/25 - 09/01	39	-	-		X
	Total	-	386	1,715	1,288	-	-

First, since only the transect's bearing and starting location were known, transects were created using ArcGIS's "Bearing Distance to Line" tool. Next, each transect was divided into five, five m intervals. Centroids were assigned to each of these intervals, representing

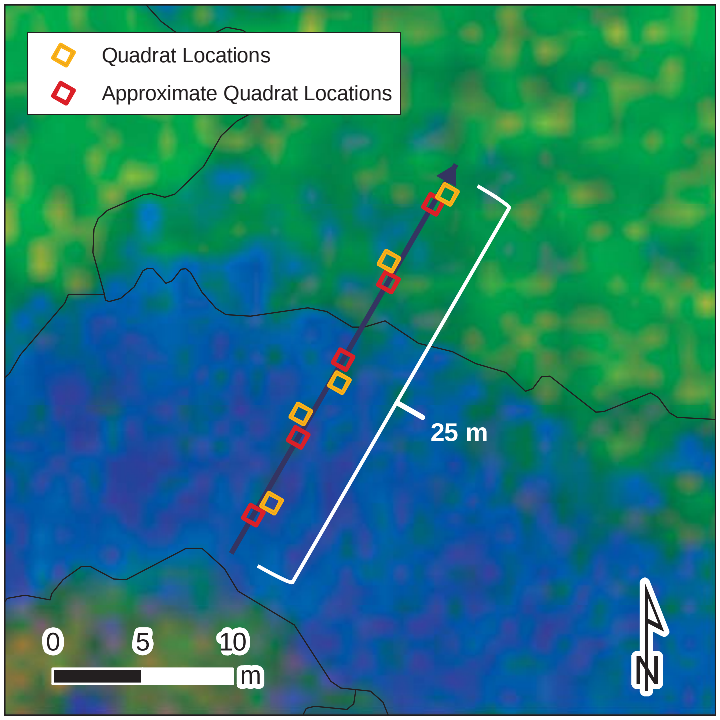


Figure 3.11. The five quadrat locations were assigned to centroids at 2.5, 7.5, 12.5, 17.5, and 22.5 m along the 25 m transect.

the approximate location of each habitat quadrat (Figure 3.11). Centroids were used because the recorded location of each quadrat was not readily accessible in the BB diver database. The habitat information for each quadrat was spatially linked to its associated centroid, numerically aggregated and then translated into its corresponding habitat map class. For instance, the divers' estimates for coverage of hardbottom and rubble were added to derive a measure for percent hardbottom. Analogously for biological cover, turf, fleshy, coralline and filamentous algae were combined into an *Algae* estimate for a given quadrat. Where Fx segments contained more than one quadrat, the values for habitat categories were averaged in order to create consistent ROI's within each polygon (Figure 3.12). Throughout this GV classification process, the cartographers frequently encountered scenarios where the underwater imagery, the diver habitat data, and the spatially-coincident source imagery did not agree. In many instances, these discrepancies arose from positioning error in the diver quadrat locations, or because of missing the bearings or underwater imagery. If these or other complications created uncertainty in the cartographers' final habitat classifications, the affected quadrats or entire transects were removed from the GV dataset, leaving 1,288 quadrats (Figure 3.13) within the Shallow and Aerial mapped extents. These quadrats were subsequently grouped into unique habitat shapefiles (i.e., one file for each unique combination of structure, cover, percent cover, and live coral cover) using the "Split Layer by Attribute" toolbox in ArcGIS 9.3 (Patterson 2008).

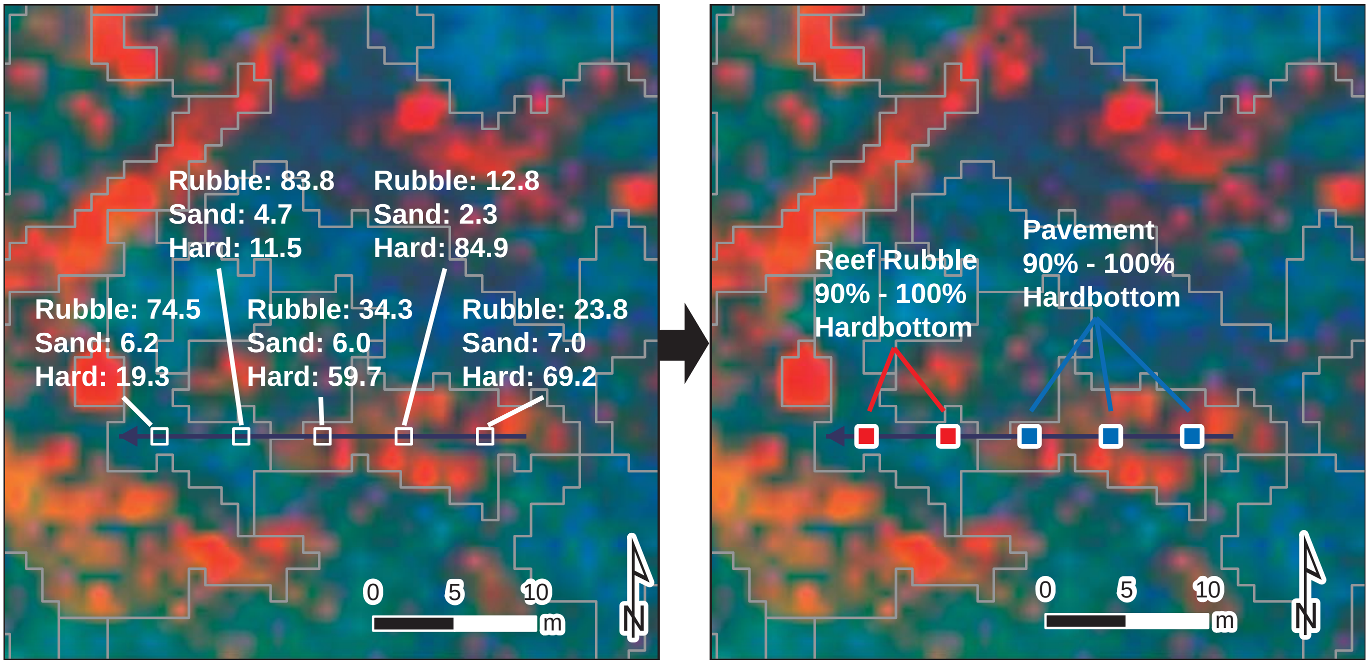


Figure 3.12. Converting the diver data into consistent GV information that fit into the NOAA classification scheme often involved aggregating and translating the divers' cover estimates. In this case, the structure proportions (left) were averaged across individual polygons and translated into valid detailed structure types and percent hardbottom classes (right).

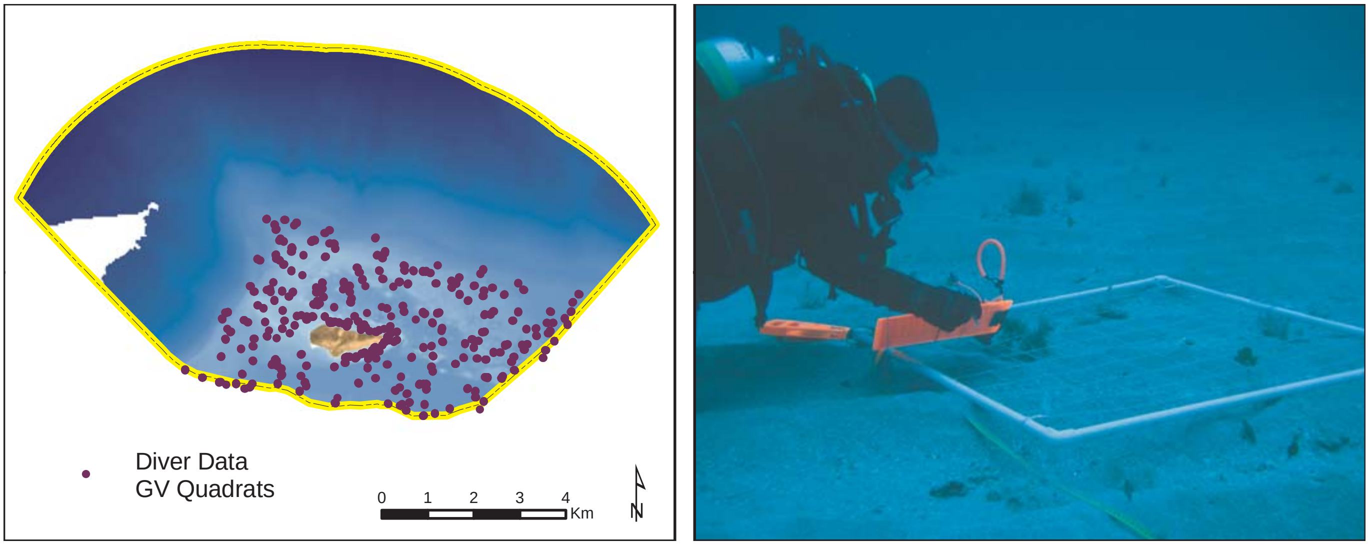


Figure 3.13. For this mapping effort, 1,288 out of 1,755 quadrats (left) collected by SCUBA divers (right) were used as GV information in the Shallow and Aerial survey areas.

Drop Camera Sites

While a traditional GV mission was not conducted for the Shallow and Aerial areas, researchers also visited 39 GV points during the Accuracy Assessment (from 8/25 - 9/1/2011) in areas where cartographers decided the draft map could be improved with additional field data (Figure 3.14). Field scientists navigated to these sites in a small NPS vessel and using a hand-held Garmin 76 WAAS-enabled GPS unit. Once in position, a SeaViewer Sea-Drop 950 camera (attached to a down weight and 100 feet of line) was deployed as waypoint logging was initiated on a Trimble GeoXH GPS receiver. While on site, the Trimble captured the vessel's position as an epic (i.e., point) approximately every 5 seconds while the underwater camera video was digitally recorded and stored topside by a SeaViewer Sea-DVR. The camera operator adjusted the camera orientation to capture a downward view of the seafloor as well as a side view of the seafloor, both taken from approximately 2 m above the bottom. This allowed for accurate measurements of percent biological cover and a broader scale understanding of the structure at each site. These classification decisions were made by another field scientist in the cockpit of the vessel, who simultaneously viewed the Sea-DVR's real-time feed and stored habitat information in the Trimble using a pre-loaded data dictionary (Figure 3.15).

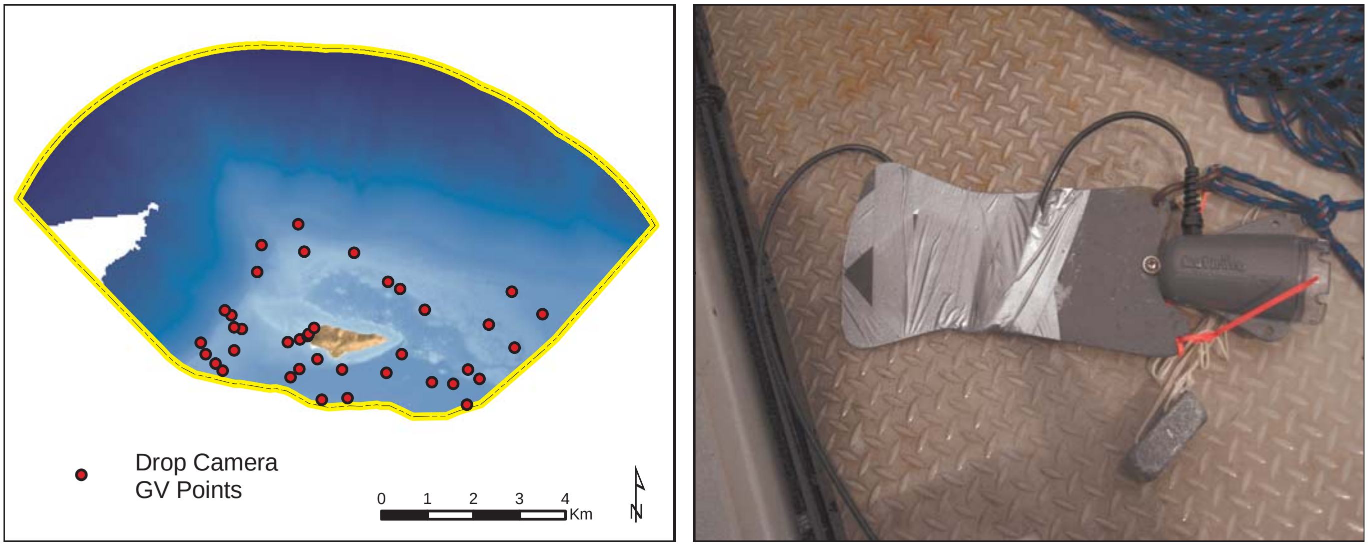


Figure 3.14. During the August 2011 BIRNM Accuracy Assessment mission, field scientists visited 39 additional ground validation sites. At each site (shown in the map at left), a Sea-Drop 950 underwater camera (right) was deployed to capture habitat video that helped cartographers revise the draft map.

Once back in the office, Trimble Pathfinder Office software was used to post process and differentially correct the raw GPS data to the Kingshill Continually Operating Reference System station at St. Croix, U.S. Virgin Islands (i.e., station VIKH). The classification of each GPS location (completed in the field) was then reviewed in conjunction with the acoustic imagery and a re-evaluation of the associated underwater video, and a final classified set of GV points was created.

Figure 3.15. Topside field equipment used to collect georeferenced underwater video at GV and AA drop camera sites. While the SeaViewer unit was in the water, a field scientist logged positioning information and entered habitat data using a Trimble GeoXH GPS receiver while viewing real-time footage via a SeaDVR.

3.3.3. Habitat Classification

Semi-Automated Classification

For the Shallow and Aerial survey areas, habitat polygons were classified using the RuleGen 1.02 add-on for ENVI 4.8 (Jengo, 2004). This add-on contains the Quick, Unbiased, Efficient Statistical Tree (QUEST) algorithm (Loh and Shih, 1997), which is implemented via ENVI's native Decision Tree Tool. QUEST is a type of Classification and Regression Tree (CART) (Breiman et al, 1984) that: (1) is nonparametric and nonlinear, (2) has negligible bias in the selection of variables, (3) is computationally simplistic, and (4) yields binary splits for categorical predictor variables, ordinal predictor variables, or a mix of both types of predictors. Unlike CART however, the QUEST algorithm separates objects in an image (i.e., habitat polygons with Fx object attributes described in section 3.3.1) into classes using univariate (axis-orthogonal) discriminat-based splits. This type of analysis separates the classification process into two parts at each split (or node) in the decision tree. The first step in this analysis, *independent variable selection*, finds the Fx object attribute that is significantly different from the other attributes in order to create the most efficient split for a given habitat class. The second step in this analysis, *binary split identification*, identifies the threshold at which to split the previously-selected Fx object attribute into two classes that are as homogenous as possible (Loh and Shih, 1997). Together, these steps use the classified GV data to find which Fx object attribute(s) are useful for splitting an image into habitat classes, and where numerically to split those object attributes into two parts. The resulting decision tree is then applied to the entire image to classify each polygon according in the classification scheme described in chapter 2.

Before developing the QUEST model, classified GV data for the Aerial and Shallow areas were parsed into unique habitat classes, based on zone, major and detailed structure, % hardbottom, major and detailed biological cover and % live coral cover. They were then imported into ENVI and converted to Regions of Interest (ROIs) using the "Import Vector Files" and "Export Active Layer to ROIs" functions. These ROIs were used to train separate QUEST algorithms, one each for the Aerial and Shallow regions. The two resulting classification trees were built using the same QUEST input parameters (Table 3.7), but different combinations of Fx attributes and associated binary split values (Costa et al. 2009). In total, the Aerial algorithm used 57 splits among 27 useful input bands (Fx attributes), and created an attributed map with 16 unique habitat classifications. The Shallow iteration included 179 node splits involving 36 important input bands and the output featured 48 different habitat types. The final classifications were exported from ENVI 4.8 as separate ESRI shapefiles.

Post-processing and quality assurance and control began once the classified shapefiles were transferred into ArcGIS. Using the software's *Eliminate* function, all polygons smaller than the minimum mapping unit (or MMU, see Table 3.8) were merged with the neighboring polygon with which they shared their longest border. Polygons were merged based on longest border (instead of habitat class) because many polygons smaller than the MMU were entirely surrounded by one larger, homogenous polygon. This function removed 88.7% and 82.7% of the polygons for the Aerial and Shallow areas, respectively (Table 3.9). The resulting 2,545 Aerial habitat polygons and 13,229 Shallow features were smoothed to diminish the segments' pixilated appearance while also improving the shapefiles' draw speeds.

Table 3.7. Descriptions of the input parameters used when building the QUEST classification trees.

INPUT PARAMETER	INPUT VALUES USED	IMPACT OF PARAMETER	DEFINITION
Minimum Node Size	5	When to stop tree from growing	The smallest number of samples in a node during tree construction. The node will not be split if it contains fewer cases than this number. The smaller this value is, the larger the initial tree will be prior to pruning. The default value is max (5, n/100), where n is the total number of observations (Shih, 2004).
Split Method	Univariate	How to split input bands	The user can choose to create discriminant-based splits using a single variable (to examine the effects of predictor variables one at time) or a linear combination of variables (Shih, 2004; StatSoft, 2007).
Variable Selection Method	Unbiased	How to select important input bands	The user can choose between the unbiased variable selection method described in Loh and Shih (1997) or the biased exhaustive search method which is used in CART described in Breiman et al. (1984) (Shih, 2004). The unbiased method uses discriminant-based split methods to prevent biased in variable selection. Thus, if all the attributes are uninformative with respect to the class attribute, then each has approximately the same chance of being selected to split a node (Lim et al., 2000).
Alpha Value (α)	0.05		Alpha value is a number 0 ≤ α ≤ 1 at which point a p-value is considered significant. If the unbiased variable selection method is used, then an alpha value is needed to conduct the tests (Shih, 2004).
Number of SEs for pruning	1	How much of tree to prune	The number of SEs (standard errors) controls the size of the pruned tree. SE = 0 gives the tree with the smallest cross validation estimate of misclassification cost or error (Shih, 2004).
Number of Folds (V)	10	How to calculate SE for tree	The user can choose the value of V in V-fold cross-validation. 10-fold is usually recommended and is the default in CART (Shih, 2004). This means that when V = 10, the dataset is randomly divided into 10 roughly equal parts. One part is left out while a regression estimate is constructed using the 9 remaining parts. The left-out part is then used to estimate the prediction mean standard error for the tree (Loh, 2002).
CV Tree Details	No	N/A	The user can choose whether the details of the cross validation tree are reported (Shih, 2004).
Output PSTricks tree?	No	N/A	The user can choose whether to use the PSTricks package (to access PostScript features that are otherwise not directly accessible from LaTeX) to draw the QUEST tree. LaTeX is a document preparation system for the TeX typesetting program, offering desktop publishing features for automating aspects of typesetting and desktop publishing.

The smoothed, MMU-compliant shapefiles for each survey area served as the starting point for the manual edits, which were conducted using the ArcGIS Editor toolbar and based on visual evaluations of the maps and additional consideration of GV data. Cartographers merged, deleted, and re-attributed habitat polygons where the automated workflow's classification differed from the cartographer's interpretation of the seafloor environment. These manual edits were made at a scale of 1:1,000. This quality assurance/quality control (QA/QC) process affected geomorphological structure and biological cover classes differently (Table 3.10). Manual editing introduced topology errors in each survey area, most notably gaps and overlapping polygons. To resolve these issues, the edited maps were subjected to topology rules addressing each type of error. In this manner the cartographer could identify each violation and correct the map's topology accordingly. The results were the final products of the semi-automated classification process: classified habitat maps of the two nearshore survey areas of BIRNM.

Table 3.8. The source imagery resolution and minimum mapping unit (MMU) for each survey area.

SURVEY AREA	SOURCE IMAGERY RESOLUTION (m)	MMU (m^2)
Aerial	0.35	100
Shallow	1	100
Moderate Shelf	10	1,000
Moderate	10	1,000
Deep	50	5,000

Table 3.9. Details and parameters involved with the training, execution, and result post-processing of the QUEST classification trees for each of the two semi-automated survey areas.

	INPUTS		QUEST TREE		POST-PROCESSING	
	ROI's	Unique ROI Classes	Nodes	End-Member Classes	Polygon Count Pre-MMU	Polygon Count Post-MMU
Aerial	364	28	115	16	22,437	2,545
Shallow	924	55	359	48	76,416	13,229

Table 3.10. Estimated number of polygons that were manually reattributed because they were deleted, added and/or reclassified. These numbers are based on three iterations of 1,000 randomly distributed points (n=3,000) stratified by detailed structure type and weighted by area. Habitat classifications contained in the original map (i.e., the unedited map produced by QUEST) and the final map (i.e., the map that was manually edited and delivered to the NPS) were extracted at each of these 1,000 points, and compared to determine whether they had been changed.

POLYGON ATTRIBUTE	ESTIMATED PERCENT OF UNEDITED POLYGONS	ESTIMATED PERCENT OF EDITED POLYGONS	CONFIDENCE INTERVAL (±95%)
Major Structure	76.6	23.4	1.70
Detailed Structure	53.2	46.8	2.73
Percent Hardbottom	40.1	59.9	3.07
Major Cover	72.7	27.3	0.24
Percent Cover	43.4	56.6	2.32
Major + Percent Cover	33.7	66.3	1.31
Percent Live Coral Cover	54.7	45.3	1.47
Unique Habitat Classification	9.7	90.3	1.13

Manual Classification

For the Moderate Shelf, Moderate, and Deep survey areas, the habitat segments were smoothed to reduce their pixilated appearance and the Fx object attributes were also removed. These columns were replaced with attribute fields representing each qualifier in the habitat classification scheme; bringing the automated portion of the methodology to a close. These areas of the Monument would be attributed by an interpreter using information gleaned from GV locations and coincident acoustic signatures. This manual classification was carried out in a manner very similar to that described by Zitello et al. (2009) for the shallow-water benthos of St. John, USVI. On a first pass through each draft map the linework was refined using the ArcGIS Editor tools, with all digitizing edits performed at a scale of 1:1,000 and in areas where the Fx delineation had either left out or overstated a habitat or ecotone. Once the polygon extents appropriately represented the habitat features present in each area, the interpreter classified each polygon based on the relevant GV and acoustic information, selecting from a set of pre-loaded habitat attributes. For the Moderate Shelf and Moderate areas, backscatter surfaces were also available and provided an enhanced understanding of the dominant substrate for several polygons. Each classified habitat polygon smaller than its survey area's MMU was removed using the *Eliminate* function. The resulting classified, MMU-compliant draft maps were again smoothed because the initial smoothing process was often hindered by areas of contiguous, small (1- to 10-pixel) polygons. The shapefiles' topologies were checked for overlapping polygons and gaps before becoming the habitat maps of each survey area.

Edge-Matching

Once classified and QA/QC'ed, the five assembled habitat maps were edge matched. This process was carried out by visually checking for clean and consistent linework and attribution on both sides of survey area boundaries. The cartographer took into account differing MMU's, variable habitat signatures for different imagery types, and the range of imagery and GV data acquisition dates when resolving discrepancies along these map borders. The great majority of these decisions deferred to the classification provided by the shallower, finer scale maps, but there were exceptions to this as well. In several cases along the Shallow/Aerial border, current seagrass extents were more accurately represented by the 2011 LiDAR reflectance dataset (incorporated in the Shallow area's feature extraction) than the 2007 orthophotography, so the linework along the border was matched according to the Shallow map. At the nexus of the Shallow and Moderate Shelf maps northwest of Buck Island, the assemblage of rhodoliths, pavement, and sand on the outer shelf was more accurately defined by the Moderate Shelf map due to the area's density of ROV GV data. Accordingly, the Shallow map was revised to more closely align with the deeper area's habitat polygons. In all cases, polygons that spanned two areas merely had to meet the MMU requirements of the shallower area. After the edge matching was completed, maps with the same MMU (i.e., Aerial/Shallow and Moderate Shelf/Moderate) were merged together and checked for topology errors. This step created three seamless benthic habitat maps (Figure 1.3), characterizing the geology and biology of the seafloor from the shoreline to 1,830 m depths inside the Monument.

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CHAPTER 4: ASSESSMENT OF CLASSIFICATION ACCURACY

An independent assessment was conducted to evaluate the thematic accuracy of the benthic habitat map for the Aerial and Shallow regions inside BIRNM. Thematic accuracy was characterized for major and detailed geomorphological structure, major and detailed biological cover, and percent coral cover classifications. No accuracy assessment was conducted for the Moderate Shelf, Moderate and Deep regions because of the difficulty accessing these habitats using traditional underwater sampling techniques.

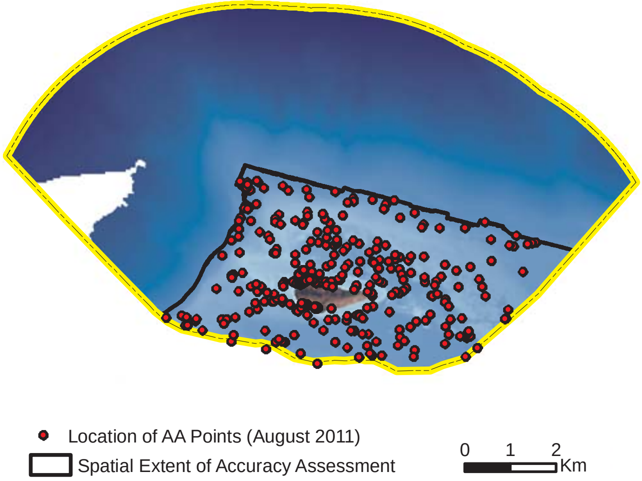

Figure 4.1. In August 2011, underwater video was collected at 350 sites within BIRNM. These data were used to assess the thematic accuracy of the Aerial and Shallow-water habitat maps.

4.1 FIELD DATA COLLECTION

Target locations for the accuracy assessment (AA) procedure were determined by an iterative, GIS-based, stratified random sampling technique to ensure that all bottom classifications would be assessed. Points were randomly placed within each geomorphological structure class of the draft habitat map using Hawth's Analysis Tools (Beyer, 2004). No buffer from polygon edges was used. Approximately 25 points were randomly distributed within each detailed structure class. Classes occupying larger areas were often allocated more than 25 points. A total of 350 sample locations were targeted, of which 344 were sufficiently surveyed to be included in the accuracy assessment (Figure 4.1). AA data were collected during a field mission from 8/25/11 to 8/30/11. The same protocol used to collect GV drop camera data (described under the "Drop Camera" heading in Section 3.3.2) was also used to collect the AA data. Sites that could not be navigated to by boat were accessed by snorkeling or walking. Videos at these locations were captured using a Canon Power Shot SD1100 enclosed in a waterproof housing.

4.2 EVALUATION OF ASSESSMENT DATA

The GPS data were processed using Trimble Pathfinder software. GPS data logged on the Trimble GeoXh receiver were differentially post-processed to the Kingshill Continually Operating Reference System (CORS) station on St. Croix, U.S. Virgin Islands (VIKH). For each survey site, individual epics were averaged to generate an "average" GPS point. The GPS data were then exported and plotted in ArcGIS along with the corresponding field notes. In most cases, the average point was a sufficient representation of the survey site; however in cases where the survey was conducted along or crossed a polygon edge, the average GPS point did not always fall into the polygon that was assessed. In these cases, the survey point was shifted to the portion of the transect and polygon that was classified.

Prior to analysis, each video clip was re-analyzed and viewed in concert with the benthic habitat map overlaid on the orthophotos, LiDAR and acoustic imagery. It should be noted that all analysis at this stage was made by a scientist independent of the cartographer who created the map. Density of the biological cover was assessed at the video level and patchiness of the biological cover polygon level. As a result, it was often necessary to adjust the classifications that were initially recorded in the field to reconcile the differences between the video and map scales. Similar adjustments were sometimes necessary to correctly characterize detailed structure. For example, heterogeneous hardbottom classes, such as pavement with sand channels, could not always be correctly classified from the video alone. In other cases, additional information on the position, size and shape of hardbottom features was needed to determine whether the structure should be classified as aggregate reef or a patch reef (either individual or part of an aggregated patch reef feature, if below the MMU).

Following these adjustments, data were then spatially joined to the benthic habitat layer to extract the map classification for each point. Sites that differed between field notes and map classification were evaluated both in GIS and from video to determine possible source of disagreement. Some of these disagreements were discussed with the cartographer to make sure that all aspects of the classification scheme were being consistently applied. The benthic habitat map was then corrected to its final version using information collected from the accuracy assessment and released for publication.

4.3 ANALYSIS OF THEMATIC ACCURACY

The thematic accuracy of the BIRNM benthic habitat map was characterized in several ways from these data. Error matrices were computed for the attributes major and detailed geomorphological structure, major and detailed biological cover, and percent coral cover. Overall accuracy, producer's accuracy, and user's accuracy were computed directly from the error matrices (Story and Congalton, 1986). The error matrices were constructed as a square array of numbers arranged in rows (map classification) and columns (accuracy assessment, or groundtruthed classification). The overall accuracy (P_o) was calculated as the sum of the major diagonal (i.e. correct classifications, divided by the total number of accuracy assessment samples).

The producer's and user's accuracies were calculated to characterize the classification accuracy of individual map categories. The producer's accuracy (omission/exclusion error) is a measure of how well the cartographer classified a particular habitat (e.g., the percentage of times that substrate ground-truthed as sand was correctly mapped as sand). The user's accuracy (commission/inclusion error) is a measure of how often map polygons of a certain habitat type were classified correctly (e.g., the percentage of times that a polygon classified as sand was actually ground-truthed as sand). Each diagonal element was divided by the column total to yield a producer's accuracy and by the row total to yield a user's accuracy.

In addition, the Tau coefficient (T_e), a measure of the improvement of classification accuracy over a random assignment of map units to map categories (Ma and Redmond, 1995), was calculated. As the number of categories increases, the probability of random agreement (P) diminishes, and T approaches P. Values of T were calculated as follows:

Tau coefficient = $T_e = (P_o – P_r) / (1 – P_r)$,
where Pr = 1/r. The variance of Tau (Ma and Redmond 1995) was calculated as:
Variance of Tau coefficient = $\sigma r^2 = P_o(1 – P_o) / n(1 – P_r)^2$

Confidence intervals were then calculated for each Tau coefficient at the 95% confidence level (1-α), using the following generalized form:

$$95\%\ CI = T_e \pm Z_{\alpha/2}(\sigma_r^{\ 2})^{0.5}$$

While stratification ensures adequate evaluation of all map categories, it has the undesired effect of introducing bias into the error matrix (Hay 1979; Card 1982). A minimum number of sites were targeted within each mapping category, which caused rare map categories to be sampled at a greater rate than common map categories. For example, although *Pavement* habitat comprised 42% of the map area, only 16% of the target points were allocated for this habitat. The bias introduced by differential sampling rates was removed using the method of Card (1982), which utilizes the map marginal proportions (i.e. the proportional areas of map categories relative to the total map area). The map marginal proportions were calculated as the area of each map category divided by the total mapped area of the BIRNM benthic habitat map. The map marginal proportions were also utilized in the computation of confidence intervals for the overall, producer's, and user's accuracies (Card 1982; Congalton and Green, 1999). This method was also used in the recent accuracy assessment of the NOAA Florida Keys benthic habitat map (Walker and Foster, 2009) and NOAA's shallow water St. John habitat map (Zitello et al., 2009).

The map marginal proportions (π_j) were computed from the GIS layer of the draft benthic habitat map for each of the four error matrices (major and detailed geomorphological structure, major and detailed biological cover), by dividing the area of each category by the total map area. Marginal proportions were not computed for the percent coral cover matrix. The map areas were exclusive to categories present in the error matrix. For the example of detailed structure category *Pavement*, π_j was 0.426 (10.60 km²/24.87 km²). The individual cell probabilities, i.e. the product of the original error matrix cell values and π_j, divided by the row marginal (total map classifications per category), were computed for the off-diagonal elements using the following equation:

Individual cell probabilities = $\hat{P}_{ij} = \pi_j n_{ij} / n_{-j}$

The relative proportions of the cell values within a row of the error matrix were unaffected by this operation, but the row marginals were forced to the map marginal proportions (i.e. the row total of a particular habitat now equaled the fraction of map area occupied by that habitat, instead of the total number of accuracy assessment points). The estimated true marginal proportions (p_i) were computed as the sum of individual cell probabilities down each column of the error matrix.

The π_j-adjusted overall, producer's, and user's accuracies were then computed from the new error matrix, now populated by individual cell probabilities. The values of the π_j-adjusted overall and producer's accuracies differ by design from those of the original error matrix, as they have been corrected for the areal bias introduced by the stratified random sampling protocol. The user's accuracy, in contrast, is not affected. The variances and confidence intervals of the overall, producer's, and user's accuracies were then computed from the following set of equations (Card 1982; Walker and Foster, 2009):

$$\text{Overall Variance} = V(\hat{P}_c) = \sum_{i=1}^{r} p_{ii}(\pi_i - p_{ii})/n_i)$$

$$\text{Overall Confidence Interval} = \text{CI} = \hat{P}_c \pm 2[V(\hat{P}_c)]^{1/2}$$

$$\text{Producer's Variance} = V(\hat{\theta}_{ii}) = p_{ii}\,p_i^{-4}[p_{ii}\sum_{j\neq i}^{r} p_{ij}(\pi_j - p_{ij})/n_{-j} + (\pi_i - p_{ii})(p_i - p_{ii})^2/n_{i-j}]$$

$$\text{Producer's Confidence Interval} = \text{CI} = \hat{\theta}_{ii} \pm 2[V(\hat{\theta}_{ii})]^{1/2}$$

$$\text{User's Variance} = V(\hat{\lambda}_{ii}) = p_{ii}(\pi_i - p_{ii})/\pi_i^{\,2} n_i$$

$$\text{User's Confidence Interval} = \text{CI} = \hat{\lambda}_{ii} \pm 2[V(\hat{\lambda}_{ii})]^{1/2}$$

4.4 ACCURACY ASSESSMENT RESULTS AND DISCUSSION

Major Geomorphologic Structure

Error matrices for major geomorphological structure are displayed in Tables 4.1 and 4.2. The overall accuracy (P_o) at the major geomorphological structure level was 94.5% (Table 4.1). The Tau coefficient for equal probability of group membership is 0.917 ± 0.044 (α=0.05). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, was 94.4% (±2.5%) (α=0.05). The user's and producer's accuracies were similarly high for both hard and soft-bottom habitats (Table 4.2). The *Other Delineations* class indicates areas of "Artificial" structure category.

Table 4.1. Error matrix for major geomorphological structure.

Accuracy Assessment (i)

		Coral Reef and Hardbottom	Other Delineations	Unconsolidated Sediment	$n_{.j}$	User's Accuracy (%)
Map Data (j)	Coral Reef and Hardbottom	**210**	0	12	222	**94.6%**
	Other Delineations	0	**3**	0	3	**100.0%**
	Unconsolidated Sediment	7	0	**112**	119	**94.1%**
	$n_{i.}$	217	3	124	n=344	
	Producer's Accuracy (%)	**96.8%**	**100.0%**	**90.3%**	P_0 = 94.5%	
					T_e = 0.917 ± 0.044	

Table 4.2. Error matrix for major geomorphological structure using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

Accuracy Assessment (i)

		Coral Reef and Hardbottom	Other Delineations	Unconsolidated Sediment	$\pi_{.j}$	User's Accuracy (%)	User's CI (±%)
Map Data (j)	Coral Reef and Hardbottom	**0.6304**		0.0360	0.6664	**94.6%**	**2.2%**
	Other Delineations		**4.15498E-06**		0.0000	**100.0%**	**0.0%**
	Unconsolidated Sediment	0.0196		**0.3140**	0.3336	**94.1%**	**1.9%**
	$p_{i.}$	0.650	0.000	0.350	π=1		
	Producer's Accuracy (%)	**97.0%**	**100.0%**	**89.7%**	P_o = 94.4%		
	Producer's CI (±%)	**3.7%**	**0.0%**	**6.4%**	CI(±) = 2.5%		

Detailed Geomorphologic Structure

Error matrices for detailed geomorphological structure are displayed in Tables 4.3 and 4.4. The overall accuracy (P_o) at the detailed geomorphological structure

Table 4.3. Error matrix for detailed geomorphological structure.

Accuracy Assessment (i)

Map Data (j)

	Aggregate Reef	Aggregated Patch Reefs	Artificial	Rock/Boulder	Individual Patch Reef	Mud	Pavement	Pav w/ Sand Channels	Reef Rubble	Sand	Sand w/ SCR	Rhodoliths	Rhodoliths w/ SCR	$n_{\cdot j}$	User's Accuracy (%)
Aggregate Reef	**16**	3					2							21	**76.2%**
Aggregated Patch Reefs		**49**									1			50	**98.0%**
Artificial			**3**											3	**100.0%**
Rock/Boulder				**20**						2				22	**90.9%**
Individual Patch Reef	0	5			**16**									21	**76.2%**
Mud						**20**								20	**100.0%**
Pavement	1	1					**46**	3			3	1		55	**83.6%**
Pav w/ Sand Channels							2	**19**						21	**90.5%**
Reef Rubble		4					12		**3**					19	**15.8%**
Sand							1		1	**73**	1			76	**96.1%**
Sand w/ SCR		2			1		3			10	**7**			23	**30.4%**
Rhodoliths							2			4	2	**4**	1	13	**30.8%**
Rhodoliths w/ SCR													**0**	0	**N/A**
$n_{i\cdot}$	17	64	3	20	17	20	68	22	4	89	14	5	1	n=344	
Producer's Accuracy (%)	**94.1%**	**76.6%**	**100.0%**	**100.0%**	**94.1%**	**100.0%**	**67.6%**	**86.4%**	**75.0%**	**82.0%**	**50.0%**	**80.0%**	**0.0%**	**P_0 = 80.2%**	

T_e = 0.786 ± 0.047

Table 4.4. Error matrix for detailed geomorphological structure using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

Accuracy Assessment (i)

Map data (j)

	Aggregate Reef	Aggregated Patch Reefs	Artificial	Rock/Boulder	Individual Patch Reef	Mud	Pavement	Pav w/ Sand Channels	Reef Rubble	Sand	Sand w/ SCR	Rhodoliths	Rhodoliths w/ SCR	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
Aggregate Reef	**0.0189**	0.0035					0.0024							0.0247	**76.2%**	**1.2%**
Aggregated Patch Reefs		**0.1330**									0.0027			0.1358	**98.0%**	**0.9%**
Artificial			**4.2E-06**											0.0000	**100.0%**	**0.0%**
Rock/Boulder				**0.0015**						0.0001				0.0016	**90.9%**	**0.1%**
Individual Patch Reef	0.0000	0.0043			**0.0136**									0.0179	**76.2%**	**0.9%**
Mud						**0.0002**								0.0002	**100.0%**	**0.0%**
Pavement	0.0078	0.0078					**0.3565**	0.0233			0.0233	0.0078		0.4263	**83.6%**	**5.3%**
Pav w/ Sand Channels							0.0038	**0.0366**						0.0404	**90.5%**	**1.2%**
Reef Rubble		0.0030					0.0089		**0.0022**					0.0142	**15.8%**	**0.7%**
Sand							0.0037		0.0037	**0.2731**	0.0037			0.2843	**96.1%**	**1.7%**
Sand w/ SCR		0.0043			0.0021		0.0064			0.0213	**0.0149**			0.0491	**30.4%**	**2.0%**
Rhodoliths							0.0009			0.0017	0.0009	**0.0017**	0.0004	0.0056	**15.4%**	**0.4%**
Rhodoliths w/ SCR													**0.0000**	0.0000	**N/A**	**N/A**
$p_{i\cdot}$	0.027	0.156	0.000	0.001	0.016	0.000	0.383	0.060	0.006	0.296	0.046	0.009	0.000	π=1		
Producer's Accuracy (%)	**70.9%**	**85.4%**	**100.0%**	**100.0%**	**86.4%**	**100.0%**	**93.2%**	**61.1%**	**37.4%**	**92.2%**	**32.8%**	**18.1%**	**0.0%**	**P_o = 85.2%**		
Producer's CI (±%)	**43.0%**	**10.0%**	**0.0%**	**13.5%**	**29.4%**	**0.0%**	**10.8%**	**27.4%**	**54.8%**	**5.1%**	**25.3%**	**31.9%**	**0.0%**	**CI(±) = 4.6%**		

level was 80.2%, with a Tau coefficient (T_e) of 0.786 ± 0.047 (α=0.05). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, improved slightly to 85.2 (±4.6%)(α=0.05), because the classes that covered the most area were also the most correctly interpreted. Adjusted user's accuracy was generally above 70% for all categories with the exception of *Reef Rubble; Sand with Scattered Coral and Rock*; and *Rhodoliths* categories, which had a calculated user's accuracy of 15.8%, 30.4%, and 30.8% respectively. *Reef Rubble* was primarily confused with *Pavement* habitat. *Sand with Scattered Coral and Rock* and *Rhodoliths* was primarily confused with *Sand* habitat.

Categories with the lowest adjusted producer's accuracy were *Sand with Scattered Coral and Rock* (50.0%) and *Pavement* (67.6%), and *Aggregated Patch Reefs* (76.6%). In these cases, there was a comparatively high degree of variance, and *Sand with Scattered Coral and Rock* was relatively undersampled compared to the other map categories. *Pavement* was confused as *Reef Rubble*, a low reef and hard structure with similar acoustical and spectral signature.

Major Biological Cover

Error matrices for major biological cover are displayed in Tables 4.5 and 4.6. The overall accuracy (P_o) at the major biological cover level was 88.1%, with a Tau coefficient (T_e) of 0.857 ± 0.044 (α=0.05). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, was similar at 88.8 (±3.4%) (α=0.05).

Thematic accuracy was above 70% for all categories with the exception of *Seagrass*. *Seagrass* was most commonly confused with *No Cover* in areas where *Seagrass* densities were low, and *Algae*, which has a similar spectral and acoustical signature.

Table 4.5. Error matrix for major biological cover.

Accuracy Assessment (i)

Map Data (j)

	Algae	Mangrove	Live Coral	Seagrass	No Cover	Unclassified	$n_{\cdot j}$	User's Accuracy (%)
Algae	**208**	0	0	2	11	0	221	**94.1%**
Mangrove	0	**12**	0	0	0	0	12	**100.0%**
Live Coral	0	0	**0**	0	0	0	0	**N/A**
Seagrass	8	0	1	**46**	11	0	66	**69.7%**
No Cover	7	0	0	1	**34**	0	42	**81.0%**
Unclassified	0	0	0	0	0	**3**	3	**100.0%**
$n_{i\cdot}$	**223**	**12**	**1**	**49**	**56**	**3**	n=344	
Producer's Accuracy (%)	**93.3%**	**100.0%**	**0.0%**	**93.9%**	**60.7%**	**100.0%**	**P_0 = 88.1%**	
							T_e = 0.857 ± 0.044	

Detailed Biological Cover

Error matrices for detailed biological cover are displayed in Tables 4.7 and 4.8. The overall accuracy (P_o) at the detailed biological cover level was 79.4%, with a Tau coefficient (T_e) of 0.771 ± 0.048 (α=0.05). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, was similar at 81.4% (±4.6%) (α=0.05).

Table 4.6. Error matrix for major biological cover using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

Accuracy Assessment (i)

Map Data (j)

	Algae	Mangrove	Live Coral	Seagrass	No Cover	Unclassified	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
Algae	**0.6586**			0.0063	0.0348		0.6998	**94.1%**	**2.4%**
Mangrove		**0.0001**					0.0001	**100.0%**	**0.0%**
Live Coral			**0.0000**				0.0000	**N/A**	**0.0%**
Seagrass	0.0143		0.0018	**0.0823**	0.0197		0.1181	**69.7%**	**2.3%**
No Cover	0.0303			0.0043	**0.1473**	0.0000	0.1820	**81.0%**	**3.4%**
Unclassified						**4.15498E-06**	0.0000	**100.0%**	**0.0%**
$p_{i\cdot}$	0.703	0.000	0.002	0.093	0.202	0.000	π=1		
Producer's Accuracy (%)	**93.7%**	**100.0%**	**0.0%**	**88.5%**	**73.0%**	**100.0%**	**P_o = 88.8%**		
Producer's CI (±%)	**4.3%**	**0.0%**	**0.0%**	**17.4%**	**11.9%**	**0.0%**	**CI(±) = 3.4%**		

The greatest source of confusion at the detailed biological cover level involved the degree of patchiness within the *Seagrass* category. For example, the adjusted user's accuracy of the *Seagrass 10%-<50%* and *Seagrass 50%-<90%* categories were 35.3% and 60.0%, respectively (Table 4.7). Of the 17 sites mapped as *Seagrass 10%-<50%*, 8 were interpreted to be *No Cover 90%-100%* (44.4%). *Seagrass* 50%-<90% mapped polygons were confused with *No Cover 90%-100%* (12%) and with *Seagrass 10%-<50%* (8%).

Table 4.7. Error matrix for detailed biological cover.

Accuracy Assessment (i)

Map Data (j)

	Algae 10% - <50%	Algae 50% - <90%	Algae 90% - 100%	Mangrove 90% - 100%	Live Coral 10% - <50%	Seagrass 10% - <50%	Seagrass 50% - <90%	Seagrass 90% - 100%	No Cover 90% - 100%	Unclassified N/A	$n_{.j}$	User's Accuracy (%)
Algae 10% - <50%	**33**	5	1						6		45	**73.3%**
Algae 50% - <90%	3	**84**	12					1			100	**84.0%**
Algae 90% - 100%		6	**64**				1		5		76	**84.2%**
Mangrove 90% - 100%				**12**							12	**100.0%**
Live Coral 10% - <50%					**0**						0	**N/A**
Seagrass 10% - <50%	1				1	**6**	1		8		17	**35.3%**
Seagrass 50% - <90%	2					2	**15**		3		25	**60.0%**
Seagrass 90% - 100%			2					**22**			24	**91.7%**
No Cover 90% - 100%	2	4	1				1	0	**34**		42	**81.0%**
Unclassified N/A										**3**	3	**100.0%**
$n_{i.}$	**41**	**102**	**80**	**12**	**1**	**8**	**18**	**23**	**56**	**3**	n=344	
Producer's Accuracy (%)	**80.5%**	**82.4%**	**80.0%**	**100.0%**	**0.0%**	**75.0%**	**83.3%**	**95.7%**	**60.7%**	**100.0%**	**P_0 = 79.4%**	

T_e = 0.771 ± 0.048

Table 4.8. Error matrix for detailed biological cover using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the true map marginal proportions.

Accuracy Assessment (i)

Map Data (j)

	Algae 10% - <50%	Algae 50% - <90%	Algae 90% - 100%	Mangrove 90% - 100%	Live Coral 10% - <50%	Seagrass 10% - <50%	Seagrass 50% - <90%	Seagrass 90% - 100%	No Cover 90% - 100%	Unclassified N/A	$\pi_{.j}$	User's Accuracy (%)	User's CI (±%)
Algae 10% - <50%	**0.0631**	0.0096	0.0019						0.0115		0.086	**73.3%**	**2.1%**
Algae 50% - <90%	0.0060	**0.1667**	0.0238					0.0020			0.198	**84.0%**	**2.2%**
Algae 90% - 100%		0.0328	**0.3498**				0.0055		0.0273		0.415	**84.2%**	**4.3%**
Mangrove 90% - 100%				**0.0001**							0.000	**100.0%**	**0.0%**
Live Coral 10% - <50%					**0.0000**						0.000	**N/A**	**0.0%**
Seagrass 10% - <50%	0.0011				0.0011	**0.0064**	0.0011		0.0085		0.018	**35.3%**	**1.1%**
Seagrass 50% - <90%	0.0027	0.0040				0.0027	**0.0201**		0.0040		0.033	**60.0%**	**1.5%**
Seagrass 90% - 100%			0.0056					**0.0611**			0.067	**91.7%**	**1.5%**
No Cover 90% - 100%	0.0087	0.0173	0.0043				0.0043	0.0000	**0.1473**		0.182	**81.0%**	**3.4%**
Unclassified N/A										**0.0000**	0.000	**100.0%**	**0.0%**
$p_{i.}$	0.081	0.230	0.385	0.000	0.001	0.009	0.031	0.063	0.199	0.000	π=1		
Producer's Accuracy (%)	**77.5%**	**72.3%**	**90.8%**	**100.0%**	**0.0%**	**70.3%**	**64.9%**	**96.9%**	**74.2%**	**100.0%**	**P_o = 81.4%**		
Producer's CI (±%)	**17.7%**	**11.1%**	**9.2%**	**0.0%**	**0.0%**	**45.2%**	**33.2%**	**13.0%**	**13.0%**	**0.0%**	**Ci(±) = 4.6%**		

Percent Coral Cover

The error matrix for percent coral cover is displayed in Table 4.9. The overall accuracy (P_o) at the detailed biological cover level was 90.1%, with a Tau coefficient (T_e) of 0.852 ± 0.047 (α=0.05). A second matrix using the true map marginal proportions, was not computed for percent coral cover because the accuracy of the percent hardbottom class was not assessed, which was needed to calculate true map marginal proportions for percent coral cover.

Hard and soft corals were separately mapped because their optical and acoustic signatures are indistinguishable. It is worth noting the reduction in user's accuracy between 10%-<50% and 50%-<90% coral. There is very little significant coral cover at shallow depths in the U.S. Virgin Islands. Locations where coral is present are very discrete, small in area and not broadly distributed. Since percent coral cover was recorded at all sites regardless of whether it was the dominant cover type, this is a better measure of coral accuracy than is found under *Major Biological Cover*.

Table 4.9. Error matrix for percent live coral cover.

		Accuracy Assessment (i)				
		0% - <10%	**10% - <50%**	**N/A**	**$n_{\cdot j}$**	**User's Accuracy (%)**
Map data (j)	**0% - <10%**	**264**	23		287	**92.0%**
	10% - <50%	11	**43**		54	**79.6%**
	N/A		0	**3**	3	**100.0%**
	$n_{i\cdot}$	**275**	**66**	**3**	n=344	
	Producer's Accuracy (%)	**96.0%**	**65.2%**	**100.0%**	**P_o = 90.1%**	
						T_e = 0.852 ± 0.047

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CHAPTER 5: DISCUSSION

NOAA's BB, with support from the NPS, USGS, USACE, Fugro LADS, UNH and other programs within NOAA, has completed a benthic habitat map for the shallow to deep-water marine environments in Buck Island Reef National Monument. An independent accuracy assessment of the map < 50 m in depth revealed overall map accuracies (corrected for proportional bias) to be over 94% for major structure, 85% for detailed structure, 89% for major cover, 81% for detailed cover and 90% for live coral cover classes. These numbers are similar to other benthic habitat maps created using similar mapping protocols (Battista et al. 2007a; Battista et al. 2007b; Zitello et al. 2009; Bauer et al. 2010). As a result, these digital map products can be used with confidence by scientists and resource managers for a multitude of different applications. The final deliverables for this project are available to the public on a NOAA Biogeography Branch website (http://ccma.nos.noaa.gov/ecosystems/coralreef/stcroix.aspx) and through an interactive, web-based map application (http://ccma.nos.noaa.gov/explorer/biomapper/biomapper.html?id=BUIS). Brief descriptions of these deliverables are listed in Table 5.1.

Table 5.1. Final deliverables for NOAA's habitat map of BIRNM.

DATA TYPE	ITEM	FORMAT	QTY
Map	Benthic Habitat Map 2011	GIS shapefile	4
	Benthic Habitat Map 2001	GIS shapefile	1
	Habitat Symbology Layers	GIS layer files	5
Imagery	Orthophotos (Images)	GeoTiffs	3
	LiDAR Data (Images)	GeoTiffs	4
	Acoustic Data (Images)	GeoTiffs	32
Field Data	GV Dataset	GIS shapefile	6
	GV Photos of Seafloor (Divers)	jpegs	564
	GV Video of Seafloor (Drop Camera & Divers)	.mov & .flv	96
	GV Photos of Seafloor (ROV)	jpegs	1,776
	GV Video of Seafloor (ROV)	.wmv & .avi	12
	AA Dataset	GIS shapefile	1
	AA Photos of Seafloor	jpegs	0
	AA Video of Seafloor	.mov & .flv	345
Online Map	Online Interactive Map Project	Online	1
Reporting	FGDC-compliant Metadata for GIS Files	Text files	51
	Final Report	PDF	1

5.1 SUMMARY STATISTICS

Before discussing habitat trends in BIRNM as a whole, two caveats need to be made about summarizing habitat maps with different MMUs because coral reef habitats are sensitive to the resolution at which they are mapped (Kendall and Miller 2008). The first caveat is that MMU affects not only the size of habitat features delineated, but also the name that those features are given (Kendall and Miller 2008). For example, an individual patch reef that is 200 m^2 in size will be mapped as Individual Patch Reef in a map with a 100 m^2 MMU and as Aggregated Patch Reefs in a map with a 1,000 m^2 MMU. These different interpretations occur because the patch reef is too small (<1,000 m^2) to be characterized individually at a coarser scale. The second caveat is that rare map types become more common and dominant ones become less common when the size of the MMU decreases (Kendall and Miller 2008). This occurs because habitats are delineated and classified individually at a smaller MMU instead of being aggregated with adjacent or similar habitats at a larger MMU. Notably, individual patch reefs, pavement and sand patches often become more common when smaller MMUs are implemented.

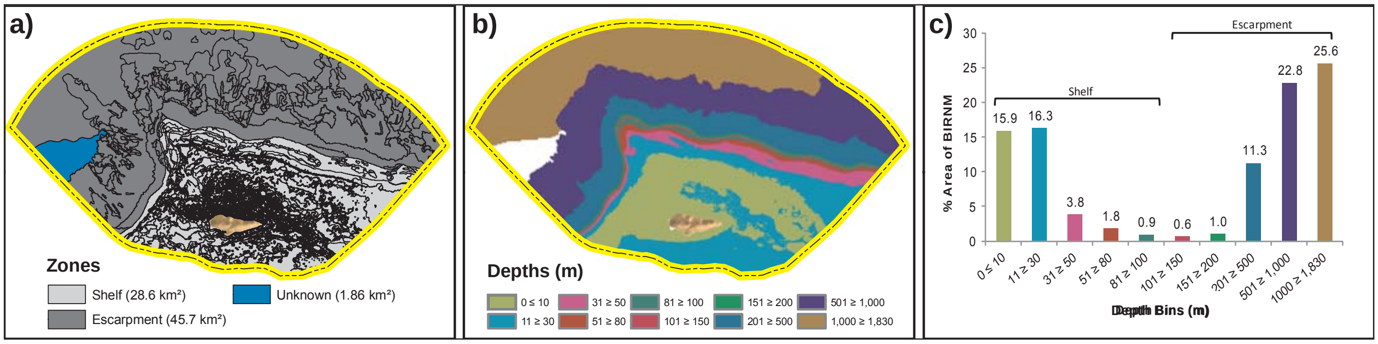


Figure 5.1. To facilitate a more appropriate analysis of the Monument's benthic composition, the final habitat map was divided into two summary zones: (a) the Shelf and Escarpment. Buck Island and areas on the seafloor that weren't classified due to a lack of source imagery (denoted in blue) were not considered in the summary statistics. (b) and (c) the Shelf and Escarpment warranted separate consideration given the different depths, ecology and MMUs used to map these environments. Notably, most of the Shelf zone was between 0 and 30 m, whereas the Escarpment was much deeper, with depths averaging between 500 and 1,830 m.

Given these factors, habitat summaries were done cautiously for BIRNM, and were mitigated by dividing the analysis into two distinct geographic regions (Figure 5.1). The transition from the Bank/Shelf zone to the Bank/Shelf Escarpment served as the dividing line, allowing for the separate examination of habitat compositions on the shelf (including the lagoon, channels, and shallow and mesophotic reefs) from those that reached down the steep escarpment. These two regions warranted separate consideration given the different depths, ecology and MMUs used to map the Shelf and Escarpment environments. In particular, the Escarpment had larger MMUs (1,000 and 5,000 m^2), encompassed deeper depths (mostly >500 m), exhibited more broad-scale geology and contained organisms uniquely equipped to live below the mesophotoic and euphotic zones. Alternatively, the Shelf had a smaller MMU (100 m^2), encompassed shallower depths (mostly < 30 m), exhibited much more diverse geological patterns, and contained fundamentally different organisms and ecosystems. In total, this mapping effort characterized the geomorphological structure and overlying biota for 74.26 km^2 (97.5%) for BIRNM. The remaining 1.9 km^2 area (in the western part of the Monument) was not characterized because it has not yet been mapped. Several patterns emerged from the summary map statistics for both the Shelf and Escarpment summary regions, as well as for the entire Monument.

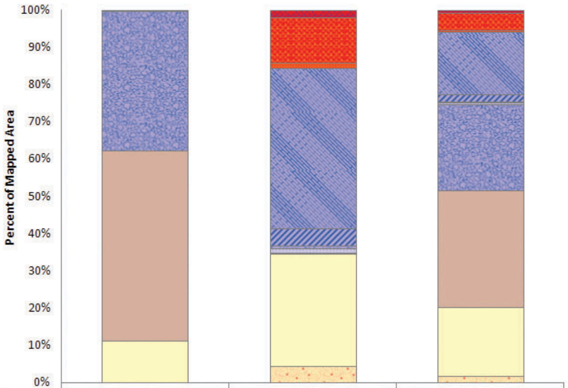
Bank/Shelf Escarpment

In the mapped area (45.67 km^2) of the Escarpment region, the softbottom habitats transition from Sand (11.1%) in the upper reaches to more fine-grained Mud (51.2%) in deeper benthos (Figures 5.2 and 5.3). Most of the Escarpment is softbottom (Figures 5.4 and 5.5) with the exception of a few patches of Pavement (only 0.19 km^2) in the northwest corner of the Monument and some Rock/Boulder habitat (37.2%) scattered throughout the Escarpment. These Rock/Boulder areas are predominately exposed in the steeper areas of the Escarpment where there is minimal sediment deposition. They also appear to be generally oriented perpendicular to the shelf edge. This pattern is particularly pronounced in the backscatter west of Buck Island on the Escarpment, possibly suggesting the influence of geologic or environmental forces. The unmapped area in this same region may also contain a mixture of mud and rock/boulder habitats with similar geologic orientations.

Only 0.62 km^2 of the Escarpment was determined to contain live biological cover, with No Cover (98.6%) constituting the remainder of the habitat polygons (Figures 5.6, 5.7, 5.8 and 5.9). While there were several areas along the Escarpment where deep corals were visible in ground validation imagery, their presence was sparse or in other cases concentrated within a very small area, often on steeper slopes. Steeper slopes often support higher deep coral covers because they experience less sedimentation than flat areas (Ohlhorst and Liddell, 1988). However, given the large minimum mapping units in the Escarpment regions, the live coral cover for all polygons in this zone was generally 0% - <10% with most areas having live coral covers closer to 0% (Figures 5.10 and 5.11). These trends in biological cover suggest that the remaining unmapped area on the Escarpment would also contain little biological cover and very little live coral cover. However, this prediction is speculation, and efforts should be made to map and characterize this remaining 1.9 km^2 area in the future.

Bank/Shelf

Concentrated primarily north and east of Buck Island, Coral Reef and Hardbottom habitats comprise 65.5% of the Shelf inside the Monument, while *Unconsolidated Sediment* covered much of Buck Channel to the south and large swaths of the Shelf's deepest areas. *Pavement* is the dominant detailed structure type. It accounts for 65.6% of all hardbottom on the Shelf, and is found primarily in the expansive, topographically homogeneous *Bank/Shelf* zone north of the island. *Pavement with Sand Channels* and *Rhodoliths* also figure notably in the habitat mosaic of this area, and make up 7.0% and 2.1% of all Shelf hardbottom, respectively. Further inshore, especially north and east of Buck Island and in parts of the *Lagoon*, *Aggregated Patch Reefs* dominate the benthos, covering 18.2% of all Shelf hardbottom. *Aggregate Reef* and *Independent Patch Reefs* are also very important contributors to the habitat complexity of BIRNM, and were found to comprise 3.3% and 2.3% of hard substrate on the Monument's Shelf, respectively. Sand constituted nearly a third of the entire Shelf and 87.5% of the 9.87 km^2 of *Unconsolidated Sediment* habitat, with the rest of the softbottom made up of the *Mud* encountered in the small salt pond on the island and 12.4% *Sand with Scattered Coral and Rock*. It is also interesting to note that, unlike the geomorphology of the Escarpment, habitats on the Bank were generally oriented in bands parallel to the shore. This pattern is particularly pronounced on the east side of Buck Island, possibly suggesting the influence of different physical forces at work in this region.



	Geomorphological Structure	ESCARPMENT (km²)		SHELF (km²)		Total (km²)	
Coral Reef and Hardbottom	Aggregate Reef	17.19	0.000	18.72	0.619	35.92	0.619
	Aggregated Patch Reefs		0.000		3.411		3.411
	Individual Patch Reef		0.000		0.434		0.434
	Pavement		0.194		12.285		12.479
	Pavement with Sand Channels		0.000		1.316		1.316
	Reef Rubble		0.000		0.222		0.222
	Rhodoliths		0.000		0.392		0.392
	Rhodoliths w/ Scattered Coral & Rock		0.000		0.004		0.004
	Rock/Boulder		16.999		0.040		17.039
Unconsolidated Sediment	Mud	28.47	23.397	9.87	0.005	38.35	23.402
	Sand		5.075		8.642		13.717
	Sand with Scattered Coral and Rock		0.000		1.229		1.229

Figure 5.2. Summary statistics describing the total amount of mapped area by major and detailed structure types. These numbers are further divided into the amount of mapped area within the two summary regions: the Shelf and Escarpment.

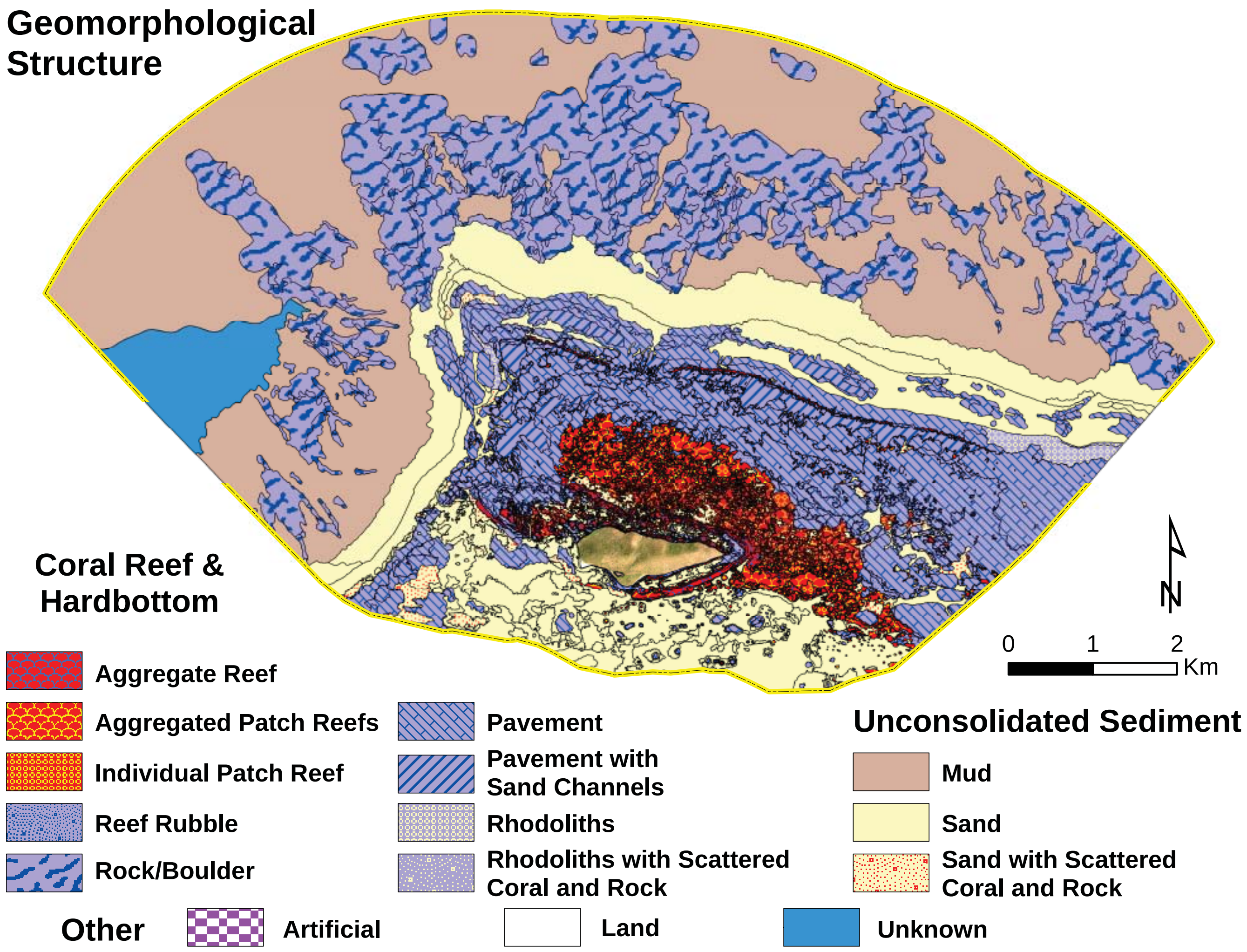
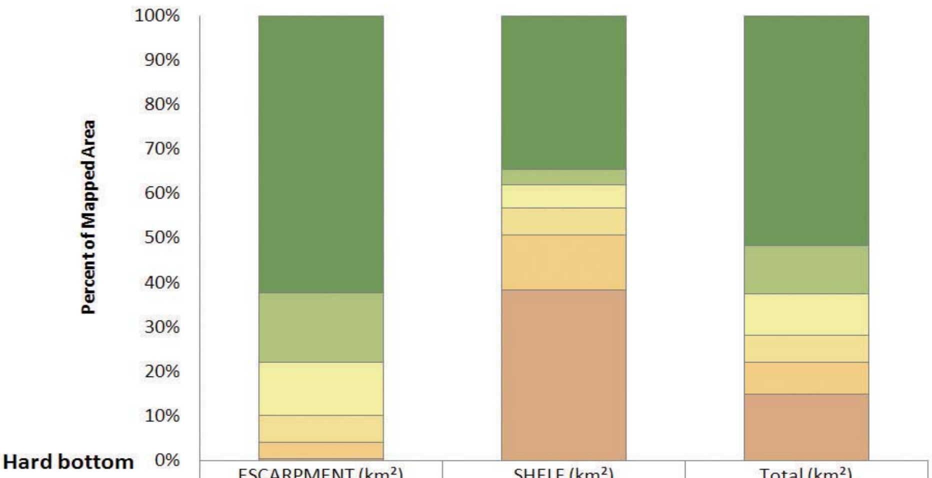


Figure 5.3. Spatial extent of major and detailed geomorphological structure types in the Monument.



Hard bottom		ESCARPMENT (km²)	SHELF (km²)	Total (km²)
0% - <10%	🟩	28.472	9.875	38.348
10% - <30%	🟩	7.140	0.980	8.119
30% - <50%	🟨	5.377	1.521	6.898
50% - <70%	🟨	2.806	1.699	4.505
70% - <90%	🟧	1.697	3.565	5.262
90% - 100%	🟫	0.173	10.958	11.131

Figure 5.4. Summary statistics describing the total amount of mapped area by percent hard-bottom. These numbers are further divided into the amount of mapped area within the two summary regions: the Shelf and Escarpment.

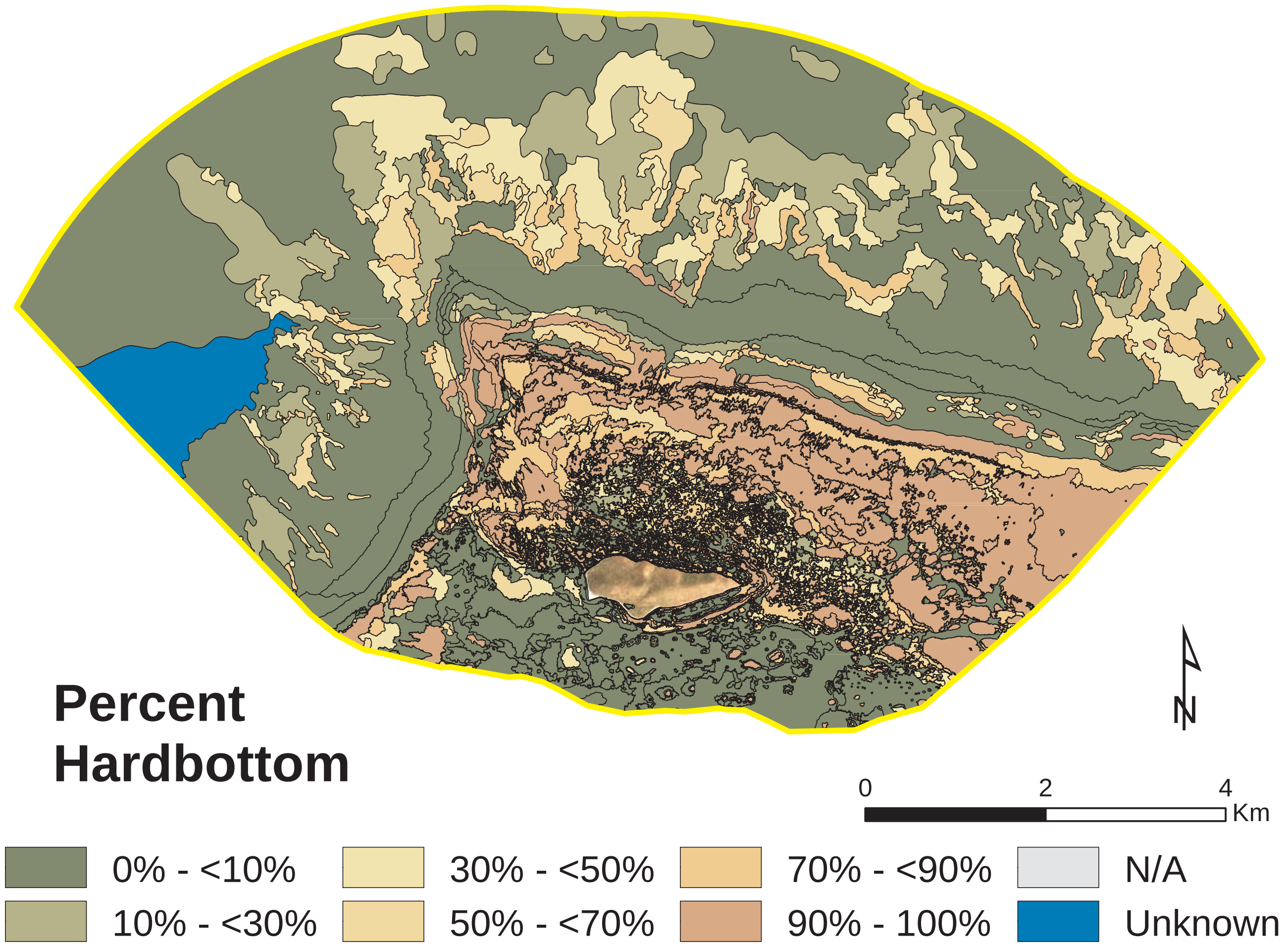
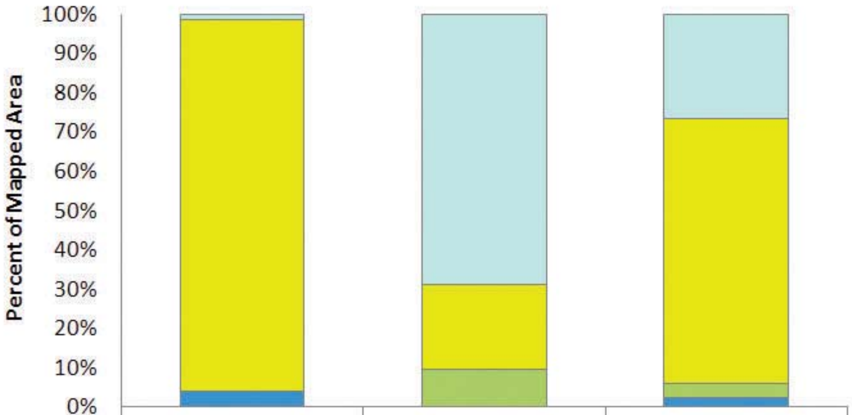


Figure 5.5. Spatial extent of percent hardbottom classes in the Monument.



Major Biological Cover		ESCARPMENT (km²)	SHELF (km²)	Total (km²)
Algae	🟦	0.619	19.642	20.261
Mangrove	🟩	0.000	0.002	0.002
No Cover	🟨	45.046	6.245	51.292
Seagrass	🟩	0.000	2.702	2.702
Unknown	🟦	1.899	0.000	1.899

Figure 5.6. Summary statistics describing the total amount of mapped area by major biological cover type. These numbers are further divided into the amount of mapped area within the two summary regions: the Shelf and Escarpment.

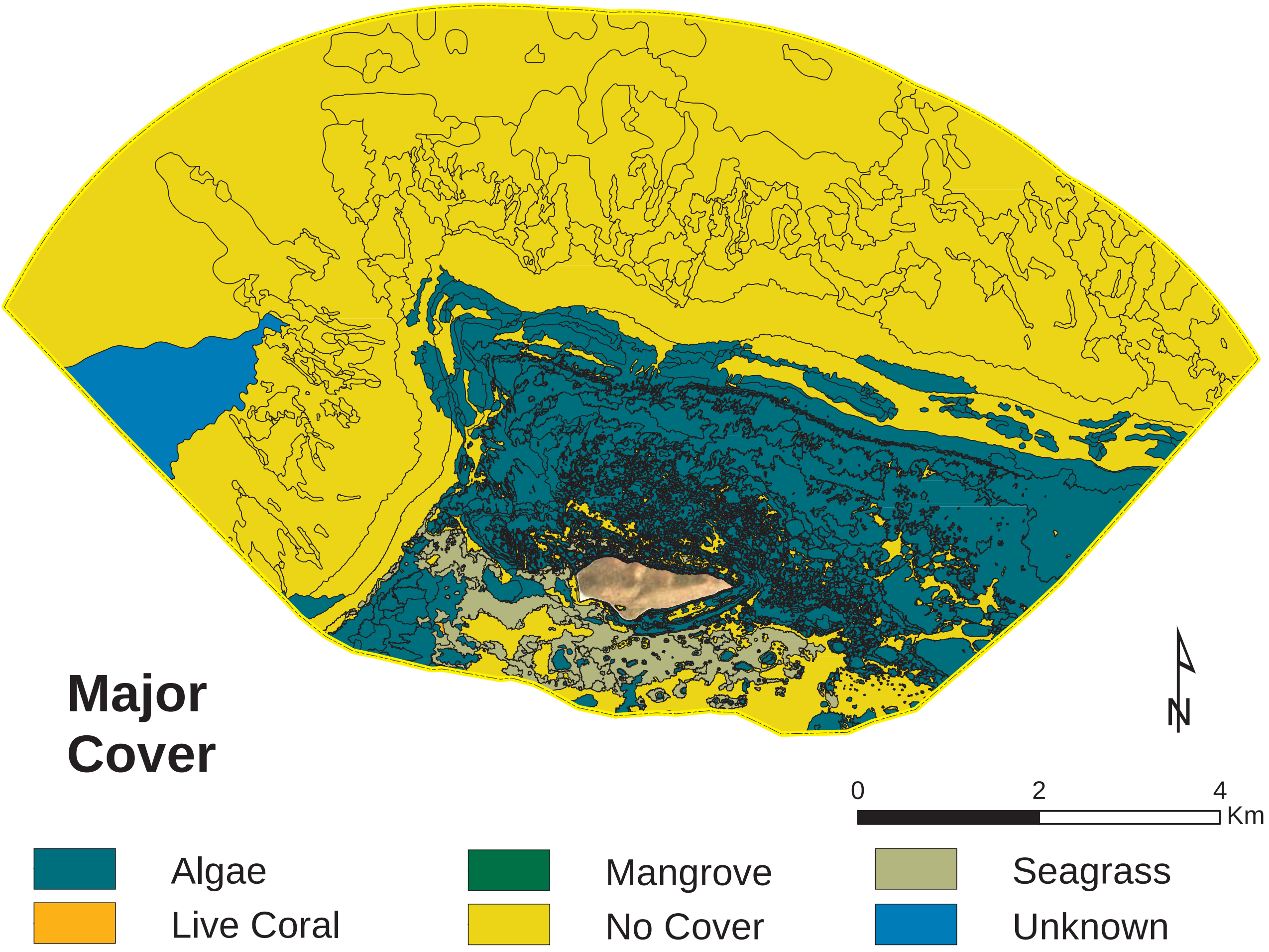
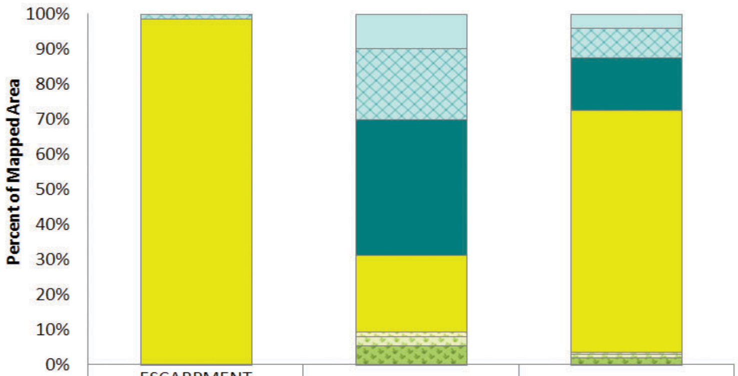


Figure 5.7. Spatial extent of major biological cover types in the Monument.



Detailed Biological Cover		ESCARPMENT (km^2)	SHELF (km^2)	Total (km^2)
Algae 10% - <50%	■	0.076	2.819	2.894
Algae 50% - <90%	▨	0.511	5.777	6.288
Algae 90% - 100%	■	0.032	11.046	11.078
Live Coral 10% - <50%	■	0.000	0.007	0.007
Mangrove 90% - 100%	■	0.000	0.002	0.002
No Cover 90% - 100%	■	45.046	6.245	51.292
Seagrass 10% - <50%	▨	0.000	0.361	0.361
Seagrass 50% - <90%	▨	0.000	0.761	0.761
Seagrass 90% - 100%	▨	0.000	1.580	1.580

Figure 5.8. Summary statistics describing the total amount of mapped area by detailed biological cover type. These numbers are further divided into the amount of mapped area within the two summary regions: the Shelf and Escarpment.

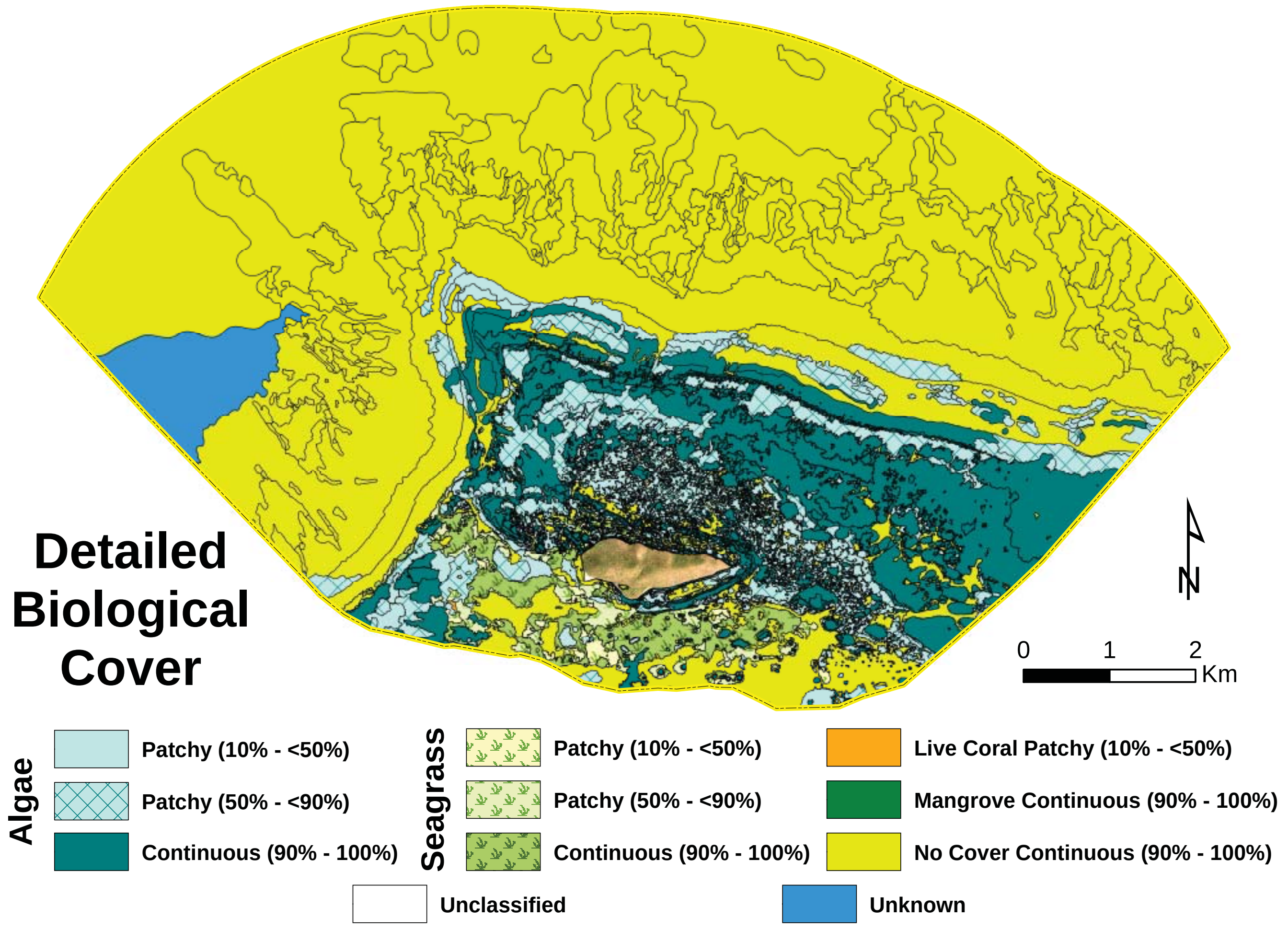
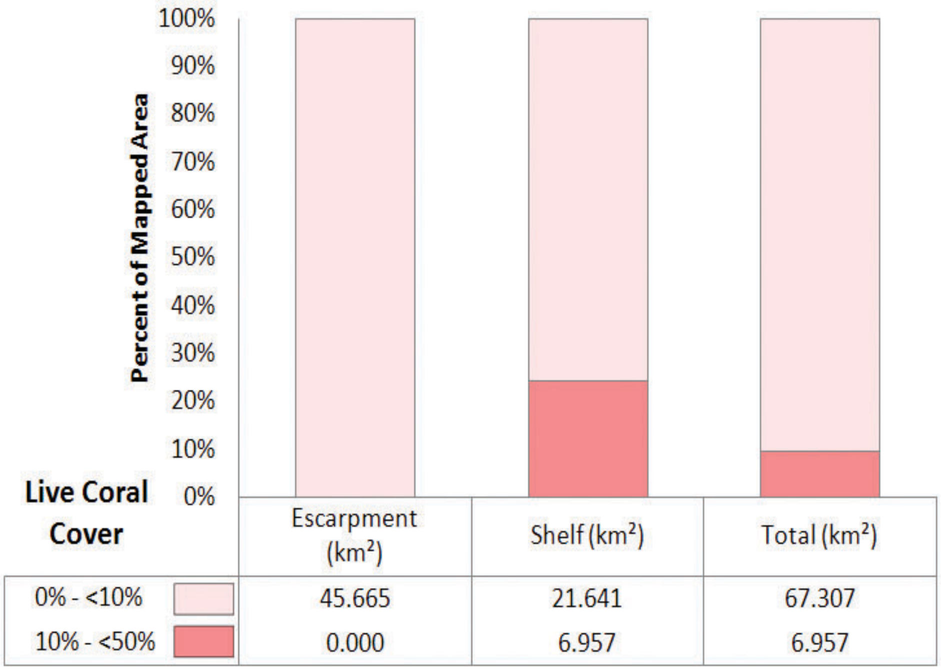


Figure 5.9. Spatial extent of detailed biological cover types in the Monument.



Live Coral Cover		Escarpment (km²)	Shelf (km²)	Total (km²)
0% - <10%	▭	45.665	21.641	67.307
10% - <50%	🟥	0.000	6.957	6.957

Figure 5.10. Summary statistics describing the total amount of mapped area by percent coral cover class. These numbers are further divided into the amount of mapped area within the two summary regions: the Shelf and Escarpment.

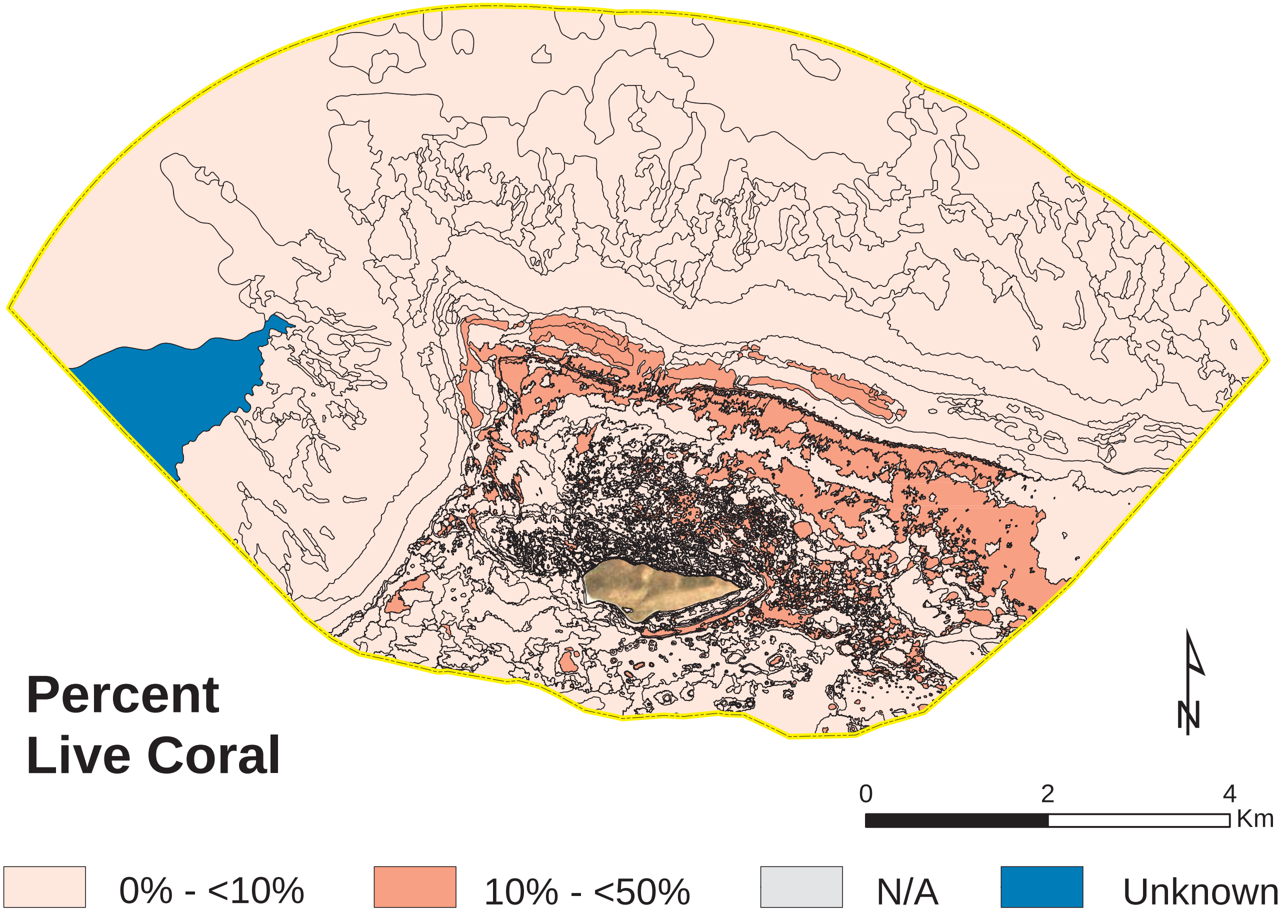


Figure 5.11. Spatial extent of live coral cover classes in the Monument.

BIRNM Totals

The non-terrestrial mapped area (74.26 km^2) of the entire Monument is split nearly evenly between *Coral Reef and Hardbottom* (48.4%) and *Unconsolidated Sediment* (51.6%) major structure types. *Mud* comprises the greatest area (23.40 km^2) of *Unconsolidated Sediment,* followed by *Sand* (13.72 km^2), and *Sand with Scattered Coral and Rock* (1.23 km^2). The hardbottom detailed structure compositions differ greatly between summary regions, but the most prevalent is *Rock Boulder* (17.03 km^2), followed closely by *Pavement* (16.80 km^2), *Aggregated Patch Reefs* (3.41 km^2) and *Pavement with Sand Channels* (1.32 km^2), and then by *Aggregate Reef, Individual Patch Reef, Rhodoliths, Reef Rubble*, and *Rhodoliths with Scattered Coral and Rock*.

The majority (69.1%) of the Monument was mapped as uncolonized, owing largely to the scant biological cover found along the reserve's large deep-water escarpment. When only taking into account areas of the BIRNM that do have biological cover (22.97 km^2), the seafloor is dominated by *Algae* (88.2%), followed by *Seagrass* (11.8%) and a tiny *Mangrove* extent. More specifically, *Algae* is the dominant biological component in 33.5% of the Monument's 4.06 km^2 of colonized softbottom, with *Seagrass* responsible for nearly all the rest (66.5%). BIRNM's hardbottom habitats in the photic zone are almost exclusively algal-dominated, with just one small polygon in Buck Channel classified as *Live Coral*-dominated.

5.2 COMPARISON TO PREVIOUS HABITAT MAP

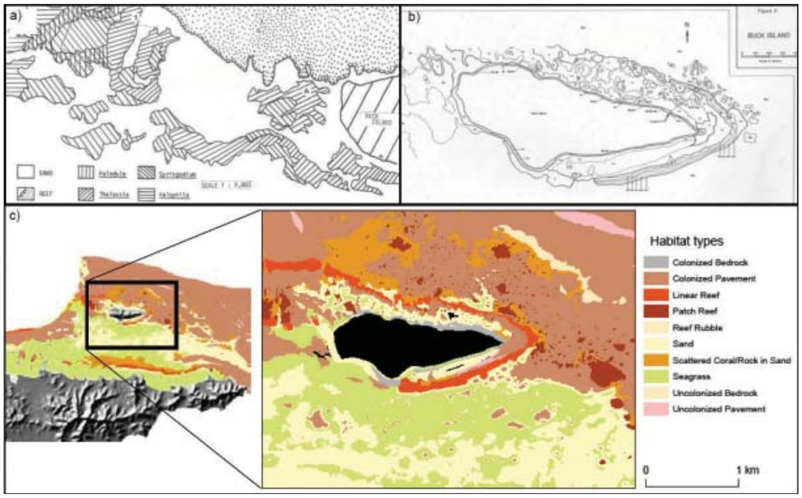


Figure 5.12. Benthic habitat maps constructed for Buck Island region since the 1960s. (a) Subset of Gladfelter et al. 1977; (b) Anderson et al. 1986; and (c) subset of CCMA-BB's digital map using a 100 m^2 MMU based on methods described by Kendall et al. 2001. This figure was reproduced from Pittman et al. 2008.

The mapping effort described in this chapter marks the fourth time that the shallow-water (≤ 30 m) habitats of BIRNM have been mapped (Gladfelter et al. 1977; Anderson et al. 1986; Kendall et al. 2001) (Figure 5.12). However, the moderate and deep-water maps developed during this project were the first of their kind, as previous mapping efforts were only able to characterize habitats shallower than 30 m using aerial orthophotos. For habitats deeper than 30 m, this habitat map will serve as a critical baseline for monitoring changes in mesophotic coral reef ecosystems inside the Monument. In addition to mapping a larger geographic area, several changes were made to the 2011 NOAA map compared to the 2001 NOAA map (Kendall et al. 2001). These improvements specifically include the use of: (1) a new classification scheme with a higher thematic resolution, (2) a finer scale of delineation, and (3) a smaller minimum mapping unit (in areas < 50 m)(Table 5.2). These changes were made because a smaller geographic area was mapped using higher resolution imagery. Kendall et al. (Kendall and Miller, 2008) also did produce an additional habitat map with a finer scale MMU (i.e., 100 m^2) from the same imagery used to create the 2001 habitat map.

Table 5.2. Comparison of map and feature characteristics where the 2001[a] (4,046 m^2 MMU), 2001[b] (100 m^2 MMU) and 2011 benthic habitat maps intersect. Reported numbers are for the same shallow-water 24 km^2 area where the three maps intersect.

		NOAA MAPPING EFFORT		
	METRIC	**2001[a]**	**2001[b]**	**2011**
Map	Imagery Acquisition Date	1999	1999	2007 - 2011
	Spatial Resolution of Optical Imagery (m)	2.40	2.40	0.3 - 3
	Scale of Delineation	1:6,000	1:6,000	1:1,000
	MMU (m^2)	4,046	100	100
Feature	Number of Unique Classes	19	29	79
	Number of Polygons	168	1,436	4,481
	Number of Polygons < 4,046 m²	0	1,173	3,883
	Mean Area of Polygons (m^2)	143,022	16,732	5,362
	Mean Perimeter of Polygons (m)	413,252	557	385

Although the different classification schemes and delineation scales prohibit a comprehensive and detailed quantitative comparison between the 2001 map (with a 100 m² MMU) and 2011 map (Kendall and Miller, 2008), a broader thematic comparison was conducted qualitatively. This comparison illuminated some important differences between the two maps and potential changes in the benthic habitats in BIRNM during the last ten years. For geomorphological structure, slightly less *Coral Reef and Hardbottom* was delineated in the 2011 map (Figure 5.13; Table 5.3). *Pavement, Individual Patch Reef, Reef Rubble, Rock/Boulder* habitats made up the majority of this decrease, while the area classified as *Aggregate Reef, Aggregated Patch Reefs* and *Pavement*

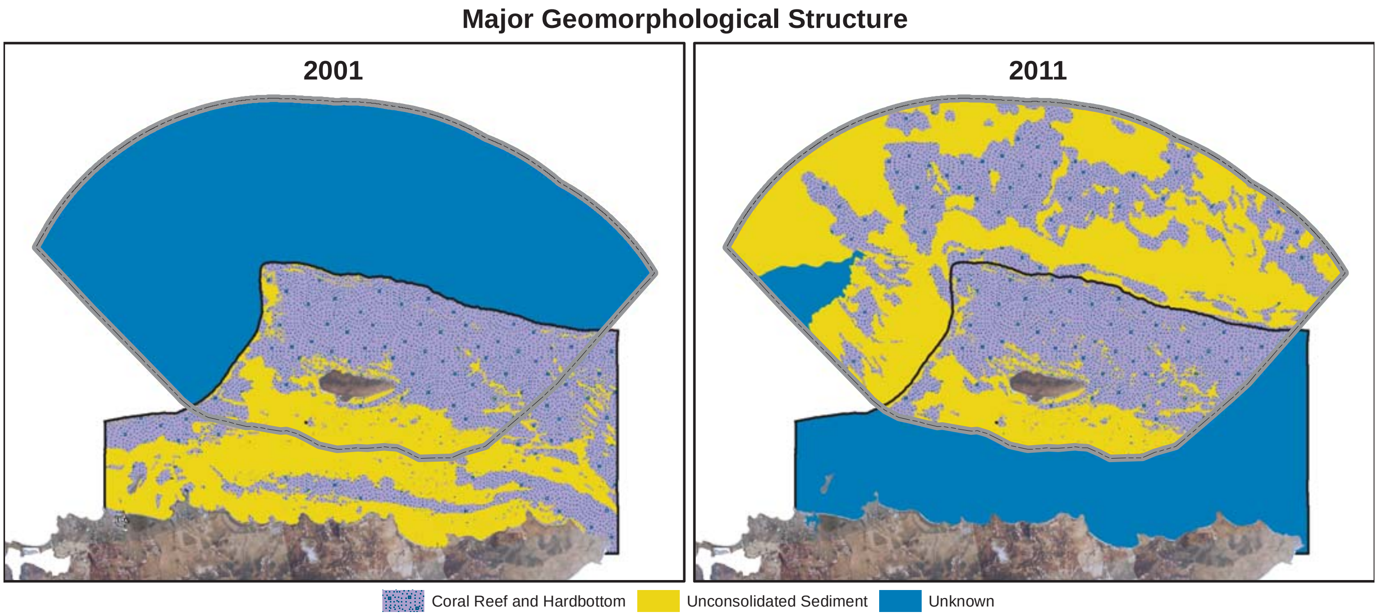


Figure 5.13. Major geomorphological structure types mapped at a 100 m² MMU in 2001 and in 2011.

Table 5.3. Comparison of the 2001 (100 m² MMU) and 2011 benthic habitat maps.

	CLASS NAMES		AREA (km²)	
	2001 (100 m² MMU)	**2011 (100 m² MMU)**	**2001**	**2011**
Major Structure	Coral Reef and Hardbottom	Coral Reef and Hardbottom	16.59	16.13
	Unconsolidated Sediment	Unconsolidated Sediment	6.74	7.22
Detailed Structure	Linear Reef	Aggregate Reef	0.60	0.62
	-	Aggregated Patch Reefs	-	3.41
	Artificial	Artificial	0.0004	0.0001
	Patch Reef	Individual Patch Reef	0.81	0.43
	Land	Land	0.70	0.67
	-	Mud	-	0.005
	Colonized/Uncolonized Pavement	Pavement	13.24	10.28
	-	Pavement with Sand Channels	-	1.02
	Reef Rubble	Reef Rubble	0.30	0.22
	-	Rhodoliths	-	0.11
	-	Rhodoliths with Scattered Coral and Rock	-	0.004
	Colonized/Uncolonized Bedrock	Rock/Boulder	0.13	0.04
	-	Sand	-	6.04
	Sand with Scattered Coral and Rock	Sand with Scattered Coral and Rock	1.51	1.18
Major Cover	Algal Dominated (on softbottom)	Algae	1.70	16.89
	-	Live Coral	-	0.01
	-	Mangrove	-	0.002
	-	No Cover	-	3.76
	Seagrass	Seagrass	2.89	2.70

with Sand Channels increased slightly (Figure 5.14; Table 5.3). This 0.46 km^2 decrease in coral reef and hard-bottom habitat was most likely due to the coarser scale at which features were delineated. For major biological cover, more algae and less seagrass were delineated (Figure 5.15; Table 5.3). This increase in algae is due to the inclusion of macro, crustose, turf and filamentous algae in the *Algae* class in the 2011 map. The 2001 map only included macro algae on softbottom and ignored the other algal classes. It is also important to note that between 2005 and 2006, a massive bleaching event caused live coral cover to decrease inside the Monument (Clark et al. 2008; Pittman et al. 2008; Miller et al. 2009; Eakin et al. 2010). Data on coral cover collected before 2007 was excluded from this mapping process to ensure that the current map most accurately describes current ecological conditions.

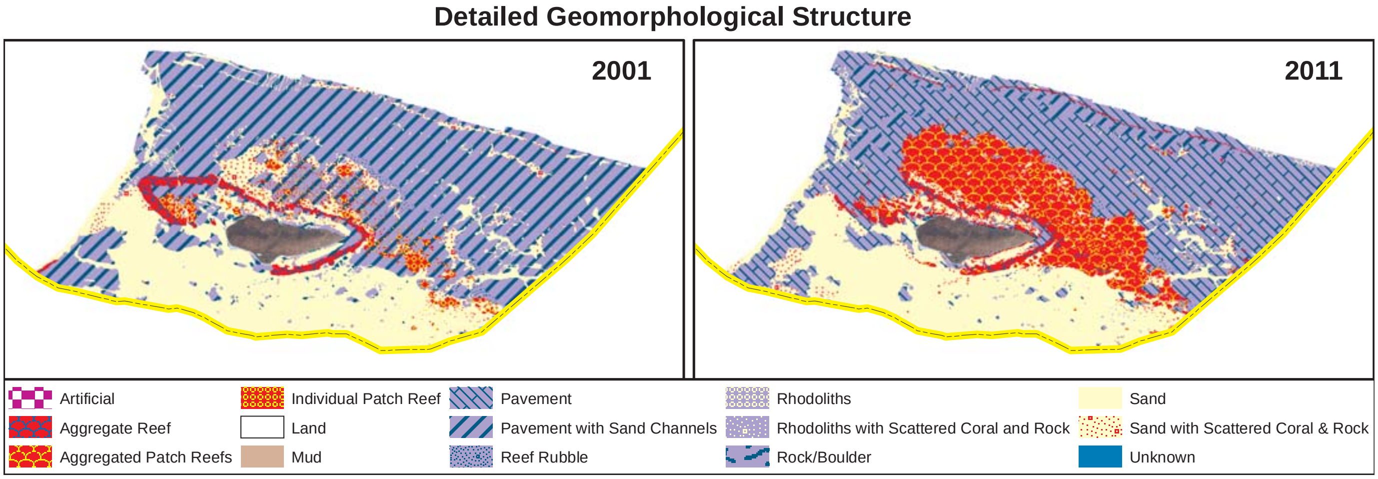


Figure 5.14. Detailed geomorphological structure types mapped at a 100 m^2 MMU in 2001 and in 2011.

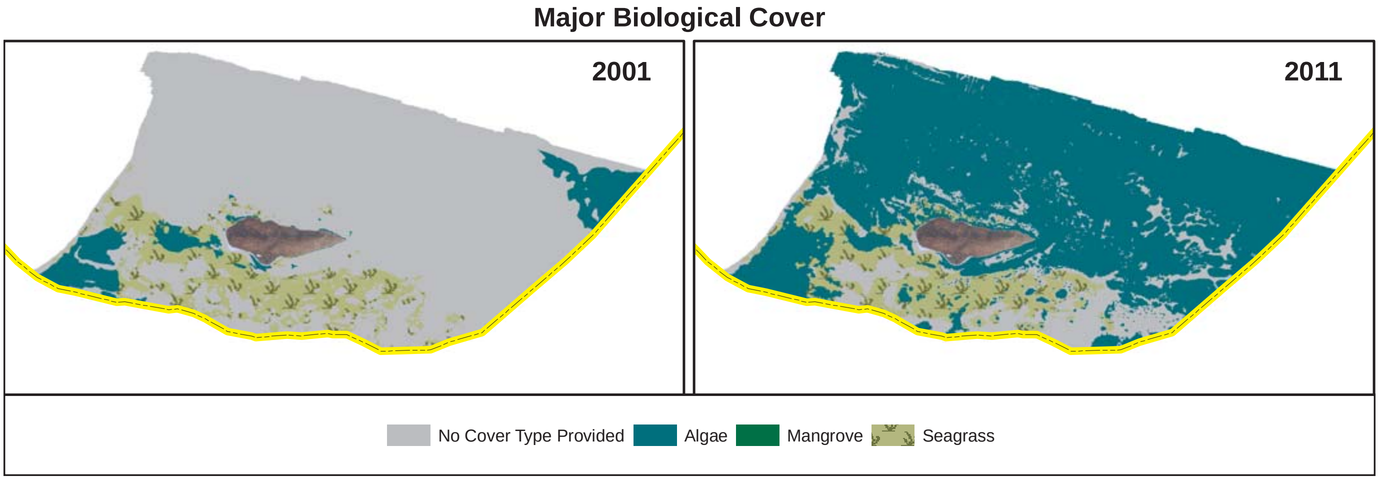


Figure 5.15. Major biological cover types mapped at a 100 m^2 MMU in 2001 and in 2011.

Although this mapping exercise cannot be used to detect changes in live coral cover, it may have revealed minor changes in seagrass cover between 2001 and 2011. In particular, areas immediately north and west of Buck Island experienced some changes in seagrass cover (Figure 5.16). A more detailed comparison of the two habitat maps, as well as of the 1999 aerial imagery, 2007 orthophotos, 2010 acoustic imagery and 2011 LiDAR imagery may reveal additional fine scale habitat changes.

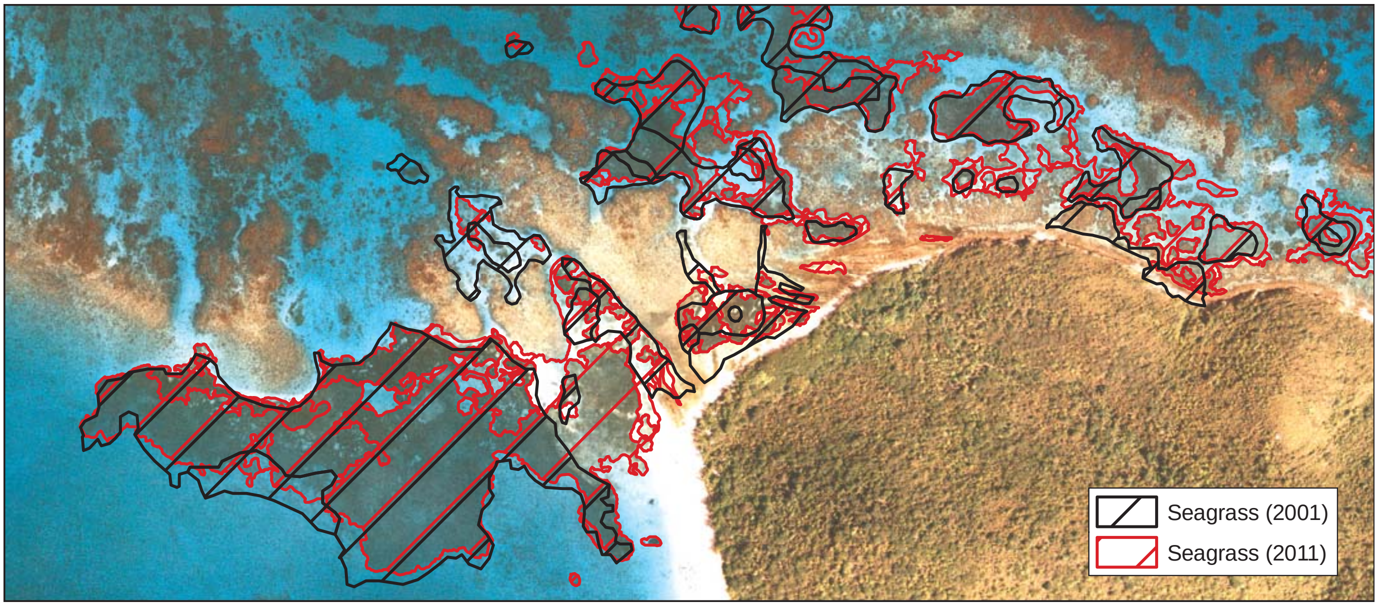


Figure 5.16. A few areas immediately west of Buck Island experienced some loss and regrowth of seagrass between 2001 and 2011.

5.3. MAP USES

As described in the beginning of section 5.1, summarizing habitat maps with two different MMUs needs to be done cautiously because the same seafloor feature may be given different names in maps with different MMUs, and may be included in one map and excluded in another. These two caveats have important implications for not only summarizing, but also applying habitat maps with different MMUs for ecosystem based management. These implications include potentially impacting decisions concerning zoning, anchoring, mooring as well as other management actions because the location and size of an area earmarked for additional actions will change depending on the habitat map used to make this selection. For example, if regulations require that new moorings are installed in sand patches larger than 100 m^2, the number of potentially suitable locations would be far fewer if a habitat map with a 4,047 m^2 MMU was used to conduct this spatial analysis versus using a map with a 100 m^2 MMU. However, too small of an MMU may be prohibitively time intensive and expensive to meet the objectives of the management action. The development parameters, like MMU, used to create habitat maps should be balanced with time and cost to support as many different management applications as possible. The development parameters used to create this map were determined in consultation with resource managers at BIRNM.

In the past, scientific and management communities have used NOAA benthic habitat maps to structure monitoring programs, support management decisions (like siting infrastructure) as well as to establish and manage marine conservation areas (Friedlander et al. 2007; Pittman et al. 2008; Bauer et al. 2010; Pittman et al. 2010; Whitall et al. 2011). The habitat maps created during this effort can also be used for similar applications, provided the implications of using habitat maps with different MMUs are considered during the analysis. In addition to these applications, several additional research and management applications may be possible using the bathymetry and benthic habitat maps developed during this project. These additional applications may include, but are not limited to:

- Updating the management plan of the BIRNM, including evaluating different zoning options for multiple use areas.
- Evaluating the efficacy of management actions taken by BIRNM.
- Mapping ecosystem services and estimating economic value of goods and services across the seascape.
- Understanding the seascape requirements for species and identifying the most productive and diverse seascape types.
- Predicting habitat suitability for priority species to help target monitoring and prioritize protection. For example, identifying the most highly suitable habitat for juvenile and adult spiny lobster can inform management actions and risk assessments.

- Mapping best habitat for *Acropora* species or Nassau grouper can help with restoration efforts and threat assessments.
- Determining the utility of mapped classes as surrogates for priority species distributions and for community type and biodiversity mapping. Can mapped features or benthic habitat types alone be used as reliable predictors of species occurrence or to identify diversity hotspots?
- Understanding the importance of seafloor complexity as a driver of faunal distribution and diversity, and identifying thresholds beyond which abrupt declines occur.
- Development of 3D visualizations and fly-throughs of BIRNMS seascapes for outreach purposes.

Looking forward, these additional map applications may help scientists and managers to better understand the benthic communities and their relationship with particular species and groups of species inside the Monument. This understanding is the key to beginning to forecast how the distribution of these benthic communities and their associated animals may change in the future.

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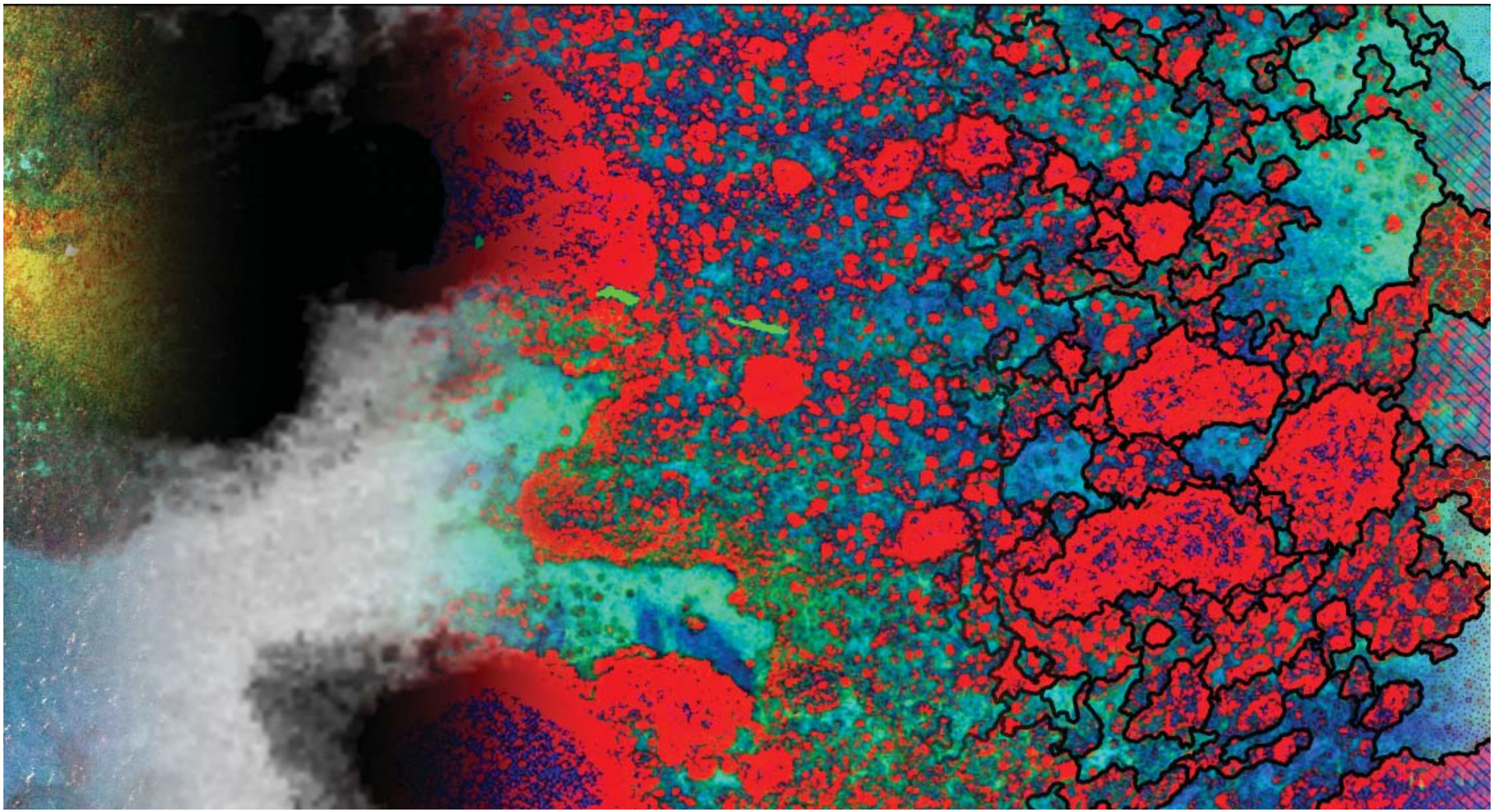

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