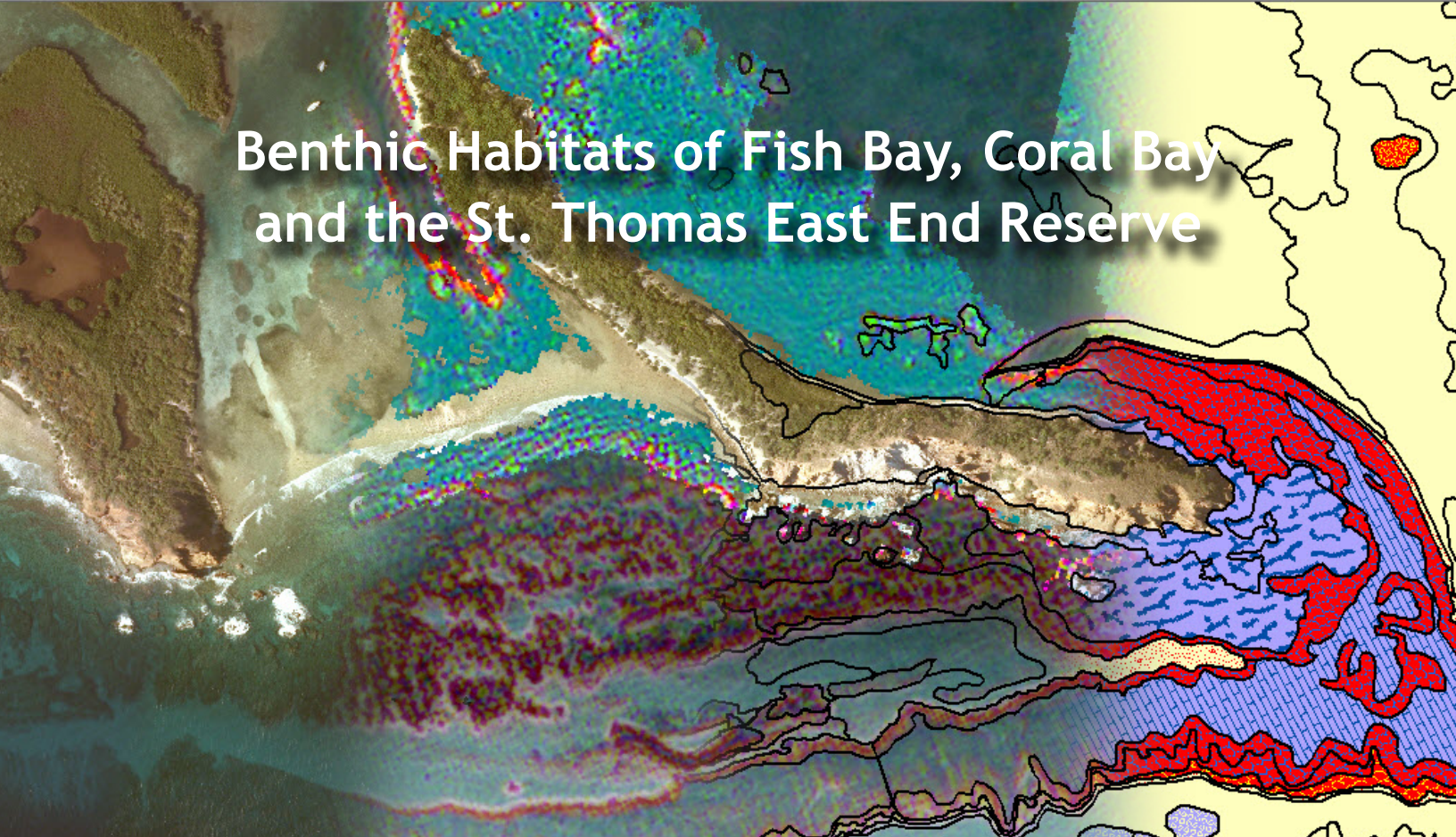


# Benthic Habitats of Fish Bay, Coral Bay and the St. Thomas East End Reserve



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NOAA National Centers for Coastal Ocean Science



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NOAA NCCOS Center for Coastal Monitoring and Assessment



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# Benthic Habitats of Fish Bay, Coral Bay and the St. Thomas East End Reserve

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Atmospheric Administration

National Ocean Service

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## ABOUT THIS DOCUMENT

This report describes the development and assessment of shallow (0 ≤40 m) benthic habitat maps for Fish Bay, Coral Bay and the St. Thomas East End Reserve (STEER) in the U.S. Virgin Islands. The objective of this effort, conducted by NOAA's National Centers for Coastal Ocean Science in partnership with the Nature Conservancy (TNC), the U.S. National Park Service (NPS) and the Virgin Islands Department of Planning and Natural Resources (DPNR), was to provide spatially-explicit information describing the benthic habitat types and live coral cover present in these three locations. This habitat information will support the development of local action strategies for coral reef conservation in each of these places, providing roadmaps to address key issues and remedy specific threats to coral reefs. The three habitat maps, generated using a combination of semi-automated classification and visual interpretation techniques, represent the first digital maps that describe nearly 100% of the seafloor in these areas. This effort also marks the first time that high resolution imagery describing seafloor depth was collected in these locations.

This report consists of four 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 maps, 3) an assessment of the habitat maps' thematic accuracies, and 4) a discussion and summary of the habitats in each area. These habitat maps will be used by TNC, NPS, DPNR and other local partners for planning research and monitoring activities, and will support the management and conservation of the St. Thomas East End Reserve, Virgin Islands National Park and Virgin Islands Coral Reef National Monument.

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.

For more information on this effort please visit: <http://coastalscience.noaa.gov/projects/detail?key=33>

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## EXECUTIVE SUMMARY

NOAA's National Centers for Coastal Ocean Science 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 and qualitatively compare marine ecosystems in tropical U.S. waters. The Biogeography Branch used similar protocols to generate new benthic habitat maps for Fish Bay, Coral Bay and the St. Thomas East End Reserve (STEER). While this mapping effort marks the third time that some of these shallow-water habitats ( $\leq 40$  m) have been mapped, it is the first time that nearly 100% of the seafloor has been characterized in each of these areas. It is also the first time that high resolution imagery describing seafloor depth has been collected in each of these areas. Consequently, these datasets provide new information describing the distribution of coral reef ecosystems and serve as a spatial baseline for monitoring change in the Fish Bay, Coral Bay and the STEER.



Coral nursery for staghorn coral (*Acropora cervicornis*) inside the St. Thomas East End Reserve, St. Thomas.

Benthic habitat maps were developed for approximately 64.3 km<sup>2</sup> of seafloor in and around Fish Bay, Coral Bay and the STEER. Twenty seven percent (17.5 km<sup>2</sup>) of these habitat maps describe the seafloor inside the boundaries of the STEER, the Virgin Islands National Park and the Virgin Islands Coral Reef National Monument. The remaining 73% (46.8 km<sup>2</sup>) describe the seafloor outside of these MPA boundaries. These habitat maps were developed using a combination of semi-automated and manual classification methods. Habitats were interpreted from aerial photographs and LiDAR (Light Detection and Ranging) imagery. In total, 155 distinct combinations of habitat classes describing the geology and biology of the seafloor were identified from the source imagery.

Unconsolidated sediments dominate these three areas, with rhodoliths being the most common habitat on the bank/shelf and sand colonized by seagrass being most common habitat inside Fish Bay, Coral Bay and the STEER's boundary. Live coral cover rarely exceeded 10%, only constituting 6.5% of the total mapped area. Most of the habitat features with high amounts of live coral cover were located outside of existing marine protected area boundaries. The overall accuracies (corrected for proportional bias) for these habitat maps were 93.0% for major structure, 75.1% for detailed structure, 86.2% for percent hardbottom, 86.5% for major cover and 74.5% for detailed cover. The live coral and dominant coral type classes had 83.3% and 88.2% thematic accuracies respectively, although these classes should be used with caution. These numbers are similar to the other benthic habitat maps created by NCCOS's Biogeography Branch. As a result, these digital map products can be used with confidence by scientists and resource managers for a multitude of different applications.

This report documents the process and methods used to create the benthic habitat maps for Fish Bay, Coral Bay and the STEER. Chapter 1 provides a short introduction to these three areas, including their history, marine life

and reason for being selected as priority sites by local managers. 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 the benthic habitat maps using a combination of semi-automated and manual classification techniques. Chapter 4 details the steps used in the accuracy assessment and reports on the thematic accuracy of the final shallow-water maps. Chapter 5 summarizes the type and abundance of each habitat class, how these habitats compare to past habitat maps and outlines how these new habitat maps may be used to inform future management activities. The final deliverables for this project are available to the public: (1) on the web (<http://coastalscience.noaa.gov/projects/detail?key=33>), (2) through an interactive, web-based map application (<http://maps.coastalscience.noaa.gov/biomapper/biomapper.html?id=STEER>), and (3) by request through the University of the Virgin Islands, Center for Marine and Environmental Studies.



Mangrove prop roots and macroalgae growing in unconsolidated sediment inside Mangrove Lagoon, St. Thomas.



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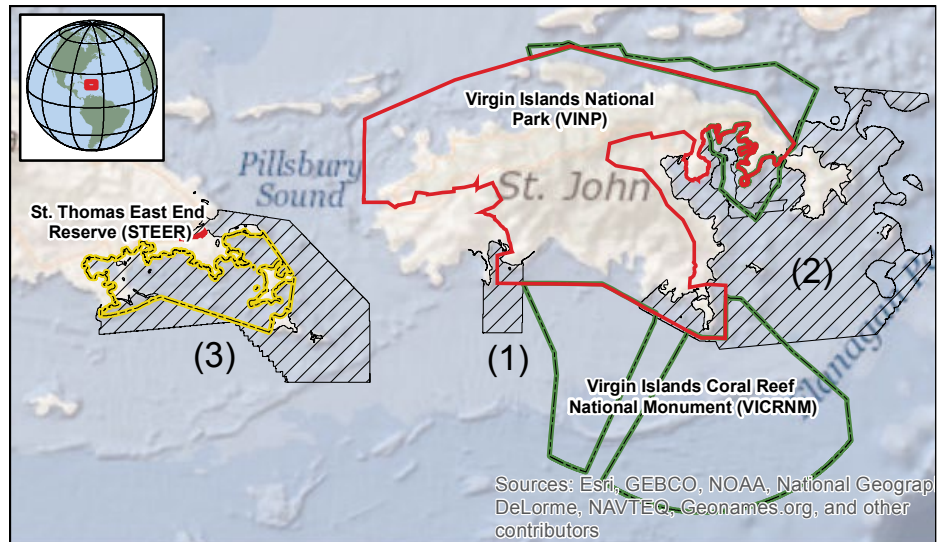
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## CHAPTER 1: INTRODUCTION

### 1.1. WHERE DID WE DEVELOP BENTHIC HABITAT MAPS?

In 2011, the National Oceanic and Atmospheric Administration (NOAA) collected imagery of the nearshore, marine areas (0-40 meters deep) around St. John and north of St. Thomas in the U.S. Virgin Islands (USVI). This seafloor imagery was collected with a number of applications in mind (USVI and NOAA CRCP, 2010), including hydrodynamic modeling, chemical contaminant and sediment dispersal modeling, water quality monitoring, nautical chart updates and benthic habitat mapping. NOAA's National Centers for Coastal Ocean Science (NCCOS) Biogeography Branch used this imagery to develop benthic habitat maps for three locations identified as high priorities by local resource managers (Figure 1.1; USVI and NOAA CRCP, 2010). These areas included the marine areas in and around:



**Figure 1.1.** Location and spatial extent of the new habitat maps for: (1) Fish Bay, (2) Coral Bay and (3) the STEER. The St. Thomas East End Reserve's boundary is denoted in yellow, the Virgin Islands National Park's boundary in red, and the Virgin Islands Coral Reef National Monument's boundary in green.

- *Coral Bay*  
(from Cabritte Horn Point east to the Flanagan Passage, and Brown Bay south to Ram Head)
- *Fish Bay*  
(from Dittlif Point east to Reef Bay, and the inner bay south to the 30 meter depth contour)
- *The St. Thomas East End Reserve (STEER)*  
(from Long Point east to Pillsbury Sound, and Red Hook Point south to Buck Island National Wildlife Refuge)

These geographic areas will be called (respectively) “Coral Bay”, “Fish Bay” and “the STEER” from here forward (Figure 1.2). Each of these marine areas encompasses a mosaic of seagrass, algal, mangrove and coral reef habitats. These habitats provide sources of food and refuge for a diversity of juvenile and adult marine organisms, including several species of fish, lobsters, sea turtles, rays and sharks (Rothenberger et al. 2008). 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).

The STEER is a territorial marine protected area (MPA) encompassing about 9.1 km<sup>2</sup> situated on the eastern side of St. Thomas. The STEER is one management unit that includes several, smaller marine protected areas, including Cas Cay, Mangrove Lagoon, St. James, and Compass Point Marine Reserves and Wildlife Sanctuaries. In 2011, efforts to develop a management plan began for the STEER with the participation from community groups, the Department of Planning and Natural Resources, the University of the Virgin Islands and The Nature Conservancy. This management plan will guide conservation and sustainable use activities in the STEER over the next five years to restore and maximize the ecological, economic and cultural benefits for the USVI community.

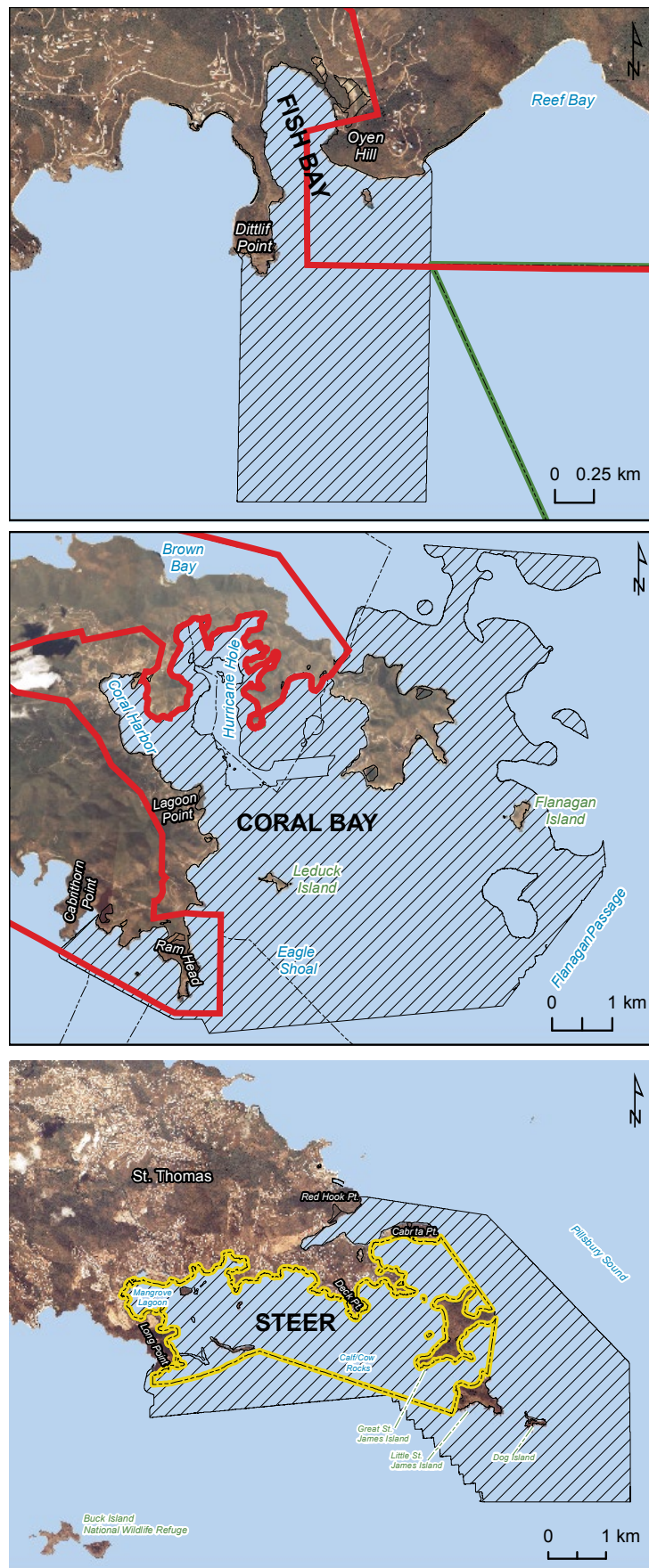
Fish Bay and Coral Bay are both inlets located on the southern coast of St. John. Unlike the STEER, only portions of the areas in and around these Bays are managed as marine protected areas. These MPAs include the Virgin

Islands National Park and the Virgin Islands Coral Reef National Monument, both of which are managed by the U.S. National Park Service. The Virgin Islands National Park was established in 1956, and expanded in 1962 and again in 1978. It encompasses approximately 32.8 km<sup>2</sup> of land, including tropical forests that provide habitat for over 800 species of plants. It also encompasses 23.5 km<sup>2</sup> of ocean, including coral reef ecosystems with over 50 species of coral and 300 species of fish (NPS, 2013). The Virgin Islands Coral Reef National Monument also protects portions of Coral Bay. This MPA was established in 2001 by executive order, and prohibits almost all fishing and other extractive uses (Boulon et al. 2008). It encompasses over 51.0 km<sup>2</sup> of submerged habitats, which include nearshore coral reefs, mid-shelf reef structure and algal plains (Boulon et al. 2008).

## 1.2. WHY MAP AND CHARACTERIZE THESE AREAS?

These locations were chosen by local managers as priority sites during scoping meetings hosted by NOAA's Coral Reef Conservation Program (USVI and NOAA CRCP, 2010). In each of these places, a local action strategy for coral reef conservation will be developed, providing a roadmap of actions to address key issues and remedy specific threats regarding the health of the coral reefs. It will focus on important issues, and will detail specific actions targeted at the causes of the threats as well as provide guidance on how these actions will be implemented and evaluated. The written plan will include: clearly framed goals and objectives; actions that are aimed at addressing and reducing threats (e.g., land-based sources of pollution); assessment of required resources; an implementation timeline; and an evaluation process, including performance measures. The development of these strategies will be a participatory process that includes place-based managers and decision-makers as well as stakeholders.

To support this process, a baseline understanding of the benthic communities and associated living marine resources is needed. Habitat maps, in particular, are an integral component to this process, as they support 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 managers about the existing distribution of resources, (2) help locate sensitive marine communities, and (3) guide monitoring efforts and prioritize subsequent management actions. Furthermore, benthic habitat maps can help scientists and managers understand different ecological pat-



**Figure 1.2.** Maps of Fish Bay, Coral Bay and the STEER. The black hatched polygons denote the seafloor area that was mapped and characterized for this project. The STEER's boundary is denoted in yellow, the Virgin Islands National Park's boundary in red, and the Virgin Islands Coral Reef National Monument's boundary in green. shallow-water habitat map.

terns and processes across the seascape. Recent research has demonstrated that the spatial arrangement of habitat types and the composition of the seascape 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 NCCOS Biogeography Branch developed the analytical protocols used for mapping benthic habitats throughout all U.S. jurisdictions, states, and territories, including the U.S. Caribbean (Kendall et al. 2001). These protocols enable scientists and managers to compare marine ecosystems throughout the U.S. NCCOS used similar protocols to generate seamless habitat maps of the marine areas in and around Fish Bay, Coral Bay and the STEER. In addition to filling information gaps about coral reef ecosystems, the products developed during this project filled knowledge gaps about the depth and topography of the seafloor around St. John and St. Thomas. Remote sensing technologies used in previous mapping efforts were not designed to collect bathymetric (i.e., depth) information. New sensors, specifically LiDAR, 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).

The products generated by this project are designed to help monitor benthic habitats and support the local management of Fish Bay, Coral Bay and the STEER. These products specifically include:

- Three benthic habitat maps (one of Fish Bay, Coral Bay and the STEER);
- Description of the methods used to create the habitat maps;
- A classification manual;
- Bathymetry (i.e., depth imagery);
- Other source datasets, including aerial photographs, LiDAR reflectivity;
- Ground validation underwater video and photos; and
- Accuracy assessment underwater video and photos.

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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 used to guide the delineation and attribution of polygons during the mapping process. It is, consequently, 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 applications and limitations of the habitat map.

The habitat classification scheme in Fish Bay, Coral Bay and the STEER 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 and dominant type. Habitat features are described by varying levels of detail (i.e., major and minor categories nested within them), so users can depict the habitat information that meets their research or management needs. In total, 155 distinct combinations of major structure, detailed structure, percent hard bottom, major cover, percent cover and live coral cover were identified from LiDAR and aerial photographs.



Colorful sponges and fire coral (*Millepora* spp.) in the cut between St. Thomas and Great St. James Island.

Habitat features are described by varying levels of detail (i.e., major and minor categories nested within them), so users can depict the habitat information that meets their research or management needs. In total, 155 distinct combinations of major structure, detailed structure, percent hard bottom, major cover, percent cover and live coral cover were identified from LiDAR and aerial photographs.

#### 2.1.1. Comparison to Previous BB Classification Scheme

Many important factors were considered when developing the habitat classification scheme. These factors included: (1) how it would dovetail with existing classification schemes for marine habitats; (2) what limitations were associated with the source imagery; (3) how best to create a habitat maps from two imagery sources (aerial photographs and LiDAR) with different spatial resolutions; (4) what would be an appropriate minimum mapping unit (MMU); and (5) how much ground validation (i.e., underwater video) would be needed to create a habitat map.

To simplify this process, we based the habitat classification scheme implemented in Fish Bay, Coral Bay and the STEER on the scheme previously developed by NOAA to map benthic habitats around St. John (Zitello et al. 2009; Costa et al. 2009) and in Buck Island Reef National Monument north of St. Croix in the U.S. Virgin Islands (Costa et al. 2012). Generally speaking, the geographic zones, major and detailed geomorphological structure and biological cover types were the same across these habitat maps (Table 2.1), although some habitat types were not present everywhere. Also, we mapped the habitats in Fish Bay, Coral Bay and the STEER at a finer minimum mapping unit (MMU) (100 m<sup>2</sup>) than the previous mapping efforts in the area around St. John (which had an MMU = 1,000 m<sup>2</sup>).

While the maps created for Fish Bay, Coral Bay and the STEER are similar to the previous maps in the region, they are fundamentally different from the benthic habitat map created in 2001 by NOAA's Biogeography Branch for all of the U.S. Caribbean (Kendall et al. 2001). The primary differences between NOAA's 2001 and 2013 habitat maps include: (1) the separation of biological cover from habitat structure; (2) different MMU sizes (i.e., 4047 m<sup>2</sup> versus 100 m<sup>2</sup>); (3) the addition of more detailed structure classes due to the higher resolution of the source imagery and smaller geographic scope of the map project; and (4) the addition of three new map attributes called *Percent Hardbottom*, *Percent Live Coral Cover* and *Dominant Coral Type*. The *Percent Hardbottom* attribute describes the percent area of a polygon that contains hardbottom habitats. The *Percent Live Coral Cover* attri-

**Table 2.1.** The classification scheme used to classify benthic habitats in Fish Bay, Coral Bay and the STEER in 2013. 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 Fish Bay, Coral Bay and the STEER but were included for comparison purposes.

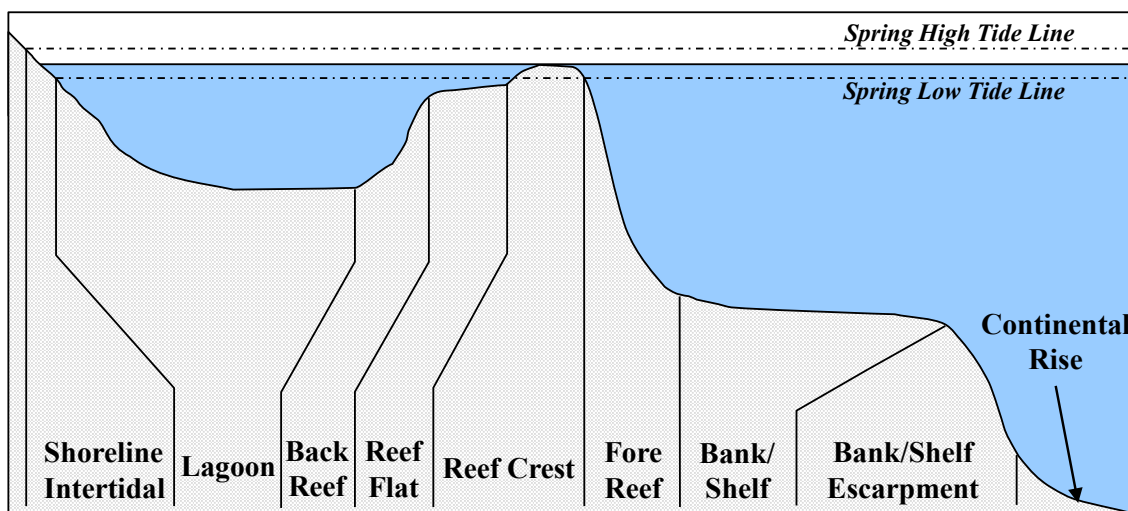
GEOGRAPHIC ZONE		GEOMORPHOLOGICAL STRUCTURE		BIOLOGICAL COVER
Back Reef	Coral Reef and Hardbottom (Hard)			Major Cover
Bank/Shelf	Aggregate Reef			Algae
Bank/Shelf Escarpment	Aggregated Patch Reefs			Live Coral
Channel	Individual Patch Reef			Mangrove
Dredged	Pavement			No Cover
Fore Reef	Pavement with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

bute describes the percent area on the seafloor that is colonized by live coral. It is important to note that *Percent Hardbottom* is interpreted at the scale of the polygon (i.e., >100 m<sup>2</sup>). Conversely, *Percent Live Coral Cover* is interpreted at the scale of the underwater video (i.e., ≤ 2-3 m<sup>2</sup>) and only refers to the hardbottom component of any mapped polygon (and not to the entire polygon itself). For instance, an attribution of “percent hardbottom of 50% ≤ 70% and live coral of 10% ≤ 50%” denotes that 10% ≤ 50% of the hardbottom within that polygon is colonized by live coral. The remainder (30% < 50%) of that polygon is not colonized by live coral. The *Dominant Coral Type* modifier denotes whether hard coral or soft corals were dominant in a polygon, which had >10% live coral cover.

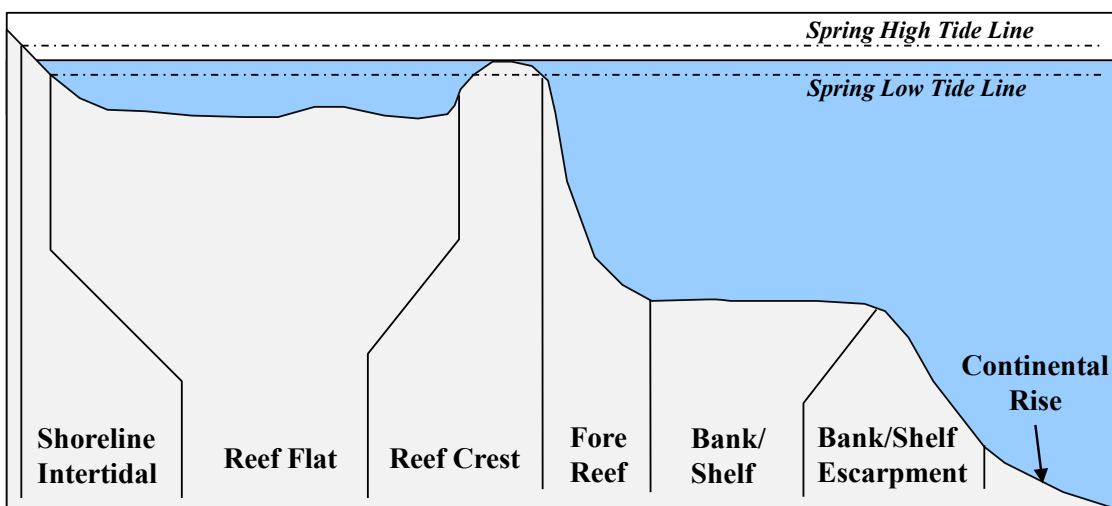
### 2.1.2. Geographic Zones

Ten distinct and non-overlapping geographic zone types were mapped by visually interpreting aerial photographs and LiDAR bathymetry and reflectivity. Zone refers to each benthic community’s geographic location. It does not describe a polygon’s substrate or biological cover types. For example, the zone *Fore Reef* is always located adjacent to a *Reef Crest* on the seaward side. However, neither *Fore Reef* nor *Reef Crest* 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 MMU (i.e., 100 m<sup>2</sup>) were not considered. A brief description of each geographic zone is provided in the following text.

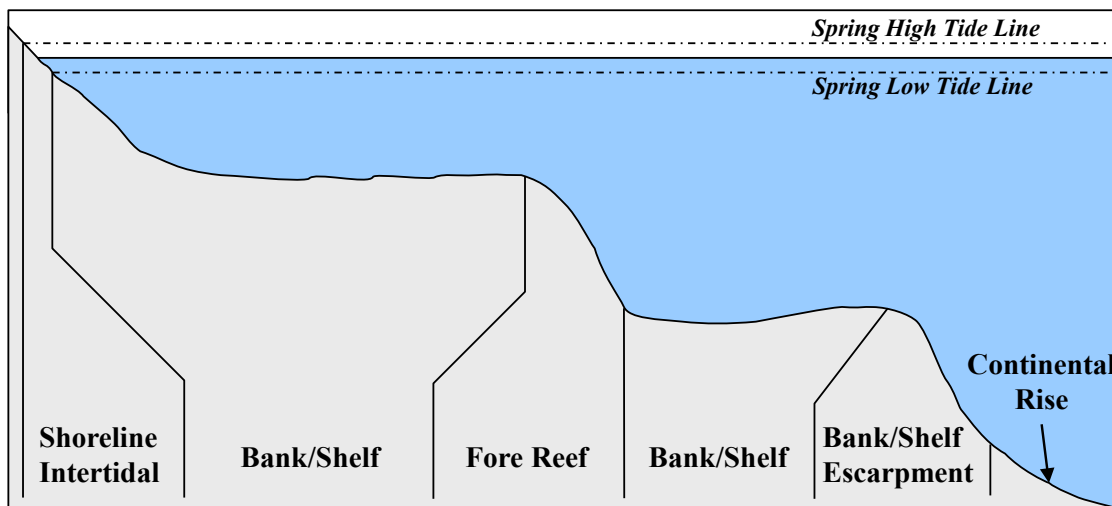




**Figure 2.1.** Cross-section of zone types when a barrier reef is present. The reef is separated from the shore by a relatively wide, deep lagoon.



**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**

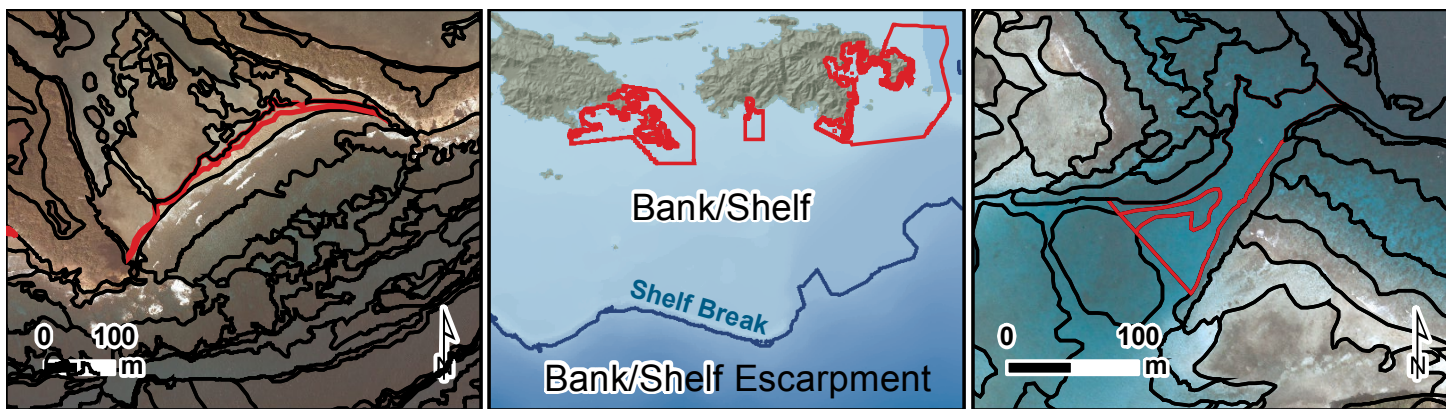
Area immediately landward of a *Reef Crest* that slopes downward towards the seaward edge of a *Lagoon* floor or *Bank/Shelf*. This zone is present only when a *Reef Crest* exists (Figure 2.4 left).

**Bank/Shelf**

Deeper water area (relative to the shallow water in a lagoon) extending offshore from the shoreline or seaward edge of the *Fore Reef* to the beginning of the *Bank/Shelf Escarpment*. 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 2.4 middle).

**Bank/Shelf Escarpment**

The edge of the *Bank/Shelf* where the seafloor drops off rapidly into deep oceanic water. This zone extends well into depths exceeding those that can be seen on aerial photos or LiDAR and is intended to capture the transition from the bank/shelf to deep waters of the open ocean (Figure 2.4 middle). This zone is crossed out because it was not present in the Coral Bay, Fish Bay or the STEER habitat maps.



**Figure 2.4.** The red polygon outlines an example of the geographic zone, *Back Reef*, inside the STEER (left); the red polygons outline the location of the 3 mapped areas on the *Bank/Shelf* (middle); and the red polygon outlines an example of the geographic zone, *Channel*, northwest of Coral Bay (right).

**Channel**

Naturally occurring channels that often cut across several other zones (Figure 2.4 right).

**Dredged**

Area in which natural geomorphology is disrupted or altered by excavation or dredging. This zone is crossed out because it was not present in the Coral Bay, Fish Bay or the STEER habitat maps.

**Fore Reef**

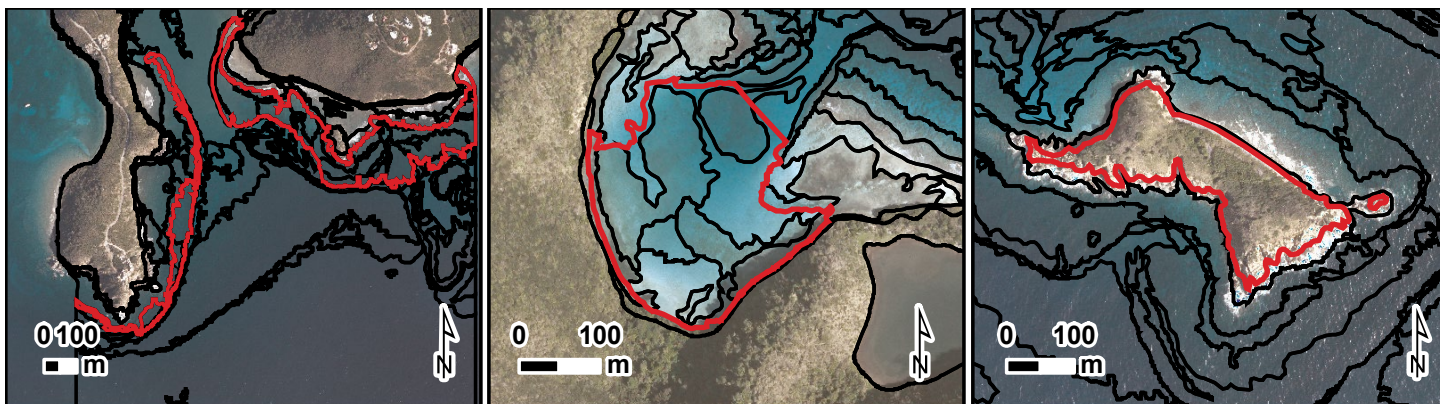
Area along the seaward edge of the *Reef Crest* that slopes into deeper water to the landward edge of the *Bank/Shelf* platform. Features not associated with an emergent *Reef Crest* (but still having a seaward-facing slope that is significantly greater than the slope of the *Bank/Shelf*) are also designated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

**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 2.5 middle).

**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 2.5 right). The wrack line is a line of organic and/or anthropogenic debris (above the mean high tide line) that has been deposited by previous higher than normal tides.



**Figure 2.5.** The red polygons outline examples of the geographic zone, *Fore Reef*, south Fish Bay (left); the red polygon outlines an example of the geographic zone, *Lagoon*, northeast of Coral Bay (middle); and the red polygon outlines an example of the geographic zone, *Land*, inside Coral Bay (right).

#### *Reef Crest*

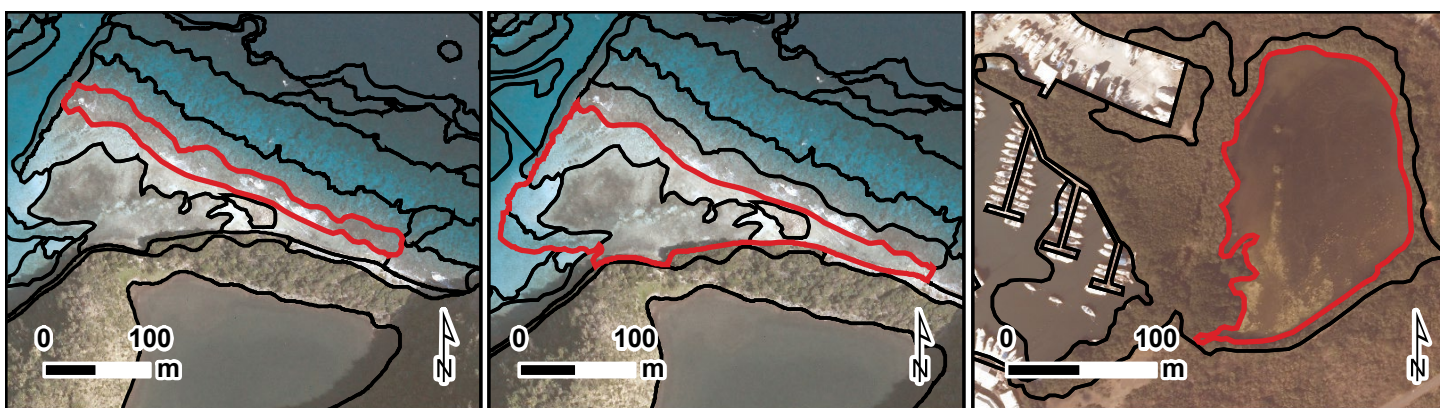
The flattened, emergent (especially during low tides) or nearly emergent segment of a reef. This zone of high wave energy lies between the *Fore Reef* and *Back Reef* or *Reef Flat* zones. Breaking waves are often visible in overhead imagery at the seaward edge of this zone (Figure 2.6 left).

#### *Reef Flat*

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

#### *Salt Pond*

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



**Figure 2.6.** The red polygons outline an example of the geographic zone, *Reef Crest*, northeast of Coral Bay (left); the red polygon outlines an example of the geographic zone, *Reef Flat*, northeast of Coral Bay (middle); and the red polygon outlines an example of the geographic zone, *Salt Pond*, in the STEER (right).

### Shoreline Intertidal

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

#### 2.1.3. Geomorphological Structure Types

Fifteen distinct and non-overlapping geomorphological structure types were mapped by interpreting aerial photos and LiDAR imagery. Geomorphological structure refers to a feature's dominant physical composition and does not address its geographic location (e.g., in a *Lagoon*). Structure types are hierarchically defined ranging from three major classes (*Coral Reef and Hardbottom*, *Unconsolidated Sediment*, and *Other Delineations*), to fifteen detailed classes (*Aggregate Reef*, *Aggregated Patch Reefs*, *Individual Patch Reef*, *Pavement*, *Pavement with Sand Channels*, *Reef Rubble*, *Rhodoliths*, *Rhodoliths with Scattered Coral & Rock*, *Rock/Boulder*, *Spur & Groove*, *Mud*, *Sand*, *Sand with Scattered Coral & Rock*, *Artificial*, and *Land*). Habitats or features with areas smaller than the MMU (i.e., 100 m<sup>2</sup>) were not considered.

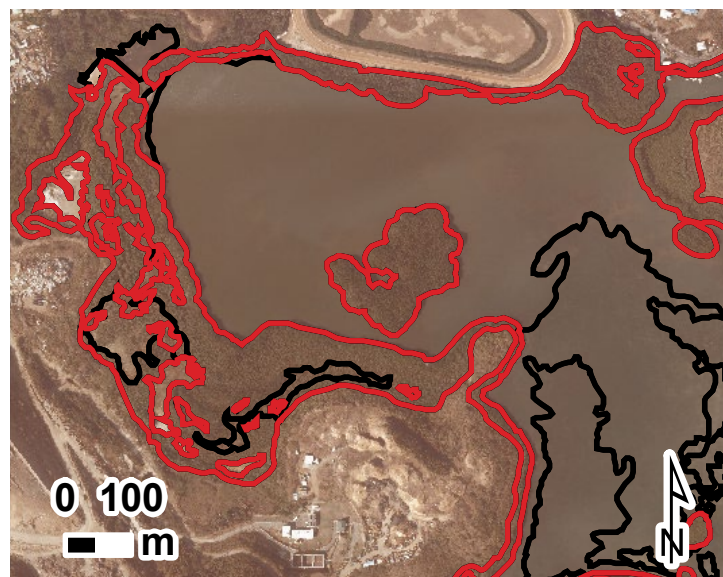


Figure 2.7. The red polygons outline examples of the geographic zone, *Shoreline Intertidal*, in Mangrove Lagoon in the STEER.

### 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 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*, *Rock/Boulder* and *Spur & 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).

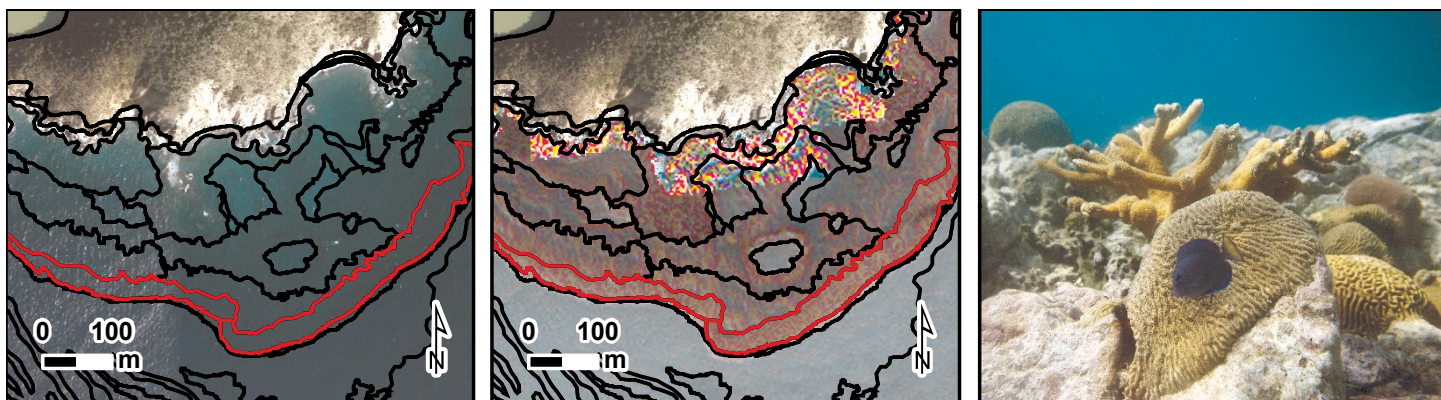
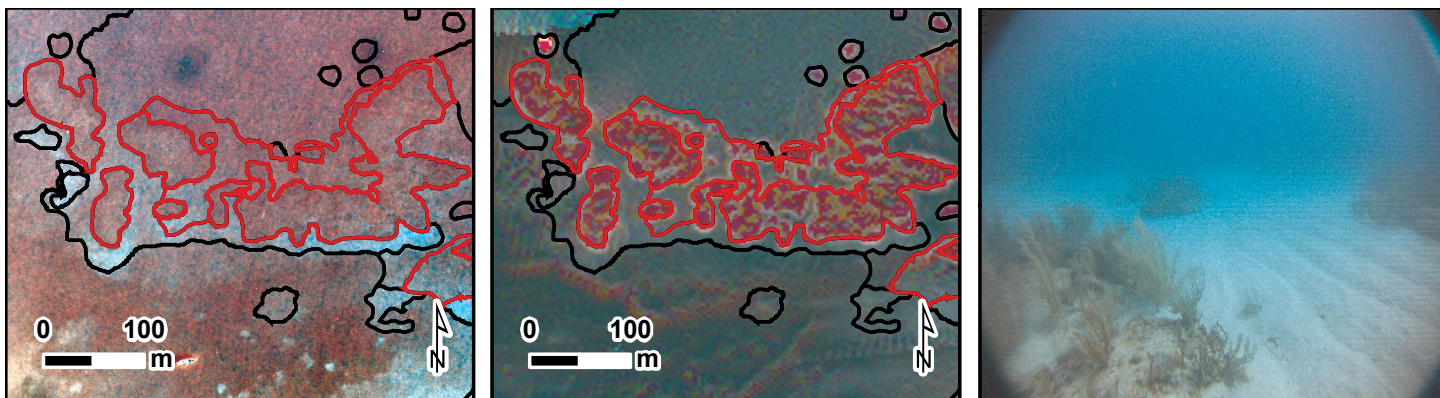


Figure 2.8. The red polygons outline an example of the detailed structure type, *Aggregate Reef*, in Coral Bay as seen in the aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of aggregate reef in Coral Bay.

### Aggregated Patch Reefs

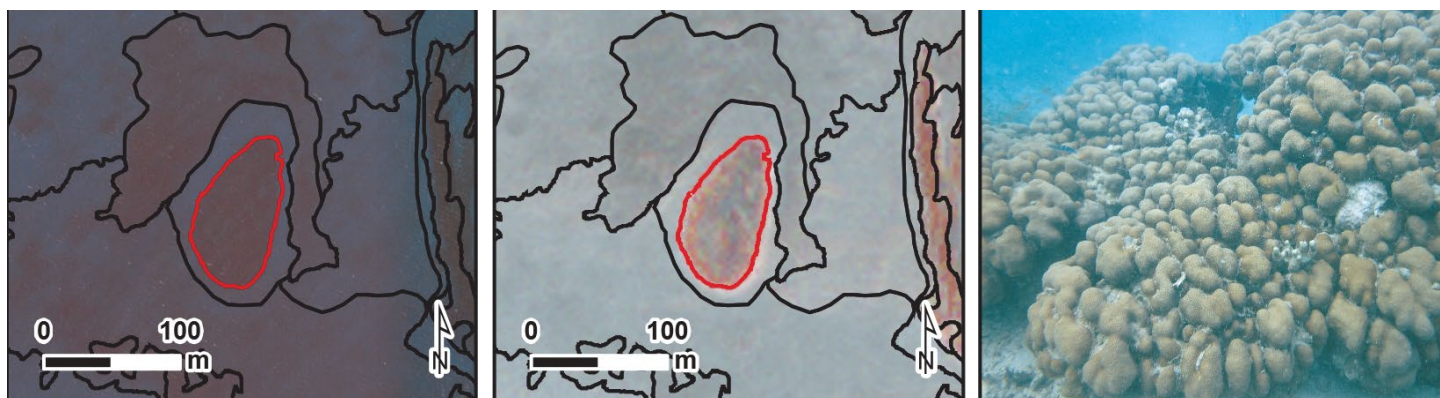
*Aggregated Patch Reefs* have the same defining characteristics as an *Individual Patch Reef*. However, this class refers to clustered patch reefs that cover  $\geq 10\%$  of the entire polygon, but are too small (i.e., smaller than the MMU) or are too close together to map individually. Where aggregated 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 red polygons outline an example of the detailed structure type, *Aggregated Patch Reefs*, in Coral Bay as seen in the aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of aggregated patch reefs in Coral Bay.

#### *Individual Patch Reef*

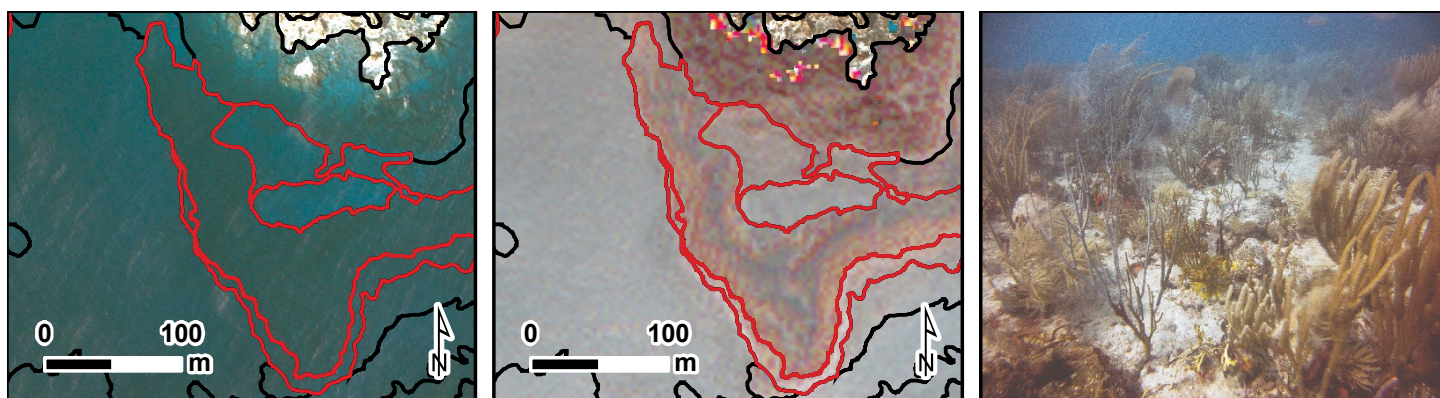
*Individual Patch Reefs* are coral formations that are isolated from other coral reef formations by bare sand, sea-grass or other habitats and that have no organized structural axis relative to the contours of the shoreline or shelf edge. They are characterized by a roughly circular or oblong shape with 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 red polygons outline examples of the detailed structure type, *Individual Patch Reef*, in the STEER as seen in aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of an individual patch reef in the STEER.

#### *Pavement*

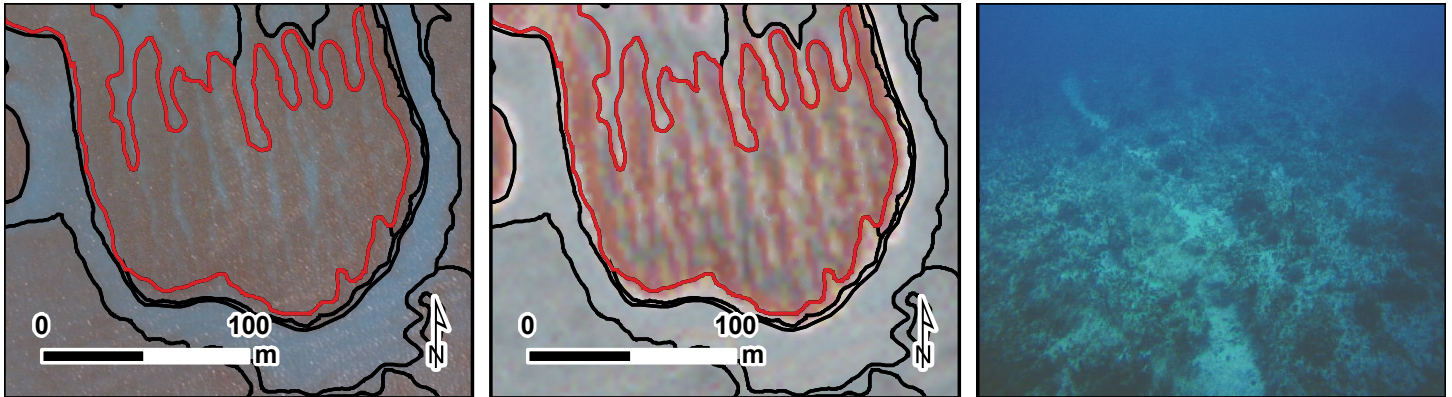
Flat, low-relief or sloping solid carbonate rock with little or no fine-scale rugosity that is covered with algae, hard coral, gorgonians, zooanthids or other sessile vertebrates that are dense enough to partially obscure the underlying surface. On less colonized *Pavement* features, rock may be covered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



**Figure 2.11.** The red polygons outline examples of the detailed structure type, *Pavement*, in the STEER as seen in aerial ortho-photos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of pavement in the STEER.

### *Pavement with Sand Channels*

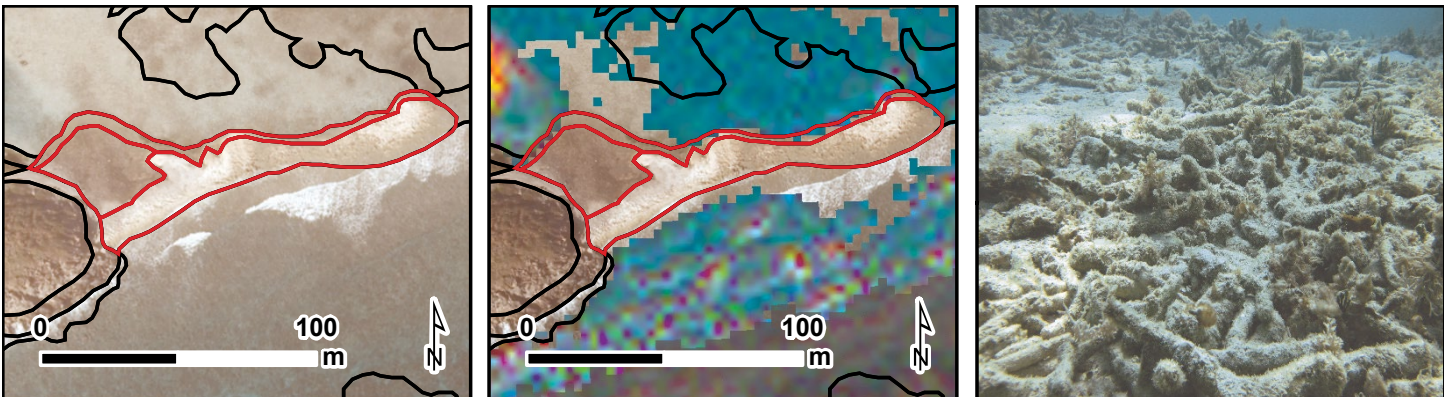
*Pavement with Sand Channels* have the same defining characteristics as *Pavement*, in addition to having periodic sand/surge channels oriented perpendicular to the *Bank/Shelf Escarpment*. The sand/surge channels of this feature have low vertical relief and are typically erosional in origin. This habitat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



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

### *Reef Rubble*

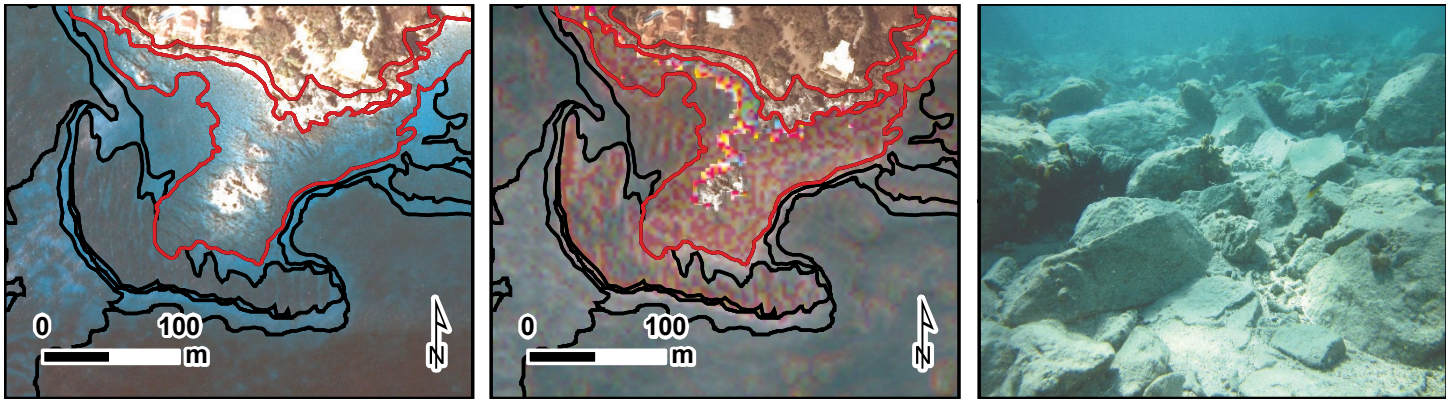
Dead, unstable coral rubble often colonized with filamentous or other macroalgae. This habitat often occurs landward of well developed reef formations in the *Reef Crest*, *Back Reef* or *Reef Flat* zones. Less often, *Reef Rubble* can occur in low density aggregations on broad offshore sand areas (Figure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



**Figure 2.13.** The red polygons outline examples of the detailed structure type, *Reef Rubble*, in the STEER as seen in aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of reef rubble in the STEER.

### Rock/Boulder

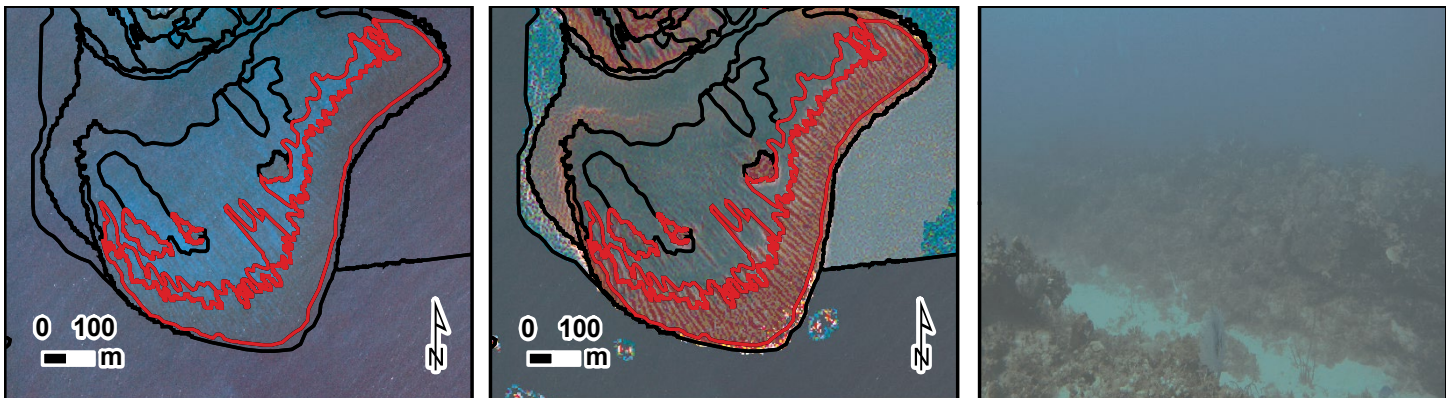
Aggregation of solid carbonate blocks extending offshore from the island bedrock or loose carbonate fragments that have been detached and transported from their native beds (Figure 2.14). Individual boulders range in diameter from 0.256-3 m as defined by the Wentworth scale (Wentworth, 1922).



**Figure 2.14.** The red polygons outline examples of the detailed structure type, *Rock/Boulder*, in the STEER as seen in aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of rock/boulder in the STEER.

### Spur and Groove

Structure having alternating sand and coral formations that are oriented perpendicular to the shore or reef crest (Figure 2.15). 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.



**Figure 2.15.** The red polygons outline examples of the detailed structure type, *Spur and Groove*, in Coral Bay as seen in aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of spur and groove in Coral Bay.

### Unconsolidated Sediment

Areas on the seafloor consisting of particles <256 mm in diameter, and covered with less than 10% hardbottom. Detailed structure classes include: *Mud*, *Rhodoliths*, *Rhodoliths with Scattered Coral and Rock*, *Sand* and *Sand with Scattered Coral and Rock*.

#### *Mud*

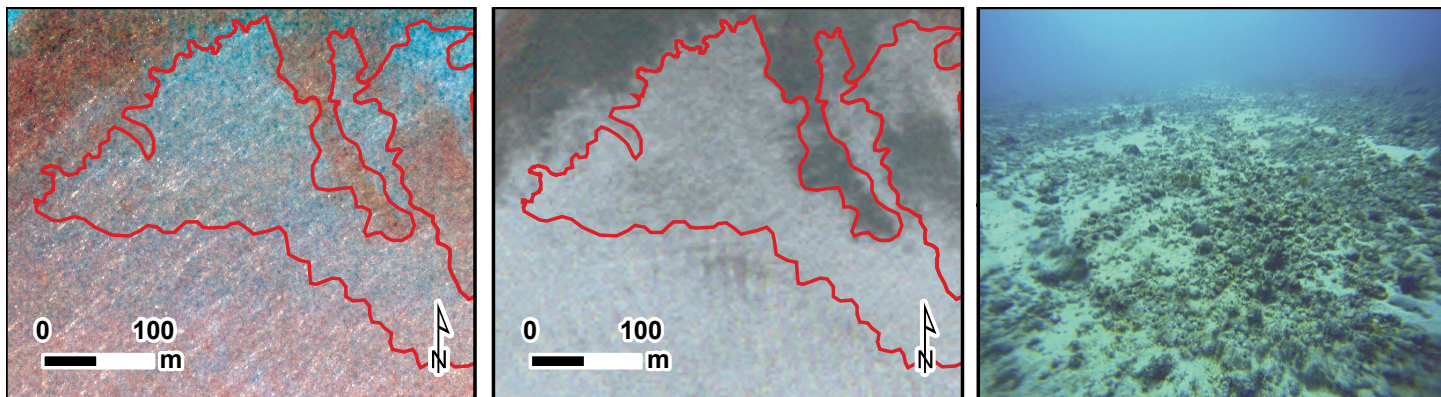
Fine sediment often associated with river discharge and build-up of organic material in areas sheltered from high-energy waves and currents (Figure 2.16). Particle sizes range from < 1/256 - 1/16 mm (Wentworth, 1922).



**Figure 2.16.** The red polygon outlines an example of the detailed structure type, *Mud*, in Mangrove Lagoon in the STEER as seen in aerial orthophotos (left). The underwater photographs (middle and right) depict examples of mud in the STEER.

#### *Rhodoliths*

Areas on the seafloor that are covered by  $\geq 10\%$  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 2.17). Since *Rhodoliths* are unattached to the seafloor and mobile, their distributions can change quantifiably from year to year.

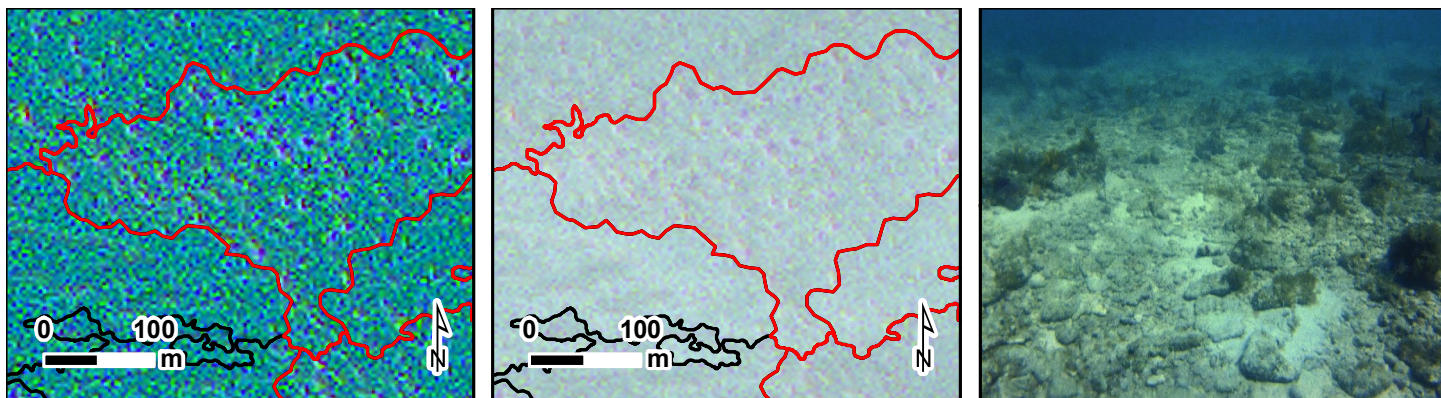


**Figure 2.17.** The red polygons outline examples of the detailed structure type, *Rhodoliths*, outside Coral Bay as seen in the aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of rhodoliths outside Coral Bay.

#### *Rhodoliths with Scattered Coral and Rock*

Areas on the seafloor where  $\geq 10\%$  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 2.18). If the density of the rocks and/or coral heads is  $\geq 10\%$  of the entire polygon's area, then the structure type is described as *Aggregated Patch Reefs*.

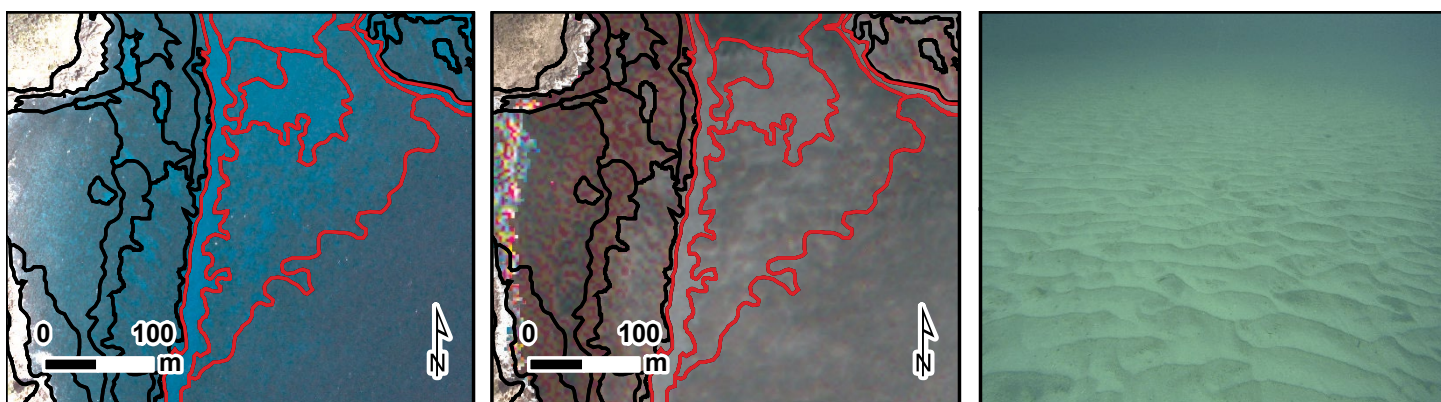




**Figure 2.18.** The red polygons outline examples of the detailed structure type, *Rhodoliths with Scattered Coral and Rock*, outside Coral Bay as seen in the LiDAR bathymetry (left) and LiDAR reflectivity (middle). The underwater photograph (right) depicts an example of rhodoliths outside Coral Bay.

### Sand

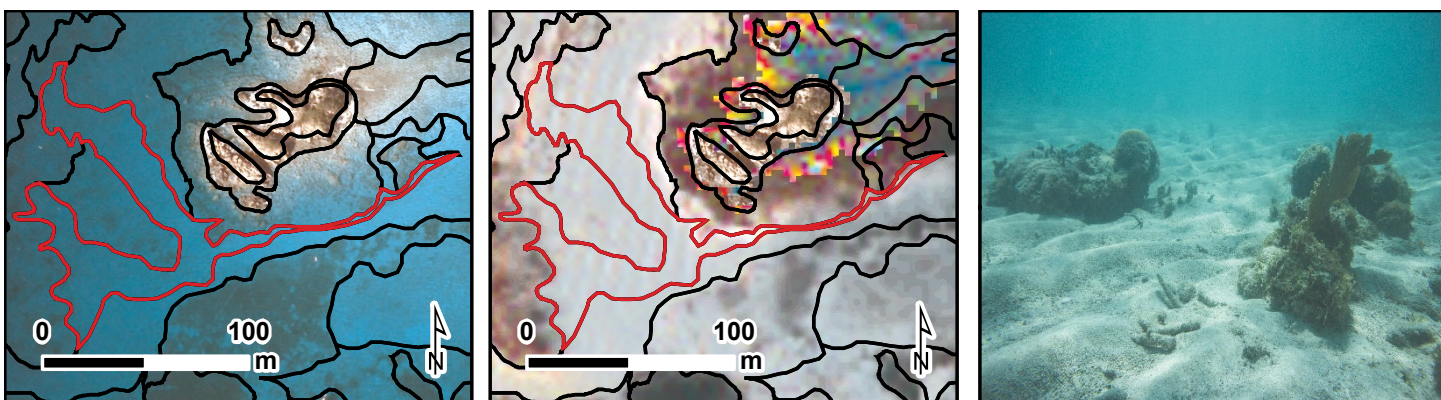
Coarse sediment typically found in areas exposed to currents or wave energy (Figure 2.19). Particle sizes range from 1/16–256 mm, including pebbles and cobbles (Wentworth, 1922).



**Figure 2.19.** The red polygons outline examples of the detailed structure type, *Sand*, in Coral Bay as seen in aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of sand in Coral Bay.

### *Sand with Scattered Coral and Rock*

Areas where  $\geq 10\%$  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 2.20). If the density of small coral heads is  $\geq 10\%$  of the entire polygon, this structure type is described as *Aggregated Patch Reefs*.



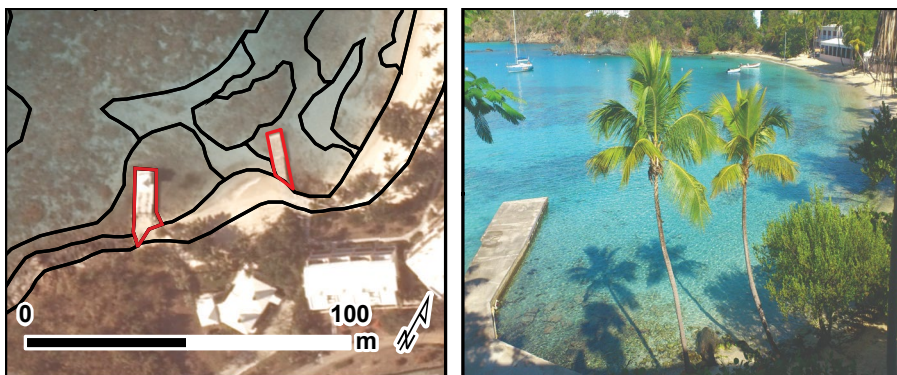
**Figure 2.20.** The red polygons outline examples of the detailed structure type, *Sand with Scattered Coral and Rock*, in the STEER as seen in aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts an example of sand with scattered coral and rock in the STEER.

### 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

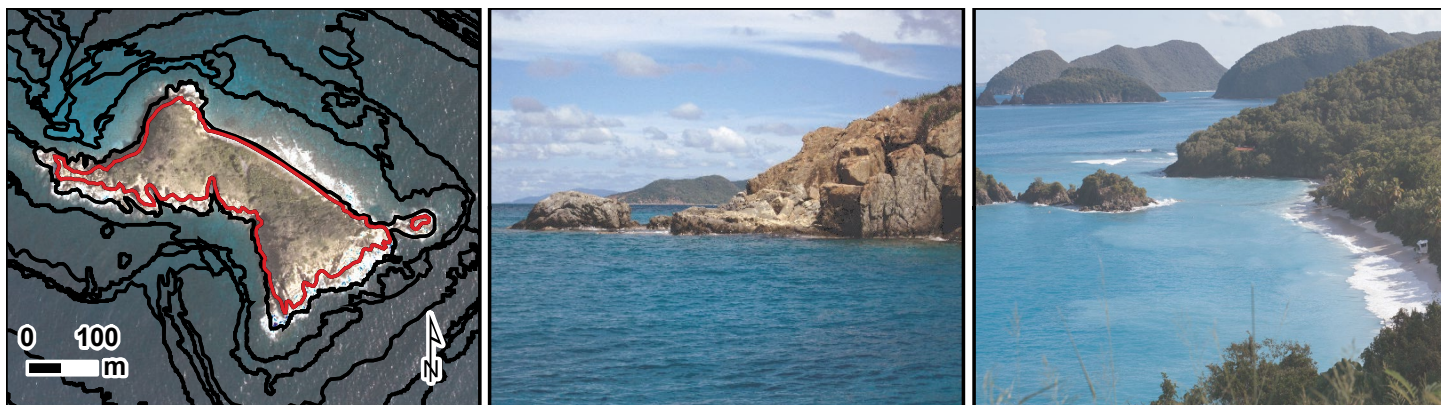
Man-made habitats such as submerged wrecks, large piers, submerged portions of rip-rap jetties, and the shoreline of islands created from dredge spoil (Figure 2.21).



**Figure 2.21.** The red polygons outline examples of the detailed structure type, *Artificial*, as seen in aerial orthophotos (left). The photograph (right) was taken in Nazareth Bay in the STEER.

#### Land

Terrestrial features at or above the spring high tide line (Figure 2.22).



**Figure 2.22.** The red polygon outlines an example of the detailed structure type, *Land*, as seen in aerial orthophotos (left). The photograph (middle and right) was taken north of Luduck Island in Coral Bay.

#### Unknown

Major and/or detailed structure that is indistinguishable in the aerial photographs or LiDAR imagery due to water depth, turbidity, cloud cover, wave action, sun glint or other interference with the optical signature of the seafloor.

### Percent Hardbottom

Percent Hardbottom refers to the amount (i.e., patchiness) of hardbottom habitat within a habitat polygon (Figure 2.23). It does not describe the type of hardbottom that is located within a polygon.

#### $0\% \leq 10\%$

Discontinuous cover of hardbottom with breaks in coverage that are too small to be mapped as a different feature (i.e., smaller than the MMU). Hardbottom is estimated to cover  $0\% \leq 10\%$  of the entire polygon.

#### $10\% \leq 30\%$

Discontinuous cover of hardbottom with breaks in coverage that are too small to be mapped as a different feature (i.e., smaller than the MMU). Hardbottom is estimated to cover  $10\% \leq 30\%$  of the entire polygon.

**30% ≤ 50%**

Discontinuous cover of hardbottom with breaks in coverage that are too small to be mapped as a different feature (i.e., smaller than the MMU). Hardbottom is estimated to cover 30% ≤ 50% of the entire polygon.

**50% ≤ 70%**

Discontinuous cover of hardbottom with breaks in coverage that are too small to be mapped as a different feature (i.e., smaller than the MMU). Hardbottom is estimated to cover 50% ≤ 70% of the entire polygon.

**70% ≤ 90%**

Discontinuous cover of hardbottom with breaks in coverage that are too small to be mapped as a different feature (i.e., smaller than the MMU). Hardbottom is estimated to cover 70% ≤ 90% of the entire polygon.

**90% - 100%**

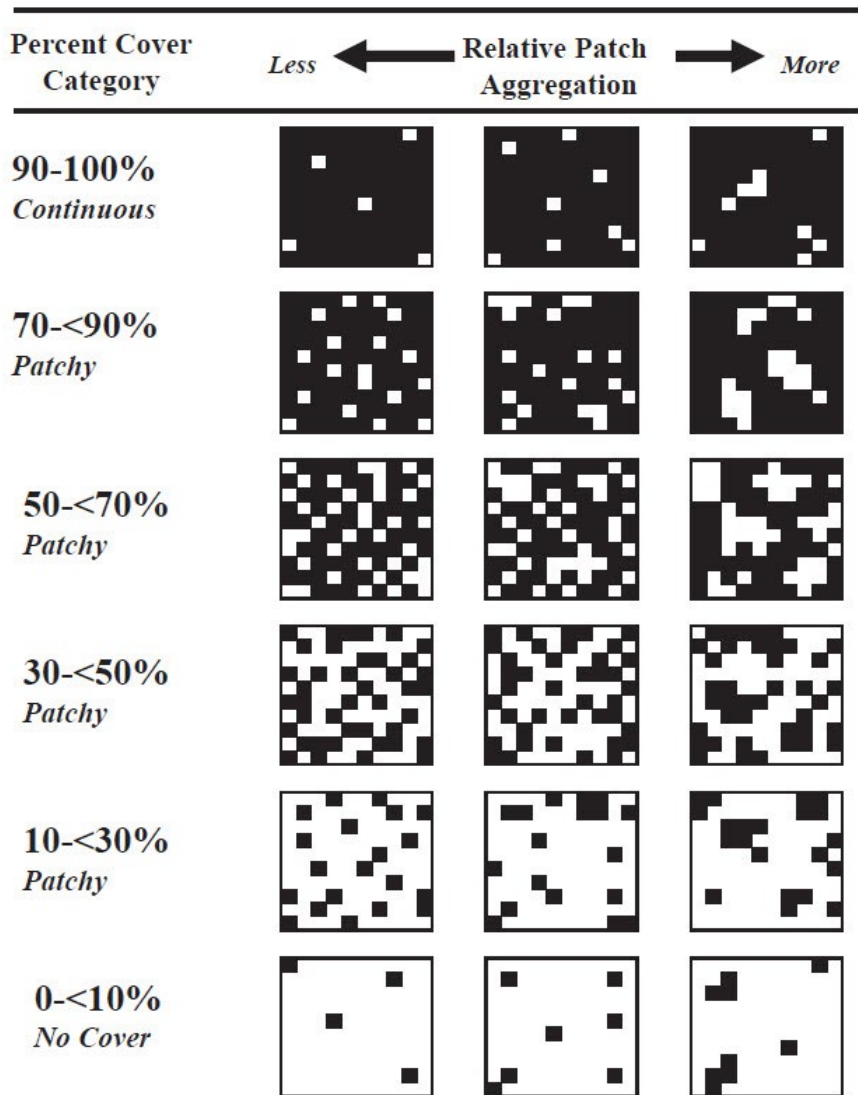
Continuous cover of hardbottom. Hardbottom is estimated to cover 90% - 100% of the entire polygon.

**Not Applicable (N/A)**

An estimate of percent hardbottom is not appropriate for this particular structure class (e.g., for *Land* polygons).

**Unknown**

Percent estimate of hardbottom is indistinguishable in the aerial photographs or LiDAR imagery due to water depth, turbidity, cloud cover, wave action, sun glint or other interference with the optical signature of the seafloor.



**Figure 2.23.** This chart outlines the process used to estimate patchiness when assigning a percent hardbottom and percent biological cover value to a polygon (Kendall et al., 2001).

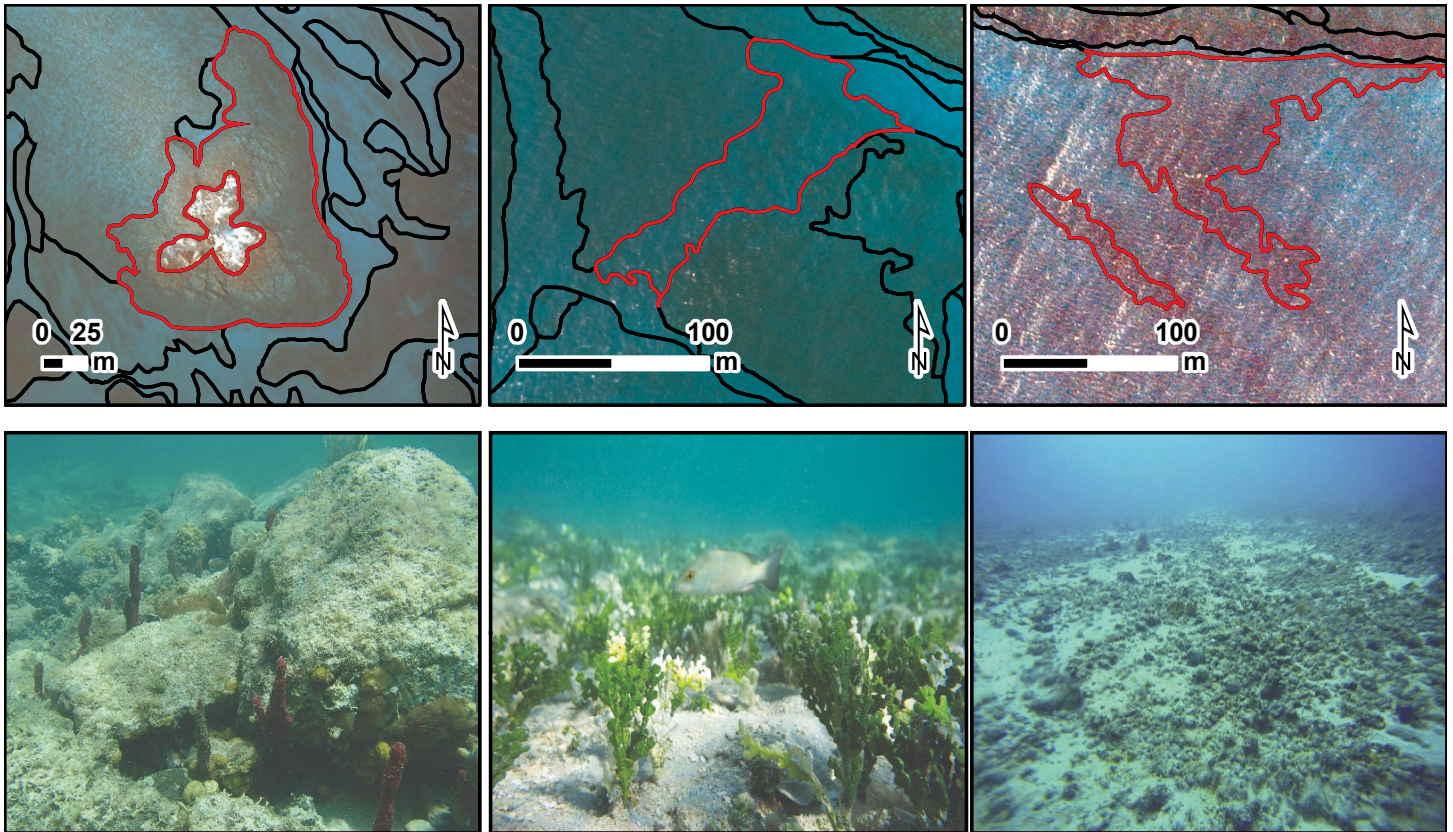
### 2.1.4. Biological Cover Classes

Twelve distinct (i.e., major plus detailed) biological cover classes were mapped by interpreting aerial photographs and LiDAR imagery. Biological cover denotes the dominant biological component colonizing the seafloor in a polygon. It does not describe the location (e.g., on the *Bank/Shelf*) or structure (e.g., *Sand*) of the polygon. Habitat features smaller than the MMU were not considered. Five major cover types were identified from the aerial photographs and LiDAR imagery (i.e., *Algae*, *Live Coral*, *Mangrove*, *No Cover*, and *Seagrass*) and combined with three modifiers describing the distribution of the dominant cover within the polygon (i.e.,  $10\% \leq 50\%$ ,  $50\% \leq 90\%$ , and  $90\% - 100\%$ ). It is important to note that this modifier represents a measure of patchiness of the biological cover at the polygon scale. It does not denote the density of organisms seen in the underwater video or photos. For example, a seagrass bed can be described as covering 90%-100% of a given polygon, but may have sparse densities of shoots in the underwater video. Figure 2.23 illustrates how patchiness was used to assign a biological percent cover.

## Major Cover

*Algae*

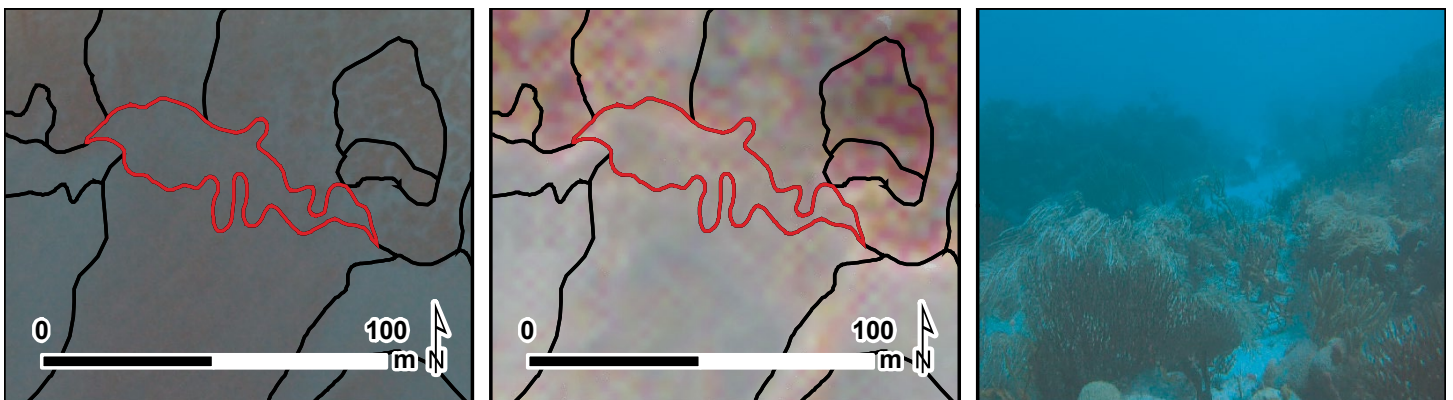
Substrates with 10% or greater distribution of any combination of numerous species of red, green, or brown algae. *Algae* may be turf, fleshy, coralline or filamentous species. Occurs throughout many zones, especially on hardbottom with low coral densities and on unconsolidated sediment in deeper waters (Figure 2.24).



**Figure 2.24.** The red polygons in the maps (top) depict examples of the biological cover type, *Algae*, as seen in the aerial orthophotos in the STEER. The underwater photographs (below) depict examples of algal habitat (i.e., turf algae, macroalgae, and coralline algae, respectively) in the STEER.

*Live Hard and Soft Coral*

Substrates colonized with 10% or greater live reef building corals and other organisms including hard scleractinian corals (e.g., *Acropora* sp.) and soft octocorals (e.g., *Briareum* sp.) (Figure 2.25).



**Figure 2.25.** The red polygon in the maps depict an example of the biological cover type, *Live Coral*, in the STEER as seen the aerial orthophotos (left) and LiDAR imagery (middle). The underwater photograph (right) depicts examples of a habitat dominated by live soft corals in the STEER.

### Mangrove

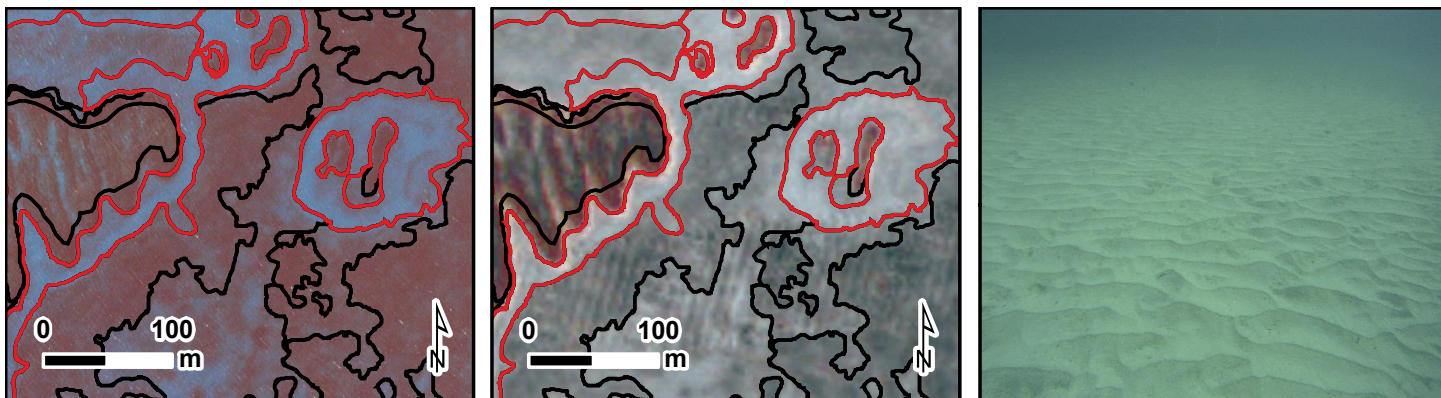
This habitat is comprised of semi-permanently, seasonally or tidally flooded coastal areas occupied by any species of mangrove (Figure 2.26). This habitat type is usually found in the *Shoreline Intertidal* zone. Mangrove trees are halophytes (i.e., they thrive in and are especially adapted to salty 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.



**Figure 2.26.** The red polygons outline examples of the biological cover type, *Mangrove* (left). The photographs (middle and right) depict examples of mangrove habitat in Mangrove Lagoon in the STEER.

### No Cover

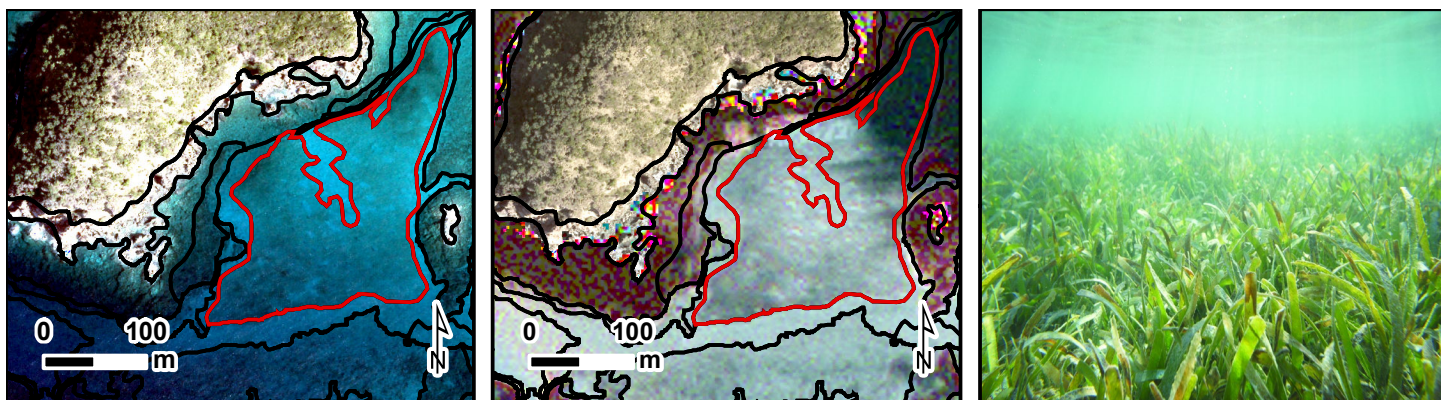
Substrates not covered with a minimum of 10% of any of the other biological cover types. This habitat is usually associated with *Mud* or *Sand*. *No Cover* is always estimated at 90%-100% of the bottom (Figure 2.27).



**Figure 2.27.** The red polygons in the maps depict examples of the biological cover type, *No Cover*, as seen in the aerial orthophotos (left) and LiDAR images (middle). The underwater photograph (right) depicts an example of an area on the seafloor colonized by little or no biological organisms in the STEER.

### Seagrass

Habitat dominated by any single species of seagrass (e.g., *Syringodium sp.*, *Thalassia sp.*, *Halophila sp.*) or a combination of several species (Figure 2.28).



**Figure 2.28.** The red polygons depict examples of the biological cover type, Seagrass, as seen in the aerial orthophotos (left) and LiDAR images (middle). The underwater photograph (right) depicts an example of seagrass habitats in Salt Pond Bay outside of Coral Bay.

### Unclassified

A different biological cover type, such as upland, deciduous forest, that is not included in this habitat classification scheme. Most often used for polygons classified as *Land*.

### Unknown

Biological cover that is indistinguishable in the aerial photographs or LiDAR imagery due to water depth, turbidity, cloud cover, wave action, sun glint or other interference with the optical signature of the seafloor.

### Percent Major Cover

#### $10\% \leq 50\%$

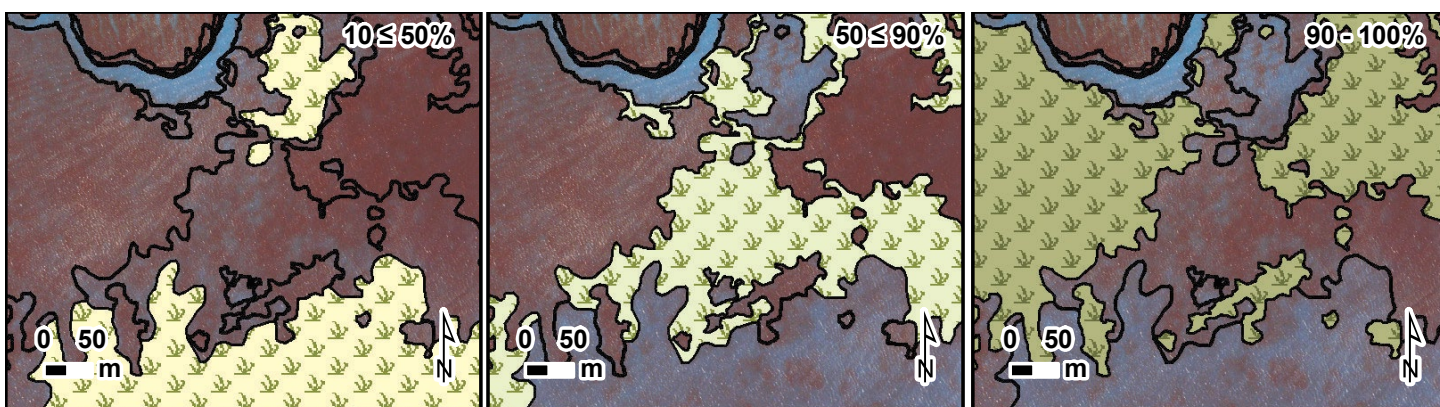
Discontinuous cover of the major biological type with breaks in coverage that are too diffuse to delineate or too small to be mapped as a different feature (i.e., smaller than the MMU). Overall cover of the major biological type is estimated to cover  $10\% \leq 50\%$  of the entire polygon feature (Figure 2.29 left).

#### $50\% \leq 90\%$

Discontinuous cover of the major biological type with breaks in coverage that are too diffuse to delineate or too small to be mapped as a different feature (i.e., smaller than the MMU). Overall cover of the major biological type is estimated to cover  $50\% \leq 90\%$  of the entire polygon feature (Figure 2.29 middle).

#### $90\% - 100\%$

Major biological cover type covering 90% or greater of the seafloor (Figure 2.29 right).



**Figure 2.29.** The symbolized polygons in the maps have:  $10\% \leq 50\%$  (left),  $50\% \leq 90\%$  (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 photographs or LiDAR imagery due to water depth, turbidity, cloud cover, wave action, sun glint or other interference with the optical signature of the seafloor.

## 2.1.5 Percent Live Coral Cover Classes

Four distinct and non-overlapping percent live coral classes were mapped by interpreting aerial photographs and LiDAR imagery. This attribute is an additional biological cover modifier denoting the abundance of live hard and soft corals (Figure 2.30), even when they are not the dominant cover type within a polygon. Four classes were used to describe the combined abundance of hard and soft corals:  $0\% \leq 10\%$ ,  $10\% \leq 50\%$ ,  $50\% \leq 90\%$ , and  $90\% - 100\%$ .



**Figure 2.30.** Both scleractinian and octocorals are included when estimating live coral cover. STEER hosts several species of scleractinian corals, including *Acropora palmata* (left) and several types of octocorals including sea rods (Gorgoniidae; right).

Live hard and soft coral cover describes the abundance of live hard and soft corals on hardbottom features as seen in the underwater video. It is important to note that this metric is different from percent biological cover, which denotes the patchiness of biological cover at the scale of the polygon. Due to these different scales of interpretation, the percent biological cover and percent live hard and soft 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 live coral at the scale of the underwater video.

**0% ≤ 10%**

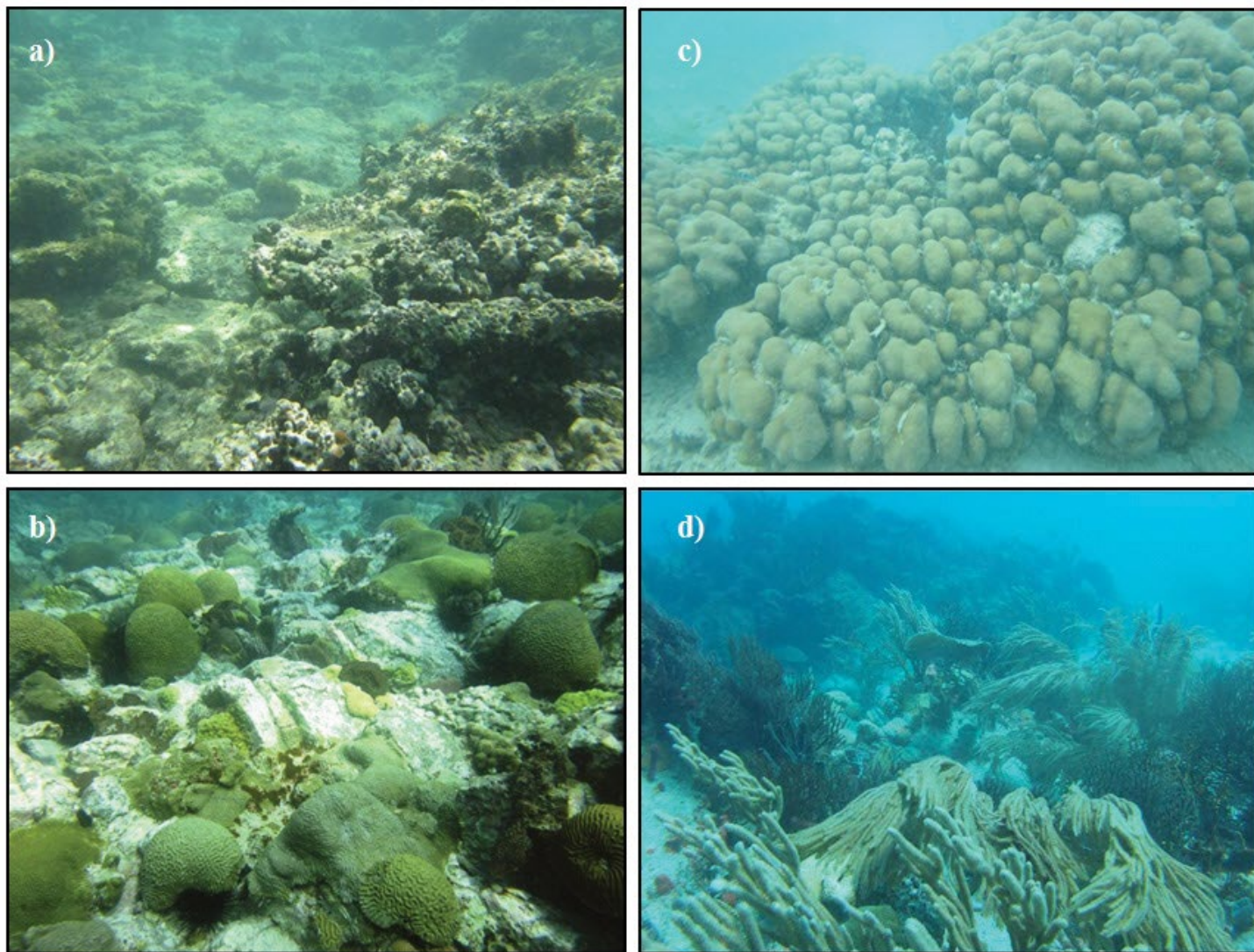
Live hard and soft corals colonize less than 10% of the hardbottom as seen in the underwater video (Figure 2.31a).

**10% ≤ 50%**

Live hard and soft corals colonize between 10% and 50% of the hardbottom as seen in the underwater video (Figure 2.31b).

**50% ≤ 90%**

Live hard and soft corals colonize between 50% and 90% of the hardbottom as seen in the underwater video (Figure 2.31c and d).



**Figure 2.31.** Examples of live coral cover in the (a) 0% ≤ 10% range; (b) 10% ≤ 50% range; (c) and (d) 50% ≤ 90% range.

**90% – 100%**

Continuous live hard and soft corals colonizing 90% or greater of the hardbottom as seen in the underwater video. This live hard and soft coral cover class is crossed out because it was not present in the Fish Bay, Coral Bay or the STEER habitat maps.

**Unknown**

The percent estimate of live coral cover is unknown for both hard and soft corals.



### **2.1.6 Dominant Coral Type**

The dominant coral type modifier denotes whether hard coral or soft corals were dominant in a polygon at the scale of the underwater video. Hard or soft coral dominance was only classified when live coral cover was estimated to be >10%. This class was experimental, and was included in this mapping effort to provide resource managers with additional information about corals. Hard corals were dominant in Figure 2.31 (c) and soft corals were dominant in Figure 2.31 (d).

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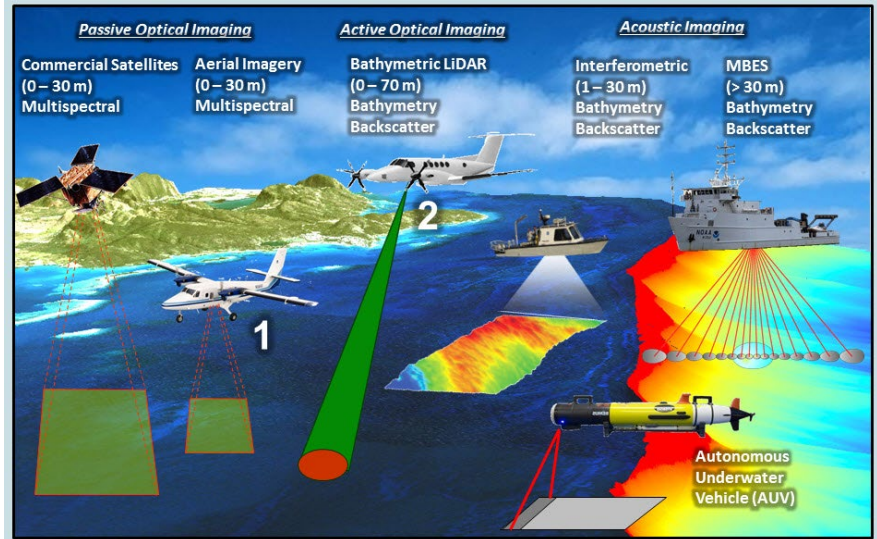
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## CHAPTER 3: METHODS

### 3.1. GENERAL MAPPING APPROACH

Six steps were used to map shallow-water habitats in Fish Bay, Coral Bay and the STEER:

1. Imagery Acquisition – Aerial photographs and LiDAR imagery were collected in 2012 and 2011 (respectively) covering the full geographic extent of project area. We used these images to generate benthic habitat maps for Fish Bay, Coral Bay and the STEER.
2. Habitat Boundary Delineation – Edge-detection algorithms and manual, heads-up digitizing were used to delineate habitat features visible in the aerial photographs and LiDAR imagery.
3. Ground Validation (GV) – Underwater video cameras were used to explore select habitat features delineated in step 2. This video was used to classify each polygon and generate draft habitat maps.
4. Expert Review – Local marine biologists, scientists, resource managers and community groups reviewed these draft maps online to assess (qualitatively) the thematic accuracy of each map.
5. Accuracy Assessment (AA) – Underwater videos were collected (using a random stratified sampling plan) to independently and quantitatively evaluate the accuracy of the habitat maps.
6. Final Product Creation – Errors identified during the expert review were corrected and accuracy assessment was used to produce final habitat maps for Fish Bay, Coral Bay and the STEER.



**Figure 3.1.** Diagram illustrating the various sensors used to map shallow-water to deep-water benthic habitats. For this mapping effort, two types of technologies were used: (1) a aerial digital camera, and (2) a LiDAR sensor. We integrated the imagery produced by these sensors to develop habitat maps for Fish Bay, Coral Bay and the STEER.

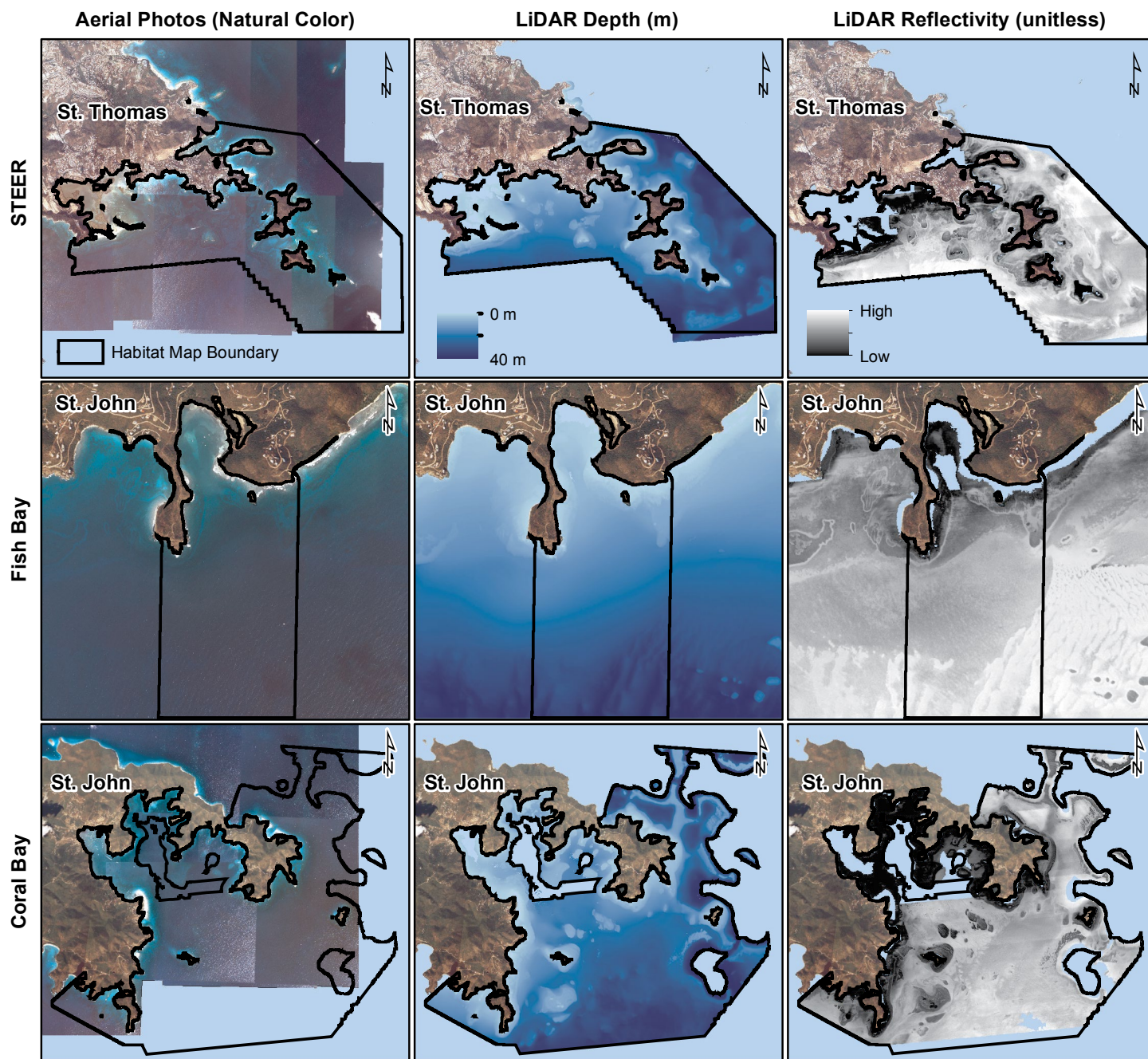
### 3.2. REMOTELY SENSED IMAGERY

#### 3.2.1. The Sensors

Two types of technology were used to map Fish Bay, Coral Bay and the STEER (Figure 3.1, Table 3.1): (1) a digital aerial camera and (2) a Light Detection and Ranging (LiDAR) sensor. Digital cameras are passive sensors, recording the sunlight (in the visible spectrum) that reflects off the land and seafloor to produce a photograph (Figure 3.2). Unlike aerial cameras, LiDAR sensors actively pulse light to measure the depth and reflectivity of the seafloor. LiDAR sensors calculate depths by measuring the time needed for a pulse of light to travel from the sensor to the seafloor and back again. These measurements are used to create seamless images of the seafloor's depth, also called "bathymetry" (Figure 3.2). LiDAR sensors calculate reflectivity by measuring the intensity of a pulse of light returned from

**Table 3.1.** Images from two different sensors were used to produce habitat maps in Fish Bay, Coral Bay and the STEER. Approximately sixty-three km<sup>2</sup> were mapped and characterized in total. The majority of habitats were delineated from the LiDAR images.

SENSOR	DIGITAL CAMERA (Z/I IMAGING DMC-II 230)	LIDAR (LADS MARK II)
Type of Imagery Produced	Aerial Photos (Orthophotos)	Bathymetry, Reflectivity
Year Acquired	2012	2011
Dates Acquired	January - March	January 29 - February 28
Native Spatial Resolution	0.3 x 0.3 m	3 x 3 m, resampled to 0.3 x 0.3 m
Area Characterized for the STEER	3.2 km <sup>2</sup>	21.5 km <sup>2</sup>
Area Characterized for Fish Bay	0.3 km <sup>2</sup>	2.5 km <sup>2</sup>
Area Characterized for Coral Bay	3.0 km <sup>2</sup>	32.7 km <sup>2</sup>
Total Area Characterized	6.5 km <sup>2</sup>	56.7 km <sup>2</sup>



**Figure 3.2.** These maps depict the aerial photos (left) and LiDAR bathymetry (middle) and LiDAR reflectivity (right) used to delineate and characterize the benthic habitats inside Fish Bay, Coral Bay and the STEER.

the seafloor. These reflectivity measurements were used to create continuous images describing the seafloor's physical structure and biological cover (Figure 3.2). Bathymetry and reflectivity are both valuable tools for natural resource managers and researchers because they provide baseline information describing the location and extent of seafloor habitats.

### 3.2.2. Acquisition and Processing of Remotely Sensed Imagery

#### *LiDAR Imagery*

Fugro LADS acquired LiDAR bathymetry and reflectivity for depths between 0 and 40 meters using a Laser Airborne Depth Sounder Mark II System. This collection took place between 1/29/2011 and 2/28/2011. This system uses a 900 Hertz laser, which is split by an optical coupler into an infrared (1,064 nm) beam and a green (532 nm) beam. The infrared beam measures the datum height at nadir and the green beam oscillates across-track to measure depths and/or elevations. The Fokker F-27 aircraft flew this hydrographic survey at altitudes between 1,200 and 2,200 feet, and at ground speeds between 140 and 210 knots. Environmental factors such

as wind strength and direction, water clarity and depth influenced data acquisition on a daily basis. Depths were referenced to the North American Datum 1983 Universal Transverse Mercator Zone 20 North horizontal coordinate system and to the Mean Lower Low Water vertical tidal coordinate system. CARIS HIPS & SIPS, CARIS Base Editor and proprietary software were used to process and create the bathymetry and reflectivity images. The reflectivity image was corrected for changes in gain, and energy lost at the air/water interface, in the water column, and from optical filtering due to polarization and the receiver field of view (Collins et al. 2007; Sinclair and Ramsay 2011). The bathymetry image was corrected for sensor offsets, latency, roll, pitch, yaw and the influence of tides. This survey met International Hydrographic Organization Order 1 uncertainty standards (IHO, 2008), which is  $\pm 5$  meters plus 5% of depth for horizontal uncertainty and  $\pm$  the square root of  $[0.52 + (0.013 * \text{depth})^2]$  for vertical uncertainty. These equations translate into a maximum of  $\pm 7.0$  m and  $\pm 0.52$  m of horizontal and vertical uncertainty, respectively. We received the final bathymetry and reflectivity images 32-bit GeoTiff files with 3x3 meter spatial resolutions.

### *Aerial Photographs*

The U.S. Army Corps of Engineers collected aerial photographs over St. Thomas and St. John in the U.S. Virgin Islands between January 2012 and March 2012 using a Z/I Imaging DMC-II 230 digital camera. We used two of these aerial photos in Fish Bay, ten in Fish Bay and eleven in the STEER to develop habitat maps where there were gaps in the LiDAR imagery. Each aerial photo had a 0.3x0.3 meter spatial resolution. Four bands (i.e., Red, Green, Blue, and Infrared) were captured at a 12-bit radiometric resolution and converted to 8-bits during post processing. Aerial photos were captured with 30% sidelp between all adjacent flight lines. Each photo was referenced to the North American Datum 1983 State Plane Puerto Rico / US Virgin Islands Zone 5200 coordinate system and corrected for relief displacement using digital elevation models. Photo control points were used to assess the aerial photos' horizontal positional accuracy. The horizontal root mean square error was  $0.6 \text{ m} \pm 0.28 \text{ m}$ . The National Standard for Spatial Data Accuracy Circular Error was 1.03 m. Originally, these aerial photos were collected to provide the U.S. Army Corps of Engineers with current information to support regulatory, land management and acquisition, planning, engineering and habitat restoration projects. We used these aerial photos in this mapping effort because they met our spatial resolution and accuracy requirements.

### **3.2.3. Post Processing Of Remotely Sensed Imagery**

We standardized the geographic extents, coordinate systems, formats and spatial resolutions of the aerial photos and LiDAR images before using them for benthic habitat mapping. These images were standardized to reduce the likelihood of introducing positional errors in the habitat maps. To make the images consistent, we:

1. Clipped the images to the project area's boundaries using the "Extract by Mask" tool in ArcGIS;
2. Reprojected the images into the North American Datum 1983 Universal Transverse Mercator Zone 20 North coordinate system using the "Reproject" tool in ArcGIS;
3. Resampled the LiDAR bathymetry and reflectivity images from 3x3 to 0.3x0.3 meters using the "Resample" function in ArcGIS; and
4. Saved all the images in a GeoTiff (.tif) format.

### *Applying Radiometric Corrections to Aerial Photos*

Light attenuates (i.e., is absorbed and scattered) as it passes through the atmosphere and the water column. Attenuation rates are influenced by several environmental conditions (e.g., aerosols in the atmosphere or turbidity in the water column), which change over space and through time. These changing conditions cause a benthic habitat in one location and/or at one depth to look different than the same habitat at a different location and/or depth (e.g., algae at 5 m will look different than algae at 20 m in aerial photographs). Such variability makes it harder for an algorithm or visual interpreter to discriminate among different habitat types, and hinders the consistent and accurate characterization of aerial photos (Mumby et al. 1998). To reduce this potential source of error, we corrected the aerial photos for changing water column conditions (Figure 3.3) using the Lyzenga method (Lyzenga, 1978, Mumby and Edwards, 2000). We did not atmospherically correct them because they were acquired at low altitudes, which minimized the variability of the atmospheric conditions. The Lyzenga method calculates a correction coefficient by measuring the ratio of attenuation between pairs of spectral bands. To estimate this ratio for each aerial photo, we:

1. Used expert knowledge to locate uncolonized sand habitats at a range of depths (i.e., from 0.5 to 21 meters)
2. Placed points (n=100 in Fish Bay, n=127 in Coral Bay and n=106 in the STEER) in these locations, where there was little/no sun glint
3. Extracted the red, green and blue band digital numbers at each of these points
4. Converted these red, green and blue digital numbers to their natural log
5. Derived the correction coefficients using Lyzenga's equations for the red and green bands in relation to the blue band, and the blue band in relation to the green band.
6. Applied these correction coefficients to each aerial photo using ArcGIS's raster calculator (Equation 1):

Depth Invariant Red Band = [natural log red band] - (attenuation coefficient \* [natural log blue band])

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

Depth Invariant Blue Band = [natural log blue band] - (attenuation coefficient \* [natural log green band])

After these steps, we color-balanced and mosaicked the normalized (i.e., water-column corrected) aerial photos using ENVI software, and used this final mosaic to characterize the benthic habitats in areas that did not have LiDAR imagery.

#### *Creating Derivative Surfaces from Bathymetry*

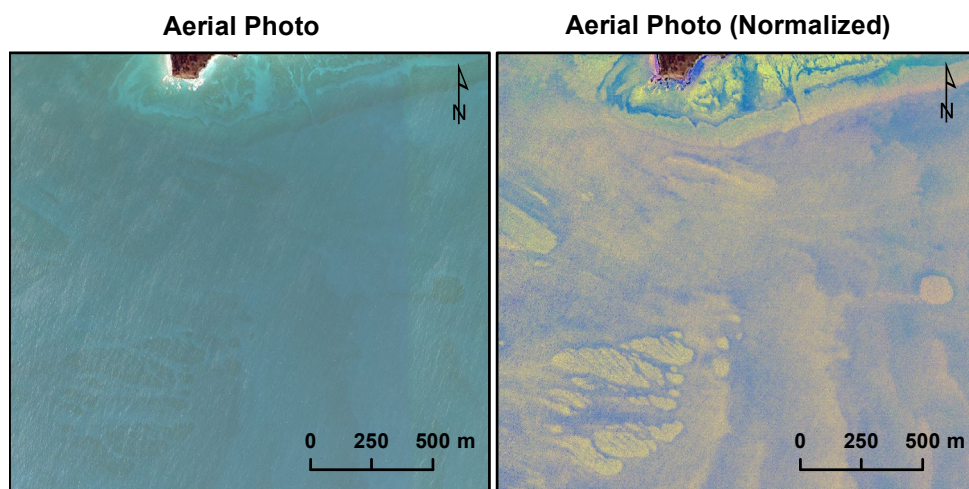
We derived eight topographic surfaces from the LiDAR bathymetry. We used this topographic information to describe and characterize the geomorphological structure of the seafloor. These topographic surfaces specifically included: (1) mean depth, (2) standard deviation of depth, (3) curvature, (4) plan curvature, (5) profile curvature, (6) rugosity, (7) slope, and

(8) slope of slope. They are described in more detail in Table 3.2. Each topographic surface was calculated using a square 3 x 3 cell neighborhood, where the central pixel in the neighborhood was assigned the calculated value. We stacked these eight surfaces, and exported them to create one image with several different bands (i.e., each band representing a specific metric). This image was transformed into its first three principal components using the "Principal Components Analysis" (PCA) (Mather 2004; Lillesand and Kiefer, 2000) function in ENVI 5.0. This transformation removed information that was highly correlated (and thus, redundant) across the different bands. The resulting three-band PCA image contained information that uniquely described the complexity and structure of the seafloor. Finally, we converted the three-band PCA image from 16-bit, floating point values and to 8-bit, integer values, so that they could be imported into ENVI 5.0 for further analysis.

### 3.3 HABITAT FEATURE DELINEATION AND CLASSIFICATION

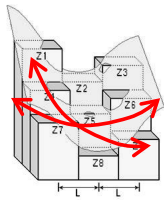
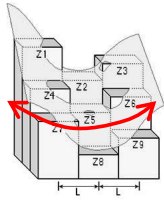
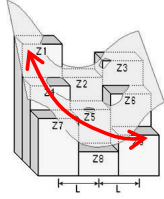
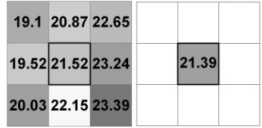
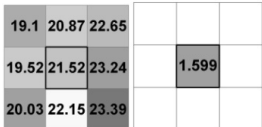
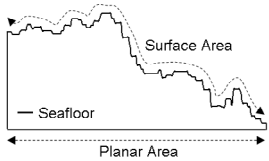
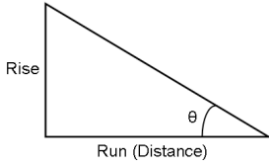
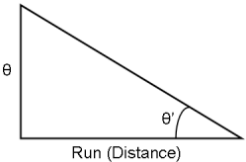
Historically, NOAA's Biogeography Branch has developed shallow-water coral reef habitat maps by manually delineating and interpreting habitats visible in remotely sensed imagery (Kendall et al., 2001; Battista et al., 2007; Zitello et al., 2009). This approach produced habitat maps with consistently high thematic resolutions (i.e.,  $\geq 32$  classes) and high overall accuracies ( $>80\%$ ) (Kendall et al., 2001; Battista et al., 2007; Zitello et al., 2009). Although this approach consistently generated high quality maps, it has a few disadvantages, which make it difficult to compare different maps over time. These disadvantages include being:

- Time intensive (because the maps are produced manually)
- Subjective (because the quality of the maps depends on the experience and expertise of the analyst)
- Limited to coarser spatial scales and resolutions (because the finer the spatial resolution and scale of delineation, the more time required to make the map)



**Figure 3.3.** The aerial photos were corrected for changing water column conditions before being used to characterize benthic habitats in Fish Bay, Coral Bay and the STEER. As an example, the map (left) shows an aerial photo before being water column corrected south of the STEER. The map (right) shows this same aerial photo after being normalized for changing water column conditions (most notably depth).

**Table 3.2.** Descriptions of the topographic surfaces used to characterize the seafloor in and around Fish Bay, Coral Bay and the STEER. The GIS tools used to derive these metrics from the LiDAR bathymetry surface are also included in the table below.

DATASET	UNIT	DESCRIPTION	TOOL
Curvature 	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
Plan Curvature 	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
Profile Curvature 	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
Depth (Mean) 	Meters	Average water depth (3 x 3 cell neighborhood)	Focal statistic function in ArcGIS Spatial Analyst
Depth (Standard Deviation) 	Meters	Dispersion of water depth values about the mean (3 x 3 cell neighborhood)	Focal statistic function in ArcGIS Spatial Analyst
Surface Rugosity 	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)
Slope 	Degrees	Maximum rate of change in slope between cell and 8 neighbors (3 x 3 cell neighborhood)	ArcGIS Spatial Analyst's slope function
Slope of the Slope 	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

The Biogeography Branch has sought to address these issues in more recent maps (Costa et al. 2009, 2012) by semi-automating the process of delineating and attributing habitat features using object- and pixel-based classification techniques. Here, we used this new approach (with some modifications) to develop habitat maps from the LiDAR bathymetry and reflectivity images in Fish Bay, Coral Bay and the STEER (Figure 3.4). We manually evaluated and edited the semi-automated habitat maps to ensure they met the same thematic accuracy standards (>80%) as previous habitat maps made manually.

### 3.3.1. Habitat Delineation

In areas without LiDAR, we manually delineated habitat boundaries (at a scale of 1:1,000) that were visible in the normalized aerial photos and whose area was  $\geq 100$  m<sup>2</sup>. In areas with LiDAR, we identified and extracted habitat features on the sea-floor using the ENVI Feature Extraction (Fx) toolbox. This module uses edge detection algorithms to detect and delineate objects in a single image or in a suite of spatially coincident images (Figure 3.5). ENVI defines an object as a region of interest with unique spatial, spectral (brightness and color), and/or textural characteristics that make it visually distinct from its surroundings (ITT Excelis, 2008a). There are three steps involved in extracting discrete objects from an image (or images). Specifically, these steps include:

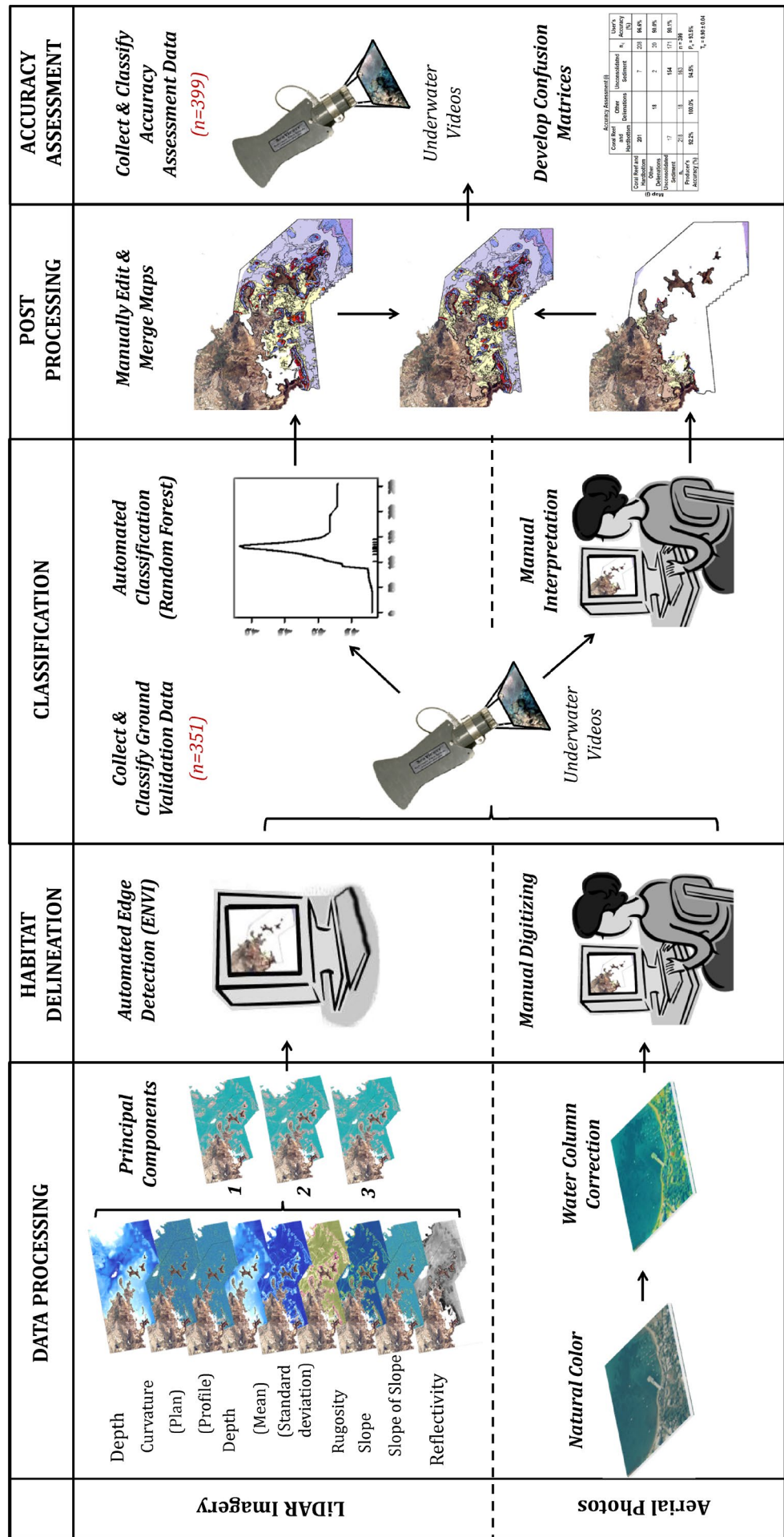
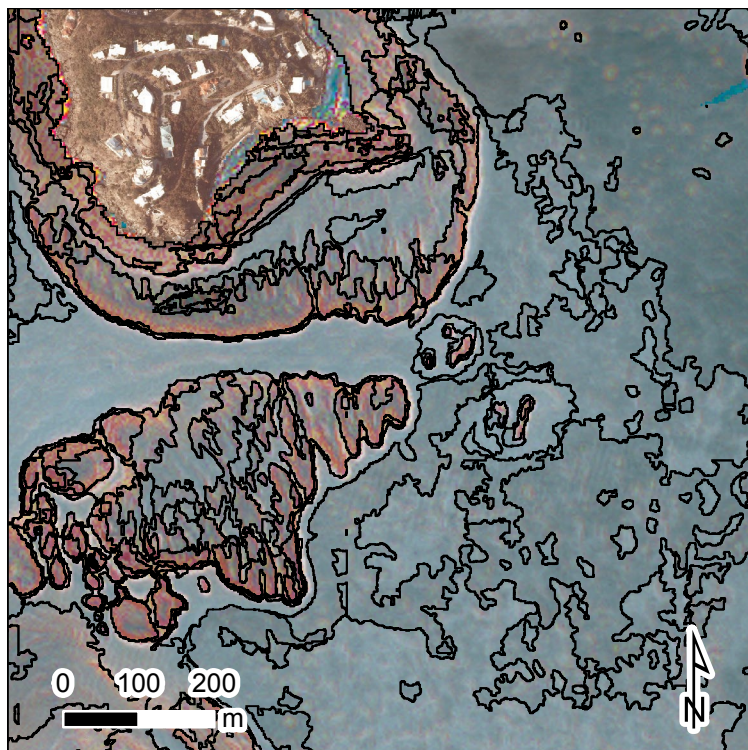


Figure 3.4. Diagram illustrates the steps taken to create habitat maps for Fish Bay, Coral Bay and the STEER.



1. segmenting the image(s)
2. merging smaller segments into larger objects
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. 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) causes a lower 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 Excelis, 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) causes segments with faded edges to be merged, while choosing a lower merge level (<25) preserves more of these features with faded edges (ITT Excelis, 2008b; Robinson et al, 2002). In step 3, ENVI 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 attributes,” and are described in more detail in Table 3.3 and Table 3.4. The user may then export all of the objects and their associated spatial, textual, HSI, ratio and spectral attributes as a single ESRI shapefile.



**Figure 3.5.** This image depicts a subset of habitat objects that were identified, delineated, and attributed by ENVI Fx.

Using this workflow, we identified and delineated discrete habitat features in the LiDAR PCA and reflectivity imagery. The input parameters for FX were the same for the three areas, and were determined heuristically:

- Input Raster: LiDAR PCA
- Ancillary Data: LiDAR reflectivity
- Segment Algorithm: Edge
- Segment Value: 0.00
- Merge Algorithm: Full Lambda Schedule
- Merge Value: 90.00
- Texture Kernel Size: 3

We exported the final habitat features from ENVI Fx as three separate ESRI shapefiles. Each shapefile’s attribute table contained 46 Fx attributes describing each segment in the shapefile. We ran ArcGIS’s “Repair Geometry” tool on each shapefile to remove any topological errors, and converted them to rasters representing each of the 46 spatial, textual, HSI, ratio and spectral metrics using ArcGIS’s “Polygon to Raster” tool. These 46 Fx attribute rasters were then stacked by project area using ArcGIS’s “Composite Bands” and used to develop habitat maps for Fish Bay, Coral Bay and the STEER.

### 3.3.2. Ground Validation

Ground validation (GV) is the process of collecting underwater photos and/or videos at discrete locations. GV data are needed to create high-quality benthic habitat maps because they help the analyst visually link (or the algorithm mathematically correlate) habitats on the ground with features visible in the source imagery. Often, the more GV data that is collected, the easier it is to consistently and accurately classify habitats. Typically, the analyst chooses GV sites using a draft map, developed by digitizing or segmenting habitat features visible in the source imagery (Zitello et al. 2009, Whitall et al. 2011). In this study, we developed the draft maps by manually

**Table 3.3.** 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 $1 / 2(\sqrt{\pi})$ .	$= \text{Sqrt}(4 * \text{AREA} / \pi) / \text{outer contour length}$
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.	$= \text{length of convex hull} / \text{LENGTH}$
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.	$= \text{AREA} / \text{area of convex hull}$
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 = $4/\pi$ .	$= 4 * (\text{AREA}) / (\pi * \text{MAX-AXISLEN}^2)$
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 $\pi / 4$ .	$= 4 * \pi * (\text{AREA}) / (\text{total perimeter})^2$
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.	$= \text{MAXAXISLEN} / \text{MINAXISLEN}$
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.	$= \text{AREA} / (\text{MAXAXISLEN} * \text{MINAXISLEN})$
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.	$= \text{AREA} / \text{outer contour area}$

digitizing habitats visible in the aerial photos and by segmenting the LiDAR data using ENVI Fx. The purposes of these GV sites are to explore habitats which were unknown, and to verify that habitat types look the same (in the source imagery) across the entire mapped area.

#### *GV Sites – Collection and Processing*

We collected underwater video and photos at 351 sites across Fish Bay, Coral Bay and the STEER between 10/23/2013 and 10/31/2013 (Figure 3.6). We navigated to these sites via boat, kayak or by swimming (depending on the depth and accessibility of the site) using a hand-held Garmin 76 Wide Area Augmentation System-enabled global positioning system (GPS) unit. At the deeper sites, we deployed a SeaViewer Sea-Drop 950 camera

(attached to a down weight and 200 feet of line), and started recording our location using a Trimble GeoXT GPS receiver (Figure 3.7). The Trimble receiver captured the vessel's position every 5 seconds while the underwater camera recorded video of the seafloor. This video was recorded on a top side SeaViewer Sea-DVR and viewed in real-time. We adjusted the camera's orientation to capture a downward view and side view of the seafloor approximately 1 m above the bottom. Standardizing the height above the seafloor let us more accurately characterize amounts of biological cover, and getting a side view of the seafloor gave us a broader scale understanding of the structure at each site. Each site was classified in real time (using the classification scheme described in Chapter 2), and the habitat information was recorded using a pre-loaded data dictionary in the Trimble receiver.

In Mangrove Lagoon (i.e., in the STEER), we collected video at GV sites by kayak because this area is closed to motor boat traffic. We used the same setup described above. The electronics were powered with a 12 volt car battery in the back of the kayak. An additional kayak was towed to carry supplies. We snorkeled GV sites that were too shallow (<5 m) or close to shore to safely access by boat (Figure 3.8). At these sites, we captured video of the seafloor using a hand held Cannon Power-Shot camera. These videos were classified while in the water, and the habitat information was entered into the Trimble once back on the boat. In addition to the SeaViewer and Cannon cameras, we also collected video in the STEER using a GoPro Hero 1 camera to compare its video quality with that of the SeaViewer. The GoPro camera was attached to top of the Sea-Drop camera (Figure 3.9), and set to record either 1080 HD video or photos every 1 second.

Once back in the office, we post processed and differentially corrected the raw GPS data using Trimble Pathfinder Office software and the St. Thomas Continually Operating Reference System station (i.e., station VITH) on St. Thomas, U.S. Virgin Islands. Afterward, we reviewed the GV video again (with their corrected locations overlaid the aerial photos and LiDAR PCA and reflectivity) to create a final set of classified GV points. Ninety-one habitat types (i.e., distinct combinations of geomorphological structure, percent hardbottom, biological cover and live coral cover) were identified and classified in total. These classified points were used to manually develop habitat maps (for areas without LiDAR) from the aerial photos. They were also intersected with the 46 Fx attribute rasters (derived from the LiDAR data), and the raster values at these locations were extracted. The resulting table was imported into R software v2.15.2 to train the classification algorithm and generate habitat maps.

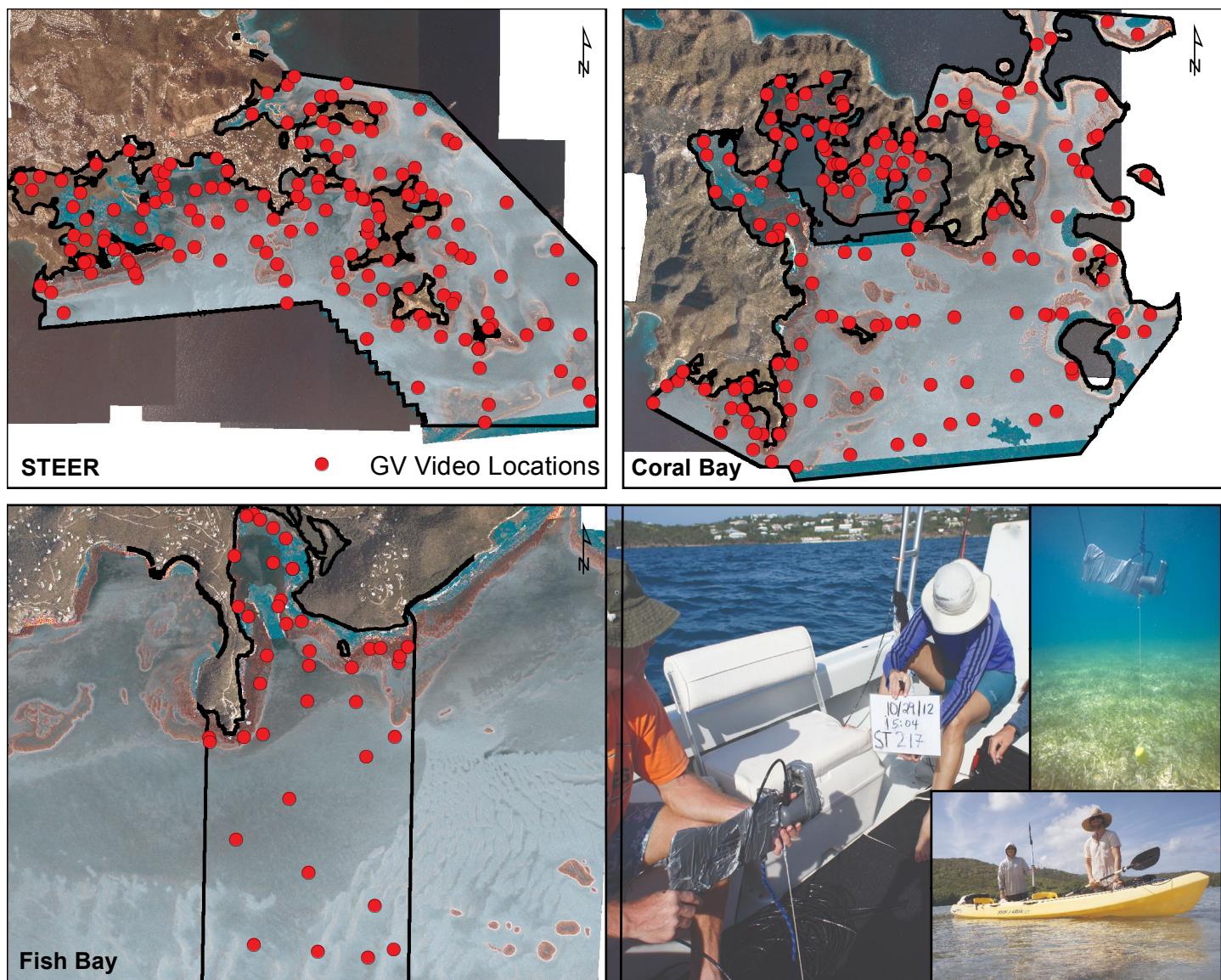
### 3.3.3. Habitat Classification

#### *Developing Random Forest Predictions*

We developed habitat maps (from the Fx attribute rasters) for Fish Bay, Coral Bay and the STEER using Random Forests in R software v2.15. Random Forests (Breiman 2001) is an ensemble modeling technique, which fits Classification and Regression Trees (CARTs) (Breiman et al, 1984) to many, random data subsets (i.e., a pro

**Table 3.4.** 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: $(B2 - B1) / (B2 + B1 + \text{eps})$ , 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 3.6.** A GoPro and SeaViewer Sea-Drop 950 camera (pictured in the lower right) were used to collect underwater video and high resolution photographs of the sea-floor at 355 locations (denoted by the red points) in Fish Bay, Coral Bay and the STEER.

cess called bagging), and selects the most common output from among the multiple trees. Each CART is developed independently, and is not influenced by earlier trees. CARTs are built by dividing objects (i.e., pixels in the Fx attribute rasters) into groups whose values are as homogenous as possible. These divisions are called “nodes” and are optimized in various ways, depending on the algorithm. Random forests adds additional stochasticity to this process by randomly selecting a subset of input variables to develop each node. This splitting process continues until the homogeneity of each group no longer increases. At this point, each fully grown tree generates a classified prediction, and the data randomly excluded from this training process (i.e., out-of-bag data) is used to calculate error rates for (i.e., cross validate) these predictions. Random forests then selects the most common prediction among the different CARTs as the final



**Figure 3.7.** Topside field equipment used to collect georeferenced underwater video at GV drop camera sites. While the SeaViewer unit was in the water, we recorded the location of the camera using a Trimble GeoXH GPS receiver (right) while viewing and classifying real-time video footage on a Sea-DVR (left).

classified output (Breiman 2001; Cutler et al. 2007; Liaw and Wiener 2002).

Separate random forest models were developed for Fish Bay, Coral Bay and the STEER using the 'randomForest' command in the random forest package v4.6 (Liaw and Wiener, 2013). This package implements Breiman's random forest algorithm (based on Breiman and Cutler's original Fortran code). For each of the three areas, we developed 10 random forest model replicates ( $n=30$  total), where the habitat class type was the response variable, and the predictor variables were the 46 Fx attribute raster values. We aggregated each group of 10 model replicates into one ensemble model (for each area) using the 'combine' command in the random forest package. We optimized the number of randomly selected predictor variables (i.e., the 'mtry' parameter) using the 'tuneRF' command in the random forest package. This function finds the mtry value with the lowest out-of-bag error estimate. The other input parameters for each of these models are listed in Table 3.5. We explored the relative importance of each Fx attribute raster (to each aggregate model) using the 'varImpPlot' command in the random forest package. Three, separate spatial habitat predictions were developed from these three aggregated models using the 'predict' command in the raster package version 2.0 (Hijmans and van Etten 2013).

We converted the three habitat predictions to shapefiles using ArcGIS's "Raster to Polygon" tool and removed topological errors using the "Repair Geometry" tool. Polygons smaller than the 100 m<sup>2</sup> minimum mapping unit were removed using ArcGIS's "Eliminate" function. This function merged polygons < 100 m<sup>2</sup> with the neighboring polygon with which they shared their longest border. This step removed 70%, 48% and 44% of the polygons in the Fish Bay, Coral Bay and the STEER habitat maps, respectively. We smoothed the pixelated appearance of the remaining polygons using ArcGIS's "Smooth Polygon" tool (using the PAEK algorithm with a tolerance = 10) so that it would match the appearance of the manually delineated polygons.

#### *Manual Classification and Edge-Matching*

We manually developed habitat maps from the aerial photos for areas in Fish Bay, Coral Bay and the STEER that did not have LiDAR imagery. The process used to develop these maps was the same as those used by the NOAA Biogeography Branch in other mapping efforts (Bauer et al. 2010, Zitello et al. 2009, Battista et al. 2007, Kendall et al. 2001). We manually classified each habitat polygon (which were digitized earlier) by visually interpreting the normalized aerial photos. Geomorphological structure, percent hardbottom, biological cover, live coral cover and dominant coral type attributes were added to each



**Figure 3.8.** We snorkeled sites that were too shallow (<5 m) or close to shore to safely access by boat. These videos were classified while in the water, and the habitat information was entered into the Trimble once back on the boat.



**Figure 3.9.** We also collected underwater video at several sites using a GoPro camera to compare its video quality with that of the SeaViewer camera. We also used the GoPro video to classify sites that had poor quality SeaViewer video.

shapefile polygon during an editing session in ArcGIS. The final habitat shapefiles were checked for gaps or overlapping polygons before being edge matched with the habitat maps generated by random forests.

To merge the habitat maps generated manually and by random forests, we overlaid them on the aerial and LiDAR imagery in ArcGIS and then edited polygon boundaries and attributes by hand to produce seamless maps between the two imagery types. These manual edits included merging, deleting, re-delineating (at a scale of 1:1,000) and reattributing polygons. Also during this process, we added a geographic zone to each polygon, and visually evaluated the habitat maps produced by random forests to ensure the algorithm's classifications matched our interpretations of the LiDAR imagery. Where they differed, we corrected these areas by manually merging, deleting, re-delineating (at a scale of 1:1,000) and reattributing polygons. Approximately 85.9%  $\pm$ 2.6% of the polygons classified by random forests were merged, deleted, redelineated or reattributed in Fish Bay; 72.8%  $\pm$ 3.5% in Coral Bay and 70.2%  $\pm$ 1.3 in the STEER (Table 3.6). The three final habitat maps were checked again for topological correctness before we assessed their thematic accuracy.

**Table 3.5.** The model parameters used to develop random forest habitat predictions for Fish Bay, Coral Bay and the STEER.

random forest Parameter	Coral Bay	Fish Bay	STEER
Type of random forest used	Classification	Classification	Classification
# Observations	378	62	195
# Habitat Classes	62	20	55
# random forest Models	10	10	10
# Trees (ntree)	10x1,000 =10,000	10x1,000 =10,000	10x1,000 =10,000
# Variables Randomly Chosen at Each Split (mtry)	4	2	4
Should importance of predictors be assessed?	Yes	Yes	Yes

**Table 3.6.** Estimated number of polygons that were manually reattributed because they were deleted, added and/or reclassified. These numbers are based on three iterations of randomly distributed points (n=3,639) stratified by detailed structure type. Habitat classifications contained in the original map (i.e., the unedited map produced by Random Forest) and the final map (i.e., the map that was manually edited) were extracted at each of these points, and compared to determine whether they had been changed.

	CLASS	EST. % EDITED POLYGONS	CONFIDENCE INTERVAL ( $\pm$ 95%)
FISH BAY	Major Structure	58.8%	1.3%
	Detailed Structure	67.8%	0.5%
	% Hardbottom	33.3%	5.1%
	Major Cover	29.1%	1.1%
	Major + % Cover	45.1%	2.3%
	% Live Coral Cover	9.3%	0.6%
	Distinct Habitat Class	85.9%	2.6%
CORAL BAY	Major Structure	19.1%	2.5%
	Detailed Structure	61.6%	3.8%
	% Hardbottom	38.8%	3.4%
	Major Cover	27.5%	2.0%
	Major + % Cover	54.1%	3.9%
	% Live Coral Cover	15.0%	1.3%
	Distinct Habitat Class	72.8%	3.5%
STEER	Major Structure	15.0%	0.3%
	Detailed Structure	57.9%	2.1%
	% Hardbottom	38.7%	1.9%
	Major Cover	18.4%	3.9%
	Major + % Cover	47.0%	2.8%
	% Live Coral Cover	10.9%	1.9%
	Distinct Habitat Class	70.2%	1.3%
TOTAL	Major Structure	24.0%	1.9%
	Detailed Structure	61.2%	1.9%
	% Hardbottom	37.8%	2.1%
	Major Cover	24.0%	2.5%
	Major + % Cover	49.6%	2.6%
	% Live Coral Cover	12.3%	1.2%
	Distinct Habitat Class	74.0%	1.8%

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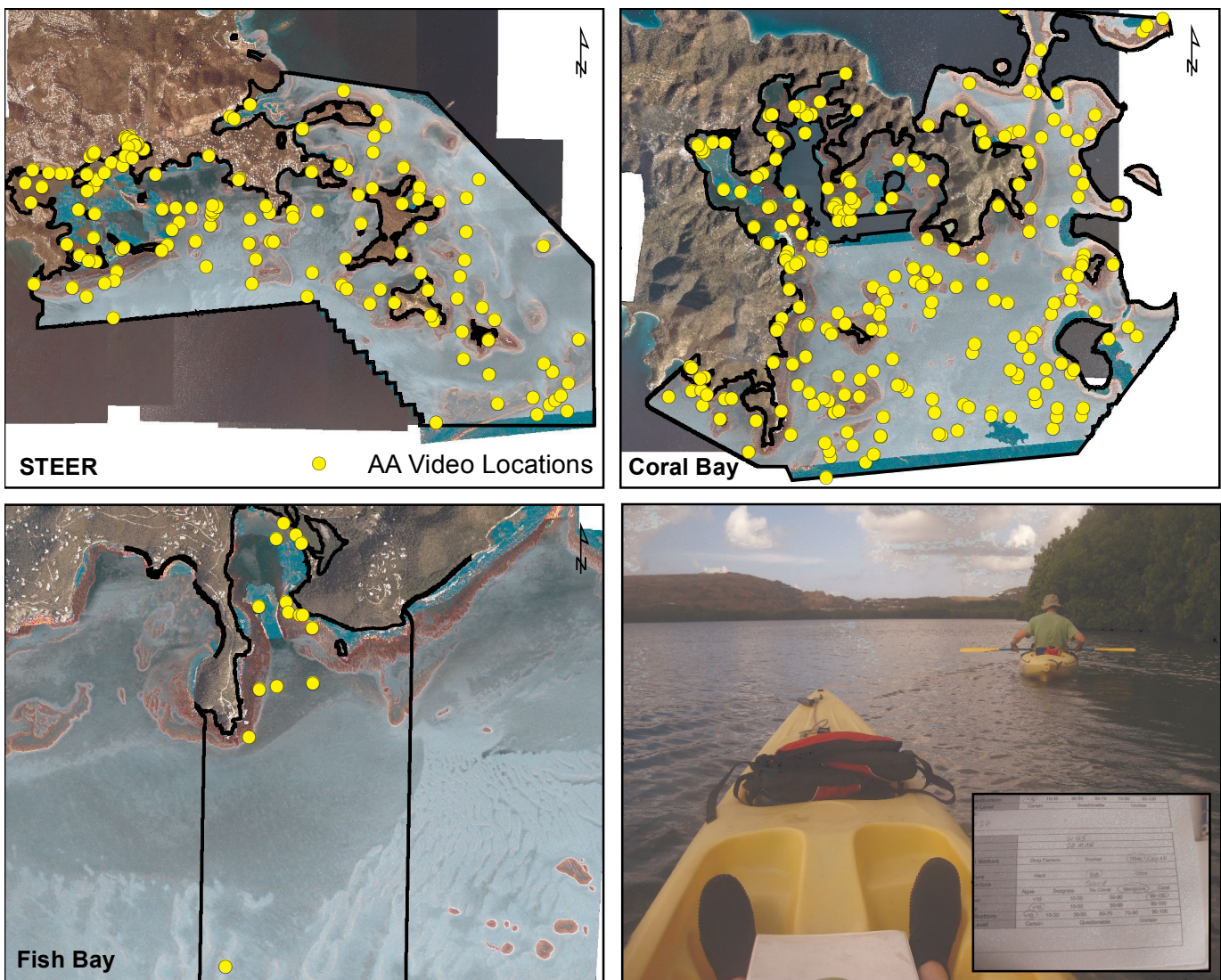


## CHAPTER 4: ASSESSMENT OF CLASSIFICATION ACCURACY

An independent assessment was conducted to evaluate the thematic accuracy of a benthic habitat map for Fish Bay, Coral Bay and the STEER. Thematic accuracy was characterized for major and detailed geomorphological structure, major and detailed biological cover, percent hard bottom, percent coral cover and dominant coral type classifications.

### 4.1 FIELD DATA COLLECTION

Locations for the accuracy assessment (AA) were determined using an iterative, GIS-based, stratified random sampling technique to ensure that all bottom classifications were evaluated. Twenty-five points were randomly placed within each of the draft map's 14 detailed geomorphological structure class using XTools Pro v 9.0. No buffer from polygon edges was used. Classes occupying larger areas were allocated more than 25 points. A total of 400 sites were selected and 399 sites were sufficiently surveyed to be included in the accuracy assessment (Figure 4.1). AA data were collected during a field mission from March 18 to March 28, 2013. The same protocol using a Seaviewer Drop Camera for collecting GV data (described under the GV Sites - Collection and Processing heading in Section 3.3.2) was also used to collect the AA data. GPS data were logged continuously during video acquisition aboard the survey boat using a Trimble Geo XH. High definition video was also recorded at many sites using a GoPro Hero 1 camera mounted on the drop camera housing. Sites that could not be navigated to by boat were accessed by kayak, snorkeling or by foot. Videos at these locations were captured using the GoPro Hero 1 camera and a Canon Power Shot SD1100 enclosed in a waterproof housing.



**Figure 4.1.** In March 2013, underwater video was collected at 399 sites within Fish Bay, Coral Bay and the STEER. These data were used to assess the thematic accuracy of the benthic habitat maps in these three locations.

## 4.2 EVALUATION OF ASSESSMENT DATA

All analysis for this assessment was made by a scientist independent of the cartographer who created the map. The GPS data were processed using Trimble Pathfinder software. GPS data logged on the Trimble Geo XH receiver were differentially post-processed to the St. Thomas Continually Operating Reference System station (i.e., station VITH) on St. Thomas, U.S. Virgin Islands. For each survey site, individual epics logged as the boat drifted over a survey site 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 some cases, the average point was a suitable representation of the survey site. However, there were a large number of cases where the AA survey crossed one or more polygon edges. This was due in part to the very high density of lines that resulted from the small MMU and computer based, semi-automated edge detection process used to create these maps. In these cases, the average GPS point often did not fall into the polygon that encompassed the randomly selected AA site. In these cases, the average point was manually shifted in ArcGIS to the portion of the transect and polygon that was intended to be sampled during the random site placement stage. Prior to analysis, each video clip was reviewed in concert with the benthic habitat map overlaid on the aerial photos and LiDAR imagery. Imagery and map overlays were viewed at the scale of feature delineation (1:1,000). GPS error, layback from camera cables on a drifting boat, and position of boundary delineations by the mapper were all considered in the context of the MMU (100 m<sup>2</sup>).

Biological cover type was identified using the underwater videos, and the patchiness of this biological cover was estimated at the polygon level. It was often necessary to adjust the classifications that were initially recorded in the field to reconcile the differences between the video and polygon 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 if the vessel/video did not drift over a sand channel. 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 at each AA point. Sites that differed between field notes and map classification were evaluated both in ArcGIS 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. Classification errors due to line position (i.e., the misplacement of drawn polygon edge) were not categorized separately from thematic errors (i.e., the correct boundary was drawn but the wrong attributes were assigned). The benthic habitat map was corrected using the information collected during the accuracy assessment.

## 4.3 ANALYSIS OF THEMATIC ACCURACY

The thematic accuracy of the Fish Bay, Coral Bay and STEER benthic habitat maps were summarized using error matrices. These error matrices were computed separately at each thematic level in the classification scheme including major and detailed geomorphological structure, major and detailed biological cover, percent coral cover and dominant coral type. Overall accuracy, producer’s accuracy, and user’s accuracy were computed directly from these 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 ground-truthed 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 ( $n_j$ ) to yield a producer’s accuracy and by the row total ( $n_i$ ) to yield a user’s accuracy.

In addition, the Tau coefficient ( $T_e$ ) was calculated, which is a measure of the improvement of classification accuracy over a random assignment of map units to map categories (Ma and Redmond, 1995). As the number of

categories increases, the probability of random agreement ( $P_r$ ) diminishes, and  $T_e$  approaches  $P_o$ . Values of  $T_e$  were calculated as follows:

$$\text{Tau coefficient} = T_e = (P_o - P_r) / (1 - P_r),$$

where  $P_r = 1/\text{number of habitat classes}$

The variance of Tau (Ma and Redmond 1995) was calculated as:

$$\text{Variance of } T_e = \sigma_r^2 = P_o(1 - P_o) / n(1 - P_r)^2$$

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

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

While stratification ensures adequate evaluation of all map categories, it has the undesired effect of introducing bias into the error matrix based on the different sizes of the areas mapped in each classification (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 density than common map categories. For example, although *Individual Patch Reefs* comprised only 1.3% of the map area, 6% of the target points were allocated for this habitat. The bias introduced by differential sampling density was removed using the method of Card (1982), which utilizes the map marginal proportions. The map marginal proportions were calculated as the area of each map category divided by the total mapped area. 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 NOAA's shallow water St. John habitat map (Zitello et al., 2009), Palmyra Atoll habitat map (Battista and Anderson, 2011), and Buck Island Reef National Monument (Costa et al., 2012).

The map marginal proportions ( $\pi_j$ ) were computed from the GIS layer of the draft benthic habitat map for each of the seven error matrices (major and detailed geomorphological structure, major and detailed biological cover and percent hard bottom) by dividing the area of each category by the total map area. Marginal proportions were not computed for the percent coral cover or coral type matrices. The map areas were exclusive to categories present in the error matrix. Proportional areas were based on the draft assessment and area values may differ slightly in the final map after errors are corrected. The individual cell probabilities (i.e. the product of the original error matrix cell values and  $\pi_j$ , divided by the row marginal or total map classifications per category), were computed for the off-diagonal elements using the following equation:

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

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

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  $\pi_i$ -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  $\pi_i$ -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 93.5%. The Tau coefficient for equal probability of group membership is  $0.90 \pm 0.04$  ( $\alpha=0.05$ ). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, was 93.0% ( $\pm 2.7%$ ) ( $\alpha=0.05$ ). The user's and producer's accuracies were similarly high for all categories.

**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 (j)	Coral Reef and Hardbottom	201		7	208	96.6%
	Other Delineations		18	2	20	90.0%
	Unconsolidated Sediment	17		154	171	90.1%
$n_i$		218	18	163	$n = 399$	
Producer's Accuracy (%)		92.2%	100.0%	94.5%	$P_o = 93.5\%$	
$T_e = 0.90 \pm 0.04$						

**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 category's proportions.

		Accuracy Assessment (i)					
		Coral Reef and Hardbottom	Other Delineations	Unconsolidated Sediment	$\pi_i$	User's Accuracy (%)	User's CI ( $\pm\%$ )
Map (j)	Coral Reef and Hardbottom	0.495		0.017	0.448	96.6%	1.5%
	Other Delineations		0.025	0.003	0.081	90.0%	0.9%
	Unconsolidated Sediment	0.003		0.023	0.470	90.1%	0.3%
$p_i$		0.498	0.025	0.043	$\pi = 1$		
Producer's Accuracy (%)		99.5%	100.0%	53.5%	$P_o = 93.0\%$		
Producer's CI ( $\pm\%$ )		2.6%	14.9%	16.7%	$\text{CI}(\pm) = 2.7\%$		

##### 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 level was 79.1%, with a Tau coefficient ( $T_e$ ) of  $0.77 \pm 0.04$  ( $\alpha=0.05$ ). The adjusted overall accuracy, corrected for bias using the true map marginal proportions, decreased slightly to

75.1 ( $\pm 5.3\%$ ) ( $\alpha=0.05$ ), because those classes with the greatest areal coverage were also the most frequently misinterpreted. Adjusted user's accuracy was  $>61\%$  for all categories, with *Aggregated Patch Reefs*, *Sand with Scattered Coral and Rock*, and *Sand* having the lowest accuracies among the different categories (Table 4.4). Image quality is also a limiting factor at the deeper ranges of these habitats. *Mud* was confused with a few other bottom types, most frequently with *Sand* along mangrove fringes.

**Table 4.3.** Error matrix for detailed geomorphological structure.

	Accuracy Assessment (i)													User's Accuracy (%)		
	Aggregate Reef	Aggregated Patch Reefs	Artificial	Individual Patch Reef	Mud	Pavement	Pavement with Sand Channels	Reef Rubble	Rhodoliths	Rhodoliths with Scattered Coral and Rock	Rock/Boulder	Sand	Sand with Scattered Coral and Rock		Spur and Groove	$n_j$
Aggregate Reef	21	1				2	1				2			1	28	75%
Aggregated Patch Reefs	2	13		1			1			1		3			21	62%
Artificial			18												18	100%
Individual Patch Reef				21										1	22	95%
Mud					42							8			50	84%
Pavement	1	1		2		27	1						1	33	82%	
Pavement with Sand Channels	1					2	19							1	23	83%
Reef Rubble									20		1	3			24	83%
Rhodoliths						5				25		1	1		34	74%
Rhodoliths with Scattered Coral and Rock						4				2		2			25	68%
Rock/Boulder	1	1									27				29	93%
Sand						3				4		27	1	41	66%	
Sand with Scattered Coral and Rock		1				3					1	3	13	21	62%	
Spur and Groove	1					1	2							24	86%	
$n_i$	27	17	18	24	42	47	24	20	31	25	32	47	16	27	$n = 397$	
Producer's Accuracy (%)	78%	76%	100%	88%	100%	57%	79%	100%	81%	68%	84%	57%	81%	89%	$P_o = 79.1\%$	$T_o = 0.77 \pm 0.04$

**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 category's proportions.

		Accuracy Assessment (i)																
		Aggregate Reef	Aggregated Patch Reefs	Artificial Reef	Individual Patch Reef	Mud	Pavement	Pavement with Sand Channels	Reef Rubble	Rhodoliths	Rhodoliths with Scattered Coral and Rock	Rock/Boulder	Sand	Sand with Scattered Coral and Rock	Spur and Groove	$\pi_j$	User's Accuracy (%)	User's CI ( $\pm\%$ )
Aggregate Reef	0.0935	0.0045					0.0089	0.0045				0.0089			0.0045	0.1247	75.0%	3.43%
Aggregated Patch Reefs	0.0045	0.0293		0.0023			0.0023					0.0023	0.0068			0.0473	61.9%	2.15%
Artificial			0.0017													0.0017	100.0%	0.00%
Individual Patch Reef				0.0122											0.0006	0.0128	95.5%	1.58%
Mud					0.0333								0.0064			0.0397	84.0%	0.92%
Pavement	0.0050	0.0050		0.0100		0.1348	0.0050							0.0050		0.1647	81.8%	3.47%
Pavement with Sand Channels	0.0012					0.0024	0.0225								0.0012	0.0273	82.6%	1.06%
Reef Rubble									0.0047			0.0002	0.0007			0.0056	83.3%	0.31%
Rhodoliths							0.0254			0.1270	0.0102		0.0051	0.0051		0.1727	73.5%	4.05%
Rhodoliths with Scattered Coral and Rock						0.0096				0.0048	0.0409		0.0048			0.0602	68.0%	2.27%
Rock/Boulder	0.0029	0.0029										0.0771				0.0828	93.1%	1.45%
Sand						0.0137				0.0182	0.0273		0.1231	0.0046		0.1869	65.9%	4.21%
Sand with Scattered Coral and Rock		0.0025				0.0074						0.0025	0.0074	0.0320		0.0518	61.9%	2.30%
Spur and Groove	0.0008					0.0008	0.0016								0.0189	0.0220	85.7%	0.76%
Pi.	0.108	0.044	0.002	0.024	0.033	0.203	0.036	0.005	0.150	0.078	0.078	0.091	0.154	0.047	0.025	$\pi_i=1$		
Producer's Accuracy (%)	86.7%	66.5%	100.0%	49.9%	100.0%	66.4%	62.9%	100.0%	84.6%	52.2%	84.8%	79.8%	68.7%	66.7%	0.0%	$P_o = 75.1\%$		
Producer's CI ( $\pm\%$ )	19.7%	28.4%	0.0%	29.6%	12.3%	13.0%	26.2%	18.3%	18.3%	19.4%	14.8%	17.1%	30.3%	28.8%	28.8%	CI( $\pm$ ) 5.3%		

Map data (j)

### 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 88.4%, with a Tau coefficient ( $T_e$ ) of  $0.86 \pm 0.04$  ( $\alpha=0.05$ ). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, was slightly lower at 86.5% ( $\pm 3.2\%$ ) ( $\alpha=0.05$ ). Adjusted producer's accuracy was  $>90\%$  for *Algae and Mangroves*, but only 74% and 69% for *No Cover* and *Seagrass*, respectively. *Seagrass* and algae beds were commonly confused because these categories are commonly intermixed and display similar spectral signatures. Accuracy of mapped live coral cover class will be discussed in the section Percent Hardbottom and Live Coral Cover.

### 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 77.8%, with a Tau coefficient ( $T_e$ ) of  $0.75 \pm 0.04$  ( $\alpha=0.05$ ). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, decreased slightly to 74.5% ( $\pm 4.4\%$ ) ( $\alpha=0.05$ ) because those classes with the greatest areal coverage were also the most frequently misinterpreted. Specifically, *Algae Patchy 50-<90%* was often misclassified as *Algae Patch 10-50%*, *Algae Continuous 90-100%* and *No Cover Continuous 90-100%*.

### Percent Hardbottom and Live Coral Cover

Hardbottom habitat comprises approximately 44.8% of the draft map area (Table 4.2). The overall accuracy ( $P_o$ ) for the percent hardbottom class was 85.7%, with a Tau coefficient ( $T_e$ ) of  $0.83 \pm 0.04$  ( $\alpha=0.05$ ) (Table 4.9). The adjusted overall accuracy, corrected for bias using the final map marginal proportions, increased to 86.2% ( $\pm 3.5\%$ ) ( $\alpha=0.05$ ) (Table 4.10). This increase relative to the raw matrix (Table 4.9) was due to the large proportion (~51%) of map area classified as 0-<10% hard (i.e. soft bottom) and high accuracy of mapping these bottom types (i.e. *Sand, Mud*).

The error matrix for live coral cover is displayed in Table 4.11. The overall accuracy ( $P_o$ ) for this class was 83.3%, with a Tau coefficient ( $T_e$ ) of  $0.75 \pm 0.06$  ( $\alpha=0.05$ ). This seemingly high overall accuracy in classification of live coral cover was driven almost entirely by the high accuracy of mapping areas with low or no coral cover (e.g. *Sand*) rather than in mapping areas with high coral cover. There are a dwindling number of areas with significant coral cover in the U.S. Virgin Islands. Consequently, *Live coral 50 - <90%* occurred very rarely in the map and accuracy assessment data even though this category comprises both hard and soft corals. Locations where live coral is present are very discrete, small in area and not broadly distributed. Caution should be used when considering use of this important but rare map category because of the negligible sample size in both the map and AA data.

**Table 4.5.** Error matrix for major biological cover.

		Accuracy Assessment (i)					$n_j$	User's Accuracy (%)
		Algae	Mangrove	Live Coral	No Cover	Seagrass		
Map (j)	Algae	261		1	5	9	276	94.6%
	Mangrove		28				28	100.0%
	Live Coral						0	-
	No Cover	18			20	4	42	47.6%
	Seagrass	5			1	20	26	76.9%
	$n_i$	284	28	1	26	33	$n = 372$	
Producer's Accuracy (%)	91.9%	100.0%	-	76.9%	60.6%	$P_o = 88.4\%$		
								$T_e = 0.86 \pm 0.04$

**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 category's proportions.

		Accuracy Assessment (i)					$\pi_j$	User's Accuracy (%)	User's CI ( $\pm\%$ )
		Algae	Mangrove	Live Coral	No Cover	Seagrass			
Map (j)	Algae	0.733		0.003	0.014	0.025	0.775	94.6%	2.3%
	Mangrove	0.000	0.001				0.001	100.0%	0.0%
	Live Coral				-	-	0.012	-	-
	No Cover	0.047			0.052	0.010	0.109	47.6%	2.9%
	Seagrass	0.020			0.004	0.079	0.103	76.9%	3.0%
	$p_i$	0.799	0.001	0.003	0.070	0.115	$\pi = 1$		
Producer's Accuracy (%)	91.7%	100.0%		74.3%	69.0%	$P_o = 86.5\%$			
Producer's CI ( $\pm\%$ )	3.6%	0.0%	-	24.5%	16.1%	CI( $\pm$ ) = 3.2%			

**Table 4.7.** Error matrix for detailed biological cover.

		Accuracy Assessment (i)											n <sub>j</sub>	User's Accuracy (%)	
		Algae 10-50%	Algae 50-90%	Algae 90-100%	Mangrove 10-50%	Mangrove 50-90%	Mangrove 90-100%	Live Coral 50-90%	Live Coral 90-100%	No Cover 90-100%	Seagrass 10-50%	Seagrass 50-90%			Seagrass 90-100%
Map (j)	Algae 10-50%	23	11	2							5	1		42	54.8%
	Algae 50-90%	3	100	7						5				115	87.0%
	Algae 90-100%	3	9	101				1				3		117	86.3%
	Mangrove 10-50%													0	-
	Mangrove 50-90%													0	-
	Mangrove 90-100%						28							28	100.0%
	Live Coral 50-90%													0	-
	Live Coral 90-100%													0	-
	No Cover 90-100%	4	12	2						20	4			42	47.6%
	Seagrass 10-50%	2									1			3	33.3%
	Seagrass 50-90%		1							1		6	2	10	60.0%
	Seagrass 90-100%		1	1								2	9	13	69.2%
	n <sub>i</sub>	35	134	113	0	0	28	1	0	26	10	12	11	n = 370	
	Producer's Accuracy (%)	65.7%	74.6%	89.4%	-	-	96.6%	-	-	76.9%	10.0%	50.0%	81.8%	P <sub>o</sub> = 77.8%	
														T <sub>e</sub> = 0.75 ± 0.04	

**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 category's proportions.

		Accuracy Assessment (i)											π <sub>j</sub>	User's Accuracy (%)	User's CI (±%)	
		Algae 10-50%	Algae 50-90%	Algae 90-100%	Mangrove 10-50%	Mangrove 50-90%	Mangrove 90-100%	Live Coral 50-90%	Live Coral 90-100%	No Cover 90-100%	Seagrass 10-50%	Seagrass 50-90%				Seagrass 90-100%
Map (j)	Algae 10-50%	0.069	0.033	0.006						0.000	0.015	0.003		0.127	54.8%	3.3%
	Algae 50-90%	0.007	0.237	0.017						0.012				0.273	87.0%	2.4%
	Algae 90-100%	0.010	0.029	0.323				0.003				0.010		0.374	86.3%	3.0%
	Mangrove 10-50%	-	-	-	-	-	-	-	-	-	-	-	-		-	-
	Mangrove 50-90%	-	-	-	-	-	-	-	-	-	-	-	-	0.001	-	-
	Mangrove 90-100%						0.001							0.001	100.0%	0.0%
	Live Coral 50-90%	-	-	-	-	-	-	-	-	-	-	-	-	0.001	-	-
	Live Coral 90-100%	-	-	-	-	-	-	-	-	-	-	-	-	0.010	-	-
	No Cover 90-100%	0.010	0.031	0.005						0.052	0.010			0.110	47.6%	2.9%
	Seagrass 10-50%	0.009									0.005			0.014	33.3%	2.2%
	Seagrass 50-90%		0.005							0.005		0.028	0.009	0.047	60.0%	3.1%
	Seagrass 90-100%		0.003	0.003								0.007	0.030	0.043	69.2%	2.4%
	n <sub>i</sub>	0.106	0.339	0.354			0.001	0.003		0.069	0.030	0.047	0.039	π = 1		
	Producer's Accuracy (%)	65.6%	70.1%	91.2%	-	-	100.0%	-	-	75.9%	15.4%	59.5%	75.9%	P <sub>o</sub> = 74.5%		
		17.8%	7.6%	7.6%	-	-	0.0%	-	-	24.7%	23.2%	29.1%	32.2%	CI(±) = 4.4%		



### Live Coral Cover Type

This experimental class attempted to distinguish between areas dominated by hard versus soft corals. Hard or soft coral dominance was classified when live coral cover was estimated to be >10%. This class was included in this mapping effort because it was requested by the National Park Service in St. John. The error matrix for this class is displayed in Table 4.12. Its overall accuracy ( $P_o$ ) was 88.2 %, with a Tau coefficient ( $T_e$ ) of  $0.82 \pm 0.05$  ( $\alpha=0.05$ ,  $n=398$ ). It is important to emphasize that this high overall accuracy value was driven mainly by the large number of sites having <10% live coral and thus, lacking either coral type (i.e., 323 out of 398 sites). Additionally, there were many cases where hard/soft dominance should have been assessed but wasn't (i.e. User classified coral >10% while Producer classified as <10% cover), as well as cases where dominance was assessed but should not have been (i.e. Producer classified coral >10% while User classified coral as >10% cover). Of greater importance was the low accuracy for distinguishing between hard and soft coral dominated areas. Producer's accuracy for identifying areas of hard coral dominance (arguably the most important bottom type in reef ecosystems) was only 21% ( $n=12$ ). The user's accuracy for hard corals was 77.8% ( $n=9$ ). Since so few points occurred in this category, these numbers may be biased and an additional assessment should be conducted for this category alone to better understand the utility of this new class.

### Conclusions

The new benthic habitat maps for Fish Bay, Coral Bay and the STEER have accuracy percentages that make them suitable for a wide range of scientific and management applications. These maps are a valuable tool for local managers interested in managing and researching coral reef ecosystems, including hardbottom and mangrove habitats. These two

**Table 4.9.** Error matrix for percent hardbottom.

		Accuracy Assessment (i)						$n_j$	User's Accuracy (%)
		0-10%	10-30%	30-50%	50-70%	70-90%	90-100%		
Map (j)	0-10%	154		4	3	3	7	171	90.1%
	10-30%	3	9	1	2			15	60.0%
	30-50%			4	2			6	66.7%
	50-70%	1	1		10			12	83.3%
	70-90%				1	55	10	66	83.3%
	90-100%	3	1		2	10	92	108	85.2%
	$n_i$	161	11	9	20	68	109	$n = 378$	
Producer's Accuracy (%)	95.7%	81.8%	44.4%	50.0%	80.9%	84.4%	$P_o = 85.7\%$		
$T_e = 0.83 \pm 0.04$									

**Table 4.10.** Error matrix for percent hardbottom, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category's proportions.

		Accuracy Assessment (i)						$\pi_j$	User's Accuracy (%)	User's CI ( $\pm\%$ )
		0-10%	10-30%	30-50%	50-70%	70-90%	90-100%			
Map (j)	0-10%	0.461		0.012	0.009	0.009	0.021	0.512	90.1%	2.8%
	10-30%	0.005	0.016	0.002	0.004			0.027	60.0%	1.7%
	30-50%			0.017	0.009			0.026	66.7%	2.5%
	50-70%	0.003	0.003		0.035			0.042	83.3%	2.0%
	70-90%				0.002	0.103	0.019	0.124	83.3%	1.9%
	90-100%	0.007	0.002		0.005	0.025	0.229	0.269	85.2%	2.6%
	$p_i$	0.478	0.022	0.031	0.063	0.137	0.269	$\pi = 1$		
Producer's Accuracy (%)	96.6%	73.4%	55.2%	55.3%	75.2%	85.2%	$P_o = 86.2\%$			
Producer's CI ( $\pm\%$ )	5.3%	36.3%	31.7%	18.1%	12.0%	8.4%	$CI(\pm) = 3.5\%$			

**Table 4.11.** Error matrix for live coral cover.

		Accuracy Assessment (i)					$n_j$	User's Accuracy (%)
		Coral Reef and Hardbottom 0-10%	Coral Reef and Hardbottom 10-50%	Coral Reef and Hardbottom 50-90%	Coral Reef and Hardbottom 90-100%	Unconsolidated Sediment 0-10%		
Map (j)	Coral Reef and Hardbottom 0-10%	125	11	1		17	154	81.2%
	Coral Reef and Hardbottom 10-50%	25	36				61	59.0%
	Coral Reef and Hardbottom 50-90%	2		-			0	-
	Coral Reef and Hardbottom 90-100%				-		0	-
	Unconsolidated Sediment 0-10%	7				153	160	95.6%
	$n_i$	159	47	1	0	170	$n = 377$	
Producer's Accuracy (%)	78.6%	76.6%	-	-	90.0%	$P_o = 83.3\%$		
$T_e = 0.75 \pm 0.06$								

ecologically important habitats both had >91% producer and user accuracies. *Mangroves* are of particular concern in the USVI because they act as nurseries for important fish species, protect the shoreline from erosion and are under threat by a number of anthropogenic stressors (pers. comm. Anne Marie Hoffmann). Similarly, *Algae* and *No Cover* major cover categories were highly accurate (Tables 4.5 and 4.6). Within the percent hard-bottom categories, the habitat map was highly accurate at the ends of the percent continuum, (i.e. 0-10%, >10-30%, >70-90% and 90-100%). While the overall accuracy of the dominant coral type class was high, the producer's accuracy for hard corals (arguably the most important class for many managers) was low. These results suggest it is likely that current mapping technology, source data, density of ground validation, and simple variability of these elements on the seafloor prevent the accurate mapping of this variable at present. This bottom type will not be included in future map products until its reliability can be better understood.

Only somewhat more useful are the categories used to map live coral cover overall (hard and soft corals combined). The high overall accuracy of this class is driven by two things. First, soft bottom sites comprised nearly half of those in the assessment and of course have virtually no coral. This has the effect of amplifying the overall accuracy in the confusion matrix, but is based on correctly identifying the absence of coral in habitats such as sand and mud. Second, the percent divisions of coral cover (i.e., 0-10%, 10-50%, 50-90%) also give a false confidence in the accuracy of this attribute. The vast majority of reefs in the area have less than 10% coral cover, the lowest category, making this an easy choice when mapping. While this class can still be very useful because it accurately predicts coral absence, extreme caution must be used when applying this variable to quantify coral presence.

The MMU restriction was set to 100 m<sup>2</sup>. The results presented here suggest that such a small value is incompatible with some of the structure categories in the classification scheme. The core of the scheme was originally designed for use with a 4,047 m<sup>2</sup> (1 acre MMU) and several of the categories are best depicted at this larger MMU (1,000 m<sup>2</sup> MMU has also been successfully applied). For example, *Pavement with Sand Channels* and *Spur and Groove* can be separated into their sand and hard bottom components when a 100 m<sup>2</sup> MMU used. It is suggested that the classification scheme be modified to improve compatibility with the finer scale and smaller MMU of similar mapping projects in the future.

Habitats (such as *Pavement* and *Rhodoliths*) that look similar in the source imagery were often confused. These habitats are both low relief, share a similar spectral signature, and are difficult to classify due to depth limitations of the imagery where these habitats commonly co-occur. This was further complicated by the addition of another *Rhodolith* class beyond those typically mapped (*Rhodoliths with Scattered Coral and Rock*). Results here show that the existing approach cannot discriminate well among such bottom types that experience gradual transitions not easily identified in the remote sensing data. Using fewer, more broadly encompassing categories is more effective and accurate than attempting use of many, more narrowly defined ones in these cases. Other common errors included *Mud* and *Sand* which often grade into each other and occur in mixtures, *Seagrass* and *Algae* which often occur in mixed beds; and between adjacent categories of percent hardbottom and coral cover.

Although the MMU was smaller, the level of accuracy for detailed structure was similar to that of other recent NOAA benthic habitat maps in Southwest Puerto Rico (83%, [82% adjusted]; Bauer et al., 2012); Vieques, (78.0% [88.8% adjusted] Bauer and Kendall, 2010), St. John, US Virgin Islands (86%, [89% adjusted]; Zitello et al., 2009), and the Florida Keys (86% [92% adjusted]; Walker and Foster, 2009). For additional details on accuracy assessment methods and computational details see the references in the literature cited section.

**Table 4.12.** Error matrix for coral dominance.

		Accuracy Assessment (i)			n <sub>j</sub>	User's Accuracy (%)
		Hard Coral	Soft Coral	N/A		
Map (j)	Hard Coral	7	2		9	77.8%
	Soft Coral	5	21	12	38	55.3%
	N/A	22	6	323	351	92.0%
	n <sub>i</sub>	34	29	335	n = 398	
	Producer's Accuracy (%)	20.6%	72.4%	96.4%	P <sub>o</sub> = 88.2%	
						Te = 0.82 ± 0.05

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## CHAPTER 5: DISCUSSION

The new benthic map completed by NOAA's NCCOS Biogeography Branch characterized approximately 64.3 km<sup>2</sup> of seafloor in and around Fish Bay, Coral Bay, and the STEER. Twenty seven percent (17.5 km<sup>2</sup>) of this habitat map described the seafloor inside the boundaries of the STEER, the Virgin Islands National Park and the Virgin Islands Coral Reef National Monument. The remaining 73% (46.8 km<sup>2</sup>) of this habitat map describes the seafloor outside of these MPA boundaries. For Fish Bay, these areas included habitats from Dittlif Point east to Cocoloba Cay, and from the inner bay south to the 30 meter depth contour. For Coral Bay, these areas included all the near-shore habitats (i.e., < 40 meters deep) from Cabritte Horn Point east to the exclusive economic zone boundary, and from Gowed Point south to the Flanagan Passage, and for the STEER, these areas include from Long Point east to Pillsbury Sound, and Red Hook Point south to Dog Island.

The overall map accuracies (corrected for proportional bias) for this habitat map was 93.0% for major structure, 75.1% for detailed structure, 86.2% for percent hardbottom, 86.5% for major cover and 74.5% for detailed cover. The live coral and dominant coral type classes had 83.3% and 88.2% accuracies, respectively. These numbers are similar to the other benthic habitat maps created by NCCOS's Biogeography Branch (Battista et al. 2007; Zitello et al. 2009; Bauer et al. 2010; Costa et al. 2012). As a result, these digital map products can be used with high levels of confidence by scientists and resource managers for a multitude of different applications. The final deliverables for this project are available to the public: (1) on the web (<http://coastalscience.noaa.gov/projects/detail?key=33>), (2) through an interactive, web-based map application (<http://maps.coastalscience.noaa.gov/biomapper/biomapper.html?id=STEER>), and (3) by request through the University of the Virgin Islands, Center for Marine and Environmental Studies. Brief descriptions of these deliverables are listed in Table 5.1.

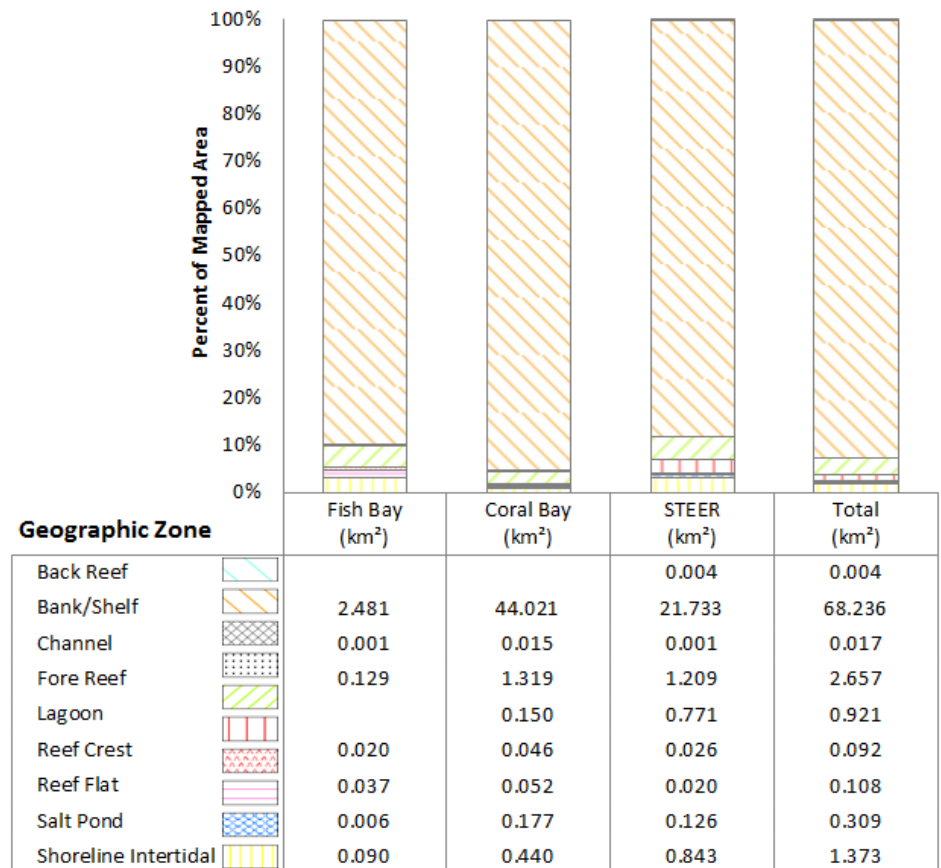
### 5.1 SUMMARY STATISTICS

#### All Areas Combined

The majority (92.6%) of the areas that were mapped in Fish Bay,

**Table 5.1.** Final deliverables for NOAA's habitat map of Fish Bay, Coral Bay and the STEER.

DATA TYPE	ITEM	FORMAT	QTY
Map	Benthic Habitat Map 2013	GIS shapefile	1
	Habitat Symbology Layers	GIS layer files	7
Imagery	Aerial Photographs (Images)	GeoTiffs	3
	LiDAR Data (Images)	GeoTiffs	9
Field Data	GV Dataset (351 sites)	GIS shapefile	1
	GV Photos of Seafloor	jpegs	7,598
	GV Video of Seafloor (SeaViewer), GoPro	.flv & .mov	705
	AA Dataset (399 sites)	GIS shapefile	1
	AA Photos of Seafloor	jpegs	1,157
Online Map	Online Interactive Map Project	Online	1
	Reporting	ISO 19115-2 Metadata for GIS Files	XML files
	Final Report	PDF	1



**Figure 5.1.** Summary statistics describing the total amount of mapped area by geographic zone in Fish Bay, Coral Bay and the STEER.

Coral Bay and the STEER were located on the *Bank/Shelf* (Figure 5.1). *Fore Reef, Shoreline Intertidal* and *Lagoon* were the next most common geographic zones. *Unconsolidated Sediments* (69.6%) dominated these zones with *Coral Reef and Hardbottom* and *Other Delineations* making up the remaining 30.3% and 0.1%, respectively (Figures 5.2 and 5.3). *Pavement* (15.3%) and *Aggregate Reef* (5.2%) were the most common hardbottom habitats, whereas *Rhodoliths* (33.8%) and *Sand* (24.3%) were the most common softbottom habitats. *Sand* dominated the seafloor inside Fish Bay, Coral Bay and the STEER, while rhodoliths were the dominate geomorphological structure outside of these locations. *Algae* colonized the majority of substrate both inside and outside of these locations (47.7%), with equal amounts being patchy (50% - <90%) and continuous (90% - 100%) (Figure 5.4). *Seagrass* was the next most common biological cover type (9.5%), followed by substrates that were uncolonized (5.2%). Live coral

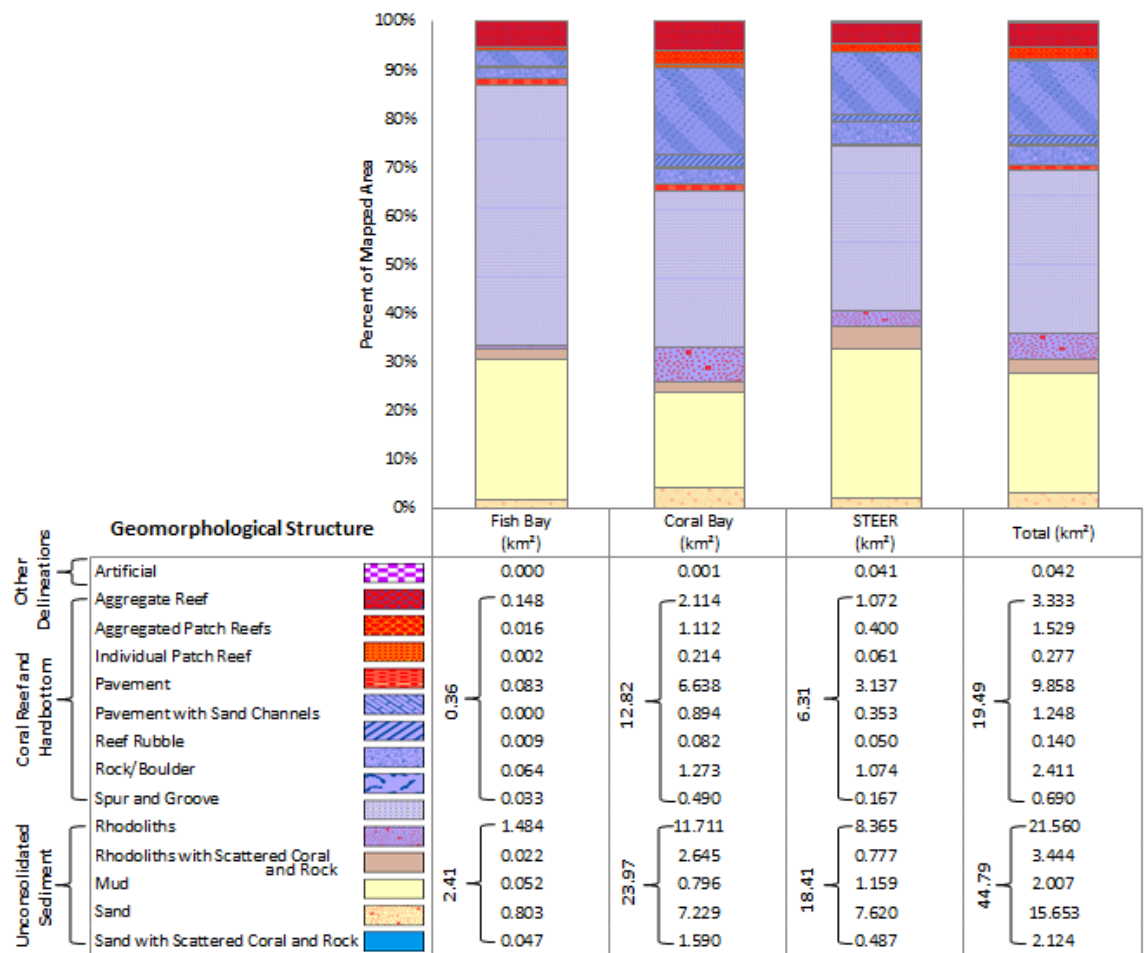


Figure 5.2. Summary statistics describing the total amount of mapped area by major and detailed structure types in Fish Bay, Coral Bay and the STEER.

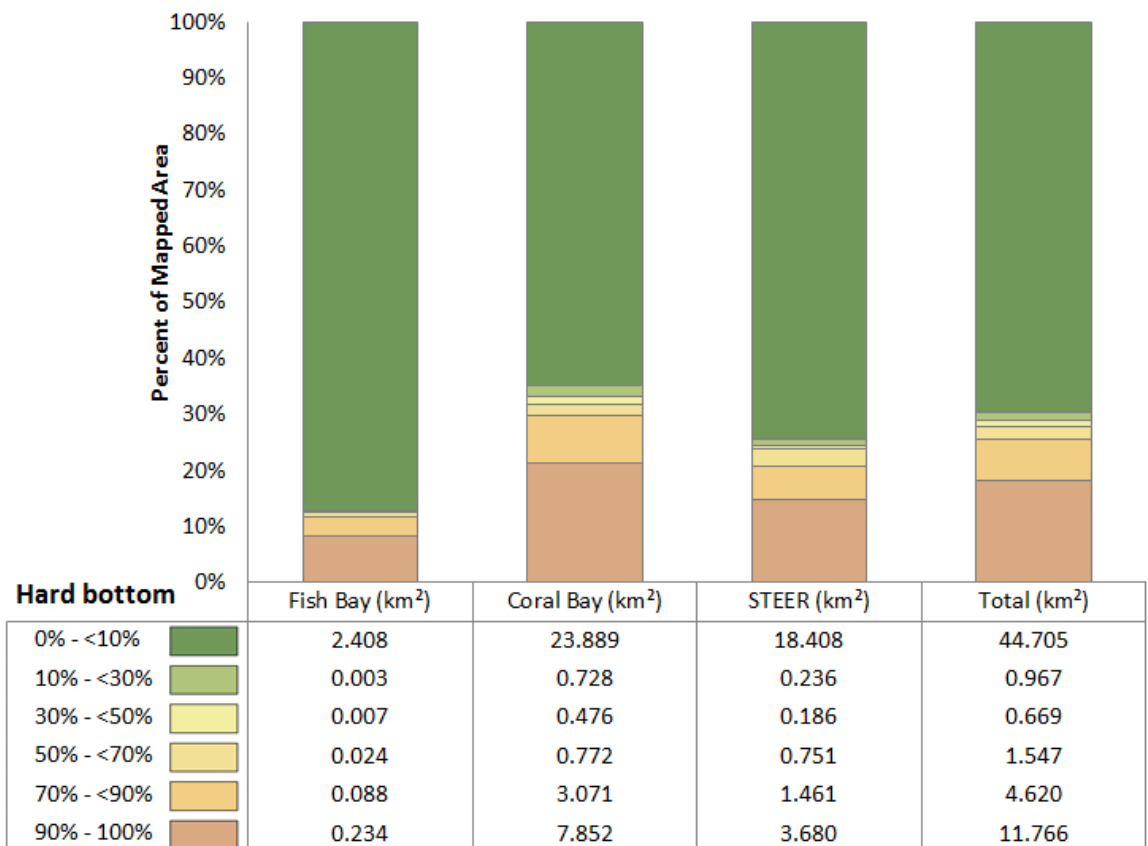
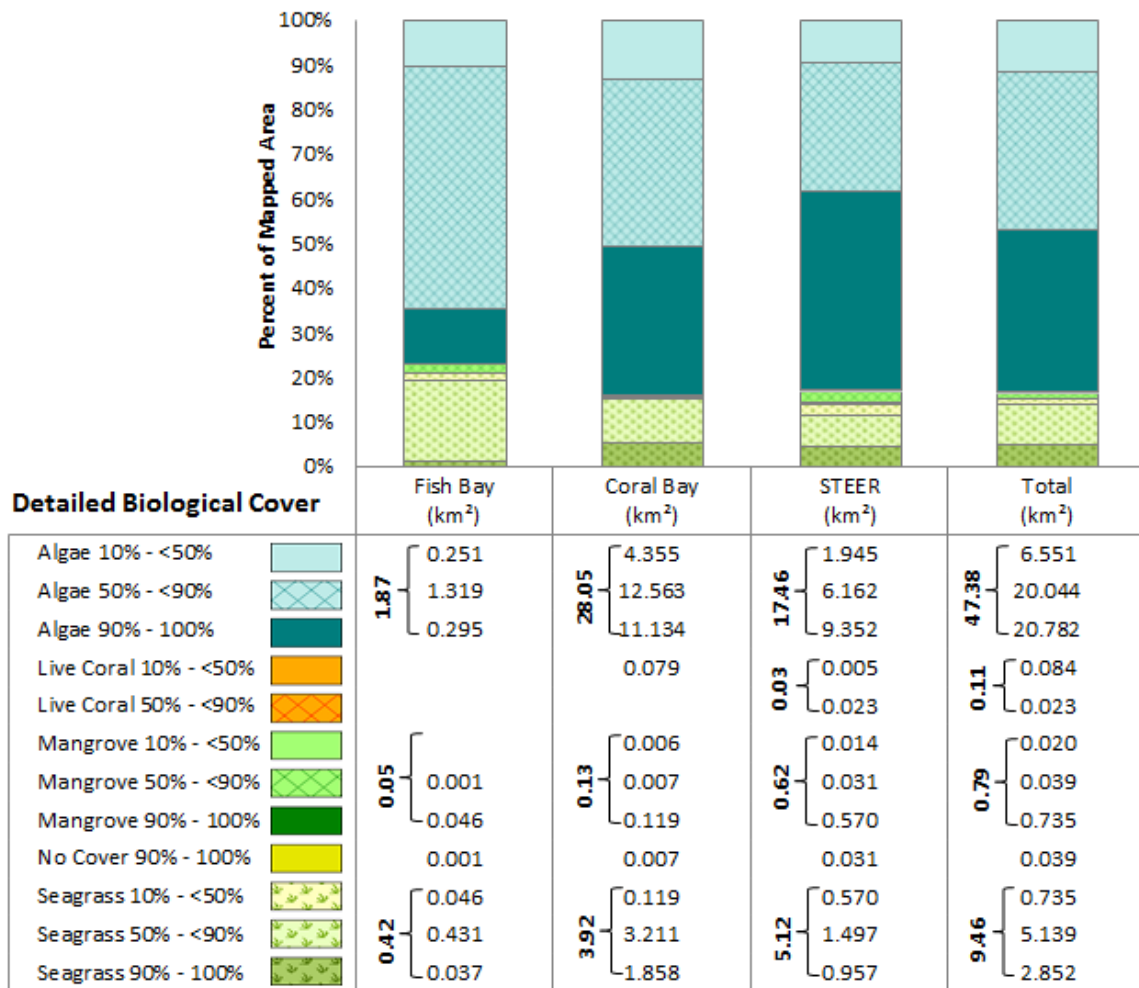


Figure 5.3. Summary statistics describing the total amount of mapped area by percent hardbottom categories in Fish Bay, Coral Bay and the STEER.

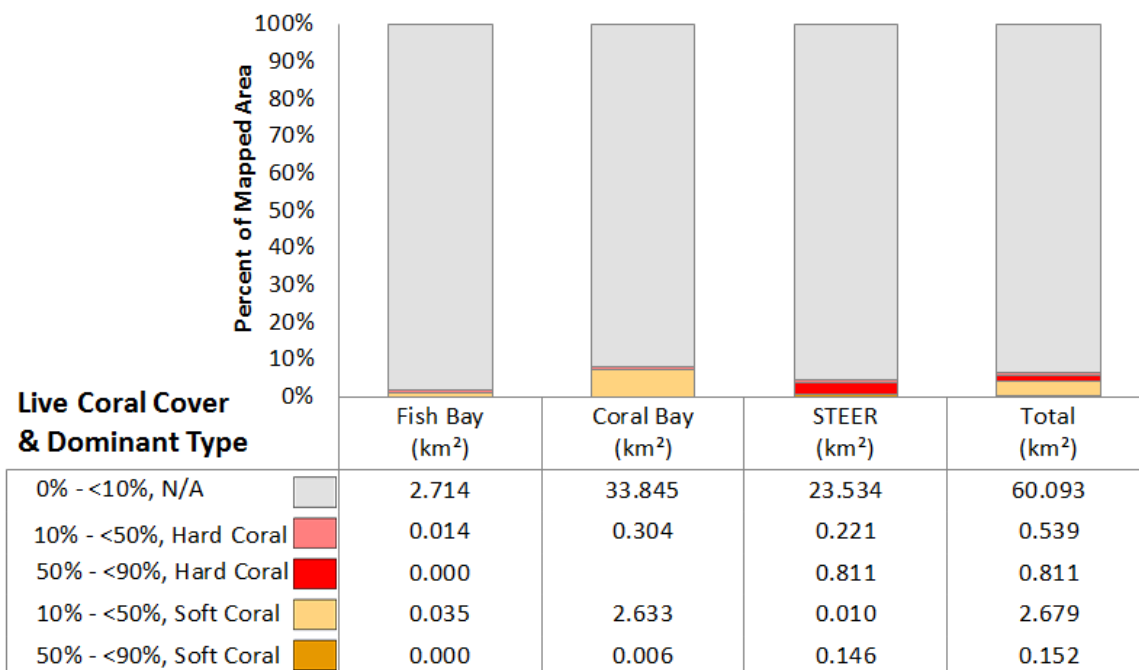
cover rarely exceeded 10% in Fish Bay, Coral Bay and the STEER, only constituting 6.5% of the total mapped area (Figure 5.5). Of those areas with >10% live coral cover, 4.4% were dominated by soft corals and the remaining 2.1% by hard corals. Most of the habitat features with high amounts of live coral cover were located outside of existing MPA boundaries, including the STEER, the Virgin Islands Coral Reef National Monument and the Virgin Islands National Park.

**Fish Bay**

The majority of area (89.8%) that was mapped for Fish Bay was on the *Bank/Shelf* (Figures 5.1 and 5.6). Geomorphological structure (Figures 5.2 and 5.7) and the amount of hardbottom (Figures 5.3 and 5.8) did not differ greatly inside the Bay versus on the *Bank/Shelf*. *Unconsolidated Sediment* dominated (87.1%) both locations, including the channel into Fish Bay as well as inside the Bay itself. *Rhodoliths* made up the majority of the unconsolidated sediments outside of the Bay (south of Dittliff Point), accounting for 53.7%



**Figure 5.4.** Summary statistics describing the total amount of mapped area by major and detailed biological cover types in Fish Bay, Coral Bay and the STEER.



**Figure 5.5.** Summary statistics describing the total amount of mapped area by percent live coral and dominant coral cover types in Fish Bay, Coral Bay and the STEER.

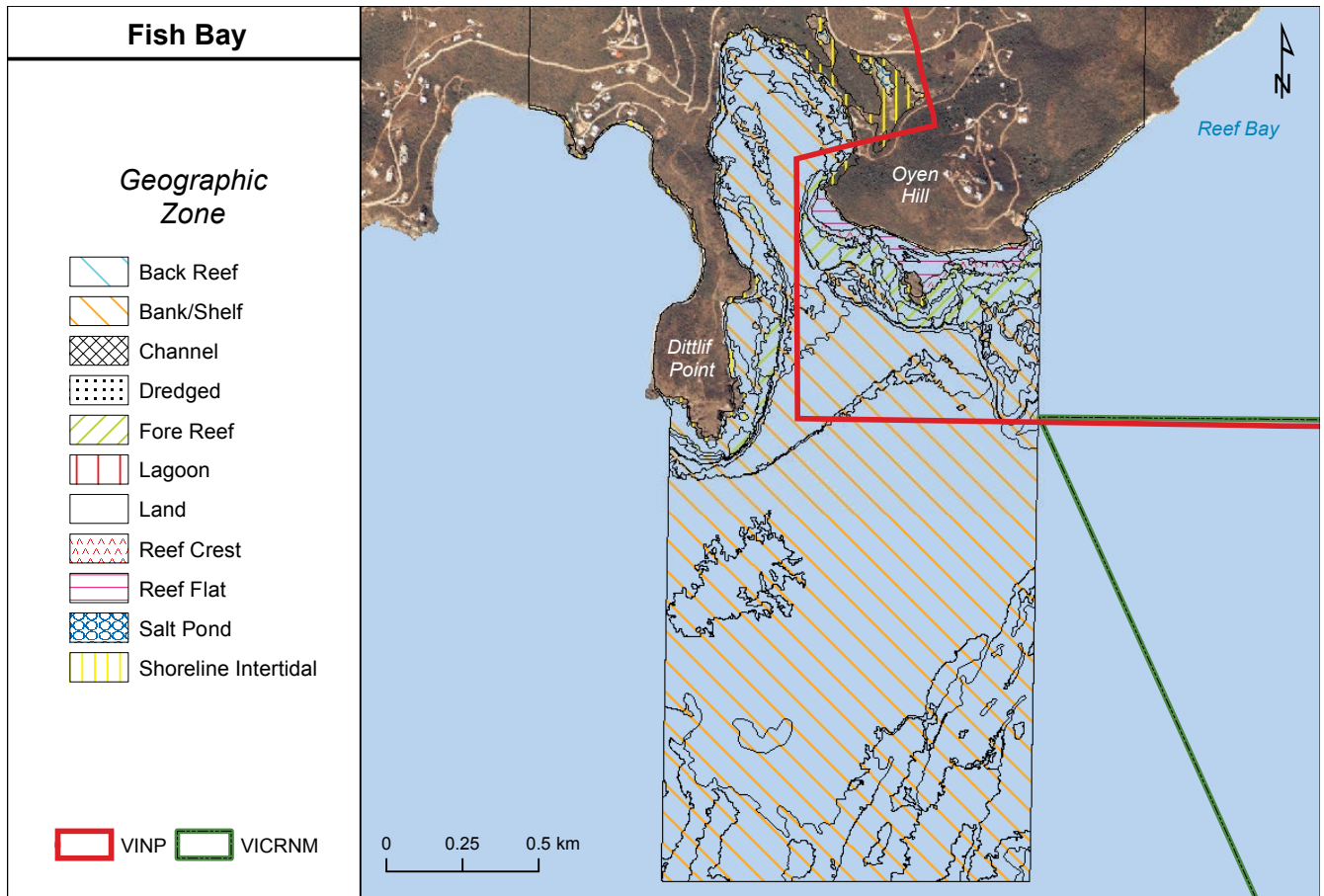


Figure 5.6. Geographic zones in Fish Bay.

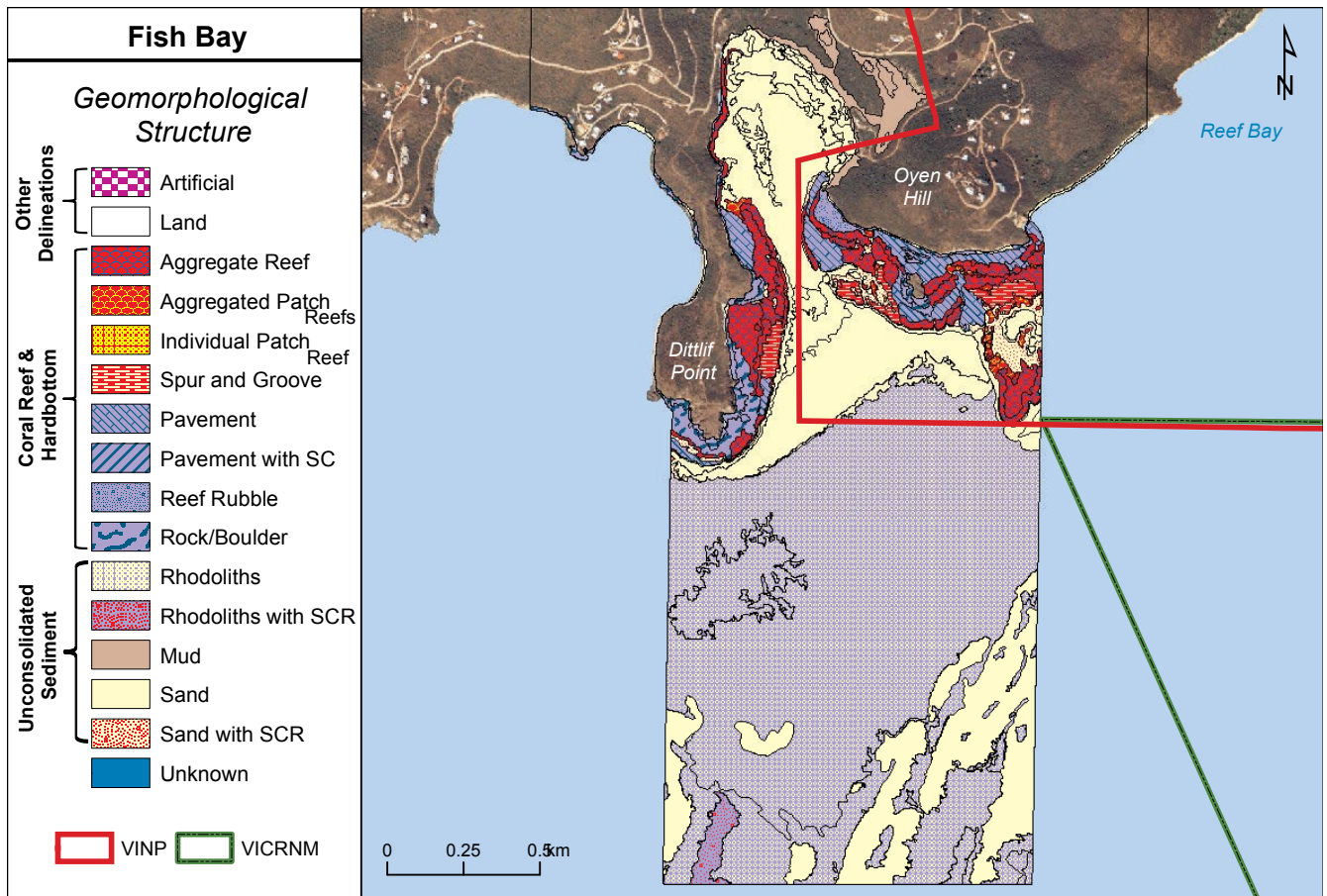


Figure 5.7. Spatial extent of major and detailed geomorphological structure types in Fish Bay.



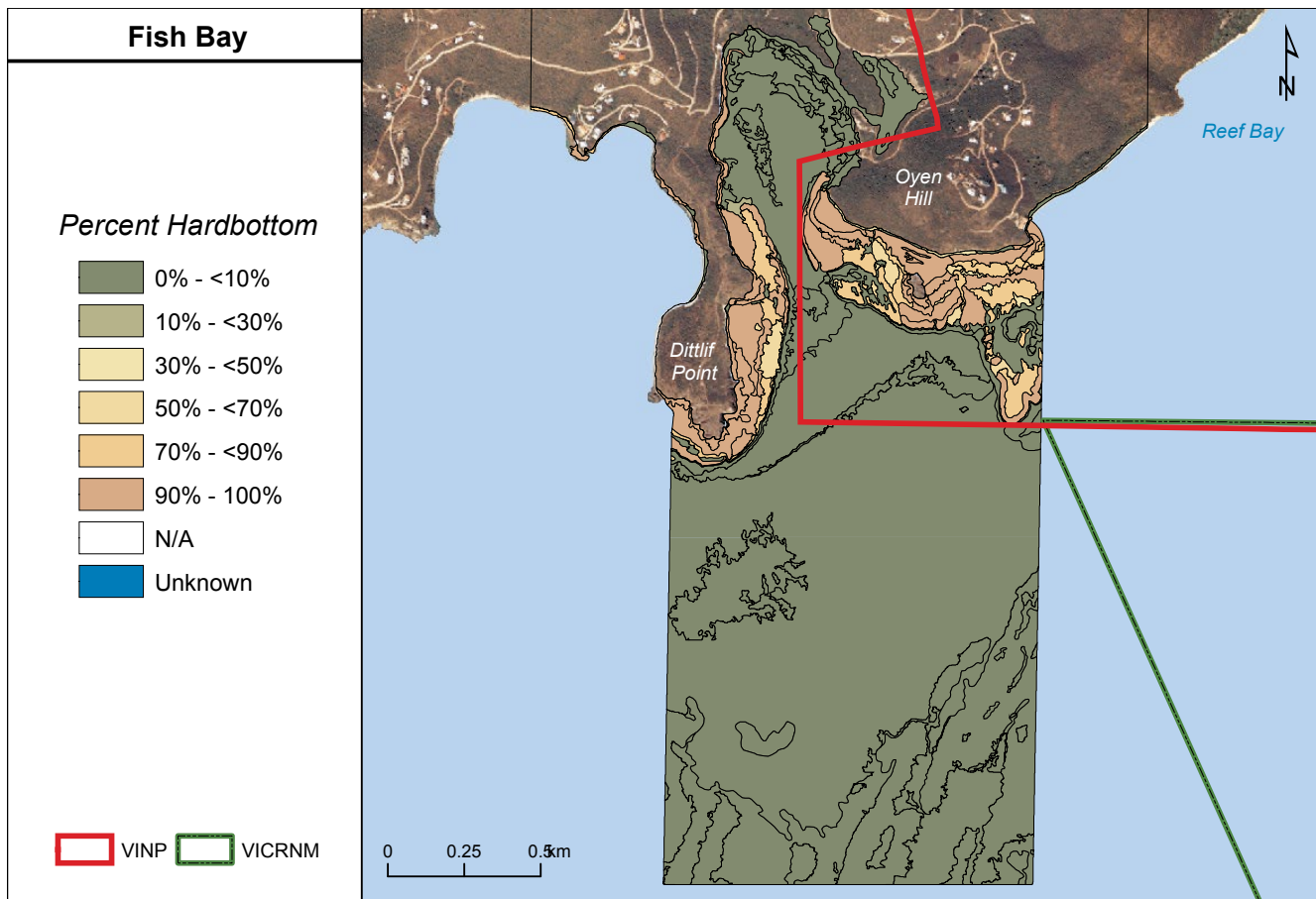


Figure 5.8. Spatial extent of by percent hardbottom categories in Fish Bay.

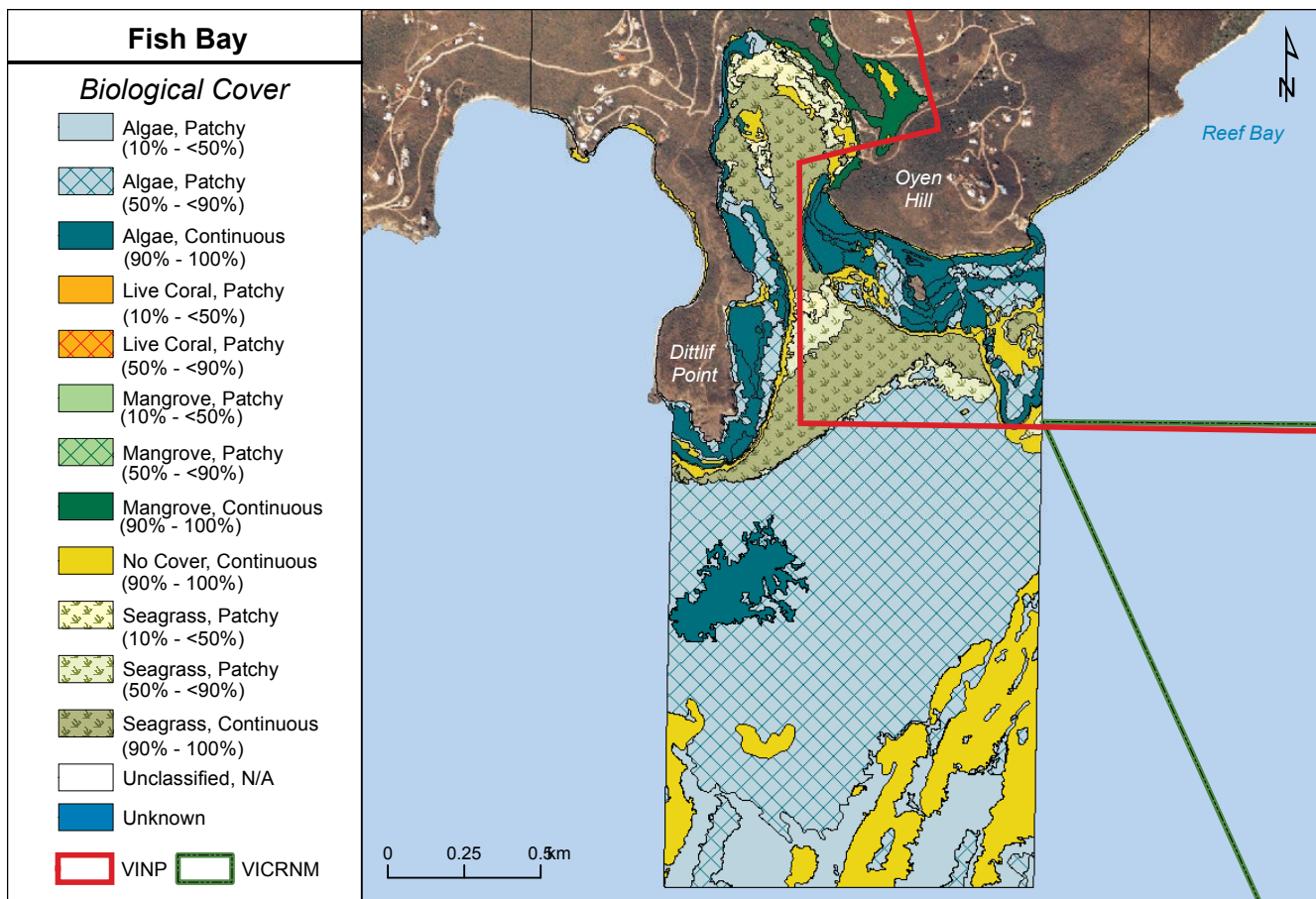
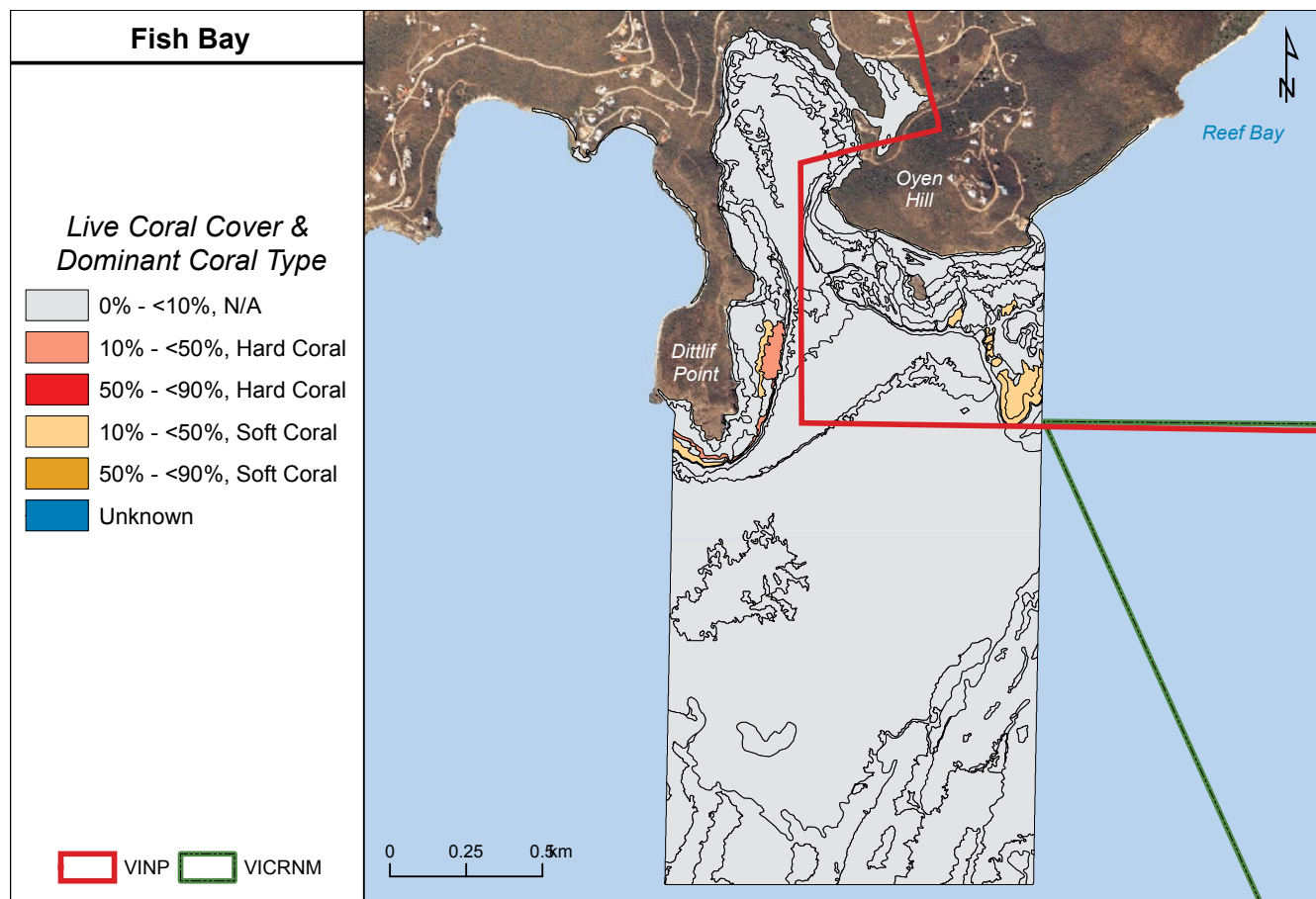


Figure 5.9. Spatial extent of major and detailed biological cover types in Fish Bay.



**Figure 5.10.** Spatial extent of percent live coral and dominant coral cover types in Fish Bay.

of the mapped area. This rhodolith dominated area was also punctuated with sand bars oriented primarily to the north-east and south-west. *Coral Reef and Hardbottom* habitats constituted 12.9% of the mapped area for Fish Bay. These hardbottom habitats were mainly comprised of linear reefs protecting the shoreline to the east and west of the entrance to the Bay. These reefs are dominated by *Aggregated Reef* and *Pavement* structure types, covering 5.3% and 3.0% of the mapped area, respectively. *Rock/Boulder* and *Spur and Groove* were also important contributors to the habitat complexity at the entrance of the Bay, comprising 2.3% and 1.2% of the substrate, respectively.

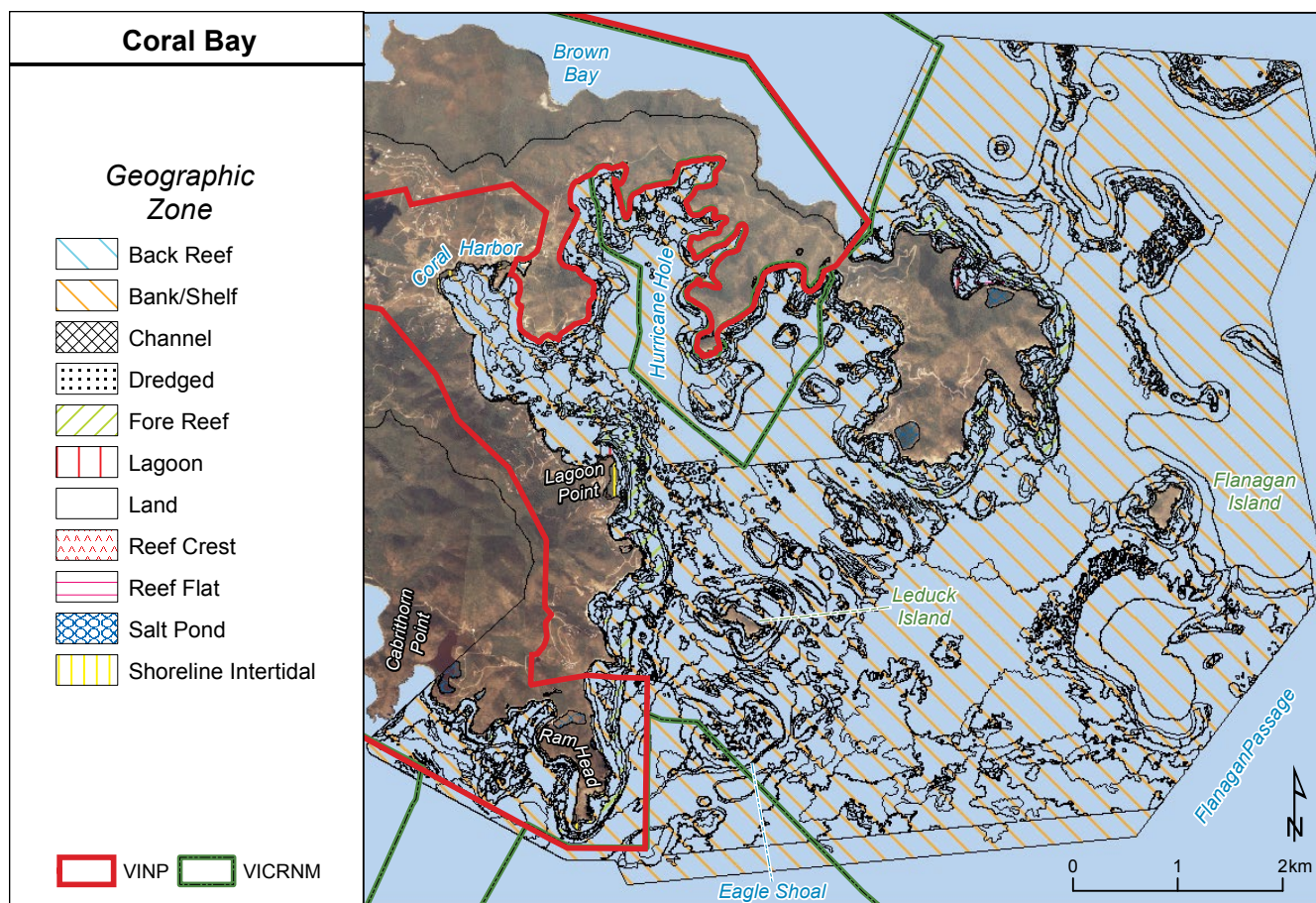
Although the structure was similar, biological cover differed greatly inside of Fish Bay versus on the *Bank/Shelf* (Figures 5.4 and 5.9). *Patchy (50% - <90%) Algae* was the dominant (46.1%) biological cover type on the *Bank/Shelf*. This cover type included various types of turf, fleshy, coralline or filamentous species, which were found primarily south of Dittlif Point. Linear reefs to the east and west of the entrance to Fish Bay were also colonized primarily by algae, with some uncolonized sand patches in between these hardbottom features. *Sand* habitats inside the Bay and adjacent to the *Fore Reef* at the entrance to the Bay were dominated by continuous (90% - 100%) seagrass beds, comprising about 10% of the total mapped area for Fish Bay. Continuous (90% - 100%) mangrove habitats were located around a salt pond inside the Bay on its eastern side, constituting 1.1% of the mapped area. For live coral, the majority (98.2%) of mapped area was colonized by 0% - <10% hard and soft corals (Figures 5.5 and 5.10). Areas with >10% live coral cover were rare (1.8%) and were located along the linear reef to the east and west of the entrance to Fish Bay. Hard corals dominated the high coral cover areas on the west side, covering 0.5% of the mapped area. Soft corals dominated on the east side, covering 1.3% of the total mapped area for Fish Bay.

#### *Coral Bay*

The majority of area (95.2%) that was mapped for Coral Bay was also on the *Bank/Shelf* (Figures 5.1 and 5.11). Geomorphological structure types (Figures 5.2 and 5.12) and the amount of hardbottom (Figures 5.3 and 5.13) were patchy across the mapped area. *Unconsolidated Sediment* dominated (65.2%) inside and outside the Bay. The seafloor was comprised mainly of *Rhodoliths* (31.8%) outside the Bay, and *Sand* (19.7%) inside the Bay.

*Mud* habitats made up a small (2.2%) of the mapped area, and were located further inside the Bay, namely in Coral Harbor and the various creeks and bays in Hurricane Hole. *Rhodoliths with Scattered Coral and Rock* was found mainly at the entrance to the Bay, acting as a transition between rhodolith and sand habitats. This transition area was punctuated by regular sand channels, suggesting this area experiences higher subsurface currents than other nearby locations. *Coral Reef and Hardbottom* habitats constituted 34.8% of the mapped area for Coral Bay. Much of this hardbottom habitat was along the shoreline inside the Bay, around Eagle Shoal and around Leduck and Flanagan Islands. These areas were comprised of a mix of *Aggregate Reef*, *Rock/Boulder*, *Aggregated Patch Reefs* and *Pavement with Sand Channels* structure types, covering 5.7%, 3.5% and 3.0% and 2.4% of the mapped area, respectively. The rest of the hardbottom habitat was to the northeast of Coral Bay. *Pavement* dominated this area (and Coral Bay as a whole), covering 18% of the mapped area. Aggregate reefs were also common in this area, and were often located adjacent to (and ran parallel with) the 40 meter isobath.

Biological cover differed greatly inside of Coral Bay versus on the adjacent *Bank/Shelf* (Figures 5.4 and 5.14). Rhodolith habitats on the *Bank/Shelf* were dominated by *Patchy (50% - <90%) Algae (55.3%)*. This cover type included various types of turf, fleshy, coralline or filamentous species, which were found primarily east of Ram Head and south of Flanagan Island. Hardbottom habitats inside and outside the Bay were also colonized primarily by algae, with some uncolonized sand patches in between these hardbottom features. Sand habitats inside the Bay were dominated by patchy (10% - <50%) seagrass beds, comprising about 3.7% of the total mapped area for Coral Bay. Continuous (90% - 100%) mangrove habitats constituted only 0.2% of the mapped area, and were located mainly inside Hurricane Hole, Coral Bay and by Lagoon Point. For live coral, the majority (92.0%) of mapped area was colonized by 0% - <10% hard and soft corals (Figures 5.5 and 5.15). Areas with >10% live coral cover were rare (8.0%). The majority of these areas were dominated by soft corals (7.2%) located along the fore reef of hardbottom features north of Flanagan Island and near the entrance to Coral Bay. The remaining 0.8% of the area with >10% live coral was dominated by hard corals, and were located north of Lagoon Point, northeast of Leduck Island and southeast of Flanagan Island.



**Figure 5.11.** Geographic zones in Coral Bay.

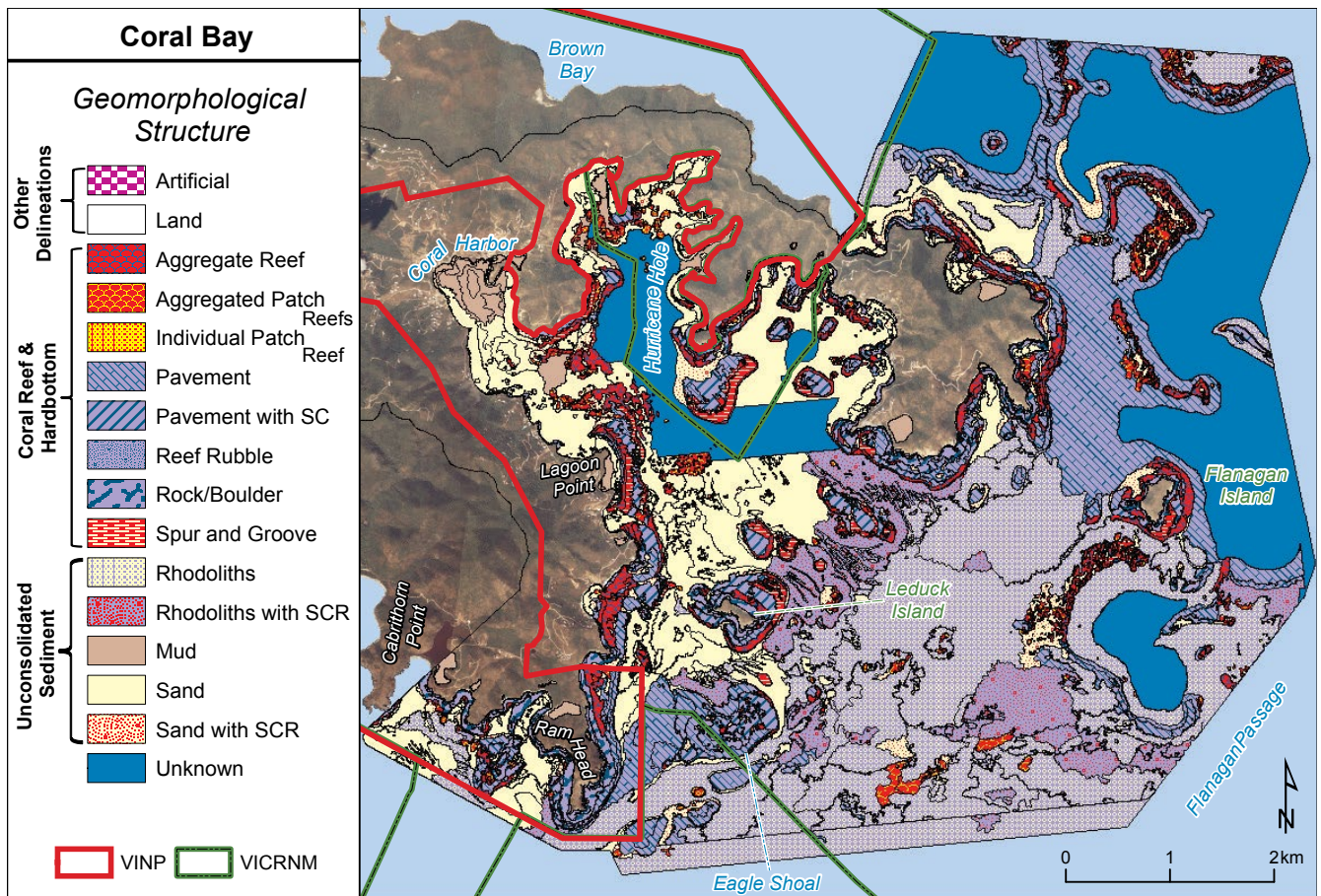


Figure 5.12. Spatial extent of major and detailed geomorphological structure types in Coral Bay.

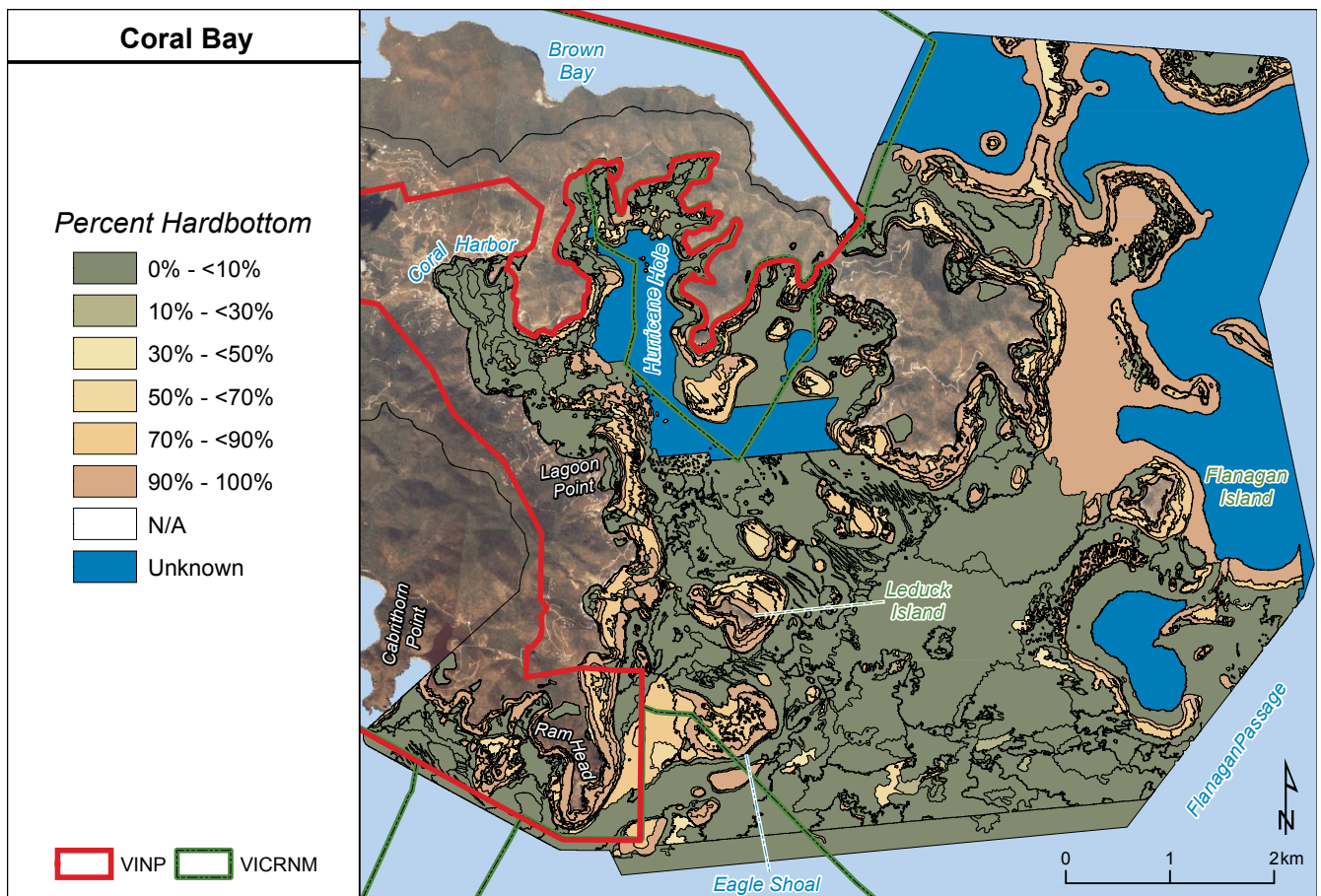


Figure 5.13. Spatial extent of by percent hardbottom categories in Coral Bay.

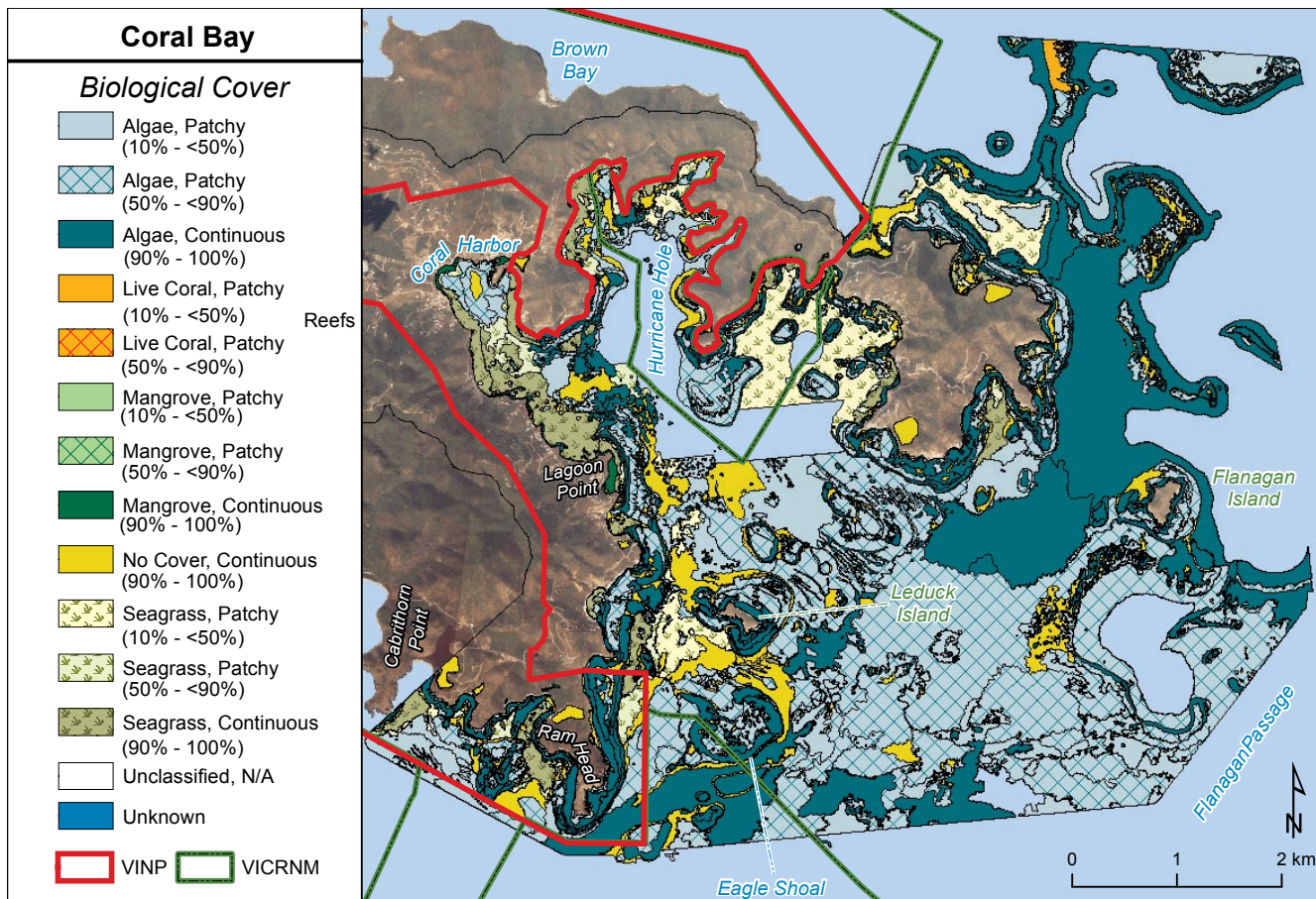


Figure 5.14. Spatial extent of major and detailed biological cover types in Coral Bay.

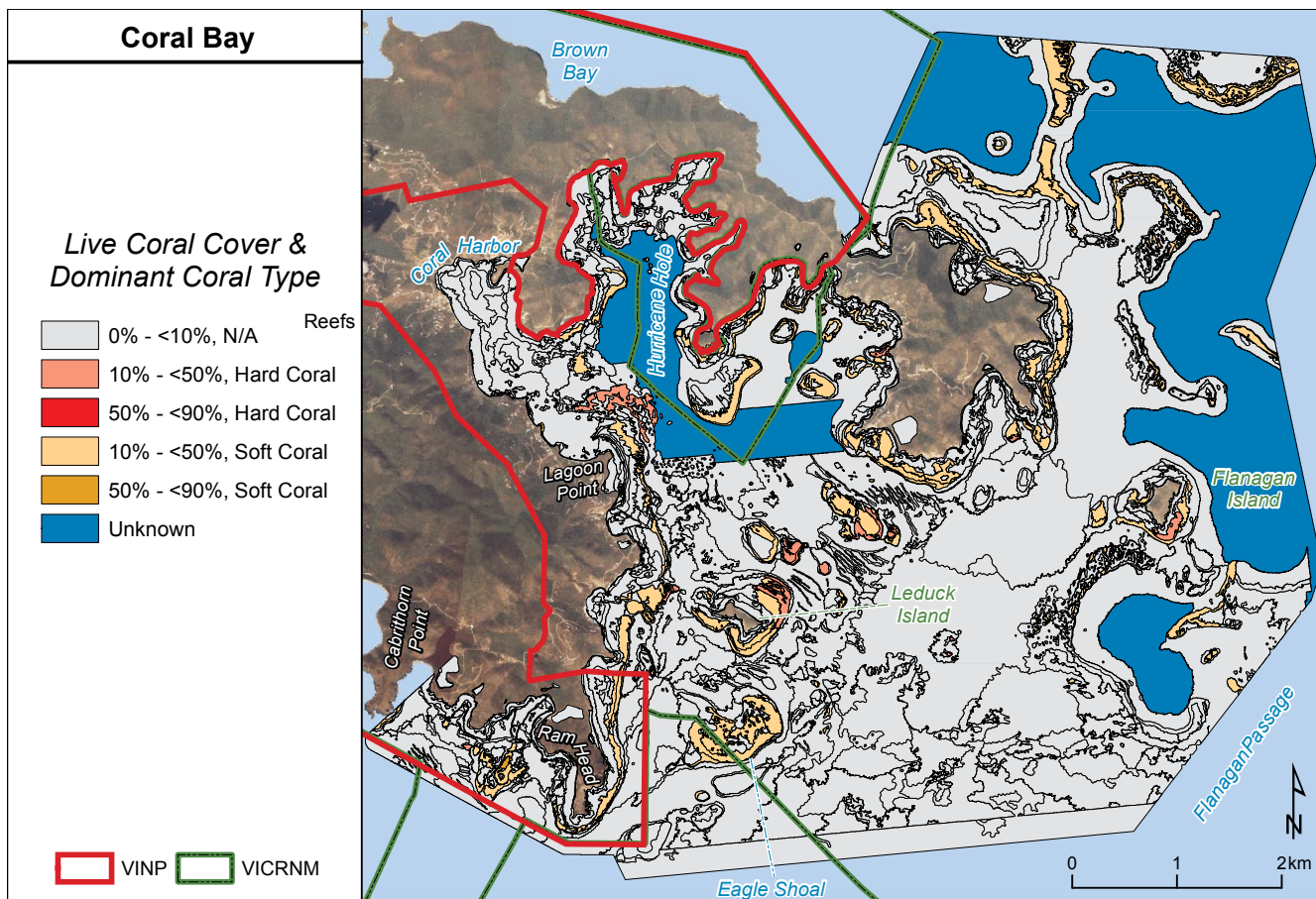
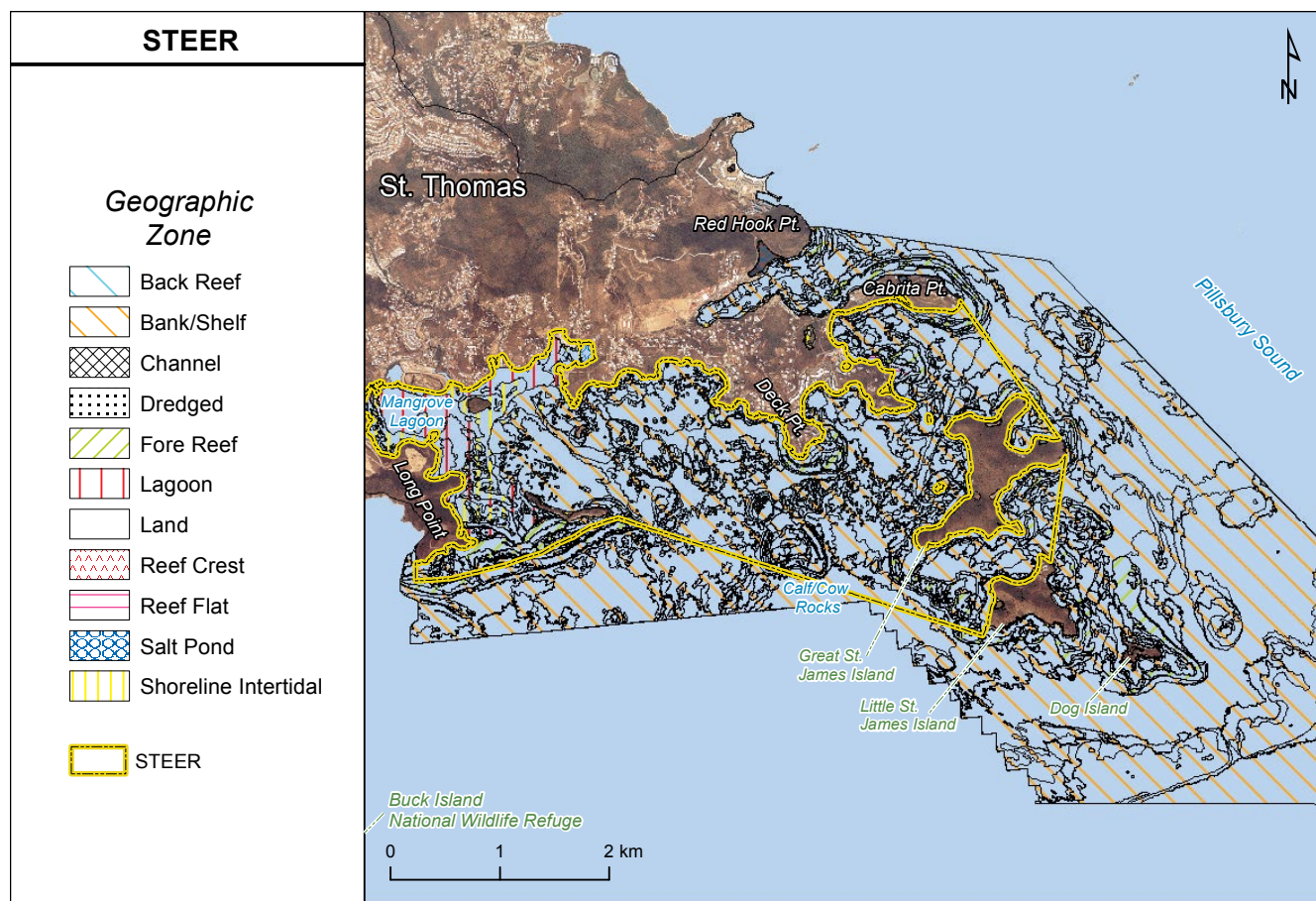


Figure 5.15. Spatial extent of percent live coral and dominant coral cover types in Coral Bay.

## STEER

The majority of area (87.9%) that was mapped for the STEER was also on the *Bank/Shelf* (Figures 5.1 and 5.16). Geomorphological structure types (Figures 5.2 and 5.17) and the amount of hardbottom (Figures 5.3 and 5.18) were patchy across the mapped area. *Unconsolidated Sediment* dominated (74.3%) the seafloor both inside and outside of the STEER's boundary. *Rhodoliths* and *Sand* were the two most common types of unconsolidated sediment, comprising 33.8% and 30.8% of the mapped area, respectively. *Rhodoliths* dominated the area outside of the STEER's boundary, while *Sand* made up the majority of the area inside the MPA. *Mud* habitats made up a small amount (4.7%) of the mapped area, and were located mainly in Mangrove Lagoon. *Coral Reef and Hardbottom* habitats constituted 25.5% of the total mapped area with *Pavement* being the most dominant (12.7%) structure type overall. Roughly 44% of this hardbottom habitat was inside the STEER's boundaries, located mainly southeast of Long Point, south of Deck Point and surrounding the nearshore waters of Cabritta Point. These areas were dominated by *Pavement, Rock/Boulder* and *Aggregate Reef* structure types, covering 7.4%, 6.4% and 5.9% of the area inside the STEER's boundary, respectively. However, some of the largest and most continuous hardbottom features were located just outside of the MPA boundaries around Little St. James and Dog Islands. These areas were mainly comprised of *Pavement* features, although aggregate reefs were also present along the shoreline of both islands.

Biological cover differed greatly inside versus outside of the STEER's boundary (Figure 5.19). Rhodolith habitats were dominated by *Algae* (39.2%), the majority of which was *Continuous (90% - 100%)* (21.0%). This cover type included various types of turf, fleshy, coralline or filamentous species, which were found primarily in Mangrove Lagoon and outside of the STEER's boundary. Hardbottom habitats inside and outside the STEER's boundary were also colonized primarily by algae. Sand habitats were dominated by continuous (90% - 100%) seagrass beds, comprising about 5.4% of the total mapped area and 21.4% of the mapped area inside the STEER's boundary. Continuous (90% - 100%) and patchy (50% - <90%) mangrove habitats constituted only 1.4% of the total mapped area, and were located mainly inside the STEER's boundary in Mangrove Lagoon. For live coral, the majority (95.2%) of mapped area was colonized by 0% - <10% hard and soft corals (Figures 5.5 and 5.20). Areas with >10% live coral cover were rare (4.8%). However, the majority of these areas were dominated by hard



**Figure 5.16.** Geographic zones in the STEER.

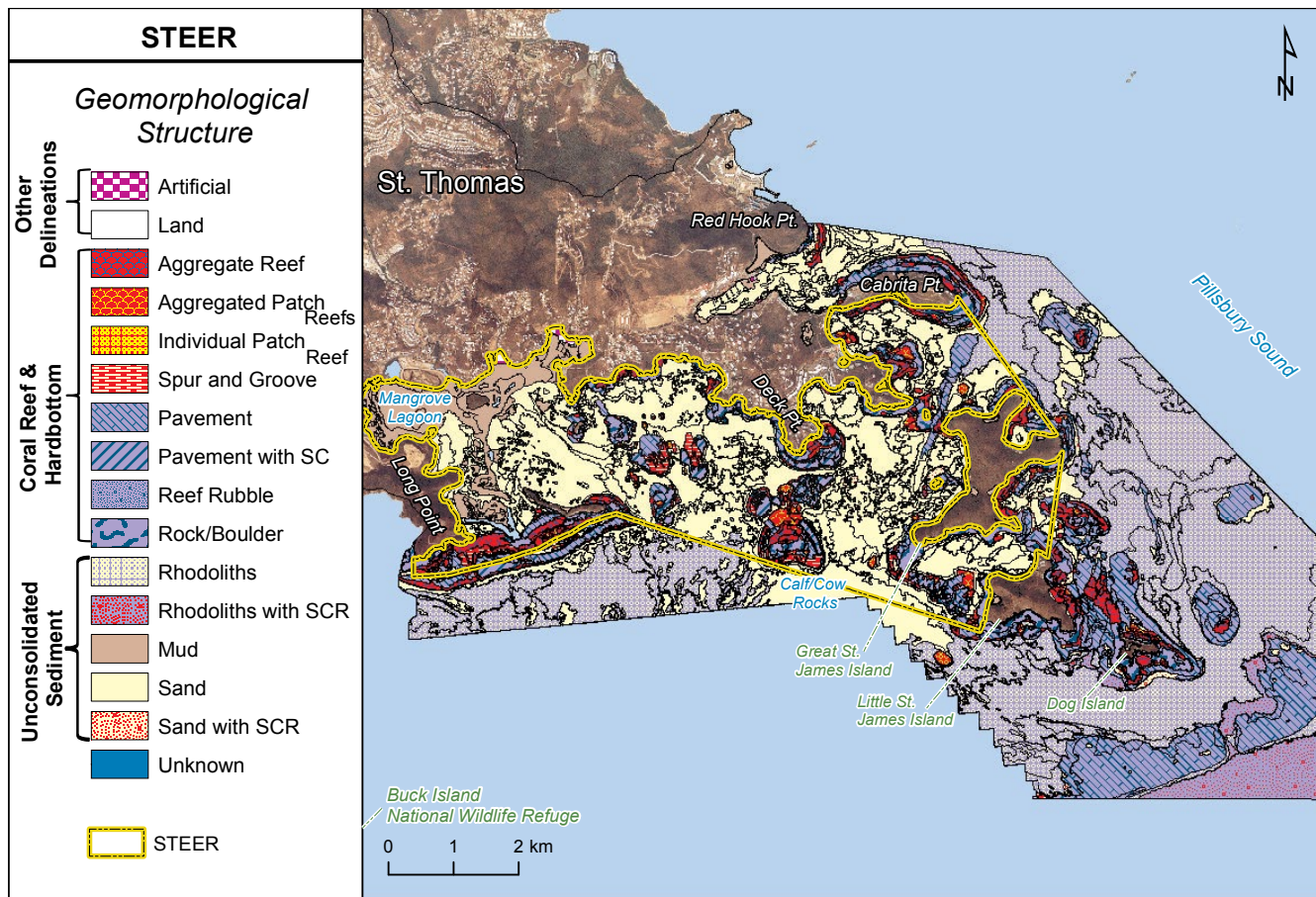


Figure 5.17. Spatial extent of major and detailed geomorphological structure types in the STEER.

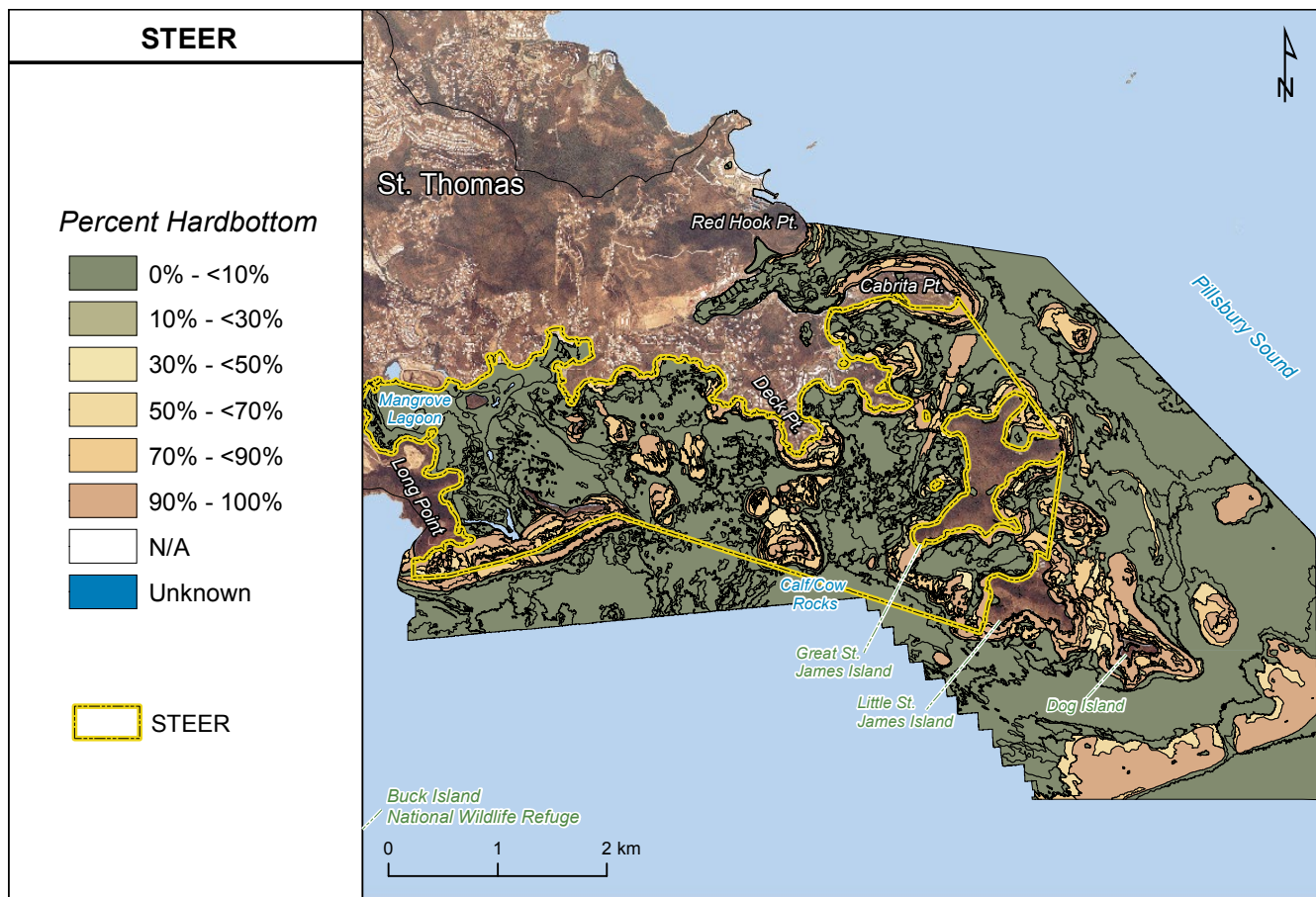


Figure 5.18. Spatial extent of by percent hardbottom categories in the STEER.

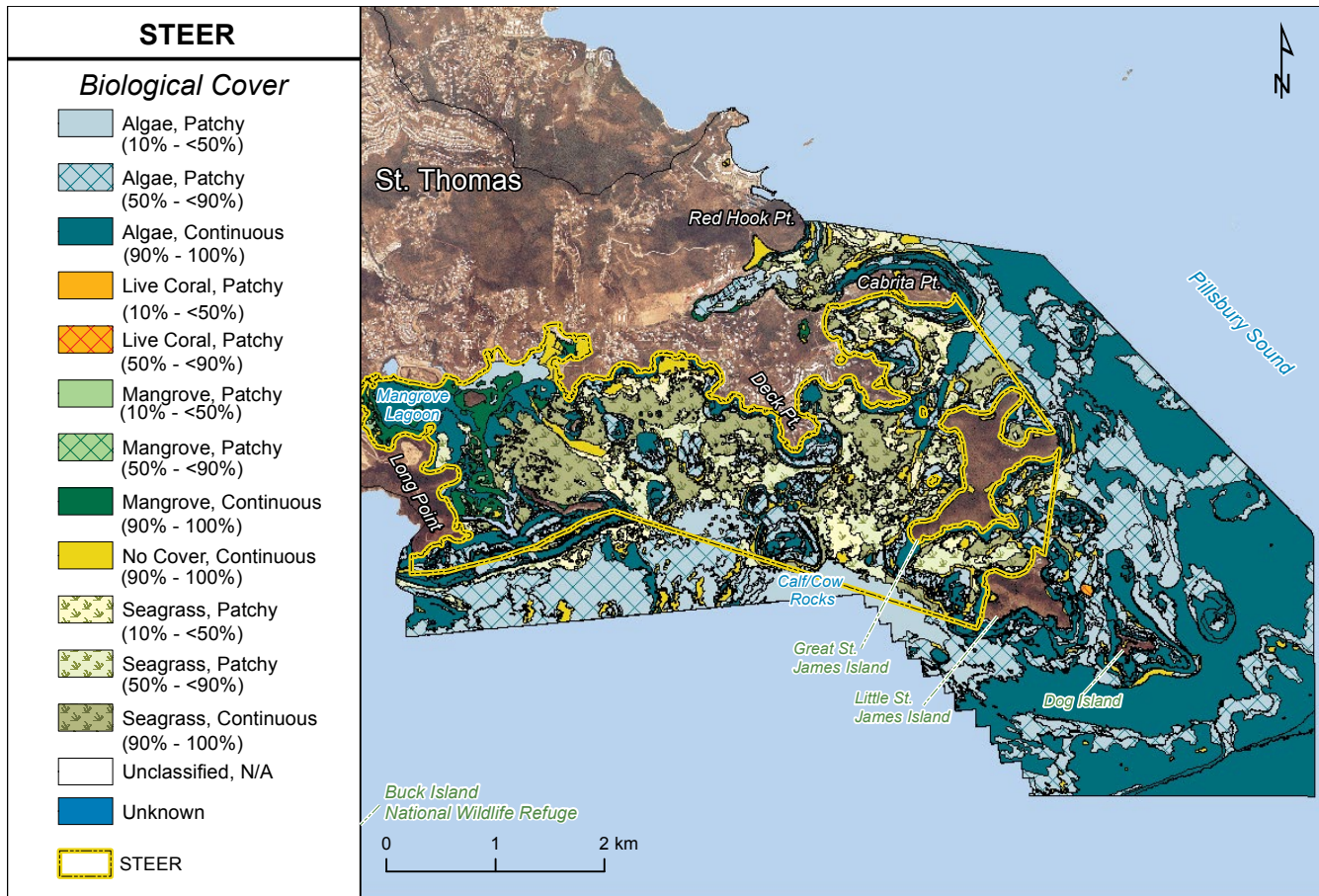


Figure 5.19. Spatial extent of major and detailed biological cover types in the STEER.

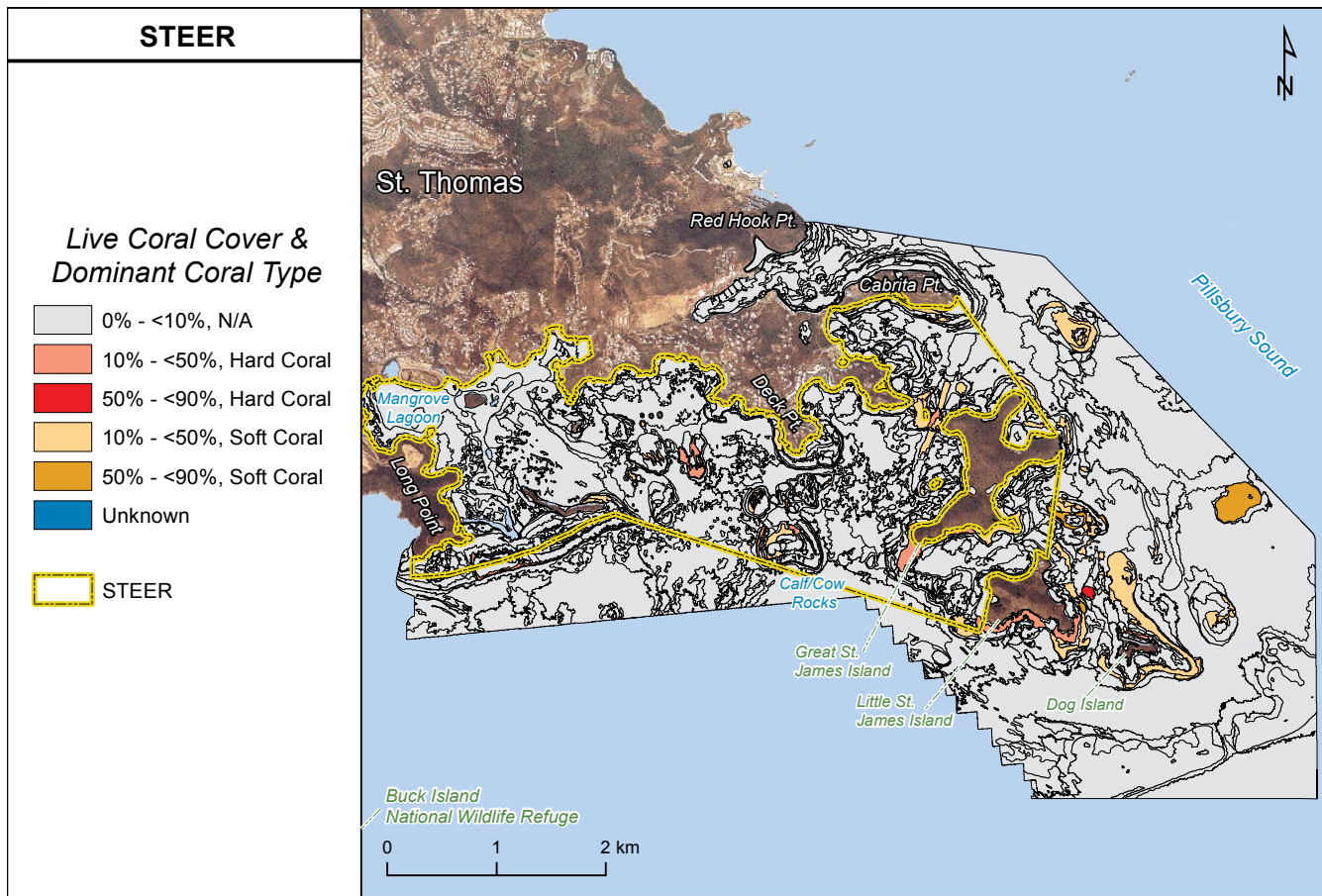


Figure 5.20. Spatial extent of percent live coral and dominant coral cover types in the STEER.



corals (4.2%), about half of which were located just outside of the STEER's boundary (south of Long Point and south and east of Little St. James Island). The other half were east of Deck Point, around Calf and Cow Rocks, and near the Stragglers on the southwest tip of Great St. James Island. The remaining areas with >10% live coral were dominated by soft corals, and were located in the cut between St. Thomas and Great St. James Island, south and east of Dog Island and in Pillsbury Sound.

## 5.2 COMPARISON TO PREVIOUS HABITAT MAP

This mapping effort marks the second time that the shallow-water ( $\leq 30$  m) habitats in the STEER, and the third time that the shallow-water habitats in Fish Bay and Coral Bay have been characterized. Habitats in the STEER were last characterized in 2001 and in Fish and Coral Bays in 2001 and 2009. Even though multiple habitat maps exist for these areas, several major improvements were made to this newest map. First, only aerial photos and satellite imagery were used to map habitats on the seafloor in 2001 and 2009. For this effort, aerial photos and LiDAR imagery were collected and used to characterize benthic habitats in these same locations. LiDAR data provides a wealth of additional information about the seafloor (compared to aerial photos and satellite imagery) including its depth and topography. This additional information was used to update nautical charts in the area. It can also be used to model spatial relationships between animals and the seascape, as well as provide local managers with baseline information important for developing monitoring sampling plans.

Second, this current map characterized over 18% area more than previous maps. In 2001 and 2009, large areas of the seafloor were not characterized in Fish Bay, Coral Bay and the STEER because the poor image quality prevented the analysts from delineating and classifying the seafloor. In many cases, the image quality was degraded because the seafloor was too deep or there was too much suspended sediment in the water column for the sunlight to reach the seafloor. These issues prevented over 27.4% (1.1 km<sup>2</sup>) of Fish Bay, 52.9% (32.6 km<sup>2</sup>) of Coral Bay and 18.8% (8.4 km<sup>2</sup>) of the STEER from being characterized in 2001, and over 18.4% (0.7 km<sup>2</sup>) of Fish Bay and 42.8% (26.4 km<sup>2</sup>) of Coral Bay from being characterized in 2009. However, this mapping effort characterized 100% of Fish Bay, 85% of Coral Bay and 100% of the STEER. More of the seafloor was characterized during this effort because the LiDAR sensor was able to map deeper depths than aerial or satellite based multispectral sensors (i.e., the LiDAR sensor mapped to 40 m versus typically 30 m for multispectral sensors).

Third, the new map characterized benthic habitats at a higher spatial and thematic resolution than previous maps. It did so because it used: (1) a new classification scheme with more classes, (2) a finer scale to delineate the boundaries of habitats, and (3) a smaller minimum mapping unit (Table 5.2). These changes were made because a smaller geographic area was mapped using better quality source imagery. These different classification schemes, delineation scales and minimum mapping units prohibit a quantitative comparison between the 2001, 2009 and 2013 benthic habitat maps because coral reef habitats are sensitive to the resolution at which they are mapped (Kendall and Miller 2008). This sensitivity is mainly due to the size of the minimum mapping unit, which 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 100 m<sup>2</sup> in size will be mapped as Individual Patch Reef in a map with a 100 m<sup>2</sup> MMU and as Aggregated Patch Reefs (assuming it is surrounded by other patch reefs) in a map with a 1,000 m<sup>2</sup> or 4,046 m<sup>2</sup> MMU. These different interpretations occur because the patch reef is too small (<1,000 m<sup>2</sup>) to be characterized individually at a coarser scale. The size of the MMU also affects the rarity of a habitat class. Rare habitat classes become more common and dominant ones become less common as 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

**Table 5.2.** Comparison of map and feature characteristics where the 2001, 2009 and 2013 benthic habitat maps intersect.

		NOAA MAPPING EFFORT		
		2001	2009	2013
Map	METRIC			
	Imagery Acquisition Date	1999	2005-2007	2011-2012
	Spatial Resolution of Optical Imagery (m)	2.40	0.3 - 4	0.3 - 3
	Scale of Delineation	1:6,000	1:2,000	1:1,000
Feature	MMU (m <sup>2</sup> )	4,046	1,000	100
	Number of Distinct Classes	23	63	154
	Number of Polygons	462	788	5,264
	Number of Polygons < 4,046 m <sup>2</sup>	0	334	3,718
	Mean Area of Polygons (m <sup>2</sup> )	229,526	81,658	20,927
	Mean Perimeter of Polygons (m)	2,289	1,188	682

comparison between the 2001, 2009 and 2013 benthic habitat maps because coral reef habitats are sensitive to the resolution at which they are mapped (Kendall and Miller 2008). This sensitivity is mainly due to the size of the minimum mapping unit, which 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 100 m<sup>2</sup> in size will be mapped as Individual Patch Reef in a map with a 100 m<sup>2</sup> MMU and as Aggregated Patch Reefs (assuming it is surrounded by other patch reefs) in a map with a 1,000 m<sup>2</sup> or 4,046 m<sup>2</sup> MMU. These different interpretations occur because the patch reef is too small (<1,000 m<sup>2</sup>) to be characterized individually at a coarser scale. The size of the MMU also affects the rarity of a habitat class. Rare habitat classes become more common and dominant ones become less common as 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 rare habitats at a larger MMU. Notably, individual patch reefs, pavement and sand patches often become more common when smaller MMUs are implemented.

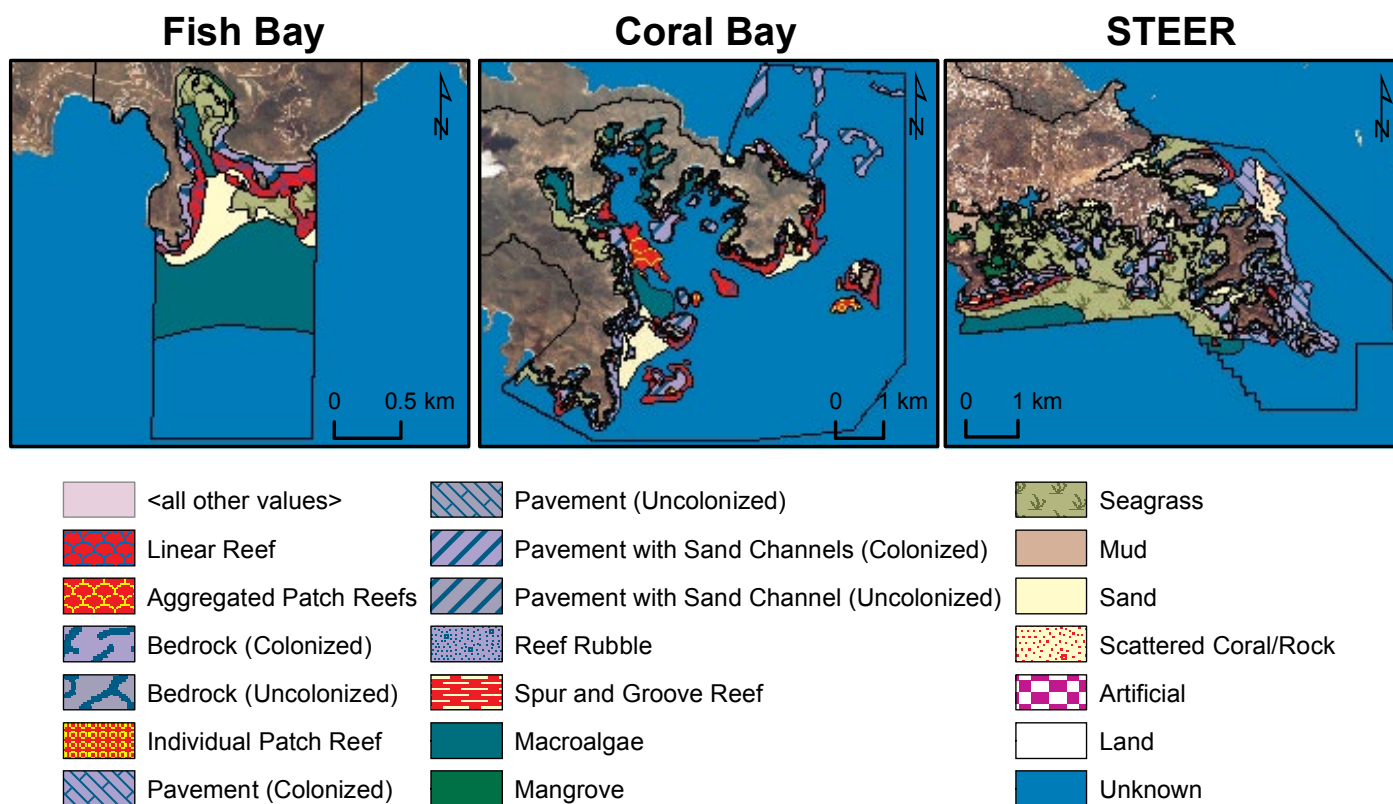
Keeping these issues in mind, a broader comparison was conducted qualitatively, highlighting the differences among the 2001, 2009 and 2013 habitat maps and identifying potential changes in the benthic habitats in Fish Bay, Coral Bay and the STEER over this time period (Tables 5.3 and 5.4; Figures 5.21 and 5.22). For geomorphological structure, less *Coral Reef and Hardbottom* was delineated in the 2001 and 2009 maps. This decrease in coral reef and hardbottom habitat was most likely due to the coarser scale at which features were delineated and the large areas on the seafloor that were left uncharacterized. For major biological cover, a substantial amount of more algae was delineated in the 2013 map as compared to the 2001 and 2009 maps. This increase is most likely due to more seafloor area being characterized in 2013, as well as to the inclusion of macro, crustose, turf and filamentous algae in the *Algae* class in the 2013 map. The 2001 map only included macroalgae on softbottom and ignored the other algal classes, while the 2009 map included all types of algae except crustose coralline algae in the *Algae* class. Interestingly, more area dominated by seagrass was delineated in the 2001 map, than in the 2009 and 2013 maps. The larger amount of seagrass delineated in the 2001 map is most likely due to the coarser MMU. However, additional analysis comparing the source imagery for these maps may reveal areas where the spatial distribution of seagrass has changed over time (Figure 5.23). The amount of delineated live coral cover was about the same in the 2009 and 2013 maps. This class was added in 2009 and consequently, is not included in the 2001 map. However, it is important to note that between 2005 and 2006, a massive bleaching event caused live coral cover to decrease across the U.S. Virgin Islands (Pittman et al. 2008; Miller et al. 2009; Eakin et al. 2010). The georeferenced underwater photos and videos collected during these mapping efforts may show changes in live coral cover over time.

**Table 5.3.** Comparison of the 2001 and 2013 benthic habitat maps in Fish Bay, Coral Bay and the STEER.

	CLASS NAMES		AREA (km <sup>2</sup> )	
	2001 (4,046 m <sup>2</sup> MMU)	2013 (100 m <sup>2</sup> MMU)	2001	2013
<b>Major Structure</b>	Coral Reef and Hardbottom	Coral Reef and Hardbottom	15.49	19.49
	Unconsolidated Sediment	Unconsolidated Sediment	18.48	44.79
<b>Detailed Structure</b>	Linear Reef	Aggregate Reef	3.71	3.33
	Patch Reef (Aggregated)	Aggregated Patch Reefs	0.68	1.53
	-	Artificial	-	0.04
	Patch Reef (Individual)	Individual Patch Reef		0.28
	Mud	Mud	0.36	2.01
	Colonized/Uncolonized Pavement	Pavement	3.94	9.86
	Colonized/Uncolonized Pavement with Sand Channels	Pavement with Sand Channels	3.45	1.25
	Reef Rubble	Reef Rubble	0.16	0.14
	-	Rhodoliths	-	21.56
	-	Rhodoliths with Scattered Coral and Rock	-	3.44
	Colonized/Uncolonized Bedrock	Rock/Boulder	3.05	2.41
	Sand	Sand	2.02	15.65
	Sand with Scattered Coral and Rock	Sand with Scattered Coral and Rock	0.99	2.12
	Spur and Groove Reef	Spur and Groove	0.14	0.69
<b>Major Cover</b>	Algal Dominated (on softbottom)	Algae	3.91	47.38
	-	Live Coral	-	0.11
	Mangrove	Mangrove	0.69	0.79
	-	No Cover	-	5.14
	Seagrass	Seagrass	10.51	9.46

**Table 5.4.** Comparison of the 2009 and 2013 benthic habitat maps in Fish Bay, Coral Bay and the STEER.

	CLASS NAMES		AREA (km <sup>2</sup> )	
	2009 (1,000 m <sup>2</sup> MMU)	2013 (100 m <sup>2</sup> MMU)	2009	2013
<b>Major Structure</b>	Coral Reef and Hardbottom	Coral Reef and Hardbottom	7.88	19.49
	Unconsolidated Sediment	Unconsolidated Sediment	12.46	44.79
<b>Detailed Structure</b>	Aggregate Reef	Aggregate Reef	2.08	3.33
	Aggregated Patch Reefs	Aggregated Patch Reefs	0.71	1.53
	-	Artificial	-	0.04
	Individual Patch Reef	Individual Patch Reef	0.06	0.28
	Mud	Mud	1.73	2.01
	Pavement	Pavement	2.37	9.86
	Pavement with Sand Channels	Pavement with Sand Channels	1.31	1.25
	Reef Rubble	Reef Rubble	0.10	0.14
	Rhodoliths	Rhodoliths	1.34	21.56
	-	Rhodoliths with Scattered Coral and Rock	-	3.44
	Boulder, Rock Outcrop	Rock/Boulder	1.00	2.41
	Sand	Sand	8.77	15.65
	Sand with Scattered Coral and Rock	Sand with Scattered Coral and Rock	0.61	2.12
	Spur and Groove	Spur and Groove	0.24	0.69
	<b>Major Cover</b>	Algae	Algae	15.18
Live Coral		Live Coral	0.13	0.11
Mangrove		Mangrove	0.17	0.79
No Cover		No Cover	1.28	5.14
Seagrass		Seagrass	2.94	9.46



**Figure 5.21.** Benthic habitat maps developed in 2001 for (left to right) Fish Bay, Coral Bay and the STEER (Kendall et al. 2001).

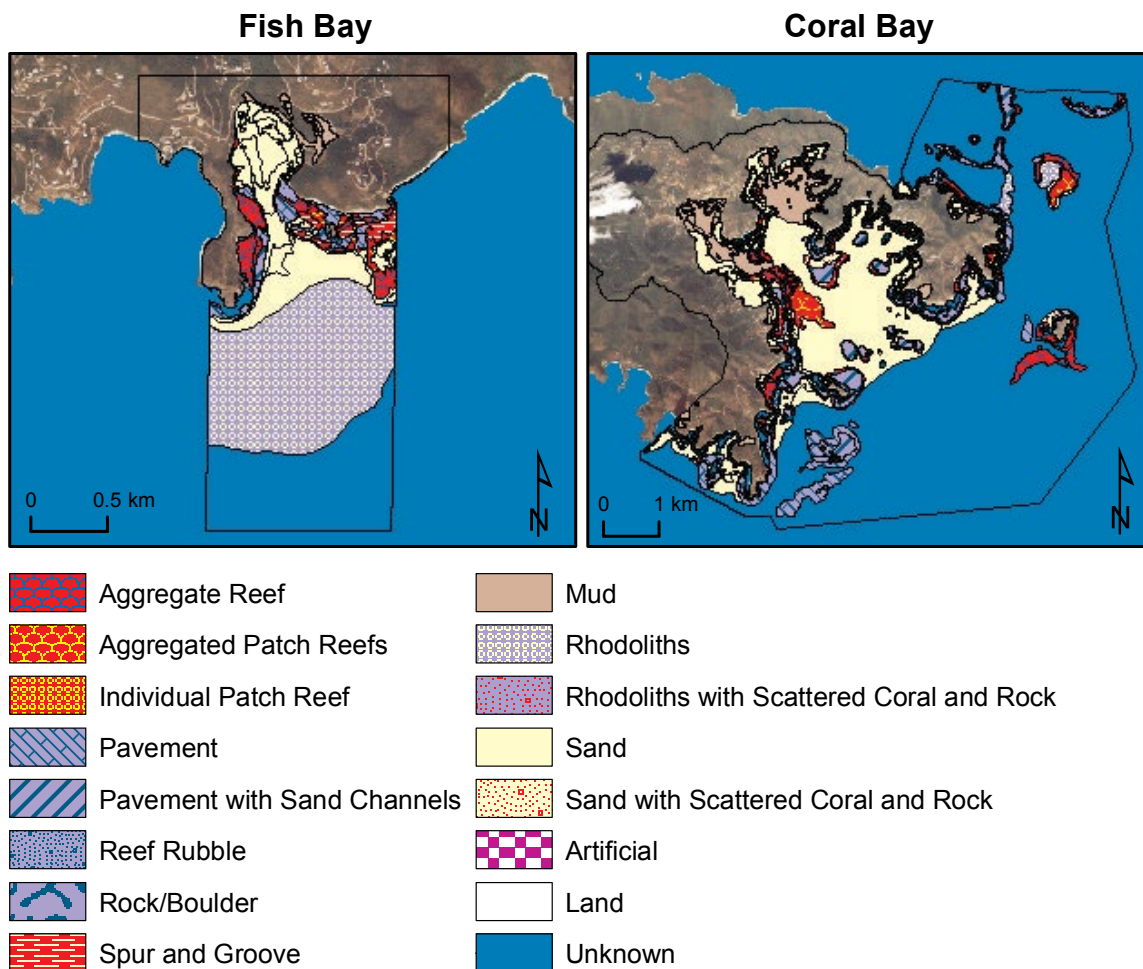


Figure 5.22. Benthic habitat maps developed in 2009 for (left to right) for Fish Bay and Coral Bay (Zitello et al. 2009).

### 5.3. MAP USES

As described above, 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. This MMU issue has important implications for not only summarizing, but also using benthic habitat maps to inform management actions. These implications include potentially impacting decisions concerning zoning, anchoring, mooring and sampling for monitoring because the location and size of an area identified for additional management 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<sup>2</sup>, the number of potentially suitable locations would be far fewer if a habitat map with a 4,047 or 1,000 m<sup>2</sup> MMU was used to conduct this spatial analysis versus using a map with a 100 m<sup>2</sup> MMU.

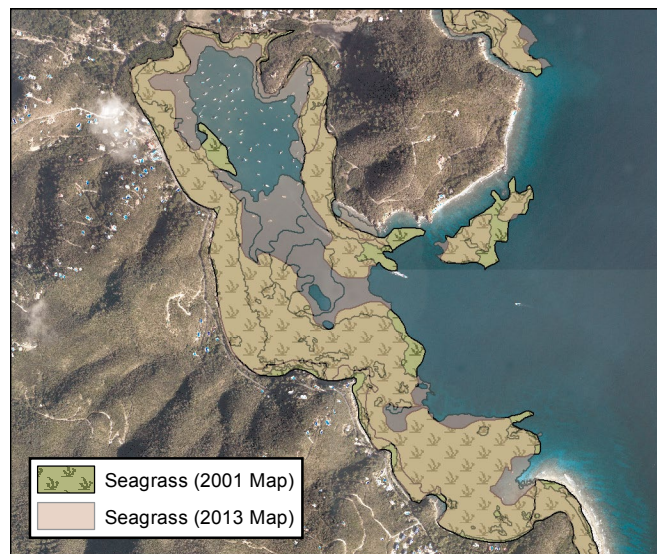


Figure 5.23. The spatial distribution of seagrass changed between 2001 and 2013 in the channel leading into Coral Harbor, St. John.

However, smaller MMUs are not always better. The scale of the habitat map should be balanced with the time and cost to develop it, and should be designed to support as many different management applications as possible. The scale and classification scheme for this latest habitat map were determined in consultation with local managers at the STEER and at the National Park Service in St. John. 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 be used for similar applications, provided the classification scheme and MMU of this map are taken into 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 STEER, including evaluating different zoning options for multiple use areas.
- Evaluating the efficacy of management actions taken by STEER.
- 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.
- 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 of the seascapes in Fish Bay, Coral Bay and the STEER 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 in Fish Bay, Coral Bay and the STEER. 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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