CERMES Technical Report No. 94

Developing a benthic habitat classification scheme and island-wide map for Barbados based on remote sensing and comprehensive ground-truthing

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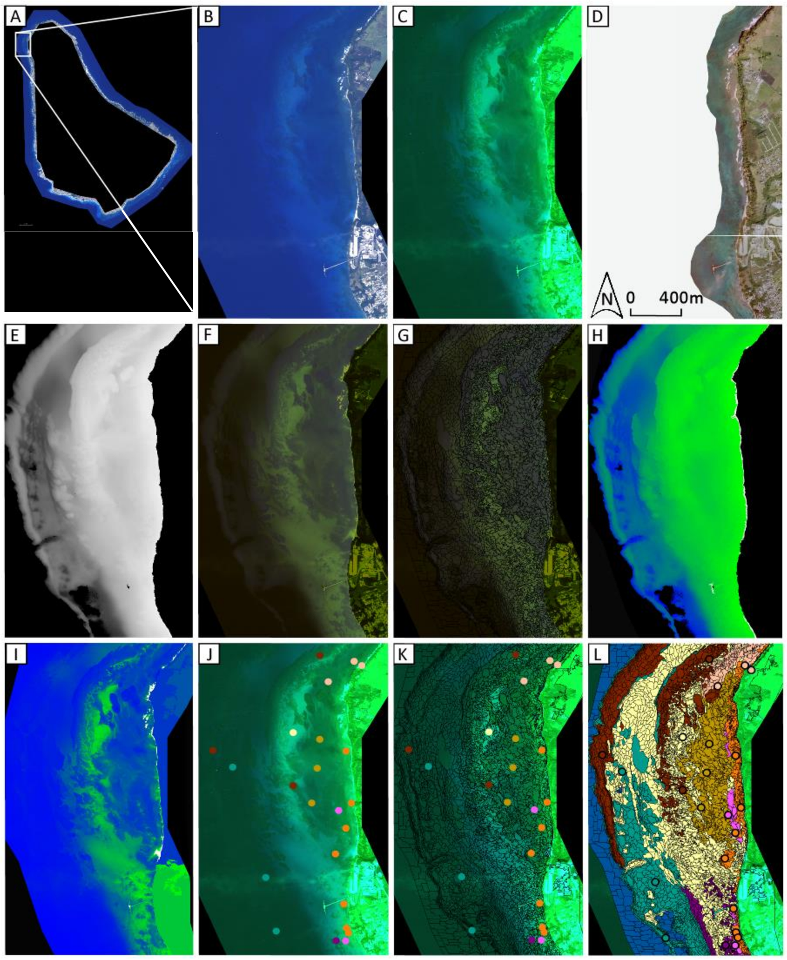

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2019

ABSTRACT

Marine habitat maps are fundamental for the management of marine resources, but are not routinely available in the small island states of the Caribbean, due largely to the cost traditionally associated with production of these maps. Furthermore, existing habitat maps, even within country, are rarely compatible since they have usually been created for different purposes using different habitat schemes, different mapping resolutions and different methods. This makes it very difficult to piece together maps over sufficiently large enough areas to inform national-level marine spatial planning. The application of modern remote sensing technologies, together with a geographical information system (GIS) and strategic ground-truthing now means that marine habitat maps can be produced over larger geographical areas with better accuracy and lower budgets than previously possible. In this study, we describe the application of relatively inexpensive methods to conduct an extensive ground-truthing video survey and analysis to support remote-sensing at an island-wide scale, in order to produce a comprehensive shallow (shoreline to a depth of 40 m) marine habitat map for the island of Barbados. A 12-class locally relevant habitat scheme was developed through an iterative process involving key stakeholders and analysis of underwater video footage. Location of ground-truthing sites was guided by: (1) the use of a draft remotely sensed habitat map allowing sites to be stratified to ensure adequate coverage of all draft habitat classes, and (2) the need to give comprehensive coverage to all eight coastal zone management areas used by the Government's Coastal Zone Management Unit. A total of 361 sites were visited and surveyed. For the majority of sites, short (30 sec) underwater video clips were taken by a combination of a Seaviewer underwater camera and a GoPro camera operated from a small boat. For a minority of sites, a handheld camera was operated by a free diver and/or SCUBA diver. Additional information (depth and geographic coordinates) were taken at each site with handheld instruments. Post-processing of the video clips was time consuming, but allowed for an iterative process in assigning habitat classes. Additional attribute data (including substrate type, rugosity, community abundance and dominant community groups) were also scored from the video footage for each site, providing an additional rich dataset beyond that required for ground-truthing. The ground-truthing exercise provided the information needed to ensure that the habitat scheme was appropriate at the island scale, and that the remotely sensed habitat map was accurate and fit for purpose (locally relevant and appropriately scaled for national-level marine spatial planning). The mapping methods used, and lessons learned in this study have broad application to other countries in the region wishing to advance the process of ecosystem-based management and marine spatial planning.

KEY WORDS: Remote sensing, marine habitat mapping, benthic habitat classification, Barbados

ACKNOWLEDGEMENTS

A very special thanks is extended to Ms. Renata Goodridge of CERMES, UWI, Stanton Thomas of Weston, St. James, and Allan Bradshaw of Conset Bay, St. John for their assistance in developing the sampling design, fieldwork logistics and field data collection aspects of this project. They ensured that our fieldwork was not only safe but a lot of fun! Many thanks to Dr. Steve Schill of The Nature Conservancy's Caribbean Program for sharing his knowledge, time and assistance with the setup of the video cameras, other field survey equipment and software support for this project. We also acknowledge the wider team of experts who worked with us on various aspects of the project: Lotte Purkis of SPP Inc., W.F. Baird & Associates, and the Coastal Zone Management Unit of Barbados. Lastly, we wish to acknowledge the project managers Pete Zuzek (Baird) and Caroline Bissada, Ramon Roach and Richard Suckoo from (CZMU) for their support over the course of this project. This project was completed for the Ecosystem Based Adaptation Pilot Project, which is one component of the Barbados Coastal Risk Assessment and Management Program (CRMP) presently being executed by the CZMU of the Government of Barbados.

TABLE OF CONTENTS

Citation:

Baldwin, K., H.A. Oxenford, S. Purkis and L. Knowles. 2016. Developing a benthic habitat classification scheme and island-wide map based on remote sensing and comprehensive ground-truthing. Centre for Resource Management and Environmental Studies, The University of the West Indies, Barbados. CERMES Technical Report No. 94: 48pp.

Reproduction:

This research was conducted in 2015 and published in 2019 as a CERMES Technical Report.

1 INTRODUCTION

Marine habitat maps are fundamental for marine resource management (Norse 2010; Ogden 2010). However, conventional scientific methods for the creation of marine habitat maps, such as extensive underwater surveys and *in situ* measurements, can be financially and logistically burdensome (Mishra 2009; Yang 2009, Baldwin and Oxenford 2014), especially over the large geographical scales relevant to national marine spatial planning, such as the entire coastline of a country. Today remote sensing, using high resolution imagery (e.g. aerial orthophotographs, WorldView-2 satellite data) with LiDAR bathymetry data and a geographical information system (GIS) as the data platform, is the preferred approach and allows large areas to be rapidly and accurately surveyed at lower cost (Rowlands 2012; Pittman et al. 2013; Purkis and Brock 2014).

Remote sensing combined with GIS technologies are increasingly being applied both globally and regionally in the Caribbean to create benthic habitat maps (Mumby and Harborne 1999, Kendall et al. 2001, Andrefouet et al. 2003, Madden and Grossman 2004, Agostini et al. 2010, Schill et al. 2011, Baldwin 2012, Rowlands et al. 2012, Purkis 2014). In Barbados, whilst the earliest maps of the marine environment (navigational charts) date back several hundred years, it was not until the early 1980s under the Inter-American Development Bank (IDB) Coastal Conservation Project that efforts were made to map the marine habitats at the scale of whole coastlines for the purpose of marine resource management. At this time Proctor and Redfern International were contracted by the Government of Barbados to, *inter alia*, map the marine habitats off the west and southwest coasts of Barbados. Habitat maps for each of the two sections of coastline were hand-drawn based on aerial photography, bathymetric data derived from side-scan sonar, underwater field surveys and expert local knowledge (Procter and Redfern et al. 1984). In the late 1990s as part of the continuing IDB Coastal Conservation Project, the Halcrow Group was contracted to, *inter alia*, map the marine habitats of the north, east and southeast coastal areas. Towards this end, the Halcrow Group produced a digital habitat atlas based on numerous detailed underwater visual surveys and acoustic bottom classification derived from high precision Light Detection and Ranging (LiDAR) bathymetry and reflectance data (Halcrow 1998).

In 2008, the Government, recognizing the need for a comprehensive map of marine habitats integrated across all the island's coastlines, supported a University of the West Indies, Centre for Resource Management and Environmental Studies (CERMES) MSc research project to create an island-wide marine habitat map for Barbados by merging the west and southwest coast marine habitat data of Proctor and Redfern et al. (1984) with the north, east and southeast coast marine habitat data of Halcrow (1998). To do this, the Proctor and Redfern et al. (1984) data had to be converted into GIS format by digitizing the hard-copy marine habitat maps (Welch 2008). Subsequently an attempt was made to use GIS technologies to merge the digitized Proctor and Redfern map with the Halcrow GIS data to create a seamless marine habitat map for the entire coastal waters of Barbados. Unfortunately, different classification schemes used by the two studies (i.e. Proctor and Redfern used 19 classes with no detailed descriptions, while Halcrow used 9 classes) created difficulties for merging the different datasets. This was partially resolved by examining the small areas of overlap between the two maps and expert judgment, but necessitated a loss of detail, such that the combined map only recognized seven broadly different habitat types. Furthermore, there were spatial mismatches (i.e. as result of applying different mapping methods) between the datasets, which meant that habitat joins were forced. Welch (2008) also noted that many features in the Proctor and Redfern data were not drawn to scale, whereas the Halcrow data were based on high precision LiDAR bathymetry. Thus the resultant merging of these two datasets into a single marine habitat map for the entire island of Barbados, even with the aid of newly acquired 2008 composite Digital Globe satellite imagery, was not found to be cohesive, and lacked the desired precision and detail for national management (Welch 2008; Figure 1). In recognition of the need to improve on this existing digital habitat map, the Coastal Zone Management Unit (CZMU) requested in 2015 that a new up-to-date shallow marine habitat map be created for the entire island of Barbados within the work programme of the current IDB Coastal Risk Assessment and Management Programme (CRMP). As a result, CERMES was solicited by the project consultants, W.F. Baird & Associates, to take the lead in the production of a remotely-sensed, benthic habitat map for the island of Barbados using the project's LiDAR bathymetric and reflectance data and high-resolution aerial orthophotographs. The geographic extent of the benthic habitat map is intended to cover all nearshore marine habitats between the shoreline and the 40 m bathymetric contour, or the limits of penetration for the LiDAR and imagery, and was therefore expected to cover an area of approximately 150 km^2.

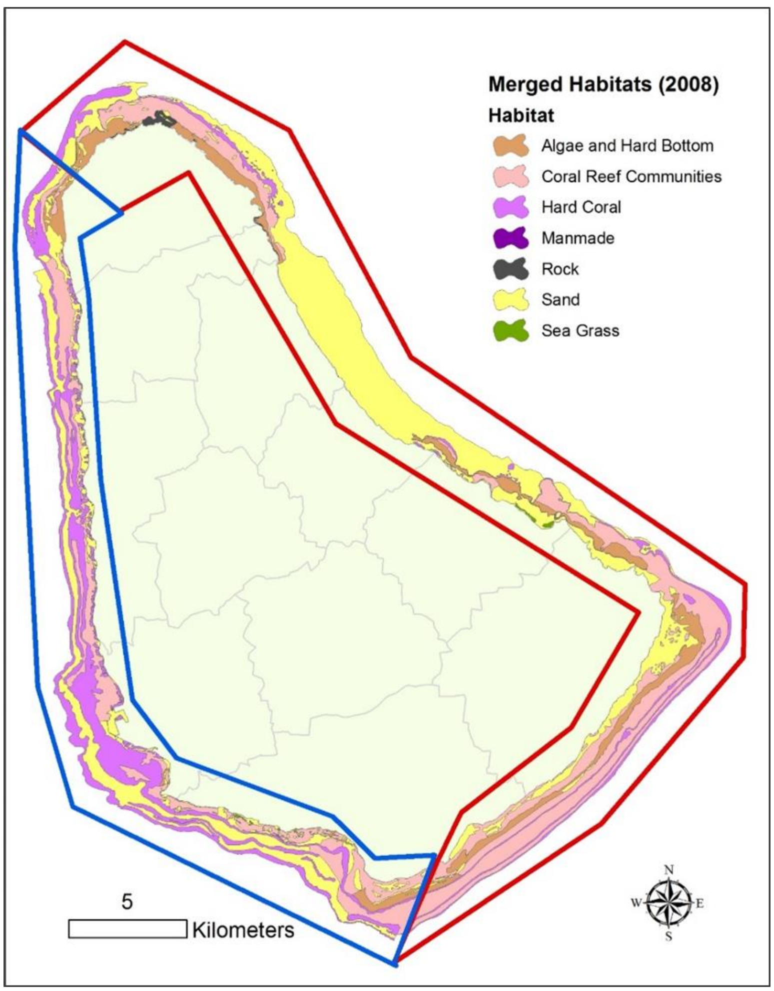

Figure 1. Island-wide shallow marine habitat map for Barbados (Welch 2008) created based on merging Proctor and Redfern et al. (1984) (blue polygon) and Halcrow (1998) (red polygon) datasets to create a simplified seamless habitat map.

2 METHODS

2.1 Habitat classification scheme

An essential step in the production of a marine habitat map is the selection of a locally-relevant habitat classification scheme, i.e. one that is appropriate for the main purpose and meaningful to the key stakeholders. In this case the main purpose of the map is to support national-level spatial planning and management of coastal resources in Barbados, and the key stakeholders were considered to be the CZMU with the mandate to manage the coastal resources of Barbados, the Fisheries Division responsible for managing the island's fishery resources and the University of the West Indies.

The first step was to review the various marine habitat classification schemes that have been or are being used to describe and map reefs and associated ecosystems within the Caribbean, both locally in Barbados (e.g. Proctor and Redfern et al. 1984, Halcrow 1998, CZMU 1999a, CZMU 1999b, Welch 2008) and elsewhere in the region (e.g. Belize: Mumby and Harborne 1999; USVI: Kendall et al. 2001; Global: Andrefouet et al. 2003, Ball et al. 2006, Madden and Grossman 2004; St. Kitts: Agostini et al. 2010; Haiti: Rowlands et al. 2012; Grenada Bank: Baldwin 2012; Pedro Bank: Purkis 2014; Grenada: Purkis 2015). Next an extensive literature and data search of secondary information on the distribution of coastal and marine habitats of Barbados was undertaken. This included marine habitat descriptions and coral monitoring reports, marine-related GIS datasets, satellite imagery, aerial photographs, marine habitat maps and other collateral marine habitat information sources (e.g., BRI 1984, Proctor and Redfern et al. 1984, Delcan 1994, Lewis and Oxenford 1996, Halcrow 1998, CZMU 1999a, CZMU 1999b, Welch 2008, Office of Research 2014). All of the existing classification schemes and associated habitat information was reviewed and assessed in terms of geographic extent, detail (i.e. scale/resolution) and appropriateness for use in a marine management context in Barbados.

A meeting was then held with experts from CZMU and Baird to review collected information and collaboratively develop an initial 18 class benthic habitat classification scheme for the mapping project (Appendix 1). This habitat classification scheme was shared with the remote sensing expert, and based on his knowledge of the limitations of remote sensing techniques and the eCognition software was subsequently revised to a slightly simpler scheme. For example, the three subclasses of macroalgae in the initial scheme were merged into one because the spectral signatures of red, green and brown algae are indistinguishable. The intertidal classes were dropped as these lie beyond the agreed extent of the marine mapping. The artificial structures were dropped, given that these are already being mapped by another component of the CRMP. Thus a 12 class benthic habitat scheme that was thought to represent all known habitat types found around the island was agreed upon (Table 1).

Table 1. Twelve-class benthic habitat classification scheme developed by the CZMU and CERMES in May 2015.

Proposed habitat class		Additional parameters/notes
Linear barrier/shoal reef		Found mostly on the south east coast. Mostly coral rock (old *A. palmata* framework) very little live coral, waves break on this reef continuously
Fringing reef (< 5m depth)	Reef flat	Closest to shore: eroded reef framework with macro- and turf algae
Fringing reef (< 5m depth)	Crest and coalesced spur zone	Middle segment: solid reef (no grooves): macroalgae with fire corals (*Millepora* spp). *Porites* spp., *P. clivosa* and some *A. palmata* regrowth
Fringing reef (< 5m depth)	Coral spur and grove zone	Seaward edge: living coral spurs and sand grooves
Bank reef		Narrow offshore bank reef: runs parallel to coastline 800-1000 m offshore, more or less continuous reef down the west and south-west coasts. Rise from 45m inshore side to 20-15m along crest to 45+ m offshore. May also extend around SE coast seaward of the linear barrier/shoal reef. Snapper bank (70m depth) is seaward of the bank reef, at least on W and SW coasts and may exist on SE.
Patch reef (5-12 m depth)	Gorgonian dominated hard ground	Veneer of sand that is quite dynamic. Gorgonians are the dominant feature, but hard corals relatively abundant and dominated by *Diploria* spp. Found along south coast inshore of the bank reef.
Patch reef (5-12 m depth)	Sponge dominated hard ground	Referred to locally as 'patch reef'. Veneer of sand that is quite dynamic. Sponges are probably the most dominant feature, but hard corals also abundant and comprise mostly *Orbicella* spp. Found along the west coast between fringing and bank reefs on flat area and seaward facing slope.
Patch reef (5-12 m depth)	Other coral communities	Mixed reef communities. Likely present on SE and N coasts and poorly documented areas elsewhere.
Seagrass		Remaining fragments of *Thalassia testudinum* grass beds mixed with *Syringodium filiforme* are heavily grazed and growing mostly on rubble substrate. Some sandy bays with very sparse cover of very fine *Halodule wrightii.*
Algal hard bottom		May comprise mostly brown algae (e.g. benthic *Sargassum* spp., *Dictyota* spp.), mostly green algae indicating high levels of nutrient pollution (e.g. *Ulva* spp., *Chaetomorpha* spp.), or a mixed diverse community (including *Halimeda* spp, *Padina* spp., *Galaxaura* spp. etc.)
Unconsolidated sediments	Sand	
Unconsolidated sediments	Coral rubble	Unconsolidated coral rubble, some semi-consolidated. In deeper areas (40+ m) inshore of bank reef, associated with sparse coral (whip corals) and sponges.

2.2 Pre-processing

2.2.1 Image preparation

Initially this project intended to map the seabed based on the combination of aerial ortho-photographs (0.1 m resolution) and LiDAR bathymetry data provided under the CRMP study (Appendices 2-3). Capturing seabed topography, the LiDAR data were useful for the characterization of habitats with topographic relief, such as reefs, and unconsolidated sediments with bed forms. However, inspection of the aerial photography by the remote sensing expert revealed that the ortho-photographs suffered from an excessive amount of sun glint which would in turn hinder the accuracy of the resulting mapping product. As such, high resolution 8-band multispectral WorldView-2 satellite data (.48 cm panchromatic and 1.85 m multispectral resolution; Appendix 4) were acquired for the entire coastal zone and used with the LiDAR as the primary data sources for the marine habitat mapping.

The WorldView-2 imagery data were acquired, mosaiced, radiometrically corrected and then atmospherically corrected to yield units of reflectance at the water surface. These routines were conducted using ENVI software (RSI Inc., v. 4.8) and Matlab (R2013a). With the bathymetric LiDAR in hand, it was possible to apply a water column correction to the shallow areas of the mosaic to enhance the fidelity of the seabed features. Lacking spectral coefficients, the aerial photographs, which have a spatial resolution of 0.1 m, were manipulated in raw units of digital number (DN). The LiDAR data were interpolated to a raster grid with a spatial resolution of 2 m and units of depth below lowest astronomical tide.

In addition, CERMES provided all secondary GIS data, habitat maps and other collateral reports as well as a slide show of aerial imagery with textual descriptions of the known marine habitats around the island of Barbados to aid aspects of the object based and visual interpolation involved in the remote sensing process (Appendix 5).

2.2.2 Object-based mapping for the draft map

An object-oriented approach was adopted for delineating benthic habitat in the WorldView-2 imagery and LiDAR bathymetry (Purkis and Klemas 2011). This approach contrasts the more commonly employed “pixel-based” unsupervised classifiers that have traditionally been used for coastal seabed mapping. The principal disadvantage of the unsupervised classification approach in a submerged setting, such as the shallow habitats of Barbados, is that since light in the visible spectrum is so rapidly attenuated by water, bathymetric variations account for the majority of spectral variation within the remote sensing imagery, rendering the seabed habitat differences challenging to separate.

In contrast to pixel-based classification methods, object-oriented image analysis - the strategy used to produce the map in this study - segments satellite data into landscape objects that have ecologically-meaningful shapes, and classifies the objects across spatial, spectral and textural scales. In this study, an object-oriented classification was employed to delineate habitat “bodies”, interpreted to be distinct patches of uniform benthic habitat. Due to the flexibility afforded by including non-spectral attributes of the imagery (e.g., texture, spatial, contextual information, and the LiDAR terrain model) into the classification workflow, object-oriented methods have been shown to yield significant accuracy improvements over traditional pixel-based image analysis techniques (Kelly and Tuxen 2009, Purkis and Klemas 2011, Purkis et al. 2014 and Purkis et al. 2015).

The software used for mapping in this study, eCognition software (v. 8.9 Trimble), tenders a suite of object-oriented image analysis algorithms having particular utility for creating thematic maps from remote sensing data, including submerged targets. Based on the secondary information of habitats, an object-based analyses of the WorldView-2 satellite imagery, LiDAR bathymetry data and aerial orthophotographs were rendered to segment the imagery into landscape objects and accordingly apply the draft classification scheme to create an initial draft benthic habitat map for Barbados (Figure 2).

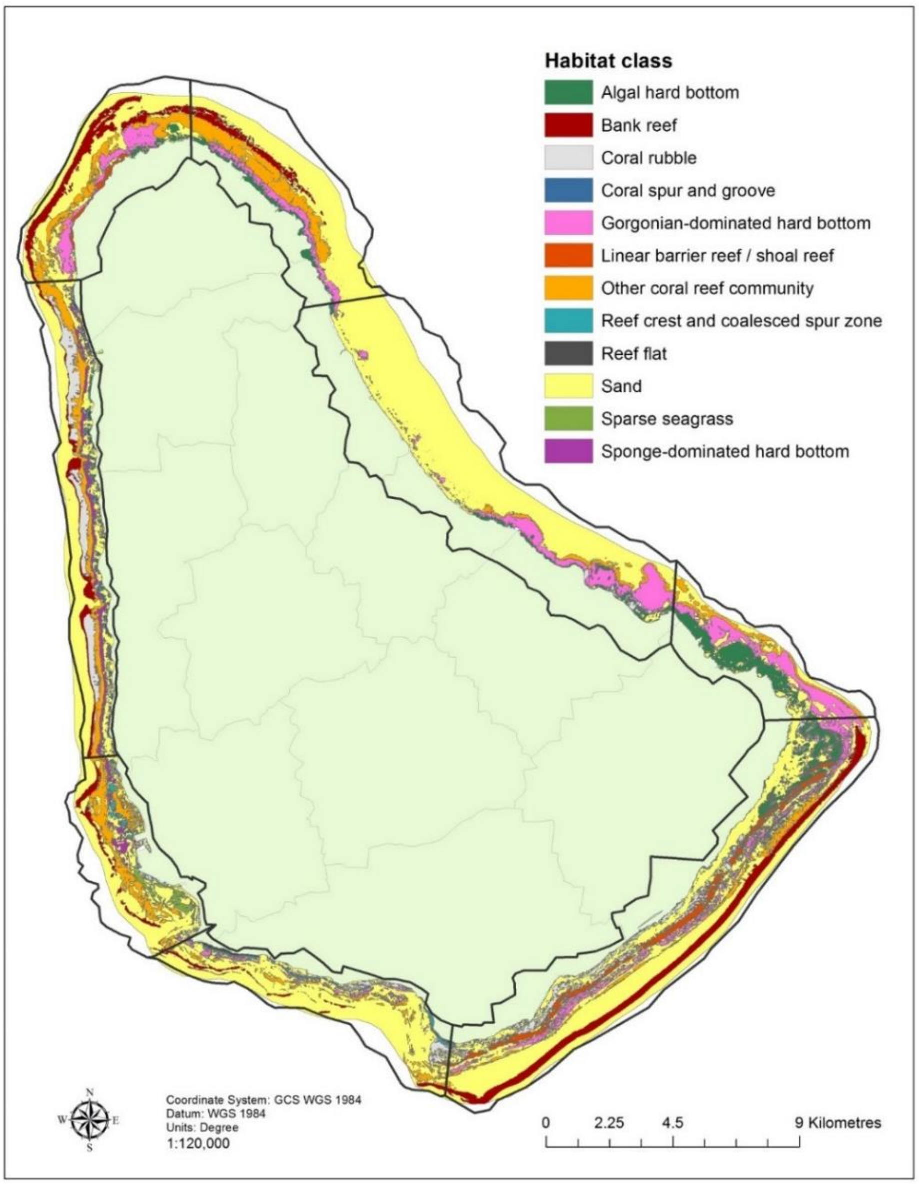

Figure 2. Draft habitat map (sub-1) overlain with the CZMU's coastal zone management areas (CZMAS shown as numbered grey polygons) that was used to design the ground-truthing field survey

2.3 Ground-truthing

2.3.1 Sampling design and site selection

The draft habitat map overlain by the eight Coastal Zone Management Areas (CZMAs) (Figure 2) was used to guide the sampling design for the ground-truthing field survey. The CZMAs, defined in the Integrated Coastal Zone Management Plan for Barbados, divide the island’s coastline into eight sectors according to local geomorphology and wave conditions (CZMU 1999a; 1999b). The sampling design was based on: (1) the need to ensure adequate coverage of each CZMA; and (2) recommendations from the remote sensing expert that somewhere between 200-400 underwater videos would be needed, with sampling effort spread across habitat classes, coasts and depth contours around the island to adequately guide the object-based mapping process across the 150 km^2 area.

As a result, a non-random sampling design was applied, firstly stratified by the eight CZMAs and then by the draft habitat map and depth contours (at 10 m increments). This was done firstly by using the ArcGIS ‘fishnet’ tool to create a (100m x100m) grid across the geographical extent of the draft habitat map. Next, the Barbados mapping extent was ‘clipped’ into the eight CZMAs and printed as 1:10,000 hard-copy maps clearly showing the presumed habitat type, depth contours and sampling grid (Figure 3). The field survey team (e.g. 3 marine biologists, 2 fishers) then reviewed each map and used their local knowledge of the marine environment around Barbados (i.e. depth, accessibility, accuracy of draft habitat polygons, etc.) to guide the selection of approximately 50 survey sites (grid cells) per CZMA according to the predetermined parameters (habitat and depth). Within each CZMA, a minimum of 5 grid cells (sites) were chosen for each benthic habitat class represented, ensuring a reasonable spread of sampling effort across the various depth contours. The GIS interface was then applied to extract the centroid of each selected grid-cell and provide an x,y coordinate point for each survey site. Lastly the Garmin GPS DNR software was used to convert these x,y points into GPS waypoints (.gpx) that were subsequently uploaded to a handheld GPS (Garmin 72H) for use in navigating the survey vessel to each selected sampling site during the field survey.

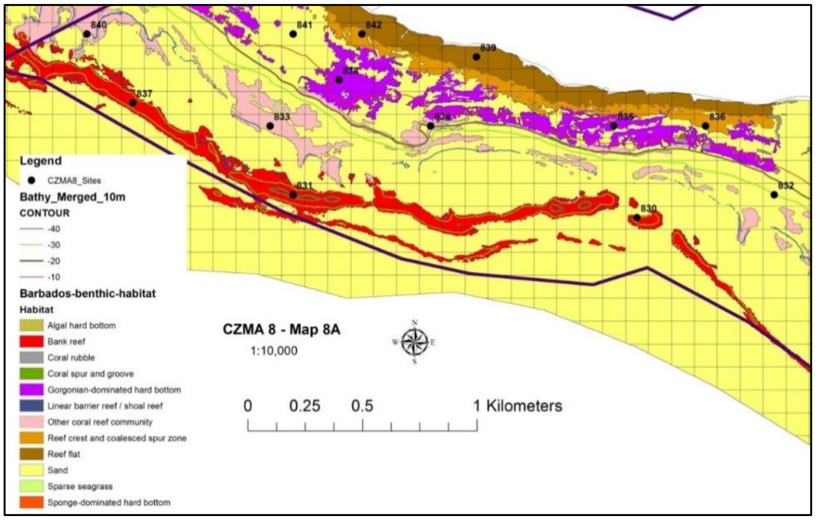

Figure 3. A section of the draft habitat map (sub-1) overlain with 100 m grid cells.
Selected grid cell centroids were converted to points and numbered sequentially according to CZMA.

2.3.2 Field survey

A list and brief description of the field equipment used in the ground-truthing surveys is given in Table 2. Field surveys were conducted using small open fishing vessels (<10 m in length) with the assistance of local captains during July-September 2015. At each survey site, a short video clip (30-60 seconds) of the benthic habitat was recorded using a tethered underwater SeaViewer drop-video camera setup with the SeaTrack GPS overlay. A second set of video footage was also collected at each site using a GoPro video camera (with two underwater lights rigged to a handlebar). This was attached to the top of the SeaViewer camera set-up (Figure 4) and provided supplemental high quality video footage. Once the SeaViewer video drop-camera was lowered to approximately 1m above the bottom and angled to a landscape perspective, the recording was started and the start location of each video clip was recorded using a Garmin E-trex handheld GPS. In addition, the SeaTrack GPS video overlay (with the attached handheld Garmin E-trex GPS) allowed for real-time site locational information (x, y) to be written to the SeaViewer video footage. Note that the supplemental GoPro camera could not be remotely controlled and was therefore set to record for the whole deployment and retrieval process.

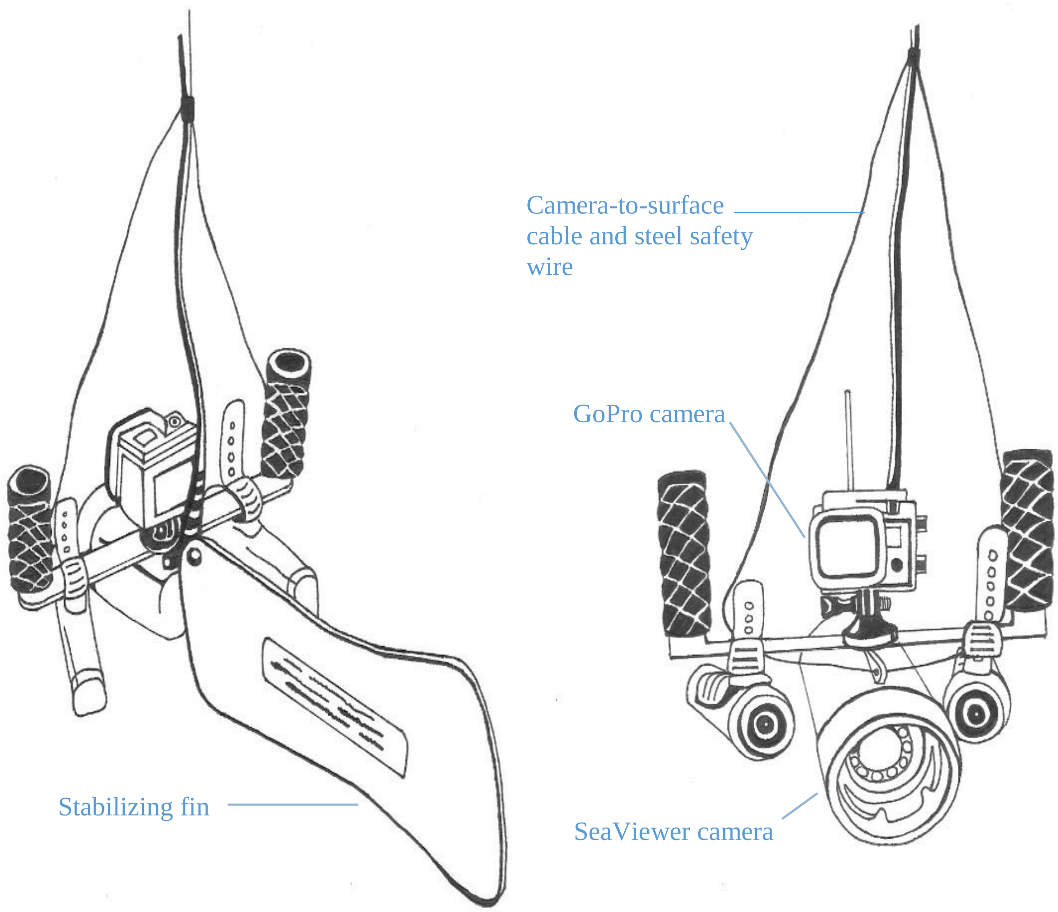

Figure 4. Diagrams showing the set-up for the tethered underwater video cameras. The SeaViewer video drop-camera (with led light surround), stabilizing fin blade, and camera-to-surface cable is shown from the back (*left*) and front (*right*). The GoPro video camera with red filter is fixed above the SeaViewer camera via a handlebar with two additional underwater lights attached.

Table 2. Detailed list of field equipment with a brief description of the use of each item.

Equipment	Purpose
Speedtech handheld depth gauge	Determine water depth at each survey site to guide the deployment of the SeaViewer video camera
Garmin 72H	Guide the captain to pre-determined ground-truthing survey sites
Garmin E-Trex	Track real-time location (points and tracks) on the SeaViewer underwater video (via the SeaTrack GPS Overlay).
GoPro Hero 3 (2)	Record supplemental, high resolution underwater video at each site. Extra batteries and camera were carried as backup.
Seiki portable screen (1)	Visual display of the underwater environment via the Seaview drop-video camera system (drawback is that it does not record footage).
Seaviewer underwater video camera with LED light array and a 75 metre cable (2)	Capture underwater video of the benthic environment with real-time viewing of video footage via the laptop or DVR. Attached to the Garmin E-Trex via the SeaTrack GPS Overlay. (An extra SeaViewer camera was obtained and reserved as a backup).
SeaTrack GPS Overlay (1)	Overwrites the real-time GPS coordinates, or spatial location of the survey data on to the video recorded using the SeaViewer system.
Light & Motion GoBe 500 flashlights (2)	Provide additional external source of light to underwater video cameras.
Backscatter GoPro double handle and tray with tripod adapter	Underwater handle bar used to rig the GoPro and SeaViewer systems together and mount additional GoBe flashlights to the camera set-up.
LG G Pad 8.0 tablet with Locus Map Pro software application	Provide real-time visualisation of the vessel's location on the draft habitat basemap. Useful in choosing additional sites or to verify field survey location.
Bestek 400W power inverter with marine battery	Provide power to the SeaViewer and SeaTrack systems and the laptop or DVR equipment.
Canon Powershot D20 waterproof camera	Capture additional photos and videos of benthic habitat at survey sites.
Additional survey equipment	Large Rubbermaid plastic container and Pelican case to protect electronic equipment at sea, pencils, slates, external hard drive for the backup and storage of video and data collected.
Dell Latitude laptop	Record and visualise video footage collected at sea using the SeaViewer underwater camera.
EZ Cap	Conversion of RCA video output to USB to allow for recording of video via the laptop.
Snorkelling gear	Validate unusual habitat *in-situ* or record video at survey sites in the case of equipment failure.

At each site, additional data were recorded on a waterproof slate, including: time of the survey, water depth to the nearest metre using a handheld depth-sounder, initial description of the benthic environment, and any other notes considered relevant. The SeaViewer and associated equipment was powered using a heavy duty marine 12 volt battery and the video footage was visualized in real-time and recorded *in-situ* using a Dell laptop computer (Figure 5). For a minority of sites, (in cases where the SeaViewer equipment malfunctioned, or for re-inspection of habitat type at sites where video recordings were of poor quality, or for additional ground-truthing of possible inconsistencies in the draft maps), a handheld camera, operated by a free diver and/or SCUBA diver was used to obtain ground control information. Additionally, the use of an LG GPad 8 tablet (with an internal GPS) loaded with MB Tiles of the WV2 imagery, survey sites and baseline habitat map allowed for real-time visualization of the vessel's location on the draft habitat map. The use of the tablet was of particular use when the pre-selected ground-truthing sites were found to be inaccessible (largely due to breaking waves) and alternate sites (within the same habitat class) needed to be selected in the field.

Figure 5. Photographs showing the setup and operation of equipment at the field sites. *Top left*: camera rigging and cable stored in a basket between sites; *top right*: dell latitude laptop resting on the pelican case; *bottom left*: deployment and monitoring of camera equipment over the side of the vessel; *bottom right*: camera equipment recording videos approximately 1 m above the substrate.

Table 3. Detailed list of software used along with a brief description of the purpose.

Software	Purpose
DNR GPS Application	Data conversion between GPS (.gpx) file format and shapefile format.
ArcGIS 10.1	Used to view benthic habitat data, create survey site maps and join attribute data to the spatial location of survey sites (x,y points).
Ulead Video Studio	Application that allowed for the Seaviewer video camera feed to be recorded to the hard drive of the laptop computer.
Handbrake Software	Compression of the video footage from the Seaviewer camera
Microsoft Excel	Spreadsheet of attribute data collected in the field. This table was then joined to locational survey site (x,y point) data.

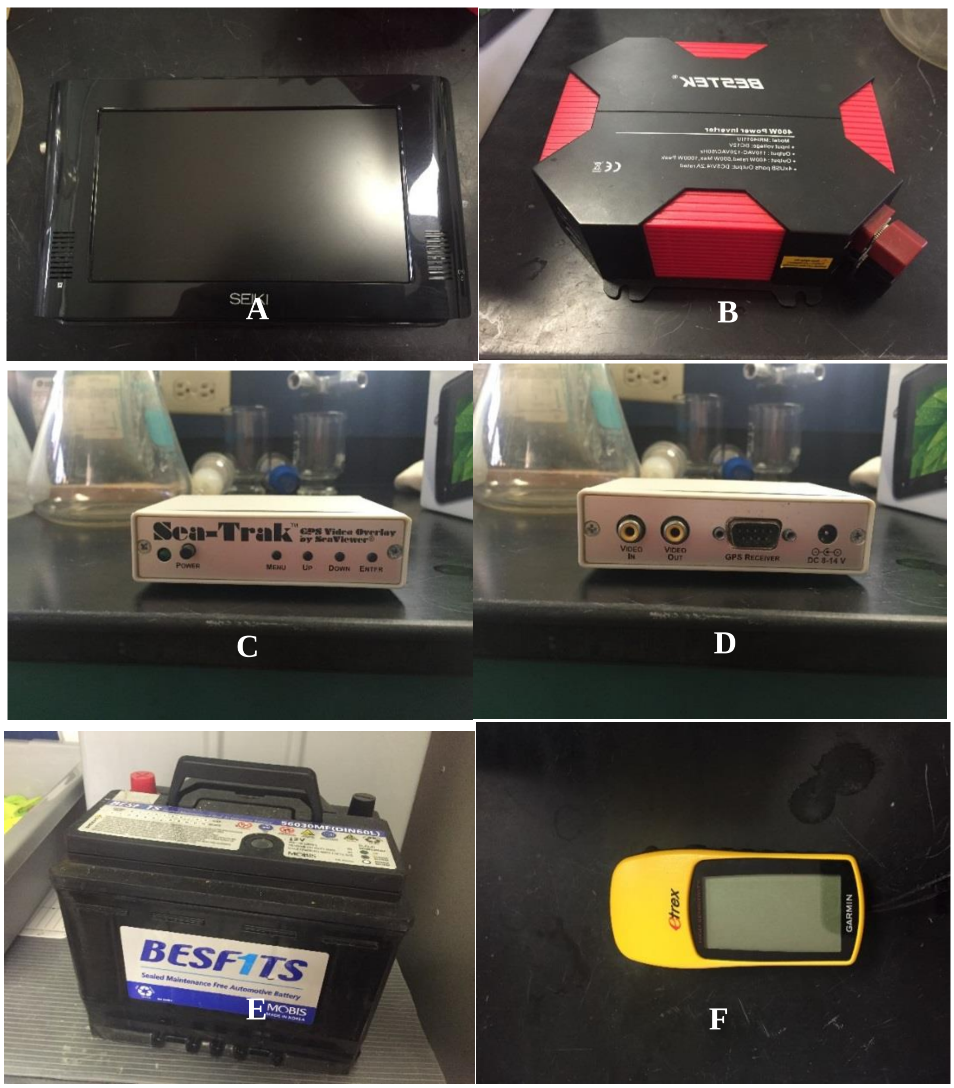

Figure 6. Photographs of some of the equipment used in the SeaViewer setup; A - seiki portable screen; B - Bestek power inverter; C - SeaTrak gps video overlay receiver (front view); D - SeaTrak gps video overlay receiver (rear view); E - Besfits 12v marine battery; F - Garmin e-Trex handheld gps.

2.3.3 Data handling

The video footage for each survey site was downloaded, compressed using Handbrake software and renamed by survey site number. All field survey attribute data and other field notes were entered by site number into an Excel spreadsheet. The GPS survey sites (points) were downloaded and converted from (.gpx) format into a shapefile format using the Garmin GPS DNR software application. Next the survey site (point) data were imported into the GIS and a table join was used to connect corresponding attribute data and videos with the spatial location of each survey site.

2.4 Post-processing

2.4.1 Classification of videos

For each site surveyed (or ground control point), both the SeaViewer and GoPro video footage were reviewed to determine the habitat class (Table 1), and to record additional habitat attributes (e.g. substrate, relief, community cover, dominant species group; Table 4) on the excel spreadsheet. Detailed descriptions of the habitat attributes and methods for classification are described in more detail below.

Table 4. Additional qualitative and semi-quantitative attributes recorded for each ground-truthing site based on the video footage.

Attribute	Type or Level	Rank
Substrate	Beach rock, pavement, reef framework, rubble, sand	Primary, secondary
Relief	High, medium, low	-
Community cover	Bare, sparse, medium, dense	-
Dominant species group	Hard corals, plume gorgonians, sea fans, cyanobacterial mat, macroalgae, encrusting coralline algae, seagrass	Top four groups noted by rank 1 – 4 (where 1 is dominant)

<u>Substrate</u>

The substrate describes the characteristics of the seabed and was classified as pavement, reef framework, rubble or sand. Sand covers all types (mostly carbonate), and ranged from coarse to fine. Rubble refers to broken coral fragments, and ranged from small *Porites* spp. corals to larger *Acropora palmata* slab rubble that may be either loose or semi consolidated. Reef framework refers to calcium carbonate coral rock where the reef structure can still be clearly seen. Pavement refers to heavily eroded flattened coral reef rock or beach rock environment where no reef structure is apparent. At sites that appeared to have a mixed substrate, both the primary and secondary substrate were recorded.

Relief

Relief describes the rugosity or three-dimensional structure of the substrate and was classified as low, medium, or high. For example, sand would generally be recorded as low relief, whereas reef framework structures can be quite variable ranging from low to high.

Community Cover

Community cover was used to describe the approximate coverage of the main living community groups (i.e. hard corals, gorgonians, sponges, algae) found on the substrate and was classified as bare, sparse, medium or dense. Bare was used to describe communities with no or virtually no living substrate cover. Sparse refers to communities with very low cover, but worth noting. Medium refers broadly to communities with a range of cover around half the substrate, whereas high was reserved for communities with virtually no substrate left uncovered.

Dominant group

After the initial screening of the videos, another round of viewing commenced to allow for a finer scale analysis or ranking of the dominant communities. This analysis scored the relative abundance of the eight living community groups of organisms found on the substrate at each site (e.g. cyanobacteria, macroalgae, hard coral, sea fans, sea plumes, sponges, encrusting coralline algae (ECA) and seagrass. This at each site, the top four groups were ranked, and all others given a value of 0. Where groups appeared equally abundant, they were given a shared rank.

Habitat classification

Although the classification of attribute data was relatively straightforward, in many cases the determination of habitat class based on the draft 12 class habitat scheme (Table 1) was not as simple as anticipated. It was therefore decided that all video footage (taken using both the SeaViewer and GoPro) would be simultaneously reviewed by two experts (with extensive knowledge of the reef environment in Barbados) until the final habitat classification for each ground control point was agreed on by both experts.

After this round, the GIS interface was used to symbolize ground control points (as colour-coded points by habitat type) overlain on top of the draft habitat map. Each coastline was then carefully inspected for consistent habitat patterns and any apparent misfits or inconsistencies were noted directly on the map (Figure 7). Any site of concern was then re-examined, using both sets of videos and any additional photographs or field comments that may have been taken and was reclassified only if both experts agreed.

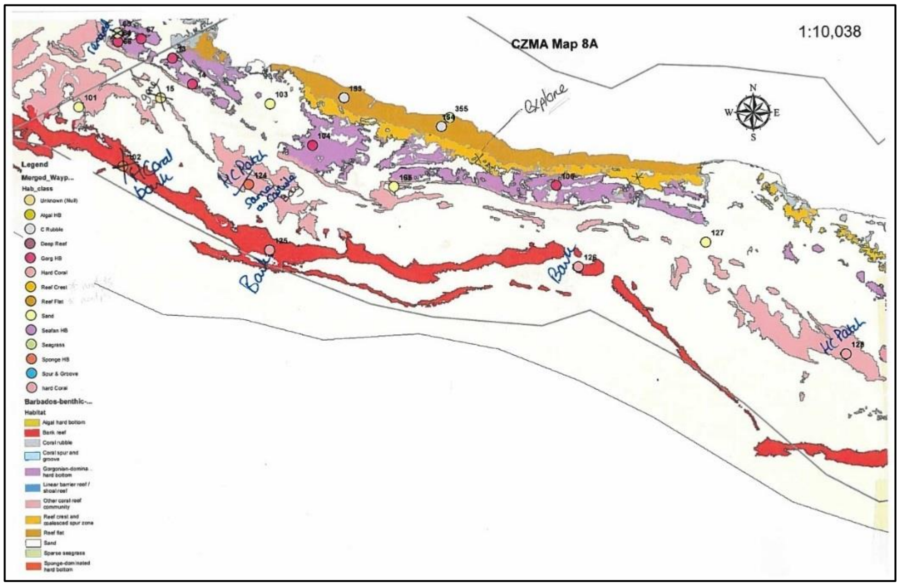

Figure 7. Example of annotated draft habitat map used in the iterative mapping process.

Quality Assurance

A quality assurance step was applied before proceeding with the full analysis to test the reliability of the habitat classification methods and scoring of the additional habitat attributes. A random integer generator (www.random.org) was used to select the 10% sub-sample, retaining only sites that had the higher resolution GoPro footage. The sub-sample (i.e. 35 sites) were checked for: (1) observer consistency; and (2) for habitat variation using both of the video clips and a series of still photographs randomly captured from each video. Screenshots were given a label different to their parent video to remove observer bias. All sub-sample videos and pictures were analyzed and the attributes scored in a spreadsheet as previously described. Further each screenshot was re-examined (i.e. scored twice) over a week period. Attribute data were compared across the videos, three screenshots and repeated screenings to assess both observer consistency and examine variability in the classification of habitat attributes.

2.4.2 Refining the classification scheme

Another meeting was held with experts from CZMU and Baird to review the ground-truthing information and analysis, and to reach agreement on any refinements needed for the benthic habitat classification scheme and the final map.

Detailed textual descriptions of each of the revised benthic habitat classes accompanied by a corresponding point shapefile of the ground control survey sites (attributed by site number, video number and habitat class) and a folder of all video footage collected (renamed by site number) were provided to the remote sensing expert to guide the production of the final marine habitat map for Barbados.

2.4.3 Object-based mapping for the final habitat map

Ground-control points and textual descriptions of each of the 12 final benthic habitat classes were used to guide the object-based mapping of benthic habitat. Statistics pertaining to the spectral and textural properties of the satellite imagery corresponding to the habitat types were extracted at points where the 361 samples provide an unequivocal determination of benthic character. These statistics were used to drive a preliminary segmentation of the imagery into landscape objects using the eCognition software. Expert experience and secondary habitat information provided by CERMES were used to subsequently assign a habitat category on the basis of their spectral and textural signatures to all landscape objects. Next, a filter was applied to remove redundant divisions between objects (i.e. those divisions separating two objects of the same habitat category). This step was accomplished within eCognition using the "merge region" algorithm. In this way, the resulting second draft of the habitat map (i.e. SUB-2) honoured all of the ground-truthing data.

2.4.4 Final iterations to the habitat map

The second draft map (i.e. SUB-2) was reviewed by CERMES for any apparent errors or inconsistencies. Where inconsistencies were thought to occur, secondary sources were checked and additional fieldwork was undertaken using a handheld camera operated by a free diver and/or SCUBA diver to obtain supplemental ground control information. Moreover, CERMES provided a slideshow of the portions of the SUB-2 habitat map where errors occurred and provided textual descriptions of the correct marine habitat characteristics to guide the remote sensing expert in the final revisions to the habitat map (Appendix 6). Lastly a group call between CERMES, CZMU and the remote sensing expert was made to discuss the final revision and other technical aspects of the remote sensing process and production of the final map product (i.e. SUB-3).

3 RESULTS

3.1 Ground-truthing survey data

A total of 361 control points (ground-truthing sites) were surveyed around the entire island during 12 full days at sea (Figure 8). Additional attribute data (including substrate type, rugosity, community abundance and dominant community groups) provided an additional rich dataset beyond what was required for ground-truthing. Post-processing of the video clips was time consuming (15 days), but allowed for an iterative process in assigning habitat classes and the refinement of the classification scheme. The ground-truthing exercise provided the information needed to ensure that the habitat scheme was appropriate at the island scale, and that the remotely sensed habitat map was accurate and fit for purpose (e.g. locally relevant and appropriately scaled for national-level marine spatial planning and other marine management objectives).

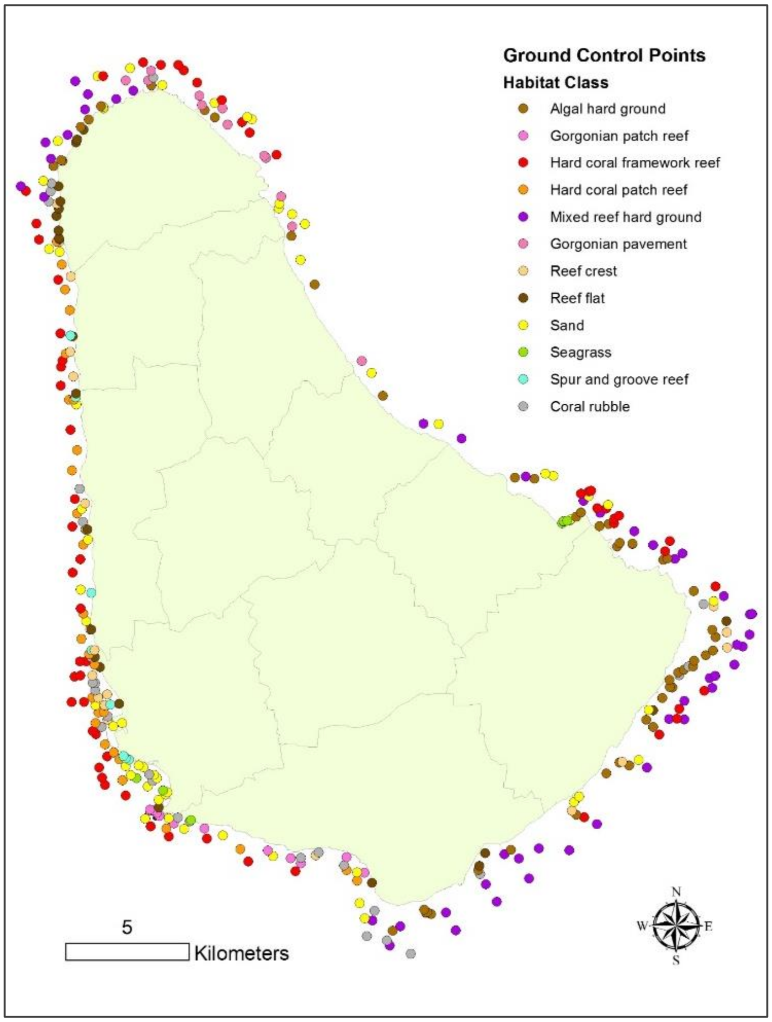

Figure 8. Map showing the locations of the 361 ground control points (coloured by habitat class) collected during the field surveys.

3.2 Marine habitat validation

3.2.1 Observer consistency

A summary of observer consistency in scoring the habitat attributes from the video footage of 35 randomly selected sites, watched twice (with the order shuffled) is provided in Table 5. The consistency for scoring both level of cover and level of relief was extremely high (> 90%). Consistency for selecting substrate type was also relatively high, with inconsistencies occurring only when there was a mix of substrates seen during the 30 second video. This in turn was addressed by adding a secondary substrate field to the attribute database allowing the observer(s) to score more than one substrate type per site.

Table 5. Summary of results of observer consistency in scoring habitat attributes based on videos (watched and scored twice each) at the 35 sub-sample sites listed by number of choices, consistency score and as a percent total.

Attribute	No. of choices	Consistency score	Percent (%) consistency
Substrate type	4	27	77.1
Density of cover	4	32	91.4
Relief / rugosity	3	33	94.3
Habitat class	12	15	42.9

Observer consistency was relatively low when selecting the habitat class (< 50%), with frequent inconsistencies among the three habitat classes 'algal hard ground' (AHG), 'reef flat' (RF) and 'reef crest' (RC) and between the two habitat classes 'other coral reef communities' (OCRC) and 'gorgonian hard bottom' (GHB). This result partly guided the process of refining the habitat classification scheme to ensure more definitive differences (better descriptions) among classes. As such OCRC and GHB were redefined and renamed to become 'mixed reef hard ground' (MRHG) and 'gorgonoian pavement' (GP). It also highlighted the need to use more than one expert observer simultaneously for the designation of habitat class as well as emphasized the need to review all of the footage multiple times.

3.2.2 Habitat variability

A summary of the results of the variability in the scoring of habitat attribute data (specifically the dominant living group) based on the three separate screenshots taken from each site (e.g. obtained from each of the 30 second videos) for each of the 35 sub-sample sites is provided in Table 6. The majority (85%) of sub-sample sites showed complete agreement with only one site (3%) resulting in no consistencies. This result confirmed that the variation in habitat observed during a 30 second site video was very low and thus was appropriate to use the entire video footage for scoring attributes.

Table 6. Summary of results of habitat variation (dominant group) based on the three screenshots derived from the same site (30 second video) at each of the 35 sub-sample sites.

No. of same selections	3/3	2/3	0/3
No. sites	30	4	1
% of sites	85.7	11.4	3.3

3.3 Refinement of the benthic classification scheme

A final 12 class benthic habitat scheme was developed and applied to habitat mapping for Barbados (Table 7; Figure 9) with a thirteenth class (deep water) used where habitats were beyond the resolution of the remote sensing technology. A summary of each marine habitat class and additional attribute data collected at each ground-truthing site, the depth ranges, average depth and an index of live community cover across all habitat classes are provided in Table 8. Detailed descriptions of each class are provided here.

Algal Hard Ground

The algal hard ground (AHG) habitat is generally characterized by a low relief, pavement substrate with a medium to dense living community cover. AHG habitat is typically dominated by a variety of macroalgal species that seem to vary with depth and location (distance from shore, exposure to wave energy and substrate type) and commonly includes: green algae genera including *Halimeda*, *Caulerpa*, *Avrainvillea*; brown algae genera including benthic *Sargassum*, *Dictyota*, *Padina*; encrusting hard corals: *Psuedodiploria clivosa*, *Porites astreoides*; Fire corals: *Millepora* spp.; and white sea urchins: *Tripneustes ventricosus*. The dominant community group in the AHG habitat class is almost always macroalgae with rare occurrence of co-dominance by hard corals, sea fans and sponges. The community group of secondary dominance is relatively evenly split by hard corals, gorgonians and sponges. This habitat is found in a median depth of this 5.5 m, but can be found from 1 to 26 m in depth and is restricted to the southeast, east and north coasts of the island.

Coral Rubble

The coral rubble (CR) habitat is generally characterized by a low relief, rubble substrate with a sparse to medium living community cover. CR is typically dominated by a variety of macroalgal (green, brown and red) species and turf algae and commonly includes: green algae genera such as *Caulerpa*, *Avrainvillea*; encrusting hard corals: *Porites astreoides*; starfish: *Oreaster reticulatus*; and white sea urchins: *Tripneustes ventricosus*. The dominant community group in the CR habitat class is often macroalgae with some co-dominance by sponges, hard corals, gorgonians, cyanobacteria and encrusting coralline algae. The community group of secondary dominance is relatively evenly split by hard corals, and sponges followed by gorgonians, sea fans, cyanobacteria and macroalgae. This habitat is found in a median depth of 6.9 m, but can be found from 1 to 39 m in depth and is found around the island with assemblages found on the north coast, the southeast coast and the southwest coast.

Gorgonian Patch Reef

The gorgonian patch reef (GPR) habitat is generally characterized by a medium relief, sand substrate with a medium to dense living community cover. GPR is typically dominated by a variety of hard and soft corals and commonly includes: *Pseudodiploria strigosa* and *Diploria labrynthiformis* along with sea plumes and sea fans. The dominant community group in this habitat class are gorgonians. The community group of secondary dominance is relatively evenly split by hard corals and sponges. This habitat has a median depth of 6.9 m, but can be found from 3 to 14 m in depth and is restricted to the southwest coast of the island.

Table 7. Final benthic classification scheme used to map the coastal marine habitats of Barbados in 2015.

Habitat Class		General Description
Name	**Code**	
Reef flat	RF	Flat, usually eroded coral rock or beach rock pavement, dominated by turf and or macroalgae, always shallow. Mostly along shore, occurs on all coasts, and inner (shoreward) zone of all fringing reefs
Reef crest	RC	Pitted, eroded reef framework with low diversity of corals – often dominated by fire corals and *Porites asteroides* and may have large areas of the encrusting zoanthid *Palythoa caribaeorum*. Shallow, generally high wave energy. Found as middle zone of fringing reefs, and some other high energy areas offshore especially along SE coast.
Spur and groove reef	SPGR	Low to high coral cover, distinct reef framework on outer (seaward) zone of fringing reefs of W coast. Dominated by fire corals, finger coral, *Porites porites*, pencil coral, *Madracis mirabilis*. Sides of spur may have significant growth of *Orbicella annularis*, and ends of spur may have large *Siderastrea sideria* colonies.
Gorgonian patch reef	GPR	High density of plume gorgonians on flat substrate of coral rock pavement with sand veneer. May have relatively high abundance of coral heads and sponges. Found along SW coast in shallow water.
Hard coral patch reef	HCPR	Generally dominated by corals (usually *Orbicella annularis*) on a flat substrate – usually sand or rubble, no substantial reef framework. Often high density of sponges and some gorgonians with sand/rubble patches in the reef.
Hard coral framework reef	HCFR	Massive reef framework, rugose, often steep sided, usually dominated by hard corals with sponges and gorgonians abundant. Corals often in plate-like growth forms. Shallower parts of reef may have more sand, more gorgonians and higher community diversity. Deeper areas of slopes are dominated by encrusting coralline algae and sponges, bottom of slopes are deep with little living. Occurs on classic bank reefs of W and SW coasts and steep slopes of W, SE, E and N coasts. High species diversity.
Gorgonian pavement	GP	Scoured flat pavement with relatively sparse but diverse community - usually gorgonian dominated (including seafans) but other classes (sponges and macroalgae) present. Very little if any hard coral. Found predominately on the Northeast coast of Barbados.
Mixed reef hard ground	MRHG	Usually on flat pavement with sand veneer or rubble. Diverse dense community - usually gorgonian or seafan dominated but other classes (hard coral, sponges, macroalgae) may be equally or almost as dominant.
Algal hard ground	AHG	Macroalgae dominant, similar to reef flat in some cases. May have encrusting corals or seafans. Usually fairly flat substrate.
Coral rubble	CR	Mostly bare coral rubble or with very sparse community of turf algae, small coral heads or sponges.
Sand	SD	Mostly bare sand or with very sparse community.
Seagrass	SG	Very sparse seagrass on sand or rubble substrate. Maybe mixed species, often with rhizophorous macroalgae (*Caulerpa* spp.) and *Halimeda* spp.

Figure 9. Photographic images showing typical appearance of each habitat used in the final benthic classification scheme to map the coastal marine habitats of Barbados in 2015.

Gorgonian pavement

The gorgonian pavement (GP) habitat is characterized by a low relief, pavement substrate with a sparse to medium living community cover. GP is typically dominated by gorgonians and commonly includes: gorgonian sea fans; sea plumes; small encrusting hard corals: *Porites astreoides;* and white sea urchins: *Tripneustes ventricosus*. The dominant community group in this habitat class is almost always equally shared by gorgonians and sea fans. The community group of secondary dominance is often macroalgae followed by sponges, gorgonians, hard corals and sea fans. This habitat has a median depth of 12.8 m, but can be found from 6 to 20 m in depth and is restricted to the northeast coast of the island.

Hard Coral Framework Reef

The hard coral framework reef (HCFR) habitat is characterized by a low relief, pavement substrate with a medium to dense living community cover. HCFR is typically dominated by a high diversity of hard coral species whose growth forms and health vary with depth and location. Plate-formed corals are found along the slopes whereas the deeper sites near the base of slopes are mostly dead hard coral species (with encrusting coralline algae cover) with some sea whips and sponges. Also found in this habitat is green algae (*Halimeda* spp.), various brown algae families, and red algae (*Amphiroa* sp.) with the occurrence of plume gorgonians in the shallower areas. The dominant community group in this habitat class is almost always hard corals with occurrences of co-dominance by sponges, encrusting coralline algae, gorgonians and macroalgae. The community group of secondary dominance is relatively evenly split by sponges, gorgonians and encrusting coralline algae followed by hard corals, macroalgae and sea fans. This habitat has a median depth of 25.6 m, but can be found from 13 to 50 m in depth and is found consistently along all coasts of the island.

Hard Coral Patch Reef

The hard coral patch reef (HCPR) habitat is characterized by a medium relief, sand substrate with a medium to dense living community cover. HCPR is typically dominated by a variety of hard coral species but most frequently (*Orbicella annularis)*. The dominant community group in this habitat class is almost always hard corals with rare occurrence of co-dominance by sponges and gorgonians. The community group of secondary dominance is sponges, followed by hard corals, gorgonians, macroalgae and encrusting coralline algae. This habitat has a median depth of 11.7 m, but can be found from 5 to 38 m in depth and is restricted to the southwest and west coasts of the island.

Mixed Reef Hard Ground

The mixed reef hard ground (MRHG) habitat is characterized by a medium relief, pavement substrate with a medium to dense living community cover. MRHG is typically dominated by a high diversity of hard coral, sponge and gorgonians and commonly includes green algae genera (*Avrainvillea* spp.) and white sea urchins. The dominant community group in this habitat class is almost always gorgonians with rare occurrence of co-dominance by sea fans, sponges, macroalgae and hard corals. The community group of secondary dominance is relatively evenly split by sponge, hard corals, macroalgae followed by gorgonians and sea fans. This habitat has a median depth of 13 m, but can be found from 4 to 33 m in depth and is found along the north, east, and southeast coasts of the island.

Reef Crest

The reef crest (RC) habitat is characterized by a low to medium relief, reef framework substrate with a sparse to medium living community cover. RC is typically dominated by a variety of macroalgae species that seem to vary with depth and location (distance from shore, exposure to wave energy and substrate type) and commonly includes: green algae genera: *Avrainvillea* spp.; brown algae genera: *Dictyota* spp.; hard corals: *Psuedodiploria clivosa, Porites astreoides, Acropora palmata, Siderastrea siderea, Porites porites*; fire corals: *Millepora* spp.; and zooanthids: *Palyothoa caribaeorum*. The dominant community group in this habitat class is almost always macroalgae with occurrences of co-dominance by hard corals, sea fans, gorgonians, encrusting coralline algae and sponges. The community group of secondary dominance is almost always hard coral with rare occurrences of co-dominance by macroalgae, sponges, encrusting coralline algae, sea fans, gorgonians and cyanobacteria. This habitat has a median depth of 3.9 m, but can be found from 1 to 8 m in depth and is restricted to the southeast, southwest and west coasts of the island.

Reef Flat

The reef flat (RF) habitat is characterized by a low relief, a pavement substrate with medium to dense living community cover. RF is typically dominated by a variety of macroalgae species and commonly include: green algae general: *Valonia* spp.; brown algae genera: *Padina*; red algae: *Galaxaura* spp.; and encrusting hard corals: *Psuedodiploria clivosa*, *Porites astreoides*. The dominant community group in this habitat class is almost always macroalgae with rare occurrence of co-dominance by hard corals. The community group of secondary dominance is relatively evenly split by hard corals, sponges, encrusting coralline algae and sea fans. This habitat has a median depth of 2.3 m, but can be found from 1 to 9 m in depth and is found along the southeast, southwest and west coasts of the island.

Sand

The sand (SD) habitat is characterized by a low relief, sand substrate with a bare to sparse living community cover. SD is typically covered by a layer of cyanobacteria and commonly includes: green algae genera: *Halimeda*, and *Caulerpa*. The dominant community group in this habitat class is almost evenly split by cyanobacteria and macroalgae. The community group of secondary dominance is relatively evenly split by sponges and macroalgae. This habitat has a median depth of 15.6 m, but can be found in 2 to 51 m in depth and is commonly found around the island.

Seagrass

The seagrass (SG) habitat was rarely observed to occur yet is characterized by a low relief, sand substrate with a sparse to medium living community cover. SG abundance was always found to be sparse (never dominant) and commonly includes: *Halodule wrightii*, *Syringodium filiforme*, *Thalassia testudinum*, and *Halophila decipiens*; and commonly associated with green algae genera: *Caulerpa* and *Avrainvillea* or in coral rubble habitat. This habitat has a median depth of

3.3 m, but can be found from 1 to 15 m in depth and is restricted to only a few remaining locations found on the east and southwest coasts of the island.

Spur and groove

The spur and groove (S&G) habitat is characterized by a medium relief, reef framework substrate with a medium to dense living community cover. S&G is typically dominated by a variety of hard coral species and commonly includes: hard corals: *Orbicella annularis*, *Porites spp.*, *Siderastrea siderea* and rarely *Acropora palmata*; brown algae genera: and *Dictyota*; red algae genera: *Galaxaura* spp. The dominant community group in this habitat class is almost always hard coral with rare occurrence of co-dominance by macroalgae and gorgonians. The community group of secondary dominance is relatively evenly split by hard corals, macroalgae, gorgonians, encrusting coralline algae and sponges. This habitat has a median depth of 5.0 m, but can be found from 1 to 7 m in depth and is restricted to the west coast of the island.

Table 8. Average depth, depth range and modal index of community cover for all habitat classes in Barbados in 2015, based on additional attribute data collected at ground-truthing sites (n = 361).

Habitat Class		Depth (m)			Living Community	No. Sites (n)
Code	**Name**	**Average**	**Maximum**	**Minimum**	**Modal cover**	
GP	Gorgonian pavement	12.3	19.5	6.6	Sparse	12
MRHG	Mixed reef hard ground	13.5	32.5	4	Medium	47
HCFR	Hard coral framework reef	26.9	50	13.2	Medium	61
GPR	Gorgonian patch reef	7.8	13.7	3.8	Medium	12
HCPR	Hard coral patch reef	14.8	37.7	5	Medium	28
SPGR	Spur and groove reef	4.6	6.2	1.9	Dense	11
RC	Reef crest	4.1	8	1.9	Medium	23
RF	Reef flat	2.8	8.9	1.2	Medium	25
AHG	Algal hard ground	5.9	25.9	1.1	Medium	52
SG	Seagrass	5.6	14.9	1	Sparse	7
CR	Coral rubble	10.6	39.1	1.6	Sparse	27
SD	Sand	18.9	50.4	2	Bare	56
Total		**13.5**	**50.4**	**1**		**361**

Habitats were found over a relatively wide depth range. Although reef flat, reef crest and spur and groove reef were restricted to shallow areas, other habitats including sand, coral rubble and hard coral framework reef were found from shallow areas right down to the foot of seaward and shoreward slopes to the greatest depths surveyed (40 m). The latter habitat class, however, had very little living hard coral at these depths. Community cover ranged from typically none (bare) in sand habitats, to sparse in coral rubble, gorgonian pavement and seagrass habitats, and medium or dense coverage in all other habitats. The relative level of rugosity recorded across habitat classes is shown in Figure 10. The most rugose habitats were mixed reef hard ground, hard coral framework reef, hard coral patch reef and the spur and groove reef zone, whilst the habitats with lowest rugosity include gorgonian pavement, reef flat, seagrass, coral rubble and sand. Species groups ranking first in dominance within each habitat class are given in Figure 11 and demonstrate clear differences among them. The mixed reef hard ground and hard coral framework reefs show the highest variation in dominant species groups, whilst the reef flat, seagrass and algal hard ground habitats show low variation and consistent species group dominance.

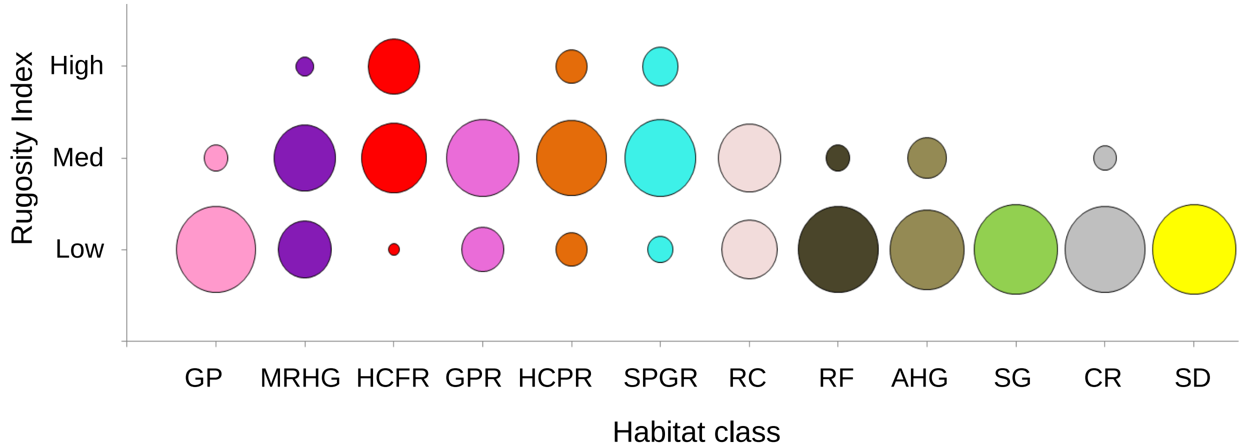

Figure 10. Plot showing relative frequency of low, medium and high rugosity by habitat class in Barbados in 2015, based on additional attribute data collected at ground-truthing sites (n = 361). Size of bubbles is relative to frequency of occurrence of rugosity index at a given class of habitat. Key to habitat colours and codes is given in Figure 8 and Table 8.

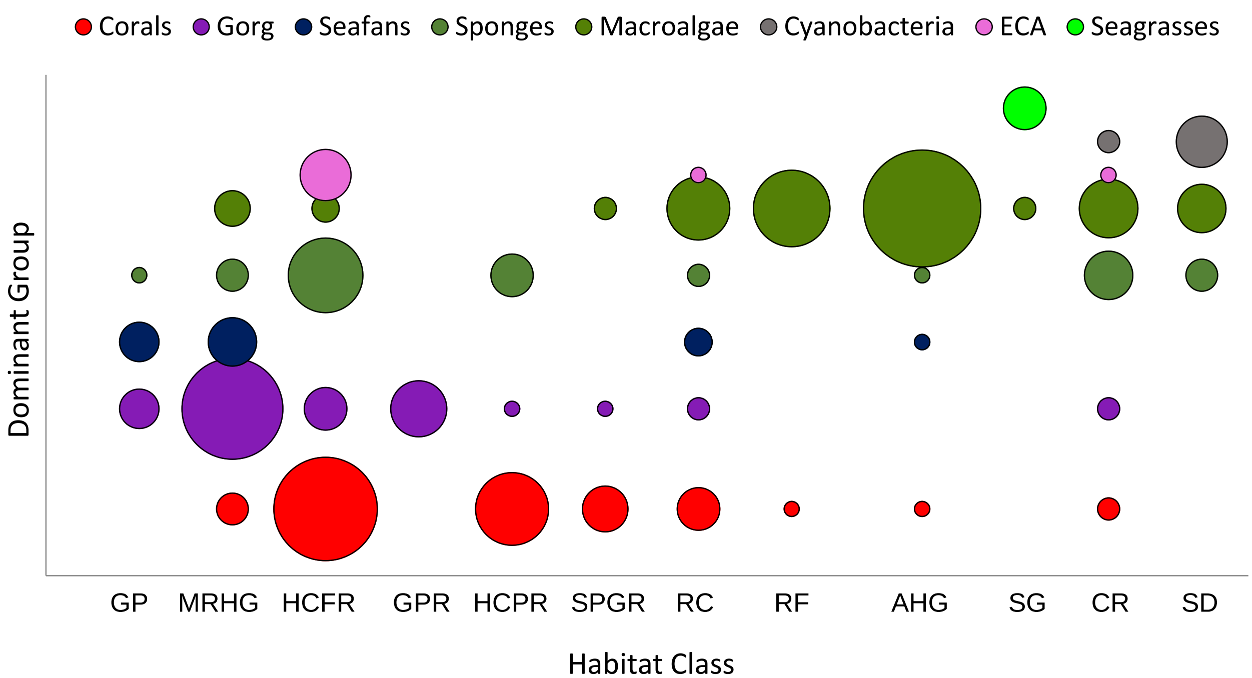

Figure 11. Plot showing the species groups which rank first in dominance across each of the habitat classes in Barbados in 2015, based on additional attribute data collected at ground-truthing sites (n = 361). Size of bubbles is relative to frequency of occurrence of dominant species group at a given class of habitat. Key to habitat codes is given in table 8.

The substrate type of each site was plotted by habitat class (Figure 12). Variation in substrate type is often also determined by the depth and degree of exposure to wave energy. Algal Hard Ground, Mixed Reef Hard Ground, Gorgonian Pavement and Reef Flat habitats were largely found on a pavement substrate. Hard Coral Reef Framework, Reef Crest, and Spur and Groove habitats were found on a reef framework substrate, whereas Gorgonian Patch Reef, Hard Coral Patch Reef, Sand and Seagrass comprised mainly of sand substrate.

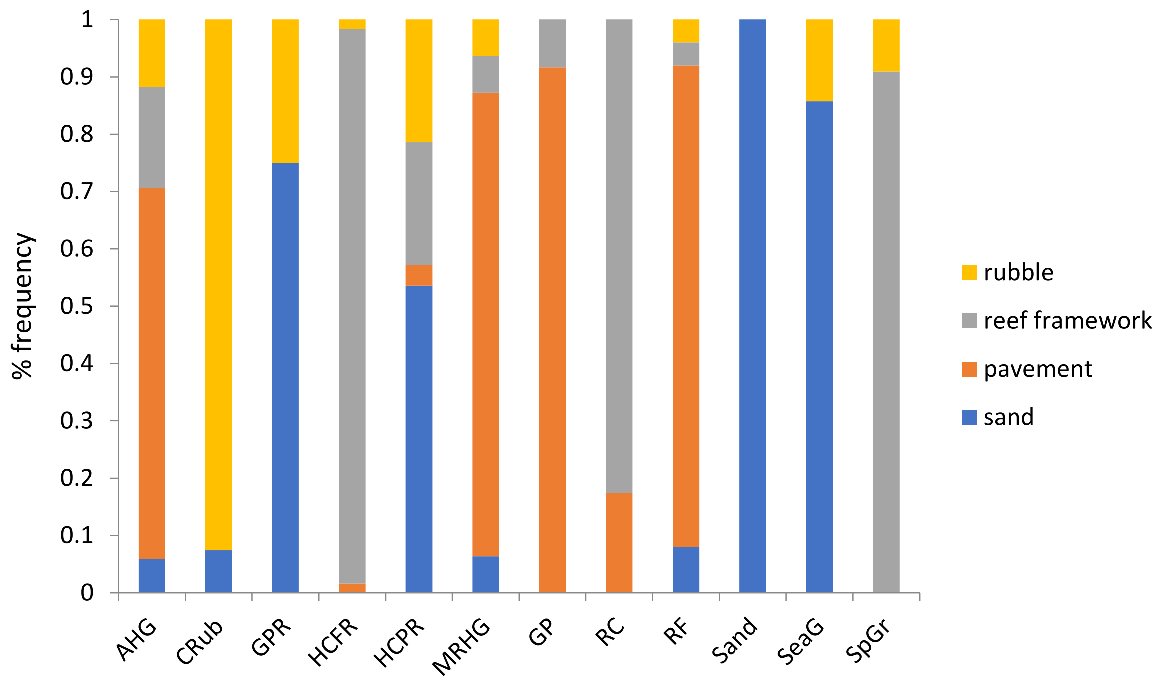

Figure 12. A comparison of the substrate recorded for each site and then grouped together by habitat class.

3.4 Marine habitat map

3.4.1 Object-based mapping

An example of the object-based mapping procedure is depicted in Figure 13 for a section of seafloor off the northwest coast between Half Moon Fort and Stroud Bay, St. Lucy. First, the WorldView-2 image is observed by applying a linear stretch across the visible bands (Figure 13C). The aerial mosaic (Figure 13D) and LiDAR terrain model (Figure 13E) are then layered atop the WorldView-2 imagery. Because of their excellent penetration of water, the short-wavelength coastal, blue and green bands of the Worldview-2 mosaic offer the most complete spectral audit of the seabed (Figure 13F). Next, statistics pertaining to the spectral and textural properties of the WorldView-2 imagery, the mosaic of aerial-orthophotographs, and the LiDAR terrain model are harvested and used to drive a preliminary segmentation of the layered dataset into landscape objects using eCognition (Figure 13G). Landscape object values for water depth (Figure 13H) and the visible blue WorldView-2 band (Figure 13I) are used to accomplish a preliminary classification of the dataset into broad classes, which are iteratively refined with reference to the available ground-truthing information (Figure 13J). Next, the GPS-located seabed samples are assembled within a GIS atop the imagery and corresponding habitat types are extracted at points where the samples provide an unequivocal determination of benthic character (Figure 13K). With reference to the seabed data, all landscape objects are assigned to a habitat category on the basis of their spectral and textural signatures (Figure 13L). A filter is then applied to remove redundant divisions between image-objects (Figure 13M) and a cleaning algorithm deployed to cull objects resulting from image noise (i.e. white caps, sun glint, etc.) to yield the final habitat map (Figure 13N).

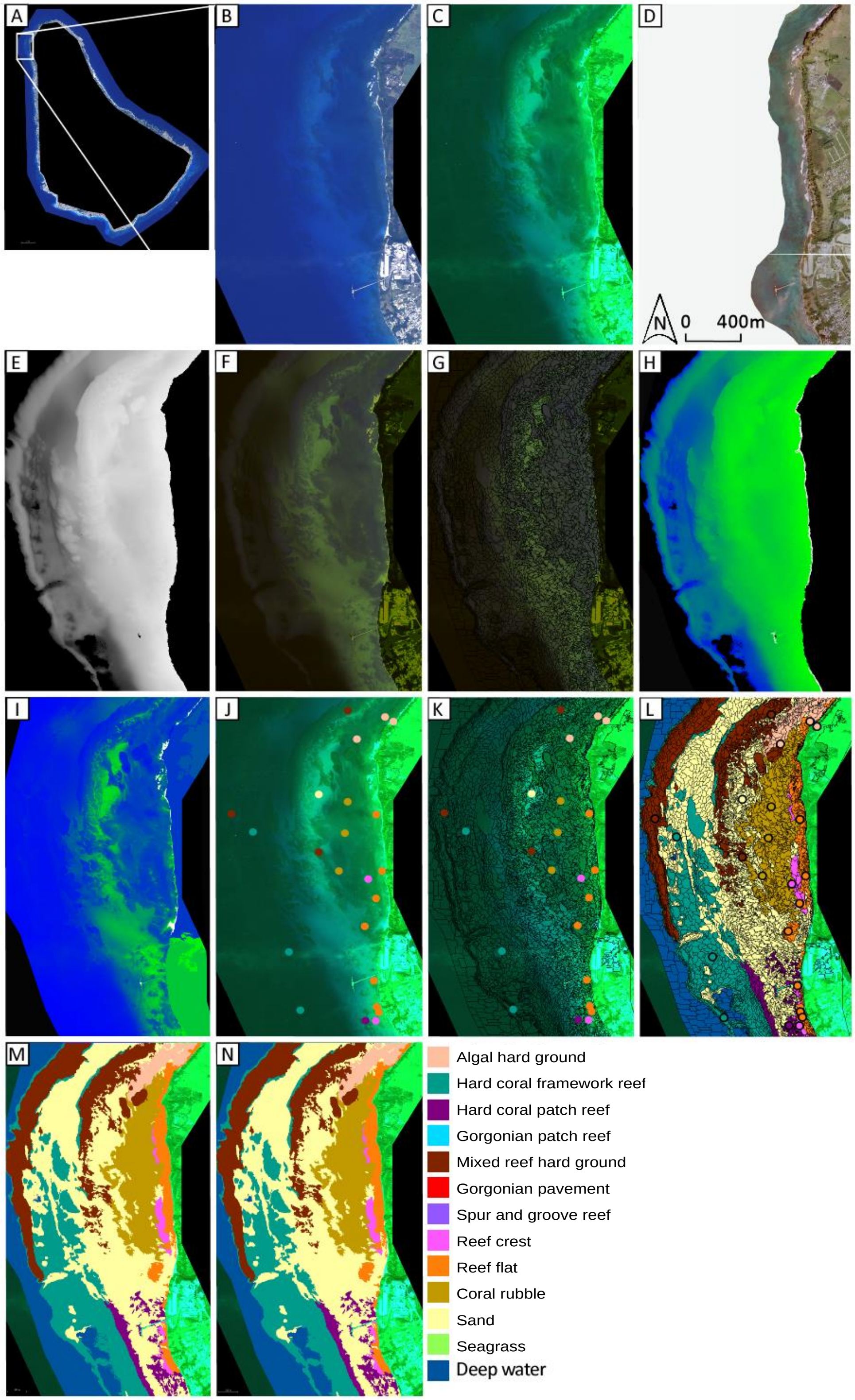

Figure 13. Workflow for the creation of the habitat map developed for a section of seafloor off the northwest coast from Half Moon Fort to Stroud Bay, St. Lucy. See text for details.

3.4.2 Final map and products

The class 'deep water', or the areas where marine habitats were beyond the resolution of the remote sensing technology, comprised a total area of 4,235.1 hectares of the mapping extent (Figure 14). Therefore, the final 12-class benthic habitat map produced for Barbados is provided in Figure 15 and is available electronically as GIS data (i.e. shapefile format). Several composite maps (e.g. shallow reefs, hard coral framework reefs, mixed reef hard grounds and patch reefs) were also produced (Figures 16-19).

Figure 14. Map of the class (deep water) showing areas around the coastline where habitats were beyond the resolution of the remote sensing technology.

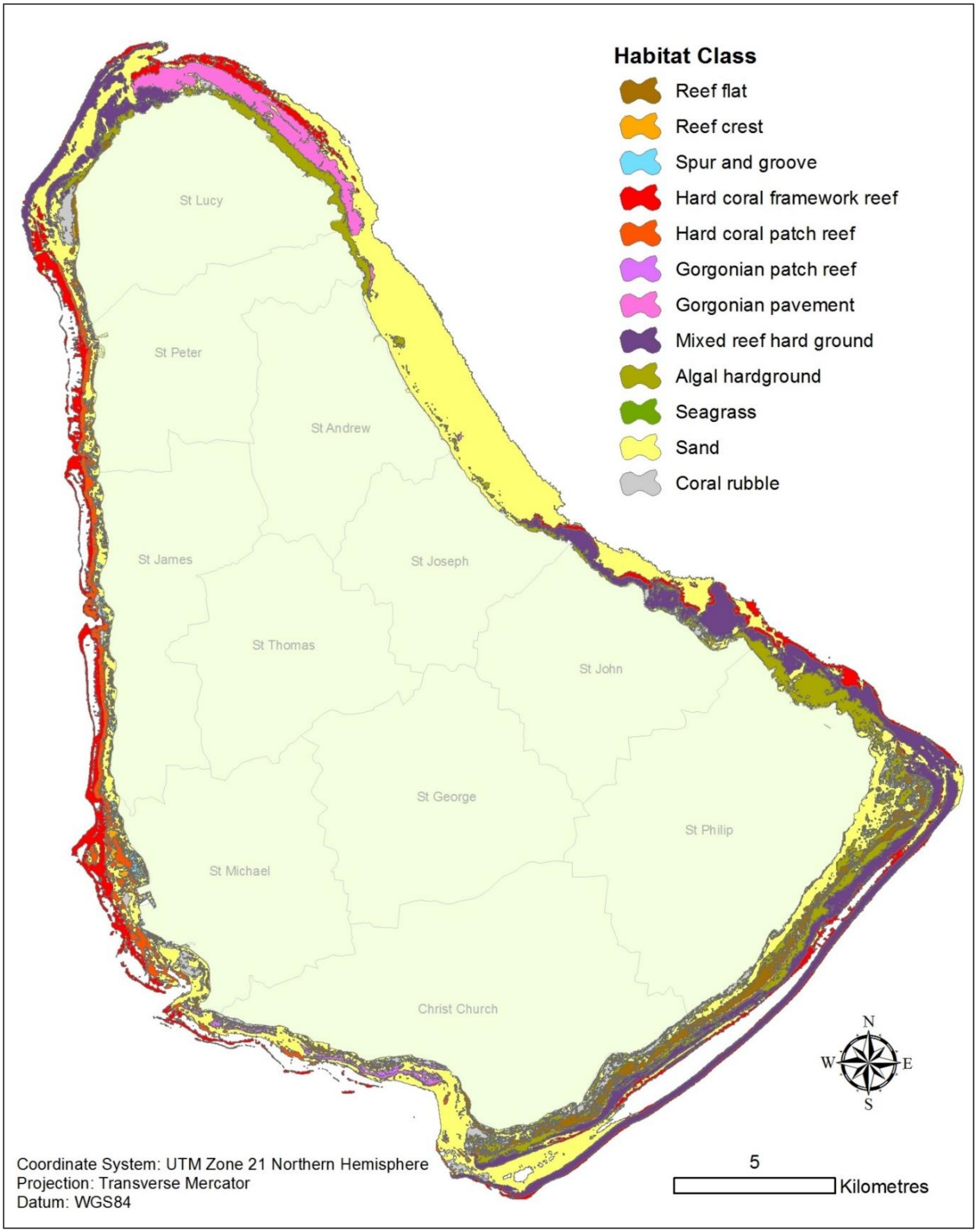

Figure 15. Final 12-class benthic habitat map of the coastal marine environment of Barbados.

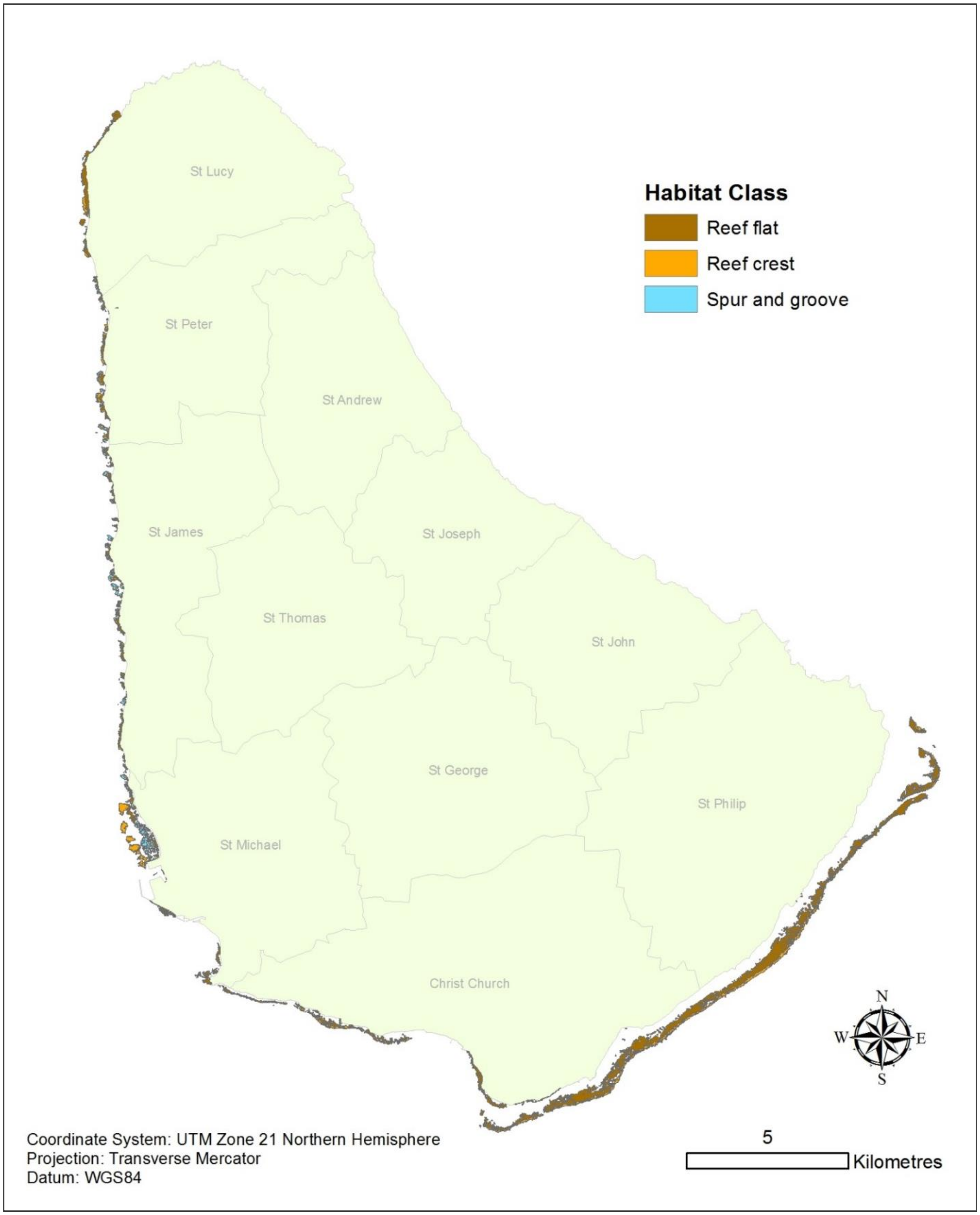

Figure 16. Map of the shallow reefs (fringing reefs comprising reef flat, reef crest and spur and groove zones and other reef flats) around Barbados.

Figure 17. Map of the hard coral framework reefs (bank reefs and other reef slopes) around Barbados.

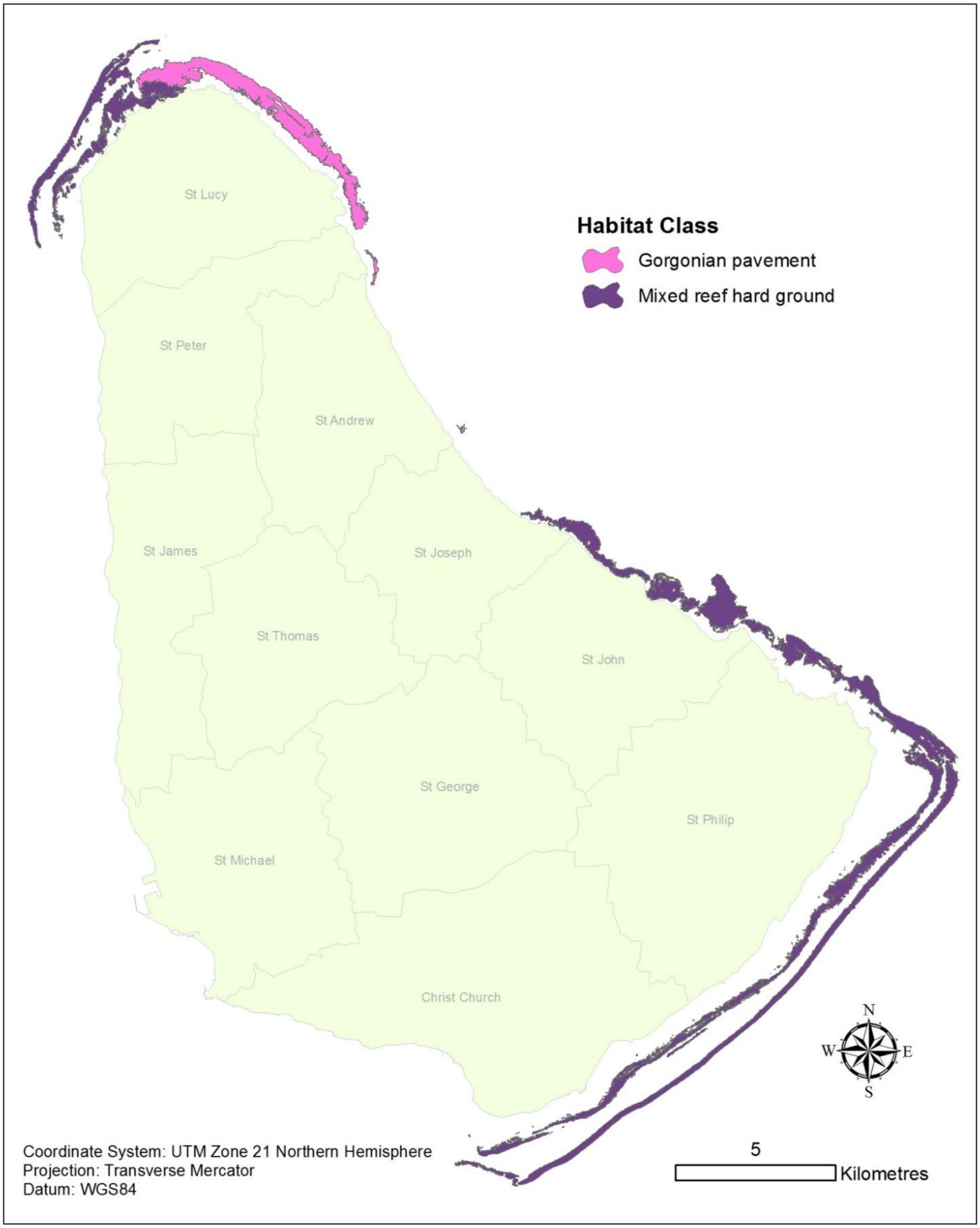

Figure 18. Map of the mixed reef hard ground and gorgonian pavements typical of the high wave energy coastal waters of Barbados.

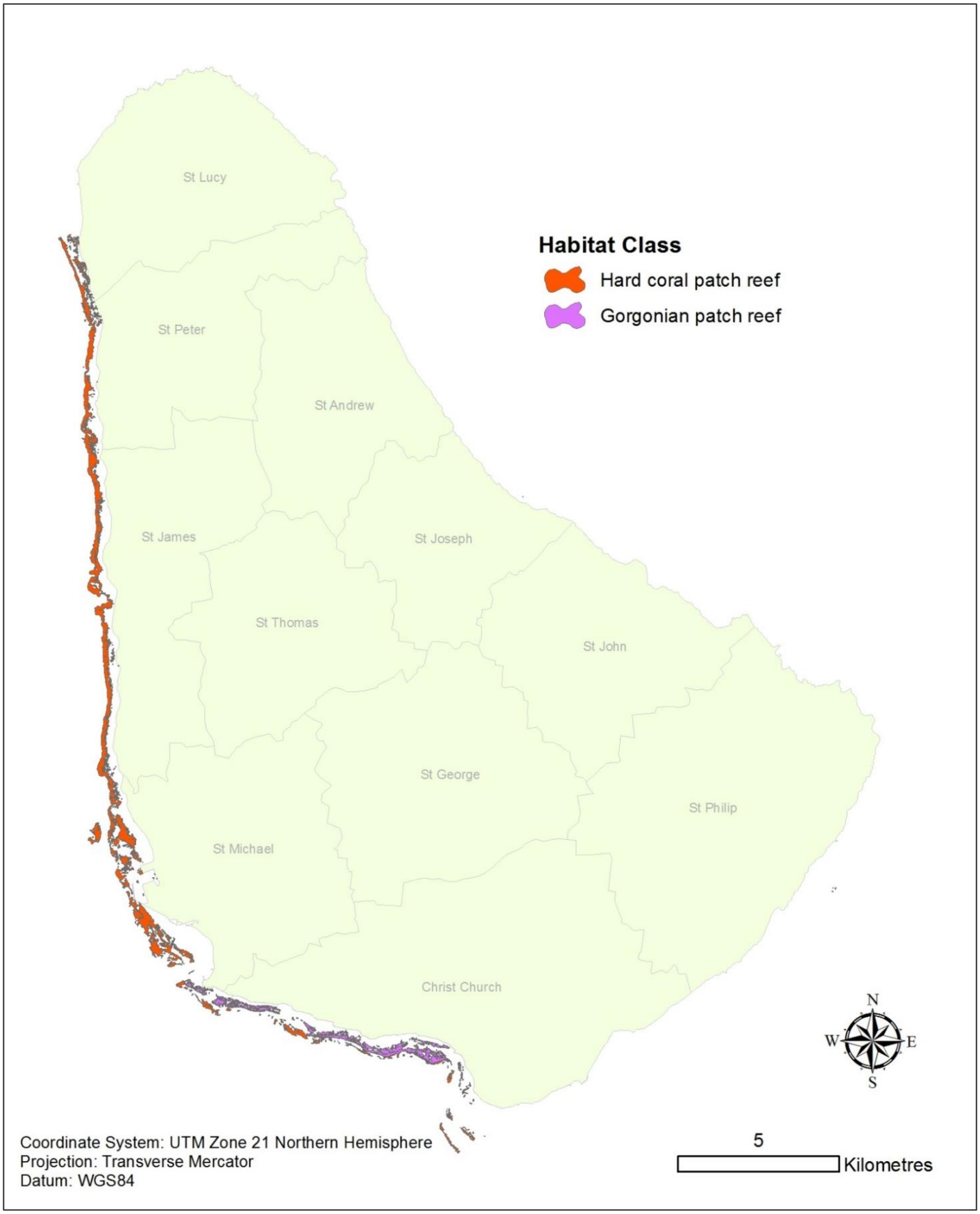

Figure 19. Map of the hard coral and gorgonian patch reefs found along the more sheltered coastlines of Barbados.

Understanding the amount and distribution of ecosystems, structurally and functionally, is essential for marine management. To demonstrate, the GIS interface was used to quantify the total amount of marine habitat for Barbados as well as summarized by coast and by CZMA.

The benthic habitat mapping extent for Barbados comprised an area of 116.6 km^2 (Table 9). The largest amount of habitat is sand (42%), with mixed reef hard ground (16%), hard coral framework reef (12%) and algal hard grounds (11%) comprising approximately 81% of all benthic habitats of the coastal shelf of Barbados.

Table 9. Estimate of area of each habitat class on the coastal shelf of Barbados (mapping extent).

Habitat Class	Area (km2)	Area (ha)
Algal hard ground	12.7	1269.4
Coral rubble	4.7	465.6
Gorgonian patch reef	1.1	112.0
Hard coral framework reef	14.1	1414.6
Hard coral patch reef	5.0	502.4
Mixed reef hard ground	18.0	1804.1
Gorgonian pavement	4.7	468.4
Reef crest	1.7	174.4
Reef flat	4.8	475.4
Sand	49.2	4917.7
Seagrass	0.0	1.1
Spur and groove reef	0.6	56.0
Total area	116.6	11661.2

The total amount of habitat summarized by each coastline of Barbados is given in Table 10. The largest amount of coastal shelf habitat was found on the east and southeast coasts (> 3,000 ha each), yet the largest number of habitat classes (10) was found off the southwest coast. The west coast was found to host the largest amount of hard coral framework reef (601 ha) whereas the largest amount of patch reef (161.5 ha) is found along the southwest coast of Barbados.

Table 10. Estimate of area (in hectares) for each habitat class and habitat diversity (number of habitat classes) for each coastline of Barbados. N.B. North coast comprises coastal zone management area (CZMA) 4 & 5; east coast comprises CZMA 2 & 3, southeast coast represents CZMA 1, southwest coast represents CZMA 8 and the west coast comprises CZMA 6 & 7. Borders of CZMAs are shown in Figure 2.

Habitat Class	**Coast**				
	North	East	Southeast	Southwest	West
Algae hard ground	291.4	407.3	551.8	18.9	-
Coral rubble	75.3	35.0	176.1	91.4	87.7
Gorgonian patch reef	-	-	-	109.1	2.9
Hard coral framework reef	267.1	211.7	280.4	54.0	601.4
Hard coral patch reef	-	0.0	0.2	52.4	449.7
Gorgonian pavement	464.3	4.2	-	-	-
Mixed reef hard ground	392.9	599.7	811.6	14.8	-
Reef crest	4.8	2.6	86.2	21.5	59.2
Reef flat	30.6	6.3	325.3	42.7	70.5
Sand	838.6	1987.7	902.1	509.9	677.4
Seagrass	-	0.8	-	0.0	0.2
Spur and groove reef	-	-	-	-	56.0

Habitat Class	Coast				
	North	East	Southeast	Southwest	West
Total Area (ha)	**2365.0**	**3255.4**	**3133.7**	**914.8**	**2005.1**
Habitat diversity (no. habitats)	**8**	**9**	**8**	**10**	**9**

Area estimates were calculated for each CZMA (Table 11). Despite its relatively small size, CZMA 8 hosts the highest diversity of habitats (10). The largest amount of hard coral framework reef (369.1 ha) can be found in CZMA 6, whereas CZMA 5 contains the largest amount of mixed reef hard ground (378 ha), and CZMA 4 contains the largest amount of gorgonian pavement habitat (335.7 ha).

Table 11. Estimates of area (in hectares) by each habitat class and habitat diversity (number of habitat classes) for each coastal zone management area (CZMA). CZMA borders are shown in Figure 2.

Habitat Class	CZMA								Total
	1	2	3	4	5	6	7	8	
Algal hard ground	551.8	292.9	114.4	227.9	63.5	-	-	18.9	1269.4
Coral rubble	176.1	5.4	29.6	3.6	71.7	24.5	63.2	91.4	465.6
Gorgonian patch reef	-	-	-	-	-	-	2.9	109.1	112.0
Gorgonian pavement	-	-	4.2	335.7	128.6	-	-	-	468.4
Hard coral framework reef	280.4	125.5	86.2	122.7	144.5	369.1	232.3	54.0	1414.6
Hard coral patch reef	0.2	-	0.0	-	-	273.6	176.1	52.4	502.4
Mixed reef hard ground	-	-	328.5	-	-	-	-	14.8	343.3
Mixed reef hard ground	811.6	271.2	-	-	378.0	-	-	-	1460.8
Reef crest	86.2	2.6	-	-	4.8	30.9	28.4	21.5	174.4
Reef flat	325.3	6.3	-	-	30.6	42.3	28.2	42.7	475.4
Sand	902.1	175.8	1811.9	400.5	438.1	342.0	335.4	509.9	4915.6
Seagrass	-	-	0.8	-	-	-	0.2	<0.0	1.1
Spur and groove	-	-	-	-	-	33.7	22.3	-	56.0
Total (ha)	**3133.7**	**879.8**	**2375.6**	**1090.4**	**1259.8**	**1116.0**	**889.1**	**914.8**	**11659.2**
Habitat diversity (no. classes)	**8**	**7**	**8**	**5**	**8**	**7**	**9**	**10**	**12**

3.4.3 Metadata

Two shapefiles, a benthic habitat polygon shapefile (attributed by habitat class, habitat code, and total area in hectares) and a ground control point shapefile (attributed by site number, CZMA, depth, video number, habitat class, habitat code, substrate, relief, community density, predominant species and comments), and a folder of 700+ ground-truthing survey videos and photographs (23 GB in size) accompany this report. Shapefiles were produced using the WGS84 datum and the UTM Zone 21N projection. Datasets were also transformed and re-projected into the Barbados National Grid (BNG) projection for national applications. Moreover shapefiles were converted into Google Earth (.kmz) files to allow for visualization and use of information by non-GIS users. Associated metadata produced includes: title, keywords, data model, coordinate system, scale, accuracy, data creation methodology (geoprocessing applied), data sources, citation, data limitations, date created, data creator and contact information.

4 LESSONS LEARNED

The methods used and lessons learned in this study have broad application to other countries in the region wishing to advance the process of marine habitat mapping and spatial planning. We found that a comprehensive benthic habitat map for Barbados was able to be created relatively quickly using limited technical and financial resources, typical of Small Island Developing States (SIDS). As a result of our technological limitations, a partnership with a remote sensing expert was sought. We found the application of local knowledge of the marine environment of Barbados was useful to guide several aspects of the remote sensing process (i.e. classification scheme development, object-based interpretation, sampling design and site selection, post-processing of videos, validation of final mapping product). Moreover, this collaborative approach employed the strengths of each party and resulted in the development of both a scientifically-sound and locally-relevant benthic habitat mapping product at a level of detail appropriate for national scale resource management.

Local knowledge and stakeholder participation not only reduced survey costs and improved safety at sea, but was also found useful in guiding the selection of survey sites. The use of GIS technologies to stratify the sampling design with the baseline habitat map, bathymetry data and CZMAs ensured that both conventional scientific principles and national management priorities were incorporated into the selection of representative ground control points. Moreover the inclusion of local fisher captains in the site selection process and field survey team not only allowed their knowledge of marine habitats to be included but was found to be a simple yet valuable enhancement to this conventional technique.

A number of easy to use and low-cost technologies (e.g. hardware and software) not only reduced the effort traditionally required for habitat mapping surveys but resulted in the production of high quality data. On the other hand, field surveys were relatively cheap and simple to conduct. The use of small local fishing vessels, handheld cameras and GPS units, and the SeaViewer drop-camera system rigged with a Go-Pro to conduct field surveys provided a relatively low-cost option to quickly access sites and collect high definition video ground control samples around Barbados. Survey of the marine environment around the entire island (150 km^2) was conducted in only 12 field days. Logistically, the additional GoBe flashlights were found to be somewhat helpful in illuminating the GoPro footage of the deeper survey sites, whereas the built in LED lights on the Seaviewer camera proved sufficient. The Android tablet was of use to help navigate the location of the field surveys on the draft habitat map in real-time, and was particularly useful in the identification of the randomly selected sites. In the future, obtaining a waterproof case for the tablet, that allows easy access to the touch screen and a screen shade, would be ideal.

It should be noted that survey conditions around the island of Barbados are extremely variable with large differences in sea state between the exposed windward and sheltered leeward shores, especially during the season of high NE Trade Winds (December to April). This is typical of the small Caribbean islands and adds a level of difficulty in accessing east coast sites (cannot be accessed in a small boat except in the low wind, summer months) and in keeping the drop camera system at a suitable height.

Post-processing of the video clips was time consuming, but allowed for an iterative process in assigning habitat classes. Thirty second video clips were found to be adequate to assess benthic type and associated habitat parameters. The largest issue encountered with the video footage was found in the height of the cameras off of the substrate. Ideally video would be recorded within 1 m of the seafloor; yet we found particularly when the sea was rough and the vessel was bouncing up and down, the camera was not lowered close enough to the substrate and footage was therefore reviewed multiple times to correctly identify habitat. Moreover the availability of two video samples per site with cameras having very different fields of view and resolution was found to be valuable as the utility of each camera system varied depending on available light and other environmental conditions (such as depth and turbidity).

The classification of video samples into the habitat classification scheme at each ground control point was not as straightforward as anticipated. In retrospect, an additional (2^{nd}) GoPro camera mounted to the SeaViewer but facing in a downward direction (towards the seafloor) would have been useful in providing another perspective to benthic samples (especially when the camera was too high above the substrate) and would have assisted with the determination of the associated habitat attributes (e.g. substrate, relief, community cover, predominant species). The attribute data collected on-site and from watching the videos helped in the classification refinement process. Quantifying the ranking of substrate, relief, living community cover and then scoring the dominant living organisms on each site helped to paint a more comprehensive picture of each site as well as along the coasts and was used to refine the habitat classification scheme. Furthermore the use of a GIS interface aided the visual inspection of consistency between the ground control points (by habitat type) overlain on the draft habitat map. This allowed for the identification of large scale spatial errors or patterns of inconsistency either between field survey results or against the corresponding polygons derived from the remote-sensing object-based analyses. Although this part of the post-processing was tedious and time-consuming (15 days), it is relatively short compared with the analysis required for conventional habitat mapping surveys. Ultimately this entire project was completed over an eight month period.

The development of a classification scheme should be treated as an adaptive process involving several iterations. In our case, the secondary mapping information, together with input from experts on the marine environment of Barbados, and management needs of the CMZU was used to develop the first draft (18-class) habitat scheme. Over the course of the project, a number of factors (e.g. limitations of the remote sensing technologies, video habitat sampling and review, patterns in the spatial distribution of various habitats and species composition) influenced the refinement of the habitat classification scheme into the final 12-class scheme for Barbados. The importance of local knowledge of the marine environment was noteworthy as it provided quality control and assurance to guide the remote sensing expert and validation of the drafted mapping products.

Investment in both the remote sensing source data and the hiring of a remote sensing expert was essential to the success of this project. Although this project had access to orthophotographs, the most beneficial data for the object-based mapping was the high resolution satellite imagery (i.e. Digital Globe) and bathymetry data (i.e. LiDAR). In addition, a local GIS analyst and ArcGIS software is required to collect, convert, analyze and produce data and maps. Close collaboration with the remote sensing expert in the production of an appropriate classification scheme and to guide and validate aspects of the object-based mapping is of utmost importance in obtaining a mapping product tailored to the management needs at the national scale.

Lastly another benefit of having mapping information in a scalable GIS framework is that detail can easily be added in the future as it becomes available. As a result of this project, a number of value-added layers can now be produced from the benthic habitat mapping data (e.g. maps, survey design, spatial modelling, etc.) and allow for better understanding of the association of habitats

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6 APPENDICES

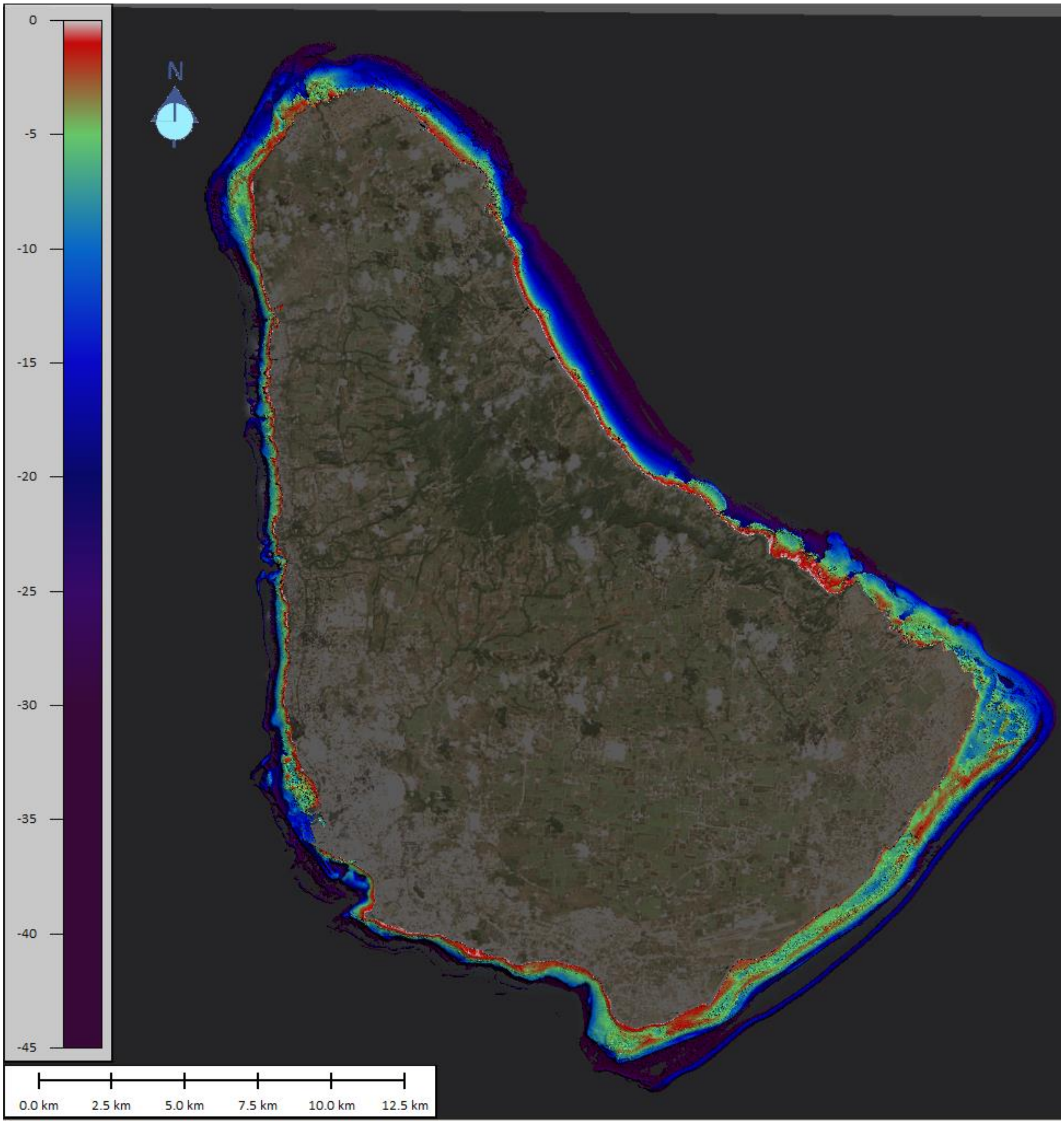
Appendix 1. Review of previous classification schemes applied in Barbados (listed by data source and year) and the initial (18 class) benthic habitat mapping scheme collaboratively developed with CZMU and Baird in May 2015.

Proctor and Redfern et al. (1984)	Halcrow (1998)	Welch (2008)	Proposed Classification Scheme (this project)
Diverse coral communities (flourishing to stressed) Shole Slope Patch Bank	Hard Coral		Linear barrier/shoal reef
Fringe Reef (west coast- stressed to decadent or eroding)			Fringing reef (< 5m depth)
Reef flat			Reef flat
Crest and coalesced spur zone		Hard Coral	Crest and coalesced spur zone
Coral spur and sand grove zone			Coral spur and sand grove zone
Bank Reefs (diverse coral communities to 40m or greater – local stress) Inshore slope Crest zone Offshore slope			Bank reef
Fringe reefs (south coast decadent and eroding)			
Coral undefined	Coral Rubble		
Coral rubble flats, mainly *Acropora palmata* – local sand veneer	Broken gorgonian pavement		Other coral reef communities (5-12 m depth)
In-situ based of A. palmata, local sand channels parallel to shore	Gorgonian Pavement	Coral reef communities	Gorgonian hard ground (south coast)
Sand veneer/coral rubble/ coral patch complex			Sponge dominated hard ground (west coast)
Turtle grass	Sea Grass	Sea grass	Sea grass
Algal mats Algal mats of pollution origin	Broken algal pavement Algal Pavement Brown Algal Pavement	Algae and Hard bottom	Algal hard bottom Brown algae Green algae Mixed algae
Sand (unstable at shallow depths) Sand seldom thicker than 1 meter (except in Oistins bay)	Bare Sand	Sand	Unconsolidated sediments Sand
			Coral rubble
Beach Rock	Scoured Rock	Rock	Beach scoured rock Intertidal zone
Seaward Structures (Breakwaters and Jetties)	N/A	Manmade	Artificial structures *(breakwater, groin, jetty)*

Appendix 2. Mosaic of orthophotographs acquired in late 2014 / early 2015 stacked atop world-imagery of the island. The spatial resolution is 10 cm. While useful to guide the mapping, excessive sun-glint in the orthomosaic necessitated that WorldView-2 imagery be supplemented in the analysis to accurately resolve seabed character.

Appendix 3. The true-colour (RGB) WorldView-2 mosaic for Barbados overlain atop 30 m resolution world-imagery of the island. The WV-2 image was acquired by DigitalGlobe Inc. on February 6th, 2013. Water depths across the coastal shelf are in the range of 0-30 m and for this reason, the imagery appears progressively bluer in colour with increasing depth, with only faint spectral differences representing changes in benthic character. Specialised spectral processing of the imagery was required to extract the seabed map. Reefs, rocks and shallow-water habitat are turquoise.

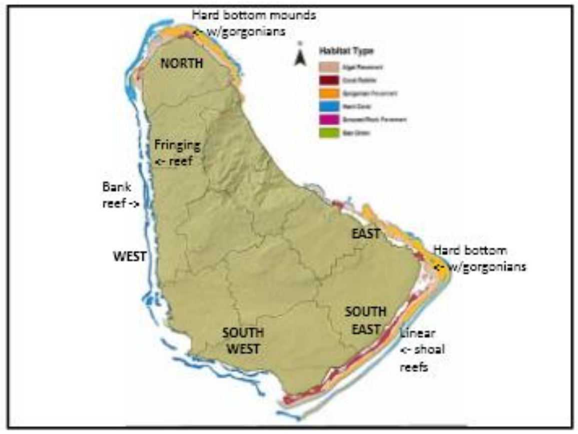
Appendix 4. Bathymetric LiDAR acquired for the study displayed atop 30 m resolution world-imagery. The LiDAR data were acquired in late 2014 / early 2015 and were interpolated to a raster grid with a spatial resolution of 2 m and units of depth below lowest astronomical tide. Lidar data was used to apply a water column correction to the shallow areas of the WorldView-2 mosaic to enhance the fidelity of the seabed features.



Appendix 5. 'Screen grabs' of marine imagery, accompanied by textual descriptions of the type of marine habitat thought to be found on each coast, used to guide the production of the draft map.

Images of reefs around Barbados

- Down West Coast
- Across the South West Coast
- Over to South East Coast
- Up the East Coast
- Around the North Point



West Coast (leeward) Habitats

- Fringing reef
  - Reef flat, Crest and coalesced spur zone, coral spur and groove
- Patch Reef (not like a traditional patch reef)
  - reefs occur between fringing reefs (or nearshore hard bottom) and the offshore bank reefs.
- Bank reef
  - Runs parallel to coastline 800-1000 m offshore, more or less continuous reef down west & SW Coast. Rise from 45m inshore side to 20-15m along crest to 45+ m offshore.
    - Proctor and Redfern 1984

Mullins

Brighton Beach

Carlisle Bay (Bridgetown)

South-west coast

- Fully exposed to Atlantic swells / heavy surf
- Fringing (old eroded relict) reefs
- Patch reefs
  - occur between fringing reefs (or nearshore hard bottom and the offshore bank reefs.
  - Veneer of sand that is quite dynamic. Gorgonians are the dominant feature, but the corals are dominated by Diploria spp
  - Seaward of patch reefs is a sandy trough channel (40-55m)
- Bank Reef
  - About 1000 m from shore and more or less continuous reef down west & SW Coast. Rise from 45m inshore side to 20-15m along crest to 45+ m offshore.
    - Proctor and Redfern 1984

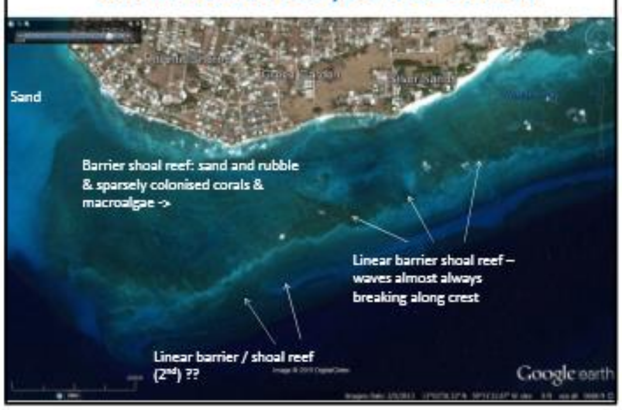
Hastings

St. Lawrence

South East Coast

- Fully exposed to Atlantic swells & Heavy surf
- Linear barrier/shoal reef
  - Prominent flat shallow bank runs parallel to shore about 400-800 m offshore (marked by breaking surf). Bank (up to 100 m wide) rises to a few metres of the surface
  - Inshore of barrier shoal reef is sand and rubble & sparsely colonised corals & macroalgae (lacking fringing reefs).
  - Seaward of reef and separated by a deep channel is a second narrow ridge which rises to within 14-20m of the surface
    - Halcrow 1998

Atlantic Shores / Silver Sands



Foul Bay to Crane Bay

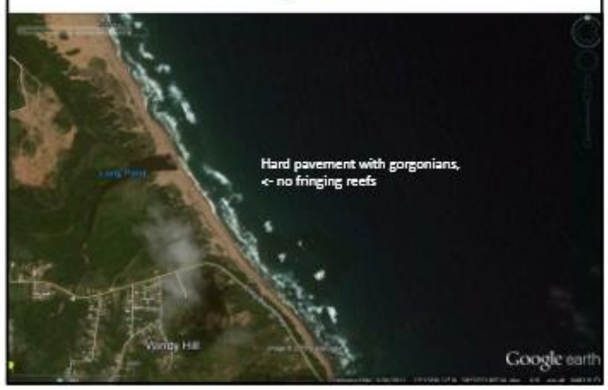
East Coast (windward)

- Fully exposed to Atlantic swells & wide sandy beaches, intertidal rock pools & heavy surf
- Featureless, gently sloping ramp from beach to shelf break at 40-60m
- Hard pavement with gorgonians, no fringing reefs
  - Halcrow 1998

Conset Bay to Skeetes Bay

Tent Bay to Martins Bay

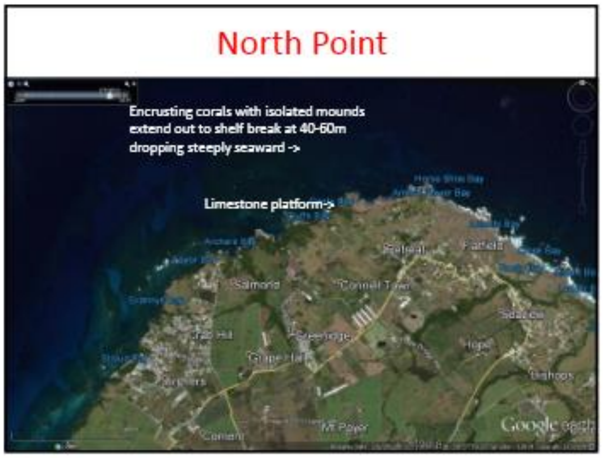
Long Pond



River Bay

North Coast

- Exposed to Atlantic swells and heavy surf. Coral cliffs with small bays with coarse sand and pebble beaches to a depth of 15-20m. Thin veneer of sediment & encrusting corals
- Offshore limestone platform or rock terrace terminating 500-1000 m from coast in a ridge that runs parallel to shore & drops to 25-30 m.
- From this ridge another terrace & isolated mounds extend out to shelf break at 40-60m dropping steeply seaward.
  - See pictures in folder taken (May 2015)


North Point
Encrusting corals with isolated mounds extend out to shelf break at 40-60m dropping steeply seaward ->
Limestone platform->
Google earth


Stroud Bay to Maycocks Bay
Sand ->
Hard ground with some Acropora, macroalgae, seafans receiving heavy swells and strong currents much of the time->
Google earth