

SUMMARY REPORT
OF
SATELLITE MAPPING OF MORPHOLOGICAL AND BENTHIC HABITATS FOR THE HONDURAN NORTH SHORE
SMITHSONIAN INSTITUTION, FORT PIERCE

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Marine Station at Fort Pierce
701 Seaway Drive
Fort Pierce
FL 34949

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Contract Manager: Steve Canty (CantyS@si.edu)
Prepared By: Charlotte Purkis (lotte@purkispartnership.com)

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2. Executive Summary

- Geographic zones and benthic habitats were interpreted from Landsat 8, Pleiades, QuickBird, GeoEye, WorldView-2 and SPOT-6 satellite imagery, aerial ortho-photographs and the General Bathymetric Chart of the Oceans (GEBCO)
- The Honduran North Shore hosts two motifs of reef development– shore-attached systems and isolated carbonate platforms
- Geographic zones were determined using an adaptation of the scheme proposed by Zitello et al. (2009)
- Habitat mapping was conducted using eleven, ecologically-relevant, marine classes and two terrestrial classes
- The habitat mapping was calibrated against field data, both contemporary and historic
- It is hoped the resulting GIS products will be used to enact marine conservation for the north shore of Honduras

3. Motivation

This study is the final piece of the Honduras country-wide mapping endeavor. Initial work was completed on the Miskito Cays in May 2014, followed by the Eastern Honduras Cays and Banks in April 2015 and now this study of the Honduran North Shore delivered in December 2016. The purpose of the mapping is the creation of a GIS product that will be used to support ongoing marine spatial planning in the country.

4. Description of the Honduran North Shore

The mapped region of interest (ROI) of the Honduran north shore is 7,000 sq. km in area and spans from the coastal town of Cortes in the west, which lies on the border of Guatemala, to Colon in the east (Fig. 1).

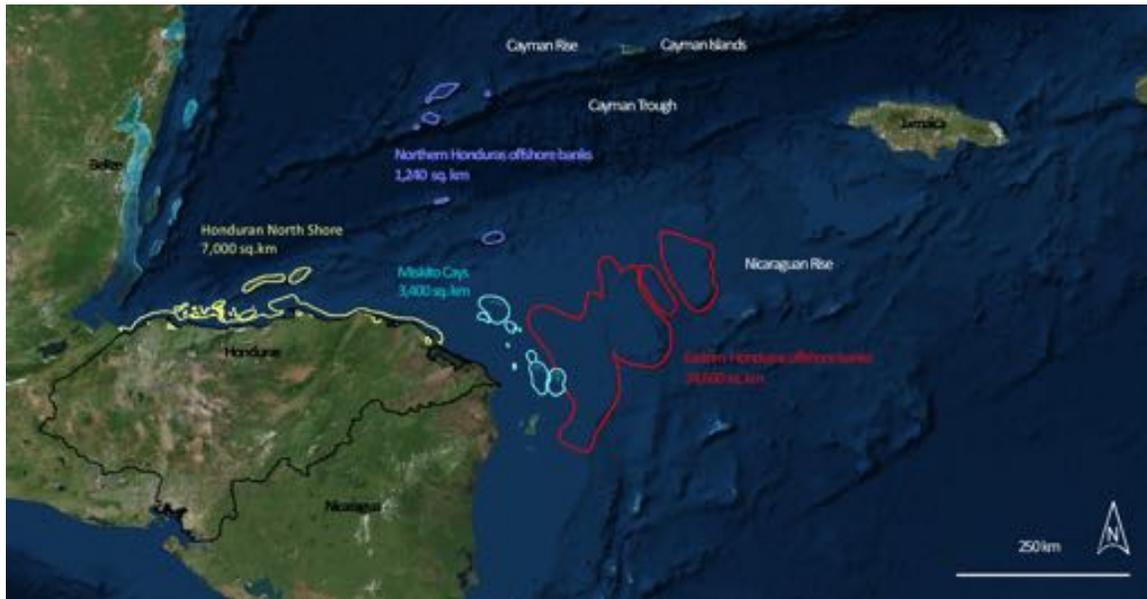


Figure 1 | World imagery with regions of interest (ROIs) over-plotted (coloured polygons) describing the evolution of the project. Three ROIs have previously been mapped – the northern and eastern Honduran offshore banks (purple and red, respectively), the Miskito Cays (cyan) and this project, the Honduran north shore (yellow). Combined, the ROIs encompass an area of 50,240 sq. km.

All four regions of interest (ROIs) examined under the auspices of this project sit atop the Nicaraguan Rise, a vast carbonate platform that developed in the Oligo-Miocene and spanned the seaway separating the Honduras/Nicaraguan mainland to the modern island of Jamaica. Present understanding is that this carbonate platform partially drowned in the latest Late Oligocene at around 27 Ma (million years ago) and finally floundered during the late Early Miocene around 20 Ma. The eastern Honduran offshore banks and Miskito Cays are composed of isolated carbonate platforms which have successfully tracked eustatic sea level in the intervening period, though much of their area languishes at water depths representing the limits of meaningful carbonate production (20-30 m) which, coincidentally, also represents the limits for seabed mapping via remote sensing. The ROI targeted in this study, the Honduran North Shore, lies farther inboard on the Nicaraguan Rise and covers an extensive shore-attached reef complex and the Bay Islands (Roatan, Utila and Guanaja) which form an offshore archipelago in the Gulf of Honduras. The Bay Islands are separated from mainland Honduras by a ca. 50-km-wide stretch of ocean up to 1,000 m deep. The archipelago comprises three other small islands (Morat, Barbaretta and St. Elena) and more than 60 small (50–500 m long and 20–200 m wide) sandy coral islands (cays). Roatan is

the surface-reaching part of the ENE-trending submarine Bonacca Ridge and owes its position to late Eocene tectonic movements along the northern Swan Island fault zone and subsequent early Oligocene uplift. Although Roatan is located within the hurricane belt, hurricanes are quite infrequent at less than one direct hit per decade (www.nhc.noaa.gov).



Figure 2 | World Imagery of the Honduran north shore region of interest. Yellow polygons depict areas mapped with meter-resolution satellite imagery and/or aerial ortho-photographs. The remaining areas (green polygons) were mapped using 30 m resolution Landsat 8 data.

Prior to embarking on the present study, the area was scoped using Landsat 8 imagery to identify potential areas of shallow marine habitat. During this exercise, 25 sites for satellite mapping were delineated which covered a combined area of 1,528 sq. km (green and yellow polygons in Fig. 2). These sites were emplaced to capture all shallow water reef habitats within the overall Honduran north shore ROI. With limited budget available for the purchase of meter-resolution satellite imagery, these 25 areas were prioritized on the basis of their ecological importance and feasibility for seabed mapping. Aerial ortho-photographs were already in hand for the Bay Islands which include; Roatan (AOI 24), Utila (AOI 23) and Guanaja (AOI 25) and so these areas could be mapped at maximum resolution. The aerial photos for Guanaja did not cover the entire area, so high-resolution imagery was purchased for the eastern side of the AOI (delineated by the yellow line). The ranking of the remaining areas prioritized; Cayos Cochinos (AOI 16), Anchor Bank to the west of Utila (AOI 10), and offshore Tela (AOI 7) for which meter-resolution satellite imagery was

purchased. The remaining AOIs and the entire coastline for the region was mapped from Landsat 8 imagery.

5. Satellite Image Pre-processing

All remote sensing data used in the project were 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). A water column correction was not applied in this study for two reasons. First, no accurate bathymetric surface exists for the study site from which to reliably estimate per-pixel water depths. Second, the object-based textural algorithms deployed to delineate seabed character are not as confounded by variable water depth as more traditional pixel-based classifiers that solely consider the spectral quality of the imagery (Purkis et al., 2006).

6. Remote Sensing Imagery Employed in the Study

This project called upon both aerial-orthophotos and satellite imagery. The latter were acquired from a variety of different platforms - WorldView-2, Pléiades, GeoEye, QuickBird, SPOT-6 and Landsat 8. The aeriels covering the Bay Islands date from 1999 and were captured for the PMAIB project. The native projection of these photographs was NAD27, but once mosaicked, they were re-projected to UTM Zone 16 with the WGS84 datum to normalize their positioning to that of the satellite imagery.

WorldView-2, launched Oct. 2009 and operated by DigitalGlobe Inc., is the first high-resolution 8-band multispectral commercial satellite. Operating at an altitude of 770 km, WorldView-2 provides 0.48 m panchromatic resolution and 1.85 m multispectral resolution. Like WordView-2, QuickBird also formed part of DigitalGlobe's constellation. It was launched in 2001 and decommissioned in 2015. During its operational lifetime, QuickBird collected panchromatic imagery at 61 cm resolution and multispectral at 2.4 m. Meanwhile, Pléiades is a high-resolution instrument boasting 2 m multispectral pixels across its 20 km swath width. Launched in 2012, Pléiades is operated by the Centre National D'études Spatiales (CNES). SPOT-6, launched in 2012 and also administered by CNES, operates in the same orbit as Pléiades, collecting panchromatic data at 1.5 m resolution and multispectral at 6 m. The final instrument utilized by this study, Landsat 8, launched in 2013, has a 30 m spatial resolution and is the latest member of the Landsat program – the longest running civilian Earth observation mission.

The Honduran north shore ROI is covered by a mosaic of Landsat 8 scenes which were assembled in the software ENVI (v. 4.8). All of the scenes in this Landsat mosaic were acquired in 2014, save for one in 2016 (Fig. 3, Table 2). The source of the imagery for each mapped area is presented in Figure 3 and Tables 1 and 2 capture the acquisition date of each scene.



Figure 3 | Guide to the different remote sensing data used by the project. Yellow polygons stipulate Landsat 8 data, white polygons with numbered area of interest (AOIs) delineate sites where high-resolution imagery was available for mapping. True-colour representations of these high-resolution scenes are shown for each AOI.

Table 1 | Captures the date of acquisition and sensor for each area of interest (AOI) within the Honduran north shore mapping project – see Figure 3 for AOI locations.

AOI #	Date of Acquisition	Sensor
7	Feb. 24, 2016	Pleiades
10	Dec. 6, 2009	WorldView 2
10	May. 7, 2014	GeoEye
16	Aug. 28, 2015	WorldView 2
16	Sept. 13, 2015	SPOT 6
23	1999	PMAIB-Orthophotos
24	1999	PMAIB-Orthophotos
25	1999	PMAIB-Orthophotos
25	Jun. 14, 2011	QuickBird
21	Nov. 2016	Landsat 8
ROI	2014 mosaic	Landsat 8

Table 2 | Specifics and dates of acquisition for the Landsat-8 imagery. Scenes in bold italics were used to create the base mosaic.

Image ID#	Date of Acquisition	Path	Row
LC80160482014105LGN00	2014-04-15	16	48
LC80160482014265LGN00	2014-09-22	16	48
LC80170492014144LGN00	2014-05-24	17	49
LC80170492016342LGN00	2016-12-07	17	49
LC80170492014096LGN00	2014-04-06	17	49
LC80170492014272LGN00	2014-09-29	17	49
LC80180492014055LGN00	2014-02-14	18	49
LC80180492014087LGN00	2014-03-28	18	49
LC80180492014327LGN00	2014-11-23	18	49
LC80180492016093LGN00	2016-04-02	18	49

7. Object-based Mapping of Geographic Zones and Benthic Habitats

An object-oriented approach was adopted for delineating geographic zones in the Landsat mosaic and for delineating benthic habitat in the orthophotos, Landsat, GeoEye, QuickBird, Pleiades and SPOT imagery. Two independent GIS data layers were created, one for the geographic zones and a second for benthic habitat. As per the three previous studies, the two-tier GIS adopted in this study hybridizes that of Zitello et al. (2009), in which coral reef systems encompass a three tier GIS including; geographic zone, geomorphological structure, and biological cover. In this exercise, geomorphological structure, and biological cover are blended into “benthic habitat.”

An object-oriented approach was adopted for delineating benthic habitat in the imagery. This approach contrasts the more commonly employed “pixel-based” classifiers that have traditionally

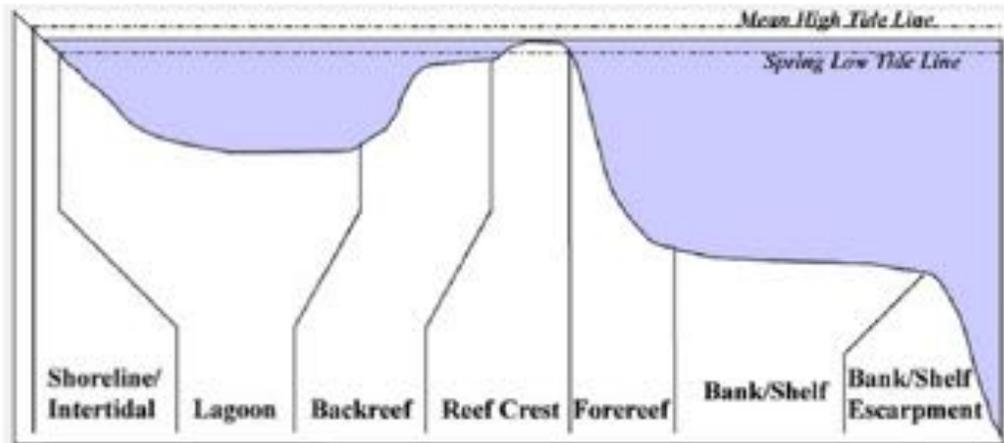
been used for coral reef mapping. The principal disadvantage of the pixel-based approach in a submerged setting, such as the shallow habitats of Northern Honduras, is that, since light in the visible spectrum is so rapidly attenuated by water, bathymetric differences account for the majority of spectral variation within the remote sensing imagery.

In contrast to pixel-based classification methods, object-oriented image analysis, the strategy used to produce the maps 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 the context of this study, we employ object-oriented classification to delineate habitat “bodies,” interpreted to be distinct patches of uniform benthic habitat. Because of the flexibility afforded by including non-spectral attributes of the imagery (e.g., texture, spatial and contextual information) 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). The software used for mapping in this study, eCognition (v. 8.9, Trimble Inc.), tenders a suite of object-oriented image analysis algorithms having particular utility for creating thematic maps from remote sensing data, including coral reefs.

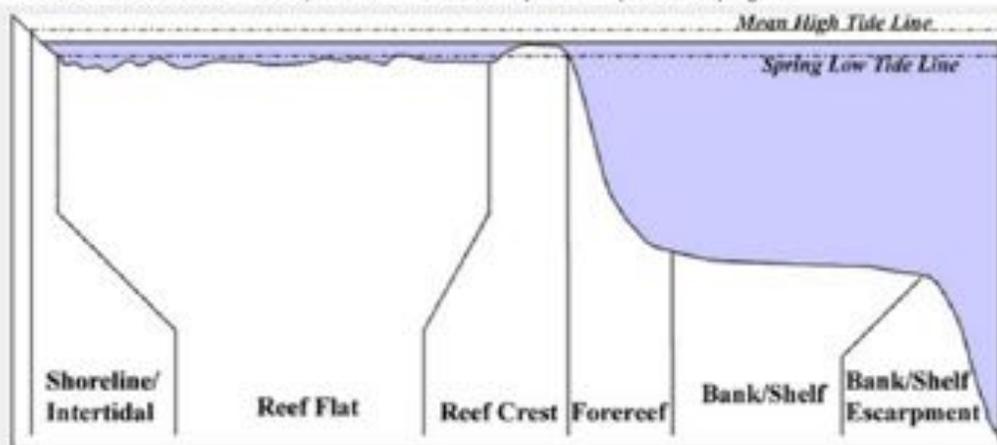
Satellite Mapping of Geomorphological Zones

As shown in Figure 4, Zitello’s assignment of geographic zones was developed for platforms characterized by the presence of extensive reef growth and for this reason, Zitello’s zones are cast on the basis of their position relative to conspicuous reefal features (e.g. reef crest, fore-reef, etc.). As per the mapping for the Miskito Cays and the Honduran offshore banks, two modified schemes based on Zitello were applied to Northern Honduras (Fig. 5). The first, characteristic also of the Miskito Cays, may be termed as “reef-rimmed carbonate platform”. In these areas the zone "reef flat" and “back-reef” was added to the Zitello’s atoll model to yield six classes that were sufficient to capture the geographic zones of the platforms - Bank-shelf/Escarpment, Fore-reef, Reef-crest, Reef-flat, Back-reef and Lagoon. Other banks in the north shore are characterized by a different model, similar to the one found in the Honduran offshore banks. This adapted scheme uses four zone classes as follows and may be termed as a “flat-topped carbonate platform”.

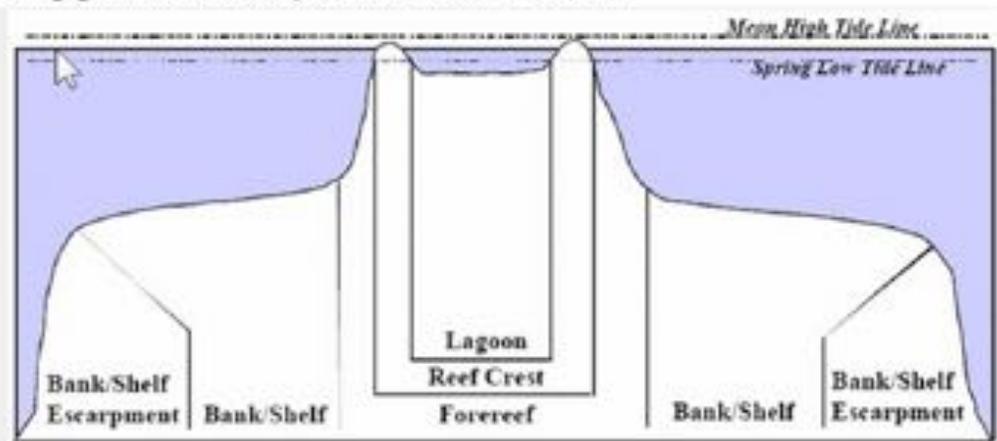
- The “platform-top” is the top of the platform (typically flat and always its shallowest point)
- The “platform margin” demarks the termination of the flat-top and the initiation of the slope
- The “platform slope” is inclined oceanward and always lies oceanward of the margin
- The Bank-shelf/Escarpment is a continuation of the platform slope, inclined oceanward and always lying oceanward of the platform slope. It may well not be visible from the satellite imagery due to its depth.



A. Barrier reef cross-section. Reef separated from the shore by a relatively wide, deep lagoon

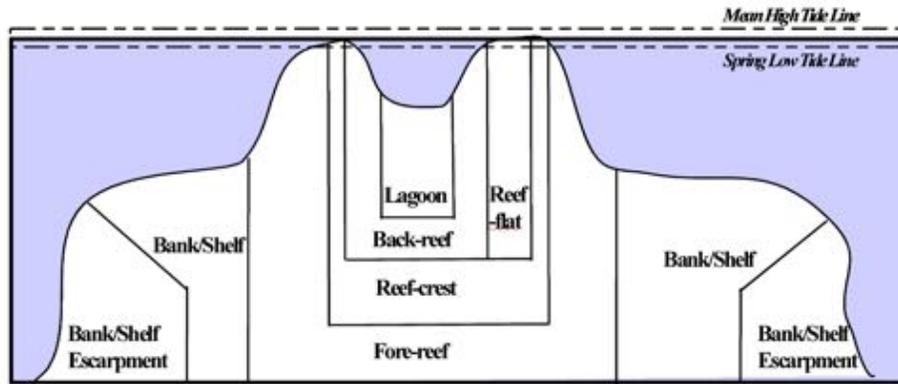


B. Fringing reef cross-section. Reef platform is continuous with the shore

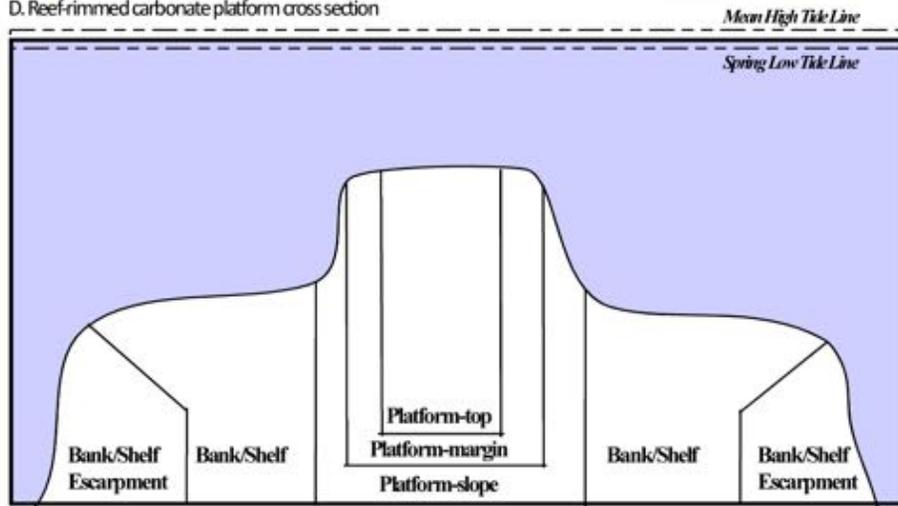


C. Atoll cross-section. Reef surrounding lagoon

Figure 4 | Application of the Zitello scheme of geographic coral reef zones. After Zitello et al. (2009).



D. Reefrimmed carbonate platform cross section



E. Flat-topped carbonate platform cross section

Figure 5 | Modification of the Zitello scheme from Figure 4. Zonation scheme developed for the “reef-rimmed” morphology and the “flat-topped” morphology. Both of these types are found in the Honduran North Shore.

Since the framework for the development of conservation policy is well established for zone maps adhering to the original Zitello (2009) scheme, divergence from this classification demands a means of converting between Zitello zones and those employed in this study. To this end, a conversion matrix is developed in Table 3.

Table 3 | Conversion matrix between Zitello *et al.* (2009) zonation scheme for an ‘atoll’ and the ‘reef-rimmed’ and ‘flat-topped’ geomorphology found within the Honduran study area.

Atoll: Zonation scheme according to Zitello <i>et al.</i> (2009)	Reef-rimmed: Zonation scheme used in Honduras	Flat-topped: Zonation scheme used in Honduras
Lagoon	Lagoon, Back-reef	Platform top
Reef crest	Reef crest, Reef-flat	Platform margin
Fore-reef	Fore-reef	Platform slope
Bank-shelf/Escarpment	Bank-shelf/Escarpment	Bank-shelf/Escarpment

The zone maps were developed as follows. First, a coarse eCognition segmentation of the combined Landsat and GEBCO (General Bathymetric Chart of the Oceans) 2014 global 30 arc-second grid imagery was conducted. Second, from this segmentation, the Bank-shelf/Escarpment were manually assigned, and all eCognition objects lying seaward of this boundary were discarded (i.e. those corresponding to deep water). The remaining eCognition objects were assigned to zones through manual attribution into the predefined zone categories. Zitello’s zonation of a reef platform continuous with the shore (as in Fig. 3B) was used to classify the shore parallel zones. The Zitello zone map shows the geomorphological shape of the subsurface platform; it does not show substrate or cover.

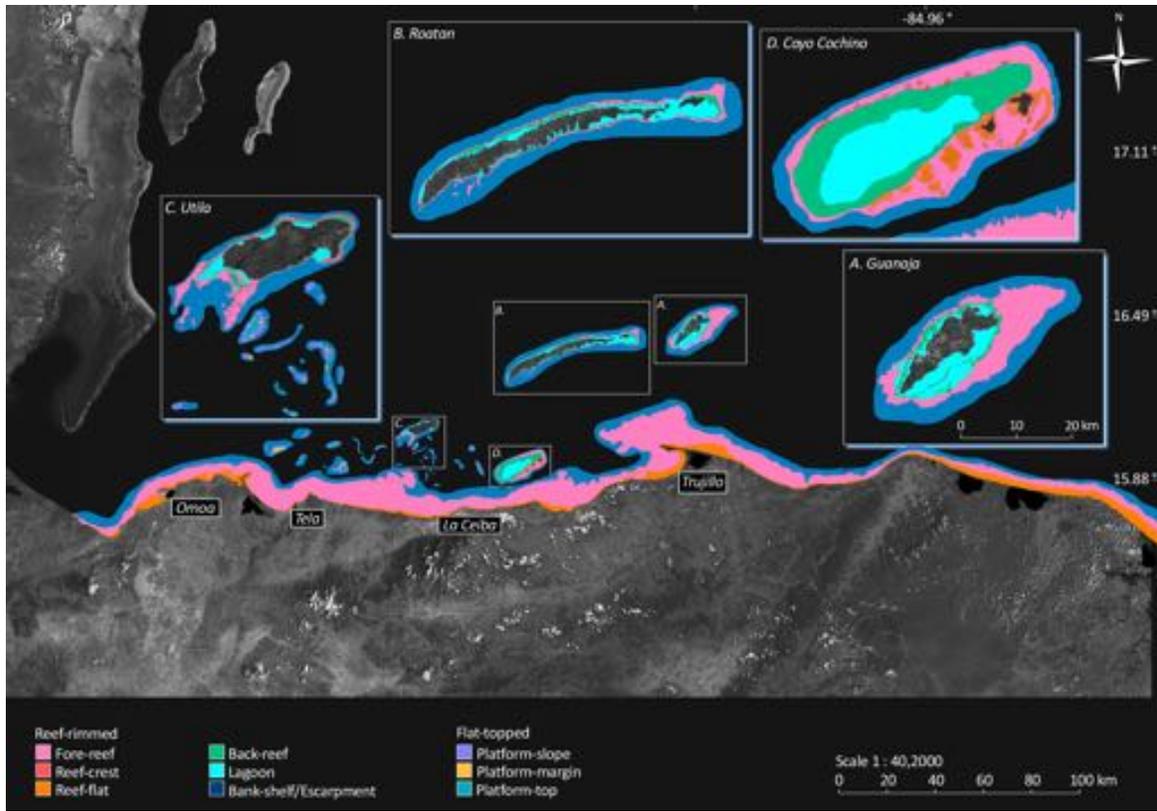


Figure 6 | Map of geomorphological zones for the Honduran North Shore derived from remote sensing data. Projection is UTM Zone 16 North and datum WGS84.

Satellite Mapping of Benthic Habitats

As for the Miskito Cays and the offshore Honduran banks, this study uses the same habitat classes derived from the Zitello (2009) schemes for geomorphological structure and biological cover. With reference to the available ground information for Northern Honduras, these thirteen ecologically-relevant habitat categories are described and their appearance in the image data highlighted (Fig. 7).

Table 4 | Habitat classes and definitions.

Habitat Class	Description and notes
Aggregate reef	Continuous reefs where the individual pinnacles exceed 250 m in diameter
Aggregate reef with algae	Dark brown in color in true color satellite imagery develops in areas that are too shallow or too inclement to sustain coral communities
Aggregate patch reef	Areas populated by complexes of individual patch reefs that, due to restrictions in image resolution, could not be digitized as separate entities. It is predominantly found in the fore-reef zone and is created either by the differential erosion of a formerly “aggregated” reef terrace i.e. fragmented reef or from the up-growth of individual coral pinnacles having less than 250 m in diameter
Individual patch reef	Isolated coral reef formations, which are circular, or elongate. Aggraded from the seafloor near sea surface, with coral community determined by the frameworks development stage. Halo effect of seagrass grazers leaving a bright highly reflective ring of bare sand surrounding reefs.
Reef rubble with algae	Grey-to-green-to-brown colouration and is texturally homogeneous. Further, rubble is contextually easy to identify as accumulates leeward of the reef flat, carried over the reef crest by storms into the “back reef” zone. Because it is situated on hard-bottom in areas of medium topographic relief, habitat class “reef rubble with algae” is likely to prove to be the most suitable for the placement of casitas
Seagrass	Dark green to black color in enhanced true-colour imagery, with complex sinuous shapes that the meadows adopt
Sand with algae	Tinged gray as compared to the highly reflective “sand” class
Sand	Homogeneous areas with high reflection
Pavement with gorgonians and turfing algae	Typically low-relief planation hardground inhabited by sparse to dense forest of gorgonians. The hardground may either be covered by a thin veneer of sand, else colonized by turf algae, sponges, and rare coral heads. Often dark blue to black, smooth texture when compared to the proximal coral framework. Pavement edges occasionally visible.
Pavement with sand channels	Regions of hard-bottom veneered with unconsolidated sand sheets, which appear as bright beige to white in the imagery
Intertidal vegetation	Includes mangroves, palm trees and some scrubby coastal undefined plants. All vegetation is visible as bright green in true-colour satellite imagery and bright red in false-colour infrared band combinations utilizing the infrared channel
Mud	Predominantly fine-grained sediments with low relief found at 0-2m water depths. The benthic community is primarily microbial with isolated invertebrate communities due to aerial exposure during low tides. Appears light gray to dark brown in the imagery.
Land	Identified by its high infrared spectral response and includes all terrestrial habitats, both natural and man-made

The only variation on the above scheme comes in the form of the addition of the class “mud” which was introduced to capture inshore areas where river run-off and terrestrially derived detritus forms a fine veneer of mud to cover the substrate.

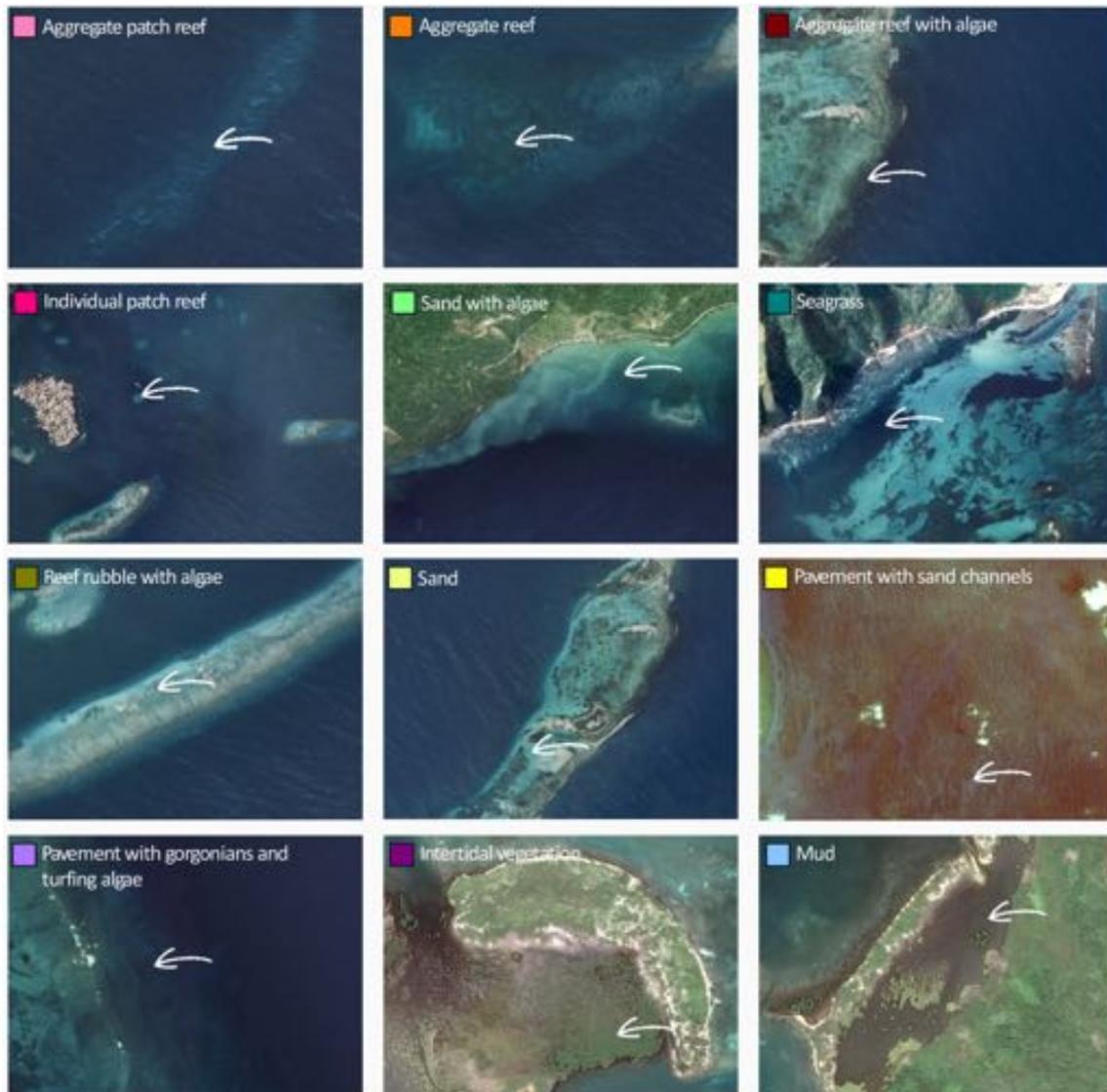


Figure 7 | Examples of twelve benthic habitat classes as resolved by the PMAIB orthophotos, WordView 2 and World Imagery. Only the land class is missing from the examples.

A total of 394 ground-control points were assembled from both historical field excursions and more recent visits to the area. These points were assembled into a single GIS and each location matched with the most closely fitting habitat class in preparation for calibration of the imagery (Fig. 8). Ground-truth points classified into Zitello’s (2009) three tiered scheme of geographic

zone, geomorphological structure and biological cover were assigned a single habitat class based upon their three assigned classes. Table 5 shows examples of the habitat assignment based upon Zitello’s (2009) scheme.

Table 5 | Conversation matrix used for the assignment of a single habitat class from Zitello’s (2009) three tiered classification scheme

Zone	Geometric Structure	Biological Cover	Assigned Habitat
	NA	Live coral	Aggregate reef
NA	Aggregate reef	Algae	Aggregate reef with algae
Fore reef	NA	Live coral	Aggregate patch reef
NA	Spur and groove	Live coral	Pavement with sand channels
NA	Unconsolidated sediment	No cover	Sand
NA	Unconsolidated sediment	Algae	Sand with algae

These field observations straddle all of the benthic habitats found atop the coastal shelf of the three study areas. Statistics pertaining to the spectral and textural properties of the satellite imagery corresponding to the habitat types were extracted at points where the samples provide an unequivocal determination of benthic character. These statistics were used to drive a preliminary segmentation of the imagery into landscape objects using eCognition. Using expert experience, all landscape objects were subsequently assigned to a habitat category on the basis of their spectral and textural signatures. 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.

An example of the object-based mapping procedure is developed for a section of seabed surrounding Cayos Cochinos (Fig. 9). This method was carried out on each of the available orthophotos, WorldView-2, Pléiades, QuickBird, GeoEye, SPOT and Landsat image mosaics. Once classified, the classes were exported into Global Mapper (Blue Marble Geo Inc., v. 18.3), where the habitat maps were subjected to a round of QA/QC and changes manually implemented.



Figure 8 | World Imagery of Honduran North Shore AOI. Projection is UTM Zone 16N; datum is WGS84. Field surveys for calibration were assembled into a single GIS totaling 394 GPS-located ground-truth points. North is top, and each ground-truth point (dots) has been color-coded into the most appropriate habitat class.

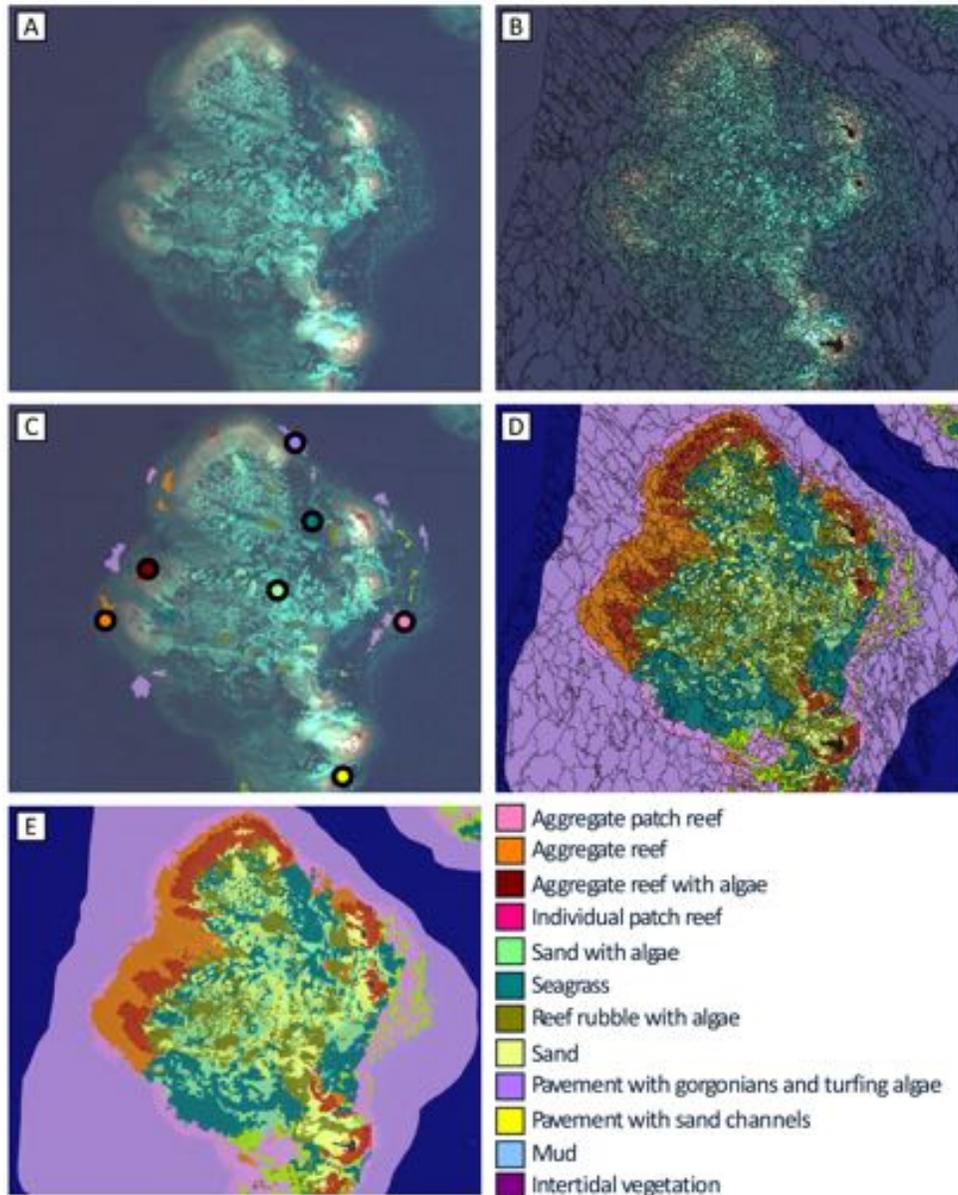


Figure 9 | Workflow for the creation of the habitat maps developed for a section of seabed south of Cayos Cochinos (A). (B) Statistics pertaining to the spectral and textural properties of the WorldView 2 imagery are used to drive a preliminary segmentation of the imagery into landscape objects using eCognition. (C) If available, GPS-located seabed samples are assembled within a GIS atop the satellite imagery, corresponding habitat types are extracted at points where the samples provide an unequivocal determination of benthic character, and (D), with reference to the seabed data, all landscape objects are assigned to a habitat category on the basis of their spectral and textural signatures. Next, (E) a filter is applied to remove redundant divisions between objects to produce the final habitat map composed of polygons

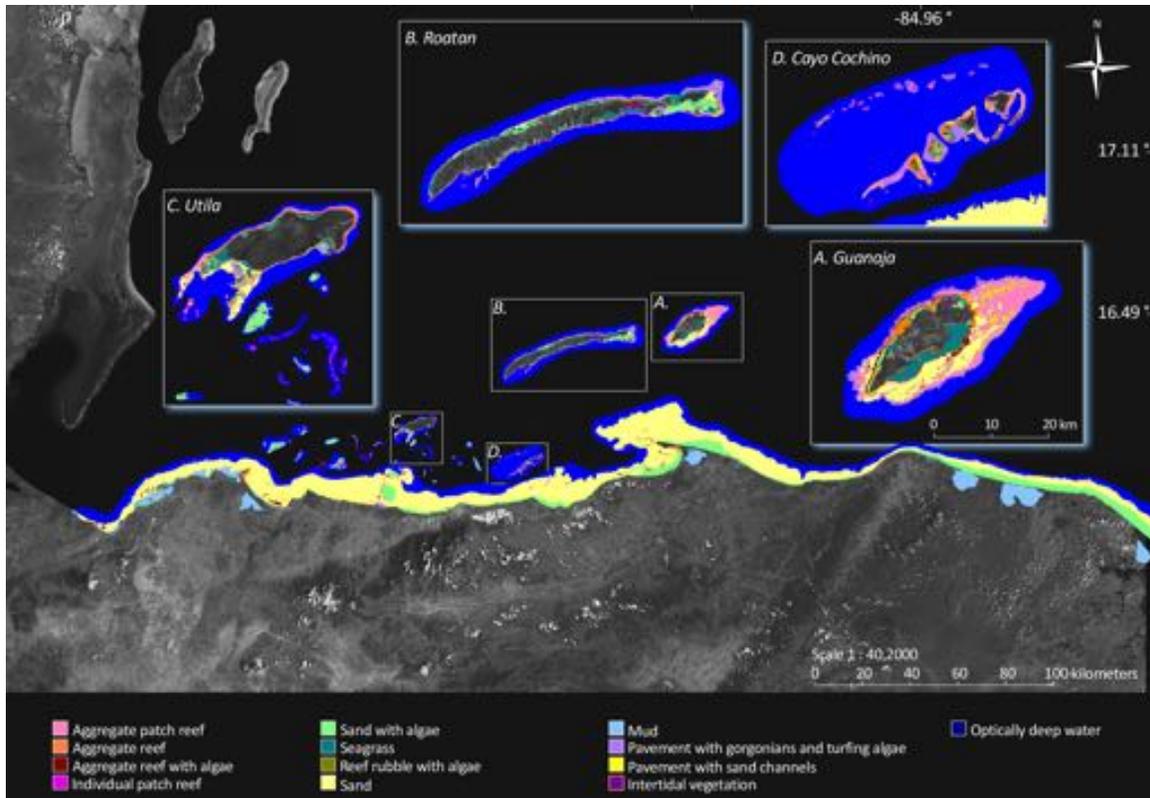


Figure 10 | Benthic habitat maps for the Honduran north shore derived from remote sensing data. Projection UTM Zone 16 North with datum WGS84.

8. Habitat and Zone Maps

In the submitted GIS, all habitats and zones descriptions are structured in a single shape file. The attributes include:

- "Habitat": As per table 4
- "Zone": As per Figure 5
- "AOI": Internal identifier used to describe the particular area of interest
- "Author": Lotte Purkis in all cases
- "High-Res Imagery": Indicates the type of high resolution imagery used to map that particular feature.
- "Landsat": indicates the path and row of the Landsat imagery used to map that particular feature
- "Name": geographical region mapped

Also submitted in the GIS bundle, is a shapefile containing interpreted ground-truth observations used in the calibration. Here, attributes were inherited from their original source with the additional attribute "Habitat" holding the assigned class ID.

Examination of the habitat maps reveals the shore-attached system that fringes the north coast of Honduras to consist of a broad sandy shelf. Coastal embayments are muddy and the nearshore

is dominated by algal meadows. Farther offshore, the Bay Islands are variably rimmed by aggregate reefs behind which patch reef complexes have developed. Reef framework is typically best developed on the windward (northern) margins of the islands, whereas the shelf is broader on the leeward side and sand-dominated. Both Roatan and Guanaja are noteworthy in hosting expansive stands of mangroves, which are reflected within the class 'intertidal vegetation'.

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