Summary Report for the Benthic Habitat Mapping of the Southern Belize and Guatemalan Mesoamerican Reef

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Motivation

The Smithsonian has requested production of marine benthic habitat maps to support their work in Guatemala and Belize. These maps seamlessly tie into the 50,000 sq. km of country-wide Honduras habitat maps developed under the auspices of the same project in 2016. The Smithsonian is working alongside in-country partners to develop its Healthy Reef for Healthy People Initiative (HRI) throughout the Mesoamerican Reef. Expanding the Honduras maps into neighboring Guatemala and Southern Belize delivers a single, coherent, product that can be tendered to partners and stakeholders via the Mesoamerican Reef Data Explorer.

Study Site

The study site spans the territorial sea boundaries of Southern Belize and Guatemala (Fig. 1). The project has two areas of interest. Covering 1,100 sq. km, Area 1 includes the recently designated marine protected areas (MPAs) of the Sapodilla Cayes Marine Reserve in Belize, the Punta Manabique in Guatemala, and the Cayman Crown corals that bridge the territories of the two countries. Area 2, meanwhile, spans the Southern Barrier Complex of Belize for an area of 3,200 sq. km. Hence, the total area considered in the study is 4,300 sq. km. (Fig. 2). The study area abuts and integrates into the previously-created Honduran North Shore maps and those of the eastern Honduran offshore banks. The resultant map product covers a combined area of 55,000 sq. km, an area on par with the most expansive satellite-derived marine habitat maps yet produced.

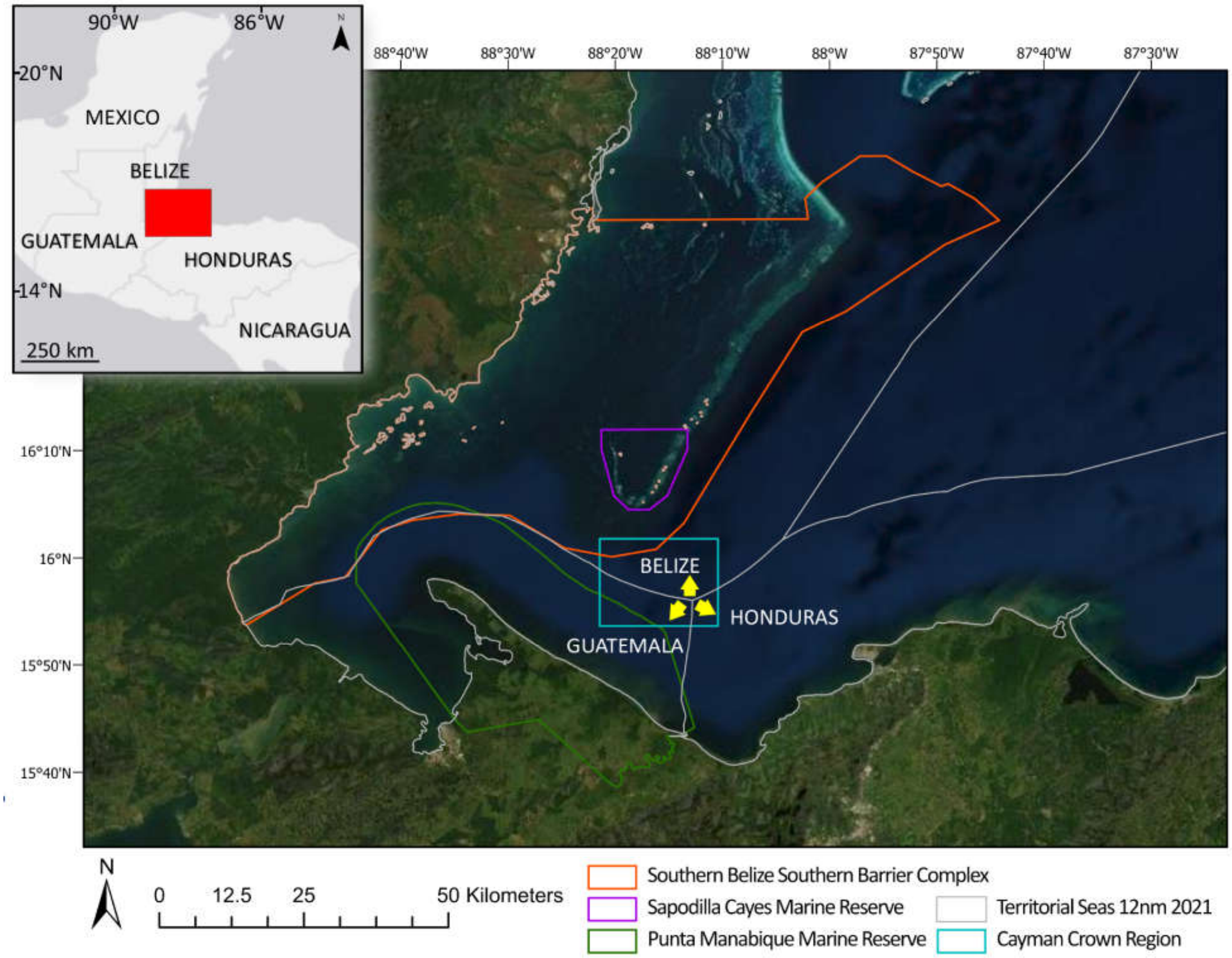


Figure 1: Shows the location of the study area that lies along the Belize and Guatemalan coastlines. Areas of particular importance include the Sapodilla Cayes Marine Reserve, delineated in purple, the Punta Manabique Marine Reserve, delineated in green, and the location of the Cayman Crown corals. Territorial Seas are delineated in grey. The Southern Barrier Complex of Belize, meanwhile, is delineated in orange.

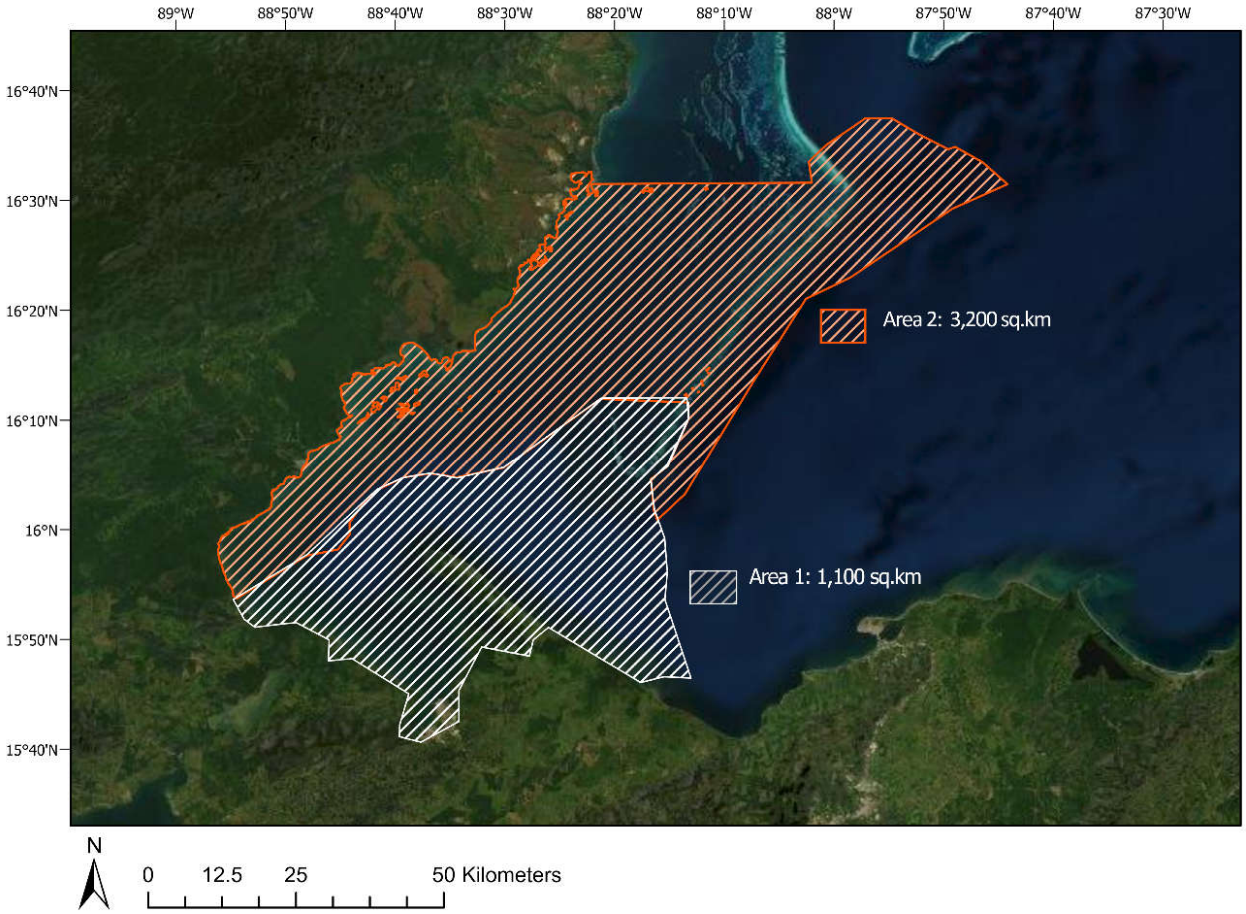


Figure 2: Shows the two areas of interest included in the study. In the south, Area 1 covers the Guatemalan waters and, to the north, Area 2 spans the Southern Belize Barrier Complex. The total area is 4,300 sq. km.

Existing Maps

Prior to this study, the 'go-to' maps for the considered areas include the Belize National Marine Habitat Map produced in 1997 by the Coastal Zone Management Authority & Institute (CZMAI) (Mumby and Harborne, 1999). This map was created using Landsat satellite imagery with a 30 m pixel resolution. Cherrington (2013), updated these maps with her baseline assessment of seagrass, mangroves, and coral cover (Fig. 3). Alongside the study conducted herein, other projects are running concurrently, of which the most notable are the Allen Coral Atlas, The Caribbean Science Atlas, and a follow-up from the CZMAI. These parallel projects are all being developed using machine-learning processes and PlanetScope imagery. Whereas the future of marine mapping and monitoring is moving rapidly toward automated production, the map products created via machine learning currently lack the local fidelity demanded by targeted regional conservation and decision making. Hence, the motivation for this study.

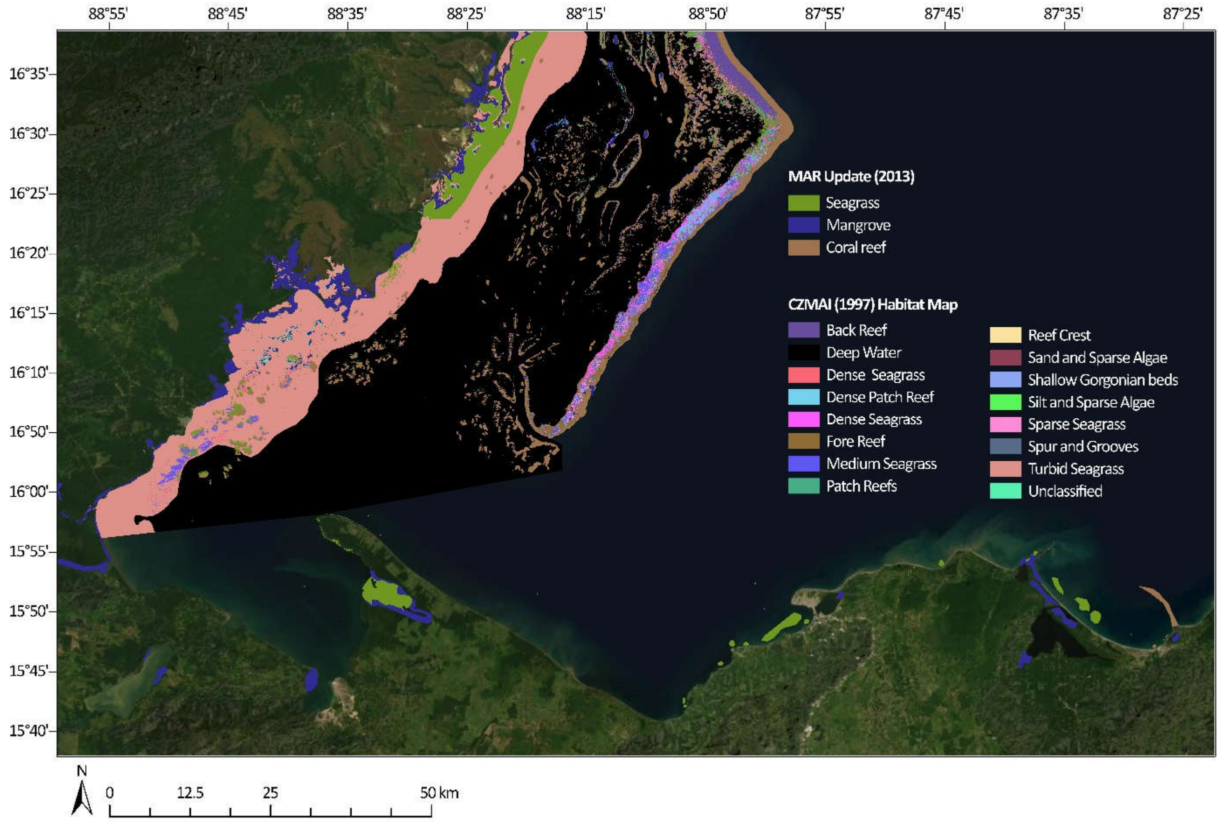


Figure 3: Shows the two existing habitat maps for the study areas. The Belize Coastal Zone Management Authority and Institute (CZMAI) maps were created in 1997 and the Mesoamerican Reef updates for seagrasses, mangroves, and coral reef were released in 2013.

Satellite Imagery

Selecting the optimum satellite imagery for any given mapping project requires balancing budget against resolution. In this study, SPOT-7, Sentinel-2, and Lansat-8 imagery were used in combination to accomplish the study's objectives. Data acquired by the PlanetScope and Dove missions were also reviewed, but ultimately not used due to excessive cloudiness, image artifacts, and the low radiometric resolution (8-bit) of these sensors. To the latter, SPOT-7, Sentinel-2, and Lansat-8 are all 11-bit sensors, which conveys a considerable advantage. Each of the sensors will be reviewed in turn.

SPOT-7

SPOT-7 was launched in 2014 and is administered by CNES. The instrument collects panchromatic data at 1.5 m resolution and multispectral data at 6.0 m. For the purposes of this study, 517 sq. km of 1.5m 4-band panchromatoc multi-spectral imagery was acquired and mapped for Area 1A. These data were collected in 2018.

Sentinel-2

The Copernicus Sentinel-2 program has two polar-orbiting satellites in its constellation; Sentinel 2A, launched in June 2015, and Sentinel 2B, launched in March 2017. The two satellite have a combined site revisitation and data acquisition cycle of five days. Both satellites are equipped with a state-of-the-art multi-spectral imager, producing four 10 m resolution bands – band 2 (blue – centered on 490 nm), band 3 (green – 560 nm), band 4 (red – 665 nm), and band 8 (near infrared - 842 nm). Sentinel-2, Level 1C products were downloaded from the Sentinel datahub and prepared for image analysis. Cloud free images acquired in 2020 and 2021 were obtained for both Areas 1 and 2.

Landsat-8

Landsat 8 was 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. Landsat-8 imagery used in this study was acquired in January 2017 and cover the entirety of Areas 1 and 2. The scene is both cloud and glint free and the date of acquisition places it in the middle of the dry season, thereby lessening seawater turbidity induced in the winter rainy season by river discharge.

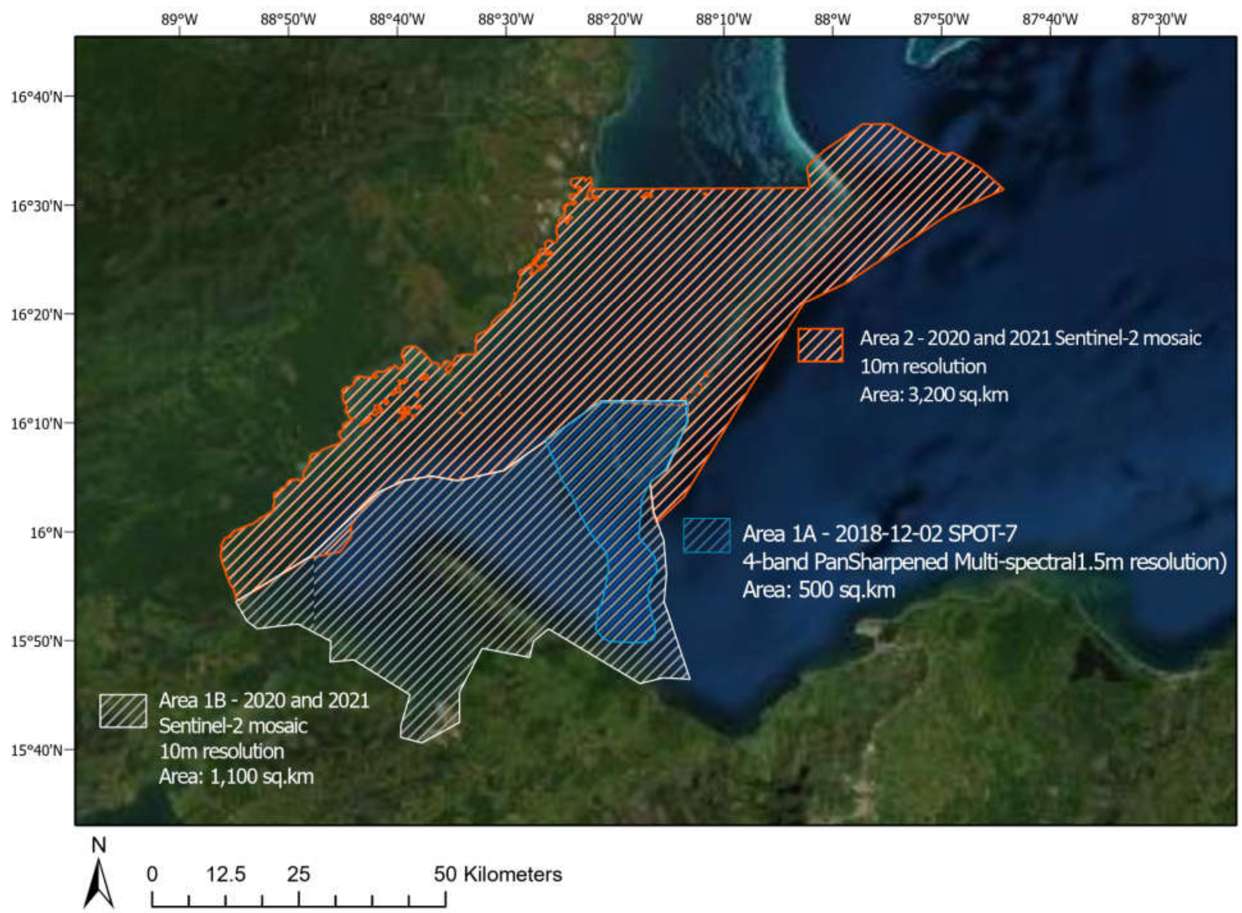


Figure 4: Shows the two mapping areas. Area 1 in white hatch was mapped using Sentinel-2 imagery and the area with blue hatch from SPOT-7 imagery. Area 2 (orange hatch) utilizes Sentinel-2 imagery. Landsat-8 imagery acquired in January 2017 was used for the combined areas covering the entire study area.

Supplementary Data

GEBCO Data

The General Bathymetric Chart of the Oceans (GEBCO) provides the most authoritative publicly available water-depth maps for the world oceans. The most evolved iteration of this product is GEBCO-2019, which is a global terrain model for ocean and land at 15 arc-second intervals. The typical data source of GEBCO in the coastal zone is public domain multibeam. The land data values are sourced from previously published digital elevation models predominantly derived from SRTM15+ program. The combined GEBCO (2019) bathymetry and terrain models were used together with Sentinel-2 satellite imagery for object-based image analysis to derive the habitat maps.

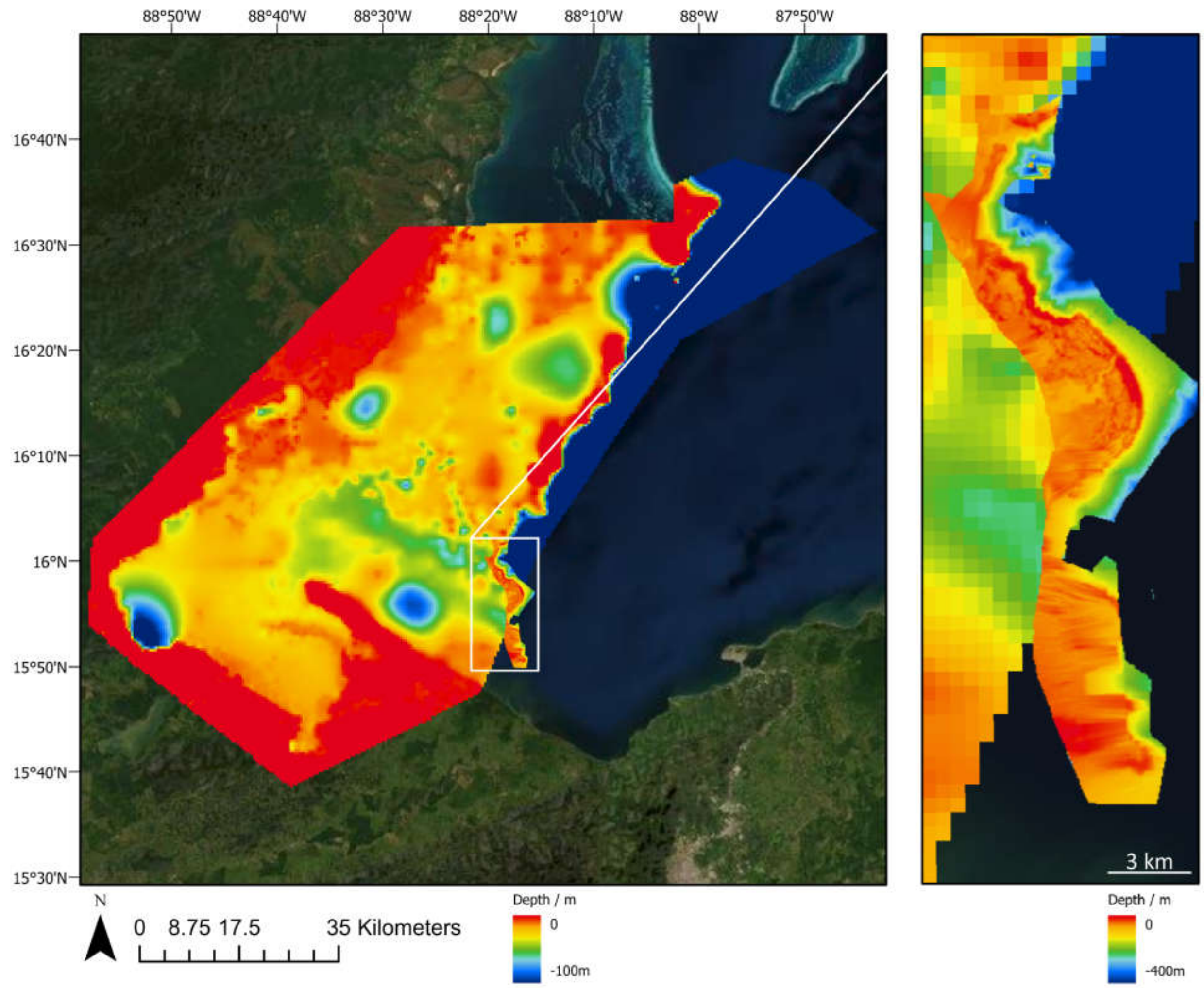


Figure 5: On the left is the GEBCO model for the study area. The image on the right-hand right is swath multibeam data collected in 2015 and 2016 covering the Corona Crown reef area.

High-resolution Imagery

WorldView-2 (WV2) satellite imagery acquired in November 2020 was made available for this study and was used for ground verification (Fig. 6). WorldView-2 imagery is particularly adept as the instrument images in eight multispectral bands with pixel widths of 1.85 m for data acquired with look angles <20° off-nadir, coarsening to 2.07 m for angles >20°. Pixel brightness values are digitally encoded with 11-bit radiometric resolution. WV2 is particularly well poised for imaging the shallow seabed since five of the eight spectral bands are of sufficiently short wavelength to have meaningful penetration in water—these five are the coastal blue band (400–450 nm), blue (450–510 nm), green (510–580 nm), yellow (585–625 nm), and red (630-690 nm). Experience suggests that under ideal conditions, the seabed could routinely be imaged for habitat mapping down to water depths of 25 m (Purkis et al. 2019). In addition to the WorldView-2 imagery, two samples of georeferenced drone images and one non-georeferenced image were available for ground verification. Drone images were captured in February 2021 and are located in Cramp Caye, Lazy Caye and South Cramp Caye (Fig. 6). In Guatemala, field observation locations were provided together with corresponding underwater photographs (Fig. 7).

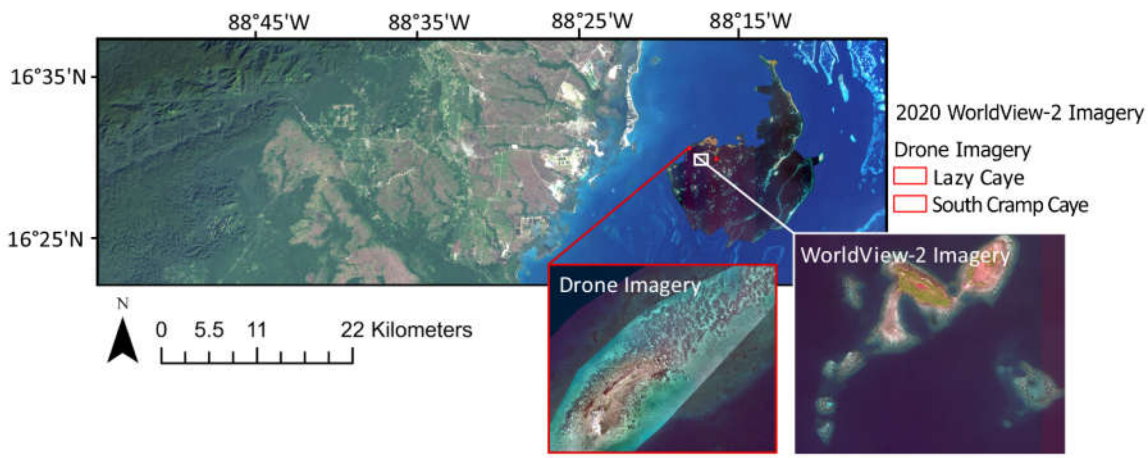


Figure 6: Shows the location of the WorldView-2 satellite and the drone images in Belize. These data were used to guide mapping from SPOT-7, Sentinel-2, and Lansat-8.

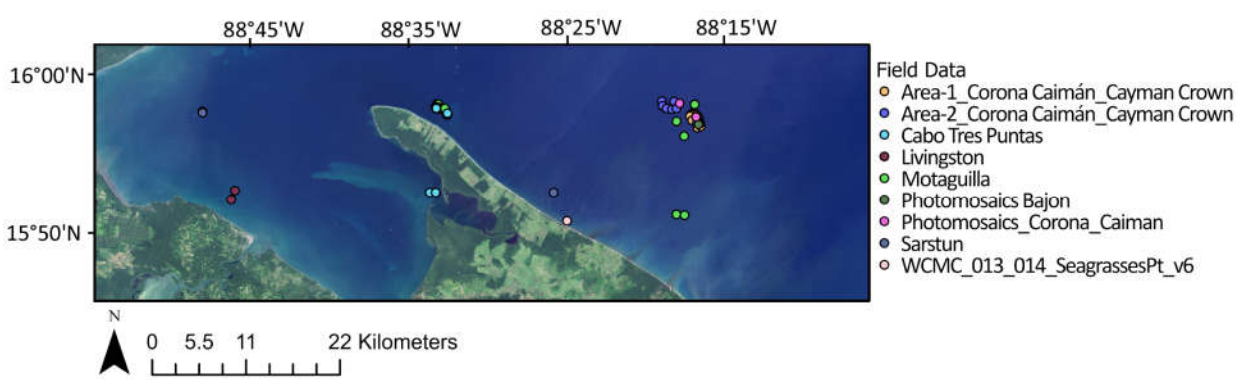


Figure 7: Location of ground-truth points in Guatemala.

Object-Based Mapping

An object-oriented approach was adopted for delineating benthic habitat in the available imagery. This approach contrasts with the more commonly employed "pixel-based" unsupervised classifiers that have traditionally been used for reef mapping. The application of Object Based Image Analysis (OBIA) allows for the integration of both geomorphological and benthic habitat characteristics into a single habitat scheme. Moreover, it is possible to apply distinct rules at each hierarchical level, fitting the natural functional breakdown of coral reef systems. The software used for mapping in this study, eCognition (v.9, Trimble Inc.), tenders a suite of object-oriented image analysis algorithms having particular utility for creating such thematic maps from remote sensing data, including for coastal and marine benthic habitats (Purkis et al, 2019). The eCognition software was used to segment the imagery into polygons in an object-based mapping approach (Knudby et al., 2011; Phinn et al., 2012; Purkis et al., 2012ab, 2014; Roelfsema et al., 2013, 2014, 2018; Zhang et al., 2013; Warren et al. 2016). Subsequently, the polygons were labeled by zone, geomorphology, habitat class, and convolved to ultimately yield a benthic habitat map. In a workflow termed 'hierarchical classification,' edge-detection routines are used to segment imagery into eCognition 'objects,' which are areas of the image set with similar spectral and/or textural attributes. These objects are subsequently assigned into one of several map classes based on rules which consider spectral/textural signatures, shape, and contextual relationships with surrounding classes. Note that an automated solution to the eCognition workflow exists, see Saul and Purkis (2015), but contextual editing by an expert delivers enhanced accuracy in most instances and is therefore adopted here.

Landsat-8, Sentinel-2, SPOT-7 imagery, bathymetry models were all brought into eCognition as separate layers. Segmentation algorithms were applied using the water-penetrating spectral bands of the highest resolution imagery for each location. Where possible, image objects were assigned as samples when ground-verification were available, as provided by the WorldView-2 and drone imagery in Belize and the field-truthed points in Guatemala. The training data were used to guide classification within the eCognition workflow. For this study, two map products were developed of which the first maps geomorphological zones. The second, and more detailed product is benthic habitat. Landsat-8 imagery provides the base layer for the generation of the geomorphological zones. Despite its 30 m resolution, Landsat-8 has several advantages over the Sentinel-2 imagery for understanding reef zonation. First, it has an additional two water penetrating bands as compared to Sentinel-2. Secondly, a single Landsat scene covers the entire study area, thereby reducing the spectral disparities that are invariably introduced when blending multiple scenes into a single mosaic.

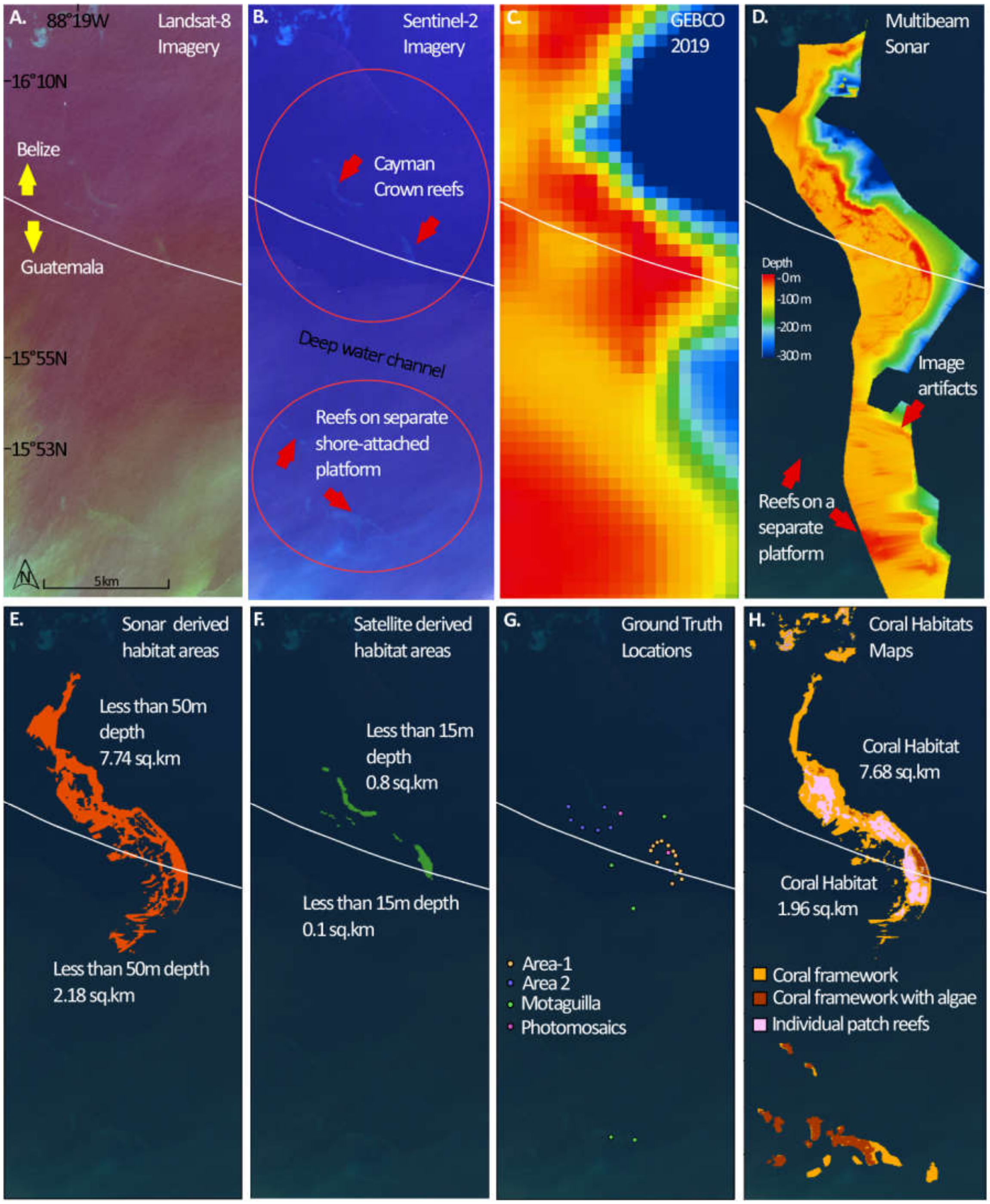


Figure 8: Shows the workflow for the development of the maps for the Corona Crown reef system. (A) shows the observed Corona Crown reefs from Landsat-8 Imagery together with the location of the territorial seas separating Belize and Guatalama. (B), meanwhile, depicts the same location, but with Sentinel-2 imagery, to which a stretch has been applied to the blue and green image bands in order to emphasize the reef systems – the offshore Corona Crown and the Guatamalan shore-attached reefs. (C) is the GEBCO bathyemtry and (D) is the multibeam sonar model, both used to extract and verify the locations of these reef system. In (E), eCognition was used to extract the seabed situated shallower than 50 m from the depth data. (F) eCognition workflows used to extracted habitats shallower than 15 m depth from the Landsat-8 and Sentinel-2 satellite imagery. (G) Field observation points where seafloor chractater is unequivocally know. (H) Final coral habitats.

Classification Scheme

The classification scheme adopted for this study meets the requirements for the Healthy Reef Initiative (HRI) in Belize and Guatemala. The regional maps comprise two levels; Level 1 is the map of geomorphological zones and Level 2 is the benthic habitat map. This pairing of maps for Belize and Guatemala seamlessly tie into the adjacent maps created for Honduras created in 2016 under the predecessor to this project. The Honduras classification schemes for both geomorphological zone and benthic habitat were based on the NOAA Biogeography Reef Mapping Program (Monaco et al., 2012), and were modified by Purkis (2016) to meet the requirements of the Honduras mapping initiative, such that they adhered to the standards of the Atlantic and Gulf Rapid Reef Assessment (AGRAA). Habitat class names align with those adopted by prior mapping endeavors and those currently in progress. Table 1 shows a crosswalk and provides a means of translating the classification schemes. In that table, the class names used in this study are highlighted in bold font with a yellow background. Geomorphological zone names, by contrast, are in bold font and green.

Table 1. shows geomorphological zone names (Level 1) in green and benthic habitat class names (Level 2) in blue and yellow. Class names adopted in this mapping initiative are in yellow and in **bold**. Comparative benthic habitat classification schemes are colored in blue.

<table>
<tr><th>Geomorphological Zones (Level 1)</th><th colspan="5">Benthic Habitats (Level 2)</th></tr>
<tr><th>NOAA/AGGRA, Healthy Reef Initiative (HRI) - 2021</th><th>Belize Coastal Zone Management Authority and Institute (CZMAI) - 1997</th><th>Honduras Countrywide Mapping (HND) - Purkis, 2016</th><th>Healthy Reef Initiative (HRI) - 2021</th><th>Caribbean Science Atlas TNC / The Nature Conservancy (in progress)</th><th>Allen Coral Atlas (in progress)</th></tr>
<tr><th>Honduras, Belize & Guatemala</th><th>Belize National Marine Habitat Classes</th><th>Honduras</th><th>Honduras, Belize & Guatemala</th><th>Caribbean</th><th>Global</th></tr>
<tr><td rowspan="2">Land</td><td rowspan="2">-</td><td rowspan="2">Land</td><td>Terrestrial unvegetated</td><td>Fore reef</td><td>-</td></tr>
<tr><td>Terrestrial vegetation</td><td>-</td><td>-</td></tr>
<tr><td>Reef crest</td><td>Reef crest</td><td rowspan="3">Intertidal vegetation</td><td>Dense mangroves</td><td>Reef crest</td><td>-</td></tr>
<tr><td>Reef flat</td><td>Reef flat</td><td>Sparse mangroves</td><td>-</td><td>-</td></tr>
<tr><td>Back reef</td><td>Back reef</td><td>Microbial mats</td><td>Back reef</td><td>Microbial mats</td></tr>
<tr><td>Fore reef</td><td>Silt and sparse algae</td><td>Intertidal mud</td><td>Interntial muds</td><td>Muddy bottom</td><td rowspan="4">Sand</td></tr>
<tr><td>Bank-shelf / Escarpment</td><td>-</td><td rowspan="2">Sand</td><td>Intertial sands</td><td rowspan="3">Sand</td></tr>
<tr><td>Lagoon</td><td>-</td><td>Subtidal sands</td></tr>
<tr><td>Channel</td><td>Sand and sparse alage</td><td>Sand with algae</td><td>Sand with algae</td></tr>
<tr><td>Patch reef</td><td>Dense seagrass</td><td rowspan="2">Seagrass</td><td>Dense seagrass</td><td>Dense seagrass</td><td rowspan="2">Seagrass</td></tr>
<tr><td>Deep water</td><td>Sparse seagrass</td><td>Sparse seagrass</td><td>Sparse seagrass</td></tr>
<tr><td></td><td>-</td><td>Reef rubble</td><td>Reef rubble</td><td rowspan="2">Boulders and rocks</td><td>Rubble</td></tr>
<tr><td></td><td>-</td><td rowspan="2">Pavement</td><td rowspan="2">Pavement</td><td rowspan="4">Rock</td></tr>
<tr><td></td><td>-</td><td>Dredged</td></tr>
<tr><td></td><td rowspan="2">Shallow gorgonians</td><td rowspan="2">Pavement with gorgonians and turfing algae</td><td rowspan="2">Pavement with gorgonians and turfing algae</td><td rowspan="3">Hardbottom with dense algae</td></tr>
<tr><td></td></tr>
<tr><td></td><td>-</td><td rowspan="2">Aggregate reef with algae</td><td rowspan="2">Coral framework with algae</td><td rowspan="5">Coral / Algae</td></tr>
<tr><td></td><td>-</td><td>Hardbottom with sparse algae</td></tr>
<tr><td></td><td>Spur and grooves</td><td rowspan="2">Aggregate reef</td><td>Spur and groove reef</td><td>Spur and groove reef</td></tr>
<tr><td></td><td>-</td><td>Coral framework with algae</td><td rowspan="2">Coral / Algae</td></tr>
<tr><td></td><td>Patch reefs</td><td>Individual patch reef</td><td>Individual patch reef</td></tr>
<tr><td></td><td></td><td></td><td>Deep lagoonal water</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td>Deep water</td><td></td><td></td></tr>
</table>

Habitat Class Descriptions

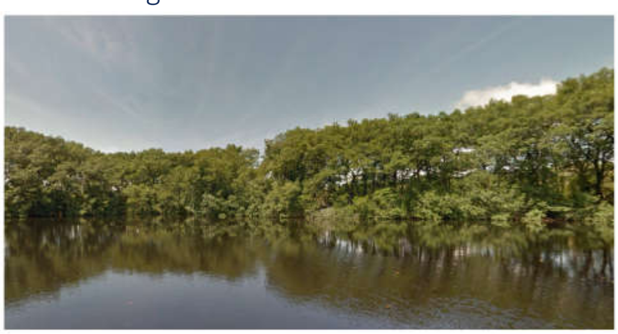
Terrestrial Unvegetated


Unvegetated terrestrial landscapes, including urban development.

Terrestrial Vegetated


Vegetated terrestrial landscapes encompassing closed- and open-canopy woodlands and forests, as well as shrublands and grasslands.

Dense Mangroves




Dense mangrove forests and their intertidal organic-rich muds populated by pneumatophores (aerial roots). This habitat is typically incised by tidal creeks. Mangrove species include *Avicennia germinans*, (black mangrove), *Laguncularia racemose* (white mangrove) and *Rhizophora mangle* (red mangrove).

Sparse Mangroves


As for dense mangrove forests, but encompassing areas where mangrove coverage is less well developed - typically patchy.

Microbial Mats


Dense microbial mats, typically cyanobacterial, in the intertidal zone down to 1 m water depth. Mats are well laminated and serve to trap and bind mud, often delivering tidal flats.

Intertidal Muds


Expansive mudflats developed inboard of sheltering reefs, islands, and mangroves. Sediments are fine and organic rich. Development of a microbial veneer to the flats less pervasive as in the previous habitat class.

Intertidal Sands


Intertidal sands exposed at low tide, flooded at high. Typically, a beach. This habitat is of sufficiently high energy to winnow muds, deliver sand-dominated sediment, and exclude any meaningful development of submerged aquatic vegetation (seagrass, macroalgae, etc.).

Subtidal Sands


Unconsolidated sediment sheets in the subtidal. Bedforms present in high-energy setting, absent in low energy. This class occurs at all depths and in all geomorphological zones and the sediment can be colonized by sparse coverage (<20%) of submerged aquatic vegetation.

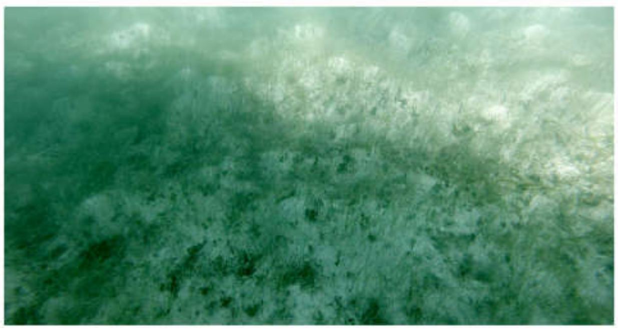
Sand with Algae


Unconsolidated sediment sheets with >20% macroalgal cover. This class also occurs at all depths and in all geomorphological zones. Biotic cover spans brown fleshy algae (e.g. *Lobophora variegate and Padina spp*.), brown algae (*Laurencia spp., and Sictyota spp.*), and green algae (*Halimeda spp. Phipocephalus spp, Penicillus spp. And Udotea spp.*).

Dense Seagrass


Seagrass meadows exceeding 60% space cover of the seafloor. The assemblage comprising the meadows is typically dominated by *Thalassia* and *Syringodium*, but both *Halophyla* and *Halodule* may also be present, albeit at lower density (Mumby and Harborne, 1999).

Sparse Seagrass

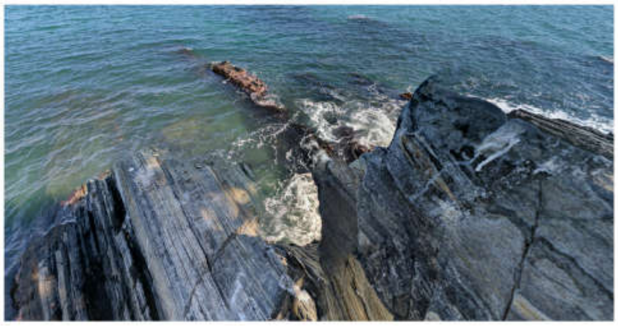



As for dense seagrass, but space cover by the meadow <60%.

Reef Rubble


Accumulations of coarse reef debris, typically situated leeward of the reef flat in the back-reef zone. The majority of debris production and transport occurs during storm events. If the time between storms is of sufficient duration, the matrix of debris consolidates and cements. Coral skeletons are typically heavily encrusted by calcareous red algae. Turf algae can be pervasive.

Pavement




Planation hardgrounds encompassing eroded reef terraces and bed-rock pavements. Biotic colonization is typically turf algae with occasional isolated coral colonies (<1% space cover). Thin veneers of sediment may accumulate in topographic lows and other quiescent environments.

Pavement with Gorgonians and Algae


As above – planation hardgrounds – but densely colonized by biotic cover. Typical assemblage spans gorgonians, macro- and turf-algae, sponges, and occasional corals.

Coral Framework


Dense interlocking frameworks of live and some dead corals. This class spans both the back- and fore-reef environments, and does not include the spur and groove reef formations.

Coral Framework with Algae

As for the coral framework class, but rather than being live-coral dominated, the framework is heavily overgrown by fleshy macroalgae, as is common after the demise of the reef assemblage.

Patch Reefs

Isolated, relatively small, growths of coral framework, surrounded by sand. Patch reefs are particularly common in the lagoon but may also occur in the fore- and back-reef environments. If the sediment surrounding the patch reefs are colonized by submerged aquatic vegetation, halos of bare sediment may develop around the base of the reef, caused by increased grazing in close proximity to the patches by the fish and invertebrates which inhabit them.

Spur and groove reef

Spurs are formed by accreting massive and encrusting corals, leaf corals and calcified green algae, whereas the grooves usually contain sand and bedrock. Spur and groove reef formations are located immediately seaward of the reef crest in the forereef zone (Kramer and Kramer, 2002

Geomorphological Zone and Benthic Habitat Maps

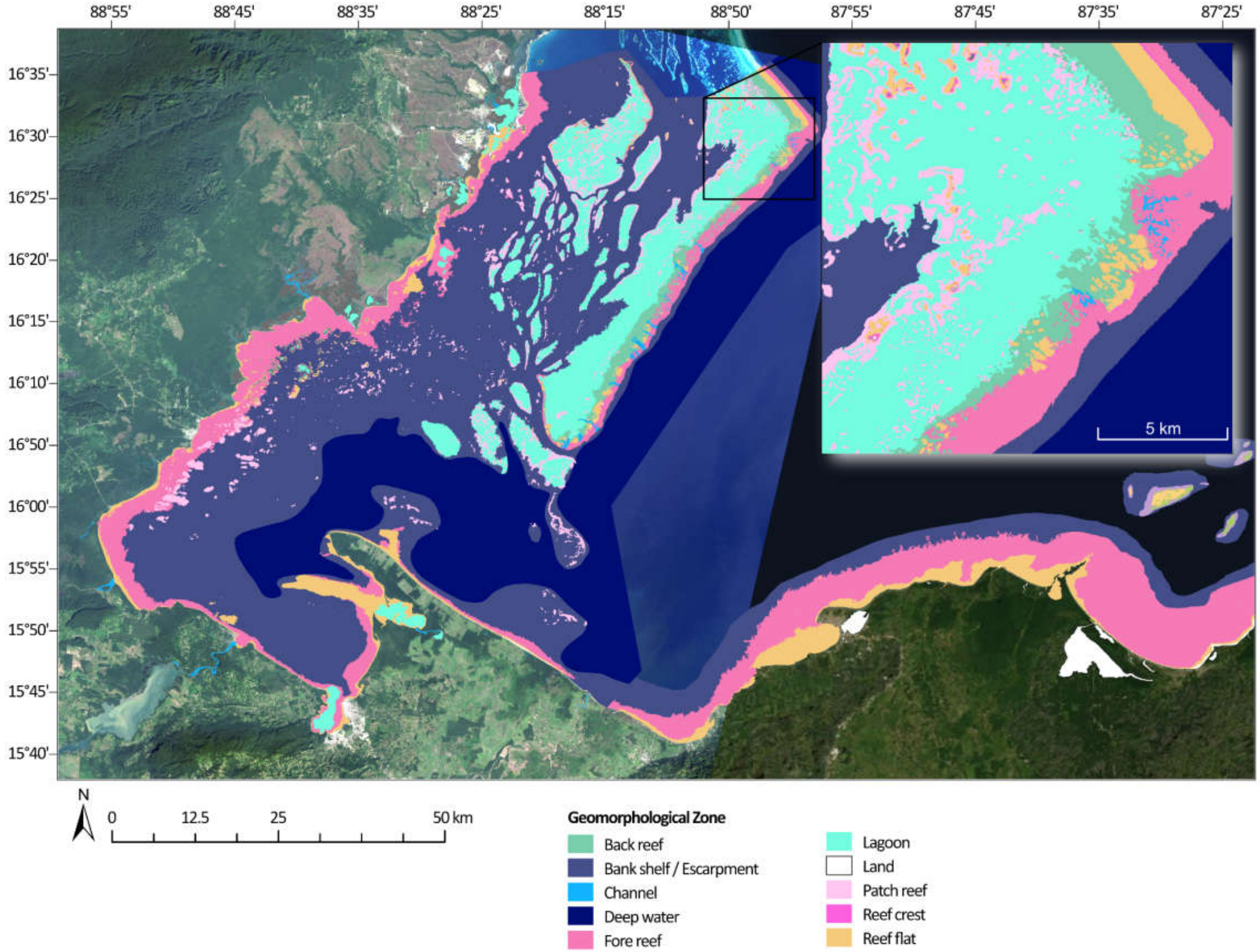


Figure 9: Map of geomorphological zones for the study area (4,300 sq.km).

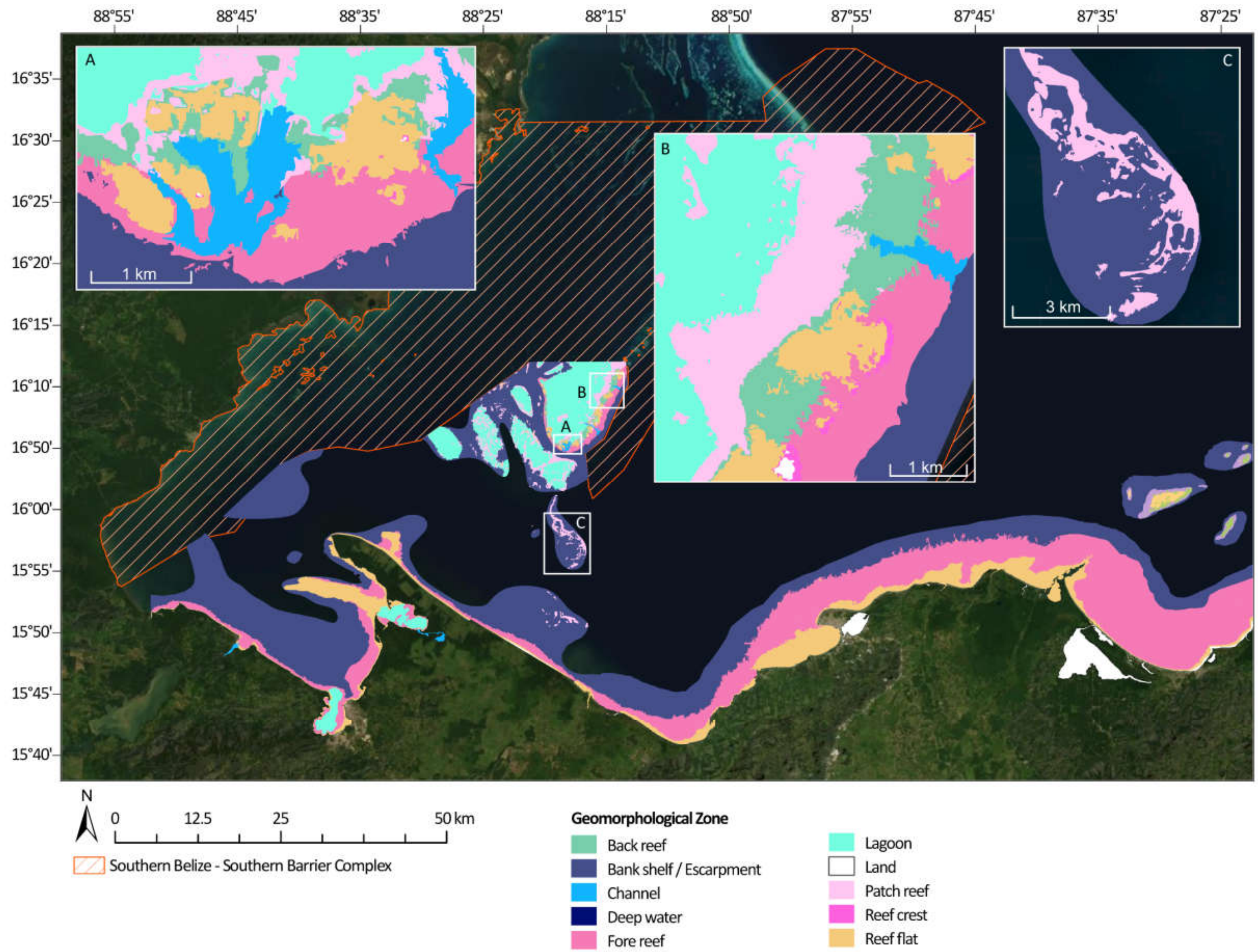


Figure 10: Map of geomorphological zones for Area 1 (1,100 sq km).

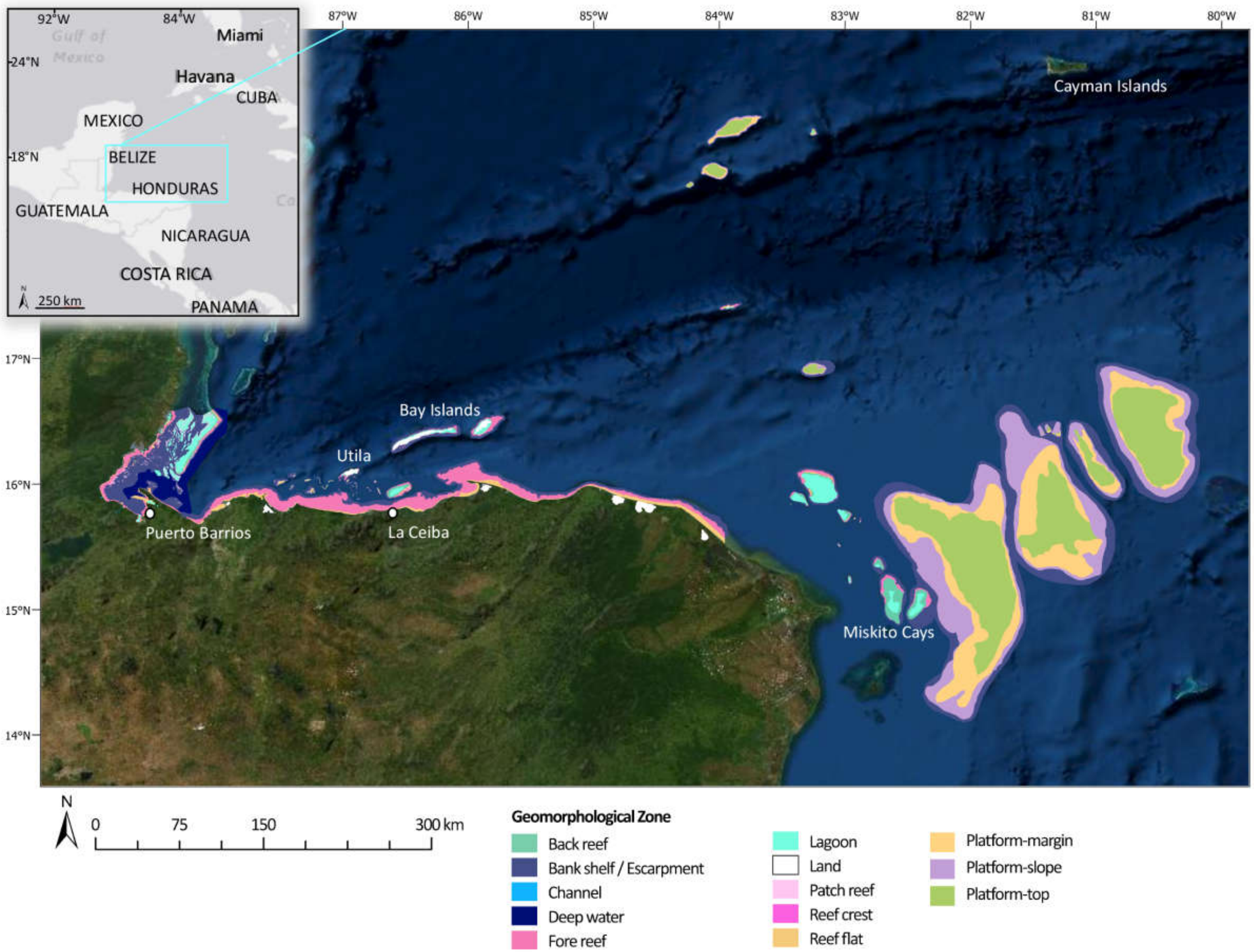


Figure 11: Map of geomorphological zones for Honduras, Guatemala, and Southern Belize (55,000sq.km).

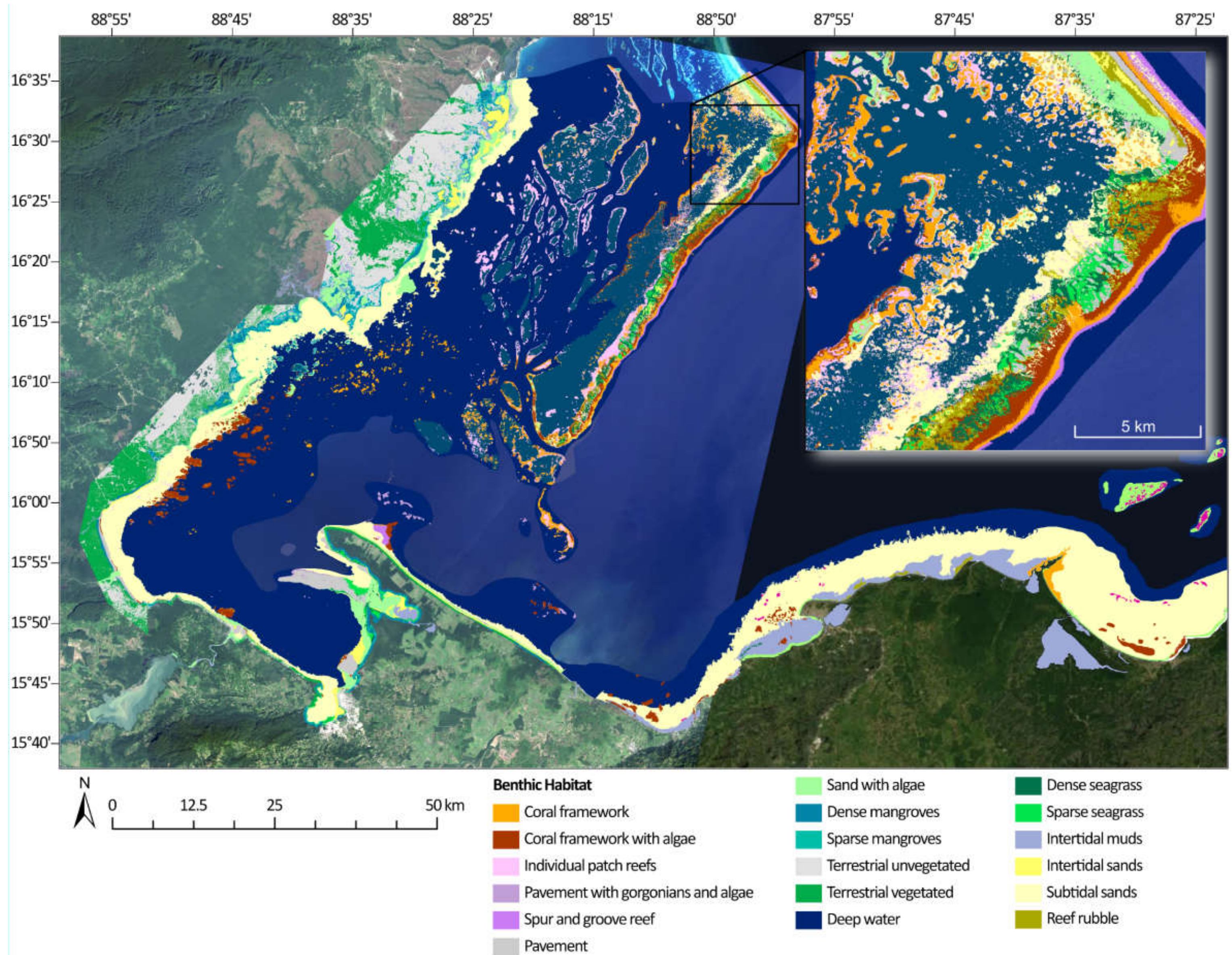


Figure 12: Map of benthic habitats for the study area (4,300 sq.km).

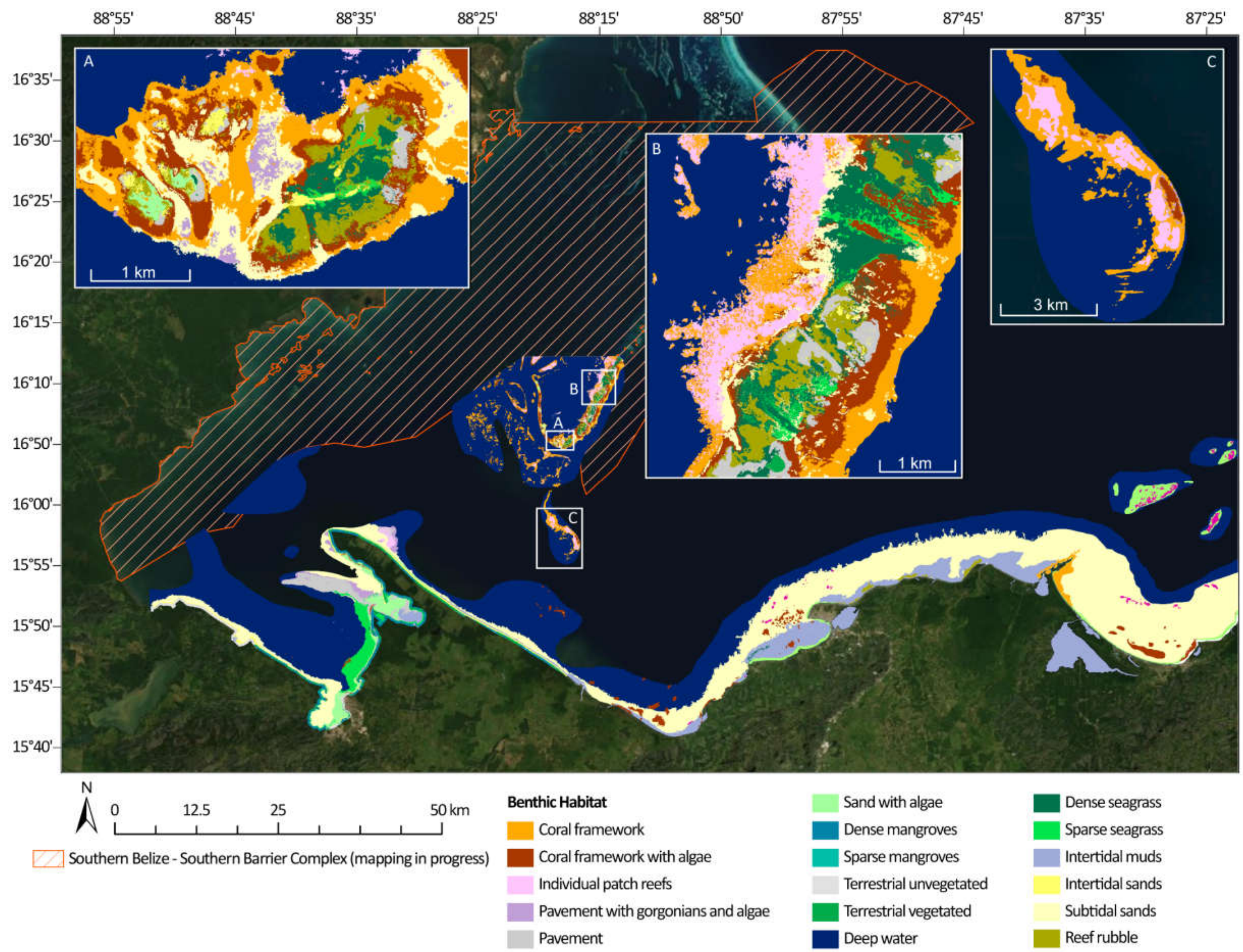


Figure 13: Map of benthic habitats for Area 1 (1,100 sq.km).

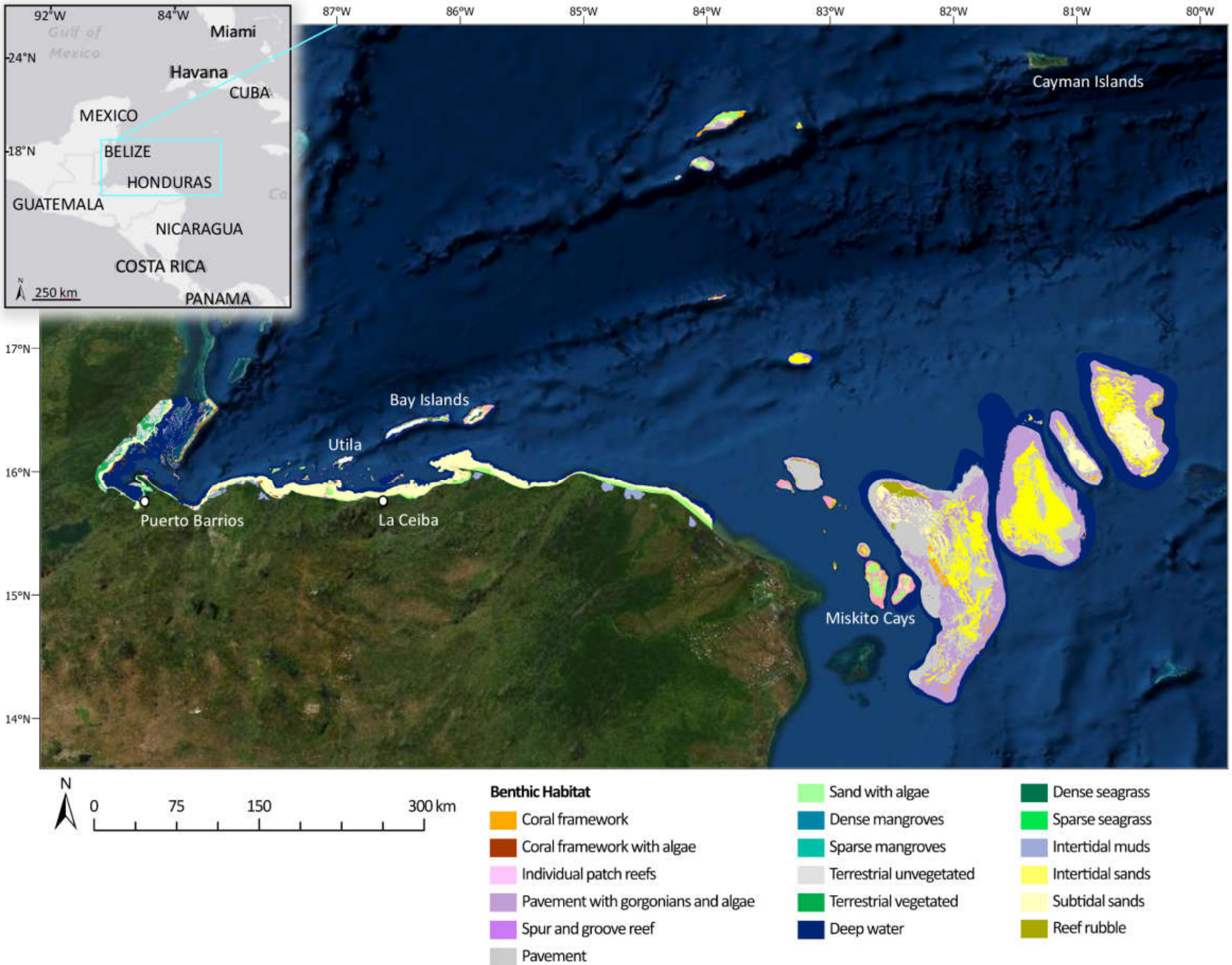


Figure 14: Map of benthic habitats for Honduras, Guatemala, and Belize (55,000 sq.km).

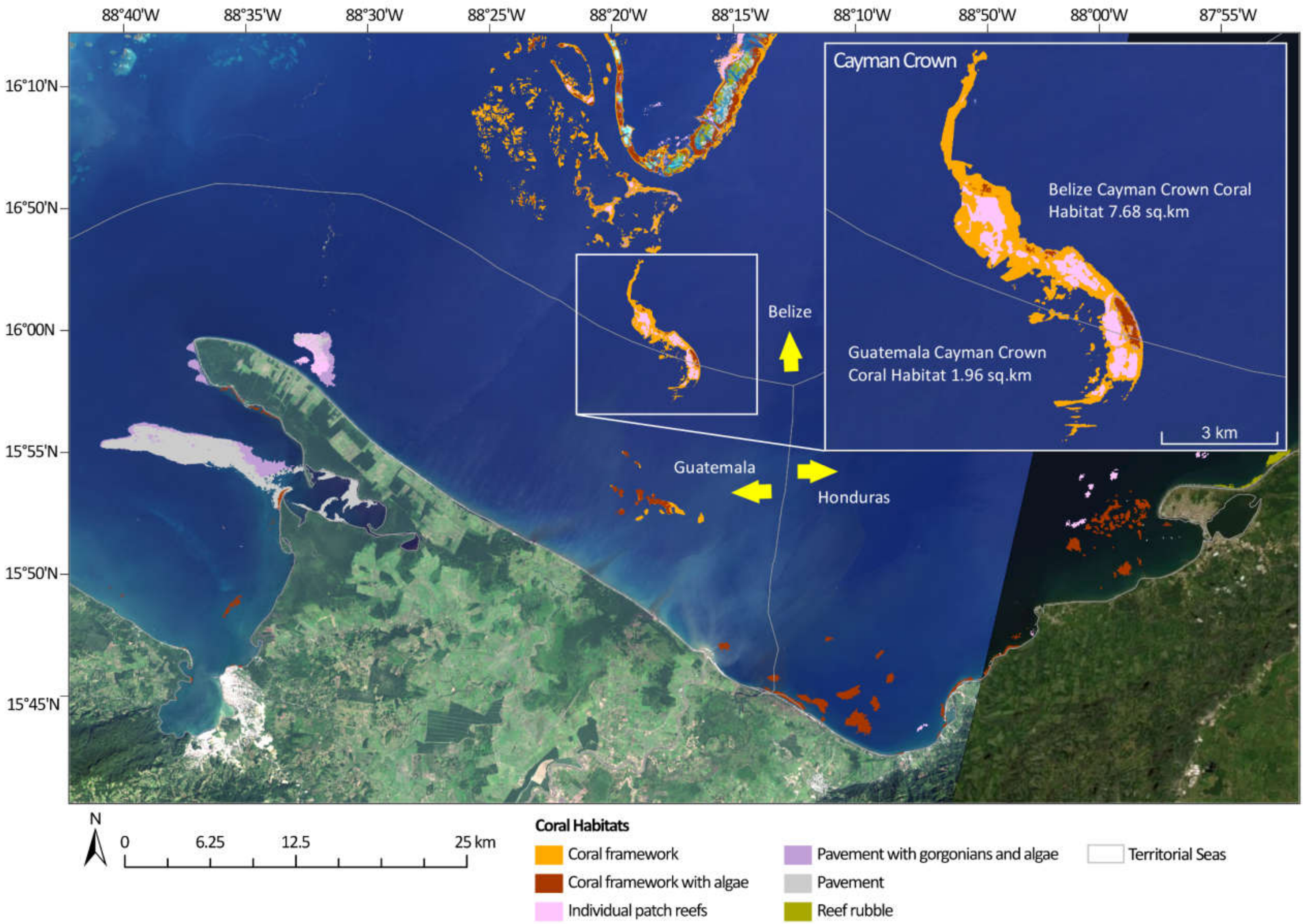


Figure 15: Map of the coral habitats that surround the Cayman Crown reefs, Sapodilla Cayes Marine Reserve and the Punta Manabique Marine Reserve.

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