

SUMMARY REPORT
OF
SATELLITE MAPPING OF BENTHIC HABITATS AND BATHYMETRY FOR
ANTIGUA, DOMINICA AND SAINT LUCIA, CARIBBEAN

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Contents

1.	List of Figures.....	3
2.	Executive Summary	4
3.	Motivation	4
4.	Description of the Study Area	4
5.	Satellite Imagery Employed in the Study	9
6.	Image Preparation.....	9
7.	Object-based Mapping of Benthic Habitat.....	9
8.	Habitat Classification Scheme	12
	Coral Framework	12
	<i>Acropora</i> Framework.....	13
	Rocky Outcrops with Corals.....	13
	Gorgonian Hardground	14
	Algal Hardground.....	14
	Reef Rubble	15
	Boulders and Rocks	15
	Sparse Seagrass	16
	Dense Seagrass.....	16
	Sand with Macroalgae	17
	Sand.....	17
9.	Habitat Maps	18
10.	Spectral Mapping of Bathymetry	22
11.	References.....	25

1. List of Figures

Figure 1 World imagery showing the Organization of Eastern Caribbean States (OECS), of which Antigua, Dominica and Saint Lucia and members. The figure shows the location of these three islands within the greater Caribbean. North is top.	5
Figure 2 True-colour (red, green, blue) Pléiades mosaic of Antigua acquired in 2014. Projection is UTM Zone 20N, datum is WGS84. The field team collected 107 GPS-referenced ground-truth points using a tethered drop camera (dropcam). These videos were examined and interpreted, serving as training sites to classify the satellite image. North is top and each ground-truth point (<i>dots</i>) has been color-coded into the most appropriate map class.	6
Figure 3 A true-colour (red, green, blue) WorldView-3 mosaic of Dominica acquired in 2016. Projection is UTM Zone 20N, datum is WGS84. The field team collected 107 GPS-referenced field points using a dropcam. These video samples were examined and interpreted, serving as training sites to classify the satellite image. North is top and each ground-truth point has been color-coded into a map class.	7
Figure 4 True-colour (red, green, blue) Pléiades mosaic of Saint Lucia acquired in 2015. Projection is UTM Zone 20N, datum is WGS84. The field team collected 143 GPS-referenced field points using the dropcam. North is top and each ground-truth point has been color-coded into the most appropriate map class.	8
Figure 5 Workflow for the creation of the habitat maps developed for a section of seabed surrounding FreeTown, Antigua (A): (B) Statistics pertaining to the spectral and textural properties of the Pléiades imagery are used to drive a preliminary segmentation of the imagery into landscape objects using eCognition. (C) 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.	11
Figure 6 Benthic habitat map for the Antigua area partitioned into eleven habitat classes.	19
Figure 7 Benthic habitat map for Dominica study area partitioned into eleven habitat classes.	20
Figure 8 Benthic habitat map for St. Lucia study partitioned into eleven habitat classes.	21
Figure 9 Digital elevation model for Antigua spectrally derived from Pléiades imagery and calibrated by single-beam sonar soundings.	23
Figure 10 Digital elevation model for Dominica spectrally derived from Landsat 8 imagery and calibrated by single-beam sonar soundings.	24
Figure 11 Digital elevation model for Saint Lucia, spectrally derived from Pléiades imagery and calibrated by single-beam sonar soundings.	25

2. Executive Summary

- Antigua, Dominica and St. Lucia are part of the Organisation of Eastern Caribbean States (OECS), a body contributing to the sustainable development of OECS Member States by supporting their strategic insertion into the global economy while maximizing the benefits accruing from their collective space.
- This project calls upon satellite imagery acquired by WorldView-3, Pléiades and Landsat 8. Seabed mapping is accomplished using an object-based classification procedure.
- Antigua and St. Lucia are noteworthy in hosting extensive stands of *Acropora*. While all three islands have areas variably dominated by massive corals, those of Dominica are the least extensive.
- Whereas spectral derivation of bathymetry could be conducted for both Antigua and St. Lucia using Pléiades imagery, the WorldView-3 mosaic for Dominica was compromised by spectral artifacts and therefore bathymetry was derived from Landsat 8.
- It is envisioned that these geospatial products will aid marine spatial planning and conservation in Antigua, Dominica and St. Lucia.

3. Motivation

The Nature Conservancy (TNC) has developed satellite-derived maps for both biological cover and bathymetry for Antigua, Dominica and Saint Lucia. The purpose of the mapping endeavor is the creation a GIS product that will be used to support ongoing marine spatial planning initiatives within the Organization of Eastern

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Caribbean States (OECS).

4. Description of the Study Area

Antigua, Dominica and St. Lucia reside within the Lesser Antilles in the Caribbean Sea (Fig. 1). Like all components of this island chain, the sites lie on a volcanic island arc between the Greater Antilles to the north-west and the continent of South America. Sitting on a single shallow water platform, the shelf of Antigua (Fig. 2) is often considered in unison with its close neighbour, Barbuda, and both islands combine to form the largest Economic Exclusive Zone (EEZ) (108,085 sq. km) and shelf area (3,930 sq. km) in the region. Meanwhile, Dominica (Fig. 3)

has the smallest shelf area of the three countries considered which consists of stretches of seagrass meadows, a variety of coral reefs and limited wetlands. Antigua is one of the largest of the Eastern Caribbean islands covering 603 sq. km of land with 208 km of coastline (Fig. 4). While hosting coral reefs in various degrees of health, the nearshore waters of Antigua, Dominica and St. Lucia are affected by the usual insults to ecosystem health, including rampant coastal development, sediments, pollution, unsustainable fishing practices, storms and coral bleaching. A team from The Nature Conservancy (TNC) collected ground-truth points around the three sites to guide subsequent satellite mapping. This exercise was achieved using a tethered drop camera (dropcam) with which high-definition seabed video was acquired.

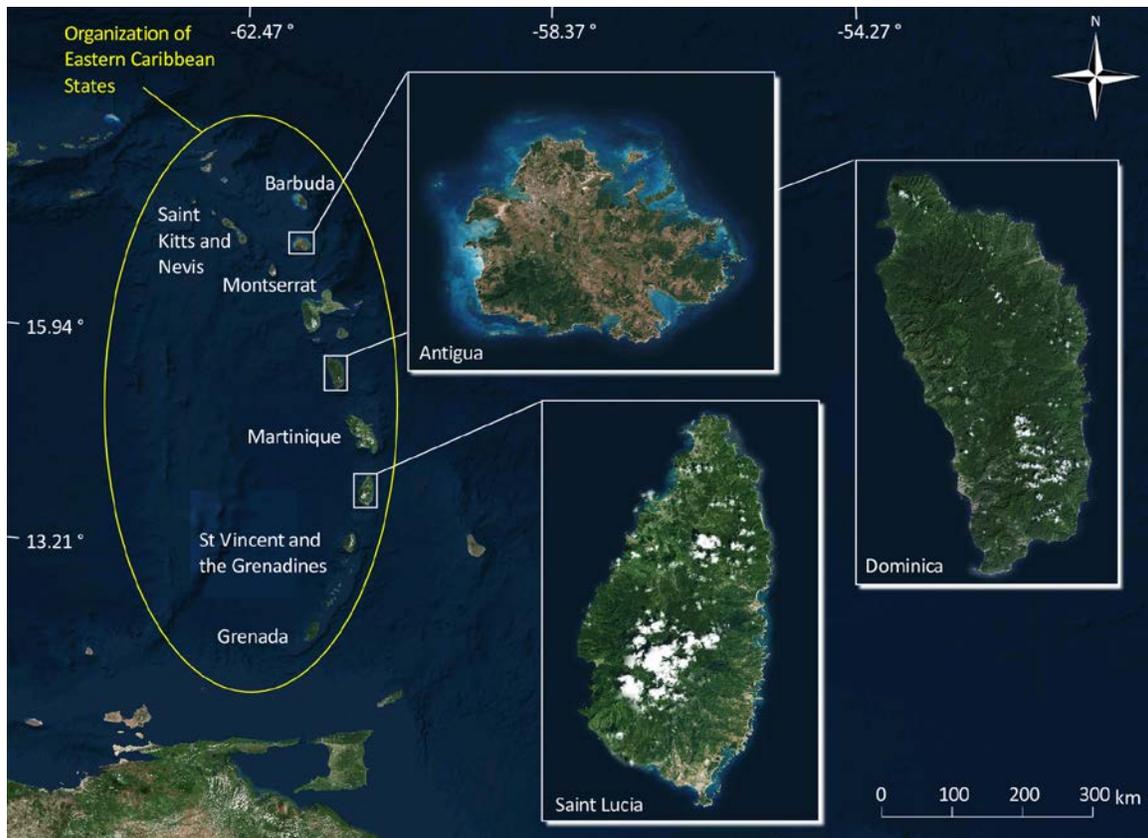


Figure 1 | World imagery showing the Organization of Eastern Caribbean States (OECS), of which Antigua, Dominica and Saint Lucia and members. The figure shows the location of these three islands within the greater Caribbean. North is top.

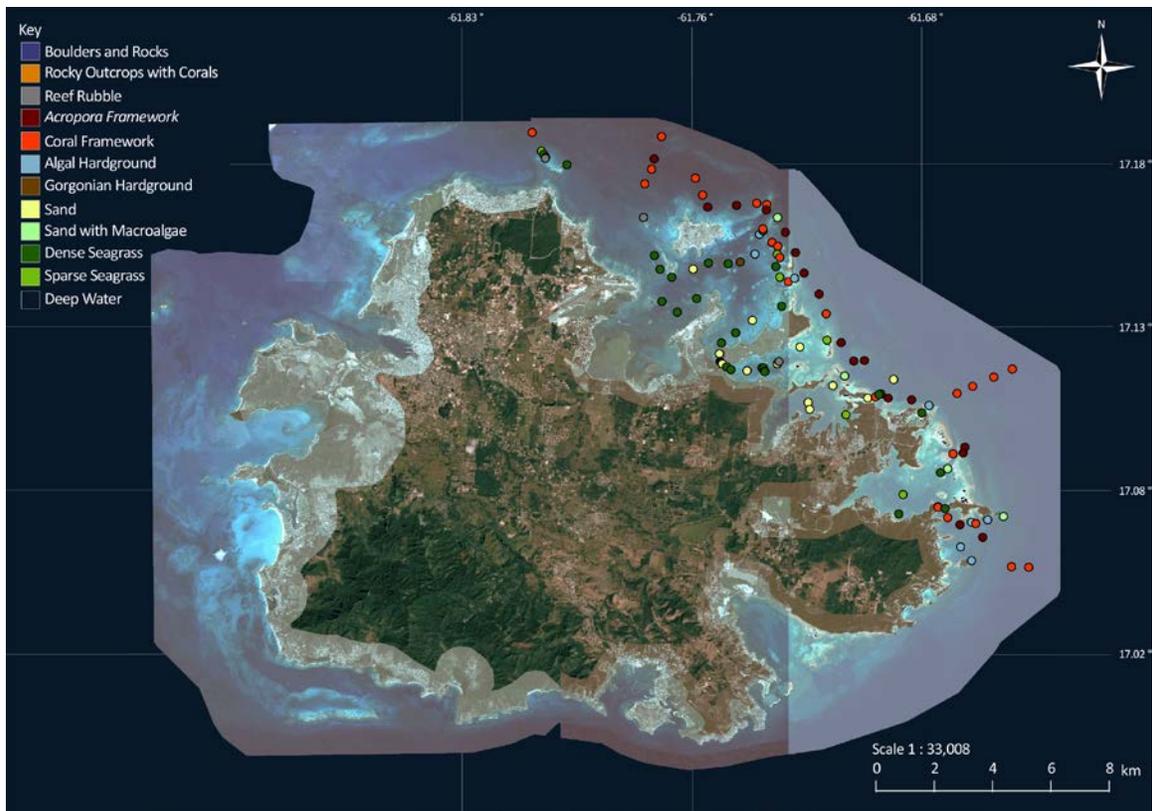


Figure 2 | True-colour (red, green, blue) Pléiades mosaic of Antigua acquired in 2014. Projection is UTM Zone 20N, datum is WGS84. The field team collected 107 GPS-referenced ground-truth points using a tethered drop camera (dropcam). These videos were examined and interpreted, serving as training sites to classify the satellite image. North is top and each ground-truth point (*dots*) has been color-coded into the most appropriate map class.

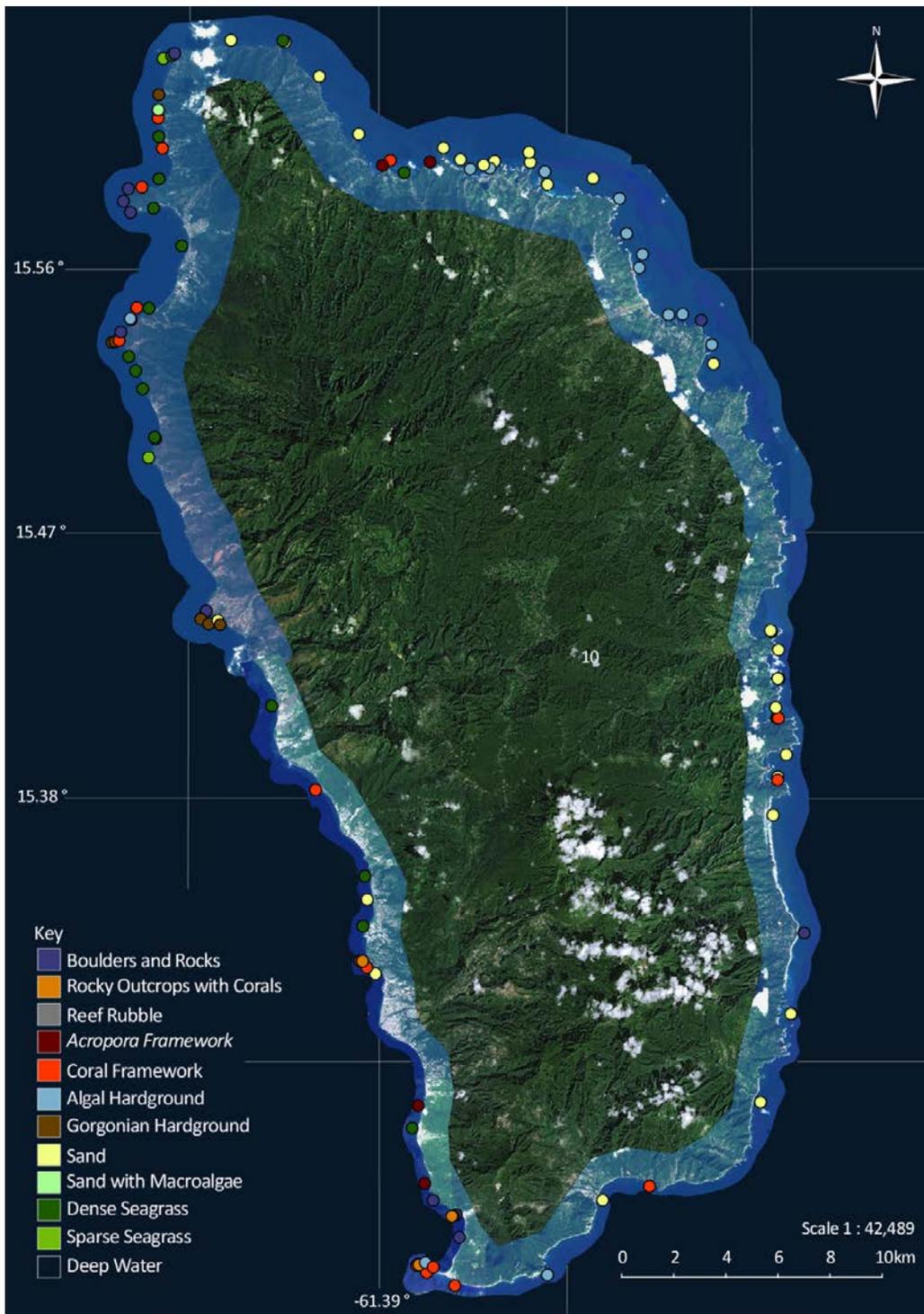


Figure 3 | A true-colour (red, green, blue) WorldView-3 mosaic of Dominica acquired in 2016. Projection is UTM Zone 20N, datum is WGS84. The field team collected 107 GPS-referenced field points using a dropcam. These video samples were examined and interpreted, serving as training sites to classify the satellite image. North is top and each ground-truth point has been color-coded into a map class.

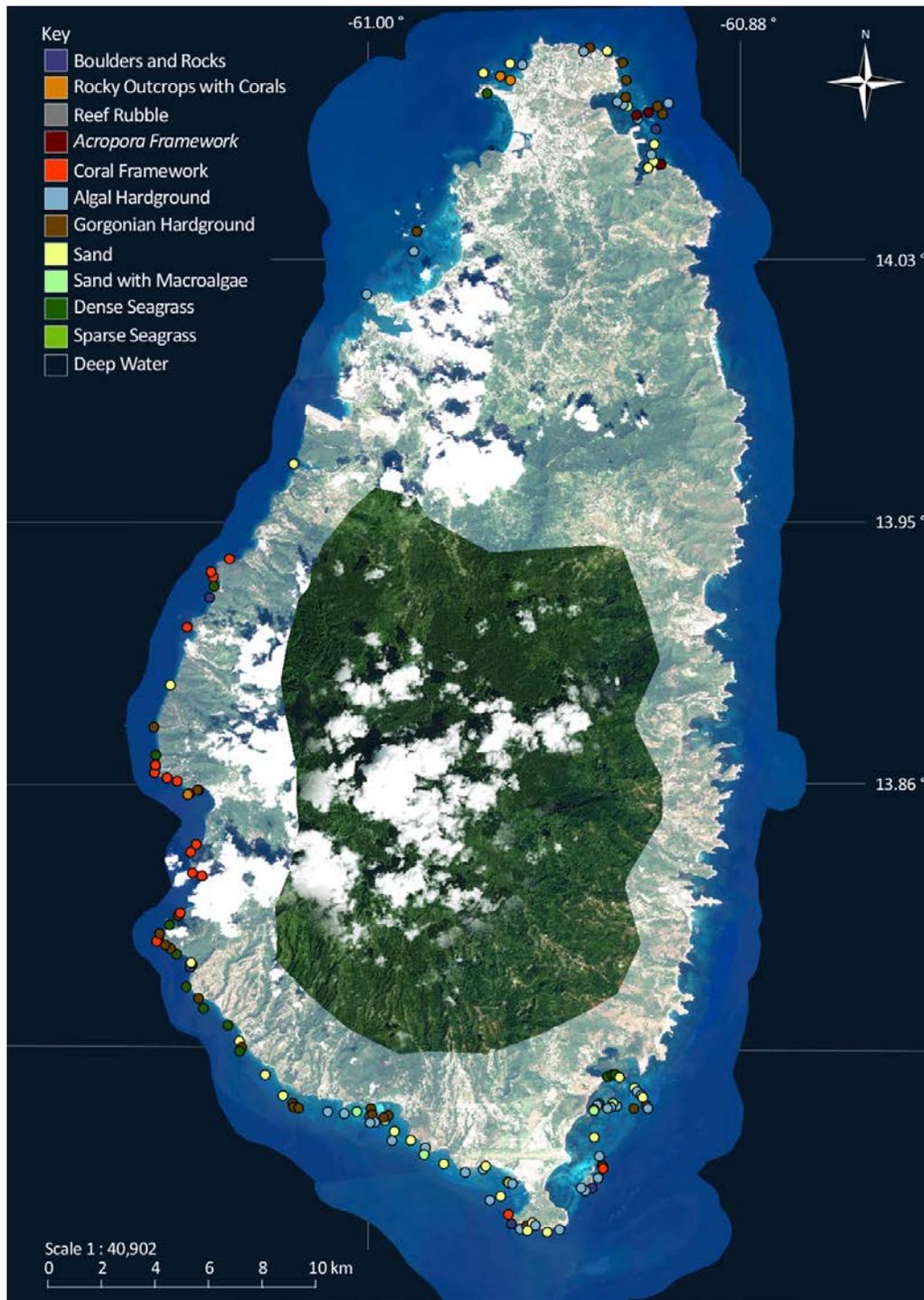


Figure 4 | True-colour (red, green, blue) Pléiades mosaic of Saint Lucia acquired in 2015. Projection is UTM Zone 20N, datum is WGS84. The field team collected 143 GPS-referenced field points using the dropcam. North is top and each ground-truth point has been color-coded into the most appropriate map class.

5. Satellite Imagery Employed in the Study

This project called upon satellite imagery acquired from WorldView-3, Pléiades and Landsat 8. WorldView-3, launched October 2014 and operated by DigitalGlobe Inc., has the same specifications as its predecessor WorldView-2, which was the first high-resolution 8-band multispectral commercial satellite. Operating at an altitude of 770 km, WorldView-3 provides 0.48 m panchromatic resolution and 1.85 meter multispectral resolution. Like WorldView-3, Pléiades is a high-resolution instrument boasting 2 m multispectral pixels across its 20 km swath width. This satellite is operated by CNES and was launched in 2012. 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.

6. Image Preparation

All of the satellite images 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). Since ancillary bathymetry data were collected by the field team, it was possible to apply a water column correction to the shallow water areas that were not confounded by excessive sun glint.

7. Object-based Mapping of Benthic Habitat

An object-oriented approach was adopted for delineating benthic habitat in the WorldView-3 and Pléiades imagery. This approach contrasts the more commonly employed “pixel-based” unsupervised classifiers that have traditionally been used for coral reef mapping. The principal disadvantage of the unsupervised classification approach in a submerged setting, such as the shallow habitats of Antigua, Dominica and St. Lucia, 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 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., 2014a,b). 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.

A total of 357 ground-control points were provided to guide the object-based mapping of benthic habitat. 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 357 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. In this way, the habitat maps honour all of the ground-truth data to the extent of the 357 samples available, they are therefore 100% accurate. An alternative strategy would have been to set aside a proportion of the ground-control points for the purpose of conducting an independent accuracy assessment of maps. With so few control points available, though, it was decided that all the survey data should be used to guide the mapping.

An example of the object-based mapping procedure is developed for a section of seabed surrounding FreeTown, Antigua (Fig. 5). This method was carried out on each of the available WorldView-3 and Pléiades 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.

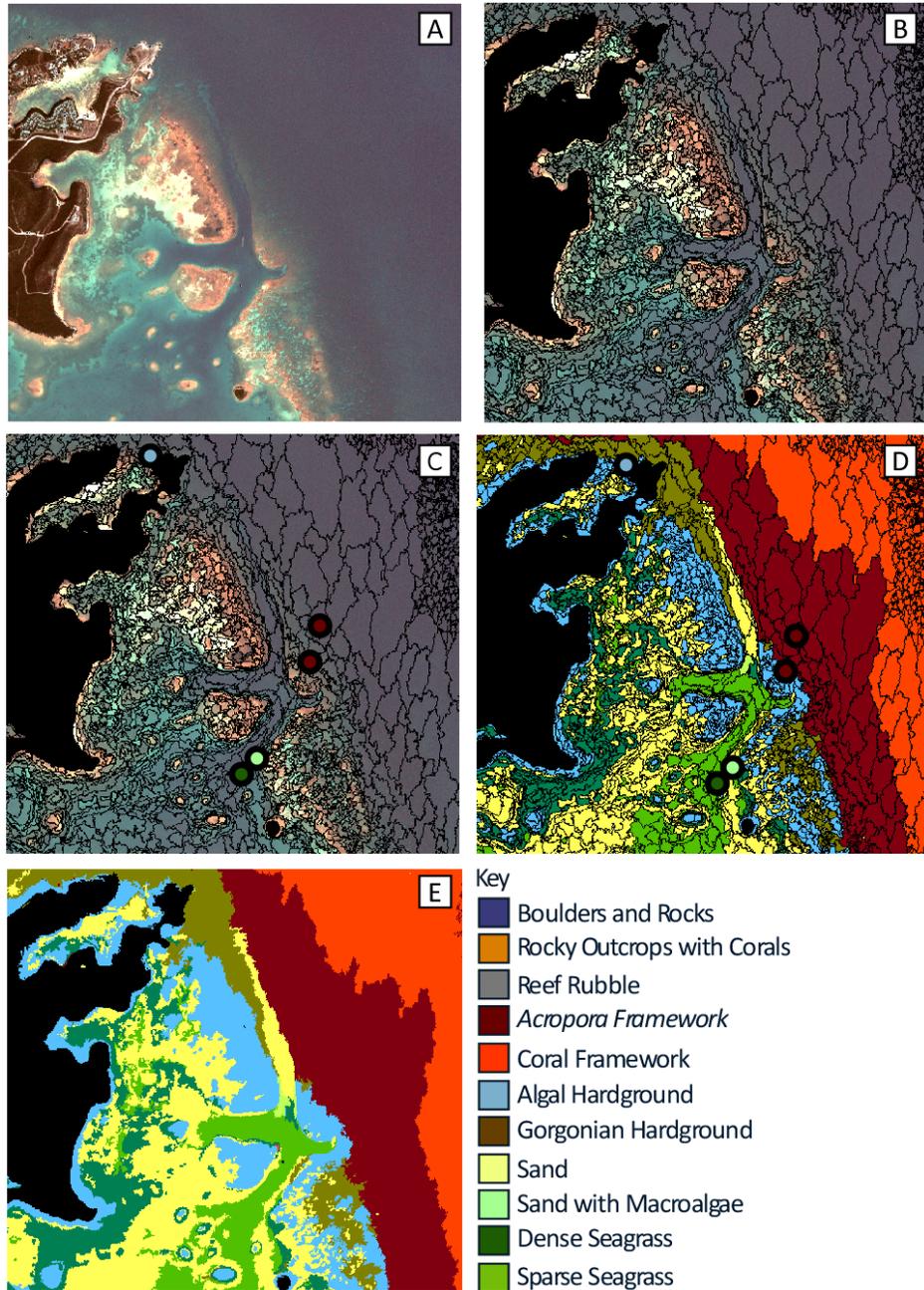


Figure 5 | Workflow for the creation of the habitat maps developed for a section of seabed surrounding FreeTown, Antigua (A): (B) Statistics pertaining to the spectral and textural properties of the Pléiades imagery are used to drive a preliminary segmentation of the imagery into landscape objects using eCognition. (C) 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.

8. Habitat Classification Scheme

Coral Framework



High-relief coral framework, typically with 0-5% live coral cover. Occasional dense coral colonies range from sub-meter to meter-scale in size. Assemblage dominated by massive and submassive species such as *Siderastrea*, *Faviidae*, *Monastrea*, *Diploria*, *Porites* and *Colpophylia* spp. Dead coral skeletons inhabited by both calcareous and fleshy algae (predominantly *Sargassum*, *Dictyota* spp.). Gorgonians and clinoid sponges occupy the remaining substrate. Sand pockets may develop in the lows of the framework.

Acropora Framework



Dense interlocking framework of live and dead branching corals. This class may consist of mixed or monospecific assemblages of *Acropora palmata* and *A. cervicornis*.

Rocky Outcrops with Corals



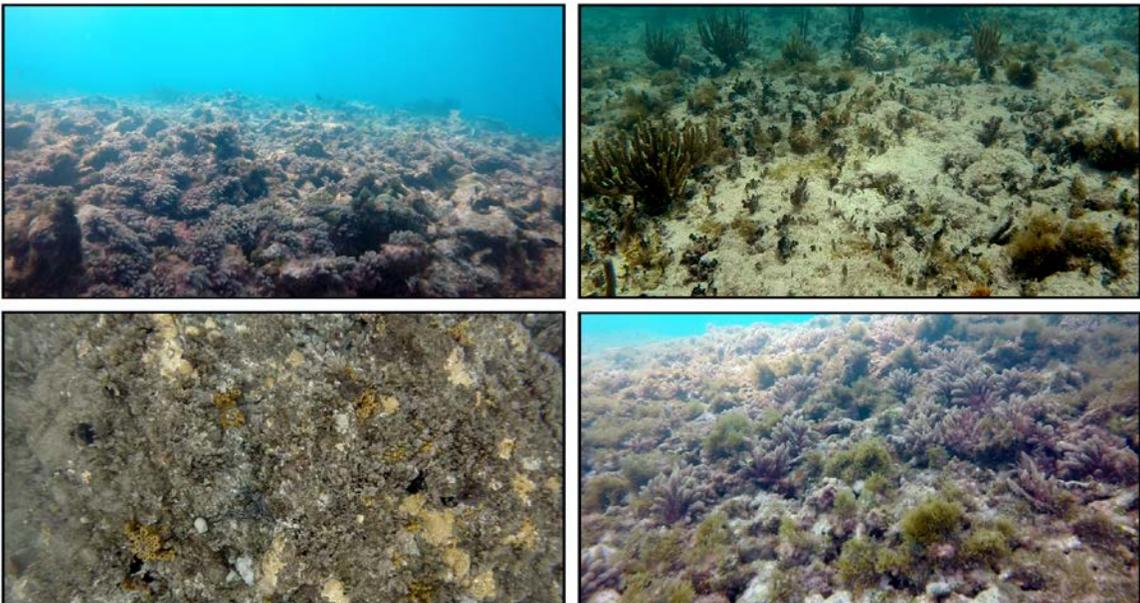
High-relief outcrops of rock inhabited by a sparse coral community encompassing branching, submassive and massive species. Sponges, gorgonians and turfing algae complete the assemblage.

Gorgonian Hardground



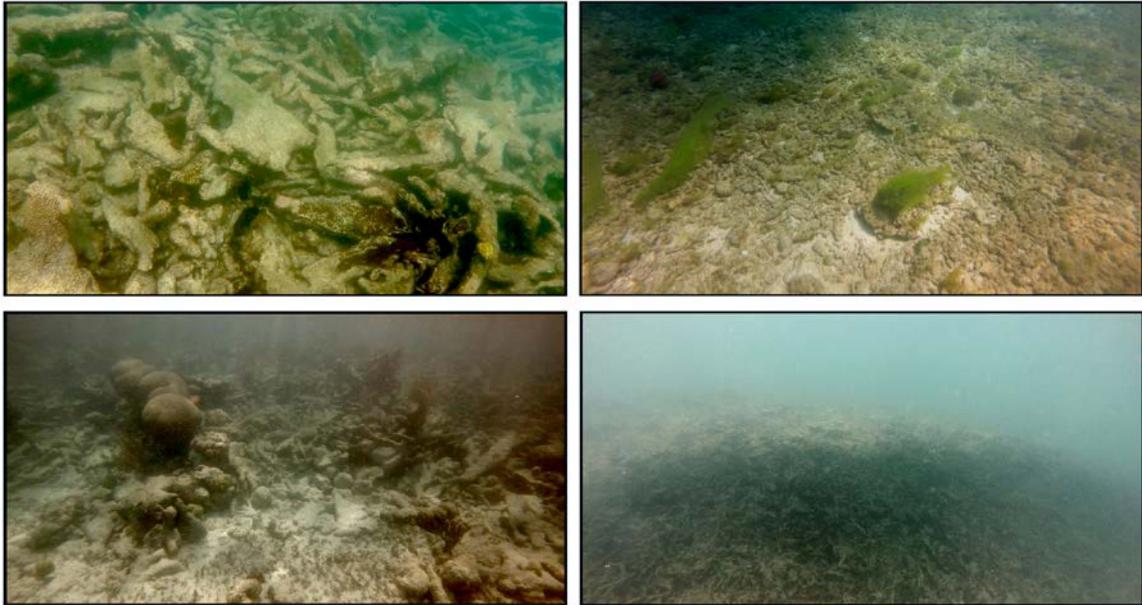
Typically low-relief planation hardground inhabited by a dense forest of gorgonians. The hardground may either be covered by a thin veneer of sand, else colonized by turf algae, sponges and rare coral heads.

Algal Hardground



As for gorgonian hardground, a low-relief planation terrace, but lacking gorgonians and instead colonized by a diverse assemblage of turfing and fleshy algae. Occasional live corals and sponges also present.

Reef Rubble



Accumulations of reef-derived clasts (predominantly coral rubble). These piles of detritus are variably cemented together through diagenetic processes. Biotic cover is low because the substrate is intermittently mobile and unconsolidated. Calcareous red algae and turfing algae are prominent. Rhodoliths may accumulate in high energy areas.

Boulders and Rocks



Piles of terrestrially-derived boulders and rocks which typically accumulate beneath sea cliffs. These rocks are rounded and, depending on the time elapsed since submergence, variably colonized by turfing and fleshy algae with very occasional live coral colonies.

Sparse Seagrass



Sparse meadows of seagrass (>20% to <60% coverage of leaves on a sandy substrate). The meadows may be interspersed with occasional stands of macroalgal. Dominant seagrasses species are *Thalassia testudinum* and *Syringodium filiforme*, though *Halophila spp.* may also be present.

Dense Seagrass



Dense seagrass meadows (>60% coverage of leaves on sandy substrate). Species complement as for sparse seagrass and stands of macroalgae also variably interspersed. Dense seagrass meadows effectively baffle water flow leading to the accumulation of muds which, in turn, can yield reduced water clarity.

Sand with Macroalgae



Unconsolidated sediment sheets inhabited by dense stands of fleshy seaweed which may occasionally be interspersed by small patches of seagrass.

Sand



Unconsolidated sand sheets, often barren, else sparsely colonized by small patches of algae or seagrass. Well-developed bedforms present in areas where the seabed is subjected to continuous wave agitation.

9. Habitat Maps

In the submitted GIS, all habitats per island are structured in a single shape file. Attribute “Habitat” contains the habitat ID. Also submitted in the GIS bundle, is a shapefile containing the ground-truth stations with an interpretation into the nine-class mapping scheme based on visual inspection of each video. Attribute “Habitat” holds that class ID also, and attribute “ID_Nos” holds the ID of each ground-truth observation, per the audio stream of the videos.

The benthic habitat map for Antigua is shown in Figure 6. Coral frameworks dominate the eastern and southern shelves. Expansive stands of *Acropora* framework exist offshore the north-eastern precinct of the island, whereas the northern and western shelves are predominantly sandy. Sheltered coastal embayments are heavily colonized by seagrass, regardless of position around the island.

In contrast to Antigua, Dominica has a comparatively narrow coastal shelf and a paucity of coral frameworks (Fig. 7). Here, the eastern margin of the island is fringed by a planation terrace variably colonized by algae. Sheltered embayments in the lee of headlands host meager coral assemblages. The western shelf, meanwhile, is richly inhabited by seagrass meadows.

The eastern shelf of St. Lucia is similarly algal dominated, though this habitat grades with increasing water depth into one dominated by gorgonians (Fig. 8). Coral frameworks exist in a narrow shelf-parallel rind at intermediate water depth, likely occupying the locus of more luxuriant reef growth from the mid to later Holocene. St. Lucia, like Antigua, is noteworthy in having an extensive stand of *Acropora* framework on a shelf otherwise dominated by gorgonians. The western margin of the island is seagrass dominated in the shallows, becoming sandy as depth increases.

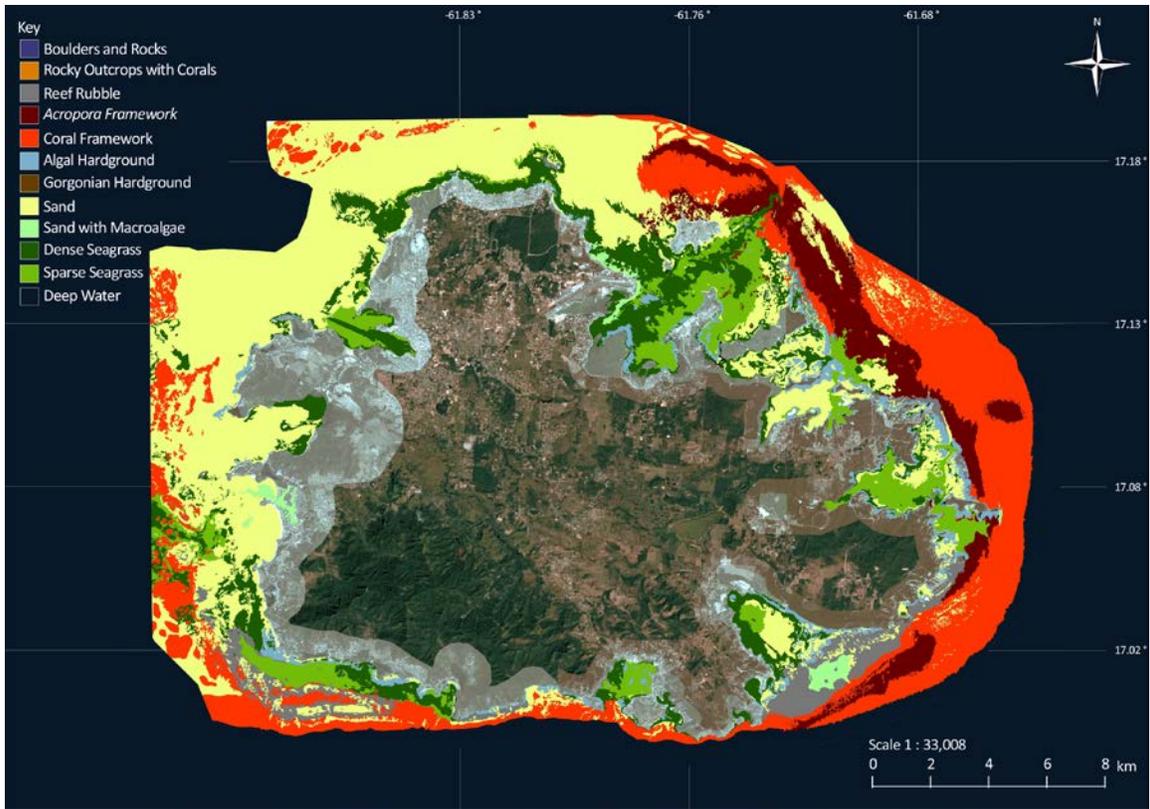


Figure 6 | Benthic habitat map for the Antigua area partitioned into eleven habitat classes.

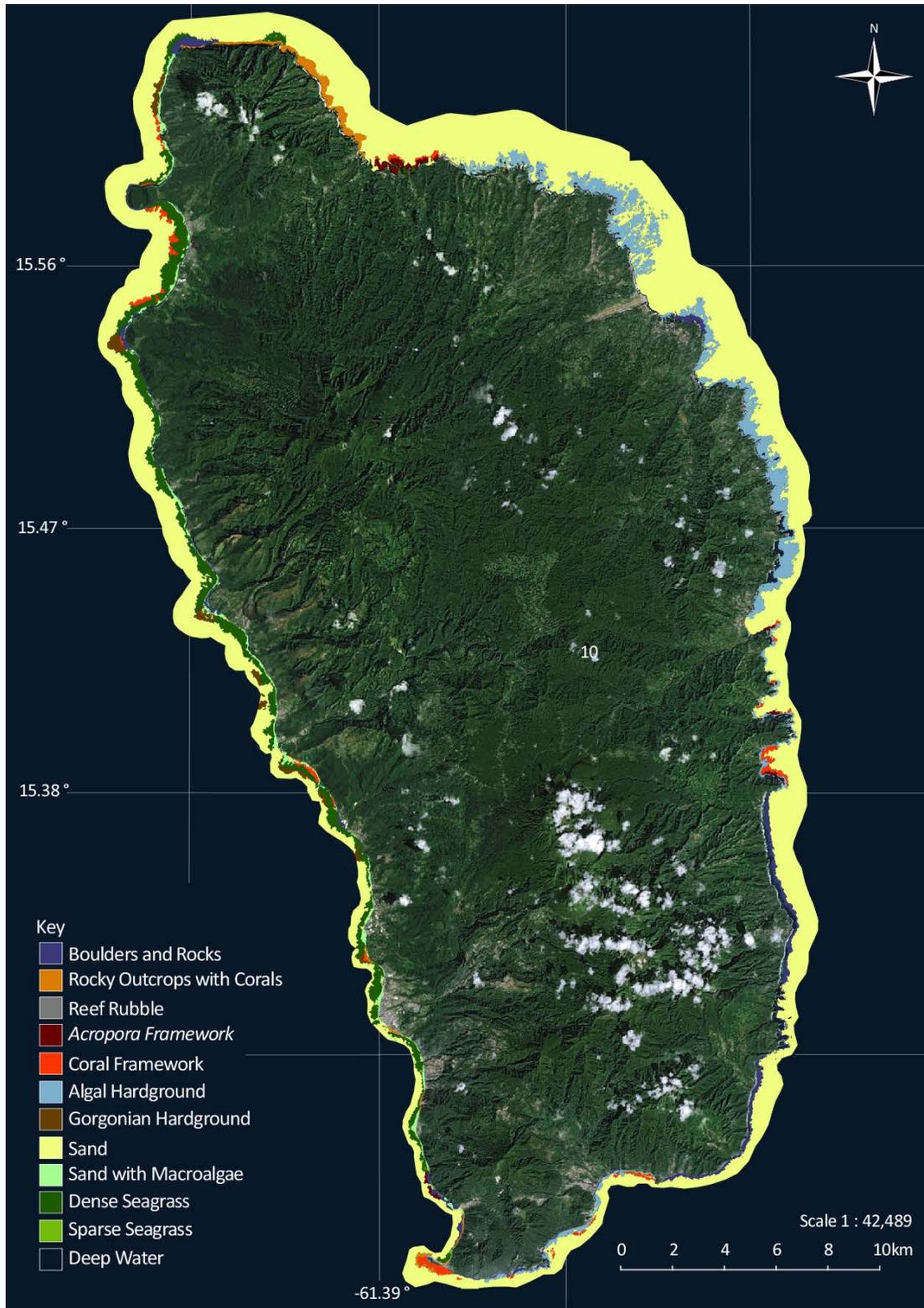


Figure 7 | Benthic habitat map for Dominica study area partitioned into eleven habitat classes.

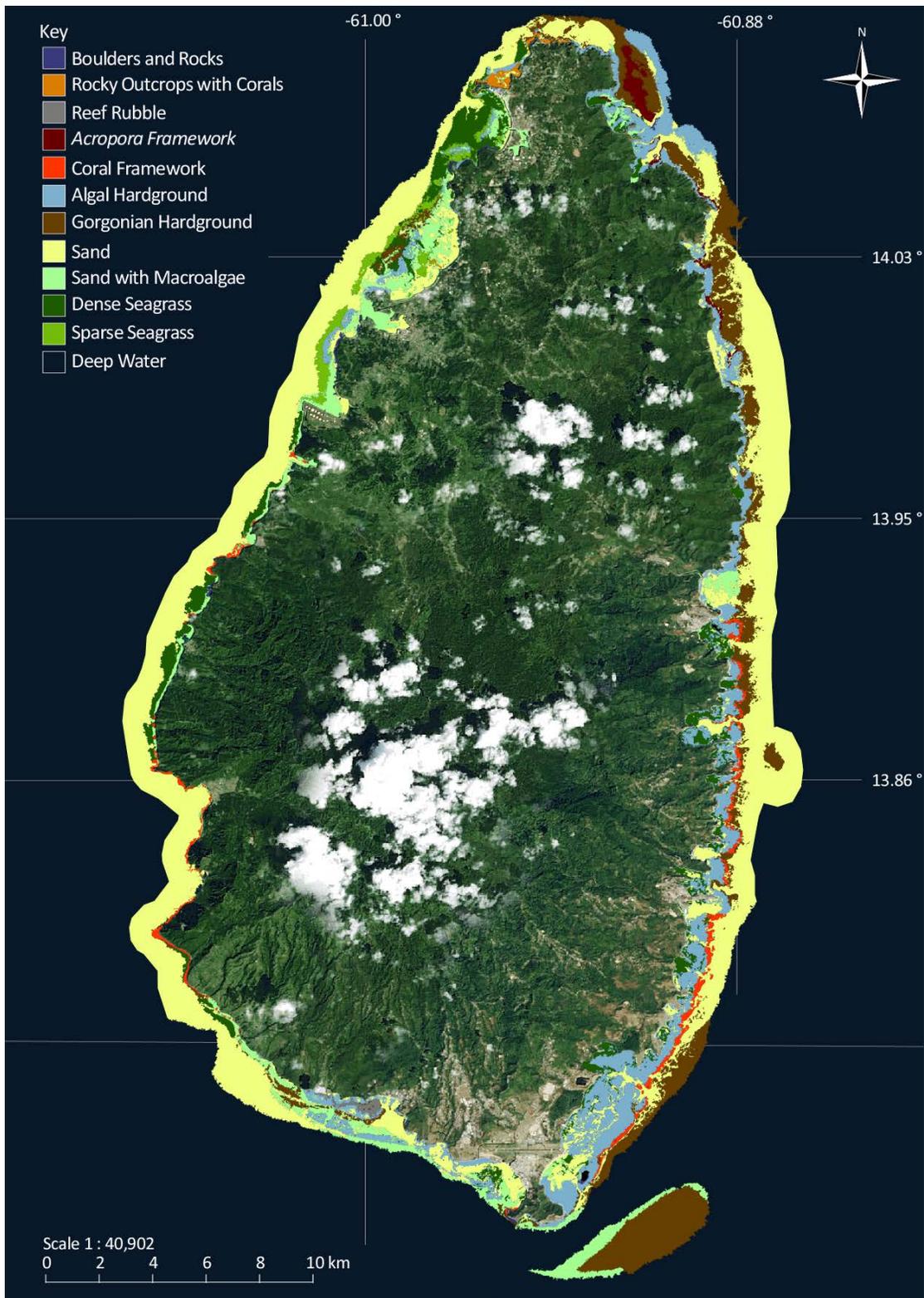


Figure 8 | Benthic habitat map for St. Lucia study partitioned into eleven habitat classes

10. Spectral Mapping of Bathymetry

Whereas spectral derivation of bathymetry could be conducted for both Antigua and St. Lucia using Pléiades imagery, the WorldView-3 mosaic for Dominica posed special problems. Here, the mosaic consisted of a large number of separate scenes acquired on different dates, each with different atmospheric conditions. Spectral balancing of adjacent scenes could not yield a mosaic of sufficient fidelity to deliver a viable bathymetry surface. Instead, bathymetry was extracted from a mosaic of Landsat 8 imagery. Whereas Landsat 8 is of lower spatial resolution than Pléiades, the derivation was aided by the fact that Landsat 8, unlike its predecessors, has a short wavelength blue channel in addition to the standard blue, which penetrates water to a high degree.

Following the ratio-algorithm method of Stumpf et al. (2003), all of the single-beam depth soundings collected in the field ($n = 75,000$) were used as training data to tune the algorithm's coefficients and spectral bathymetry was extracted from the image mosaics (Figs. 9, 10 and 11). Digital elevation models (DEMs) were constructed for the three sites. These DEMs capture seabed topography from the low-water mark to 25 m water depth. Vertical resolution of the DEM is approximately 0.01 m, but variable dependent on the quality of the spectral imagery from which it was derived.

Units in the DEM are meters with float (16-bit) precision. Values are negative such that “-5.55” represents 5.55 m below sea level. Masked areas of the bathy surface are flagged with value = 0 and areas obscured by clouds have a value of +1.

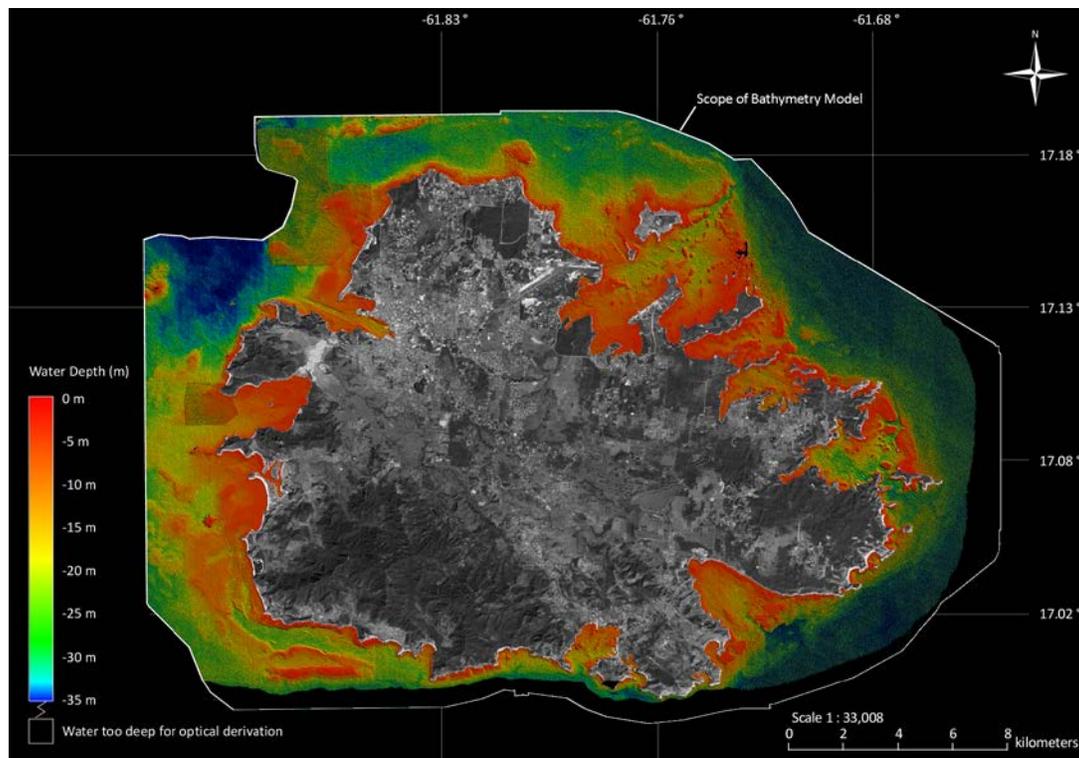


Figure 9 | Digital elevation model for Antigua spectrally derived from Pléiades imagery and calibrated by single-beam sonar soundings.

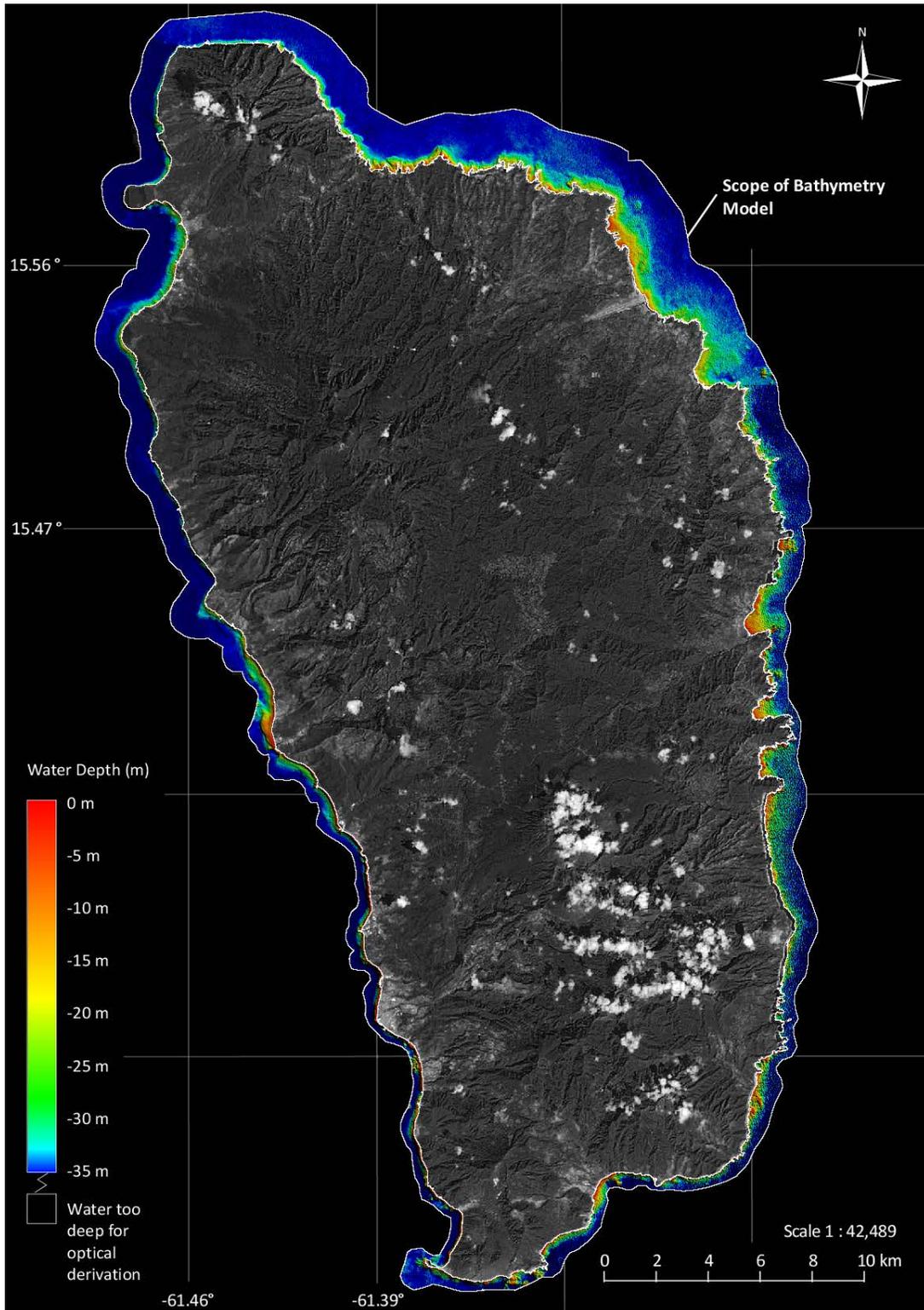


Figure 10 | Digital elevation model for Dominica spectrally derived from Landsat 8 imagery and calibrated by single-beam sonar soundings.

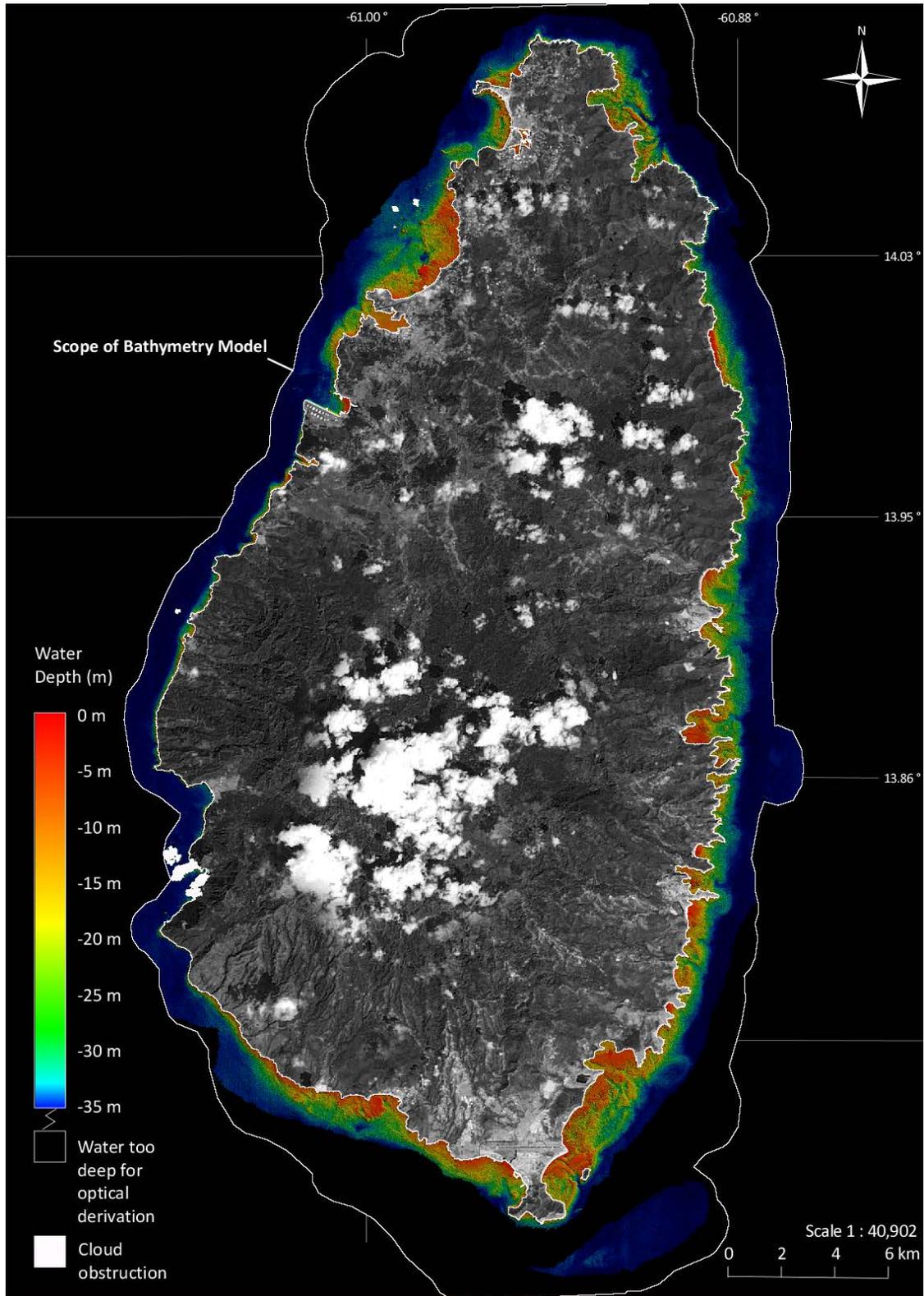


Figure 11 | Digital elevation model for Saint Lucia, spectrally derived from Pléiades imagery and calibrated by single-beam sonar soundings.

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