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Using Geospatial Tools to Assess Changes to Marine Ecosystems in Small
Island Developing States Following Hurricane Disturbances:
A Case Study of Dominica After Hurricane Maria

Ryan J. Shields

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Using Geospatial Tools to Assess Changes to Marine Ecosystems in Small Island Developing States Following Hurricane Disturbances: A Case Study of Dominica After Hurricane Maria

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Master of Science

Seagrass meadows, like coral reefs, are in decline globally but are often neglected in marine policy and conservation despite their equally critical ecosystem services. Both habitats can be heavily impacted by wave surges, rainfall-induced earth movement and flooding, changes to water temperature, salinity, and acidity, and increased levels of turbidity—all occurring at increased rates due to a changing global climate. We demonstrate that multispectral satellite imagery, geospatial tools, and classification techniques can be used to inform management by identifying and quantifying changes in seagrass distribution and the presence of sediment-related threats. Results from Dominica indicate near-shore seagrass habitat area increased by 195.7 hectares between 2016 and 2019, suggesting a continued expansion of *Halophila stipulacea*. Further analysis showed 22.4 hectares of accreted coastal sediment and 1362.2 hectares of suspended sediment captured, placing 424.4 hectares of sensitive reef area at risk of experiencing tissue abrasion or reduced photosynthetic activity. Our methods can be used by marine resource managers and policy makers to inform decisions relating to fisheries production, emissions trading, disaster risk mitigation, and invasive species monitoring, facilitating sustainable growth in the blue economy.

Keywords: *Halophila stipulacea*, Dominica, Hurricane Maria, small island developing states, natural disasters, marine management

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INTRODUCTION

The global decline of coral reefs is well documented and widely known (Chabanet et al., 2018; Guan, Hohn, Wild, & Merico, 2020; Pandolfi et al., 2003). Coral reef conservation and restoration has become a key focus of marine conservation in recent years, with 40% of the world's coral reefs found in Marine Protected Areas (MPAs) (UNEP, 2020). Deforestation for coastal development and extreme climactic events have led to a decline in mangrove forest coverage (Polidoro et al., 2010; Sippo, Lovelock, Santos, Sanders, & Maher, 2018), however restoration efforts, conservation policy, and awareness campaigns have resulted in 43% of the world's mangroves existing in protected areas (UNEP, 2020). Seagrasses, like coral reefs and mangroves, are also on the decline, however seagrasses are often neglected in the development of marine management and conservation policy. As of 2020, only 26% seagrass could be found within MPA boundaries (UNEP, 2020). Rising ocean temperatures driven by climate change along with local anthropogenic pressures create unfavorable conditions for established seagrass species to persist and survive (James, 2020; Nguyen et al., 2020). Generally, seagrasses and coral reefs help absorb wave energy from storm surges (Sheppard, Dixon, Gourlay, Sheppard, & Payet, 2005; UNEP, 2020). However, seagrasses are also vulnerable to large removal events when storm surges reach high intensity (Hernández-Delgado et al., 2020; Steiner & Willette, 2013). As storm frequency and intensity continue to increase with climate change (Hoegh-Guldberg et al., 2018), there will likely be an increase in the amount of seagrass lost to storm surge. Dominica has been highlighted as being especially vulnerable to climate risks and disaster vulnerabilities, ranking 10th out of 180 in Climate Risk Index Score and 12th out of 111 in the Commonwealth's Composite Vulnerability Index for disaster vulnerabilities in 2018 (Fobert, Singhroy, & Spray, 2021).

Tropical storms and hurricanes pose a significant threat to both terrestrial and marine ecosystems. In the past decade, Dominica has experienced two catastrophic storms resulting in significant damage to the island and impaired ecosystem structure and services (Pasch & Penny, 2016; Pasch, Penny, & Berg, 2019). In August 2015, Tropical Storm Erika degraded Dominica's landscape with approximately 50cm of rainfall, or $\sim 1/5$ the normal annual precipitation (Fobert et al., 2021), occurring in just 5 hours (Nugent & Rios-Berrios, 2018). This resulted in an increase in landslide events and elevated flooding that caused an estimated USD\$500 million in damage and killed 30 people (Pasch & Penny, 2016). In 2017, Hurricane Maria arrived as a Category 5 storm, with maximum sustained wind speeds of 280 km/h (Hu & Smith, 2018) and a total of 57.9 cm rainfall (Pasch et al., 2019). Damages from Hurricane Maria were estimated at USD\$1.37 billion (226% of GDP) (The World Bank, 2018) with 65 reported as dead or missing and presumed dead (Pasch et al., 2019). This has placed an even greater economic burden on Dominica, whose public debt holdings were estimated to be 82.7% of GDP in 2017, the fifth highest public debt-to-GDP ratio among all small island developing states in the Caribbean (Central Intelligence Agency, 2021).

The ability to detect such changes following major disturbances is essential for modifying natural resource management plans and related targets that account for changes to the post-disaster landscape. Immediately following Hurricane Maria, Hu & Smith (2018) utilized Landsat 8 OLI and Sentinel-2 satellite imagery to evaluate storm impacts to Dominica's vegetation and soil stability. Remote sensing analysis and classification methods were used to detect and quantify changes to vegetation structure and plant cover after the hurricane as well as to evaluate the timeframe for return to full canopy cover. In 2020, Schaefer et al. provided a description of methodologies they used to detect fine-scale terrestrial changes in Dominica using high resolution

small Unmanned Aerial Systems (sUAS) imagery. Applying photogrammetric tools and techniques to imagery captured before and after the hurricane at 44 locations distributed across the island, they created 3-D models for the pre- and post-hurricane periods that could be used to rapidly quantify changes to heavily damaged terrestrial landscapes. Additionally, they identified a need for methods to rapidly map and quantify changes in terrestrial areas environments, in particular those affecting human populations. These data would provide a knowledge base for guiding post-hurricane reconstruction in Dominica.

Given the significant value of coral reefs and seagrass ecosystems, the services they provide to coastal communities, and their vulnerability to impact from tropical storms and invasive species, methods and practices are needed to monitor changes to ecosystem structure and to provide data that can be incorporated into dynamic marine management and planning. Such plans are essential for developing sustainable blue economies. While low-resolution imagery from platforms Landsat 8 and Sentinel-2 are available at no-cost, high-resolution commercial satellite imagery is required for meeting this challenge. While commercial imagery carries a higher monetary cost, it may be possible to acquire free imagery through humanitarian response and research portals such as Maxar's Open Data Program, Planet's Education and Research Program, or the European Space Agency's Earth Online program. Hernández-Delgado et al. (2020) used high-resolution aerial and satellite imagery to evaluate changes to seagrass distribution surrounding Culebra Island, Puerto Rico immediately after Hurricane Maria. Results showed a significant loss of shallow seagrass at surveyed locations. However, they found that *Halophila stipulacea* had rapidly recovered and expanded beyond its pre-hurricane extent. Puerto Rico's status as a US Territory greatly benefited the study, which relied on aerial imagery collected by NOAA 2-6 days after Hurricane Maria as well as satellite imagery from the Global Enhanced GEOINT Delivery (G-EGD) portal via the US

Fish and Wildlife Service (Hernández-Delgado et al., 2020). We set out to demonstrate a solution that could benefit Small Island Developing States (SIDs) with more limited resources and provide an assessment at an island wide scale.

Remote Sensing Considerations

The scale of the research question is a critical consideration when selecting a remote sensing platform for research. TNC, and many other organizations, utilize sUAS imagery extensively to map coral reef distribution and health throughout the Caribbean (TNC, 2020a). More recently, low-cost Unmanned Surface Vehicles (USVs or “boat drones”) have been developed to collect stereo imagery for modeling and monitoring changes to reef condition using structure-from-motion technology (Raber & Schill, 2019). Using imagery collected from drones (aerial and marine) has many advantages over satellite imagery, including very high spatial resolution and flexible temporal resolution (Schaefer et al., 2020; TNC, 2020a). However, the disadvantages include potentially significant acquisition costs and the time required to collect data over broad spatial scales. For example, collecting imagery for the entire coastal shelf using sUAS would require tremendous manpower, time, and energy to acquire, especially when drone flight operations and image quality are limited by atmospheric conditions. Unmanned systems, both marine and areal, can be an effective method for monitoring fine-scale sites (Schaefer et al., 2020), however, space-borne platforms remain an optimal tool for conducting image analysis at broad spatial scales (i.e. island wide) (Li, Schill, Knapp, & Asner, 2019; Saul & Purkis, 2015).

The effectiveness of space-borne remote sensing platforms can be impeded by atmospheric conditions, especially in tropical environments where cloud cover persists due to diurnal heating (Fobert et al., 2021; Li et al., 2019; Schaefer et al., 2020). Additionally, marine targets can only be

detected using visible wavelengths of light as all other wavelengths are absorbed by water. Of the visible wavelengths that can penetrate water, not all wavelengths penetrate equally. For example, blue wavelengths penetrate to greater depths than red wavelengths because they have a higher frequency and therefore greater energy. Red wavelengths, because of their lower frequency, are the first to be absorbed by the water ([figure 1](#)) (Saul & Purkis, 2015). The particulate composition of the water column can intensify the scattering of light (Rowan & Kalacska, 2021) and rough seas and the angle of incidence can produce bright spots on the imagery, known as glint, which adversely affect image quality (Hedley, Harborne, & Mumby, 2005; Saul & Purkis, 2015). Radiometric calibration and correction algorithms are well developed and effectively remove the distortions from the atmosphere and water column to achieve a more accurate bottom reflectance.

Coral Reef and Seagrass Ecology and Biogeography

Coral reefs and seagrass meadows both provide a variety of ecosystem services in Dominica, including fisheries production, intact feeding grounds that support a diversity of fish species, and generating revenue for local people through eco-tourism (TNC & Government of the Commonwealth of Dominica, 2016; UNEP, 2020). Coral reefs also provide physical protection to coastal communities by absorbing storm surges and increased wave action (Sheppard et al., 2005). Dominica's residents have received critical benefits from its coral reefs since the first inhabitants arrived circa 3100 BC. During the 18th century, coral reefs provided rich fishing grounds for British and French colonizers (Honychurch, 1995). As the human population has increased over time, fishing pressure has increased correspondingly to meet human food demand. Modern fishing operations in Dominica target diverse habitats including coral reefs, seagrass meadows, sand, and rocky substrates (Sebastian, 2002). Non-extraction uses of marine habitats, such as SCUBA diving and snorkeling, are minimal compared to the demand and potential impact from fishing (Steiner,

2015). Today, governments are recognizing the role coral reefs play in sustaining blue economies and are electing to buy insurance policies to restore coral reefs following damaging events (TNC, 2020b).

Seagrass meadows, like coral reefs, absorb wave energy and provide habitat that sustains marine biodiversity. In addition to providing primary and secondary food source and habitat for a wide array of marine biota, including juvenile-stage fish, seagrass meadows also sequester carbon, protect reefs from sediment deposition, and provide nutrient cycling (James, 2020; Marbà et al., 2015; Willette & Ambrose, 2012; Winters et al., 2020). It is estimated that 20% of the world's largest fisheries depend on seagrass ecosystems and seagrass loss emits between 299 Tg carbon (UNEP, 2020) and 650 Tg carbon (Hoegh-Guldberg et al., 2018) per year into the atmosphere.

Despite the extensive research available on ecosystem services provided by seagrasses, the benefits have not been as widely recognized compared to coral reefs. Only 26% of global seagrass is found within the boundaries of protected areas compared to 40% of coral reefs (UNEP, 2020). This oversight will become increasingly important in the coming years as seagrass meadows may experience increased fishing pressures if coral reef health continues to decline (Unsworth, Nordlund, & Cullen-Unsworth, 2019). Protecting seagrass would also protect coral reefs as seagrass meadows trap and stabilize sediment that would otherwise become suspended (Nowicki, Thomson, Burkholder, Fourqurean, & Heithaus, 2017) and damage or smother nearby coral reefs (Fabricius, 2005). Seagrasses have also been proven to buffer ocean acidification by releasing O₂ and absorbing CO₂ via photosynthesis (James, 2020) and filter diseases (Lamb et al., 2017) that would otherwise degrade coral reefs (Guan et al., 2020). Ideally, MPAs and coastal zone

management plans should protect seagrasses, coral reefs, and mangroves, as all three provide interdependent ecosystem services critical to building strong blue economies (UNEP, 2020).

The UNEP report “Out of the Blue: The Value of Seagrasses to the Environment and People” (2020) highlights that in addition to providing economic benefits, protecting seagrass can help country’s reach their targets under various international agreements. Of the United Nations 17 Sustainable Development Goals (SDGs), SDGs 1, 2, 5, 6, 8, 11, 12, 13, 14, and 17 can be advanced by conserving and restoring seagrass (UNEP, 2020). Additionally, six of the 20 Aichi Biodiversity Targets associated with the CBD’s Strategic Plan for Biodiversity 2011-2020 (Targets 6, 8, 11, 14, 15) are related to seagrass ecosystem services and protection actions (UNEP, 2020). Lastly, seagrasses (and interconnected coastal wetlands) are relevant to both the Kyoto Protocols (more specifically the carbon offsets markets created under Article 17) and the Paris Agreement. The Kyoto protocols established the international trading of carbon offsets (United Nations, 1998) and the Paris Agreement established Nationally Determined Contributions (NDCs) as a way for countries to declare and commit to actions that will reduce Greenhouse Gas emissions (United Nations, 2015). By mapping, tracking, and calculating the total seagrass area for a SID, the amount of carbon credits made available for trade can be calculated and progress toward declared NDCs can be measured. As of 2019, 64 countries had acknowledged the key role of blue carbon habitats in achieving NDCs however only 10 countries directly referencing seagrass. Of the 10 countries, the Bahamas was the only country with a measurable seagrass target found in their NDC (UNEP, 2020).

The two dominant species of seagrasses in Dominica are *Syringodium filiforme* (Manatee Grass) and *Thalassia testudinum* *Asch* (Turtle Grass) (Christianen et al., 2019). Other less

prevalent species of seagrass include *Halodule wrightii* Ostenf. (Shoalweed) and *Halophila decipiens* Ostenf. (Paddle grass or Caribbean seagrass) (Winters et al., 2020). Steiner and Willette (2010) identified the meadows as an integral component of Dominica's largest and healthiest reefs during a 2008 survey. They also discovered the presence of *Halophila stipulacea*. Five years later, Steiner and Willette returned to Dominica and noted *H. stipulacea* had spread exponentially, displacing native seagrasses in some areas. *S. filiforme* and *H. wrightii* were reduced to isolated patches within the 2 to 12m bathymetric zone. Meadows of *H. decipiens* were completely overtaken by *H. stipulacea* and eliminated from Dominica's coastal waters (Steiner & Willette, 2013).

Halophila stipulacea

Halophila stipulacea is native to the Indian ocean, the Red Sea, and the Persian Gulf. Shortly after the completion of the Suez Canal, *H. stipulacea* spread to the Mediterranean Sea where it has slowly invaded various areas over the past 150 years (Nguyen et al., 2020; Winters et al., 2020). In 2002, it arrived in the Caribbean Sea and is now found in most Caribbean islands and extending into portions of South America (Winters et al., 2020). In both its native and extended habitat, *H. stipulacea* forms dense mats that can overtake native seagrass species in as little as 10 weeks after anchoring (van Tussenbroek et al., 2016). Only small fragments are necessary for a new mat to anchor and these fragments are easily dispersed when fish traps are retrieved from seagrass beds (Smulders, Vonk, Engel, & Christianen, 2017). The invasion of *H. stipulacea* throughout the Caribbean has been much more successful compared to its spread in the Mediterranean Sea which has been characterized as slow spreading (Winters et al., 2020).

In a recent study, *H. stipulacea* plants from in the Mediterranean were compared to those in the native ranges (Gulf of Aqaba) and revealed that invasive populations are adapted to tolerate increases in water temperature and salinity (Nguyen et al., 2020). Oscar, Barak, & Winters (2018) compared *H. stipulacea*'s salinity tolerance to that of a freshwater relative, *Vallisneria americana*, and found the former to be more resilient to changes in salinity (Oscar, Barak, & Winters, 2018). It has also been noted that, although *H. stipulacea* is characterized as a dioecious species, the majority of the invasive populations exhibit a higher proportion of male plants and native populations have a higher female population abundance (Winters et al., 2020).

Halophila stipulacea's rapid and vast expansion in the Caribbean has potential to significantly impact biodiversity in the Caribbean. Fish traps placed on beds of *H. stipulacea* supported larger, older fish while traps placed on *S. filiforme* beds support greater juvenile-stage fish densities. The lack of juvenile-stage fish near *H. stipulacea* beds is attributed to the lack of predator cover provided by *H. stipulacea*'s low-profile blades. This is a contrast to *S. filiforme*, which is characterized by longer leaves that offer more cover from predators. (Willette & Ambrose, 2012). *H. stipulacea* has also been found to be less nutrient dense than the native "Turtle Grass", *Thalassia testudinum*. However, isolated incidents of Green Sea Turtles grazing on *H. stipulacea* have been recorded (Christianen et al., 2019). This may be out of necessity rather than preference as *H. stipulacea* will rapidly propagate to fill in gaps in the native meadow after disturbance (i.e. grazing, storms, etc.) Clear Caribbean waters, a contrast to the more turbid waters of the Indian Ocean, combined with an ability to clump chloroplasts to adjust for changes in irradiance, have allowed *H. stipulacea* to establish and persist in the deeper ranges of the native Caribbean seagrass distributions (Winters et al., 2020).

Using high-resolution satellite imagery, we set out to answer the following questions relating to Dominica's marine habitats:

- How has the distribution of Dominica's seagrass meadows changed after Hurricane Maria (from 2016 – 2019)?
- How many hectares of seagrass are in Dominica's waters after Hurricane Maria (2019)?
- What do changes in the distribution suggest about the ongoing *Halophila stipulacea* invasion?
- How much coastline has been accreted and eroded after Hurricane Maria (from 2016 – 2019)
- How many hectares of fringing coral reef is impacted by accretion and erosion to the coastline?

In pursuit of those answers, we also identified areas of heavy turbidity in the water column present during satellite image capture. Additional questions pursued are as follows:

- How much sediment is in the water column on the day of imagery collection?
- How many hectares of coral reef lie within the sediment field?

METHODS & MATERIALS

Site Description

Dominica is located on the eastern end of the Caribbean Plate (15°25'N 61°20'W) and was the last island in the Caribbean formed from volcanic activity 26 million years ago (Central Intelligence Agency, 2021; Fobert et al., 2021). Current volcanic activity can be detected along the west central coastline, distinguished by heat bubbles that are emitted from geothermal rocky substrates.

Dominica has narrow coastal shelves (most < 1 km) and steep drop-offs, especially near river cuts and coastal calderas (Purkis, 2016). At the widest point, the neritic zone on the northeast coast extends seaward ~2.8 km at a depth of 50m. The next widest areas of the neritic zone are found at the southern half of Prince Rupert's Bay and the area west of Grande Savane, which extend out ~1.2 km at a depth of 50m (Steiner, 2015). Variation between the windward and leeward sides of the island is apparent in both the terrestrial and marine environments (figure 2).

Dominica's terrestrial landscape is characterized by towering peaks exceeding 1400m elevation. Approximately 60% of its rugged slopes have gradients greater than 30%, frequently producing landslides, including those in coastal locations (Fobert et al., 2021; Van Westen, 2016) (figure 3). The majority of Dominica's coral reefs are fringing reefs that abut the coast, placing reefs (and other coastline-adjacent benthic habitats) at risk of partial burial and increased sedimentation. Suspended sediment, which typically originates from run-off on the steep slopes, can lead to degraded coral condition or reduced coral distribution through abrasion of coral tissue or impairing photosynthetic rates and capabilities (Fabricius, 2005; Steiner, 2015). Likewise, sediment loading caused by elevated soil erosion levels can reduce seagrass persistence and impair seagrass meadow community structure (UNEP, 2020). To monitor coastal accretion and erosion, we mapped the seaward extent of the coastline in the pre- and post-hurricane images. We then compared the two maps to identify where accretion and erosion events had occurred and to quantify the amount of shift observed between these time periods. Suspended sediment in the water column in post-hurricane images was also mapped and then compared with our enhanced map of pre-hurricane reef features to quantify the total area of reef potentially affected by the sediment plume.

Historically, Dominica has experienced both direct and indirect impacts of tropical storms and hurricanes. Those originating in the Gulf of Mexico and the Caribbean basin have generated storm surges that severely damaged reef structures and seagrass meadows along the island's leeward side (Steiner, 2015). Surges generated by storms approaching from the Atlantic are less damaging due to the abundance of hardground habitats and rocks and boulders. With nearly all approaching storms, regardless of the direction of approach or whether it makes landfall, increased rainfall is expected (Nugent & Rios-Berrios, 2018). While wave action generated by storms can cause reef damage by uprooting and breaking reef colonies (Steiner, 2015), rainfall and torrential riverine flooding are greater threats to Dominica because of its steep slopes and low elevation habitats on the windward side. The sedimentation resulting from heavy rainfall can cause abrasion of coral tissue and in some cases bury entire sections of reef (Fabricius, 2005; Steiner, 2015).

Data Collection

The Nature Conservancy (TNC) has developed a seamless high-resolution (2m) satellite-derived 10-class benthic habitat classification and corresponding bathymetry dataset for the shallow coastal zone (<30m) within six Eastern Caribbean countries (Schill et al., in prep.) including Dominica (figure 4). In 2016, TNC collected video transects, GPS-derived locations, and bathymetric soundings to be used in the classification of Pleiades and Worldview-2 imagery to create the object-based benthic habitat classification (figure 5) (Schill et al., in prep.). High resolution satellite imagery converted to MBTile format and loaded into the Locus Pro application on a tablet was used to identify and navigate to survey point locations representing various benthic habitat types. A SeaViewer Sea-Drop 6000 HD (Tampa, FL, USA) underwater video camera with a 30 m vertical cable was used to record video transects at 1-2m above the seafloor. A GPS reference point was collected at the start and end of each transect to allow for georeferencing of

video surveys. In areas inaccessible by boat, snorkeler-based transect surveys were swam using a GoPro Hero 6 camera capturing video footage of various benthic habitat types. After enhancing the accuracy of the coral reef features, this pre-hurricane classification served as the baseline for change in our analysis. In 2019, in the aftermath of the hurricane along with the beginning of ecosystem recovery, additional field samples were collected using the methods described above and in Schill et al. (in prep.) for comparison to the 2016 field data.

Ideally, satellite imagery for classifications will be collected on the same day using the same sensor. However, constrained by the presence of clouds, glint, and high turbidity in some scenes, imagery for both the pre- and post-hurricane classification spanned multiple dates and sensors (Table 1) to maximize image quality. The scenes for the post-Hurricane Maria period are from the Pleiades (Airbus Defense, Leiden, Netherlands) and PlanetScope Dove Classic (Planet, San Francisco, CA) satellite constellations. These platforms are not ideal for marine remote sensing as they only detect blue, green, and red light in the visible spectrum whereas the Worldview platform's visible spectral resolution spans coastal blue, blue, green, yellow, and red bands. However, the Pleiades and PlanetScope scenes provided the highest quality images in terms of minimizing cloud cover, glint, and sedimentation compared to scenes from other platforms.

Enhancing Pre-hurricane Coral Reef Classification

Several scenes from the 2014 Worldview-2 (Maxar, Westminster, CO) imagery had areas distorted by glint making them unfit for use in the original 2016 pre-hurricane classification done by Schill et al. (in prep; figure 6). However, the additional bands (coastal blue and yellow) in these glint-filled images (Table 2) made them good candidates for manual classification of pre-hurricane coral reef features. This more detailed layer representing reef features enhanced our ability to

quantify changes and potential threats to the reef ecosystems. To map the extent of reef features prior to Hurricane Maria, the 2014 Worldview-2 scenes were mosaicked by common acquisition date and then radiometrically corrected using the ‘Dark Subtraction’ tool ENVI 5.5 (L3Harris Geospatial, Boulder, Colorado) with ‘Band Minimum’ set for the ‘Subtraction Method’ parameter. A detailed geomorphology layer was then used to mask out the land areas from the mosaic using ENVI 5.5 (L3Harris Geospatial, Boulder, Colorado) before applying the eCognition 9.5 (Trimble, Sunnyvale, California) multi-resolution segmentation tool on each mosaic using the coastal blue, blue, green, yellow, and red bands to generate the object segments. The multi-resolution segmentation tool, which was also used to create the pre-hurricane classification in 2016 (Schill et al., in prep.), generates polygons that encompass groups of pixels that are similar based on input criteria. The additional spectral detail provided by the coastal blue and yellow bands of the Worldview-2 sensor resulted in segments that more accurately captured reef features. Using the Steiner (2015) field survey maps and coordinates as reference data, the segmented objects that comprised the reef features in the 2014 mosaics were manually selected and classified as reef. Applying histogram stretching to the scenes using various combinations of the coastal blue, blue, green, and yellow wavelengths aided in the interpretation and identification of reef features in the mosaics (figure 7). The manually selected reef features were then merged with the existing pre-hurricane classification to enhance the detail and accuracy of the reef features shown on the map.

Post-hurricane Image Processing and Analysis

To assess changes and threats to reefs and seagrass meadows, we mosaicked the PlanetScope and Pleiades scenes and radiometrically corrected these images using the methods described previously. With a more accurate representation of coral reef features, we could compare layers representing potential threats to coral reefs, such as suspended sediment and coastal sediment

accretion, with the reef layers and quantify how much reef was under threat. Data on suspended sediment and accretion were also collected from satellite imagery. The coastline in the post-hurricane mosaics was mapped using heads-up digitization with a side-by-side comparison view of the pre-hurricane and post-hurricane imagery. The coastline polygon in the 2016 classification (Schill et al., in prep.) served as the pre-hurricane coastline. By applying the erase tool in ArcGIS Pro 2.5 (Esri, Redlands, California) to the pre-hurricane and post-hurricane feature classes we were able to estimate areas of accretion (the extent of the post-hurricane coastline extended seaward beyond that of the pre-hurricane coastline) and erosion (the extent of pre-hurricane coastline extended seaward beyond that of the post-hurricane coastline).

To identify possible changes in the pre-hurricane sand and seagrass areas, we employed an unsupervised pixel-based Iterative Self-Organizing Data Analysis Technique (ISODATA) in the ArcGIS Pro 2.5 (Esri, Redlands, CA) using the Classification Wizard. The ISODATA method analyzes each pixel and assigns similar pixels into n classes with n being determined by the user. Prior to executing the ISODATA technique we utilized feature classes representing areas of sand and seagrass features from the previously mentioned pre-hurricane benthic habitat map to separate the post-hurricane satellite mosaics into two study areas. The pre-hurricane seagrass feature classes were applied as a mask to isolate the marine space in the post-hurricane imagery that was composed of sand prior to Hurricane Maria (referred to as “the pre-hurricane sand study area”). The pre-hurricane sand feature class was applied as a mask to isolate the marine space in the post-hurricane imagery that was composed of seagrass prior to Hurricane Maria (referred to as the “pre-hurricane seagrass study area”). To adapt to the limited marine capabilities of the red, green, and blue bands on the Pleiades and Planetscope platforms, the isolated pre-hurricane sand and seagrass study areas were further isolated to waters approximately -10m and shallower using a bathymetry

mask created from digitized nautical charts (figure 8) and applied in ArcGIS Pro 2.5 (Esri, Redlands, California). This shallow zone was identified as the new reduced range for remaining stands of *S. filliforme* and *H. wrightii* after *H. stipulacea* colonized the deeper portions of their ranges (Steiner & Willette, 2013). Signs of seagrass expansion in this zone might suggest further reduction of *S. filliforme* and *H. wrightii* or even elimination of the species in Dominica. We then applied the ISODATA technique to each mosaic in the “pre-hurricane sand study area” of the post-hurricane imagery and identified pixel clusters representing seagrass, suggesting an expansion of seagrass distribution. We repeated the ISODATA process on the mosaics in the “pre-hurricane seagrass study area” of the post-hurricane imagery and identified areas of sand, suggesting a reduction in seagrass distribution. We provide an estimate of net change in seagrass distribution following Hurricane Maria by calculating the difference in area (ha) between the seagrass expansion and seagrass reduction detected in the post-hurricane imagery.

The interpretation of the pixel clusters in the ISODATA classification was done by comparing clusters with the post-hurricane benthic survey videos and the post-hurricane imagery spectral values. While inspecting the classes, we noted distinct geometric patterns in the ISODATA classification output at various locations within the marine space. Upon closer inspection, we determined these patterns likely result from suspended sediment located in the near-shore water column. The distinct edges observed were caused by ocean currents. The 2019 satellite imagery was selected for the post-hurricane period in this study due to i) the absence of clouds in the image (a rarity for Dominica), ii) limited presence of glint on the water surface, and iii) the scene capture occurring during the dry season. By selecting a dry season image, we expected to decrease the likelihood of encountering suspended sediment in the water column which would interfere with our ability to obtain accurate bottom reflectance. However, after observing significant amounts of

suspended sediment levels in the 2019 imagery we determined the sediment had introduced potential some error into our ISODATA classes representing gains and losses in seagrass meadow extent. In some areas, the suspended sediment was assigned to the class representing areas of sandy substrate, inflating the estimated area of seagrass loss. In other instances, the sediment areas were assigned to the class representing seagrass, inflating the estimated seagrass gains. The imagery for the post-hurricane period lacked sufficient spectral separability to produce accurate classes for loss, gain, and suspended sediment using an ISODATA classification. So, to account for the error induced by the sediment, we mapped the extent of the sediment separate from the ISODATA classification by applying a raster color slice in ENVI 5.5 (L3Harris Geospatial, Boulder, Colorado). To estimate the upper and lower reflectance values for turbid waters, we sampled around the island and recorded the highest and lowest observed values. We used those values as the upper and lower thresholds for creating the color slice and fine-tuned those values until the full extent of the sediment was captured (figure 9). We eliminated areas of seagrass increase or decrease in the ISODATA classification output that intersected with the sediment extent layer. This provided a more conservative estimate of seagrass loss, gain, and net expansion. Then, by overlaying the sediment extent layer (developed from the color slice) with the enhanced pre-hurricane reef features we were able to provide an assessment of potential threats to reef health (figure 10). Using the intersect tool in ArcGIS 2.5 (Esri, Redlands, CA), we were able to calculate the total how much reef area existed within the extent of the suspended sediment. After accounting for total suspended sediment, total increase and decrease in seagrass area were determined by multiplying the number of pixels in the increase and decrease classes by the pixel size. The net change in seagrass area was then estimated by calculating the difference between the seagrass increase and decrease.

RESULTS

Changes to Seagrass Meadow Distribution

We estimate that between 2016 and 2019, 51.1 hectares of seagrass were lost within the -10m bathymetry zone and 246.8 new hectares of seagrass were gained in the same area during the same period (figure 11). This resulted in a net increase of 195.7 hectares. We estimate that the total seagrass area in the 10m zone expanded from 612.3 hectares in 2016 to 808.9 hectares in 2019 (figure 12). Although satellite imagery in this analysis was ineffective for detecting occurrences of seagrass beyond 10m in depth, we were able to estimate the seagrass coverage for all meadows across the island. Because *H. stipulacea* effectively establishes in deep coastal waters throughout the Caribbean (Winters et al., 2020), it is unlikely that the extent of the meadows beyond the 10m zone decreased. By assuming no change in the extents of seagrass occurring beyond the 10m depth contour and adding 195.7 hectares of expansion detected in the 2019 satellite images with the 1,073 hectares of total seagrass in the pre-hurricane habitat map, we estimate approximately 1,268 hectares within Dominica's coastal waters in 2019, a 31% increase over pre-hurricane distribution. This estimate is in-line with the seagrass expansion rate based on 2007, 2013, and 2016 estimates (figure 13). We believe this net increase in seagrass is due to the continued expansion of *H. stipulacea*, as Hernández-Delgado et al. (2020) found that *H. stipulacea* quickly recovered and expanded at study sites where Hurricane Maria uprooted seagrass beds in Puerto Rico.

Accretion, Erosion, and Suspended Sediment

We determined that 5.9 hectares of soil material had eroded off the coastline across the island between 2016 and 2019. Accretion was nearly 4 times that amount, with 22.4 hectares of material added to Dominica's coastline (figure 14). This was especially prevalent near river mouths (figure

15). Of the 22.4 hectares of accretion, 1.6 hectares covered reef area, including 0.82 hectares potentially covering *Acropora* (figure 16).

By multiplying the number of pixels captured in the color slice by the pixel size we were able to estimate the total extent of the areas experiencing sedimentation. Approximately 1,362.2 hectares of the water surface showed visible signs of suspended sediment on February 13, 2019 when the satellite image was captured. This may have been caused by a storm in the area shortly before the image was acquired. This short-term increase in sediment may have limited our ability to detect change in those areas. However, overlaying the sediment map with the raster color slice revealed 422.8 hectares of reef (approximately 35.9% of all Dominica's reefs) was found within the sediment area (figure 17)—41 hectares of *Acropora* (42.1% of all *Acropora* in Dominica), 295.2 hectares of coral framework (35.1% of all coral framework in Dominica) and 86.6 hectares of rocky outcrops with corals (36.4% of all rocky outcrops with corals in Dominica).

DISCUSSION

The effects of Hurricane Maria have emphasized the necessity and urgency of Dominica's recent goal to become the world's first climate resilient island (Government of the Commonwealth of Dominica, 2020). Several research projects have been undertaken to evaluate and enhance the resilience of Dominica and its inhabitants after Hurricane Maria (Hu & Smith, 2018; Schaefer et al., 2020), now including an assessment of changes to coastal marine habitats.

Current benthic habitat maps are essential for effective marine planning and management efforts in a blue economy. Our research provides methods to monitor and quantify changes to seagrass distribution which can be used to estimate carbon offsets and inform decisions related to fisheries production. With the presence of *H. stipulacea* in the Caribbean basin, spatial data

relating to changes in seagrass meadow distribution generated using our methods can identify areas of potential progression of the *H. stipulacea* invasion.

The data resulting from our study show that i) *H. stipulacea* may have continued expanding between 2016 and 2019, ii) 35.9% of Dominica's reef structures are may be under threat for burial, impeded photosynthetic processes, and tissue damage from abrasion as a result of suspended sediment in the water column, and iii) accretion and erosion processes have resulted in large amounts of sediment deposition at river mouths.

Large quantities of terrestrial vegetation were stripped away by Hurricane Maria's winds and heavy rains, both during the storm and the subsequent wet seasons. These impacts were associated with increased coastal sediment movement. The presence of suspended sediment in the post-hurricane imagery is concerning for coral reefs as it was captured during the dry season. With a wet tropical climate that characterizes Dominica's landmass along with steep terrain, high turbidity levels are a typical stress that occurs on Dominica's coral reefs during the wet season. However, if changing climate patterns are resulting in greater storm frequency and intensity during the dry season, then a significant proportion of the island's reefs could experience more persistent sediment exposure than normal. Approximately 54% of Dominica's reefs are on the windward side of the island (Steiner, 2015) (figure 18) which receives significant rainfall as storms from the Atlantic Ocean are driven west and condense and release on the eastern slopes (Fobert et al., 2021; Minder, Smith, & Nugent, 2013) and bring sediment into the river channels and ocean, as shown in our February 2019 imagery. One of the variables driving the spread of *H. stipulacea* in the Caribbean is its sensitivity to light. As a plant native to the Indian Ocean and Arabian Sea, it adapted to become more sensitive to changes in light to survive in the variably turbid waters of

that region. In the crystal-clear waters of the Caribbean, that light sensitivity allows it to grow in much both deep and shallow waters (Winters et al., 2020). Increased turbidity may adversely impact remaining native seagrass species as they are not as well equipped to adapt to changes in irradiance like *H. stipulacea* (Winters et al., 2020) and can be buried as the sediment settles (UNEP, 2020).

The dominant seagrass species for the northeast portion of the island, *T. testudinum*, has exhibited resistance to the invasion of *H. stipulacea*, likely due to the strong wave energy from the Atlantic Ocean preventing the shallower roots of *H. stipulacea* from anchoring to shallow, rocky substrate where *T. testudinum* thrives. It should be noted that given the right conditions, *H. stipulacea* can grow on shallow, rocky substrates as was demonstrated in the discovery of a *H. stipulacea* bed near Scotts Head (Steiner & Willette, 2013) (figure 19). If *H. stipulacea* were able to anchor in the northeast coast, *T. testudinum* would likely be reduced as a result of sea turtle grazing. Such was the case in Lac Bay, Bonaire where *T. testudinum* distribution decreased 20% over a 5-year period, while *H. stipulacea* increased 14% during the same period as a result of sea turtle grazing. As sea turtles created voids in the *T. testudinum* coverage by grazing, *H. stipulacea* would propagate to fill the open space, preventing *T. testudinum* from reestablishing (Smulders et al., 2017). While the suspended sediment in the post-hurricane imagery limited our ability to detect changes to the *T. testudinum* beds on the northeastern shoreline, we were able to detect seagrass beds on the remaining coastline areas. Both the expansion and loss of seagrass in the -10m zone may indicate *S. filiforme* and *H. wrightii* have been further reduced by the expansion *H. stipulacea* within that zone. Additionally, researchers have observed *H. stipulacea* rapidly forming mats of dense seagrass following storm damage to native meadows (i.e. wave energy uprooting existing meadows). In Dominica, it is believed that one of the contributing factors to *H. stipulacea*'s rapid

expansion between 2007 and 2013 were the 14 tropical storms, three of which were hurricanes, that passed through the region during that time frame (Steiner & Willette, 2015). A direct impact from a storm like Hurricane Maria would have high potential for uprooting seagrasses, especially those in shallow waters. This provides an opportunity for small fragments of *H. stipulacea*, possibly dispersed by the storm wave energy, to anchor and rapidly propagate into dense mats (Smulders et al., 2017).

H. stipulacea's spread presents great challenges in marine management as it has both positive and negative consequences for other native and invasive marine species. Research suggests the expansion of *H. stipulacea* may adversely affect sea turtle populations. *T. testudinum* has a higher nutritional density than *H. stipulacea* however sea turtles have been observed eating *H. stipulacea* in some instances. One of the factors of concern with sea turtle grazing is that the sea turtle population is growing at the same time their preferred food sources are being edged out by an invasive seagrass (Christianen et al., 2019). The expansion of *H. stipulacea* may be somewhat beneficial for fishing activities in the short term as *H. stipulacea* has been shown to support larger fish and the same quantities of fish as *S. filiforme*. However, in the long term it may be more problematic as the proportions of juvenile-stage fish are observed to be lower on *H. stipulacea* meadows (Willette & Ambrose, 2012). *Tripneustes ventricosus*, which typically grazes on *T. testudinum*, has been observed on *H. stipulacea* beds (Willette et al., 2014), however the density of *T. ventricosus* found on *H. stipulacea* is much lower (Winters et al., 2020). Native *Oreaster reticularis* (Asteroidea) has seen population declines across the Caribbean due to seagrass loss, however the dense mats of *H. stipulacea* appear to benefit its feeding strategy, providing a potential opportunity for recovery (Winters et al., 2020). *Charybdis hellerii*, a native to the Indo-West Pacific, has been found in Martinique where *H. stipulacea* appears to provide adequate sanctuary

from predators (Winters et al., 2020). Prioritizing and increasing native seagrass protection and restoration efforts may be effective in mitigating the negative impacts of the *H. stipulacea* invasion.

Future Research

Further exploration is needed to examine the frequency and intensity of sediment events during the dry season, which may be adversely affecting coral health, and indeed higher than normal. This could be done by a combination of in-situ turbidity sampling throughout the dry season, analysis of data from local weather stations, and spatio-temporal analysis of satellite imagery acquired during the dry season. Further research is also needed to examine the species composition of seagrass meadows at the locations we identified as experiencing seagrass expansion between 2016-2019 in order to confirm the presence of *H. stipulacea* at the expansion sites (figure 20). Such field verification has been impeded by the ongoing COVID-19 pandemic and associated travel restrictions.

In addition to the use of *in-situ* measurements from flow gauges and Secchi disks, PlanetScope satellite imagery, which is collected daily, may be an effective tool for studying turbidity patterns in Dominica's coastal waters. Data from Dominica's two weather stations could guide the selection of imagery collection dates to observe. Scenes from days preceding and proceeding the storm event could be classified to quantify sediment coverage. The imagery and weather data from the dry and wet seasons could be compared for each year to examine whether or not significant differences in the duration or frequency of turbidity events between seasons. An alternative strategy for monitoring turbidity includes the use of sUAS. Imagery could be collected at regular intervals at selected study sites to evaluate water clarity. The results of the image analysis could then be

compared to weather data surrounding the collection dates to examine how weather patterns may be influencing turbidity patterns.

While field sampling is necessary to examine the species composition at seagrass expansion sites, sUAS could be used to conduct an accuracy assessment for our post-hurricane seagrass loss and gain classifications. Select sites where seagrass gain was indicated in the classification could be mapped using sUAS and examined to confirm the presence of seagrass.

CONCLUSION

Climate change and the *H. stipulacea* invasion both present great challenges to Dominica and other SIDs. Several research projects have been undertaken to evaluate the status of Dominica's seagrasses and to enhance the resilience of Dominica and its inhabitants after Hurricane Maria, now including an assessment of changes to coastal marine habitats.

The total seagrass area in Dominica has continued to grow despite disturbances to seagrass meadows caused by Hurricane Maria. This expansion is likely driven by the expansion of the invasive seagrass, *H. stipulacea* which benefits some species found in the Caribbean while degrading others. The continued expansion of *H. stipulacea* in Dominica may be an asset in the pursuit of climate resilience as an increase in seagrass implies greater coastal protection from storms, more stable sediment beds, and increases carbon sequestration. However, prioritizing the restoration and protection of native seagrasses will be an important step to counter the negative impacts of *H. stipulacea* on other species.

Our methods can be used by marine resource managers and policy makers to inform decisions relating to fisheries production, emissions trading, disaster risk mitigation, and invasive species monitoring, facilitating sustainable growth in the blue economy.

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FIGURES

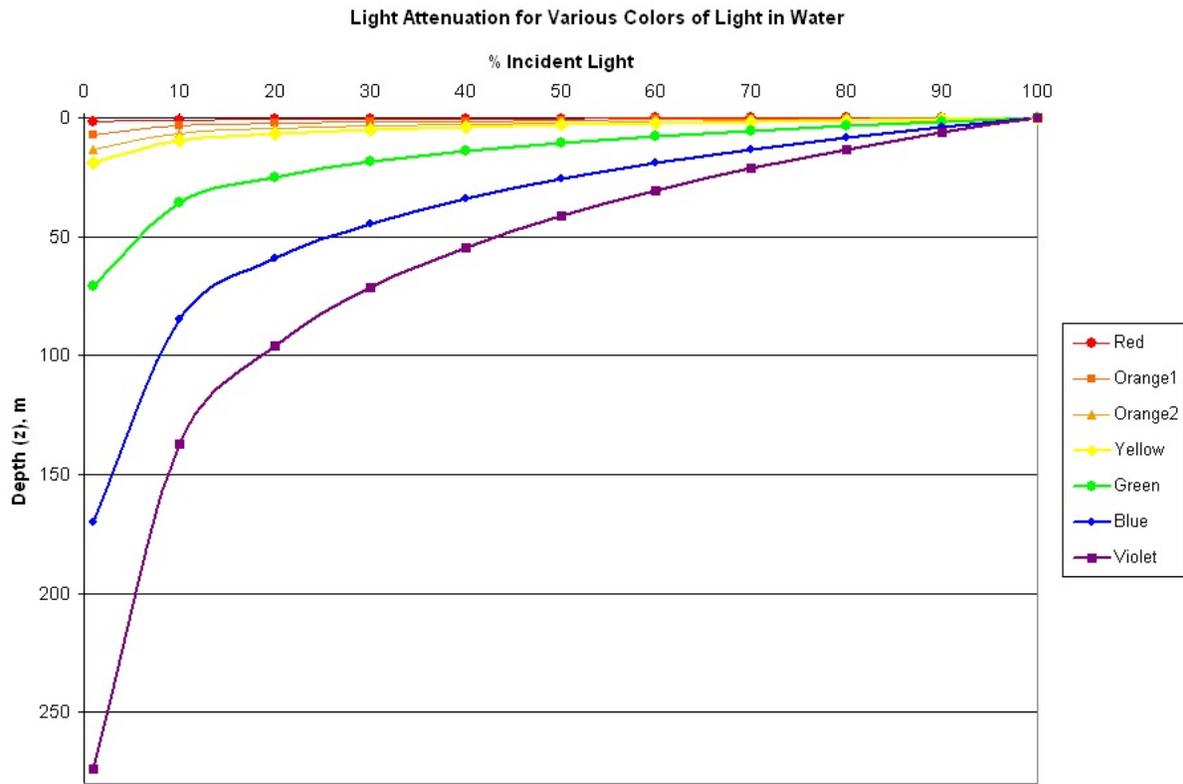


Figure 1. Graph depicting the attenuation of different wavelengths of visible light across shallow and deeper water. Adapted from "Light Attenuation for Various Colors of Light in Water," by Leah Moore, 2010, retrieved from <http://oceanography-leahmoore.blogspot.com/2010/10/light-attenuation-for-various-colors-of.html>.

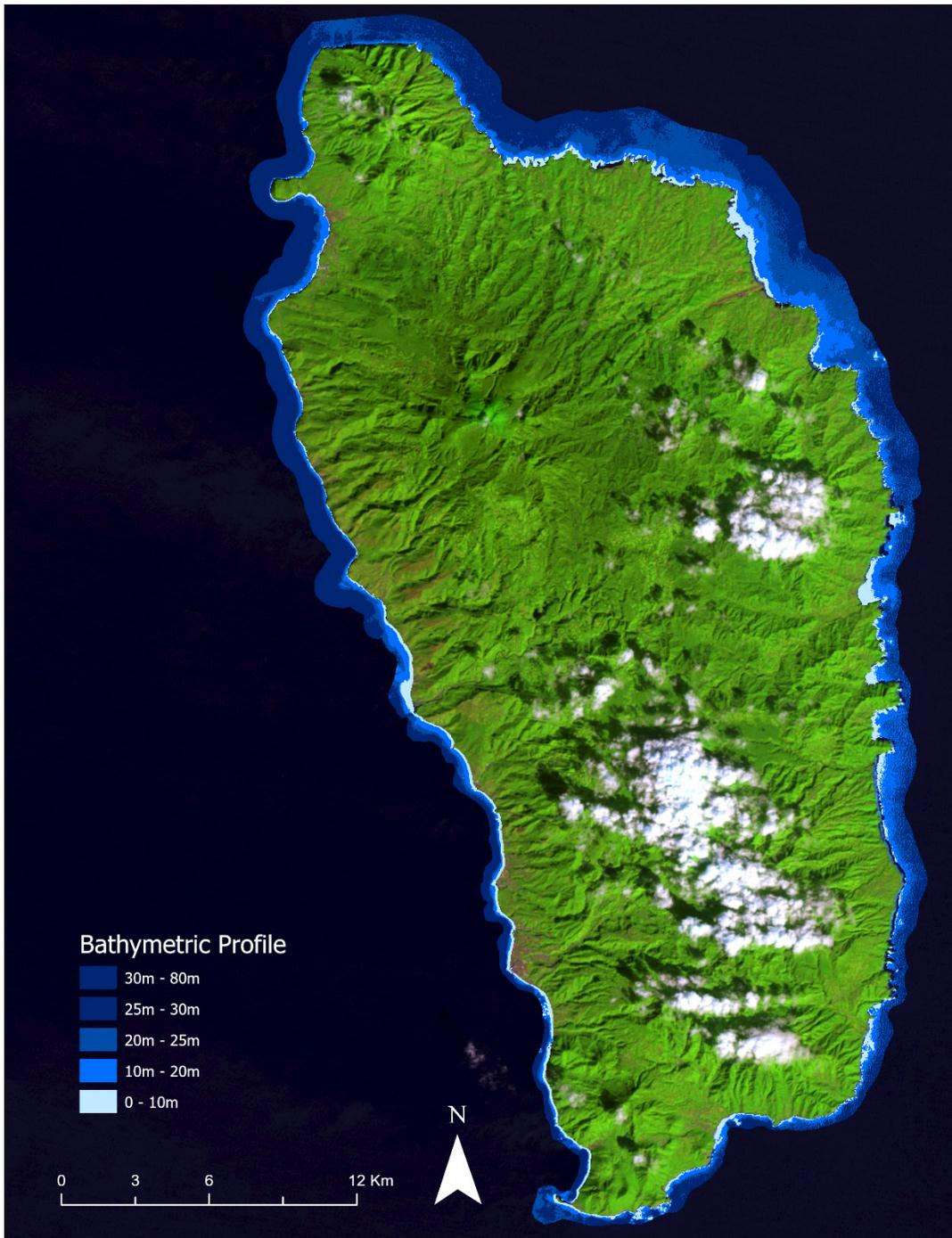


Figure 2. Landsat 7 satellite image from November 13, 2010 and satellite-derived bathymetry profile from 2016 developed using Worldview-2 and Pleiades imagery. Note the steep coastal shelves with the widest portions being found on the northeastern shoreline, home to 54% of Dominica’s corals. Also note the leeward side is more heavily populated, has a narrower coastal shelf, and dryer slopes, indicated by the brown areas in the image.



Figure 3. Image of a landslide occurring on a coastal slope in Dominica captured during field data collection on May 1, 2019. Coastal landslides can damage reefs by burying portions of fringing reef structures that abut the coastline or by introducing sediment into the water column which can damage coral tissue and impair photosynthetic capabilities. Seagrass meadow's photosynthetic processes can also be negatively impacted by increases in turbidity.

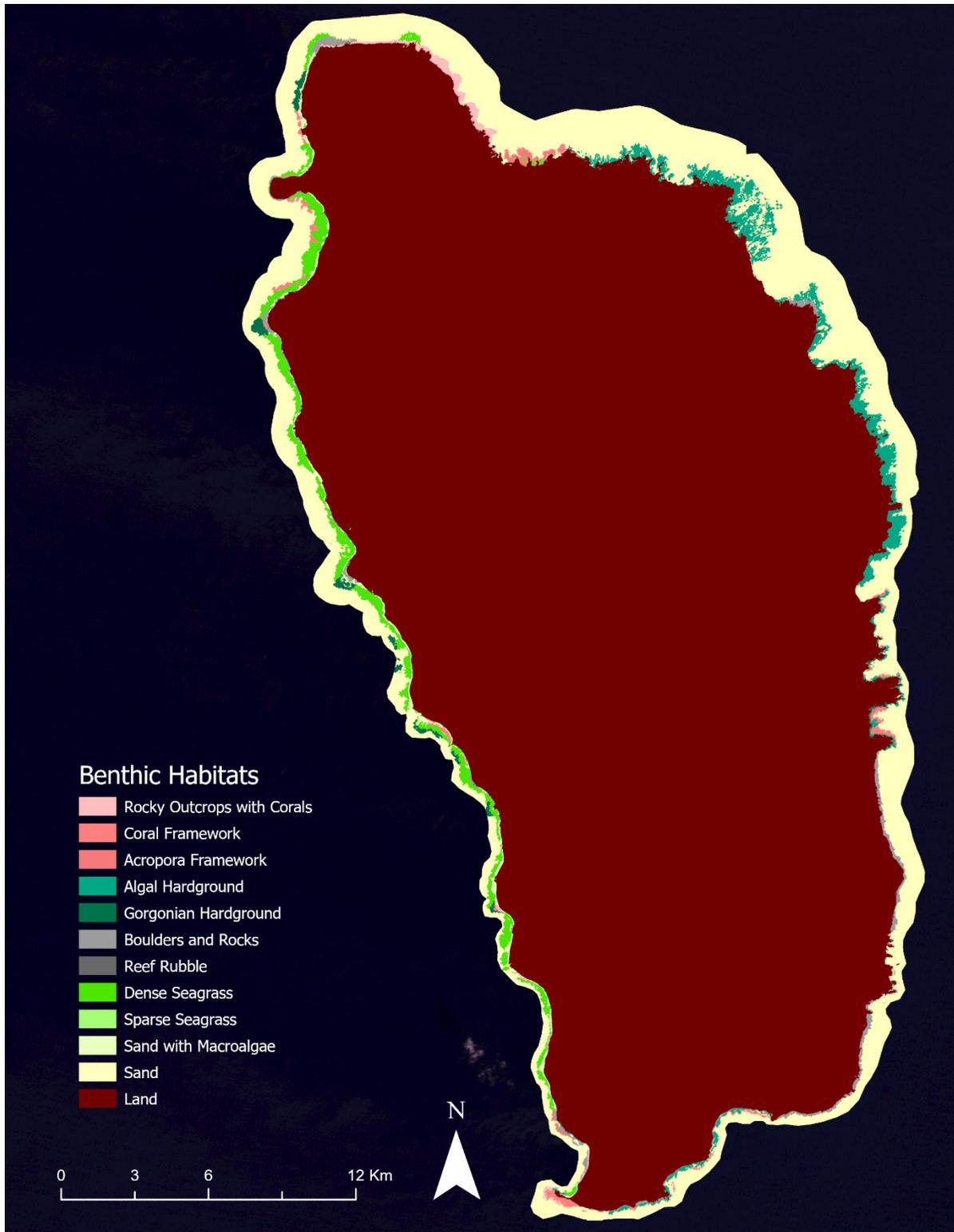


Figure 4. Pre-hurricane benthic habitat map developed by Schill et al. (2020) in 2016.



Figure 5. Instruments used for collecting field samples in 2016 and 2019 included a GoPro Hero 4 camera with a red filter affixed to a GPS-referenced SeaViewer Sea-Drop 6000 HD (Tampa, FL, USA) underwater video camera with a 30 m vertical cable and a Garmin GPSMAP 547xs transducer. The Seaviewer provided a live video feed used for obstacle avoidance while the GoPro captured high definition video footage of benthic habitat along each transect. GPS points were registered at beginning and end of each transect to allow for georeferencing of habitat information. The transducer assembly collected depth at 3 points per second with GPS antennae. High resolution imagery converted to MBTile format and loaded into the Locus Pro application

on a tablet was used to identify and navigate to survey point locations for various benthic habitats

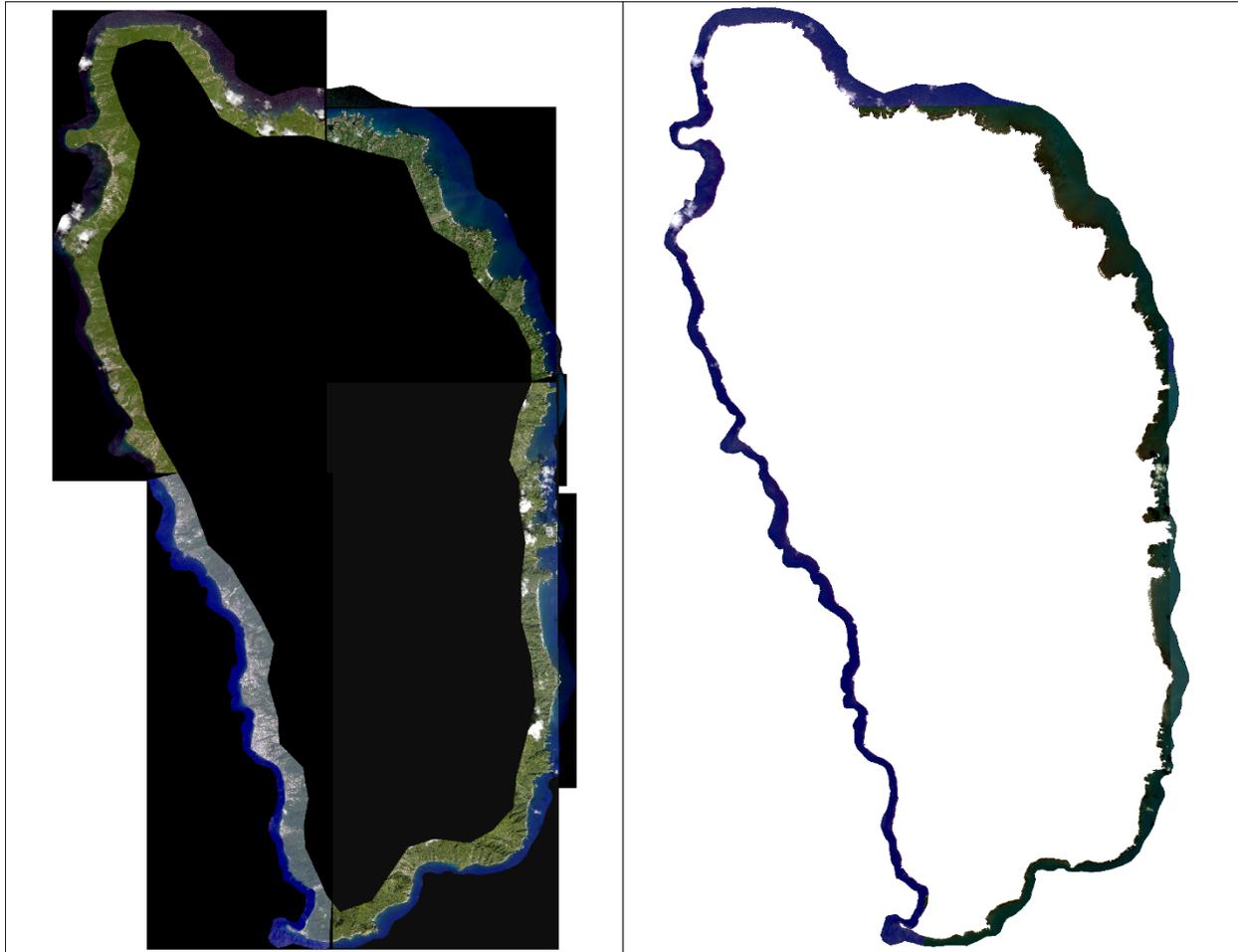


Figure 6. **Left:** Worldview-2 imagery used to map the extent of coral reefs prior to Hurricane Maria. The northern scenes were unfit for use in the automated mapping of benthic habitats done by Schill et al. (2020) in 2016 however the additional coastal blue and yellow bands available on Worldview-2 imagery made it an ideal candidate for manual mapping of reefs. **Right:** Radiometrically corrected and calibrated mosaics of the scenes on the left with land areas removed using a geomorphology mask.

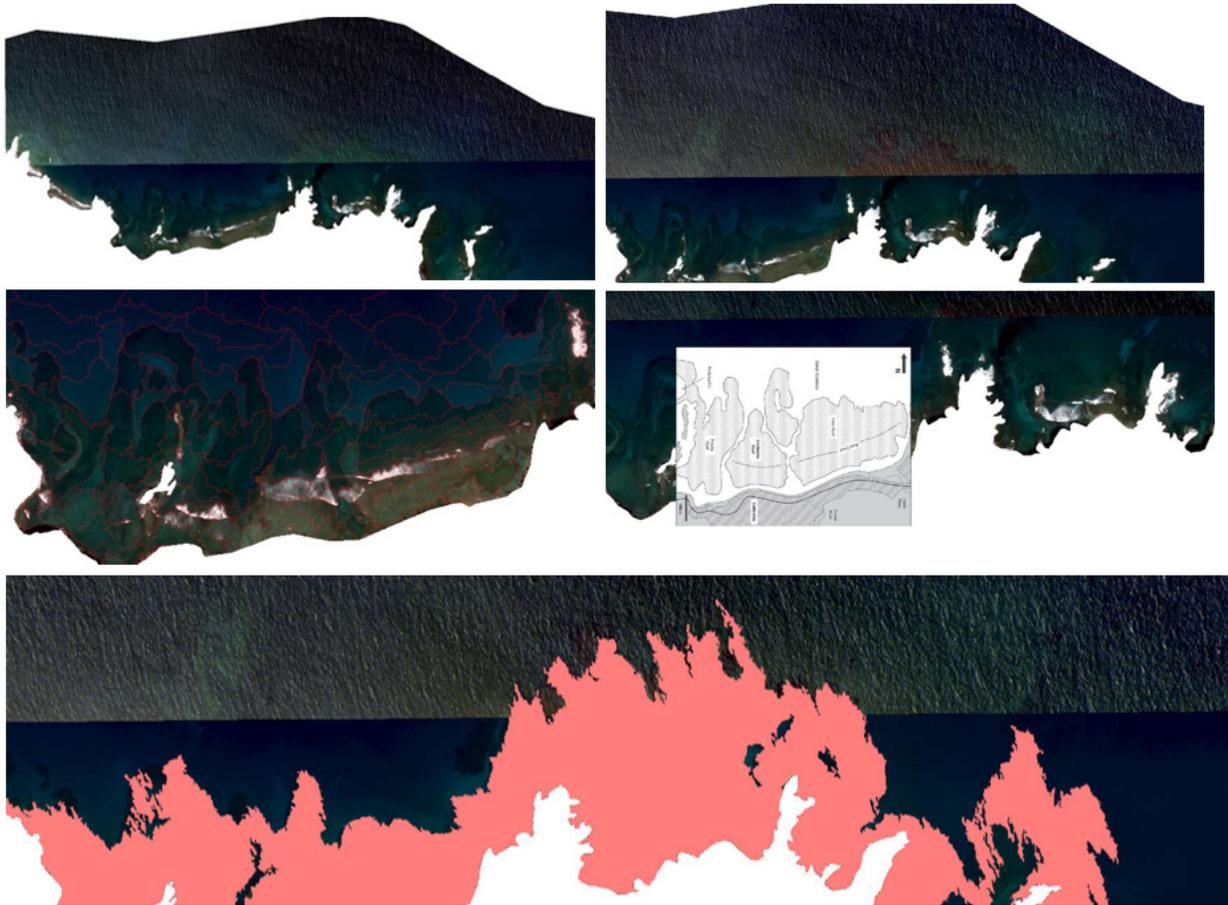


Figure 7. **Top left:** Worldview 2 scenes from 2014 rendered in true color RGB showing how glint affects image quality. The quality of the bottom image is excellent but the distortions in the top half prevented this image from being used in the pre-hurricane classification. **Top right:** Application of histogram stretching and rendering the image using high energy bands (Coastal Blue, Blue, Green) to enhance visibility and interpretation of features in the distorted image. **Middle left:** Results of using spectral information from all available visible bands (Coastal Blue, Blue, Green, Yellow, Red) to segment the pre-hurricane Worldview-2 imagery to isolate reef features. **Middle right:** Steiner's reef maps (2015) georeferenced with the 2014 Worldview-2 imagery. Segments that intersected with these maps were selected as well as features in the image that showed spectral properties consistent with coral reefs. **Bottom:** An example of a manually classified area of reef, located on the north coast of Dominica, done using the methods outlined in the above figures.

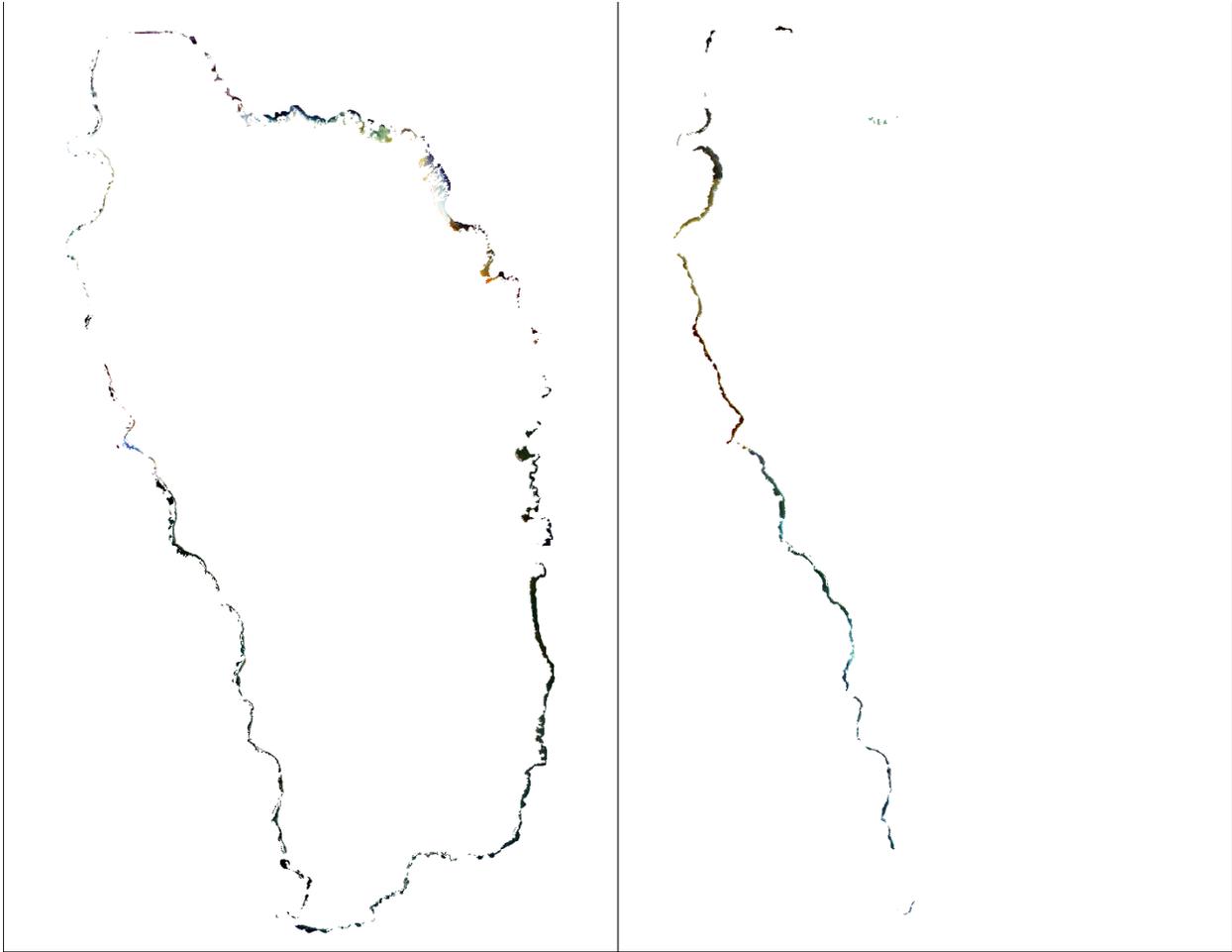


Figure 8. Radiometrically calibrated and corrected post-hurricane image mosaicks masked to using the pre-hurricane sand extent (**left**) and pre-hurricane seagrass extent (**right**). Both were also masked to the -10m bathymetric extent.

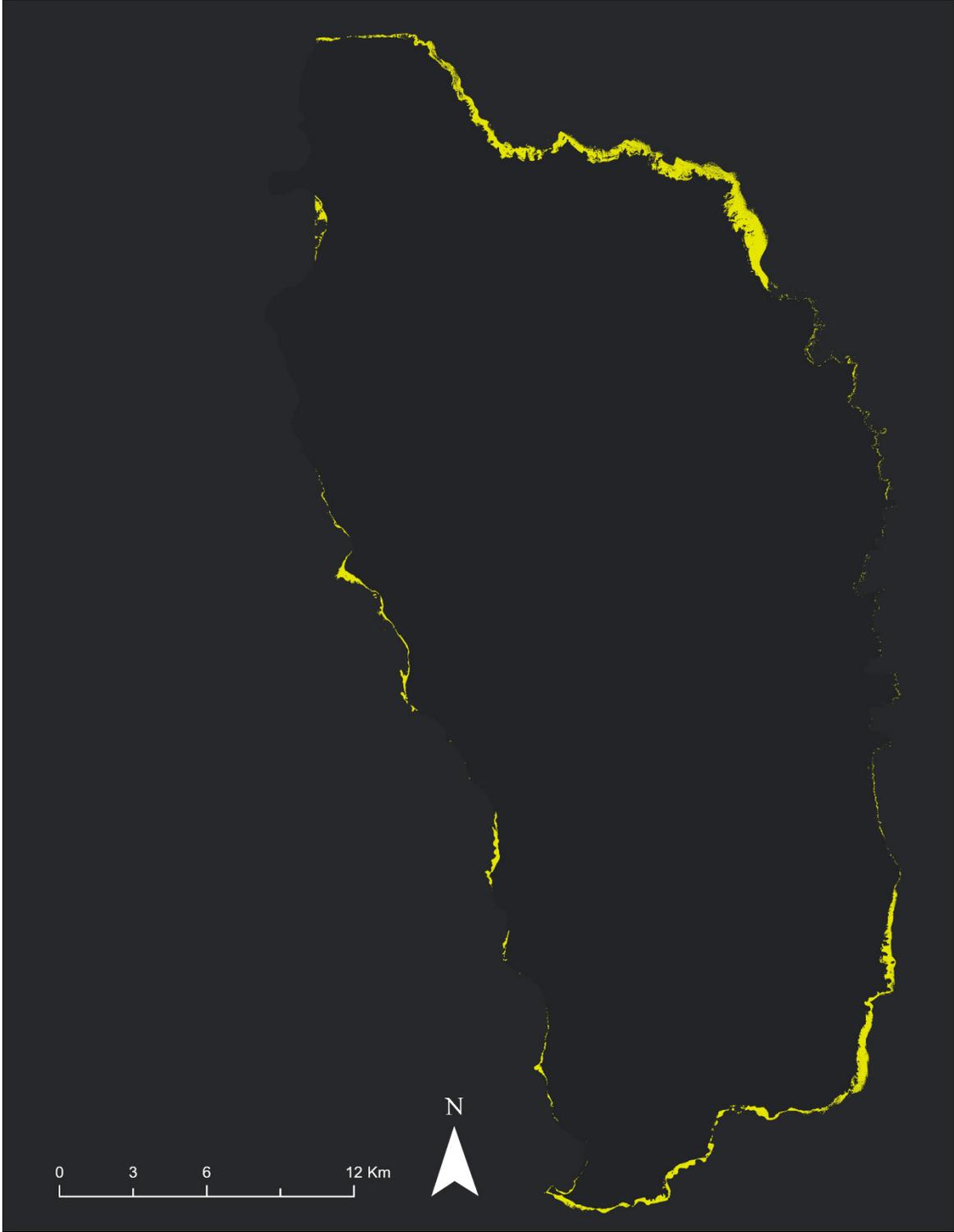


Figure 9. Extent of sediment mapped in post-hurricane imagery.

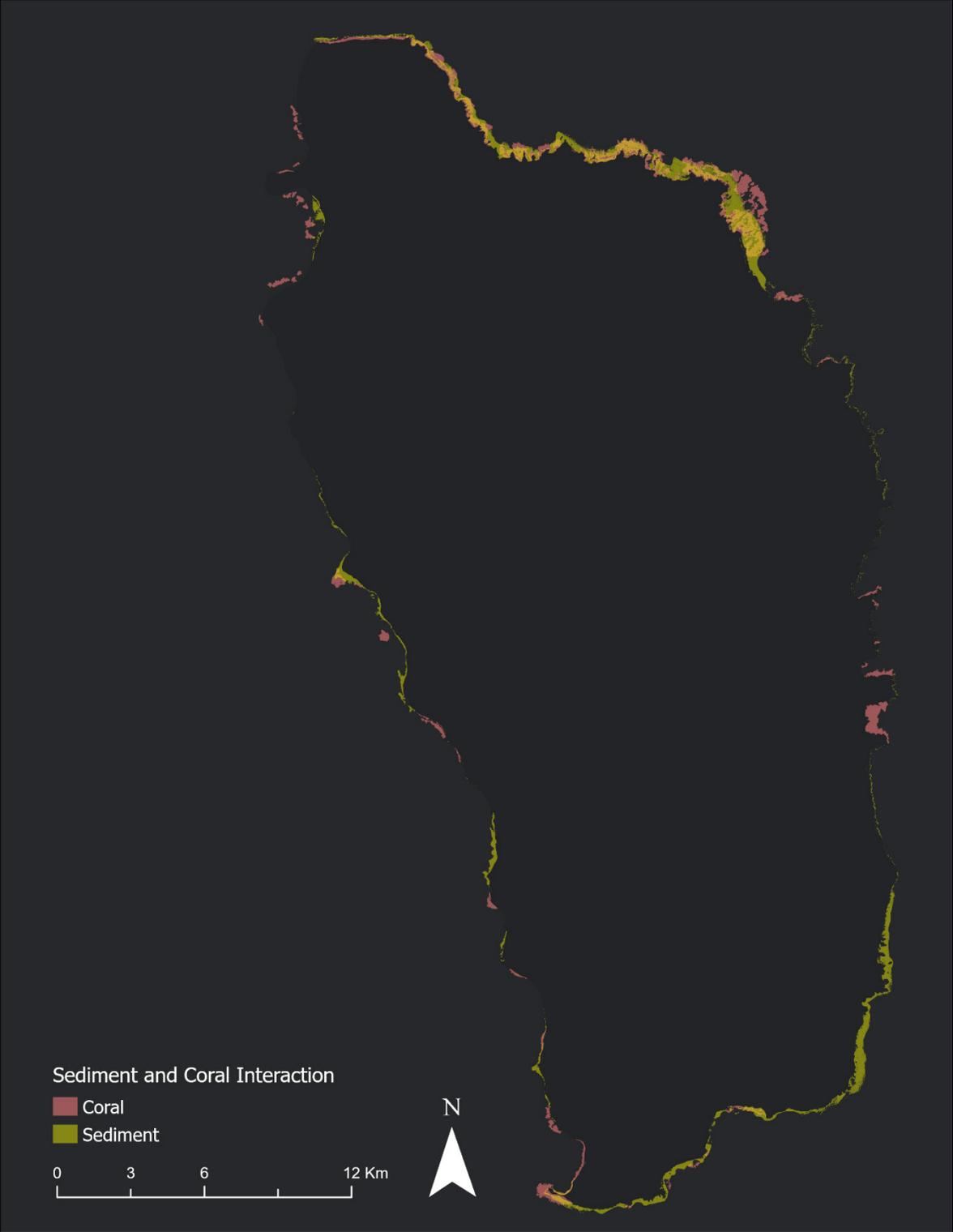


Figure 10. Map showing areas of sediment that intersected with coral reef features.

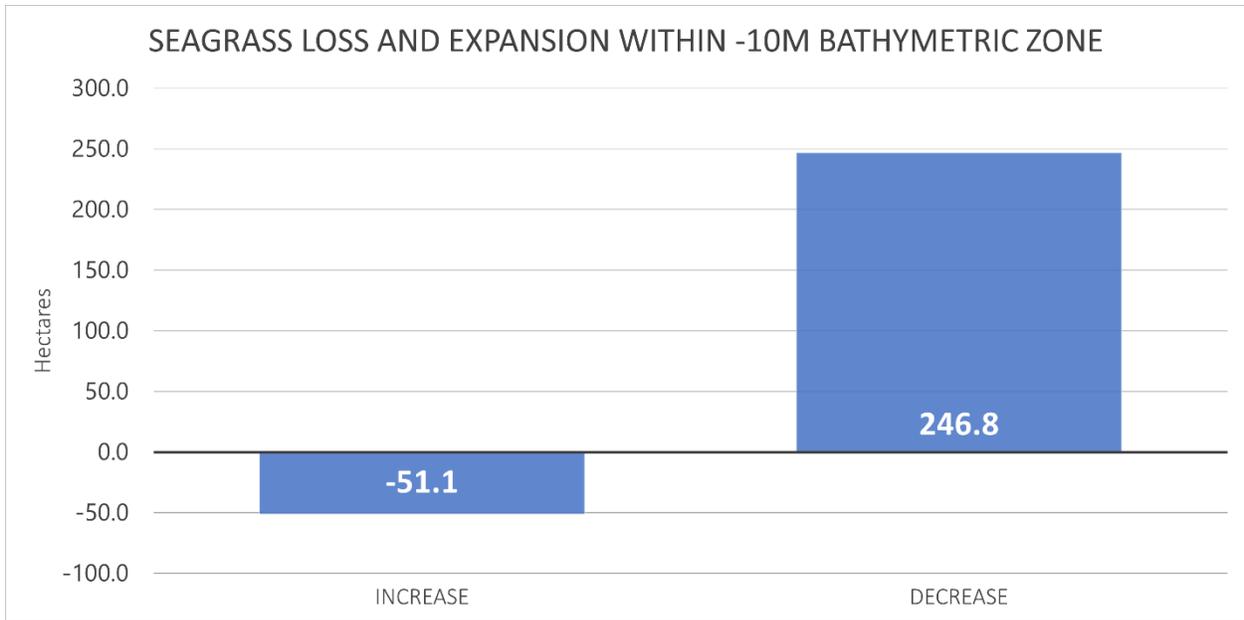


Figure 11. Graph showing seagrass loss and expansion within the -10m bathymetric zone between 2016 and 2019.

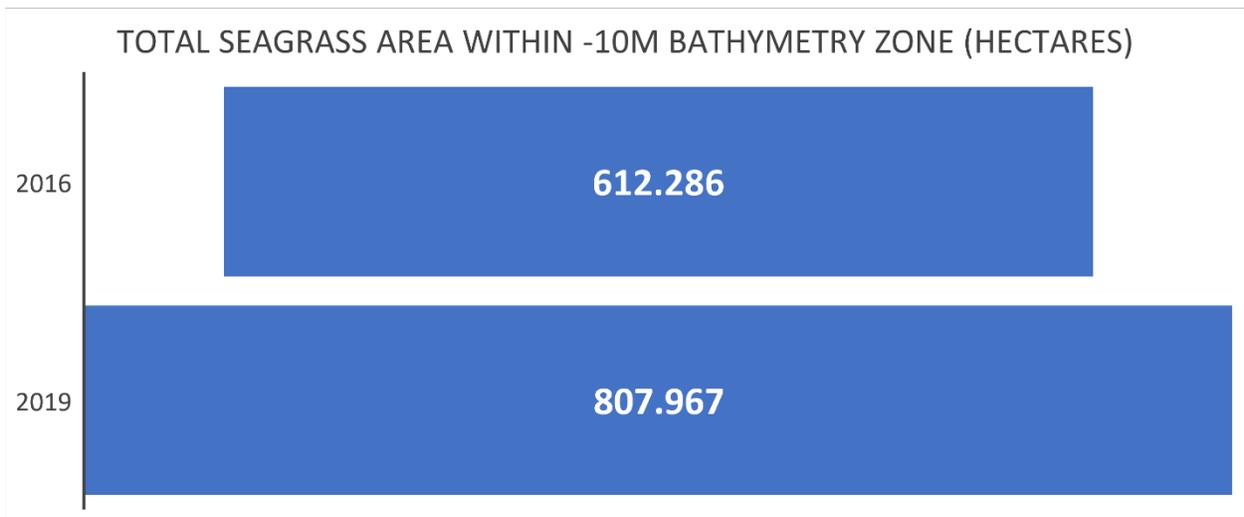


Figure 12. Graph comparing total seagrass area found within the -10m bathymetric zone in 2016 and 2019.

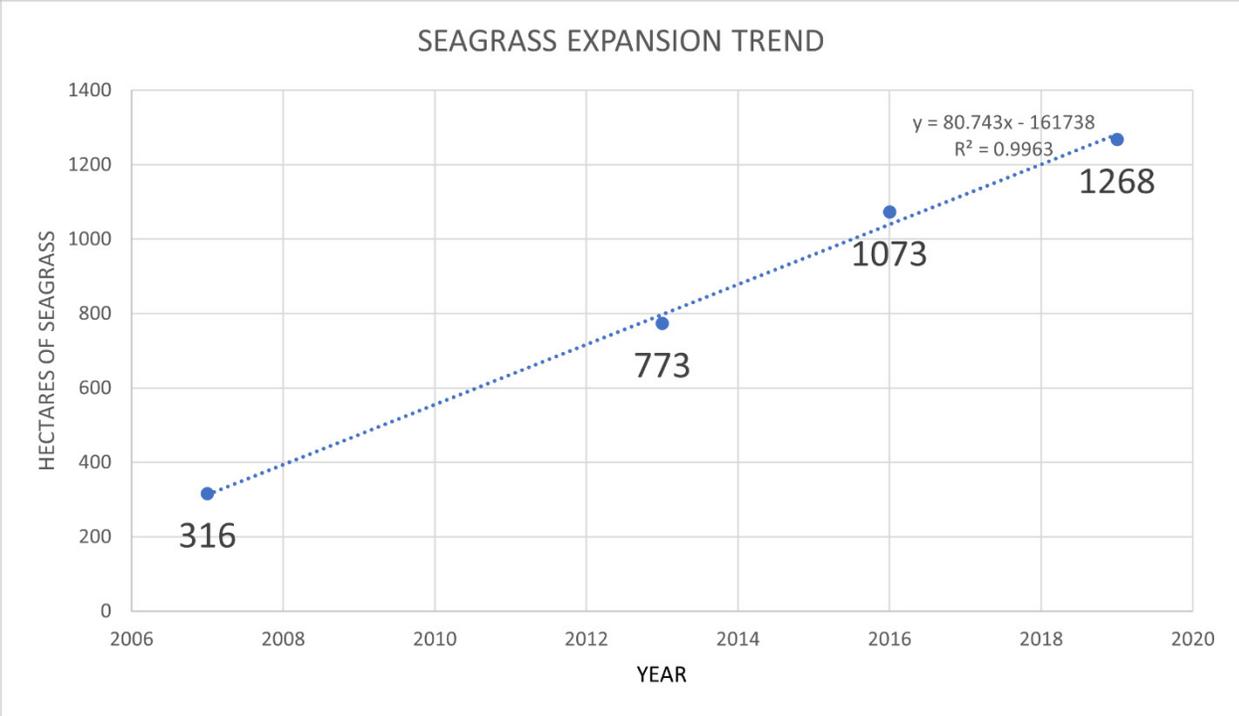


Figure 13. Graph showing trend in seagrass growth as reported by Steiner & Willette (2010,2013), Schill et al. (2020), and this study.

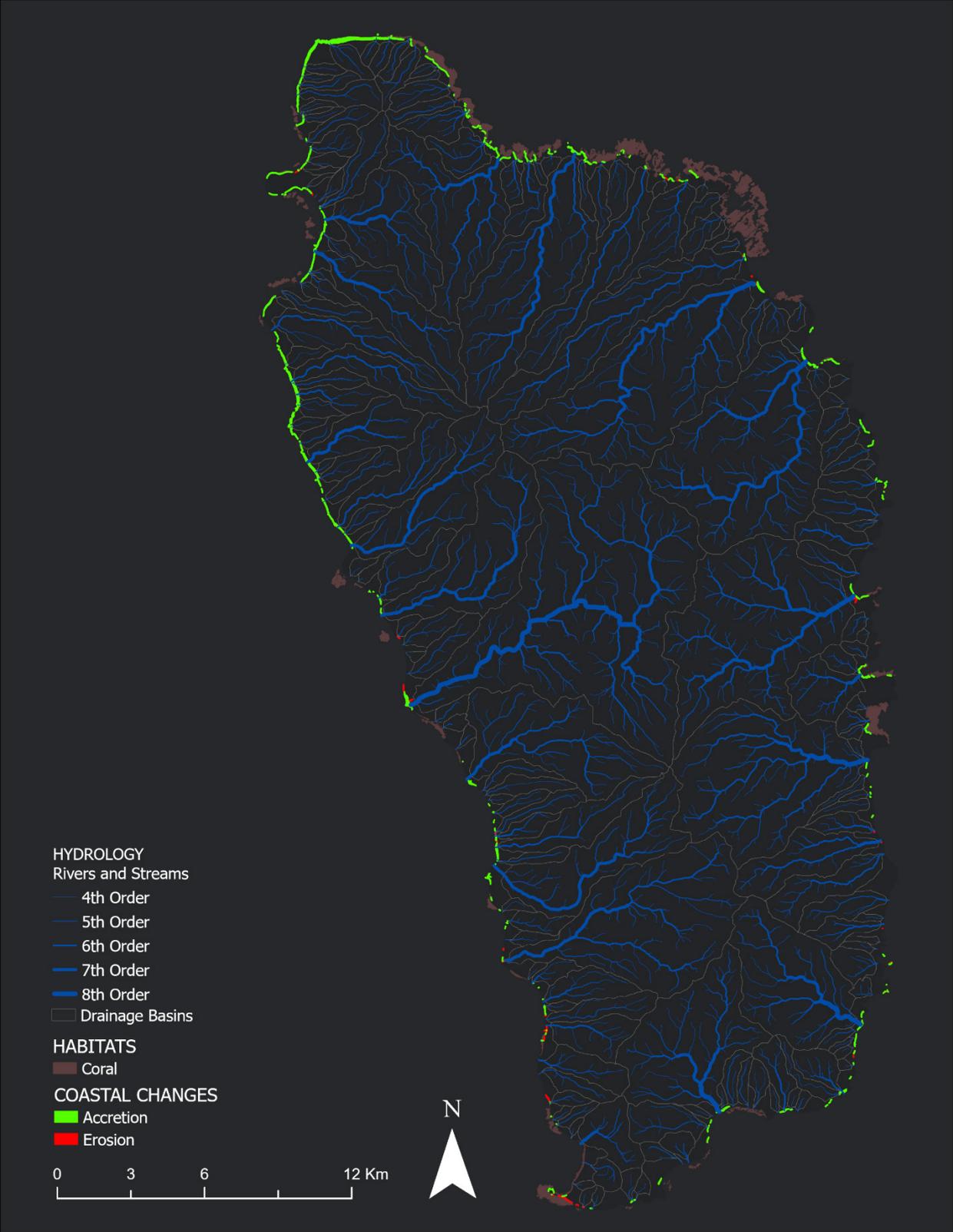


Figure 14. Map showing areas of accretion and erosion detected between 2016 and 2019 in relation to Dominica’s hydrology and coral reef distribution.



Figure 15. Satellite imagery showing accretion occurring near river mouths in 2016 (left scene) and 2019 (right scene) at twelve locations across Dominica. **Top to bottom, left to right:**

Coulibistrie, River Quayaneri, Geneva River, Champagne Bay, Canefield Airport, La Ronde River, southern La Plaine, Pt. Mulatre River, Layou River, River Bibiay, Rosalie River, Roseau (Queen's) River, Malabuka River, Petite Savanne Bay, and Belfast River.

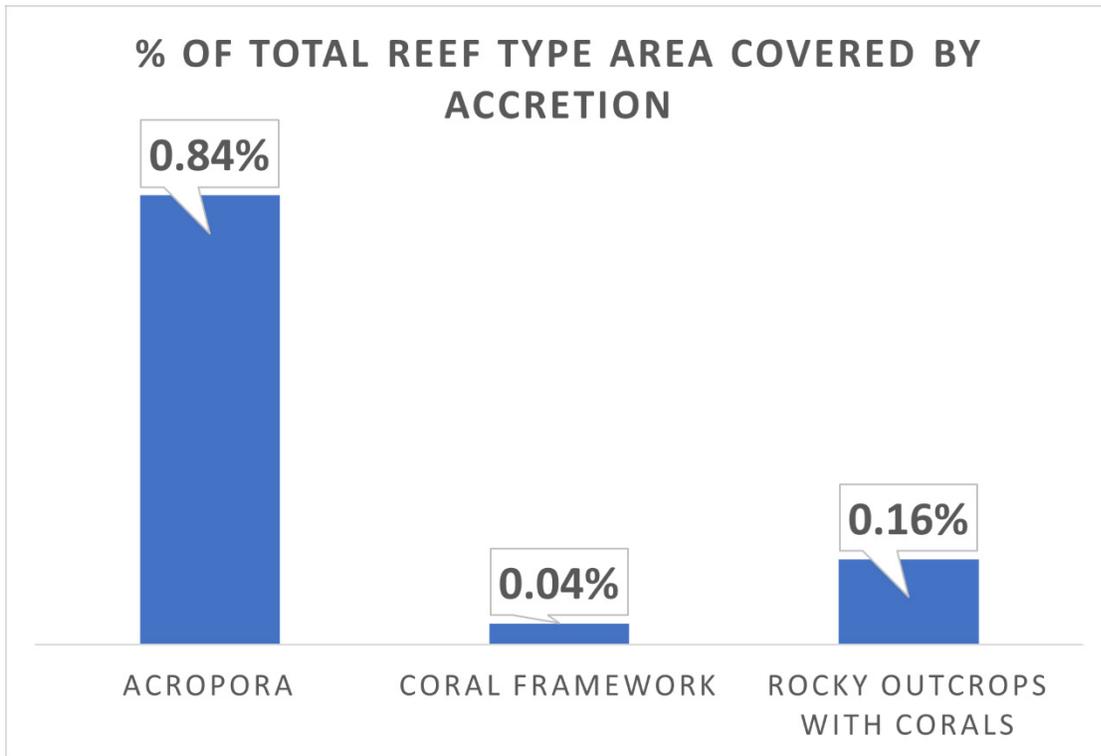


Figure 16. Graph comparing percentages of coral reef feature types affected by coastal accretion following Hurricane Maria.

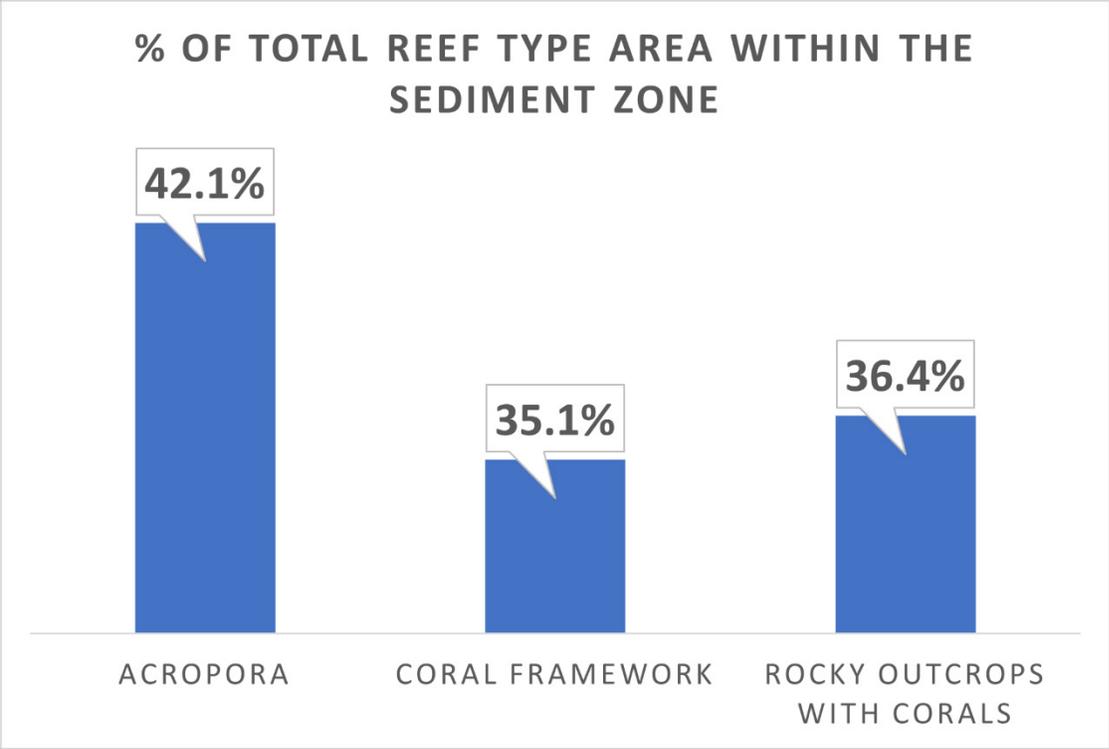


Figure 17. Graph comparing percentages of coral reef feature types found within the extent of the sediment plume observed in the post-hurricane imagery.



Figure 18. Map showing distribution of Dominica's coral reefs. Percentages are as reported by Steiner (2015).



Figure 19. Orthomosaic of Scotts Head marine park acquired with a DJI Mavic 2 Pro during field data collection in 2019. Note seagrass meadows growing in the rocky substrate in the lower right of the scene which has been identified as *H. stipulacea* by Willette and Steiner (2013).

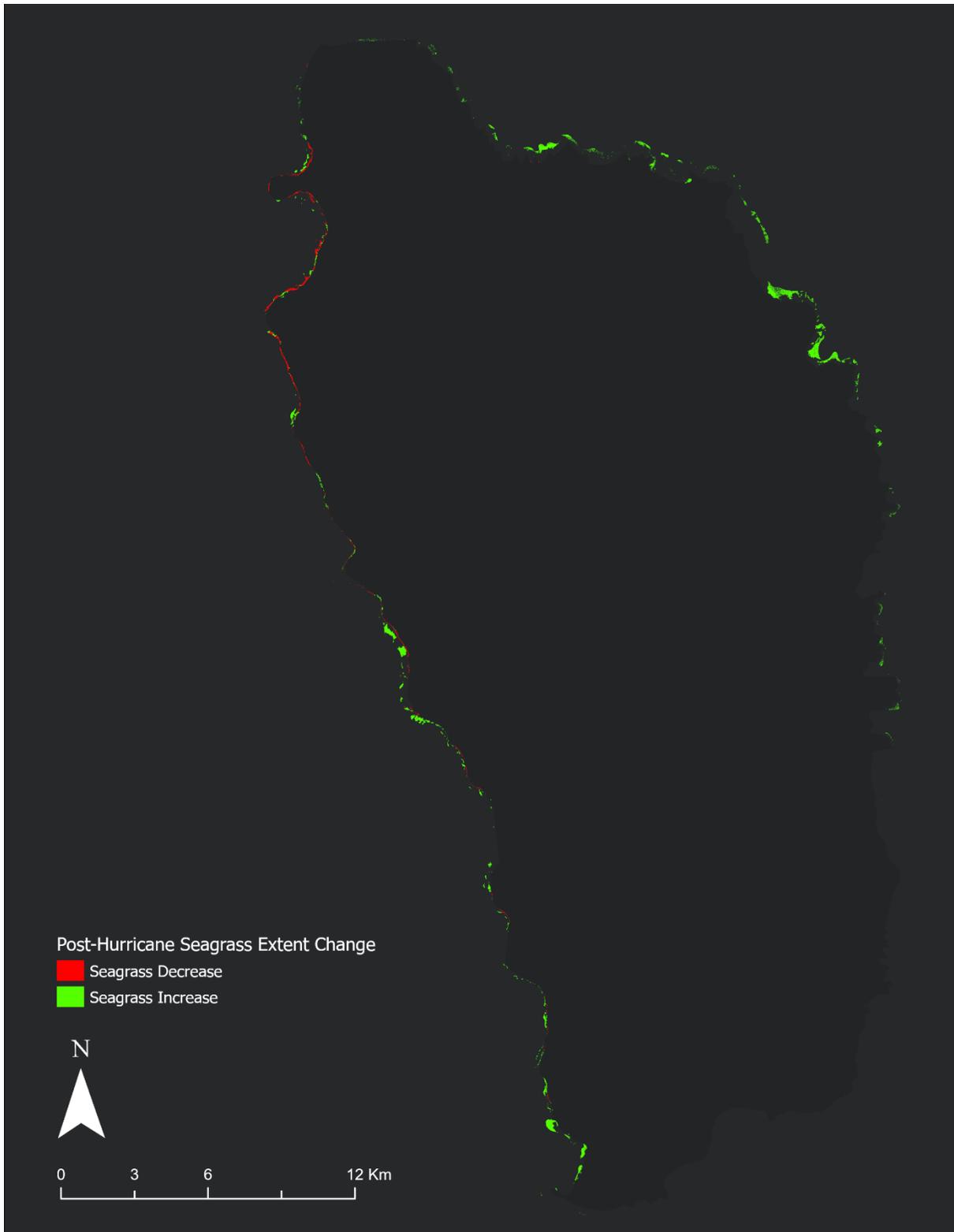


Figure 20. Map showing areas of increase and decrease in seagrass meadow extent between 2016 and 2019.

TABLES

Table 1. Scene period (2016, 2019), collection dates, and sensors relating to imagery used to track changes to coral reef and sea grass features after Hurricane Maria.

2016 CLASSIFICATION SCENES		2019 CLASSIFICATION SCENES	
Date	Sensor	Date	Sensor
April 29, 2015	Pleiades	Feb. 13, 2019	Pleiades
April 29, 2015		Feb. 13, 2019	
Dec. 16, 2014	Worldview-2	Insert Date	DoveSat
July 31, 2014			
Feb. 03, 2013			

Table 2. Scene period, collection, dates, and sensors relating to imagery used to map coral reef features prior to Hurricane Maria.

2016 REEF MAPPING SCENES	
Date	Sensor
Dec. 16, 2014	Worldview-2
July 31, 2014	
April 27, 2014	
Feb. 03, 2013	