

**ASSESSING SPATIAL AND TEMPORAL CHANGES IN SEAGRASS COMMUNITIES
USING HISTORICAL AERIAL PHOTOGRAPHY AND SATELLITE DATA**

by
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Abstract

Seagrass beds provide a number of important ecosystem services. However, reported cases of seagrass loss have increased, emphasizing the need for assessing seagrass health worldwide. This study provides a high resolution characterization of the seagrass communities and an estimate of long-term changes in seagrass extent at Caja de Muertos Island Nature Reserve in Puerto Rico. For the first part of the study, a benthic habitat map was created using a 2014 WorldView-2 satellite image and by integrating a combination of mapping techniques. A total of 164 sampling sites were used to calibrate and validate the map. For the second part of the study, a satellite image and historical aerial photography from 1950 to 2014 were used to assess spatial and temporal changes in seagrass. Benthic habitats, including seagrass, were mapped with an overall accuracy of 82.76%. The dominant seagrass species were *Thalassia testudinum*, and *Syringodium filiforme*, which were mainly located in the West and North of the island. Light availability was not a limiting factor for seagrass colonization at the study area. The time series analysis revealed an overall increase in seagrass extent of 64% over the studied period, contrasting with the worldwide seagrass declining trend. Overall the results of this study provide valuable information for the conservation and management of seagrass habitat in the Reserve.

Resumen

Las praderas de hierbas marinas proveen importantes servicios al ecosistema. Sin embargo, los casos reportados de pérdida de hierbas marinas han aumentado, resaltando así la necesidad de evaluar la condición de estas. Este estudio provee una caracterización a alta resolución de las comunidades de hierbas marinas y una estimación de los cambios a largo plazo en la distribución de estas en la Reserva Natural de Isla Caja de Muertos en Puerto Rico. Para la primera parte del estudio, un mapa de hábitats bénticos fue creado utilizando una imagen del sensor WorldView-2 del año 2014 y mediante la integración de varias técnicas de cartografía. Un total de 164 lugares de muestreo se escogieron para calibrar y validar el mapa. Para la segunda parte del estudio, se utilizó una imagen de satélite y fotografías aéreas desde el 1950 al 2014 para evaluar los cambios espaciales y temporales en las comunidades de hierbas marinas. Se cartografiaron hierbas marinas y otros hábitats bénticos con una precisión general de 82.76%. Las especies de hierbas marinas que dominaron fueron *Thalassia testudinum*, y *Syringodium filiforme*, las cuales se encontraron principalmente en el Oeste y Norte de la isla. La disponibilidad de luz no fue un factor limitante para la colonización de las hierbas marinas en el área de estudio. El análisis de la serie de tiempo reveló que durante el periodo de estudio la extensión de hierbas marinas aumentó 64%, contrastando con la tendencia mundial de disminución. En general los resultados de este estudio proveen información valiosa para la conservación y el manejo de los hábitats de hierbas marinas en la Reserva.

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General Introduction

Seagrasses provide a variety of ecosystem services and are one of the most important habitats in shallow coastal waters (Zieman and Zieman, 1989). For example, seagrasses serve as nursery and feeding grounds for a diverse number of organisms, provide fisheries resources, help with sediment stabilization, recycle nutrients, and sequester carbon from the atmosphere (Zieman and Zieman, 1989; Costanza et al., 1997; Duarte, 2002; Orth et al., 2006; Waycott et al., 2009). However, increased anthropogenic threats in the coastal zones have caused a worldwide decline in seagrass communities (Orth et al., 2006).

In situ monitoring has been the main tool used to assess spatial and temporal changes in seagrass ecosystems (Erfteemeijer and Herman, 1994; Gallegos et al., 1993; Lanyon and Marsh, 1995; and Prathep, 2003). Long-term seagrass monitoring enables researchers to precisely evaluate changes in seagrass cover due to natural or anthropogenic impacts (Seagrass-Watch, 2013), but they cannot be used to evaluate areas where field work has not been conducted. Recently, remote sensing techniques has become an innovative solution for researchers and managers to map and monitor benthic habitat such as seagrass (Armstrong, 1993; Kendall et al., 2001; Kendrick et al., 2002; Lyons et al., 2011; Maccarrone, 2010; Montefalcone et al., 2013; Moore et al., 2001; Pu and Bell, 2013).

Worldwide, passive remote sensing data such as multispectral imagery (Armstrong, 1993; Roelfsema et al., 2009; Lyons et al., 2011, 2012) and aerial photographs (Kendric et al., 2002; Maccarrone, 2010; Moore et al., 2001; Yarbro and Carlson, 2015) have been effectively used to map and monitor shallow seagrass areas. These type of data can be used in relatively clear waters and shallow depths. As an example, the Biogeography Branch of the National Oceanic and Atmospheric Administration (NOAA) have generated benthic habitat maps for Puerto Rico based

on a visual interpretation of aerial photography and imagery in combination with ground truth data (Bauer et al., 2012; Kendall et al., 2001). The 2001 NOAA Benthic Habitat Map (Kendall et al., 2001) may be considered the baseline reference for seagrass cover maps in Puerto Rico and its multiple surrounding satellite islands.

One of those islands is the Caja de Muertos Island, an island off the south coast of Puerto Rico with a varied benthic seascape. Research in this Nature Reserve have been mainly focused on coral reefs (Garcia-Sais et al., 2015) while only some aspects and areas of the seagrass community in the Reserve were studied by Vicente (2008) and Otero et al. (2014). As the rest of Puerto Rico, Caja de Muertos Island does not have an ongoing seagrass monitoring program to study seagrass status and responses to natural and/or anthropogenic threats. In the absence of long-term monitoring data, aerial photography can be an alternative way to evaluate seagrass distribution and temporal changes in seagrass cover (Kendrick et al., 2002; Maccarrone, 2010; Moore et al., 2001). The combination of high spatial resolution, large spatial extent, and long temporal coverage makes historical aerial photographs the largest source of information available for research of long-term vegetation dynamics (Kadmon and Harari-Kremer, 1999).

The main goal of this study was to estimate long-term changes in seagrass habitat extent at the CMINR. This study was divided into two chapters. The first chapter is focus on the creation of an accurate and current seagrass benthic habitat map for Caja de Muertos Island, while the second chapter aimed to reconstruct the historic distribution of seagrass at the study area.

Chapter I – A hybrid approach for mapping seagrass in a Caribbean Nature Reserve

Abstract

Given the magnitude of reported cases of seagrass loss worldwide, continue adaptive management is crucial for the long term persistence of seagrass ecosystems. Remote sensing techniques have become an innovative tool for mapping and monitoring shallow benthic habitats such as seagrasses, providing information for their management and conservation. This study provides a high resolution characterization of the seagrass communities and other benthic habitats of Caja de Muertos Island Nature Reserve in Puerto Rico by integrating a combination of mapping techniques. A supervised classification and a manual reclassification was performed on derived seafloor reflectance and bathymetry data from a WorldView-2 satellite image which was used to conduct an object-based image analysis. A total of 164 sampling sites were used to calibrate and validate the map. The overall accuracy obtained was 82.76% and the total seagrass accuracy was 85.00%. Seagrass beds were found mainly in the West and North of the Island. The dominant seagrass species were *Thalassia testudinum* and *Syringodium filiforme*. Light availability was not a limiting factor for seagrass colonization at the study area. The final benthic habitat map represents the first high spatial resolution map for the Reserve which serves as a management tool and as a baseline characterization for further seagrass monitoring in the Reserve. This hybrid mapping approach represent and alternative method for mapping benthic habitats in complex environments.

1 Introduction

Seagrasses are some of the most valuable and productive shallow water ecosystems in the ocean (Zieman and Zieman, 1989). Seagrass habitats provide a number of important ecosystem services, such as nursery and feeding grounds for a diverse number of organisms, nutrient recycling, fisheries resources, sediments stabilization and carbon sequestration from the atmosphere (Zieman and Zieman, 1989; Costanza et al., 1997; Duarte, 2002; Orth et al., 2006; Waycott et al., 2009). Seagrass meadows are vulnerable to change and are subject to a wide range of natural and anthropogenic stressors such as extreme weather events, predation, mechanical damage, increased turbidity, and eutrophication, among others (Short and Wyllie-Echeverria, 1996; Duarte, 2002; Orth et al., 2006). These ecosystems are declining worldwide, with major losses caused by human actions which lead to sediment runoff and increased nutrients (Orth et al., 2006). Given the magnitude of seagrass loss, continued monitoring and adaptive management is crucial for the long term persistence of the seagrass ecosystem.

The distribution of seagrasses is determined by a series of physical factors such as temperature, light availability, currents and wave energy, type of substrate, salinity and turbidity (Gonzalez-Liboy, 1979; Miller and Lugo, 2009). The occurrence or absence of different seagrass species depend on each species unique adaptations and tolerances to variability in these factors. Because of the high requirements of seagrass for adequate amounts of light, they are particularly affected by changes that alter water clarity (Duarte, 2002; Orth et al., 2006).

In recent years, remote sensing techniques have become an innovative solution for researchers and managers to map and monitor shallow benthic habitats such as seagrass (Armstrong, 1993; Kendall et al., 2001; Moore *et al.*, 2001; Kendrick et al., 2002; Roelfsema et al., 2009; Maccarrone, 2010; Lyons *et al.*, 2011; Pu and Bell, 2013). As an example, NOAA generated one acre minimum

mapping unit (4,046 m²) benthic habitat maps for Puerto Rico based on visual interpretation of aerial photography and imagery in combination with ground truth data (Kendall et al., 2001; Bauer et al., 2012). The 2001 NOAA Benthic Habitat Map (Kendall et al., 2001) could be considered the baseline reference for seagrass cover maps in Puerto Rico and adjacent islands.

One of those islands is Caja de Muertos Island Nature Reserve (CMINR), an island off the south coast of Puerto Rico with a varied benthic seascape. The research presented here is the first part of a larger analysis to assess long-term changes (1950-2014) in seagrasses cover within the CMINR. The objective of this paper is to provide updated, high-spatial resolution information on the benthic communities in the CMINR with an emphasis on seagrass habitats while integrating a combination of benthic mapping techniques.

2 Methodology

2.1 Study Area

The Caja de Muertos Island Nature Reserve (CMINR) contains approximately 57 km² of protected land and water area. The CMINR is composed of Caja de Muertos Island, Cayo Morillito and Cayo Berbería in the Caribbean Sea south of Puerto Rico (Fig. 1). However, in this study only Caja de Muertos Island and Cayo Morillito were considered because they are the only areas in the reserve with a historical aerial photographic record from 1950 to 2014. The boundary of the study area was delimited by two factors; a maximum depth of 12 m or 1 km of maximum distance from the coast, whichever came first.

Caja de Muertos Island is located at latitude 17°53'35.57" North and longitude 66°31'14.96" West, and is approximately 2.75 km long and 0.85 km wide, at its widest point. It is oriented

approximately at a 45-degree angle from its southernmost tip on the southwest towards the northeast. The west side is protected from the dominant incoming wind and wave energy direction from the East and Southeast. In this area, depth increases with distance from coast, and a steep drop off is encountered at approximately 250 m from the coast in its nearest point. The slope is gentler in the South and Southeast of the island. In the northeast, a reef lagoon encloses a shallow (0 to 3 m) seagrass meadow. In general, differences in bathymetry and geophysical characteristics create a heterogeneous seascape composed of coral reefs, seagrass, macroalgae, and hard and sandy bottoms (Garcia-Sais et al., 2001).

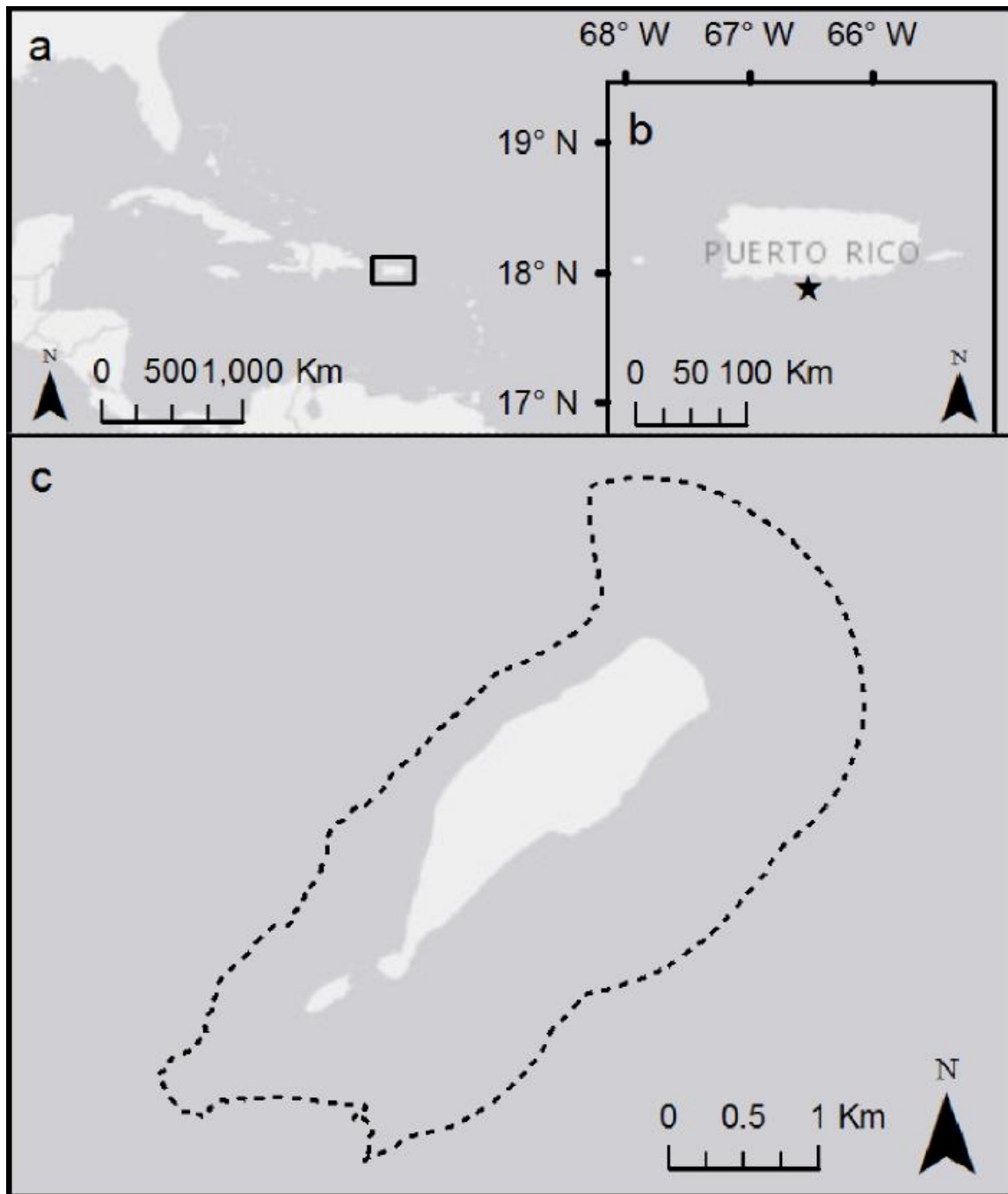


Fig. 1 Study area in CMINR: (a) Caribbean Sea and Puerto Rico (black rectangle); (b) Puerto Rico and Caja de Muertos Island (black star); (c) Caja de Muertos Island and the study area boundary (dashed line). Basemap credits: Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.

The climatology of Puerto Rico is characterized by a dry season from December through April and a rainy season from May through November (Glynn, 1973). The South coast of Puerto Rico

receives significantly less annual precipitation than the North (Miller and Lugo, 2009). Since Caja de Muertos Island is located 8.3 km off the south coast of Puerto Rico, the influence of land-based sources of sediments is minimum and clear water conditions predominate year round.

These conditions make Caja de Muertos Island a popular recreational area for visitors that access the island by ferry or private boats. The Puerto Rico Department of Natural and Environmental Resources (DNER) manages the island for recreation and conservation purposes. For example, the DNER maintains a number of mooring buoys to prevent anchor damage to seagrass and other habitats. Public access to Morillito Key or the beach on the south of Caja de Muertos is not allowed to avoid disturbance to seabird and sea turtle nesting areas, respectively. In addition, the DNER designated a no take zone in 2010 in the northeast part of the Island, an area that can only be used with DNER permits for snorkeling or research purposes. Private boat visitors usually tie-up to a mooring buoy or anchor in the West and Northwest areas of the island.

2.2 Image Data Acquisition and Pre-Processing

An October 16, 2014 multispectral image from the WorldView-2 (WV-2) sensor was acquired for Caja de Muertos Island (Image ID: 103001003868A000). This image consisted of one panchromatic band and eight multispectral bands of 0.5 m and 2 m of spatial resolution, respectively.

Image pre-processing steps were performed by EOMAP (EOMAP GmbH & Ko.KG) using the Modular Inversion and Processing System (MIP) proprietary software package (Heege, 2000; Heege et al., 2004; Kiselev et al., 2015). These modules were applied to correct the satellite sensor

noise, atmospheric effects, effect of adjacent land reflectance, turbidity, tidal influence and water column thickness. The retrieval of the atmospheric optical thickness and water column constituents was conducted by minimizing the mean square difference between the modeled top-of-atmosphere radiances and the radiances measured for all sensor channels (Heege et al., 2009). The WATCOR module was used for water depth and seafloor determinations (Heege et al., 2004; Pinnel, 2007). The equations published by Albert and Mobley (2003) were the basis for transforming the subsurface reflectance to sea floor albedo. Additional details on the processing steps and algorithms used can be obtained from Heege (2000), Albert and Mobley (2003), Heege et al. (2004; 2009), Pinnel (2007), Siermann et al. (2014) and Kiselev et al. (2015). The final products delivered by EOMAP included the bathymetry and seafloor reflectance products for the WV-2 image of Caja de Muertos Island.

2.3 Field Data Acquisition and Analysis

During March and June 2015, benthic habitat types were verified using 127 sampling sites in the study area. A Trimble® Juno 3D Global Positioning System (GPS) was used for navigation to sampling locations and the recording of geographic coordinates of each sampling site. An on-board submersible high definition video camera (Delta Vision HD camera) was used for recording a 10 second video of the benthos at each site. While the video was being recorded, 10 seconds of geographic coordinates were recorded and averaged by the Juno GPS, except during the June sampling, when GPS coordinates were recorded using a Garmin GPS 72. The shallow back reef at the northeast end of the island had to be surveyed using snorkeling gear and a Nikon Coolpix AW110 digital camera. Vertical spectral profiles of downwelling irradiance were measured using

a Satlantic HyperPro spectroradiometer and used to calculate spectral attenuation coefficients (K_d) at WV-2 wavelengths including $K_{d\text{ PAR}}$ (photosynthetic available radiation) at two sites on the North and West of the island (Fig. 2). The optical depth was calculated as $1/K_d$.²⁷ $K_{d\text{ PAR}}$ was used to calculate the depth of the 10% of surface light as $2.3/K_{d\text{ PAR}}$ (Kirk, 2011).

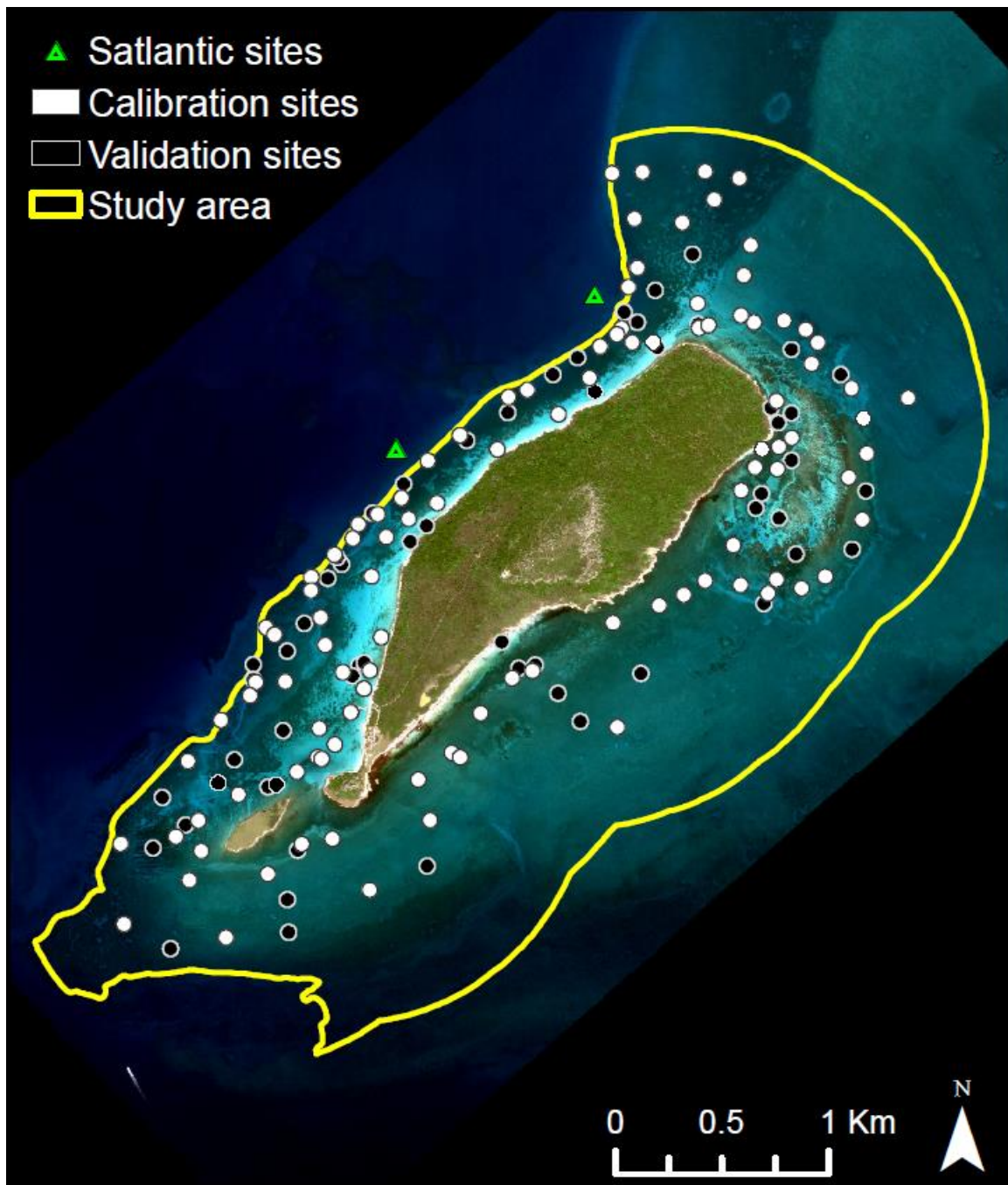


Fig. 2 Sites visited in the study area for calibrating and validating the benthic habitat map.

All sampling sites were assigned a benthic habitat classification category (Fig. 3). The seagrass percent cover categories were similar to categories used by Lyons et al. (2012), where sparse category represented habitats from 10 to 40 % cover, moderate from 40 to 70 %, and dense from 70 to 100%. Percent cover was determined by using a uniform grid of 36 points in each photo using Coral Point Count Excel V4.1 (Kohler and Gill, 2006).

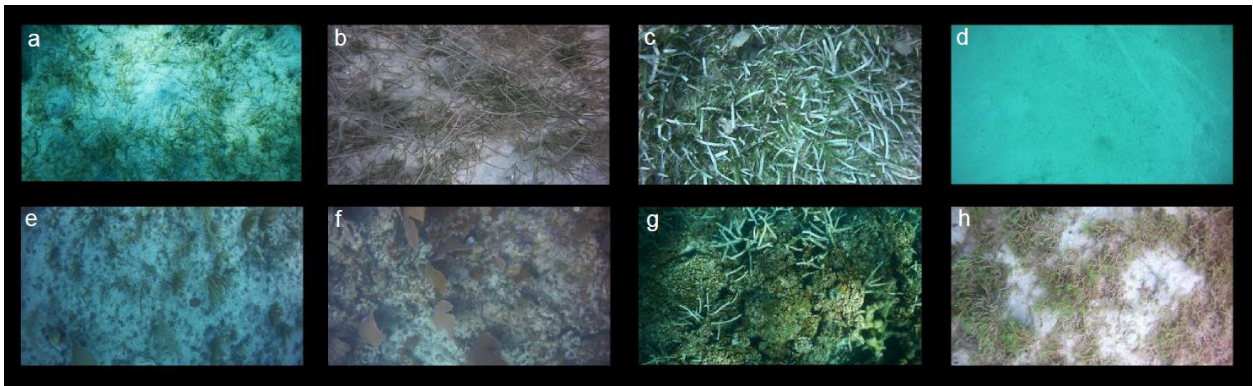


Fig. 3 Snapshots taken from videos at the study area showing the benthic habitat categories used for this study: (a) sparse seagrass (10-40%), (b) moderate seagrass (40-70%), (c) dense seagrass (70-100%), (d) sand, (e) sparsely colonized hardbottom (10-40%), (f) moderately colonized hardbottom (40-70%), (g) densely colonized hardbottom (70-100%), and (h) macroalgae.

A total of 164 sampling sites were designated either for calibration or validation of the benthic habitat map (Fig. 2). Following Roelfsema et al. (2014), approximately two thirds of each benthic habitat category were designated for calibration and one third for validation. Due to the few number of sites, an exception was made for the sparse seagrass cover category in which all sites were assigned to calibration. Additional sites were included based on the author's knowledge of the study area to increase the number of sites for categories with low numbers and/or in other areas to improve the classification results. The new sites were randomly assigned either to calibration or validation as needed. The total of 106 calibration sites were used to train the image data to

conduct a supervised classification and the total 58 validation sites were used to assess the accuracy of the classification output.

2.4 Hybrid Classification Approach

The seafloor reflectance image data provided by EOMAP was processed using the multi resolution segmentation algorithm in eCognition Essentials 1.2 (Trimble®). The corrected WV-2 bands used for this purpose were the coastal, blue, green and the bathymetry data. The process of optimizing the parameters for the segmentation process is conducted as an iterative trial and error process (Lathrop et al., 2006). The selected scale, color/shape and smoothness/compactness weights were 20, 0.05 and 0.8, respectively. Afterwards, a series of thresholds classifications were used to differentiate between land, water, and sand. The calibration field data was used to create training samples for each habitat category. Objects that were not classified in the threshold classification were subject to a supervised classification using the training objects and the coastal, blue and green bands. A final manual reclassification was conducted to visually reclassify objects that were not accurately classified based on the field data and the author's knowledge of the area.

2.5 Accuracy Assessment

The validation sites were used to evaluate the classification output. An error matrix was created to evaluate the classification accuracy of each benthic habitat category and to calculate the producer's and user's accuracy (Schowengerdt, 1983). The producer's accuracy or omission error, indicates the probability of a reference pixel being correctly classified in the map, while the user's

accuracy or commission error, indicates the probability that a pixel classified on the map indeed represents that category on the ground (Congalton, 1991).

Additionally, a reliability map was created for the entire study area to quantify the reliability level of each classified object based on a ratio of sampling sites per object area and author's expert knowledge (modified from Roelfsema et al., 2013). A ratio of sampling sites per object area was calculated and a weighted value between 1 and 3 was assigned for each object, where the value of 3 represented objects that were better represented by the sampling sites. This procedure was done to account for size differences between each object area. The same concept was applied for the expert knowledge criterion, given the authors confidence to assign a benthic category to a particular object. This expert criterion was also assigned to a weighted value between 1 and 3, with 3 being the most confident value. The following equation was used to calculate reliability level: ratio of sampling sites per object area + author's expert knowledge = estimated reliability level. A reliability level between 1 and 2 is considered low, 3 is medium and 4 to 6 high.

3 Results and Discussion

3.1 Benthic Habitat Map

The study area covered 7.56 km² of benthic habitat around the CMINR. Figure 4 displays the spatial distribution of seagrass and other benthic habitats within the study area. Areas covered by each benthic habitat category are shown in Table 1. The three seagrass categories accounted for the second most abundant benthic habitat, covering 1.49 km² (19.67%) of the study area. The species of seagrass found within the study area were *Thalassia testudinum*, *Syringodium filiforme*

and *Halodule wrightii*, sometimes occurring by themselves, intermixed, or co-occurring with macroalgae (Fig. 5).

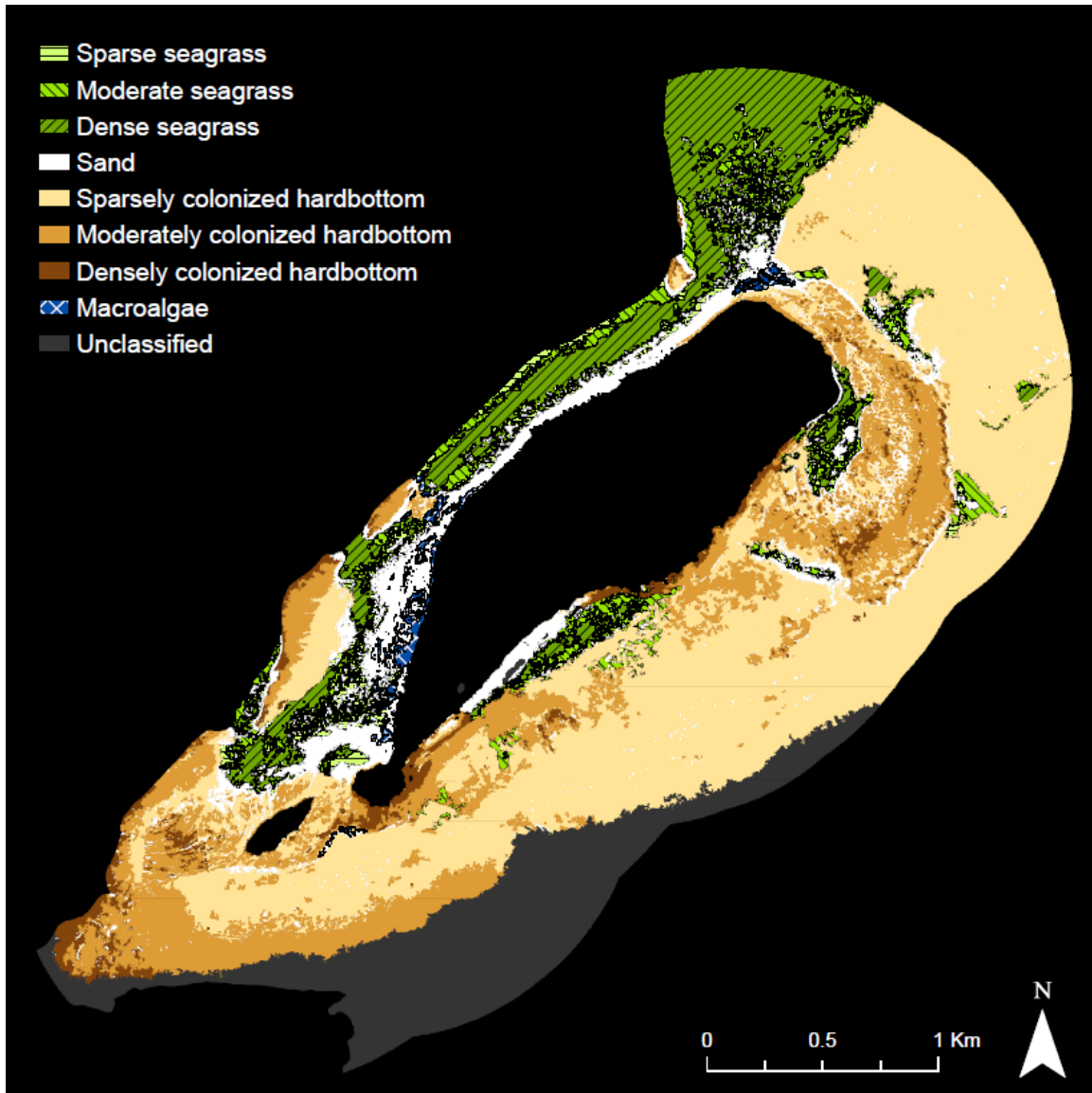


Fig. 4 Benthic habitat categories mapped at the CMINR study area.

Table 1 Area of each benthic habitat category within the study area.

Benthic Habitat Category	Area (km²)	Percent (%)	Percent of Seagrass (%)
Sparse Seagrass (10-40%)	0.2561	3.39	17.23
Moderate Seagrass (40-70%)	0.4009	5.31	26.98
Dense Seagrass (70-100%)	0.8290	10.97	55.79
Sparsely Colonized Hardbottom (10-40%)	3.2924	43.57	
Moderately Colonized Hardbottom (40-70%)	1.0594	14.02	
Densely Colonized Hardbottom (70-100%)	0.2480	3.28	
Macroalgae	0.0616	0.82	
Sand	0.5173	6.85	
Unclassified	0.8914	11.80	
Total	7.5561	100	100

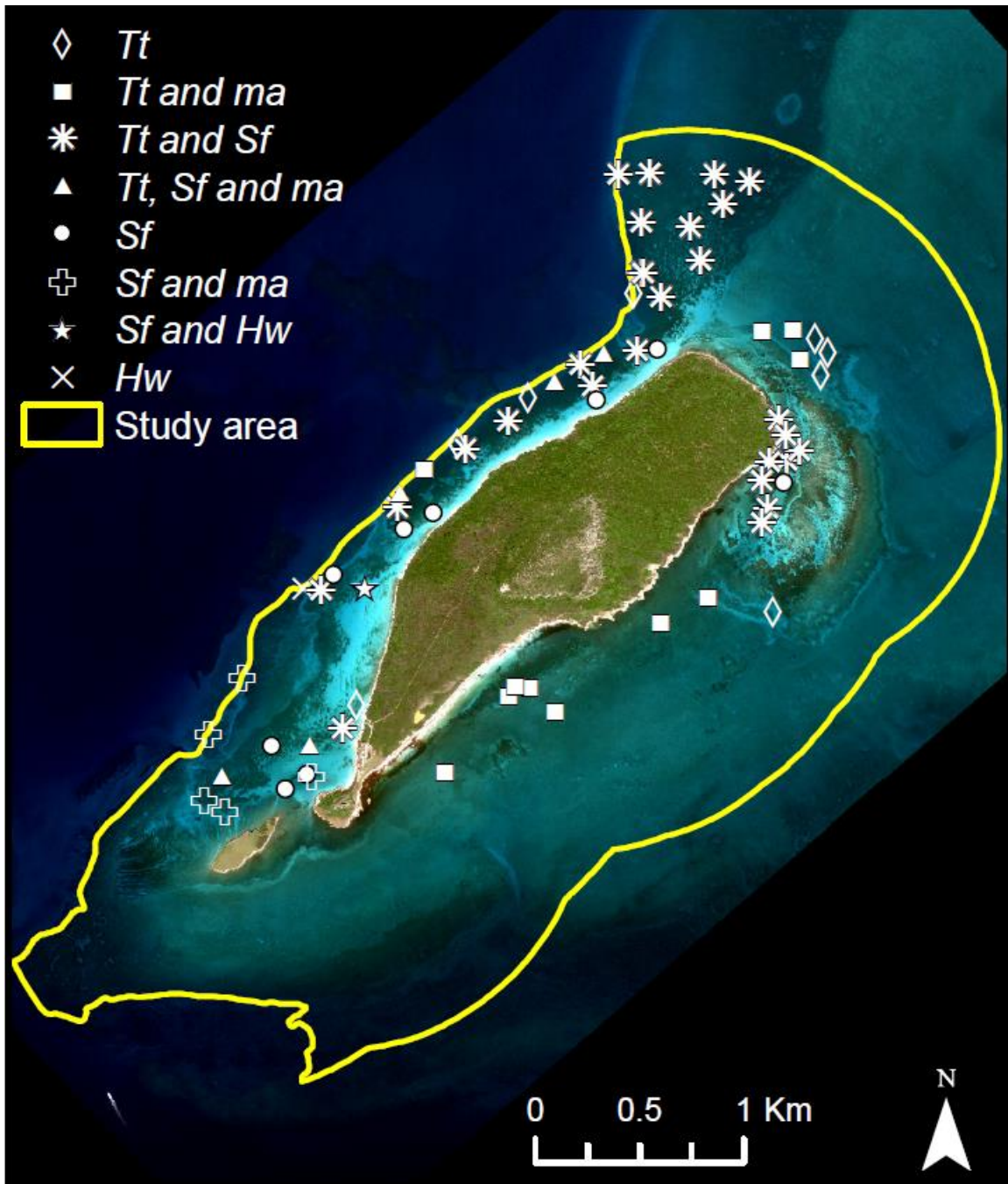


Fig. 5 Seagrass species identified in each sampling site. *Tt* = *T. testudinum*; *Sf* = *S. filiforme*; *Hw* = *H. wrightii*; *ma* = macroalgae.

The dense seagrass category represented 55.79% of the total seagrass area and mainly occurred in the North and West of Caja de Muertos Island. Seagrass beds in this area are mainly composed of *T. testudinum* mixed with *S. filiforme*. Although, *T. testudinum* has been known to be a climax

species (Creed et al., 2003), the co-existence of more seagrass species in a Caribbean *T. testudinum* community may be caused by niche partitioning when the community comes closer to its climax state (Williams, 1990). This may be the case for dense seagrass communities in the West and some areas in the North within the study area. The same applies to dense seagrass found on the Northeast reef lagoon, where all dense seagrass calibration sites showed a co-existence of *T. testudinum* and *S. filiforme*. These Northeast and West areas are more sheltered from the incoming wave energy, thus may be less subject to burial and sediment removal that could alter its stability. However, Duarte et al. (1997) showed that disturbances are needed for the occurrence of mixed meadows in the Philippines, disturbances that can be at the scale and magnitude of the ones caused by burrowing shrimps. On the other hand, dense seagrass was also found, although in less extent, in other areas unprotected from the incoming wave energy around Caja de Muertos Island and composed of monospecific stands of *T. testudinum* based on the sampling sites. This species can form dense rhizomes (Creed et al., 2003) and showed to be almost undamaged by burial and sediment removal in the experimental manipulations conducted by Cruz-Palacios and van Tussenbroek, (2005).

The presence of “blow-outs” are evident in the North part of Caja de Muertos Island. “Blow-outs” have been reported in other areas in Puerto Rico related to intense periods of wave energy, causing significant losses of seagrass (Gonzalez-Liboy, 1979; Rodriguez et al., 1994). In the study area, “blow-outs” were found in shallow areas more vulnerable to the effect of strong wave action during extreme weather events. In this study, these areas can be identified within dense seagrass meadows interrupted by small rounded areas with moderate and/or sparse seagrass and/or sand.

Moderate and sparse seagrass categories were found in the transitions zones between seagrass beds and other habitats, and within “blow-outs”. The moderate seagrass category was mainly

composed of monospecific stands of *T. testudinum* in combination with benthic macroalgae. This contrasts with the previously discussed dense seagrass category which was mainly composed of *T. testudinum* and *S. filiforme*. Almost all sparse seagrass category sites were composed of *S. filiforme* either as monospecific stands or coexisting with *T. testudinum* or *H. wrightii*. The seagrasses *S. filiforme* and *H. wrightii* are known to be pioneer species (Williams, 1990) which can propagate and colonize areas faster than *T. testudinum* (Tomlinson, 1974). The delicate rhizomes and root system of *S. filiforme* makes it more susceptible to detachment than *T. testudinum* during disturbance events (Cruz-Palacios and van Tussenbroek, 2005). Thus, areas dominated by these fast-growing seagrass species may be an indication of areas more susceptible to periodical disturbances.

The total seagrass area mapped by Kendall et al. (2001) within the study area was 1.15 km² versus 1.49 km² mapped in the present study. The discrepancies between the NOAA Benthic Habitat Map (Kendall et al., 2001) and our map could be associated with seagrass spatial changes that occurred during the sampling period of 1999 and 2014. In addition, differences in the mapping techniques and the minimum mapping unit used can be important factors. For example, Kendall et al. (2001) classified seagrass into continuous or patchy with a minimum mapping unit of 1 acre (4,046.86 m²). The patchy category may overestimate seagrass area since it is also considering the sand between seagrass patches. It is expected that, since our map has a 4 m² spatial resolution, the discrimination of smaller patches of seagrass is more accurate, thus less seagrass is misclassified as other benthic habitat. Additionally, Kendall et al. (2001) used field data and visual interpretation in the map development while in the present study a hybrid approach was used, which combined field data, multi-resolution segmentations, a supervised classification and a visual interpretation.

However, since the NOAA product was validated at another site, a direct comparison with this study mapping method could not be done.

According to Lathrop et al. (2006), sand and macroalgae could be classified as potential seagrass habitat. However, sandy areas exposed to high wave energy are not favorable for seagrass bed development (Miller and Lugo, 2009). In the study area, sand and mixed algae, mainly composed by the green algae *Cymopolia barbata*, represented 6.85% and 0.82 %, respectively (Table 1). Some of these areas can potentially be colonized by seagrass. Further studies would be needed to analyze the suitability of those habitats to seagrass colonization.

Sparsely colonized hardbottom covered most of the study area, representing 43.57% of the total area (Table 1). Similar results were found by Kendall et al. (2001). This category was mainly distributed in areas of high wave energy (East) and was mostly composed of a combination of benthic organisms such as soft corals, sponges and different algae species. The moderately and densely colonized hardbottom categories were also present in areas exposed to wave action. *T. testudinum* was present at some of these sites by less than 10% cover. The moderately and densely colonized hardbottom categories were also composed of mixed benthic habitat including coral reefs present up to 12 m depth. As an example, a coral reef monitoring site from the Puerto Rico Coral Reef Monitoring Program is located within the study area in an area classified by this study as moderately and densely colonized hardbottom (García-Sais et al., 2015). Indeed, these authors reported an average biotic percent cover of 75.36% attributed to the presence of stony corals, soft corals, sponges, benthic algae and cyanobacteria.

3.2 Light Penetration

The vertical attenuation coefficient measured at two sites in the study area were averaged and analyzed to determine the maximum light penetration for the different wavelengths of the WV-2 image (Table 2). The optical depths relevant to primary production are those equivalent to the attenuation of downward irradiance to 10% and 1%, corresponding to the mid-point and lower limit of the euphotic zone, respectively (Kirk, 2011). Duarte (1991) found that on average the depth limit of seagrass colonization is where the irradiance reaches 10.8% of the surface irradiance. The results of this study show that the 10% of light reach 21.69 meters, suggesting that light penetration is not a limiting factor for seagrass distribution in these clear oligotrophic waters. The coastal, blue and green bands had the highest optical depths of all the visible bands covering the depth range of the study area (0 – 12 m) (Table 2). For this reason, these bands were used for the object-based image analysis.

Table 2 Ecologically significant depths calculated by the field-measured K_d values.

Band Number	Band Center (nm)	K_d (m^{-1})	Optical Depth (m)
Coastal	425	0.0728	13.7279
Blue	480	0.0555	18.0164
Green	545	0.0811	12.3362
Yellow	605	0.2859	3.4975
Red	660	0.4070	2.4572

3.3 Management Implications

The west side of Caja de Muertos Island, which contains most of the seagrass cover from the study area, is also the most frequented area by visitors. Although an increase on the number of

registered boats in Puerto Rico has been reported (Ortiz, 2012), in comparison with other highly visited areas, the distance from the main island of Puerto Rico makes Caja de Muertos Island less vulnerable to intense boating activity. Additionally, excluding the shallow seagrass bed within the reef lagoon in the Northeast, which requires a permit to enter by boat, the seagrass beds in the West site are deep enough to prevent propeller scarring which were not observed during the field work. On the other hand, in order to minimize anchor damage to benthic habitats in the West and Northeast of the island, the DNER has installed and maintains mooring buoys. If an increase in anchoring is threatening seagrasses, the results of this map can help identify suitable areas for installing additional mooring buoys.

3.4 Accuracy Assessment

The combination of the mapping techniques used resulted in an overall accuracy of 82.76% and a seagrass overall accuracy of 85.00% for the CMINR study site. When compared with other studies, these values are within acceptable accuracy values for benthic habitat mapping. Kendall et al. (2001) reported an acceptable overall accuracy of 93.60% for one particular area in La Parguera, southwestern Puerto Rico. Although these authors suggested that other areas with similar conditions to La Parguera would also be mapped with comparable accuracies, this could potentially lead to misinterpretation of certain benthic habitat categories outside of La Parguera (e.g. Caja de Muertos Island). In contrast to Kendall et al. (2001), Hernández-López (2015) obtained a lower overall accuracy of 64.81%, but a 75.00% seagrass accuracy using an ISODATA classification of a WV-2 image also from La Parguera.

A small percentage of some categories were misclassified. These errors were calculated through user and producer accuracy analysis and illustrated on Figure 6. The densely colonized hardbottom category had the lowest producer accuracy over all the habitat categories. This was attributed to confusion with the sparsely colonized hardbottom and maybe to the fact that only three validation sites were available for the densely colonized hardbottom category. As expected, the sand category was accurately mapped having zero omission error. Moderate and dense seagrass categories had a producer accuracy of 80.00% and 86.67%, respectively. These errors were attributed to confusions with other seagrass categories, which can be expected from mapping continuous habitat into discrete categories, because areas close to the category boundary have a higher probability of being misclassified (Lyons et al., 2011). Regarding, the user accuracy, dense seagrass, densely colonized hardbottom and macroalgae categories had 100% probability of being represented as such categories on the map. The user accuracy for the moderate seagrass category was the lowest for the overall classification. The cause of the commission error in this category was attributed to misclassification with dense seagrass category. However, absence of validation sites for the sparse seagrass category and the limited number of validation sites for some other categories was a limiting factor in the classification accuracy. These limitations unable us to rely on the accuracy of some categories from this map based only on the results of the error matrix.

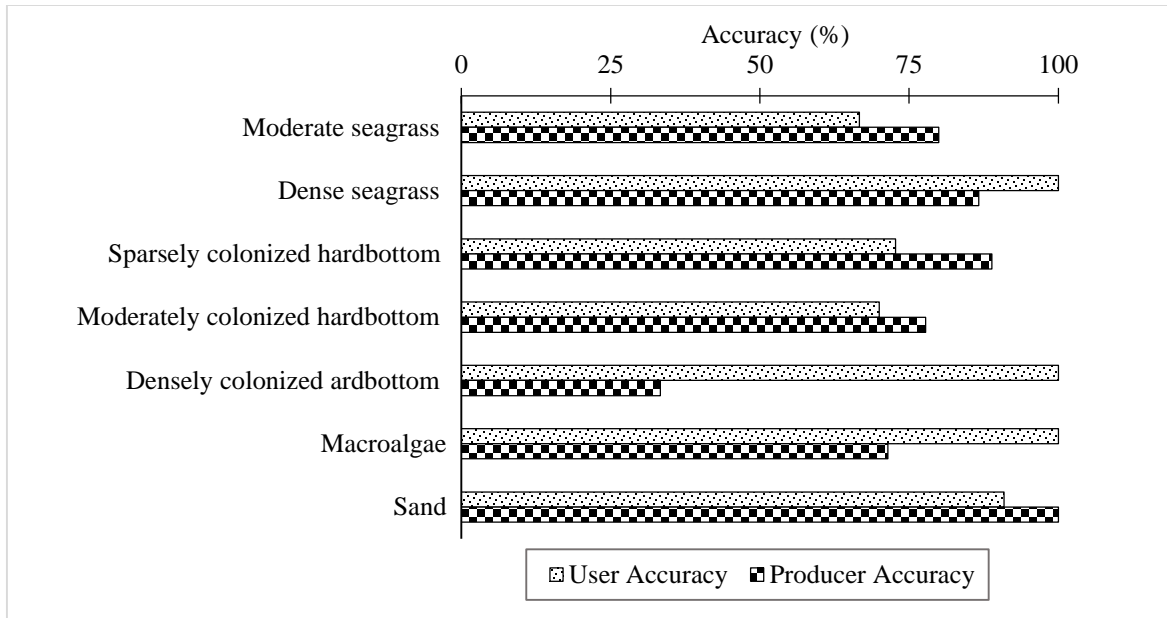


Fig. 6 User's and producer's accuracy derived from the error matrix created.

Given these limitations, a reliability analysis was conducted in order to further assess map accuracy. Figure 7 shows the level of reliability based in a ratio of sampling sites per object area and author's expert knowledge for each object classified in the map. Since the optical depth of the coastal, blue and green bands used for the object-based image analysis were deeper than the 12 m study area boundary, a depth criterion was not included in the reliability map. The dominant reliability level was medium, with 3.5946 km², representing 53.93% of the total area, followed by high (23.45%) and low (22.61%) (Table 3). However, when looking only at seagrass categories, 52.97% of total seagrass had a reliability level high, followed by medium (31.78%) and low (15.25%) (Table 3). Many seagrass areas were well known by the authors (expert knowledge), while some other areas were not. If areas lacking expert knowledge also had a low number of validation sites, they ended with a lower reliability level. An increase in the number of validation sites could increase the reliability level of seagrass objects classified as low or medium. The

comparison of the benthic habitat map with the reliability map enables a more reliable examination of the data in the context of possible errors in the classification.

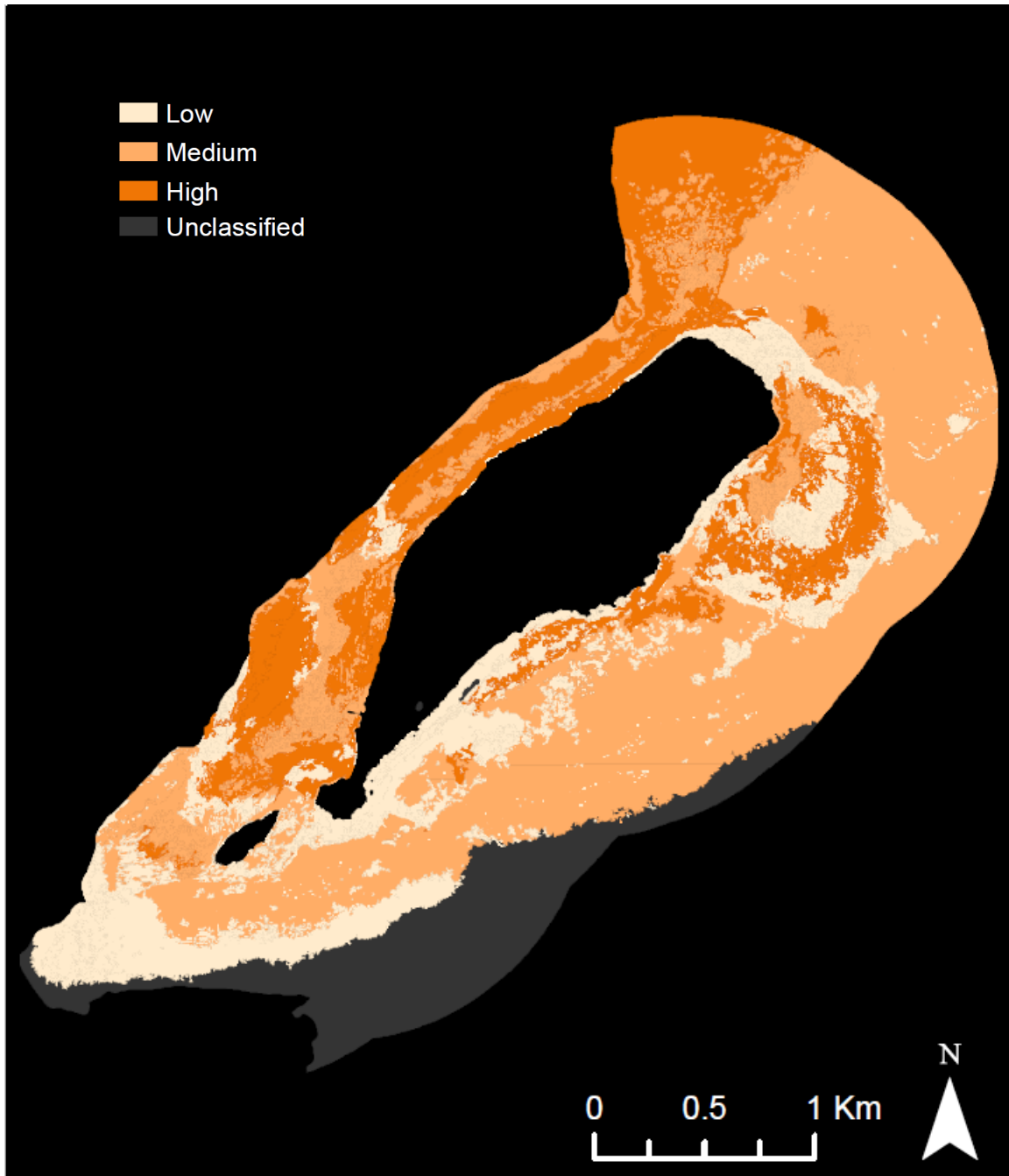


Fig. 7 Mapped reliability for the benthic habitat map of CMINR study area.

Table 3 Total benthic habitat and seagrass area covered by each reliability level in the study area.

Reliability level	Total (km²)	Percent (%)
Total Benthic Habitats Area		
Low	1.5070	22.61
Medium	3.5946	53.93
High	1.5631	23.45
Total	6.6647	100
Total Seagrass Area		
Low	0.2266	15.25
Medium	0.4722	31.78
High	0.7872	52.97
Total	1.4860	100

4 Conclusions

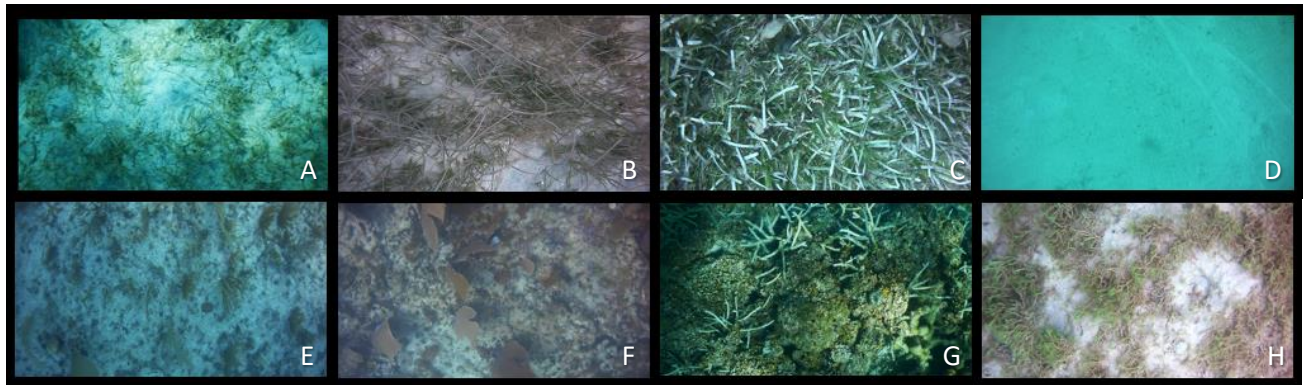
Seagrasses and other benthic habitats in the study area were accurately mapped (82.76% overall accuracy) using a high-spatial resolution (2 m) multispectral satellite image and a hybrid mapping approach. The majority of seagrass beds were found in the West and North of Caja de Muertos Island. The dominant seagrass species were *T. testudinum* and *S. filiforme*, which were found intermixed at several sites. Light availability was not a limiting factor for seagrass colonization at the study area. Periods of strong wave energy may be of more importance in regulating seagrass distribution, as it was evident in North Caja de Muertos Island where the presence of “blow-outs” were identified. It appears that seagrass beds in the study area are more subject to the influence of storm surges than impacts of boating activities or other anthropogenic threats.

This map represents the first high spatial resolution benthic habitat map for CMINR. Together with the reliability map created, the benthic habitat map can be use by researchers and managers to further study and monitor seagrass dynamics within the reserve.

The hybrid mapping method used represents an alternative for including expert knowledge in the benthic map development and in its accuracy assessment. The addition of expert knowledge during the manual reclassification could compensate for possible mapping limitations that can be present in turbid areas. The reliability map added a confidence level to the mapping product by providing the managers and users another metric for evaluating the map accuracy. Therefore, this approach could facilitate participatory mapping, which includes the input of the local community in the map development.

Appendix A: Classification scheme description

The classification scheme was composed of eight classes which refers to the main benthic habitats that could be mapped using the methodology described in the methods section of chapter I. Seagrass and colonized hardbottom were subdivided in different percent cover categories. The software Coral Point Count Excel V4.1 (Kohler and Gill, 2006) was used to assess 36 points (grid) in each photo or snapshot to determine percent cover.



A, B and C: Seagrass

Areas dominated by a single species of seagrass (e.g., *Thalassia testudinum*, *Syringodium filiforme* or *Halodule* sp.) or a combination of various species. Substrate may be composed of sand, mud or hardbottom. Three different percent cover classes were mapped.

Class	Percent cover
Sparse seagrass	between 10-40%
Moderate seagrass	between 40-70%
Dense seagrass	between 70-100%

D: Sand

Unconsolidated sediments with no biotic coverage.

E, F and G: Colonized hardbottom

Consist of consolidated grounds either covered by turf algae, sponges and corals or a combination of them. Three different percent cover classes were mapped.

Class	Percent cover
Sparsely colonized hardbottom	between 10-40%
Moderately colonized hardbottom	between 40-70%
Densely colonized hardbottom	between 70-100%

H: Macroalgae

Primarily bottoms of sand colonized by the green algae *Cymopolia barbata* and/or different species of green, red or brown algae.

Appendix B: Calibration and validation sites.

Calibration Sites			
ID	Latitud (N)	Longitud (W)	Classification Category
1	17.8984	-66.5094	Moderate seagrass
2	17.8983	-66.5102	Dense seagrass
3	17.8975	-66.5105	Sparse seagrass
4	17.8974	-66.5095	Sparse seagrass
6	17.8988	-66.5089	Dense seagrass
8	17.9003	-66.5095	Moderately colonized hardbottom
13	17.8966	-66.5111	Sparsely colonized hardbottom
14	17.8942	-66.5115	Moderately colonized hardbottom
15	17.8914	-66.5298	Sparsely colonized hardbottom
16	17.9004	-66.5037	Moderately colonized hardbottom
17	17.9008	-66.5062	Sparsely colonized hardbottom
18	17.9019	-66.5079	Dense seagrass
20	17.9033	-66.5082	Dense seagrass
21	17.9037	-66.5105	Moderate seagrass
22	17.9040	-66.5110	Sparsely colonized hardbottom
23	17.9057	-66.5109	Sparsely colonized hardbottom
24	17.9069	-66.5106	Sparsely colonized hardbottom
25	17.9098	-66.5110	Dense seagrass
26	17.9101	-66.5125	Dense seagrass
27	17.9089	-66.5121	Dense seagrass
28	17.9101	-66.5153	Dense seagrass
29	17.9101	-66.5167	Dense seagrass
30	17.9081	-66.5157	Dense seagrass
31	17.9079	-66.5136	Dense seagrass
33	17.9045	-66.5129	Sand
34	17.9035	-66.5129	Macroalgae
37	17.9052	-66.5160	Sand
39	17.9035	-66.5163	Sparsely colonized hardbottom
40	17.9029	-66.5159	Dense seagrass
41	17.9029	-66.5149	Sparse seagrass
45	17.9014	-66.5178	Dense seagrass
47	17.8999	-66.5192	Sand
48	17.9009	-66.5205	Moderate seagrass
52	17.8984	-66.5219	Sand
55	17.8962	-66.5246	Sparse seagrass
56	17.8955	-66.5259	Moderate seagrass
58	17.8964	-66.5262	Dense seagrass
60	17.8948	-66.5269	Densely colonized hardbottom

61	17.8947	-66.5284	Moderately colonized hardbottom
63	17.8931	-66.5302	Sand
66	17.8931	-66.5276	Sparse seagrass
67	17.8902	-66.5296	Sparsely colonized hardbottom
68	17.8891	-66.5289	Macroalgae
70	17.8891	-66.5277	Macroalgae
71	17.8884	-66.5280	Sparse seagrass
72	17.8874	-66.5286	Dense seagrass
73	17.8867	-66.5300	Dense seagrass
74	17.8860	-66.5293	Sand
75	17.8855	-66.5300	Dense seagrass
76	17.8887	-66.5314	Sparsely colonized hardbottom
78	17.8910	-66.5323	Moderately colonized hardbottom
83	17.8849	-66.5310	Moderate seagrass
85	17.8840	-66.5336	Dense seagrass
87	17.8854	-66.5358	Moderately colonized hardbottom
89	17.8871	-66.5343	Dense seagrass
92	17.8829	-66.5354	Sparsely colonized hardbottom
93	17.8822	-66.5364	Moderately colonized hardbottom
95	17.8819	-66.5388	Sparsely colonized hardbottom
98	17.9037	-66.5091	Sparsely colonized hardbottom
99	17.9028	-66.5076	Moderate seagrass
101	17.8995	-66.5057	Moderately colonized hardbottom
102	17.8981	-66.5055	Densely colonized hardbottom
104	17.8953	-66.5058	Moderately colonized hardbottom
106	17.8929	-66.5075	Moderately colonized hardbottom
107	17.8924	-66.5085	Moderately colonized hardbottom
108	17.8922	-66.5100	Moderate seagrass
109	17.8926	-66.5112	Sparsely colonized hardbottom
110	17.8928	-66.5128	Moderate seagrass
111	17.8922	-66.5137	Moderately colonized hardbottom
112	17.8917	-66.5148	Moderately colonized hardbottom
113	17.8910	-66.5169	Moderately colonized hardbottom
115	17.8866	-66.5168	Sparsely colonized hardbottom
118	17.8890	-66.5205	Moderate seagrass
119	17.8887	-66.5214	Dense seagrass
120	17.8873	-66.5228	Moderately colonized hardbottom
121	17.8856	-66.5241	Moderate seagrass
122	17.8845	-66.5256	Sparsely colonized hardbottom
123	17.8828	-66.5251	Moderately colonized hardbottom
125	17.8799	-66.5278	Moderately colonized hardbottom
126	17.8820	-66.5294	Macroalgae

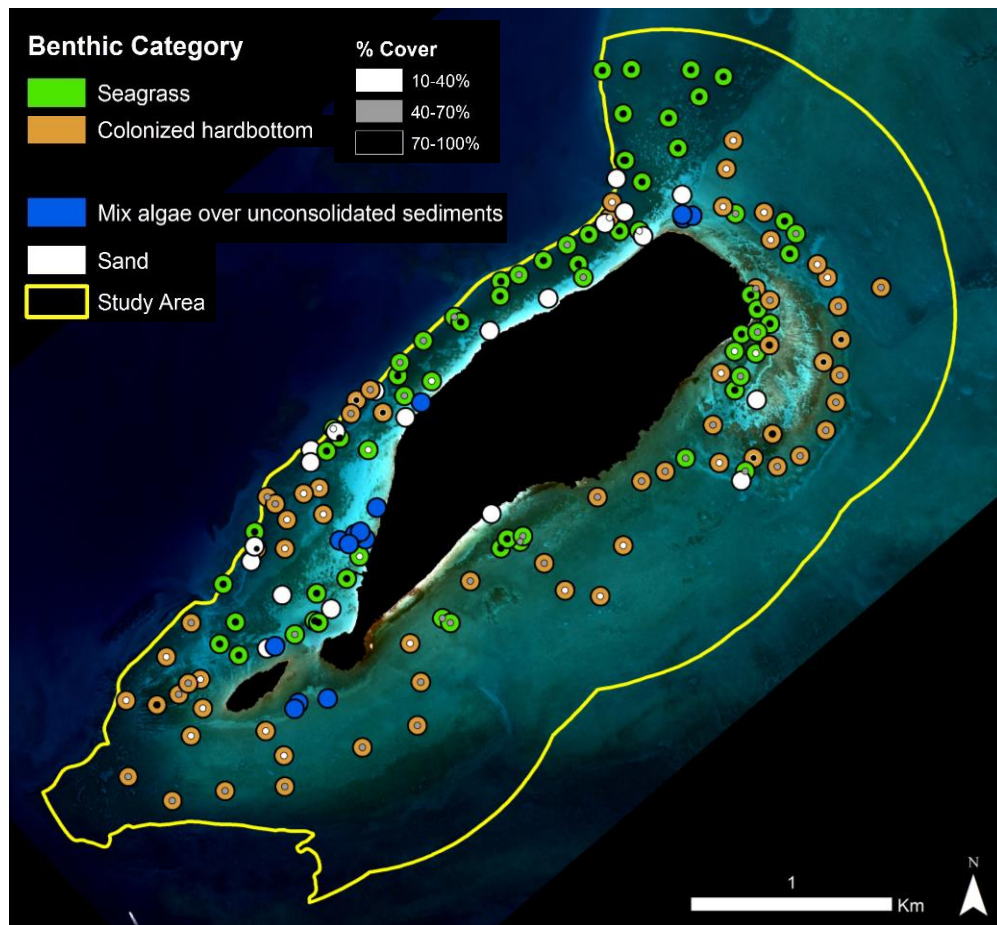
128	17.8806	-66.5323	Sparsely colonized hardbottom
130	17.8779	-66.5342	Moderately colonized hardbottom
132	17.8785	-66.5387	Moderately colonized hardbottom
133	17.8804	-66.5358	Sparsely colonized hardbottom
134	17.8816	-66.5353	Sparsely colonized hardbottom
137	17.8854	-66.5299	Dense seagrass
138	17.8887	-66.5327	Densely colonized hardbottom
140	17.8907	-66.5319	Moderately colonized hardbottom
142	17.8926	-66.5302	Sand
143	17.8941	-66.5292	Sparse seagrass
144	17.8953	-66.5281	Densely colonized hardbottom
145	17.8958	-66.5272	Sand
147	17.8980	-66.5250	Moderate seagrass
148	17.8991	-66.5236	Moderate seagrass
149	17.9006	-66.5214	Dense seagrass
151	17.9027	-66.5173	Dense seagrass
152	17.9060	-66.5156	Dense seagrass
154*	17.8928	-66.5096	Densely colonized hardbottom
155*	17.8970	-66.5064	Densely colonized hardbottom
157*	17.9032	-66.5165	Sand
158*	17.8881	-66.5330	Sand
166*	17.9036	-66.5125	Macroalgae
167*	17.8845	-66.5316	Macroalgae
168*	17.8818	-66.5308	Macroalgae
169*	17.8905	-66.5272	Macroalgae
174*	17.8854	-66.5237	Moderate seagrass

Validation Sites			
ID	Latitud (N)	Longitud (W)	Classification Category
5	17.8978	-66.5089	Densely colonized hardbottom
7	17.8998	-66.5089	Moderately colonized hardbottom
9	17.9000	-66.5098	Dense seagrass
10	17.8994	-66.5094	Dense seagrass
11	17.8964	-66.5102	40-70% Seagrass
12	17.8958	-66.5105	Dense seagrass
19	17.9025	-66.5088	Sparsely colonized hardbottom
32	17.9066	-66.5131	Dense seagrass
35	17.9051	-66.5148	Dense seagrass
36	17.9060	-66.5157	Dense seagrass
38	17.9042	-66.5162	Sparsely colonized hardbottom

44	17.9023	-66.5183	40-70% Seagrass
46	17.9008	-66.5175	40-70% Seagrass
51	17.9000	-66.5214	Dense seagrass
53	17.8988	-66.5233	Dense seagrass
57	17.8958	-66.5275	Moderately colonized hardbottom
59	17.8946	-66.5258	Sand
64	17.8931	-66.5295	Dense seagrass
65	17.8936	-66.5289	Dense seagrass
69	17.8894	-66.5282	Macroalgae
77	17.8900	-66.5313	Sparsely colonized hardbottom
82	17.8866	-66.5316	Sand
84	17.8843	-66.5323	Sand
86	17.8845	-66.5345	Dense seagrass
90	17.8854	-66.5337	Dense seagrass
91	17.8839	-66.5369	Sparsely colonized hardbottom
94	17.8817	-66.5374	Densely colonized hardbottom
97	17.8795	-66.5315	Sparsely colonized hardbottom
100	17.9014	-66.5067	Sparsely colonized hardbottom
103	17.8965	-66.5056	Moderately colonized hardbottom
105	17.8940	-66.5062	Moderately colonized hardbottom
114	17.8889	-66.5157	Sparsely colonized hardbottom
116	17.8869	-66.5184	Sparsely colonized hardbottom
117	17.8881	-66.5194	Moderately colonized hardbottom
124	17.8808	-66.5253	Moderately colonized hardbottom
127	17.8816	-66.5310	Macroalgae
129	17.8781	-66.5314	Moderately colonized hardbottom
131	17.8775	-66.5367	Moderately colonized hardbottom
135	17.8827	-66.5359	Moderately colonized hardbottom
136	17.8844	-66.5319	Macroalgae
139	17.8895	-66.5328	Dense seagrass
141	17.8912	-66.5306	Sparsely colonized hardbottom
146	17.8970	-66.5261	40-70% Seagrass
150	17.9016	-66.5194	Dense seagrass
153*	17.8938	-66.5087	Densely colonized hardbottom
156*	17.8892	-66.5211	Dense seagrass
159*	17.9037	-66.5156	Sand
160*	17.8939	-66.5291	Sand
161*	17.8954	-66.5095	Sand
162*	17.8903	-66.5218	Sand
163*	17.8888	-66.5329	Sand
164*	17.9027	-66.5148	Sand
165*	17.8918	-66.5102	Sand

170*	17.9036	-66.5129	Macroalgae
171*	17.8895	-66.5279	Macroalgae
172*	17.8889	-66.5285	Macroalgae
173*	17.8952	-66.5251	Macroalgae
175*	17.8893	-66.5203	Moderately colonized hardbottom

Appendix C: Benthic categories of each sampling site in the study area.



Appendix D: Error matrix showing the overall, user's and producer's accuracies of the benthic habitat map.

		Classification Data							TOTAL	PRODUCER'S ACCURACY	
		Sparse seagrass	Moderate seagrass	Dense seagrass	Sparsely colonized hardbottom	Moderately colonized hardbottom	Densely colonized hardbottom	Macroalgae			Sand
Validation Data	Sparse seagrass	0	0	0	0	0	0	0	0	0	0
	Moderate seagrass	1	4	0	0	0	0	0	0	5	80.00
	Dense seagrass	0	2	13	0	0	0	0	0	15	86.67
	Sparsely colonized hardbottom	0	0	0	8	1	0	0	0	9	88.89
	Moderately colonized hardbottom	0	0	0	2	7	0	0	0	9	77.78
	Densely colonized hardbottom	0	0	0	0	2	1	0	0	3	33.33
	Macroalgae	0	0	0	1	0	0	5	1	7	71.43
	Sand	0	0	0	0	0	0	0	10	10	100.00
	TOTAL	1	6	13	11	10	1	5	11	58	
USER'S ACCURACY		0	66.67	100.00	72.73	70.00	100.00	100.00	90.91		
OVERALL ACCURACY = 82.76% SEAGRASS ACCURACY = 85.00%											

Appendix E: Reliability level for each mapped category and for the seagrass categories.

Benthic Habitat Category	Reliability Level					
	Low		Medium		High	
	km ²	%	km ²	%	km ²	%
Sparse seagrass	0.06664	4.42	0.17439	4.85	0.01502	0.96
Moderate seagrass	0.10156	6.74	0.21354	5.94	0.08582	5.49
Dense seagrass	0.05841	3.88	0.08430	2.35	0.68632	43.91
Sparsely colonized hardbottom	0.22711	15.07	2.94630	81.97	0.11899	7.61
Moderately colonized hardbottom	0.67700	44.92	0.07386	2.05	0.30852	19.74
Densely colonized hardbottom	0.19116	12.68	0.02564	0.71	0.03121	2.00
Macroalgae	0.01381	0.92	0.02079	0.58	0.02704	1.73
Sand	0.17134	11.37	0.05575	1.55	0.29019	18.56
Total	1.50703	100	3.59457	100	1.56312	100

Seagrass Category	Reliability Level					
	Low		Medium		High	
	km ²	%	km ²	%	km ²	%
Sparse seagrass	0.06664	29.41	0.17439	36.93	0.01502	1.91
Moderate seagrass	0.10156	44.82	0.21354	45.22	0.08582	10.90
Dense seagrass	0.05841	25.78	0.08430	17.85	0.68632	87.19
Total	0.22661	100	0.47223	100	0.78716	100

Chapter II – Long-term changes in seagrass distribution using a high-spatial resolution satellite image, historic aerial photography and field data

Abstract

In a scenario of global climate change and increasing anthropogenic disturbances on seagrass ecosystems, it is urgent to assess temporal and spatial dynamics in seagrass beds. The objective of this study was to estimate long-term changes in seagrass extent in the Caja de Muertos Island Nature Reserve in Puerto Rico. An object-based image analysis and a visual interpretation were used to assess seagrass change using a recent high-spatial resolution satellite image and historical aerial photography from 1950 to 2014. Four zones with continuous data for the studied period were analyzed. A 64% overall increase in seagrass area was found, contrasting with the worldwide declining trend. This increase was mainly driven by an increase in the patchy seagrass cover, which was also the most persistent cover for the 64-year period. The temporal and spatial differences observed were mainly associated with natural factors. These data represent a baseline by which future seagrass changes can be compared. Thus, this study provides valuable information for the conservation and management of seagrass habitat in the Reserve.

1 Introduction

The seagrass habitat constitutes a highly productive and ecologically valuable marine community (Zieman and Zieman, 1989). They provide sediment stabilization and serve as nurseries and feeding grounds for a diverse number of organisms (Zieman and Zieman, 1989; Costanza et al., 1997; Duarte, 2002; Orth et al., 2006; Waycott et al., 2009). Past and present natural and anthropogenic factors have influenced the decline of seagrass areas worldwide (Short and Wyllie-Echeverria, 1996; Duarte, 2002; Orth et al., 2006).

In the Caribbean, and other tropical areas, hurricanes and tropical storms are a natural hazard for seagrass communities by causing sediment erosion and/or deposition on seagrass beds (Creed et al., 2003). Hurricane-related seagrass loss has been documented in Puerto Rico (Glynn et al., 1964; Gonzalez-Liboy, 1979; Rodriguez et al., 1994). Glynn et al. (1964) documented seagrass loss in La Parguera, Puerto Rico caused by Hurricane Edith in 1963. Rodriguez et al. (1994) documented the loss of tens of squares kilometers of seagrass meadows and the formation of “blow-outs” caused by hurricane Hugo in 1989. Both studies found that *Syringodium filiforme* was more affected than *Thalassia testudinum*. Seagrass species will respond differently to the impacts of burial or removal caused by an extreme weather event, in part because of each species particular adaptations to tolerate the disturbance (Duarte et al., 1997; Cruz-Palacios and Tussenbroek, 2005).

In addition, human-induced activities can have a detrimental effect on seagrass communities, as dredging and filling, effluents, propeller damage, nutrient enrichment, and sedimentation among others (Miller and Lugo, 2009). Major losses of seagrass habitats can result from anthropogenic effects which lead to increase sediment runoff and nutrients (Orth et al., 2006).

In-situ monitoring has been the main tool to assess spatial and temporal changes in seagrass communities (Vicente and Rivera, 1982; Prathep, 2003; McKenzie et al., 2003; 2014; van Tussenbroek et al., 2014). Remote sensing techniques have been effectively used by researchers and managers to map and monitor seagrass beds in shallow waters (Armstrong, 1981, 1993; Kendall et al., 2001; Moore et al., 2001; Kendrick et al., 2002; Roelfsema et al., 2009; Maccarrone, 2010; Lyons et al., 2011; Pu and Bell, 2013). However, the use of remote sensing data is dependent on the spatial and temporal availability of imagery (Uhrin and Townsend, 2016). In many areas, aerial photographs may represent the only available source of information for long-term analysis of seagrass habitat change.

In a scenario of global climate change and increasing anthropogenic disturbances, there is a need to establish a baseline reference of seagrass distribution in order to better understand seagrass dynamics at different temporal scales. In the absence of long-term monitoring programs in Puerto Rico, historical aerial photography represents the longest record of data for studying seagrass dynamics. This study aims to estimate the long-term spatial changes in seagrass distribution at Caja de Muertos Island Nature Reserve (CMINR), Puerto Rico.

2 Methodology

2.1 Study area

The Caja de Muertos Island Nature Reserve (CMINR) contains approximately 57 km² of protected land and water area. The CMINR is composed of Caja de Muertos Island, Cayo Morillito and Cayo Berbería in the Caribbean Sea south of Puerto Rico (Fig. 1). However, in this study only Caja de Muertos Island and Cayo Morillito were considered because they are the only areas in the

reserve with a historical aerial photographic record from 1950 to 2014. The boundary of the study area was delimited by two factors; a maximum depth of 12 m or 1 km of maximum distance from the coast, whichever came first.

Caja de Muertos Island is located at latitude 17°53'35.57" North and longitude 66°31'14.96" West, and is approximately 2.75 km long and 0.85 km wide, at its widest point. It is oriented approximately at a 45-degree angle from its southernmost tip on the southwest towards the northeast. The west side is protected from the dominant incoming wind and wave energy direction from the East and Southeast. In this area, depth increases with distance from coast, and a steep drop off is encountered at approximately 250 m from the coast in its nearest point. The slope is gentler in the South and Southeast of the island. In the northeast, a reef lagoon encloses a shallow (0 to 3 m) seagrass meadow. In general, differences in bathymetry and geophysical characteristics create a heterogeneous seascape composed of coral reefs, seagrass, macroalgae, and hard and sandy bottoms (Garcia-Sais et al., 2001).

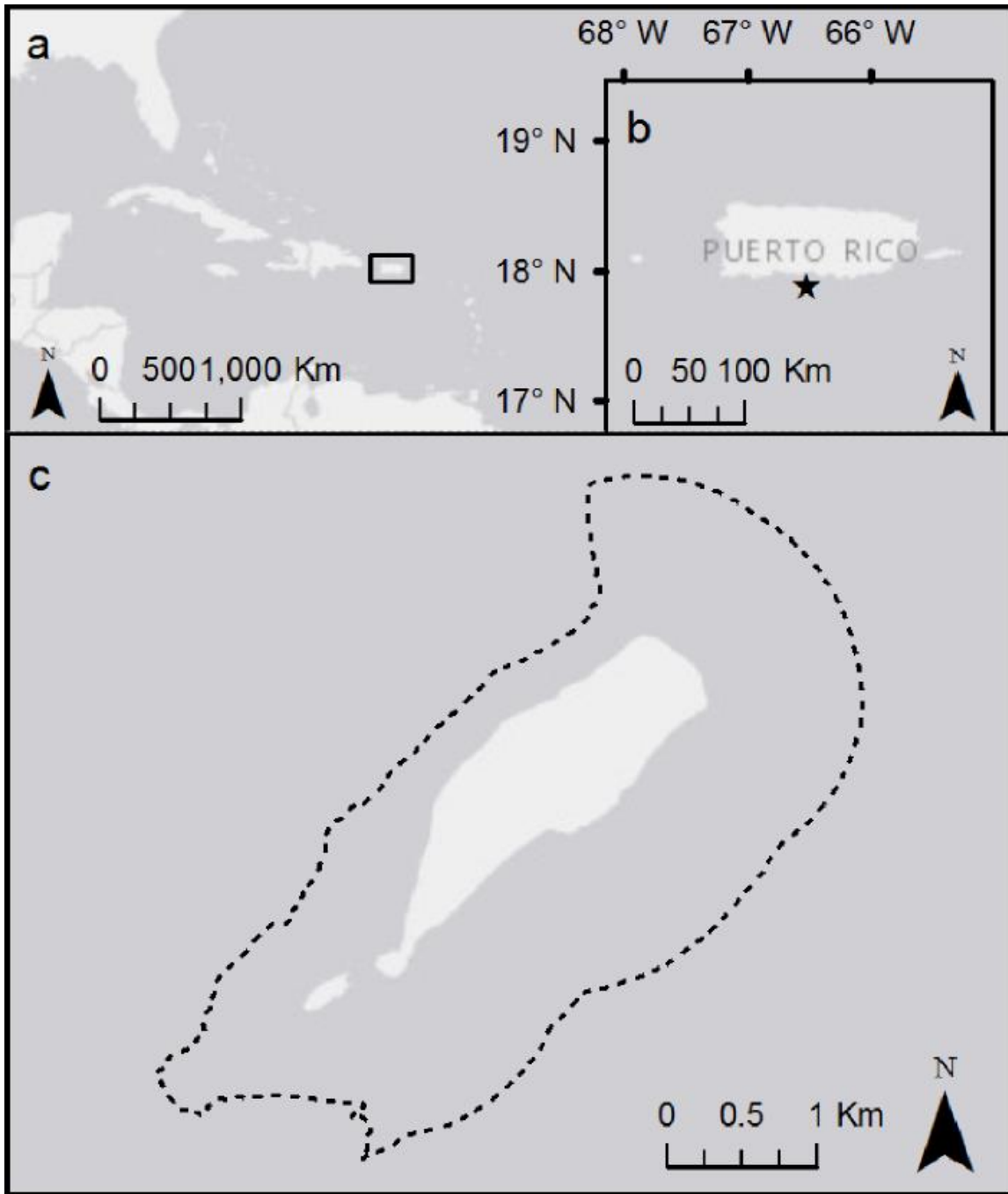


Fig. 1 Study area in CMINR: (a) Caribbean Sea and Puerto Rico (black rectangle); (b) Puerto Rico and Caja de Muertos Island (black star); (c) Caja de Muertos Island and the study area boundary (dashed line). Basemap credits: Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community.

The climatology of Puerto Rico is characterized by a dry season from December through April and a rainy season from May through November (Glynn, 1973). The South coast of Puerto Rico receives significantly less annual precipitation than the North (Miller and Lugo, 2009). Since Caja de Muertos Island is located 8.3 km off the south coast of Puerto Rico, the influence of land-based sources of sediments is minimum and clear water conditions predominate year round.

These conditions make Caja de Muertos Island a popular recreational area for visitors that access the island by ferry or private boats. The Puerto Rico Department of Natural and Environmental Resources (DNER) manages the island for recreation and conservation purposes. For example, the DNER maintains a number of mooring buoys to prevent anchor damage to seagrass and other habitats. Public access to Morillito Key or the beach on the south of Caja de Muertos is not allowed to avoid disturbance to seabird and sea turtle nesting areas, respectively. In addition, the DNER designated a no take zone in 2010 in the northeast part of the Island, an area that can only be used with DNER permits for snorkeling or research purposes. Private boat visitors usually tie-up to a mooring buoy or anchor in the West and Northwest areas of the island.

2.2 Image Acquisition and Pre-Processing

A total of 10 historical aerial photographs from CMINR were gathered from different sources, representing 8 years of historical data (Table 1). Aerial photographs used were from 1950 (2 photographs), 1967 (2 photographs), and yearly photos from 1977, 1993, 1999, 2004, 2007 and 2010. A WorldView-2 (WV-2) panchromatic satellite image from 2014 was also used. Photographs were preprocessed in ArcMap 10.1 (ArcGIS®). The pixel size was downscaled to a spatial scale of 1 meter, except for the 1999 photograph, which was rescaled from 2.4 m to 1m.

All photographs were then georeferenced to a projected coordinate system for Puerto Rico and the US Virgin Islands (NAD 1983 HARN State Plane Puerto Rico Virgin Islands FIPS 5200) similar to the WV-2 2014 panchromatic image. The root mean square error (RMS) was calculated for each georeferenced photo (Table 1). The RMS is a measure that indicates how consistent the transformation is between the control points used during the georeferencing process (ESRI, 2009). Photographs from 1950 and 1964 were mosaicked.

Table. 1 Historical record of imagery from Caja de Muertos Island.

Year	Date	Original Spatial Resolution (m)	Source	ID/Flight line	RMS error
1950	December 17	0.4	USGS	GS-LR-6 15	0.43
	December 17	0.4	USGS	GS-LR-6 17	0.37
1967	November 29	0.7	USGS	GS-VB UC 2-062	0.82
	November 29	0.7	USGS	GS-VB UC 2-063	
1977	February 17	1.0	N/A	77-2 B 119	0.96
	March 25	1.0		N/A	
1993	November 4	1.0	USDA	DI00000000848793	0.50
1999	February 9	2.4	N/A	PR 48-011	0.53
2004	September 27	1.0	USACE	1132669_1706661SE20040927	0.86
2007	Nov 1, 2006 to March 1, 2007	0.3	USACE	1139490_17066H516	0.88
2010	October 1, 2009 to January 31, 2010	0.3	USGS	2739050_PUERTORICO20100002	0.55
2014	October 16	0.5	Digital Globe	103001003868A000	N/A

2.3 Photointerpretation of Historic Aerial Photography

The WV-2 panchromatic band and the historical aerial photograph record were processed using the multi resolution segmentation algorithm in eCognition Essentials 1.2 (Trimble®). After an iterative trial and error process (Lathrop et al., 2006), a series of segmentation parameters were established to use for the entire historical record. The first one was a coarse segmentation (scale

100; color/shape 0.05; smoothness/compactness 0.4) to select objects containing seagrass. Next step was to re-segment into smaller objects (scale 35; color/shape 0.05; smoothness/compactness 0.4) to eliminate non seagrass areas. The final segmentation (scale 70; color/shape 0.05; smoothness/compactness 0.4) was used to further classify seagrass objects into continuous and patchy areas. This analysis was conducted in descending order, starting with the image of 2014 towards the oldest year (1950).

Visual interpretation for seagrass classification was conducted using black and white photographs (panchromatic in the case of the 2014 WV-2 image). The 2014 benthic map (Chapter I- Fig. 4) was used for classifying the 2014 seagrass areas. When possible, the 2014 true color image and color photographs from years before 2014, were used as a visual aid in areas where seagrass and macroalgae were difficult to differentiate. Areas where seagrass classification was confusing were not classified or further analyzed. In addition, some photographs did not contain raster information (no data) for some areas, thus preventing analysis for the entire study area. For these reasons, the assessment of the long-term changes in seagrass extent was only conducted within four zones (Fig. 2). These four zones were the only areas that contained continuous data for all the years in between the 2014 image and the rest of the photographic records. Each of these zones represent potentially different anthropogenic and natural environmental conditions, thus providing a variety of seagrass change scenarios.

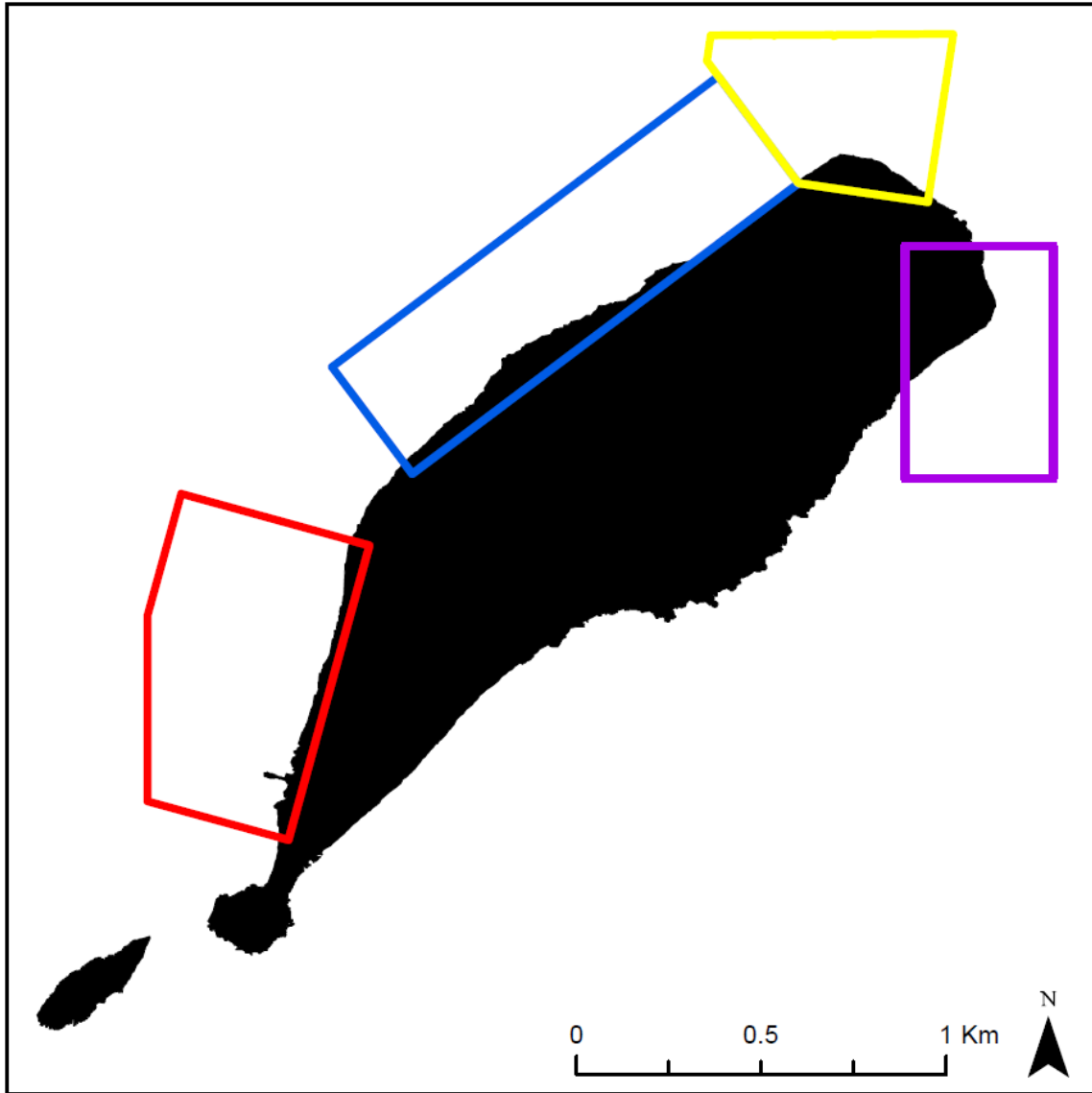


Fig. 2 The four zones selected for the long-term analysis of seagrass distribution: red = zone A, blue = zone B, yellow = zone C, and purple = zone D.

According to the 2014 benthic map (Chapter I- Fig. 4), the north of Caja de Muertos Island presented blowouts, which is evidence of an area exposed to high wave energy. Some of these blowout areas were not selected within the north zones for analysis, because they did not have the data for the complete aerial photograph record. Therefore, a smaller polygon was delimited (zone

C) in the northernmost zone and the year 2010 was not included in the analysis because it was the only year that did not have complete data for this zone C.

The Change Detection tool in eCognition was used for analyzing the overall differences in seagrass distribution for the years 1950 and 2014. Additionally, a map of seagrass persistence was created on a per-pixel basis in ArcMap. Seagrass persistence is a measure of the most frequently occurring (modal) seagrass category for each pixel (Lyons et al., 2013). As part of the analysis for the results, historical hurricane dates, magnitudes and trajectories affecting Puerto Rico were obtained from the National Oceanic and Atmospheric Administration (NOAA) Digital Coast website (<https://coast.noaa.gov/hurricanes/>).

3 Results and Discussion

The historical record of aerial imagery used (Table 1) provided a period of 64 years for long-term analysis of seagrass distribution. Contrary to the worldwide trend of seagrass area decrease (Orth et al., 2006), this study shows that from year 1950 to 2014, seagrass extent changed from 0.326 to 0.534 km² (Appendix C), representing a 64% seagrass increase in between all the zones at the CMINR. Similar results were obtained by Armstrong (1981) where seagrass area increased 170% over a period of 43 years in La Parguera, Puerto Rico.

The increase observed in the CMINR was dominated by the patchy category (124%) followed by the continuous (23%). The spatial differences in seagrass distribution between the year 1950 and 2014 are shown in Figure 3. Overall, the majority of the patchy and continuous seagrass areas remained unchanged (57%). Few areas experienced complete loss (4%) while new seagrass areas represented 31%. Some areas transitioned from patchy to continuous category or vice versa, 3 and

6%, respectively. However, when looking at the complete historical record some differences in seagrass extent were observed between years and between zones.

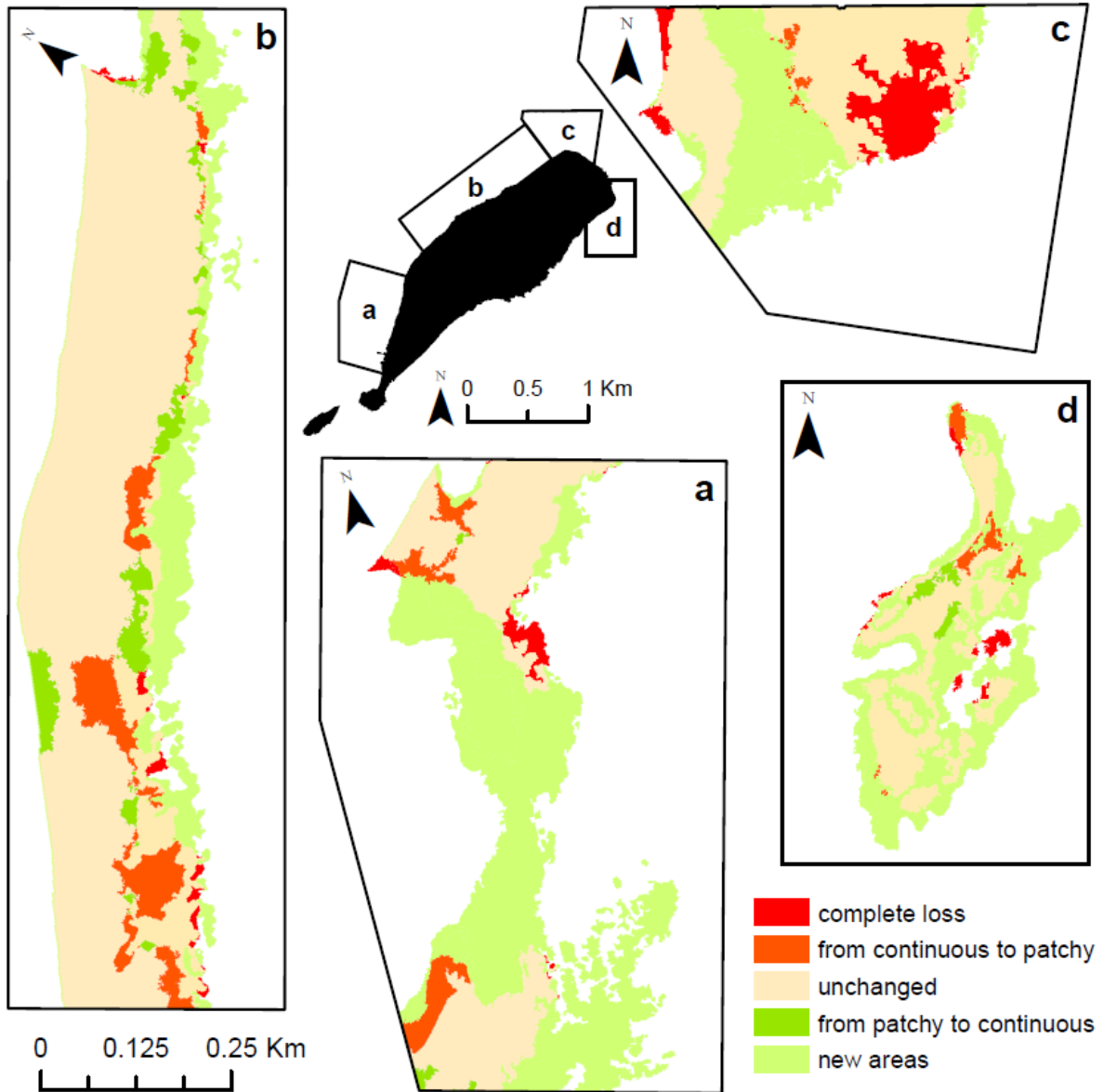


Fig. 3 Overall difference in seagrass distribution and category per zone between 1950 and 2014: (a) zone A, (b) zone B, (c) zone C, and (d) zone D.

A general trend was observed for zones A, B and C, with an increase in seagrass extent from 1950 to 1967, another increase from 1977 and 1993, a decrease from 1993 to 1999 and an increase from 1999 and 2004 (Fig. 4). Between 1950 and 1993 several weather events [e.g. Hurricane Cloe in 1964 (category 4), Hurricane Inez in 1966 (category 4), Hurricane Beulah in 1967 (category 4), Hurricane David in 1979 (category 5), Hurricane Hugo in 1989 (category 4)] affected South Puerto Rico and could impact seagrass cover in the study area. However, the impact of those events were undetectable at the large temporal scales (e.g. one decade or more). This may be one of the reasons that explains why those events were not correlated with the observed trends. Even though there were probable impacts from Hurricanes David and Hugo on seagrass communities in the study area, a noticeable increase in seagrass extent between 1977 and 1993 was documented for the three zones. A factor that possibly contributed to the observed trend is the Caribbean-wide die-off of the long spine sea urchin, *Diadema antillarum* that occurred in 1983 (Lessios et al., 1984). This species was recognized as an important herbivore in coral reefs (Mumby et al., 2014) and seagrasses (Vicente and Rivera, 1982; Creed et al., 2003; Gonzalez-Liboy, 1979). Before the die-off, Gonzalez-Liboy (1979) found a large population (1.5 individuals/m²) of *D. antillarum* in an offshore seagrass bed at Cabo Rojo, Puerto Rico, which may explain the sparser seagrass growth in that area (Gonzalez-Liboy, 1979). Vicente Rivera (1982) reported an even larger population of *D. antillarum* (3 individuals/m²) and tight aggregations on seagrass beds in south Puerto Rico. Similarly, 17 years after the die-off event, Weil et al. (2005) found tight aggregations of *D. antillarum* in seagrass beds in La Parguera, Puerto Rico, but with smaller densities (1.2 individuals/m²). The result of Weil et al. (2005) suggests that the population is slowly recovering in that area after the die-off event. However, this species was not observed during the field surveys conducted in Chapter I and neither on a coral reef area adjacent to the seagrass bed of zone D,

where another researcher conducted a survey in 2015 (HJR Reefscaping, 2015). For these reasons, it is probable that *D. antillarum* in Caja de Muertos Island has not yet recovered. The decrease of this sea urchin population may help explain an increase in seagrass cover and in benthic macroalgae, due to a decrease in herbivory pressure (Vicente and Rivera, 1982; Gonzalez-Liboy, 1979). If an increase in macroalgae occurred, it is probable that it may have been misclassified as seagrass during the visual interpretation conducted in this study.

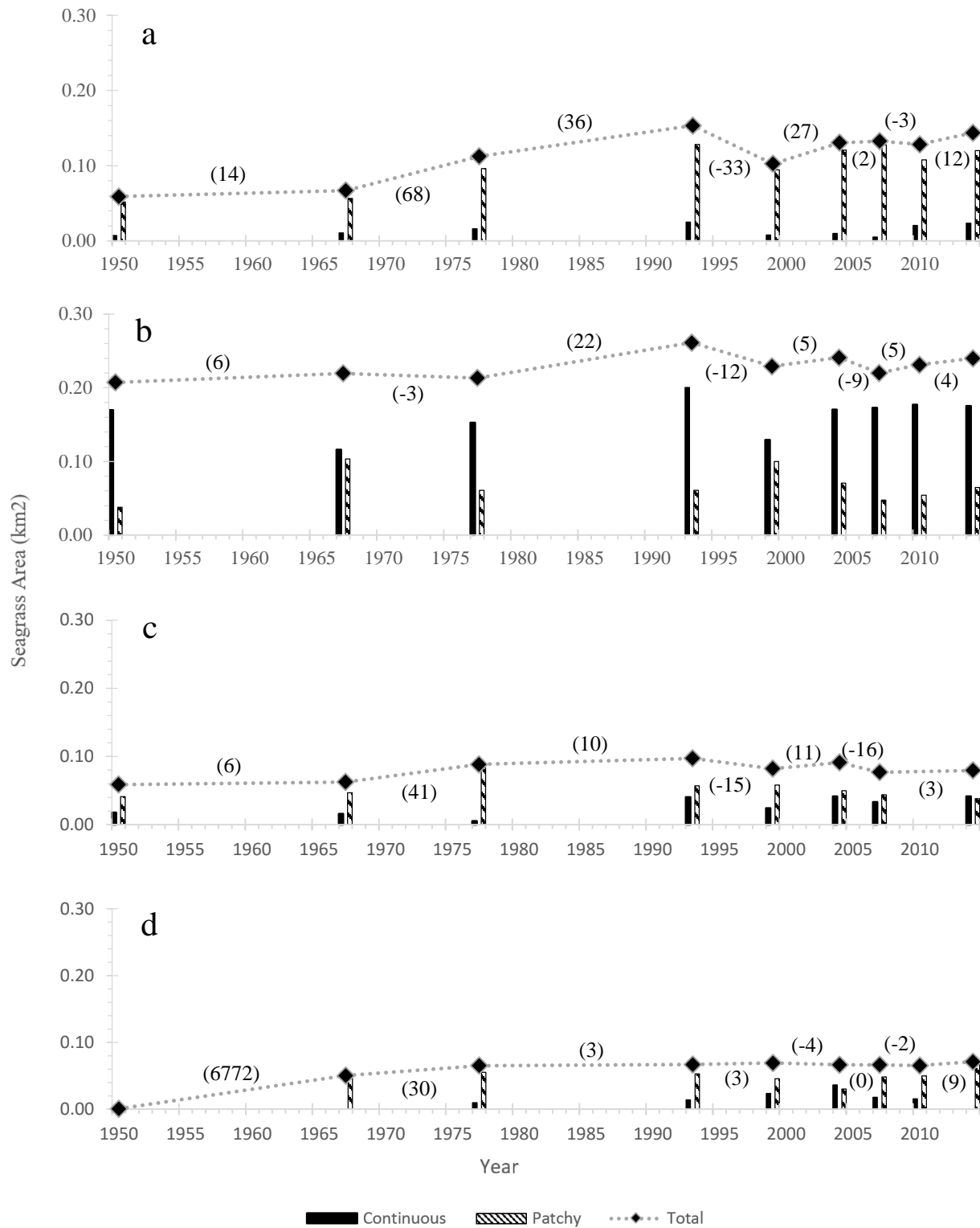


Fig. 4 Seagrass cover extent from 1950 to 2014: (a) zone A, (b) zone B, (c) zone C, and (d) zone D. Numbers in parenthesis represent percent change between adjacent years.

During the period where seagrass extent decreased (1993-1999) some relevant extreme weather events affected Puerto Rico, which could be the cause of the observed trend. For example, Hurricane Hortense in 1996 (category 1) and Hurricane Georges in 1998 (category 3). The waves generated by these systems potentially affected seagrass extent overall, with the possible exception of zone D, which is protected by a coral reef. After this period (1993-1999), an increase in seagrass extent was reported for the three zones. In 1999, Hurricane Lenny (category 4) passed further south than Hurricanes Hortense and Georges from Caja de Muertos Island. If Hurricane Lenny had an effect on seagrass cover, seagrass communities were able to recover in less than 5 years, since the 1999 image was taken before (February) Lenny's pass (November). Similarly, in 2007 Hurricane Dean (category 5) crossed the Caribbean Sea further south than Dean and large amounts of seagrass and sea fans were deposited inshore at Caja de Muertos Island (personal observation R. Armstrong). Also in 2012, DRNA (2012) reported damages in Caja de Muertos Island caused by the storm surge created by tropical storm Isaac, which had a similar path as Hurricane Dean. The damages included the removal of sand from Pelicanos Beach located south of the main pier, which was also damaged (DRNA 2012). It can also be assumed that if these last two storms impacted some seagrass, the recovery of seagrass cover probably occurred rapidly after the events, at a smaller temporal scale than the one used for this study. In addition, the distance and intensity of each hurricane or storm while passing by Caja de Muertos Island, would have resulted in different effects to the benthic communities around the Island.

Although, zone B was one of the zones that experimented the various increasing and decreasing trends in seagrass extent from 1950 to 2004 described above, results shows that in general the seagrass bed in this zone may be at a steady-state. The continuous seagrass category dominated seagrass extent during the studied time frame (Fig. 5), with an average variability of $\pm 33\%$ from

1950 to 2004 (Appendix C). After 2004, the continuous seagrass category was stable with almost no noticeable changes, suggesting a steady-state. Also, Figure 3 confirms that the majority of the seagrass area remained unchanged from 1950 to 2014 and that new areas occurred at the perimeter of the bed towards the coast. Sintes et al. (2006) indicated that when seagrasses reach a steady-state, the clonal growth becomes slower and more compacted. At a steady-state, an internal recolonization of gaps begins and the growth of the clones occurs primarily along the perimeter of the seagrass patch (Sintes et al., 2006). Additionally, Williams (1990) results suggest that when a *T. testudinum* community comes closer to its steady-state, niche partitioning may lead to the co-existence of more than one seagrass species. The field data obtained (Chapter I) confirms that the continuous seagrass category in zone B was composed of an intermixed community of *T. testudinum* and *S. filiforme*.

Similarly, after a marked increase (6772%) during the period from 1950 to 1977 (Fig. 4), zone D stabilized without any apparent dramatic increase or decrease. The benthic map data of 2014 (Chapter I- Fig. 4) and field observations indicate that the seagrass community in this zone is surrounded by a coral reef (e.g. colonized hardbottom), limiting its horizontal propagation. During 1950 and 2014, seagrass bed expanded towards all directions, filling the internal sand gaps and surrounding the areas suitable for colonization (Fig. 3). Although zone D is on the windward side of Caja de Muertos Island, it is protected from the direct wave energy by the reef crest. Thus, it seems that the impacts of the weather events that occurred during 1950 and 2014 were not significant enough to cause a dramatic decline in seagrass extent at this zone. This seagrass bed was also composed of an intermixed community of *T. testudinum* and *S. filiforme*, potentially suggesting a steady-state as for zone B. However, some variability was observed between the continuous and patchy categories, and the seagrass persistence map shows that the patchy category

dominated throughout the studied time frame by 64% (Fig. 5). In addition, Vicente (2008) documented two areas within zone D of intense grazing pressure by the green sea turtle, *Chelonia mydas*. Excessive sea turtle grazing can result in a negative impact on seagrass cover (Fourqurean et al., 2010; Heithaus et al., 2014). Thus, it may be possible that at some areas within zone D the transition from a patchy to a continuous seagrass bed was constrained due to the grazing pressure from green sea turtles.

Based on the result of this study we cannot determine specific reasons for the overall detected seagrass increase. A general tendency for increase in seagrass extent was observed both before and after the establishment of the CMINR. Thus, the establishment of the Reserve may not be directly related to the tendency observed. An input of nutrients coming from river discharges off the main island of Puerto Rico may be a contributing factor to the seagrass increase result. For example, Udy et al. (1999) was able to correlate an increase in seagrass distribution and biomass with an increase in nutrient availability in the clear oligotrophic waters of Green Island, Australia, where light is not limiting seagrass growth, such as in Caja de Muertos Island. Data collected and analyzed in Chapter I confirms that light availability is not a limiting factor for seagrass growth at the Caja de Muertos Island. In addition, field data (Chapter I) collected at zone D, showed the presence of the algae *Chaetomorpha linum*, which is an indicator of high-nutrients areas (Littler et al., 1989). Additional research is recommended in order to determine if an increase in nutrient availability is influencing seagrass cover in the CMINR. Although other areas closer to the coastline of Puerto Rico have also documented seagrass increases (Armstrong, 1981), one can assume that the CMINR seagrass areas are subject to less stressors than those closer to the shoreline of Puerto Rico.

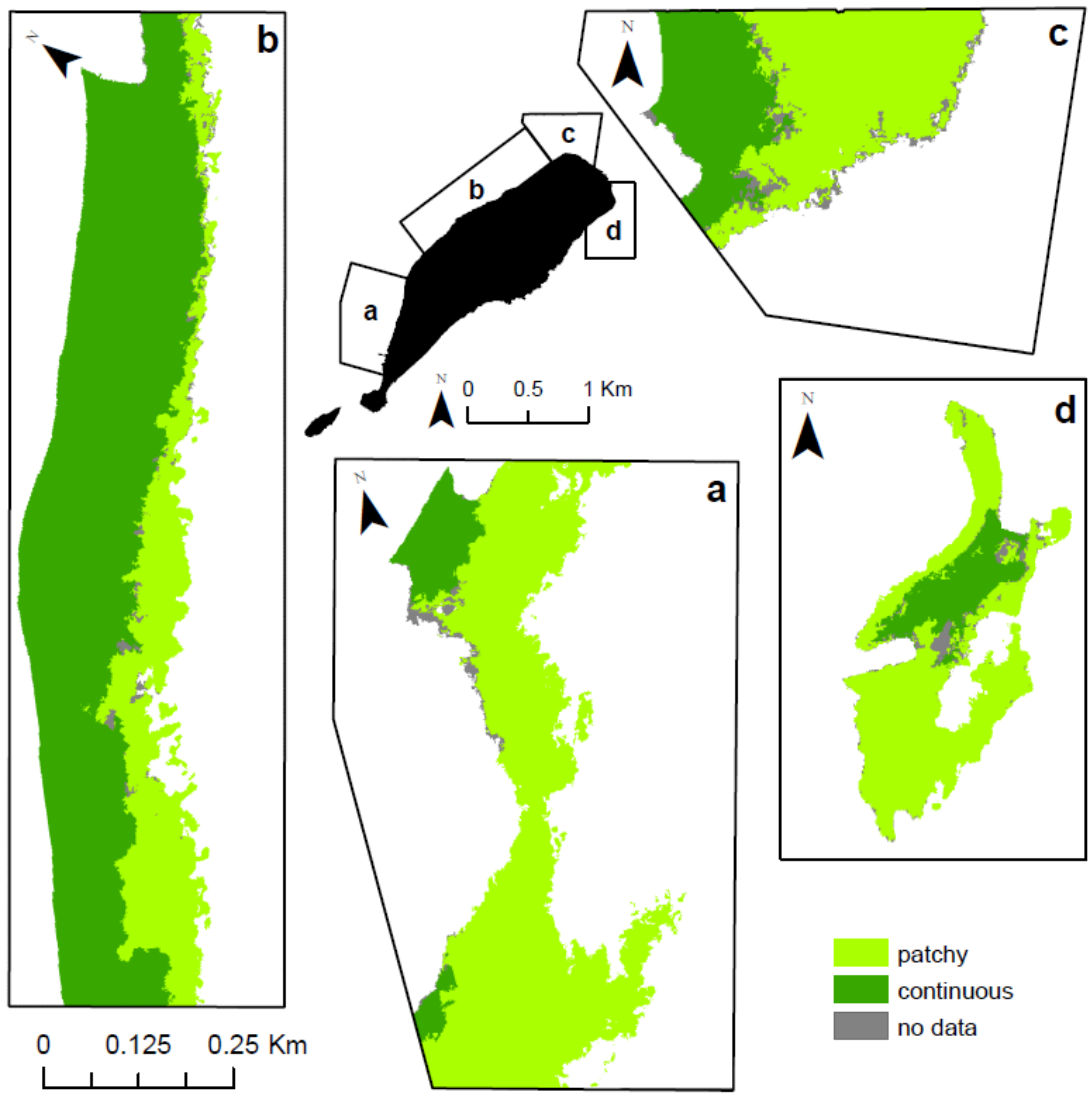


Fig. 5 Seagrass persistence, the most frequently occurring seagrass category over the studied time frame: (a) zone A, (b) zone B, (c) zone C, and (d) zone D.

The seagrass persistence map show which is the most frequent seagrass category throughout the time series for each pixel (Fig. 5). Patchy seagrass represented the most persistent seagrass category in the study area. Zones A, C, and D were dominated by patchy seagrass cover, 89%, 79% and 64%, respectively, while zone B persisted mainly as continuous (75%) for 64 years. These data provide a temporal baseline of seagrass category for the CMINR in which potential

future changes in seagrass category and their extent can be compared. Managers and researchers can use these maps to help determine the severity of a natural or anthropogenic impact within the studied zones. For example, it may be considered atypical for Zone B to change to a patchy seagrass area, since Zone B has persisted as continuous seagrass for 64 years, even after hurricane events. Zone B is used by private boat owners that either use the few mooring buoys available, or anchor in sand or seagrass, thus potentially affecting the seagrass in that zone. The same argument holds true for Zones A, C and D, if the seagrass in these areas disappeared or are further reduced. However, the long-term environmental drivers within a patchy area may not be favorable for a change to continuous seagrass cover given their 64-year persistence as patchy. Thus, management concerns may arise if the continuous seagrass areas later persist as patchy or if patchy areas are further reduced. Management should not necessarily be concerned if in the future the patchy area changes to continuous and later reverts back to patchy, given its 64-year persistence as patchy.

The methods used in this study had some limitations and possible sources of error that may include:

- Natural variation – The aerial photographs used were taken at different months (Table 1) and it is known that seagrass meadows are subject to seasonal variations (Green and Short, 2004). If indeed, seasonal changes occurred in CMINR, those changes (e.g. increase macroalgae and/or sediments deposition on seagrass) could affect the classification of seagrass areas. However, these differences may have been small as seasonal variations in the tropics are less pronounced (Erfteimeijer and Herman, 1994; Lanyon et al., 1995).
- Position shift – This can occur during the georeferencing process between two raster images. Overlaid raster images may not exactly match the control point locations used for georeferencing. The root mean square error (RMS) is a measure that indicates how

consistent the transformation is between the control points used during the georeferencing process (ESRI, 2009). This error results in a position shift of the raster pixels in between two images potentially causing errors in the seagrass changes detected between the years. However, the calculated RMS errors were close to zero for all the years (Table 1), suggesting an accurate match of the selected control points in between the images.

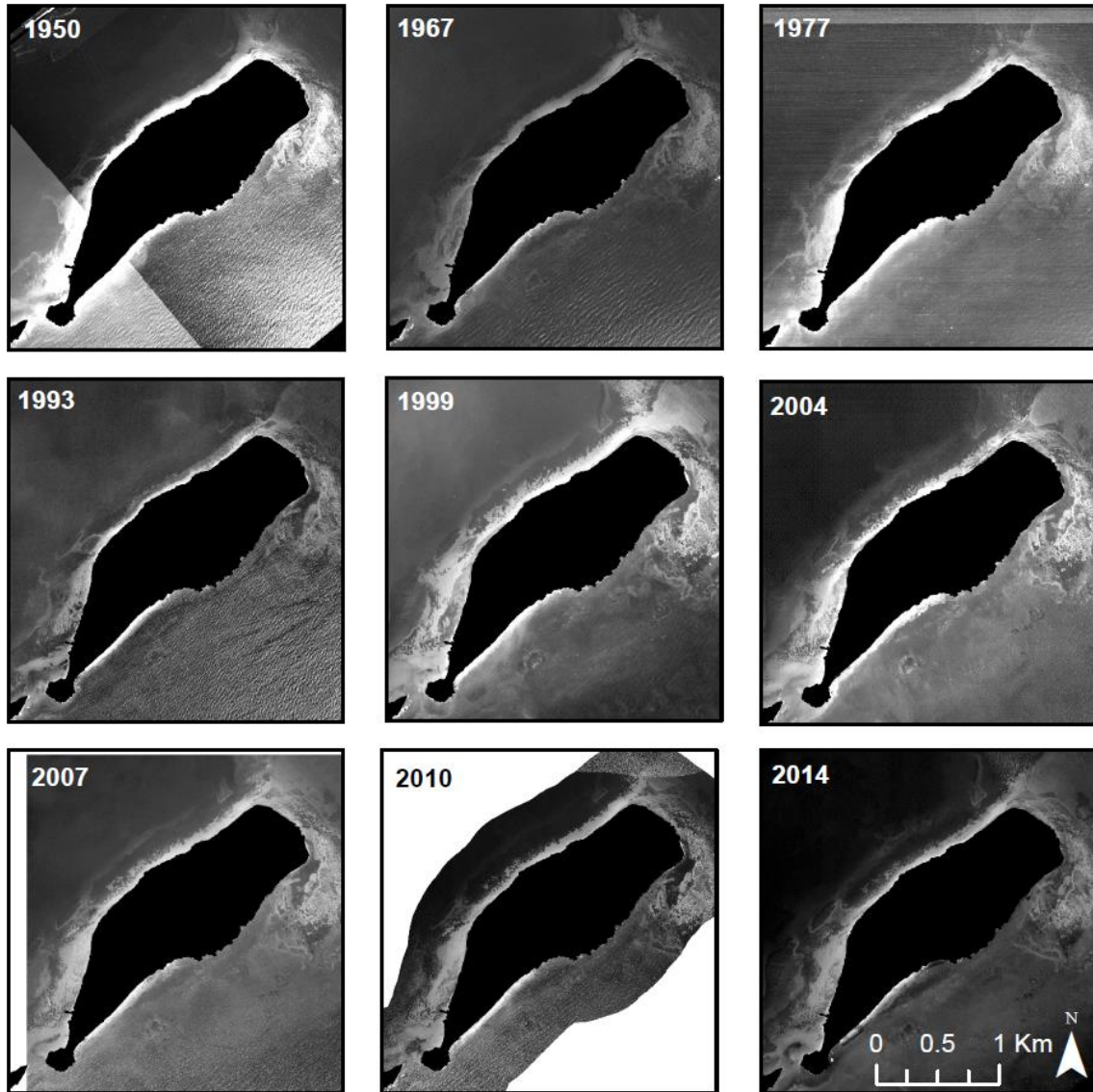
- Misclassification – The quality of the aerial photographs varied throughout the historical record and thus potentially affecting the ability to differentiate between seagrass and macroalgae areas. To account for this potential error, true-color photographs were used, when available, as a visual aid during photointerpretation and to train the visual interpreter to distinguish macroalgae areas in the black and white photographs. Additionally, in the case of the 1999 aerial photograph, a possible misclassification error can be present since the pixel size was originally 2.4 m and it was resampled to 1 m. Thus, there was less spatial data available for seagrass classification.
- No data error – During the creation of the seagrass persistence map (Fig. 5), some pixels did not return a value, thus some pixels do not have data. Therefore, seagrass persistence for those pixels could not be determined. However, these areas were relatively small (grey areas in Fig. 5) and did not affect the overall persistence map.

4 Conclusions

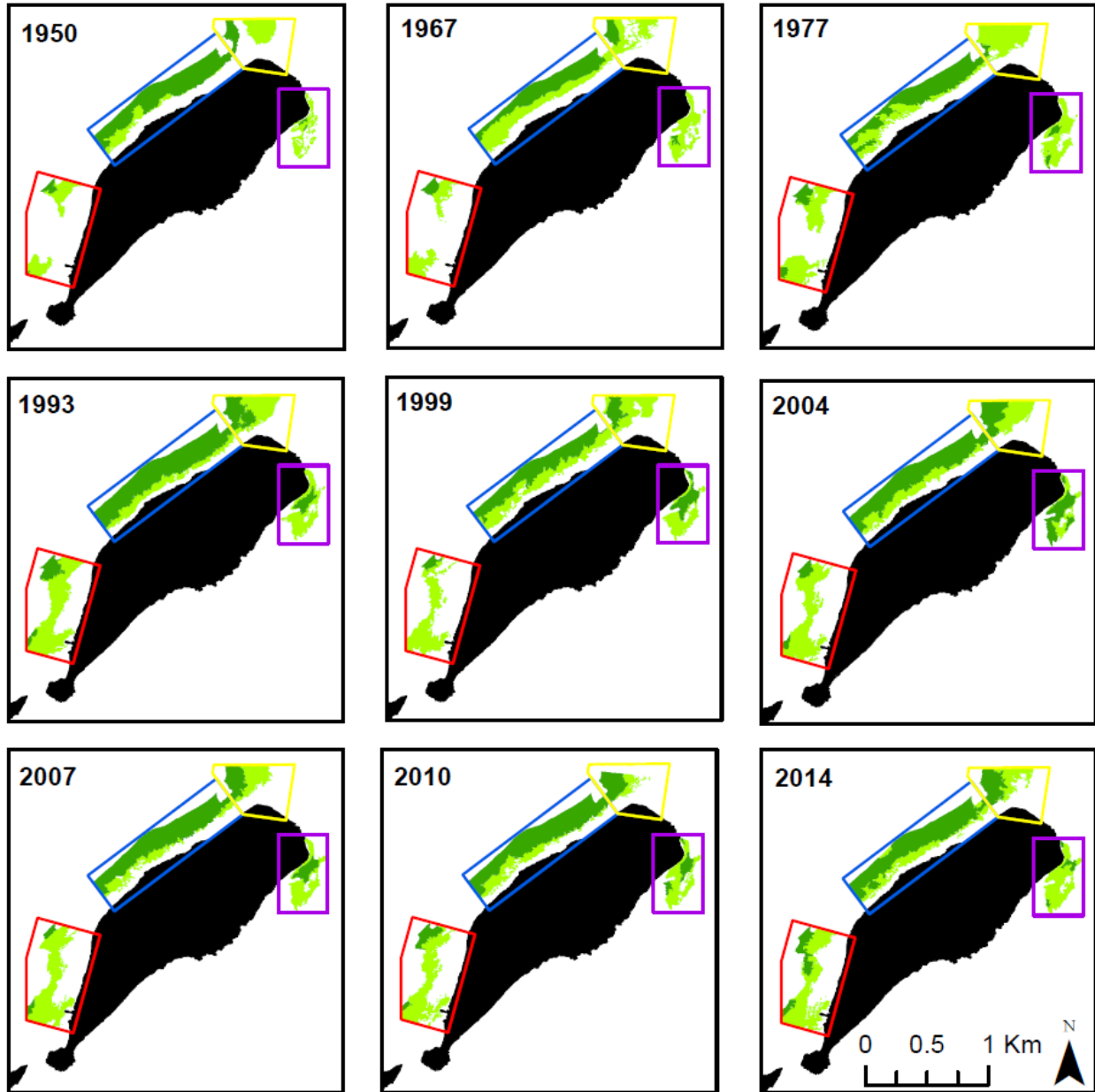
Seagrass communities in the Caja de Muertos Island experimented long-term changes in spatial distribution. An overall increase of 64% in seagrass area was documented from 1950 to 2014, mainly driven by an increase in the patchy seagrass cover. However, some differences in seagrass extent were observed between years and between zones, which were mainly associated with natural factors. On the other hand, direct human activities appear to have no detectable effects on seagrass communities in the study area for the temporal scale analyzed.

For the first time in Puerto Rico, this study provides an overview of over a six decade period of long-term changes in seagrass habitat in the CMINR. The imagery and methods used in this study prove to be effective in detecting and measuring trends in seagrass distribution that can be applied elsewhere. Also, these data represent a baseline reference by which future comparisons can be made. Future studies should focus on determining the spatial variability on a smaller temporal scale (e.g. seasonal) in order to have a better understanding of seagrass dynamics in the study area.

Appendix A: Historical imagery record from the Caja de Muertos Island. The 2014 image is a WorldView-2 satellite image, while the rest of the years are aerial photographs.



Appendix B: Seagrass extent for the CMINR study area from 1950 to 2014: dark green = continuous seagrass category, and light green = patchy seagrass category.



Appendix C: Seagrass areas within all the zones from the period of 1950 to 2014. Numbers in parenthesis represent percent change between adjacent years. Zone C had no data for the year 2010. Therefore, the percent change was calculated between the years 2007 and 2014. * This value results in an undefined number because of a division by zero.

		Seagrass Area (km ²)																
Category		1950	1967	1977	1993	1999	2004	2007	2010	2014								
Zone A	Continuous	0.007	(49)	0.011	(52)	0.016	(55)	0.025	(-68)	0.008	(23)	0.010	(-49)	0.005	(304)	0.021	(13)	0.024
	Patchy	0.052	(9)	0.056	(71)	0.096	(33)	0.128	(-26)	0.095	(28)	0.121	(6)	0.128	(-16)	0.108	(12)	0.120
	Total	0.059	(14)	0.067	(68)	0.113	(36)	0.153	(-33)	0.103	(27)	0.131	(2)	0.133	(-3)	0.128	(12)	0.144
Zone B	Continuous	0.170	(-32)	0.116	(32)	0.153	(31)	0.200	(-36)	0.129	(32)	0.170	(1)	0.173	(2)	0.177	(-1)	0.175
	Patchy	0.038	(175)	0.104	(-41)	0.061	(0)	0.061	(64)	0.100	(-29)	0.071	(-33)	0.047	(14)	0.054	(19)	0.065
	Total	0.207	(6)	0.219	(-3)	0.213	(22)	0.261	(-12)	0.229	(5)	0.241	(-9)	0.220	(5)	0.231	(4)	0.240
Zone C	Continuous	0.018	(-11)	0.016	(-68)	0.005	(707)	0.040	(-40)	0.024	(72)	0.041	(-20)	0.033	N/A	N/A	(26)	0.041
	Patchy	0.041	(14)	0.047	(78)	0.083	(-32)	0.057	(2)	0.058	(-14)	0.050	(-12)	0.044	N/A	N/A	(-13)	0.038
	Total	0.059	(6)	0.062	(41)	0.088	(10)	0.097	(-15)	0.082	(11)	0.091	(-16)	0.077	N/A	N/A	(3)	0.079
Zone D	Continuous	0.000	(0)	0.000	(*)	0.010	(42)	0.014	(68)	0.024	(55)	0.036	(-50)	0.018	(-14)	0.016	(-100)	0.000
	Patchy	0.001	(6772)	0.050	(10)	0.055	(-4)	0.053	(-14)	0.046	(-34)	0.030	(60)	0.048	(3)	0.050	(43)	0.071
	Total	0.001	(6772)	0.050	(30)	0.065	(3)	0.067	(3)	0.069	(-4)	0.067	(0)	0.066	(-2)	0.065	(9)	0.071
Total	Continuous	0.195	(-27)	0.142	(29)	0.184	(52)	0.280	(-34)	0.185	(40)	0.258	(-11)	0.229	(-7)	0.213	(13)	0.240
	Patchy	0.131	(96)	0.257	(15)	0.296	(1)	0.299	(0)	0.298	(-9)	0.271	(-1)	0.267	(-21)	0.212	(39)	0.294
	TOTAL	0.326	(23)	0.399	(20)	0.479	(21)	0.579	(-17)	0.483	(10)	0.529	(-6)	0.496	(-14)	0.425	(26)	0.534

General Conclusions

This study provides baseline information for seagrass distribution and its spatial and temporal changes in the CMINR. Seagrass communities were distributed around the island and were not limited by light availability. The seagrass beds were mainly composed of an intermixed community of *Thalassia testudinum* and *Syringodium filiforme*. The analysis conducted with the historical imagery record revealed that seagrasses increased more than two fold (64%) in 64 years at the study area. This result contrasts with many reports documenting a worldwide reduction in seagrass area (Orth et al., 2006). Differences in seagrass extent were observed both between zones and between years, which were mainly related to the influence of natural factors. However, more research is needed to evaluate variations at a smaller temporal scale (e.g. yearly and seasonal) and to study the possible causes of the overall increase in seagrass extent.

This is the first study in Puerto Rico which assesses the spatial distribution of seagrass in at a time scale of over six decades. Additionally, the method presented here represents an alternative technique to map and monitor seagrass distribution in the absence of long-term in situ monitoring data. The data provided could be used in future management decisions within the Reserve and as a baseline to compare future changes in seagrass distribution.

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