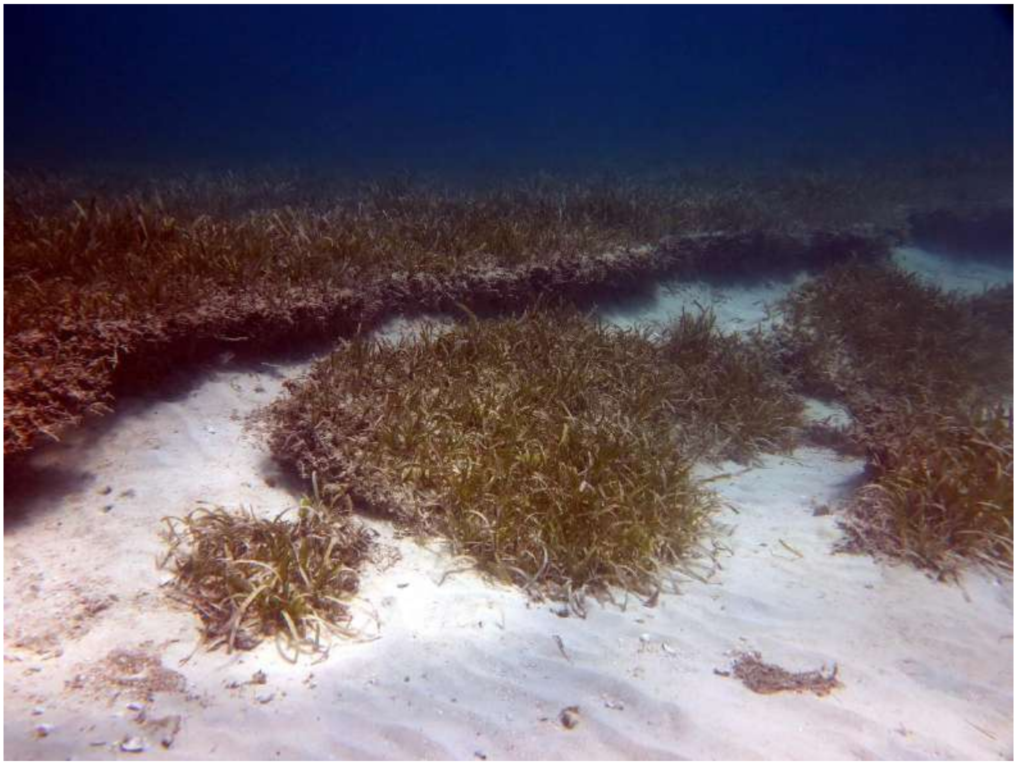

SEAGRASS RAPID ASSESSMENT OF HURRICANE MARIA IMPACTS – NORTHEAST RESERVES SYSTEM HABITAT FOCUS AREA (NER-HFA), CULEBRA ISLAND, PUERTO RICO

FINAL REPORT SUBMITTED TO:

Department of Homeland Security, Federal Emergency Management Agency (FEMA) and Department of Interior, Coordination of Natural and Cultural Resource Recovery

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Seagrass Rapid Assessment of Hurricane María Impacts – Northeast Reserves System Habitat Focus Area (NER-HFA), Culebra Island, Puerto Rico – Final Report

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1.0 ABSTRACT

Hurricanes Irma and María caused significant damage to seagrass communities and other associated ecosystems across the northeastern Caribbean region, including the Northeast Reserves System Habitat Focus Area (NER-HFA) of Culebra Island, Puerto Rico. The objective of this project was to produce a rapid quantification of the magnitude and spatial extent of hurricane impacts on representative seagrass communities in the NER-HFA of Culebra Island which are considered representative of such impacts across the region. This rapid assessment addressed important information gaps that will help NOAA, DNER and other agencies establish a baseline to develop seagrass restoration strategies in the near future across some of the most important, priority seagrass systems within the NER-HFA.

This rapid assessment has shown important findings summarized below:

1. Seagrass communities in Culebra were significantly impacted by Hurricanes Irma and María in September 2017.

2. Most of the documented impacts were associated to sediment bedload (horizontal transport), which resulted in seagrass burial and suffocation. In a lesser extent there was also common to occasional physical disruption of the seagrass habitat matrix, creating major scars on the sea bottom, and exposing seagrass structure to further disintegration by future storm events.

3. Mechanical destruction of coral reef shallow grounds located between TAM and BLI, as well as in DAK, resulted in:

    a. Physical disruption shallow reef's framework, mostly along Finger coral, *Porites porites*, biotopes.
    b. Major stochastic reef flattening.
    c. Burial and suffocation of backreefs and seagrass habitats under displaced rubble.
    d. A continuous threat of potential spatial expansion of burial (moving substrate) during future storm/winter swells events.

4. Hurricane impacts resulted in a significant shift in seagrass benthic community structure, in a net decline in percent seagrass cover (all native species), in a net decline in multiple algal functional groups (e.g., macroalgae, erect calcareous algae, *Halimeda* spp.), and even in cyanobacteria. It also resulted in a net increase in exposed sand bottom.

5. This study also revealed the concerning increase in the spatial extent and localized dominance of invasive Sea vine, *Halophila stipulacea*, which has largely displaced native seagrasses at some extensive segments at least at BLI and TAM. It was also present at 7 of the 9 surveyed locations (78%). This has become a significant seagrass management concern, particularly due to its high resistance and resilience to hurricane disturbance.

6. Ground-truthing evidence also showed a significant decline in seagrass densities dependent on species assemblages and on location exposure to wave action. Particularly, it revealed that even as early as 2004, surveyed Culebra's seagrasses were being significantly impacted by an environmental stress gradient, characterized by localized turbid, sediment-laden, nutrient-loaded runoff pulses, and recurrent anchoring impacts, particularly at TAM and BLI.

7. The present study also revealed strong water quality impacts (TAM, BLI, PCO, DAK) associated to eutrophication from Ensenada Honda Bay and Lobina Channel. Culebra is still severely impacted by multiple non-point sources of land-based pollution, sedimentation, and illegal sewage dumping, previously documented in the literature (Hernández-Delgado et al., 2006, 2017; Otaño-Cruz et al., 2017). It also revealed significant impacts by anchors (TAM, BLI), in spite of previous efforts by DNER of establishing mooring buoys at BLI.

8. Locations not ground-truthed in this study also showed significant signs of post-hurricane decline, particularly, at PCO and CNO, with seagrass loss ranging from 33 to 50%. PCO has evidence of also being frequently impacted by stranded mats of *Sargassum fluitans*. CNO was also significantly impacted during 2008 by strong

bottom swells associated to category 5 Hurricane Dean, which passed about 250 nm south of Puerto Rico in 2008.

9. There is an apparent synergy between *S. fluitans* stranded mats decay and the rapid expansion of invasive Sea vine, *H. stipulacea*. Areas along Cayo Dákity which have been impacted by *S. fluitans* have shown a rapid spread of *H. stipulacea* over the last few years (***Figure 87***). Severe impacts by hurricane-generated wave action could further open more seagrass habitats which could expose open substrate to *H. stipulacea* invasions.

10. The spatio-temporal implications of documented impacts in Culebra's seagrass communities are important. Impacted seagrass habitats are critical foraging grounds for a resident population of critically-endangered Green turtle, *Chelonia mydas*. Culebra's seagrasses up to 3 nm are designated as Resource Category 1 habitat and as DCH for *C. mydas*.

11. Sediment-buried seagrasses were also fundamental nursery and foraging grounds of multiple Federally-managed species, including Queen conch (*Lobatus gigas*), Spiny lobster (*Pannulirus argus*), Nassau grouper (*Epinephelus striatus*), Yellow-tail snapper (*Ocyurus chrysurus*), and Mutton snapper (*Lutjanus analis*), to mention some examples.

12. Some of the shallow seagrass locations, particularly those located within Canal Luis Peña no-take Natural Reserve, are fundamental for supporting local Culebra's municipality economy, as well as community-based livelihoods. Multiple nature-based tourism and recreation business operations were undertaken at locations such as BTA and PTC.

13. Observed impacts will require assisted restoration interventions to accelerate seagrass recolonization, and in some cases, may require localized benthic habitat reconstruction and stabilization, to foster the rapid recovery of ecological functions, benefits, and resilience.

This project has provided fundamental baseline information to inter-jurisdictional, and inter-agency managers and decision-makers in regards to hurricane impacts on seagrass habitats across the NER-HFA of Culebra Island. This has also provided the necessary baseline to address potential threats to the vulnerability of coastal community livelihoods, safety, properties, infrastructure, and to net ecosystem and socio-economic resilience in Culebra. This has served as a model project and has established basic metrics of hurricane impacts and the need of ecological restoration efforts applicable to other locations across Puerto Rico and the northeastern Caribbean. In addition, it has provided a critical assessment of needs and call of actions (COAs) aimed at the conservation and restoration of critical seagrass resources across the high priority NER-HFA.

2.0 INTRODUCTION

Hurricanes Irma and María caused significant damage to coral reefs and other associated ecosystems across the northeastern Caribbean region, including the Northeast Reserves System Habitat Focus Area (NER-HFA) of Culebra Island, Puerto Rico. At its closest point to Culebra, category 5 Hurricane Irma passed just 12 nm off the north coast of Culebra during September 6, 2017, with sustained winds of 185 MPH, and estimated gusts of up to 225 MPH. Wave action ranged from 30 to 40' along its northern coast, and from 20 to 30' along other areas. On September 20, 2017 Hurricane María was also a category 5 hurricane at its closest point to Culebra, just 20 nm south of the island, with sustained winds at that moment of 175 MPH, and estimated gusts over 200 MPH. Wave action also ranged from 20-40', depending on exposure.

Damage to local coral reefs was nearly unprecedented, with widespread coral fragmentation, colony dislodgment, and extensive destruction of shallow coral reef frameworks. However, Final qualitative assessments of seagrass communities also showed substantial habitat destruction on shallow grounds across multiple locations. Most of these impacts appeared to be related to a combination of direct scouring seagrass habitat matrix destruction by strong waves and wind-driven rip currents, and from sediment bedload (shifting sands). However, the spatial extent and magnitude of such impacts have not been quantified yet, either in Culebra, or across the rest of the main island in Puerto Rico. Observed impacts were significant and might have long-term local adverse consequences on seagrass ecological functions and on coastal resilience. This suggested the need to quantify the magnitude and spatial extension of hurricane-associated impacts on seagrass communities across NER-HFA. NER-HFA is an extensive system of coral reefs, seagrass communities, and small islands across northeastern Puerto Rico, with high conservation and restoration priority for NOAA and for the Department of Natural and Environmental Resources (DNER).

The objective of this project was to produce a rapid quantification of the magnitude and spatial extent of hurricane impacts on representative seagrass communities in the NER-HFA of Culebra Island which are considered representative of such impacts across the region. This rapid assessment addressed important information gaps that will help NOAA, DNER and other agencies establish a baseline to develop seagrass restoration strategies in the near future across some of the most important, priority seagrass systems within the NER-HFA.

Target seagrass communities play a vital role for the protection and maintenance of the social-ecological resilience of Culebra's coastal communities, providing stability to soft bottoms, dampening wave action and surface currents velocity, providing fundamental nursery grounds to a myriad of reef fish and invertebrate species, and constitute the most critical component of the Federally designated critical habitat (DCH) for the highly endangered Green turtle, *Chelonia mydas*. Culebra's seagrasses are also designated as Resource Category 1 habitats for endangered turtles. Seagrasses also provide important habitats in support of multiple recreational activities, such as snorkeling, SCUBA diving, kayaking, and swimming. Such low-impact tourism activities are paramount to support the local economy of Culebra. Documenting the post-hurricane condition of seagrass habitats was a critical step to provide timely information to inter-agency, and inter-jurisdiction managers and decision-makers in regards to future seagrass conservation and restoration strategies. This would support the long-term rehabilitation of Culebra's economy, community-livelihoods, and net coastal resilience.

3.0 METHODOLOGY

This project was aimed at producing a rapid quantification of hurricane impacts on representative seagrass communities in the NER-HFA of Culebra Island. The following strategies were implemented to achieve the proposed goal.

3.1 Study sites

The study was subdivided in two major strategies to complete the rapid assessment. The first strategy was based in GIS analyses of seagrass spatial extension *before* and *after* hurricanes impacts. GIS-based analyses was conducted across nine locations in Culebra Island, Puerto Rico (***Figure 1***). These included: Bahía Tamarindo (BTA), Punta Tamarindo Chico (PTC), Punta Melones (PME), Playa Tampico (TAM), Bahía Linda (BLI), Punta Colorada (PCO), Cayo Dákity (DAK), Bahía Mosquito (BMO), and Cayo Norte (CNO). The first three sampling locations are found within the Canal Luis Peña no-take Natural Reserve, which harbor resident populations of critically-endangered Green turtle, *Chelonia mydas*. TAM is located adjacent to downtown Dewey and protect soft bottoms adjacent to the main docking facilities operated by the Puerto Rico Ports Authority (PRPA). BLI is located adjacent to the underwater power cable and water pipeline approaching Culebra. It also has become in recent years a favorite spot for recreational navigators, particularly during weekends. PCO and DAK are located within the outer Ensenada Honda Bay, which protect other extensive urban areas along the upper Ensenada Honda Bay, and critical mooring and anchoring grounds. Seagrass communities across BMO and CNO have traditionally constituted important fishing grounds for artisanal fisherfolks, particularly for Queen conch (*Lobatus gigas*).

The second strategy was based in conducting an *after*-hurricanes groundtruthing field sampling of seagrass ecological condition across the first five locations listed above. Data from this assessment was compared to previous data obtained during 2004 (Hernández-Delgado, unpublished data).

Selected polygons for GIS-based and for groundtruthing assessments were *a priori* selected using ArcMAP 10.6 (ESRI), contrasting the 2007, 2010, and 2017 (post-hurricane) aerial images of Culebra Island, to qualitative determine apparently significant impacts on seagrasses. Also, polygon selection was based on Final qualitative assessments made by the authors between October 2017 and February 2018. An additional criteria for polygon selection, and for the final selection of groundtruthed locations, was based on the existence of previous quantitative data regarding seagrass conditions.

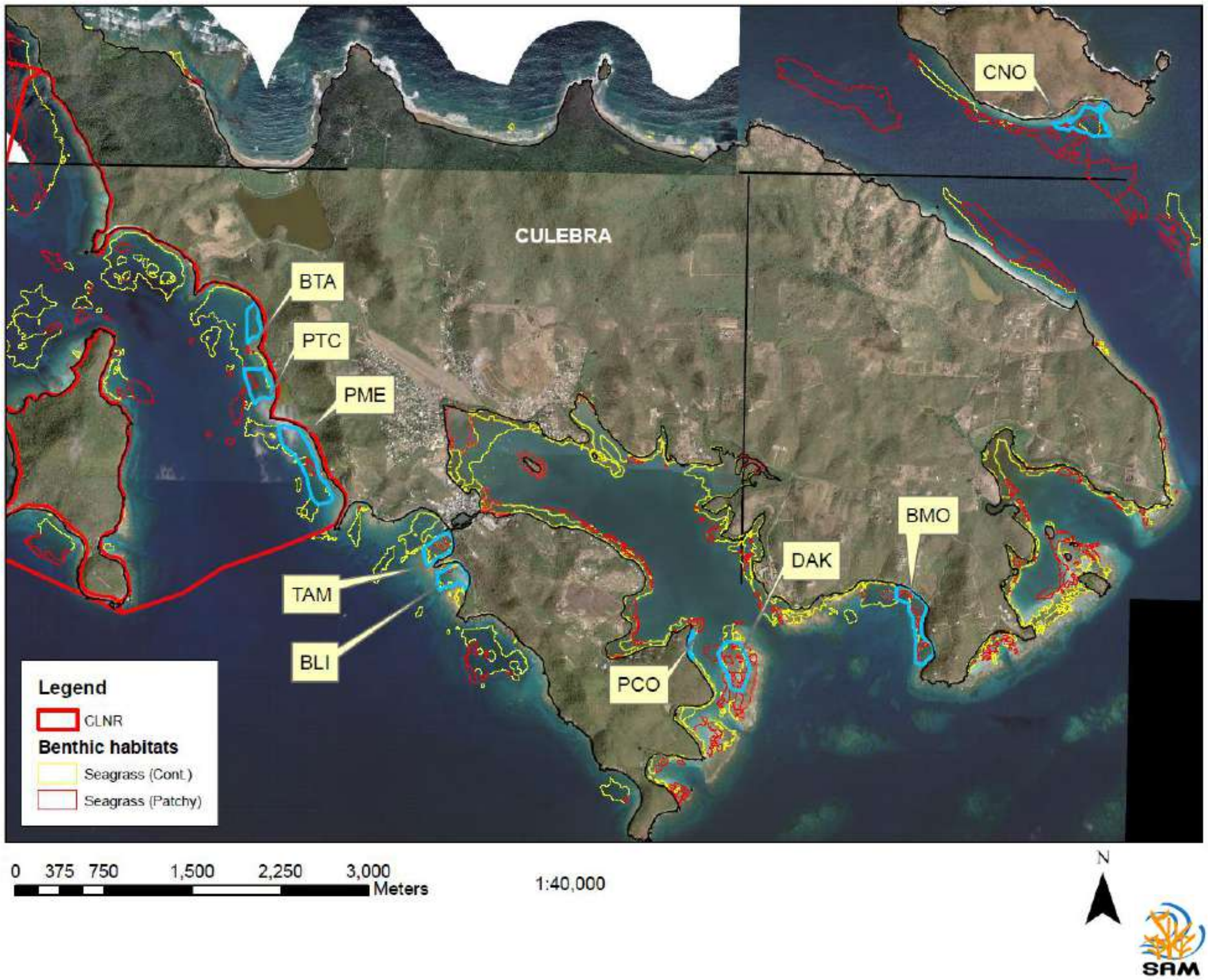

FIGURE 1. Study locations across Culebra Island, Puerto Rico. See section 3.1 for acronyms. Red polygon shows the Canal Luis Peña no-take Natural Reserve (CLPNR) and part of the NER-HFA.

Pre-selected habitats for this project were also characterized by: 1) showing signs of significant impacts by hurricane-generated wave action; 2) having *pre-hurricane* aerial imagery for *before* assessments of seagrass spatial extent; and 3) being located adjacent to existing private properties, roads, or adjacent to areas where the urban expansion of Dewey has been proposed. Selected polygons were clipped and used as baseline mapping units for delimiting the spatial extent of seagrasses within each area. All studies were limited to depths shallower than 20' (6 m), which show the most significant physical impacts. But damage on seagrasses associated to sediment bedload (horizontal transport) were observed within the Canal Luis Peña no-take Natural Reserve, off PTC, down to at least 33-39' (10-12 m).

3.2 Before – After GIS-based assessment of seagrass extension

A GIS-based assessment of recent seagrass extension was conducted across the nine selected seagrass polygons listed above (***Figure 1***). Data was analyzed across two different periods prior to hurricanes using aerial imagery from years 2007 and 2010. This was aimed at establishing a *pre-hurricane* baseline of seagrass spatial extension (m^2), and to address spatial variation within each polygon from 2007 to 2010, in the absence of major hurricanes. Post-hurricane assessments were conducted on aerial images generated during September 22-26, 2017, or just 2-6 *after* category 5 Hurricane María. Aerial imagery was obtained from an open source established by NOAA. through: https://storms.ngs.noaa.gov/storms/maria/index.html#16/18.3063/-65.2814. Aerial imagery from October 23-27, 2017 was assessed from https://evwhs.digitalglobe.com (access obtained with the collaboration of Dr. Keenan Adams, US Fish and Wildlife Service).

3.3 Ground-truthing of post-hurricanes seagrass conditions

A ground-truthing of post-hurricane seagrass conditions involving the use of a manual operated vehicle (MOV) and high-resolution underwater imagery was conducted at BTA, PTC, PME, at TAM, and at BLI. This was aimed at characterizing *post-hurricane* seagrass benthic habitat conditions (i.e., seagrass species richness, percent seagrass cover, percent algal cover, percent sand cover, and seagrass density), within the selected polygons. A hand-held MOV was lowered at each sampling point, provided with a time-lapse high resolution digital camera to collect a digital image from an integrated photo-quadrat. A total of 90-105 sampling points were haphazardously-selected in the field within each polygon to characterize benthic communities. Images were used to characterize seagrass species richness, and percent cover of seagrasses, algal functional groups, cyanobacteria, sand, mud, rubble, and other benthic components. Also, this allowed estimating seagrass shoot density, using a 15 x 15 cm integrated sub-quadrat within each main quadrat frame. Individual attribute tables were generated for each of the five selected locations. Seagrass habitats were subdivided according to percent cover categories of seagrass species following NOAA (2001): <10%, 10-30%, 30-50%, 50-70%, 70-90%, and 90-100%. Macroalgal cover was assessed using similar classification categories. GIS-based maps were generated using IDW interpolation to show the spatial variation in seagrass cover and density across each location (*data only partially shown in the Final Report – this is still work in progress*).

3.4 Before-After comparison of selected seagrass parameters

A quantitative analysis of spatio-temporal variation in a selection of seagrass parameters was conducted comparing conditions *before* (2004) and *after* hurricanes (April 2018). Previous data were obtained from Hernández-Delgado (unpublished data). Spatio-temporal variation in seagrass community structure and in selected seagrass parameters was assessed using a two-way permutational analysis of variance (PERMANOVA), with location (n=5), and time (*before*, *after* hurricanes) as main variables. Bootstrap average metric multidimensional scaling and principal coordinates ordination (PCO) were used to address indicator taxa/benthic categories to explain observed spatio-temporal patterns in seagrass benthic community structure. All statistical analyses were conducted in multivariate statistical package PRIMER v.7.0.13 + PERMANOVA v.1.0 (PRIMER-e, Quest Research Limited, Auckland, NZ), following Anderson et al. (2008).

4.0 RESULTS

4.1 Before – After GIS-based assessment of seagrass extension

4.1.1 General spatio-temporal patterns

Table 1 summarizes spatio-temporal variation in seagrass community extension across the nine selected locations. A total of 485,506.1 m^2 (48.55 ha) of seagrass habitats were assessed within nine polygons. The largest polygon was assessed at PME, followed by BMO. The smallest one was assessed at PCO. Total spatial extension of seagrasses within the total selected polygons in Culebra during year 2007 was 423,739.0 m^2 (87.3%), 415,044.7 m^2 (85.5%) in 2010, and 332,245.8 m^2 (68.4%) *after* Hurricanes Irma and María (***Tables 1-2***). Global loss of seagrass extension between 2007 and 2010 was 2.05%. Global loss of seagrass extension between 2007 and 2017, after hurricanes, was 21.6%. Global loss between 2010 and 2017, after hurricanes, was nearly 20%.

TABLE 1. Summary of seagrass spatio-temporal variation in habitat patch size across sampling location: Comparison of *before* (2007, 2010) and *after* hurricanes (2017) data.

Location	Code	Polygon (m2)	B-2007	B-2010	A-2017
Bahia Tamarindo	BTA	28632.25894	27877.58	27481.21077	19897.58
Punta Tamarindo Chico	PTC	47935.54342	44672.86	44378.81516	42071.18
Punta Melones	PME	105398.1622	101921.9	98334.07486	70160.07
Playa Tampico	TAM	39542.18637	33762.71	34703.30683	25636.59
Bahia Linda	BLI	41831.83057	23901.75	23436.95336	23149.98
Punta Colorada	PCO	6953.057871	6827.229	6808.845904	3407.954
Cayo Dakity	DAK	74172.12162	54091.56	56610.01676	50184.64
Bahia Mosquito	BMO	76986.67198	68415.23	73749.13327	64983.32
Cayo Norte	CNO	64054.23859	62268.21	49542.30477	32754.5
	Total	485506.0715	423739	415044.6617	332245.8
	Min	6953.057871	6827.229	6808.845904	3407.954
	Max	105398.1622	101921.9	98334.07486	70160.07

However, there was extensive spatial variability in the magnitude and extent of impacts, often as a combined result of factors such as: 1) geographic location in regards to wind and waves direction; 2) coastal exposure to wave action; 3) depth; 4) species composition; 5) degree of protection by adjacent coral reefs; and the abundance of invasive Sea vine, *Halophila stipulacea*, which has shown remarkable natural recovery ability.

TABLE 2. Summary of seagrass spatio-temporal variation in percent cover of sea bottom within polygons across sampling location: Comparison of *before* (2007, 2010) and *after* hurricanes (2017) data.

Location	Code	2007-%SG	2010-%SG	2017-%SG	% Loss-07-10	% Loss 07-17	$ Loss 10-17
Bahia Tamarindo	BTA	97.36	95.98	69.49	1.42	28.63	27.60
Punta Tamarindo Chico	PTC	93.19	92.58	87.77	0.66	5.82	5.20
Punta Melones	PME	96.70	93.30	66.57	3.52	31.16	28.65
Playa Tampico	TAM	85.38	87.76	64.83	(+2.79)*	24.07	26.13
Bahia Linda	BLI	57.14	56.03	55.34	1.94	3.15	1.22
Punta Colorada	PCO	98.19	97.93	49.01	0.27	50.08	49.95
Cayo Dakity	DAK	72.93	76.32	67.66	(+4.66)	7.22	11.35
Bahia Mosquito	BMO	88.87	95.79	84.41	(+7.80)	5.02	11.89
Cayo Norte	CNO	97.21	77.34	51.14	20.44	47.40	33.89
	Total	87.28	85.49	68.43	2.05	21.59	19.95
	Min	57.14	56.03	49.01	(+7.80)	3.15	1.22
	Max	98.19	97.93	87.77	20.44	50.08	49.95

*Numbers in parentheses were cases where percent seagrass extension increased.

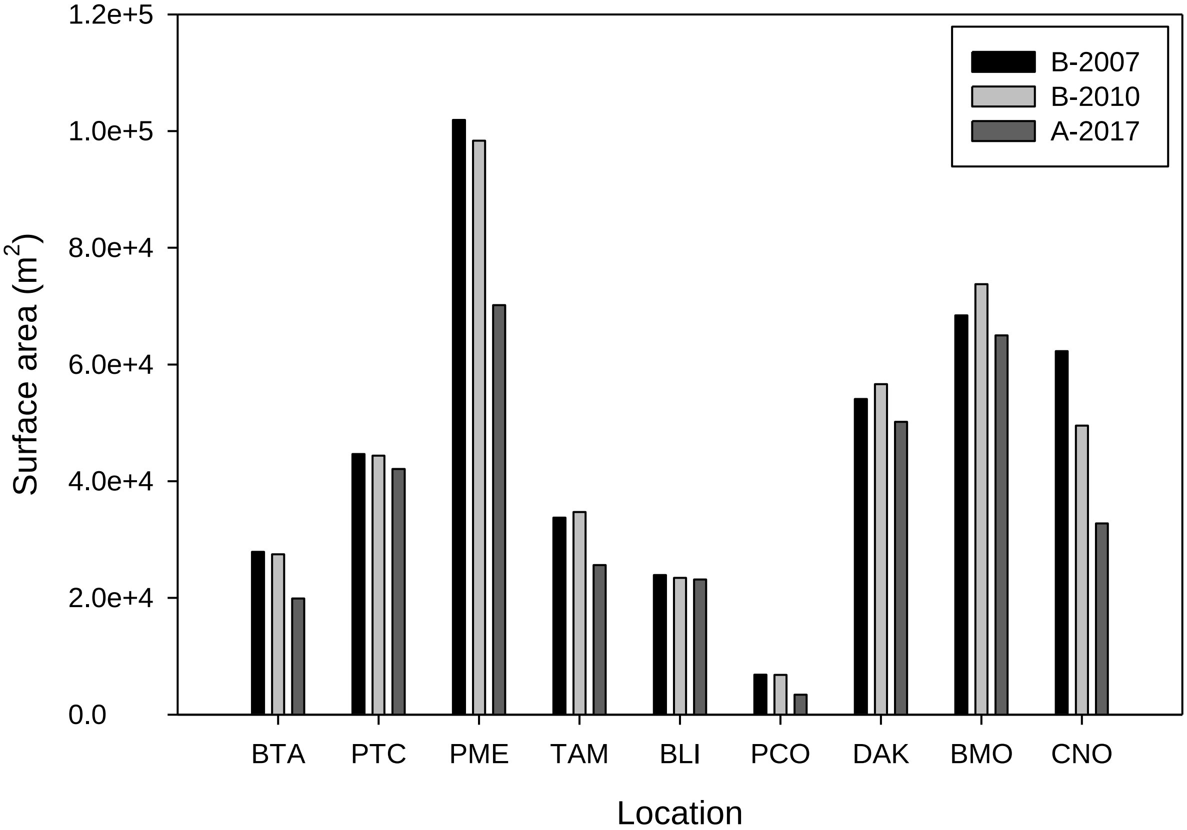

FIGURE 2. Spatio-temporal variation in seagrass extension *before* (2007, 2010) and *after* Hurricanes Irma and María.

There was a wide range of surveyed polygon sizes, with PME showing the largest continuous seagrass habitat extension in 2007 (101,929 m^2), followed by BMO (68,415.2 m^2), and CNO (62,268.2 m^2) (***Figure 2***). From the surveyed locations, CNO and PME showed the largest decline in seagrass surface extension within the period of 2007-2010. This might have probably been associated to the strong bottom swells associated to distant category 5 Hurricane Dean (2008), which passed about 250 nm south of Culebra, but that generated strong bottom swells from the south. BTA, PTC, BLI, and PCO showed no significant variation. BMO, DAK, and TAM actually showed a modest increase in surface extension, but as a result of the rapid spread of invasive Sea vine (*Halophila stipulacea*).

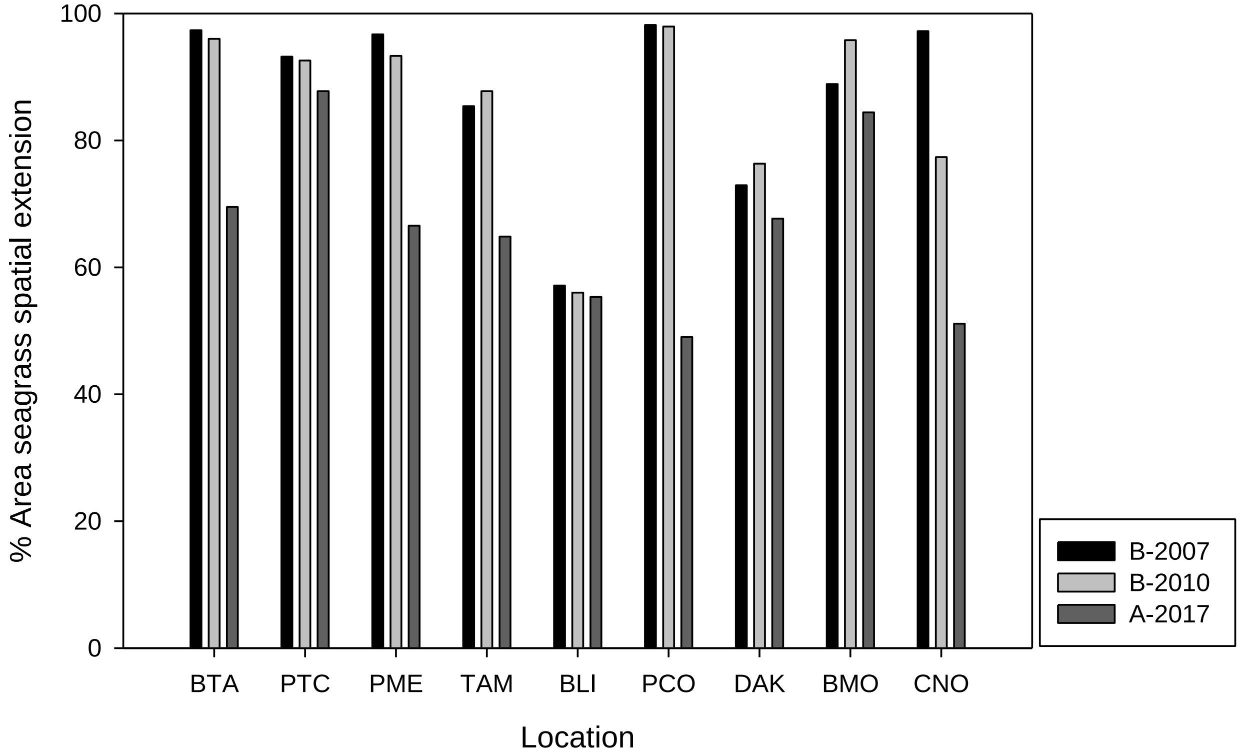

FIGURE 3. Spatio-temporal variation in the percent area of seagrass extension *before* (2007, 2010) and *after* Hurricanes Irma and María.

There was an evident widespread decline in seagrass spatial extent following impacts by Hurricanes Irma and María (***Figures 2-3***). The largest magnitude in percent decline was observed at PCO (***Table 2***), followed by PME, BTA, and CNO. Most of the observed decline was the result of a combination of mechanical dislodgment and sediment bedload (horizontal transport) and burial.

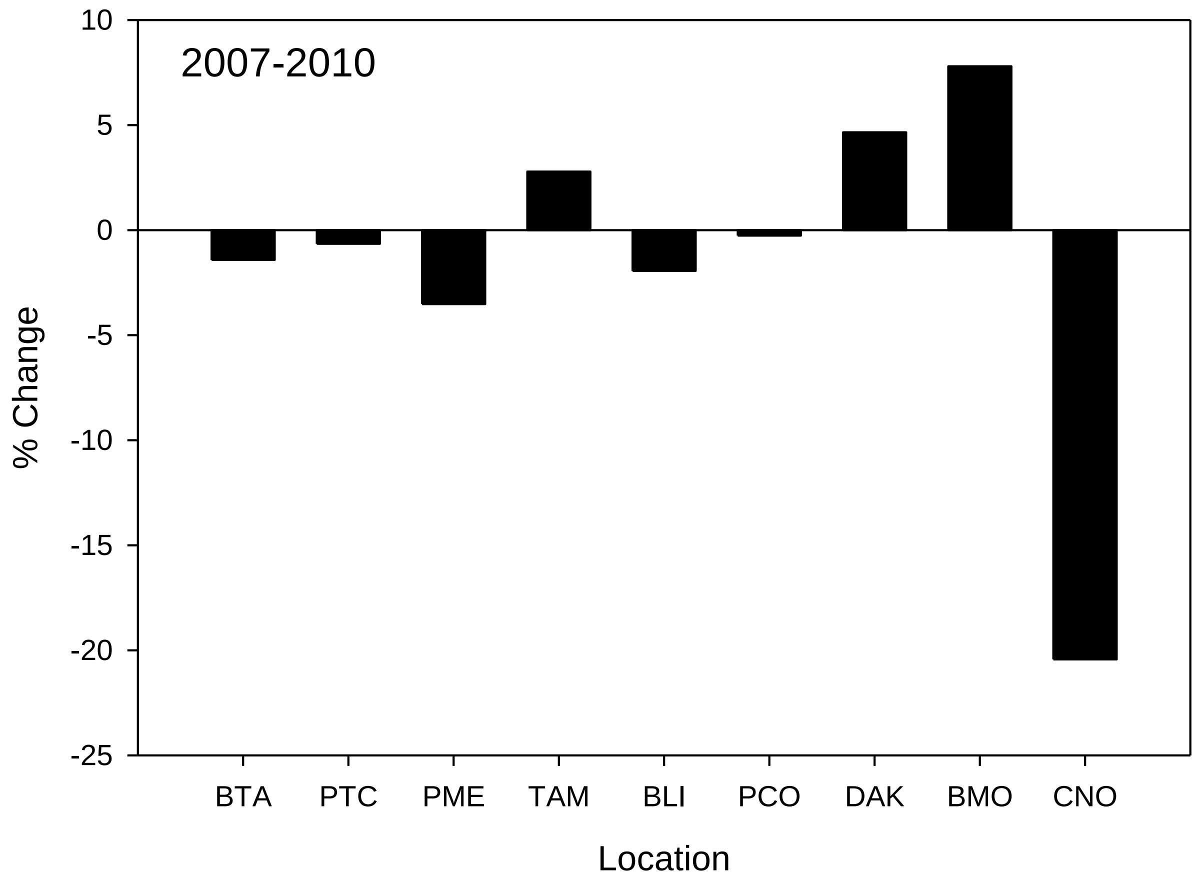

FIGURE 4. Percent change in seagrass habitat spatial extension between the period of 2007 to 2010.

Figure 4 shows the spatio-temporal variation patterns in percent change in seagrass habitat extension prior to the impacts of Hurricanes Irma and María, between 2007 and 2010. CNO was by far the only surveyed location which shows a significant decline in percent seagrass habitat extension, with 20.4% loss. Other five locations showed only minor decline (<4.7%). Three locations (BMO, DAK, TAM) showed a modest increase in habitat extension, but mostly as a result of the rapid invasion across the region of the invasive Sea vine (*Halophila stipulacea*).

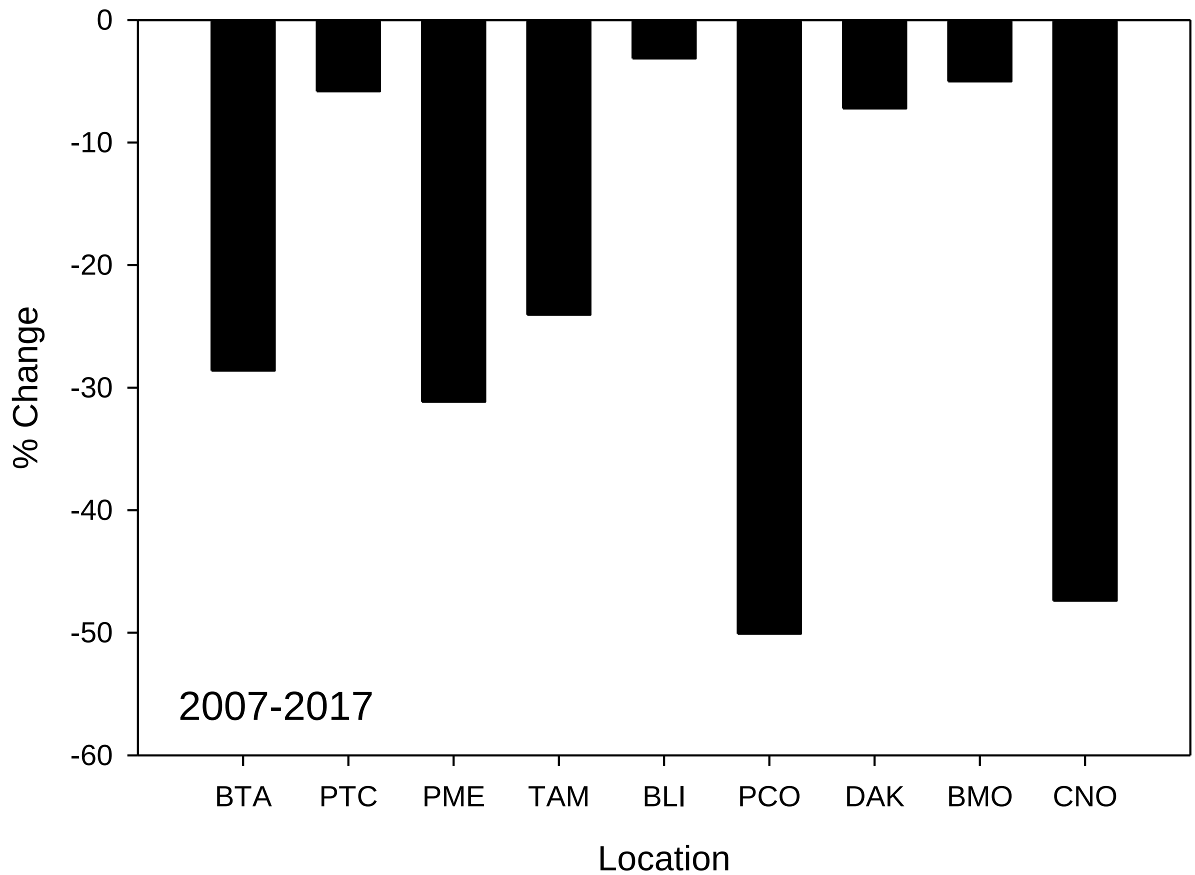

FIGURE 5. Percent change in seagrass habitat spatial extension between the period of 2007 to 2017.

All surveyed seagrass communities showed unequivocal adverse impacts by Hurricanes Irma and María (2017) when compared to *before* data (2007) (***Figure 5***). PCO lost 50.1% of its seagrass habitat, followed by CNO (47.4%), and PME (31.2%). BTA also lost 28.6% of seagrasses, followed by TAM (24.1%). DAK only lost 7.2% of seagrasses, PTC 5.8%,BMO 5.0%, and BLI 3.1%. But such small decline might be misleading as those habitats are undergoing a rapid turnover characterized by the extirpation of turtle grass, *Thalassia testudinim*, and by the rapid colonization by invasive Sea vine (*Halophila* *stipulacea*).

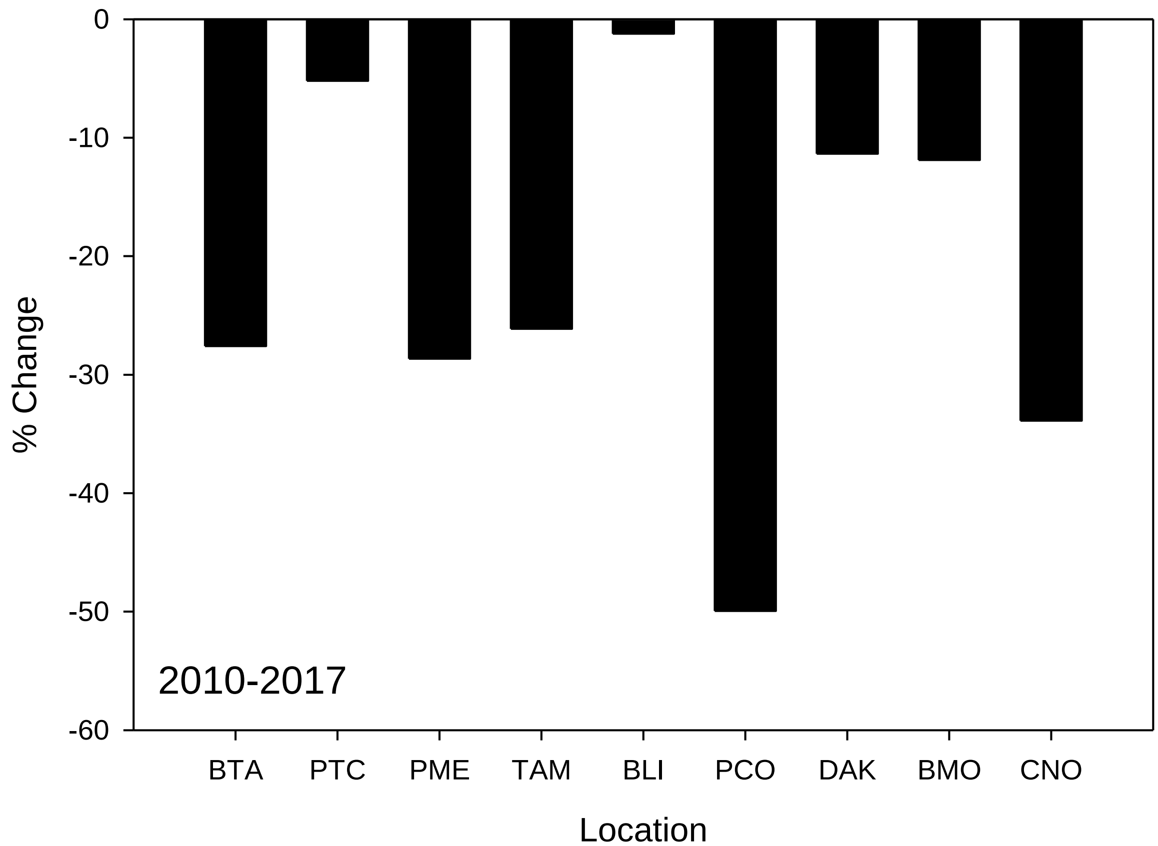

FIGURE 6. Percent change in seagrass habitat spatial extension between the period of 2010 to 2017.

All surveyed seagrass communities showed similar unequivocal adverse impacts by Hurricanes Irma and María (2017) when compared to *before* data (2010) (***Figure 6***). PCO lost 49.9% of its seagrass habitat, followed by CNO (33.9%), and PME (28.7%). BTA also lost 27.6% of seagrasses, followed by TAM (26.1%). BMO lost 11.9% of seagrasses, DAK 11.4%, and BLI only 1.2%. Similarly, such small decline might be misleading as those habitats are undergoing a rapid turnover characterized by the extirpation of turtle grass, *Thalassia testudinim*, and by the rapid colonization by invasive Sea vine (*Halophila stipulacea*).

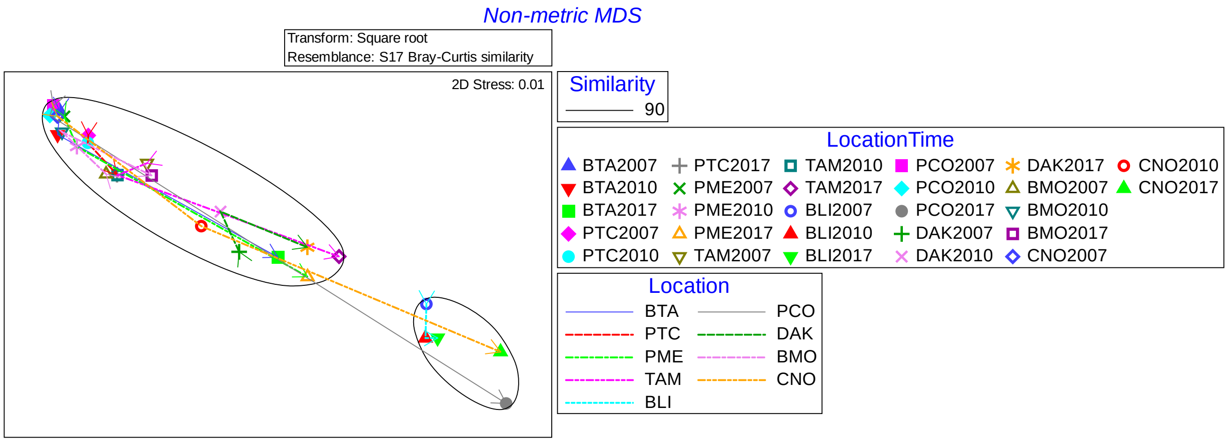

FIGURE 7. Non-metric multi-dimensional scaling (nMDS) analysis of temporal trajectories in the percentage of change in seagrass community extension

A multivariate analysis of the temporal trajectories of surveyed seagrass habitats using non-metric multi-dimensional scaling (nMDS) showed significant evidence of change in benthic seagrass community structure following Hurricanes Irma and María impacts (***Figure 7***). Clustering patterns show no difference in *before* hurricane assemblages (2007, 2010), but a clearly different *post*-hurricane assemblage for most of the locations, particularly those that suffered major mechanical damage, or those that show significant expansion of invasive Sea vine (*Halophila stipulacea*).

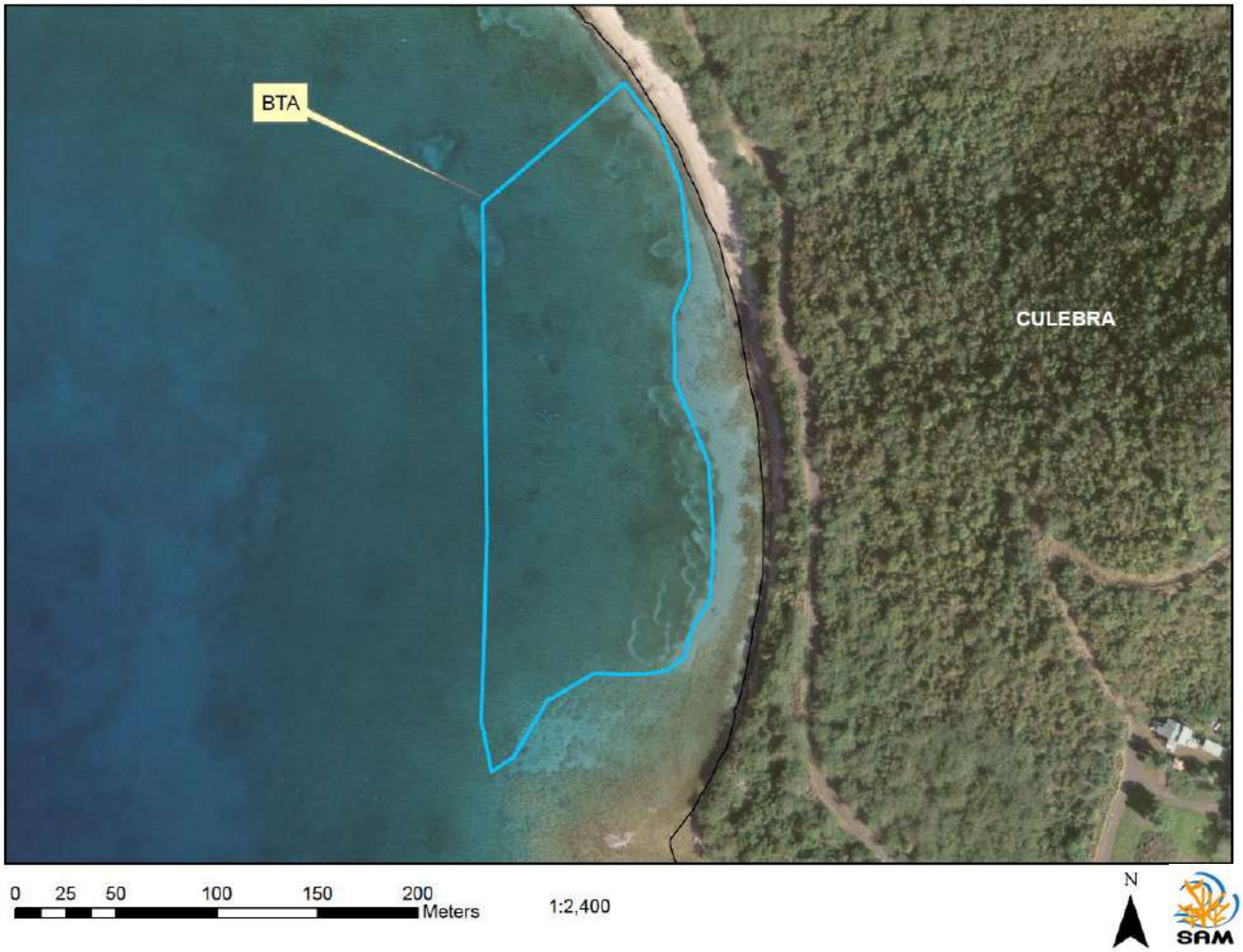

FIGURE 8. Surveyed polygon at BTA *before* hurricanes (2007).

4.1.2 Bahía Tamarindo (BTA)

The surveyed polygon at BTA is representative of its seagrass community, supports an abundant resident population of critically endangered Green turtle, *Chelonia mydas*, and an increasing nature-based tourism industry. This includes operations by multiple charter vessels from Fajardo, as well as several Culebra-based snorkeling and SCUBA diving operations, kayaking businesses, and extensive shore-based snorkeling. It is located within Canal Luis Peña no-take Natural Reserve. ***Figures 8-10*** show the extension and condition of the surveyed area *before* (2007, 2010) and *after* the hurricanes (2017). The surveyed polygon size was 28,632.3 m^2.

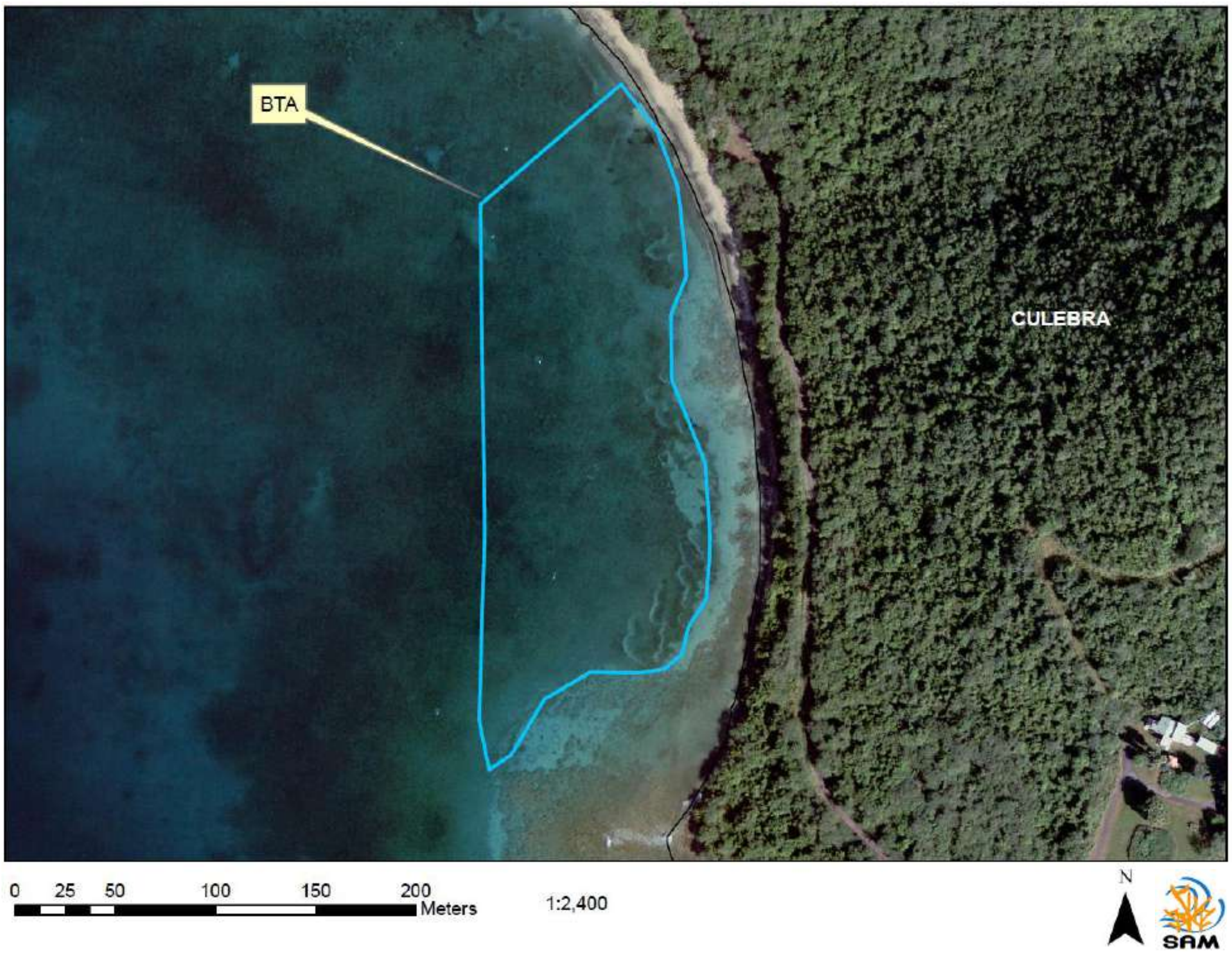

FIGURE 9. Surveyed polygon at BTA *before* hurricanes (2010).

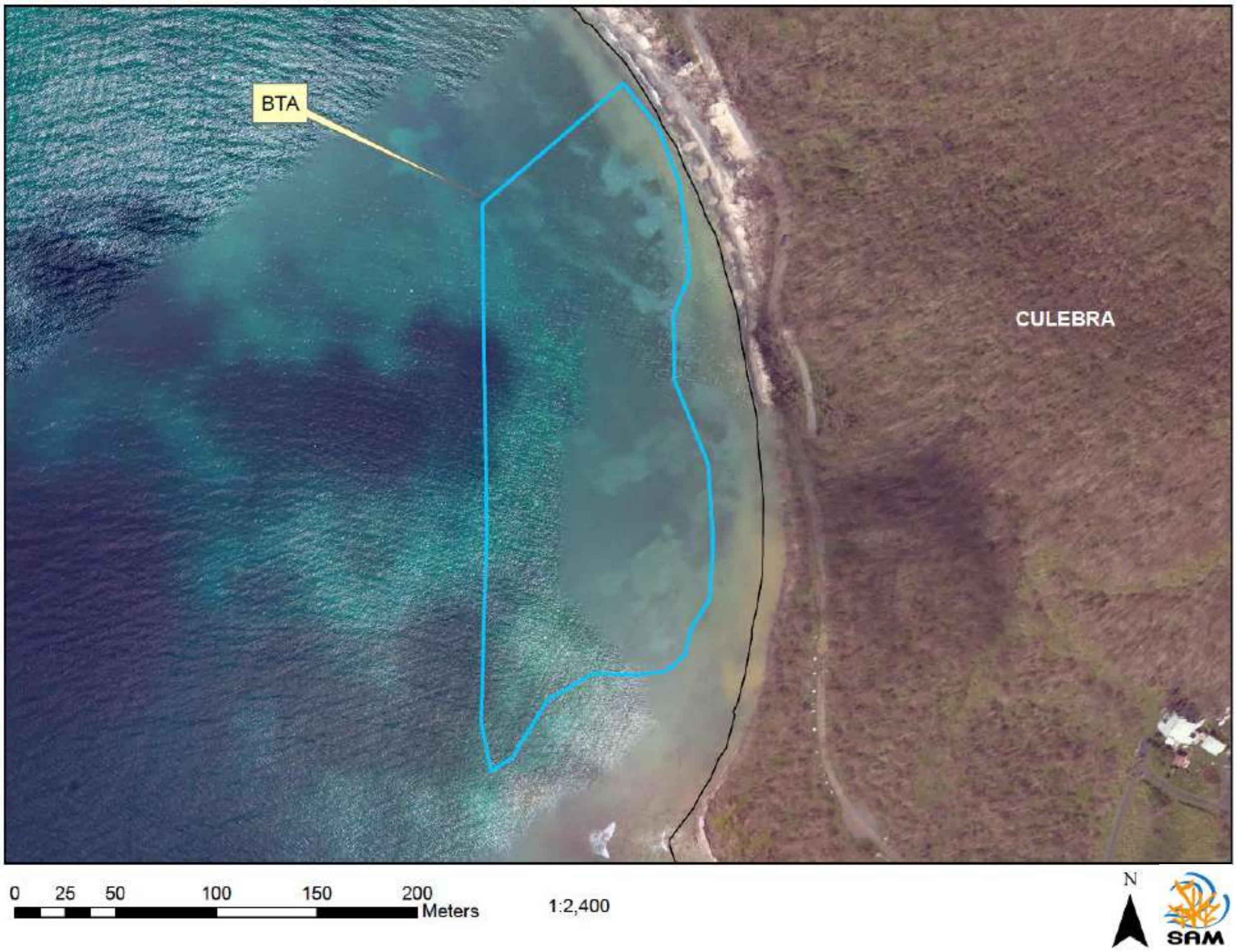

FIGURE 10. Surveyed polygon at BTA *after* hurricanes (2017).

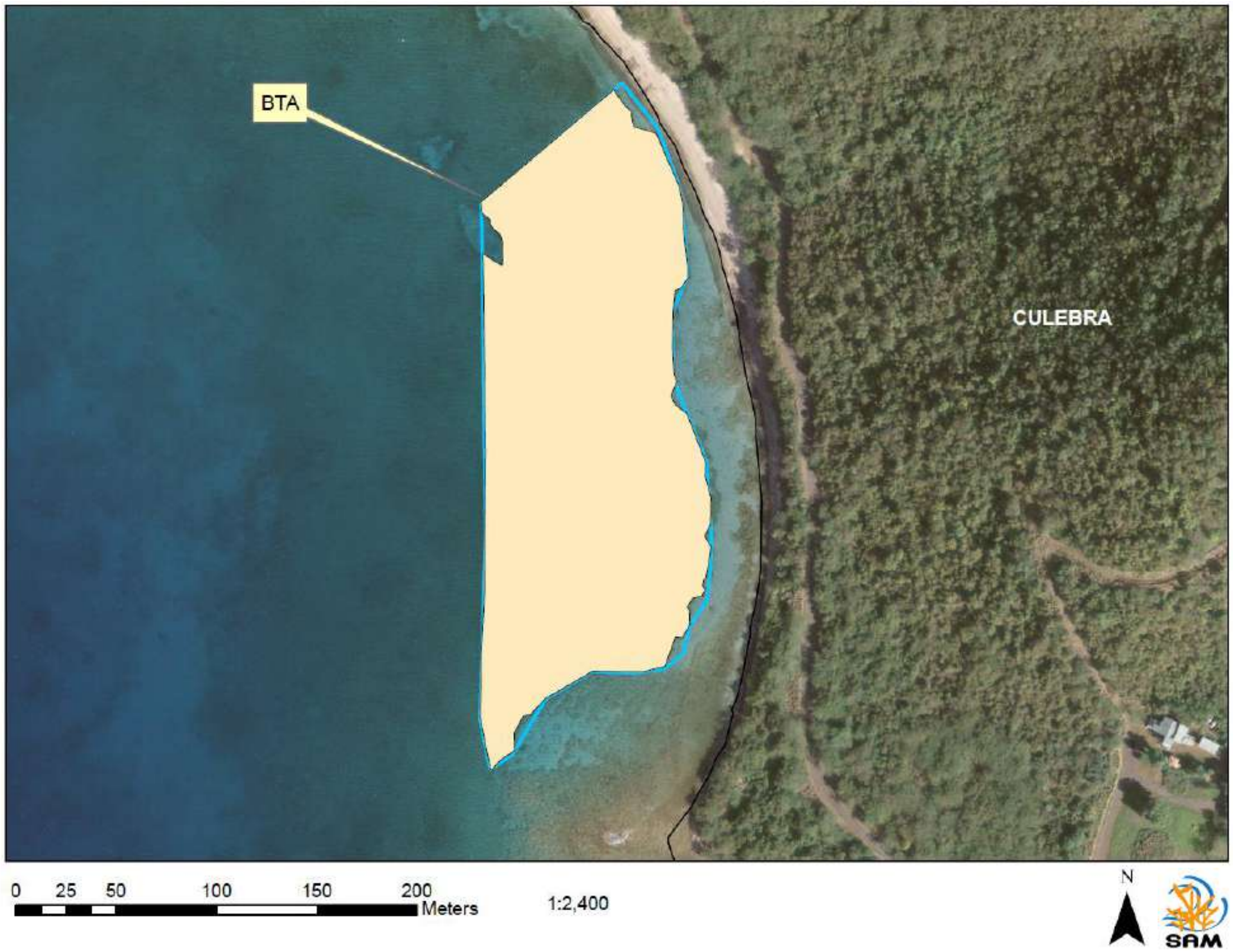

FIGURE 11. Spatial extension of seagrass habitats at BTA *before* hurricanes (2007).

Seagrass spatial extension at BTA in 2007 was 27,877.6 m^2 (97.4% cover) (***Tables 1-2***, ***Figure 11***). By 2010 it showed a slight decline to 27,481.2 m^2 (95.9% cover), or a 1.42% loss (***Figure 12***). However, after Hurricanes Irma and María in 2017 seagrass extension dropped to 19,897.6 m^2 (69.5% cover). This represented a 28.6% loss in comparison to 2007, and a 27.6% loss in comparison to 2010 (***Figure 13***). Most of the observed impacts were in the form of sediment bedload and burial, with minor seagrass matrix destruction.

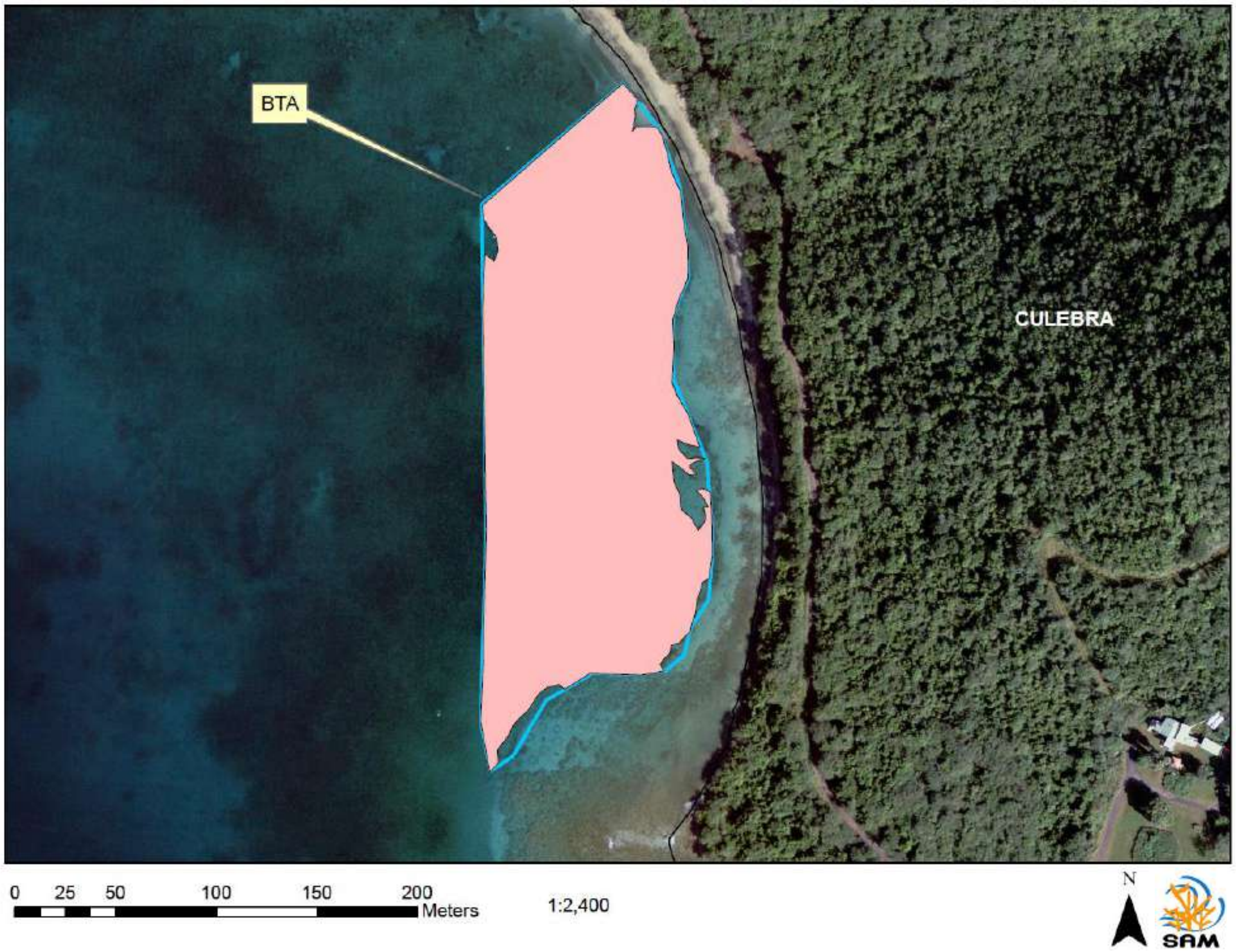

FIGURE 12. Spatial extension of seagrass habitats at BTA *before* hurricanes (2010).

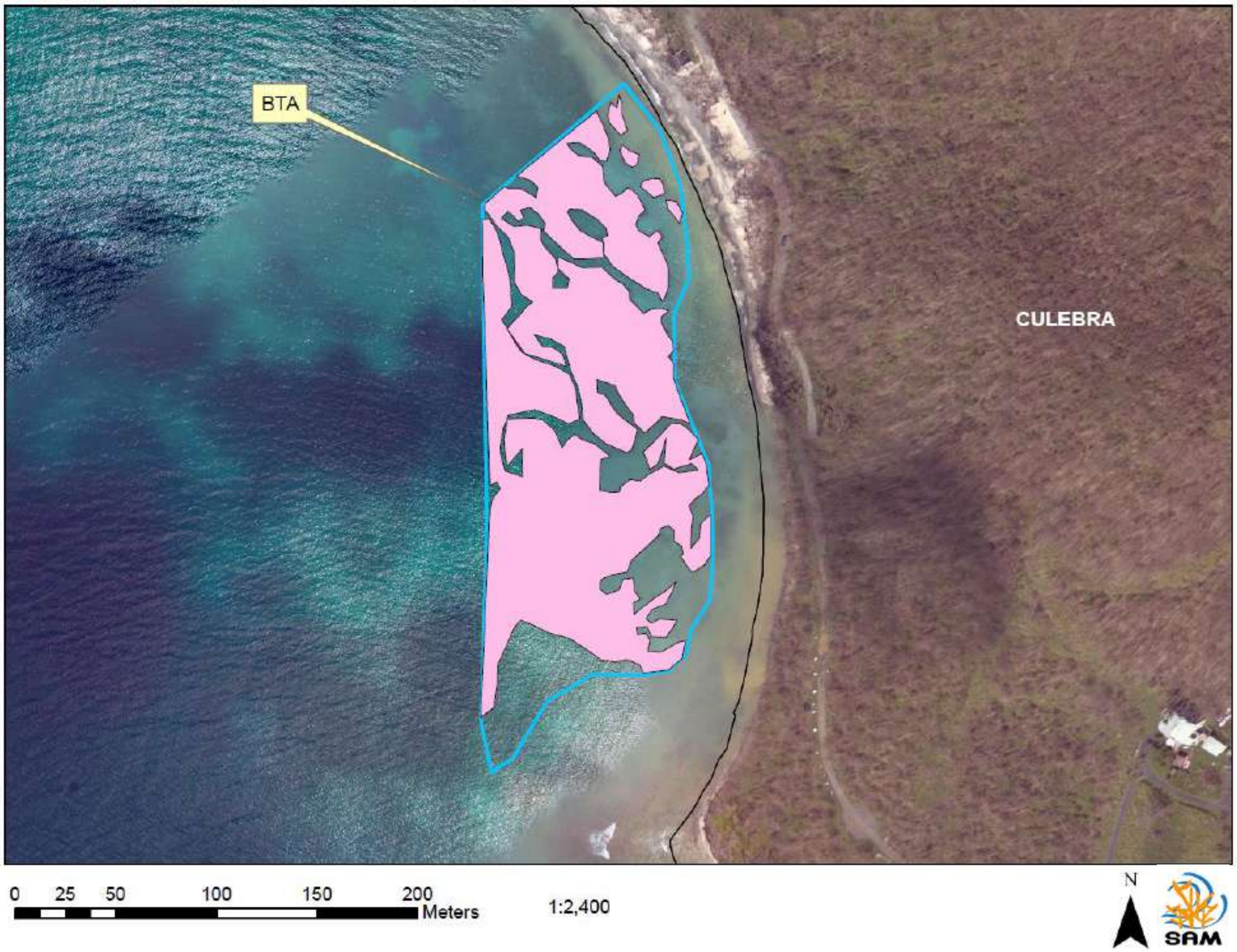

FIGURE 13. Spatial extension of seagrass habitats at BTA *after* hurricanes (2017).

FIGURE 14. Surveyed polygon at PTC *before* hurricanes (2007).

4.1.3 Punta Tamarindo Chico (PTC)

The surveyed polygon at PTC is also representative of its seagrass community, supports an abundant resident population of critically endangered Green turtle, *Chelonia mydas*, and an increasing nature-based tourism industry as in BTA. This area also supports extensive coral farming through the *Hope for the Reef* program operated by Sociedad Ambiente Marino (SAM). It is also located within Canal Luis Peña no-take Natural

Reserve. ***Figures 14-16*** show the extension and condition of the surveyed area *before* (2007, 2010) and *after* the hurricanes (2017). The surveyed polygon size was 47,935.5 m^2.

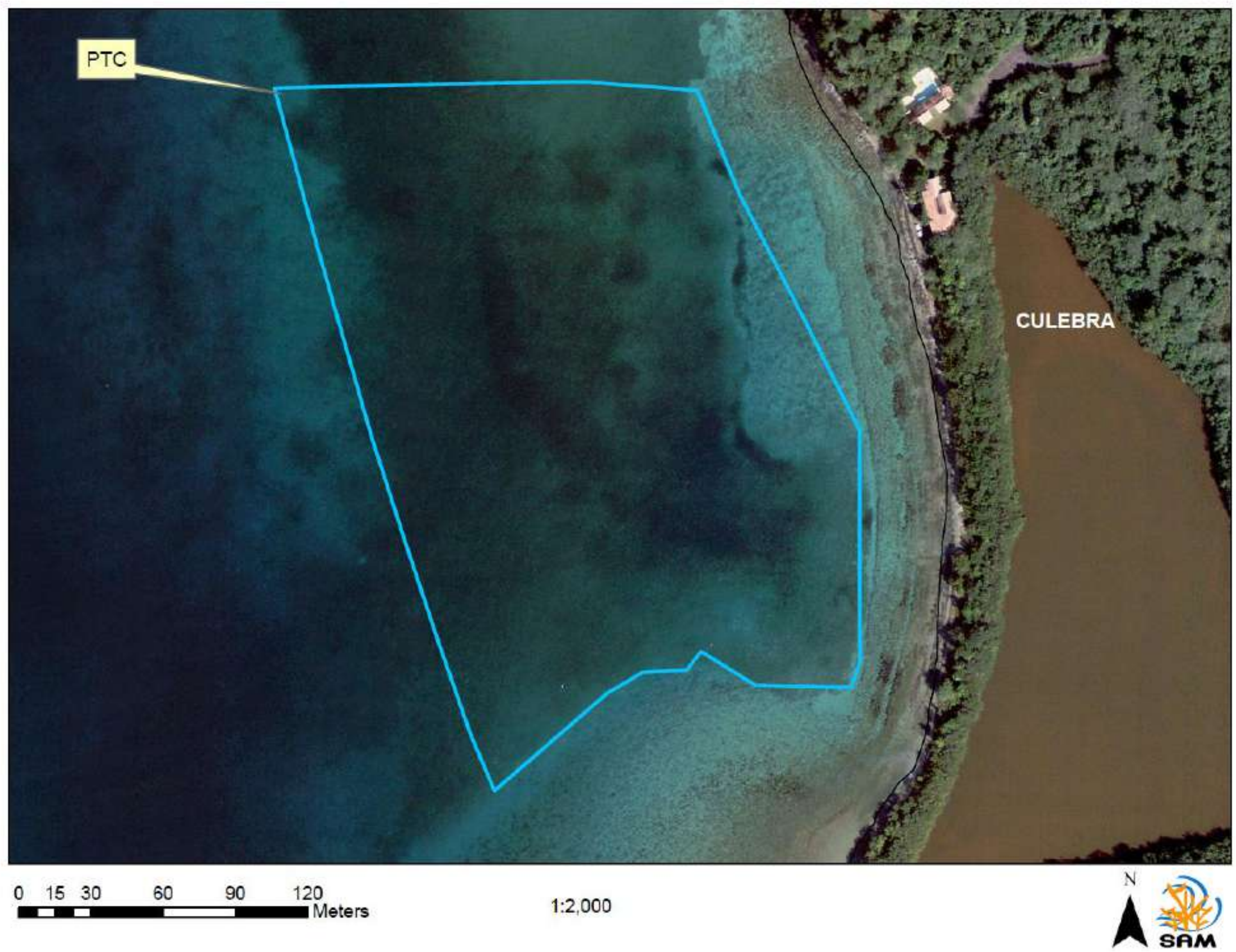

FIGURE 15. Surveyed polygon at PTC *before* hurricanes (2010).

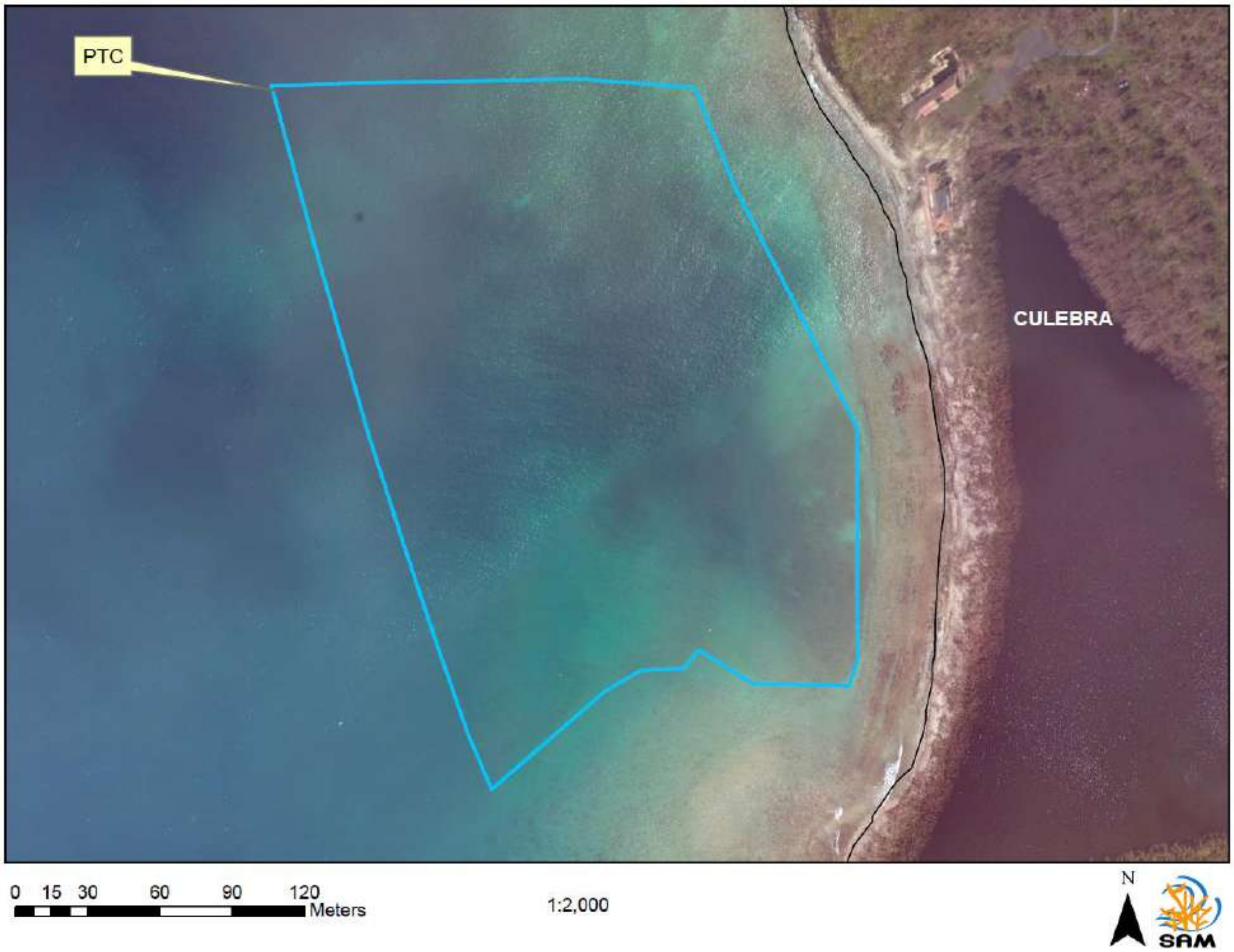

FIGURE 16. Surveyed polygon at BTA *after* hurricanes (2017).

FIGURE 17. Spatial extension of seagrass habitats at PTC *before* hurricanes (2007).

Seagrass spatial extension at PTC in 2007 was 44,672.9 m^2 (93.2% cover) (***Tables 1-2***, ***Figure 17***). By 2010 it showed a slight decline to 44,378.8 m^2 (92.6% cover), or a 0.66% loss (***Figure 18***). However, after Hurricanes Irma and María in 2017 seagrass extension dropped to 42,071.2 m^2 (87.8% cover). This represented only a 5.8% loss in comparison to 2007, and a 5.2% loss in comparison to 2010 (***Figure 19***). Most of the observed impacts were in the form of sediment bedload and burial, with minimal seagrass matrix destruction.

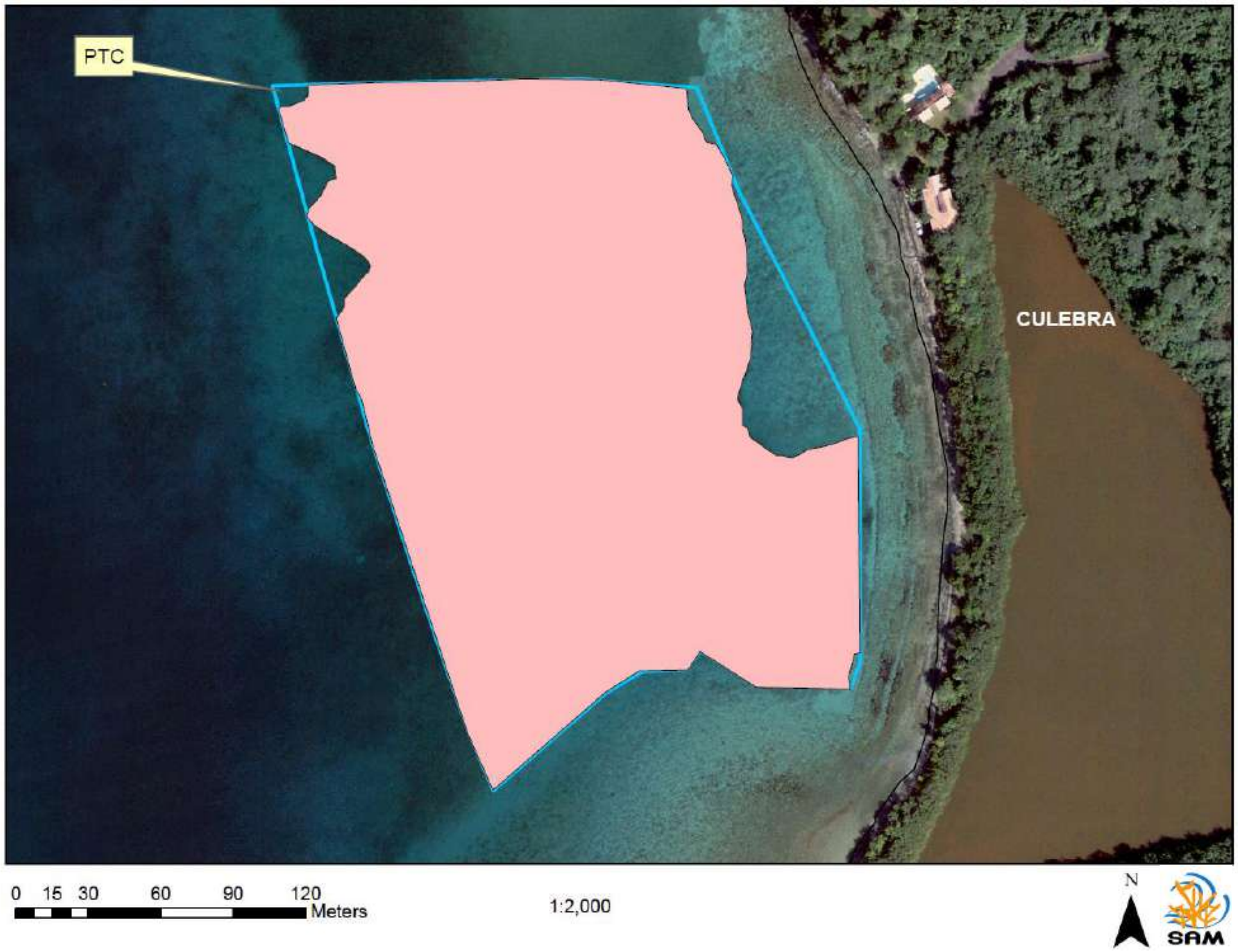

FIGURE 18. Spatial extension of seagrass habitats at PTC *before* hurricanes (2010).

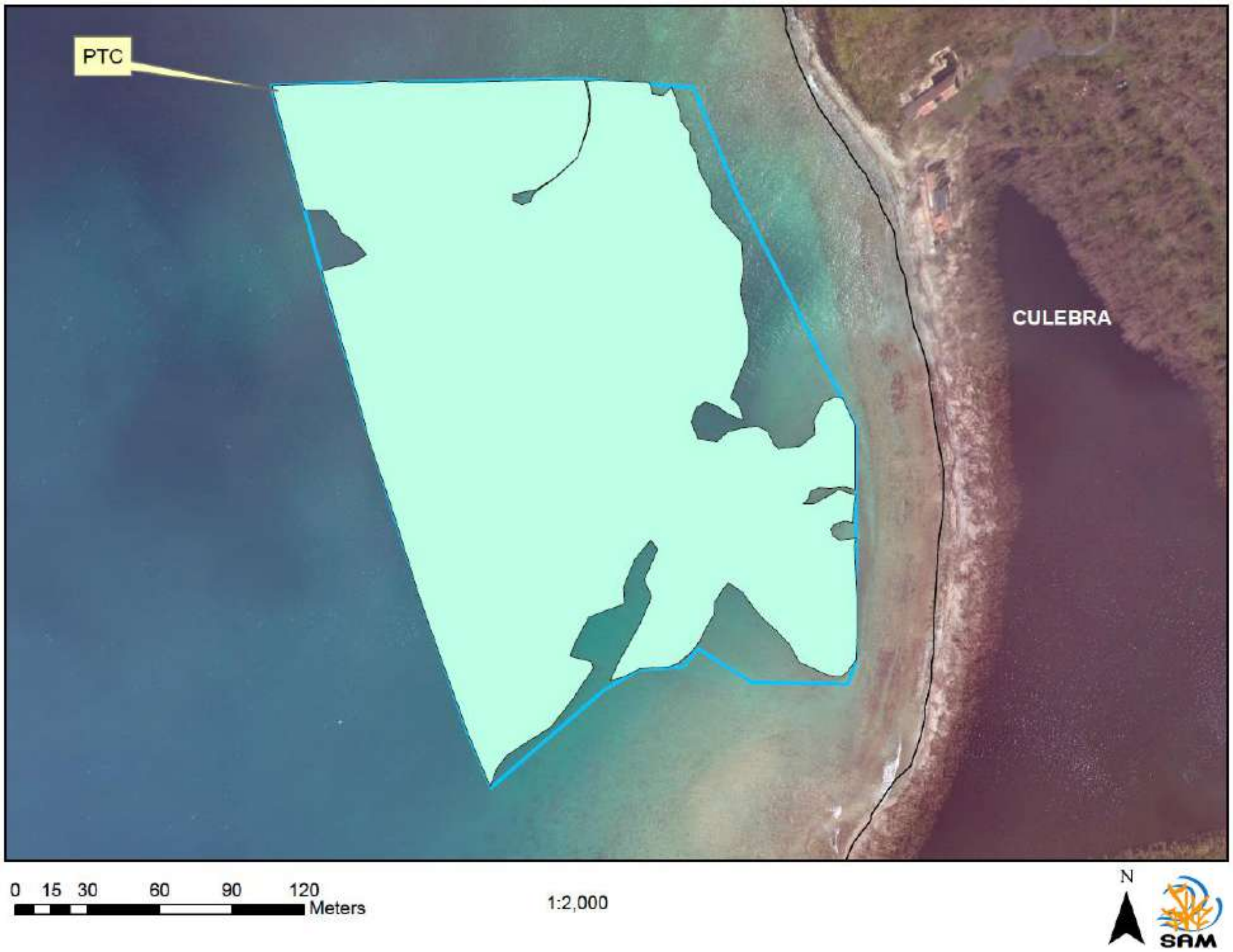

FIGURE 19. Spatial extension of seagrass habitats at PTC *after* hurricanes (2017).

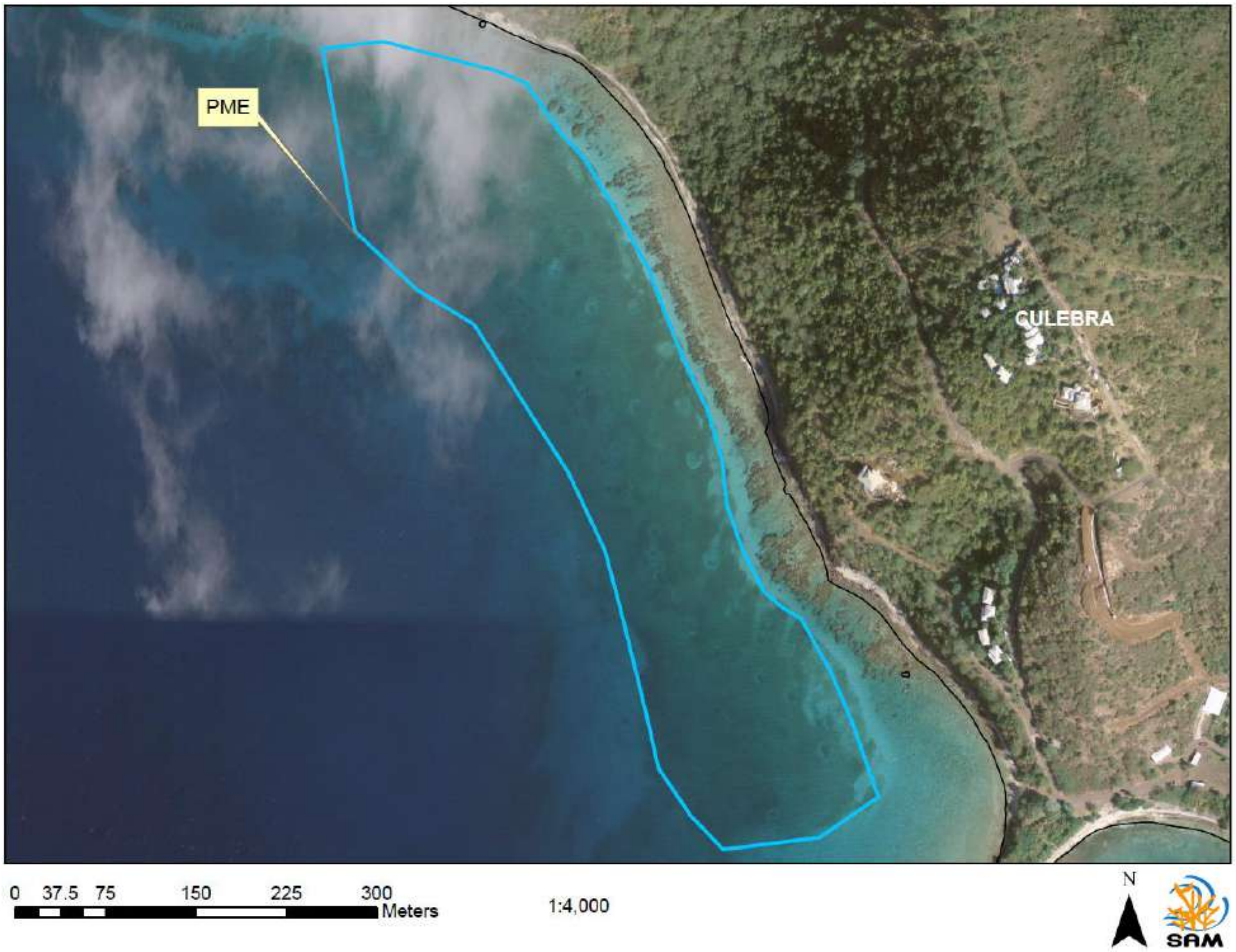

FIGURE 20. Surveyed polygon at PME *before* hurricanes (2007).

4.1.4 Punta Melones (PME)

The surveyed polygon at PME is also representative of its seagrass community, supports the frequent visit of critically endangered Green turtle, *Chelonia mydas*. This area is also getting increasing support from tourists and marine recreationists. ***Figures 20-22*** show the extension and condition of the surveyed area *before* (2007, 2010) and *after* the hurricanes (2017). It is also located within Canal Luis Peña no-take Natural Reserve. The surveyed polygon size was 105,398.2 m^2.

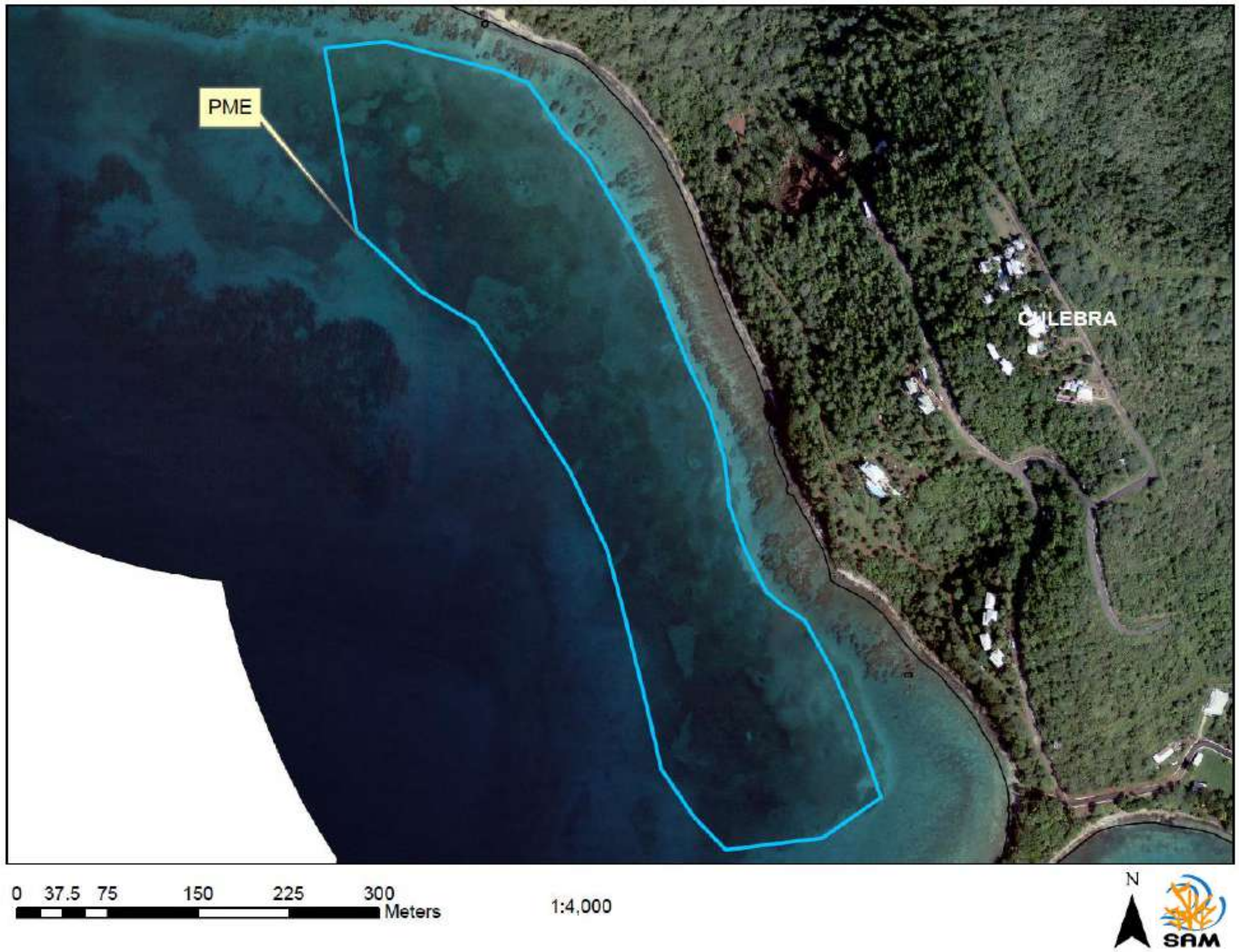

FIGURE 21. Surveyed polygon at PME *before* hurricanes (2010).

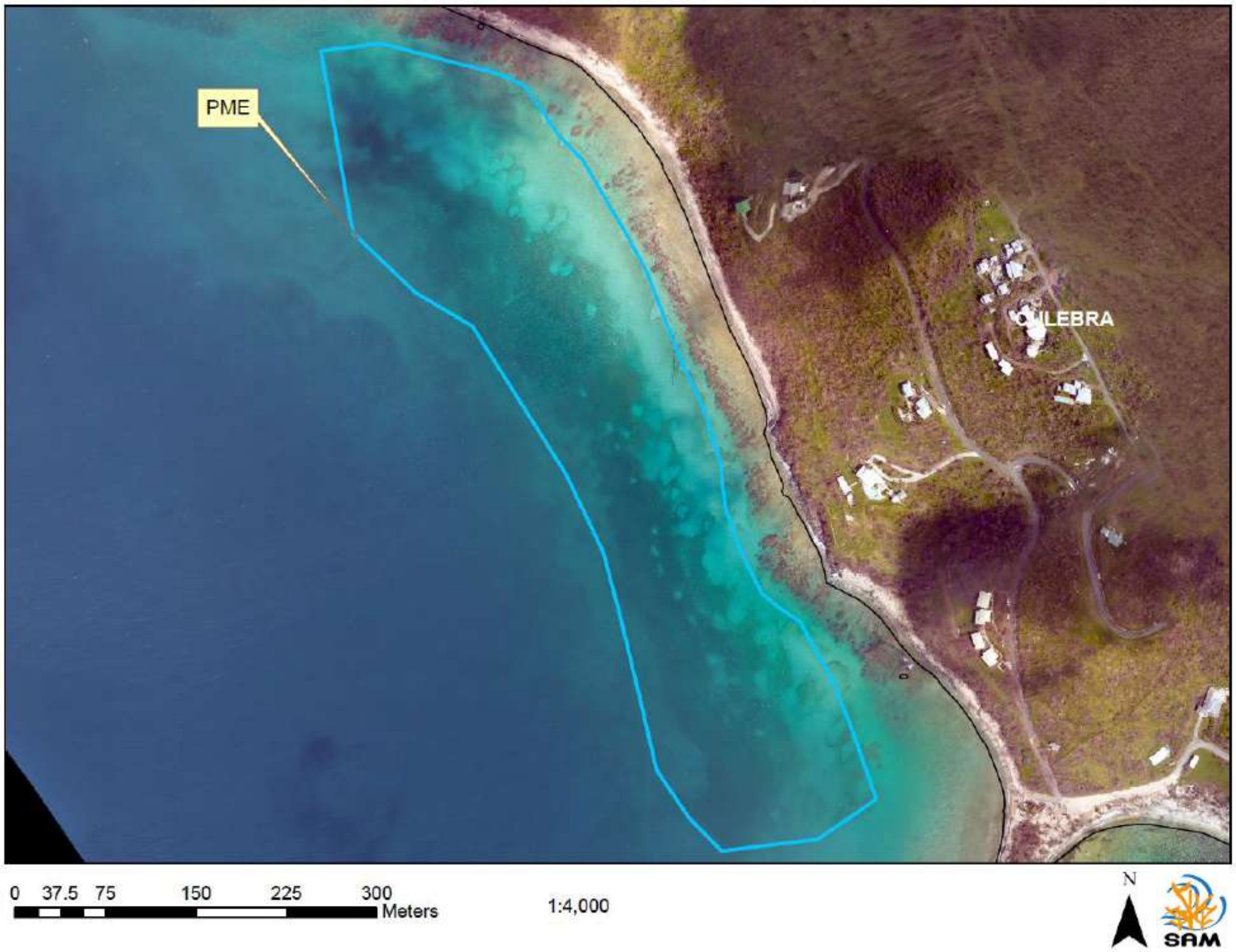

FIGURE 22. Surveyed polygon at PME *after* hurricanes (2017).

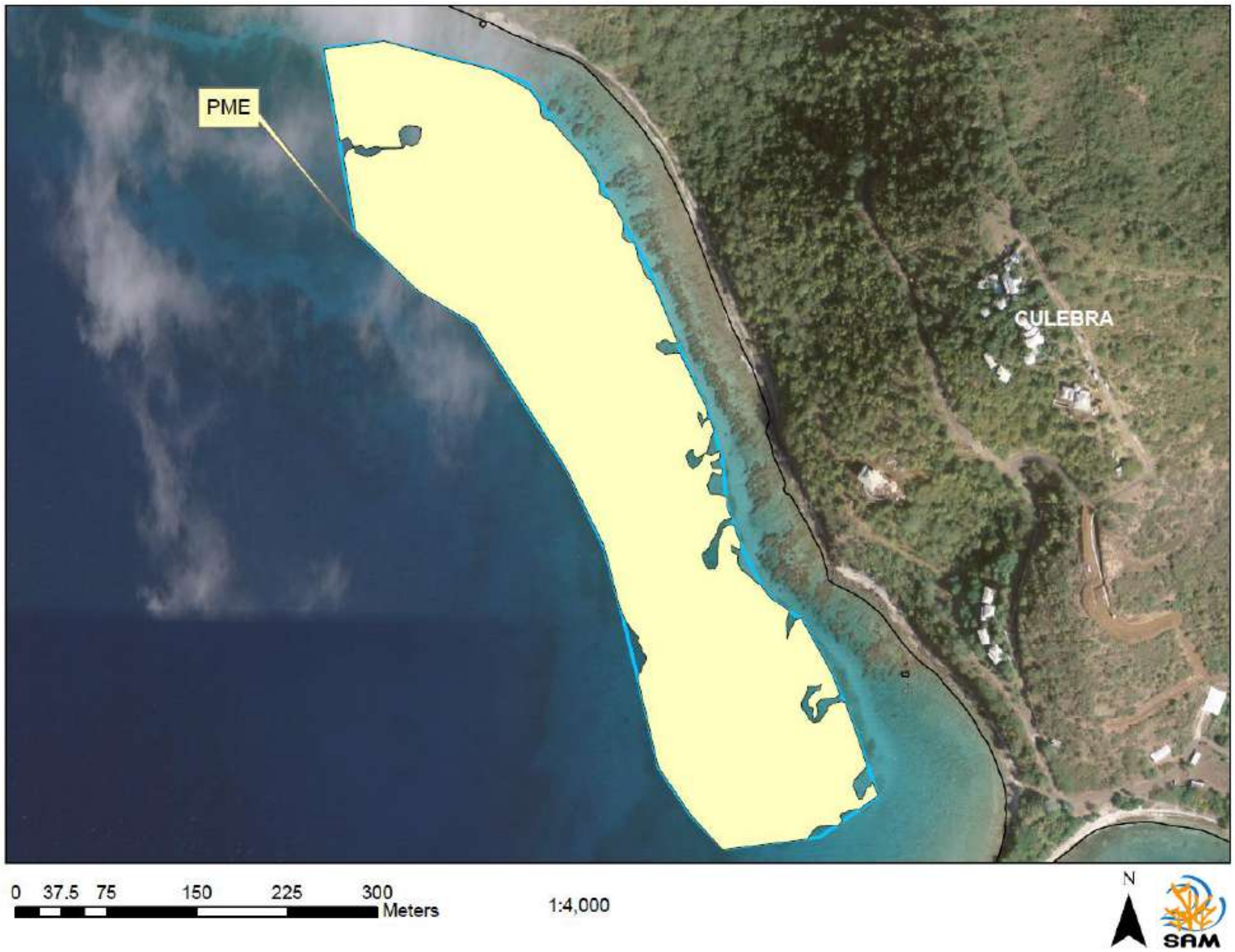

FIGURE 23. Spatial extension of seagrass habitats at PME *before* hurricanes (2007).

Seagrass spatial extension at PME in 2007 was 101,921.9 m^2 (96.7% cover) (***Tables 1-2***, ***Figure 23***). By 2010 it showed a slight decline to 98,334.1 m^2 (93.3% cover), or a 3.52% loss (***Figure 24***). However, after Hurricanes Irma and María in 2017 seagrass extension dropped to 70,160.1 m^2 (66.6% cover). This represented a significant 31.2% loss in comparison to 2007, and a 28.7% loss in comparison to 2010 (***Figure 25***). Most of the observed impacts were in the form of dramatic sediment bedload and burial, with moderate to frequent seagrass matrix destruction.

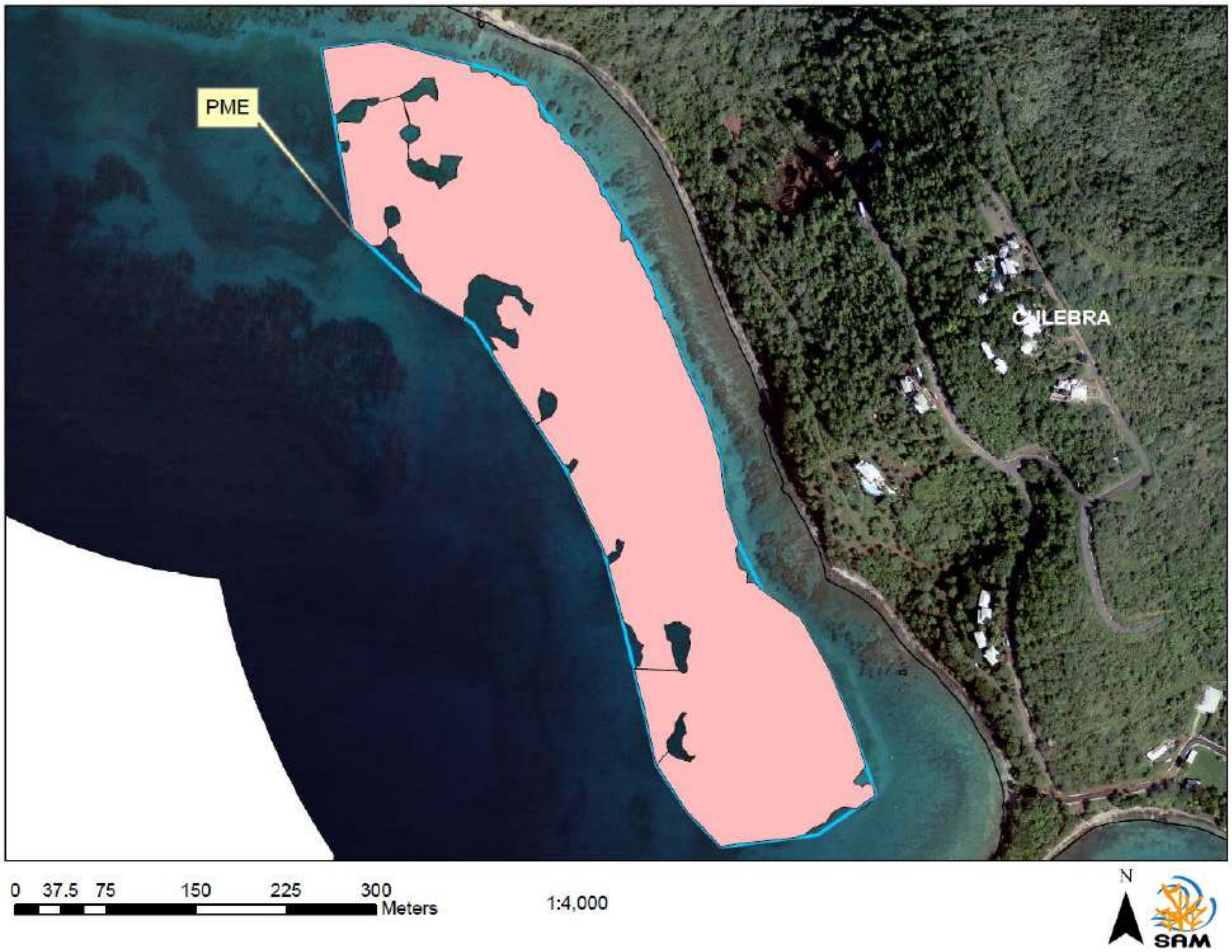

FIGURE 24. Spatial extension of seagrass habitats at PME *before* hurricanes (2010).

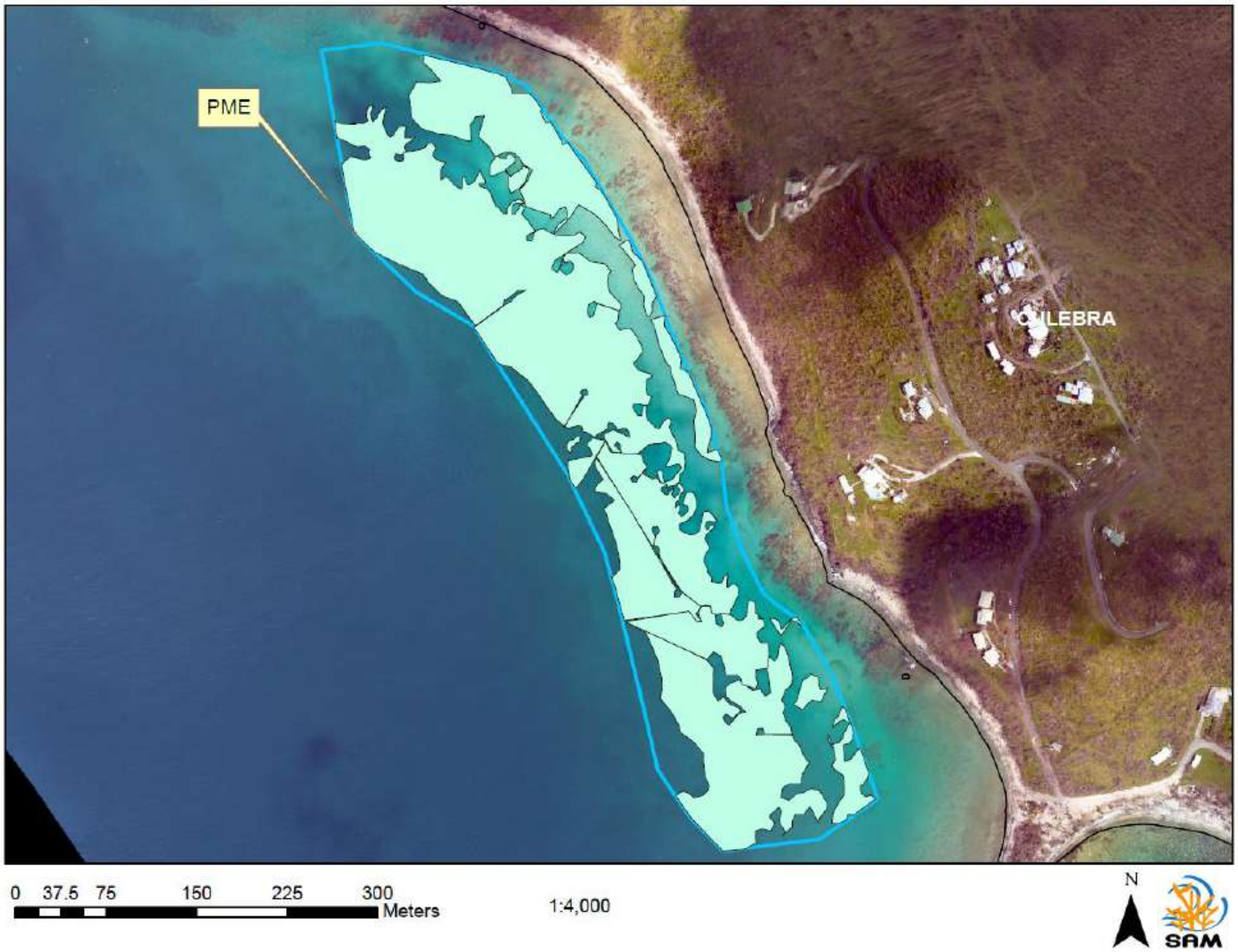

FIGURE 25. Spatial extension of seagrass habitats at PME *after* hurricanes (2017).

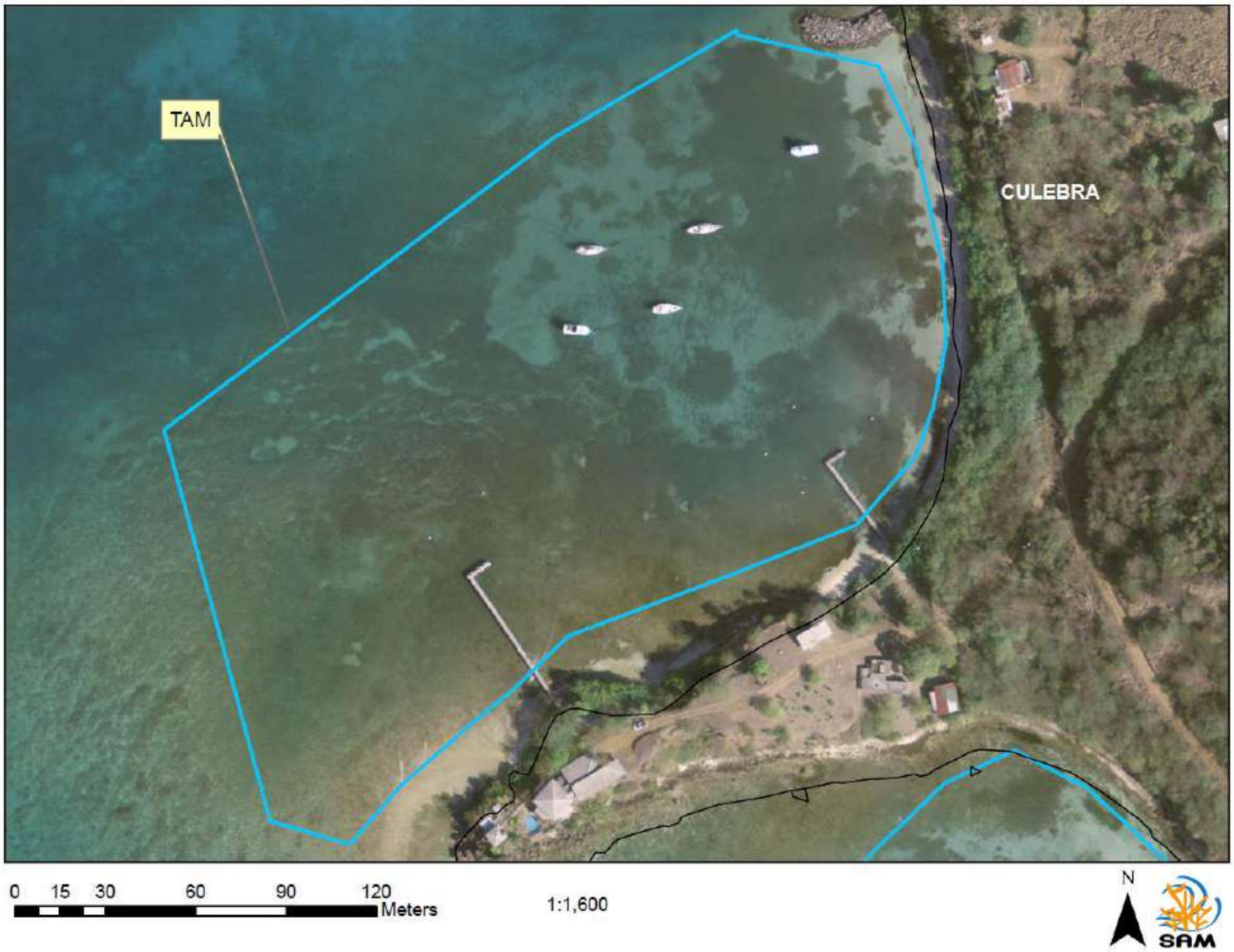

FIGURE 26. Surveyed polygon at TAM *before* hurricanes (2007).

4.1.5 Playa Tampico (TAM)

The surveyed polygon at TAM is also representative of its seagrass community and supports the common visit of critically endangered Green turtle, *Chelonia mydas*. But it is under an increasing pressure of anchoring activities by recreational vessels (***Figure 26***). It is also frequently subjected to recurrent turbid, sediment-laden, nutrient loaded runoff pulses from an adjacent steep dirt road (***Figure 27***), and from adjacent Canal de Lobina. TAM is also located right off the PR Ports Authority main docking facilities in downtown

Dewey. Therefore, sediment resuspension associated to ferry operations is recurrent several times per day. Invasive Sea vine (*Halophila stipulacea*) is rapidly spreading across TAM. This area is also getting increasing visits from tourists and marine recreationists. ***Figures 26***, ***28***, and ***29*** show the extension and condition of the surveyed area *before* (2007, 2010) and *after* the hurricanes (2017). The surveyed polygon size was 39,542.2 m^2.

FIGURE 27. Partial view during a major turbid, sediment-laden, nutrient-loaded runoff pulse event impacting Playa Tampico (TAM). Image courtesy of Mary Ann Lucking, Coralations, Inc.

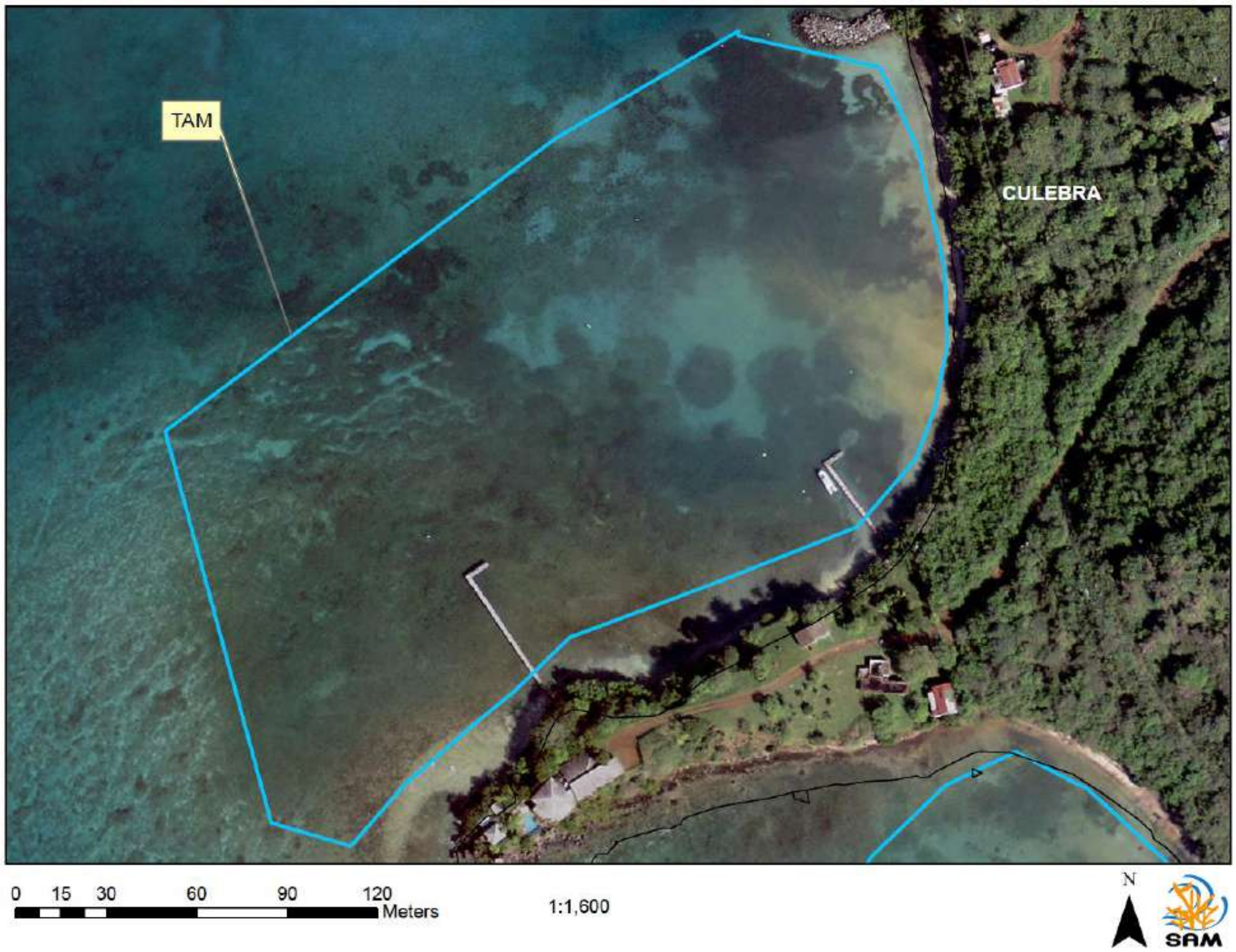

FIGURE 28. Surveyed polygon at TAM *before* hurricanes (2010).

FIGURE 29. Surveyed polygon at TAM *after* hurricanes (2017).

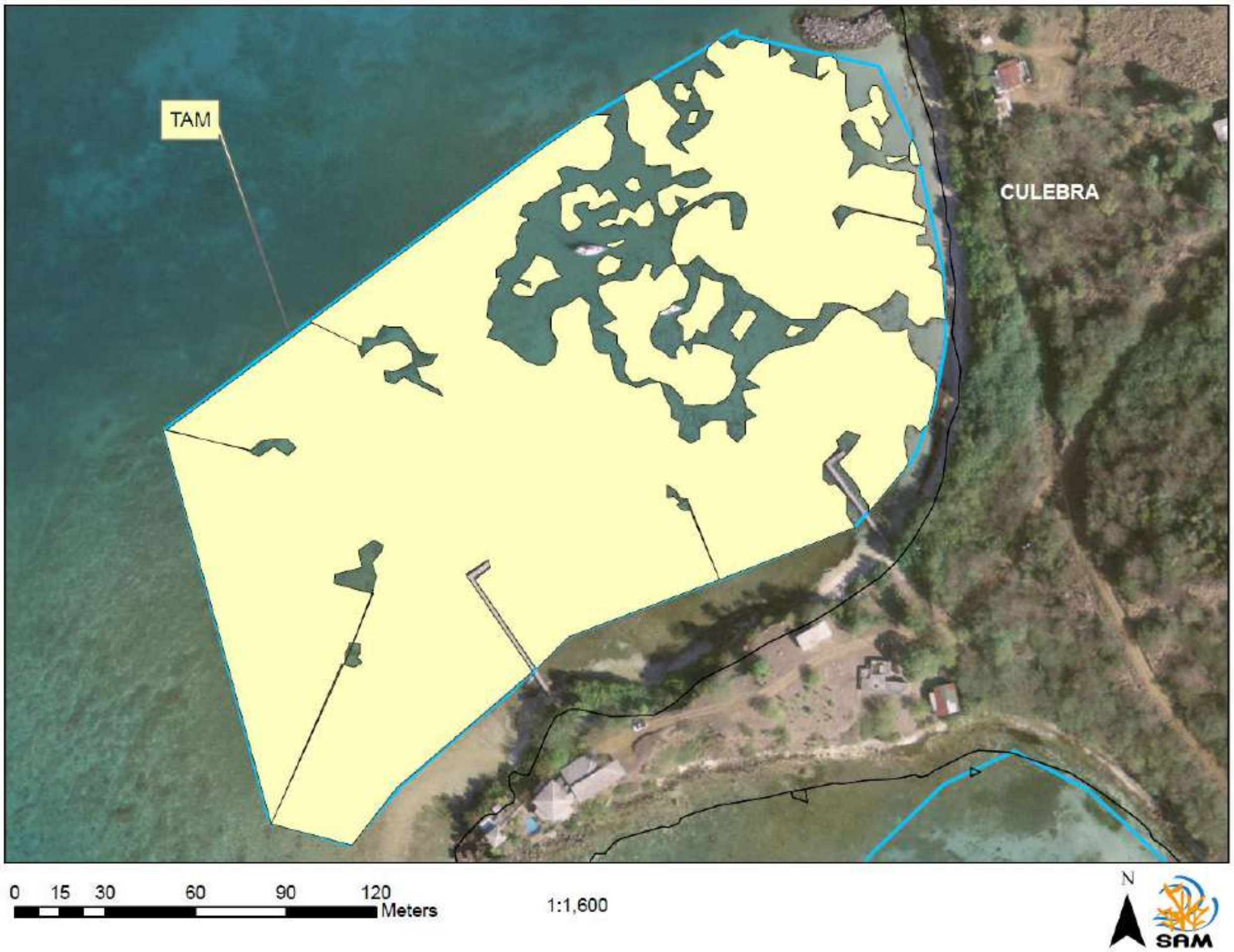

FIGURE 30. Spatial extension of seagrass habitats at TAM *before* hurricanes (2007).

Seagrass spatial extension at TAM in 2007 was 33,762.7 m^2 (85.4% cover) (***Tables 1-2***, ***Figure 30***). By 2010 it showed a modest increase to 34,703.3 m^2 (87.8% cover), or a 2.79% increase (***Figure 31***). However, after Hurricanes Irma and María in 2017 seagrass extension dropped to 25,636.6 m^2 (64.8% cover). This represented a 24.1% loss in comparison to 2007, and a 28.7% loss in comparison to 2010 (***Figure 32***). Most of the observed impacts were in the form of the indirect effect of the dramatic shallow coral reef framework demolition from the shallow fringing reef located between Bahía Linda (BLI) and TAM, which caused massive coral rubble displacement and seagrass burial at the southern segment of the TAM polygon. There were also minor sediment bedload and burial, and minimal seagrass matrix destruction.

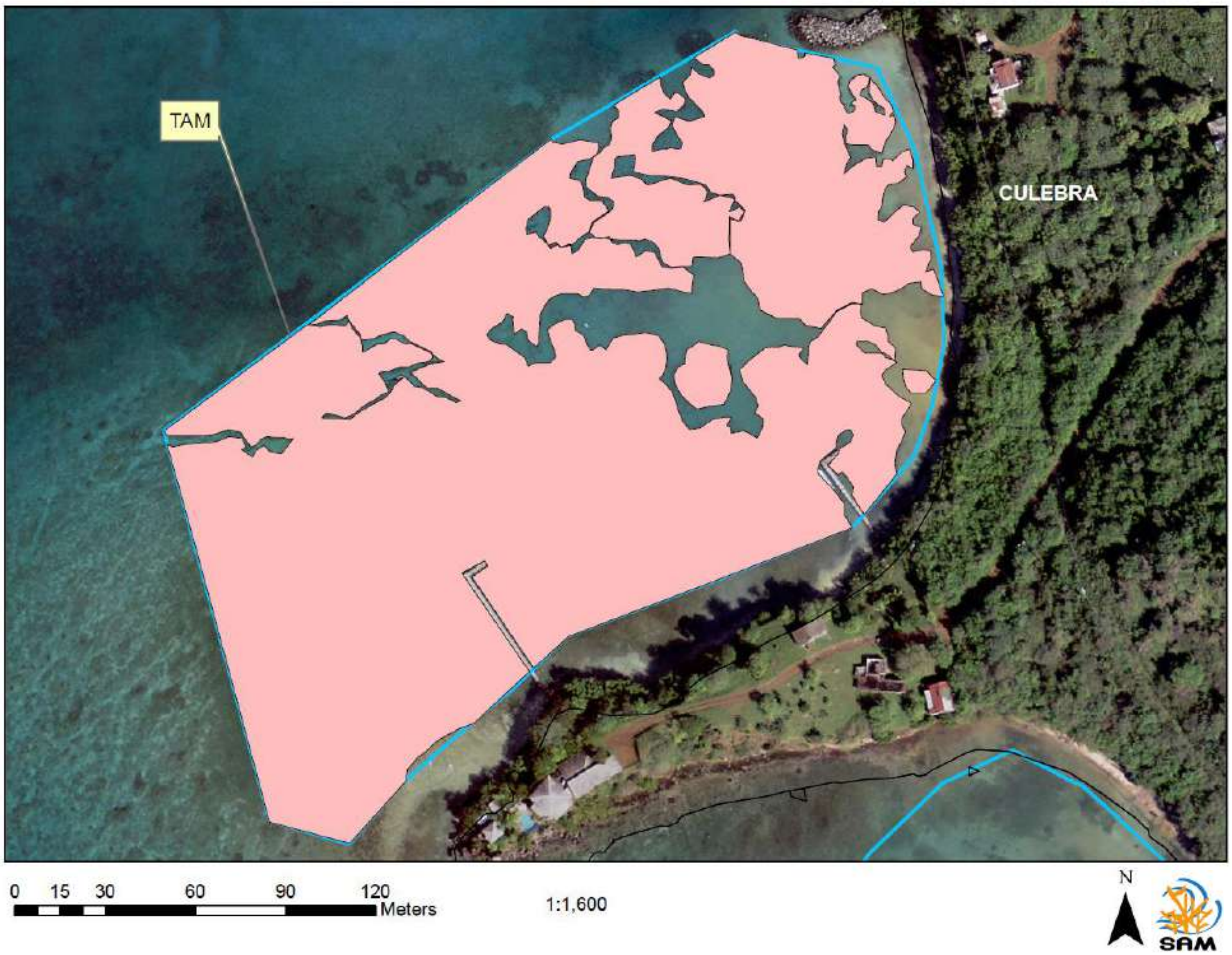

FIGURE 31. Spatial extension of seagrass habitats at TAM *before* hurricanes (2010).

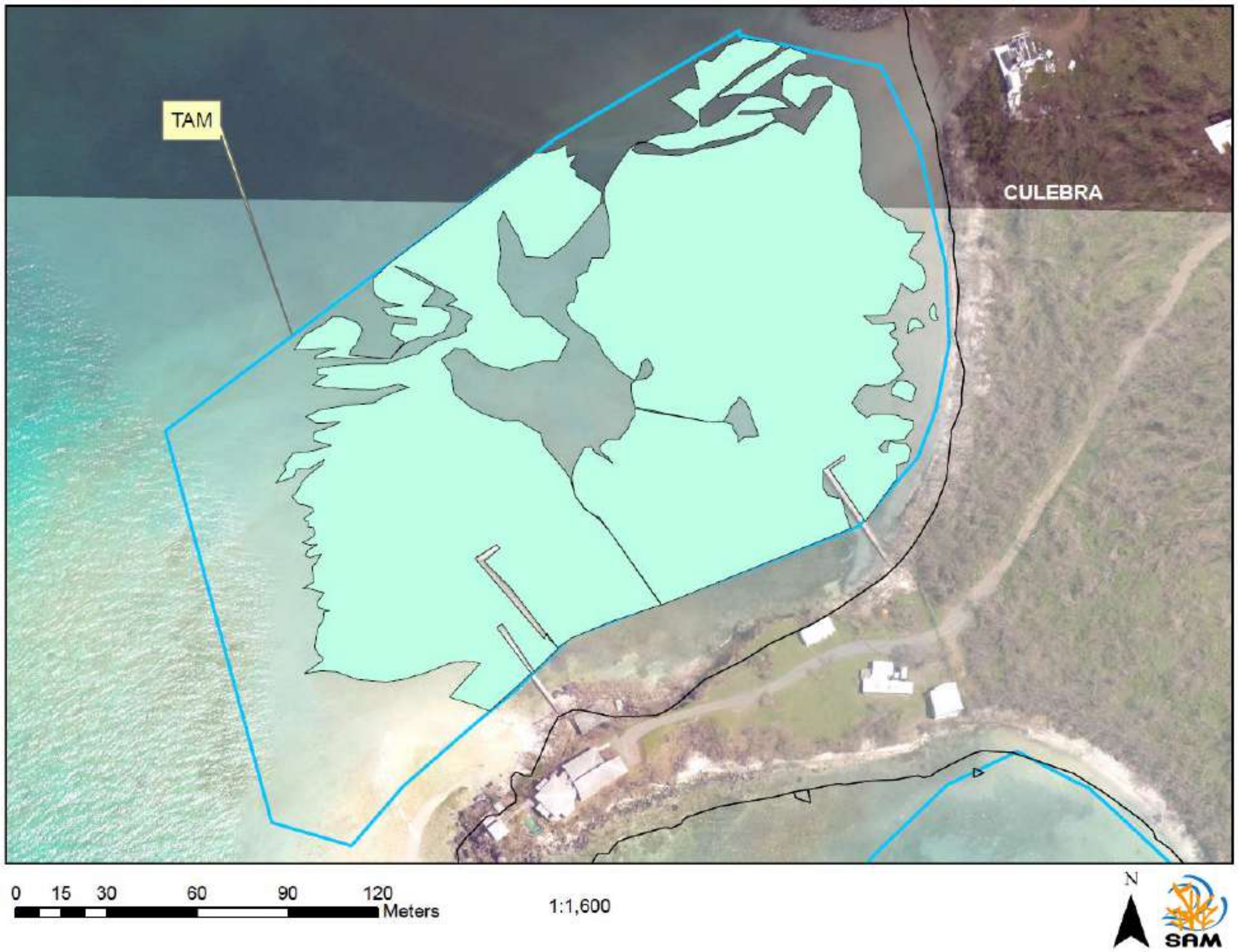

FIGURE 32. Spatial extension of seagrass habitats at TAM *after* hurricanes (2017).

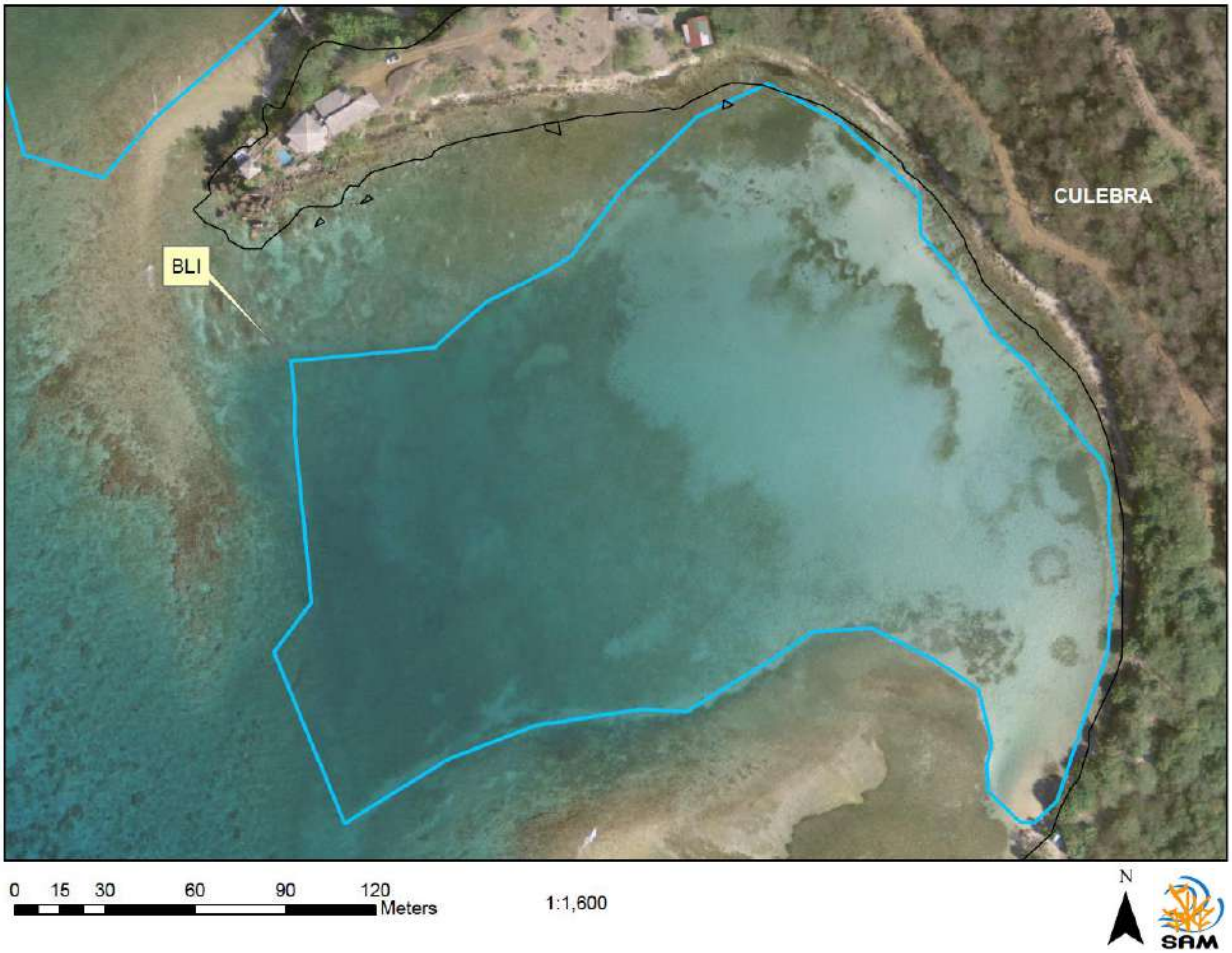

FIGURE 33. Surveyed polygon at BLI *before* hurricanes (2007).

4.1.6 Bahía Linda (BLI)

The surveyed polygon at BLI is representative of its seagrass community and supports the sporadic visit of critically endangered Green turtle, *Chelonia mydas*. BLI, which is also locally known as Playa Dátiles, is under an a very high pressure of anchoring activities by recreational vessels. Under long holiday weekends there can be over 30 private yachts anchored at BLI, exceeding the existing capacity of mooring buoys. BLI is also frequently impacted by stranded decomposing mats of brown algae *Sargassum fluitans*, which has also contributed to the massive loss of shallow native seagrass assemblages. Invasive Sea vine (*Halophila stipulacea*) has largely spreaded across BLI. ***Figures 33-35*** show the extension and condition of the surveyed area *before* (2007, 2010) and *after* the hurricanes (2017). The surveyed polygon size was 41,831.8 m^2.

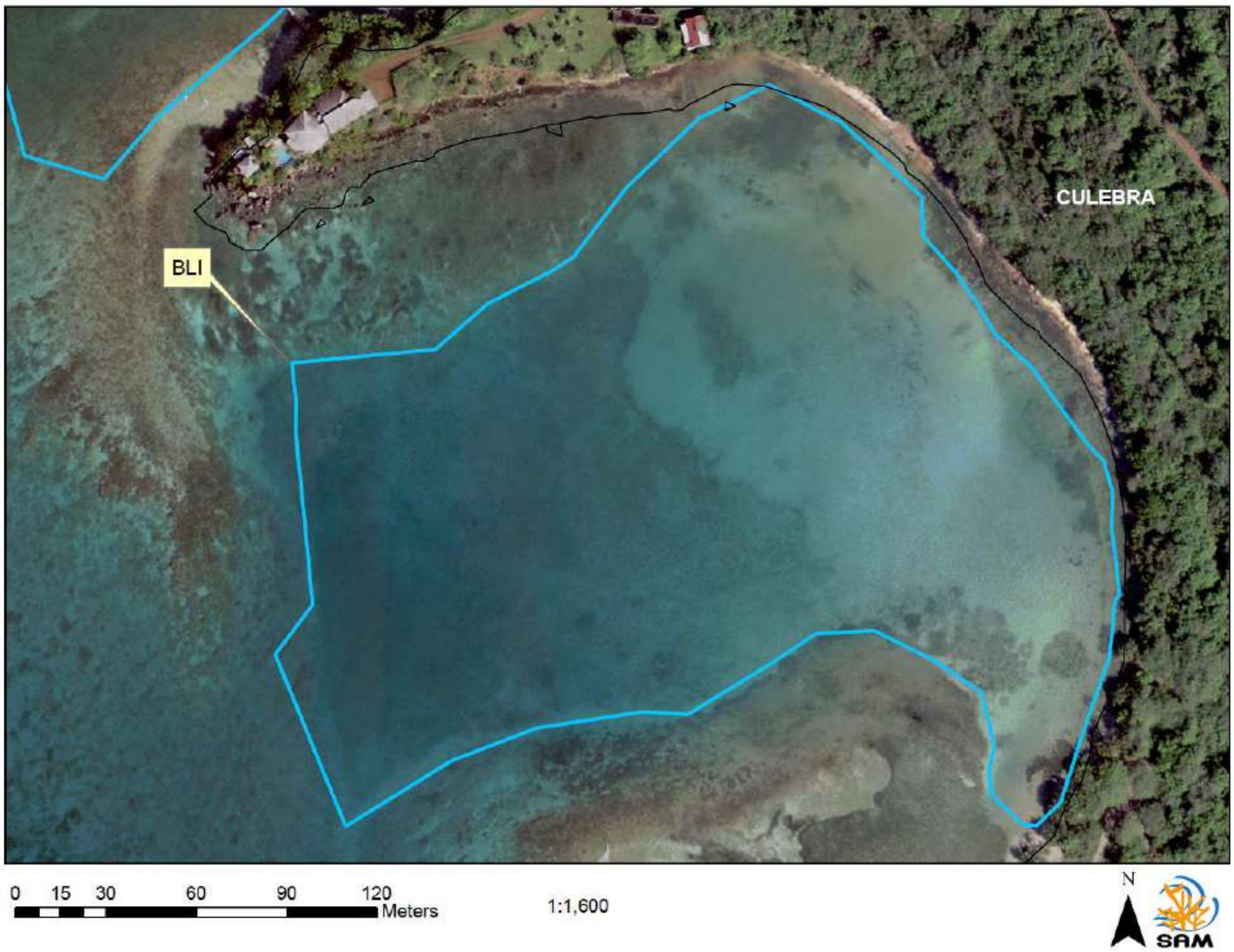

FIGURE 34. Surveyed polygon at BLI *before* hurricanes (2010).

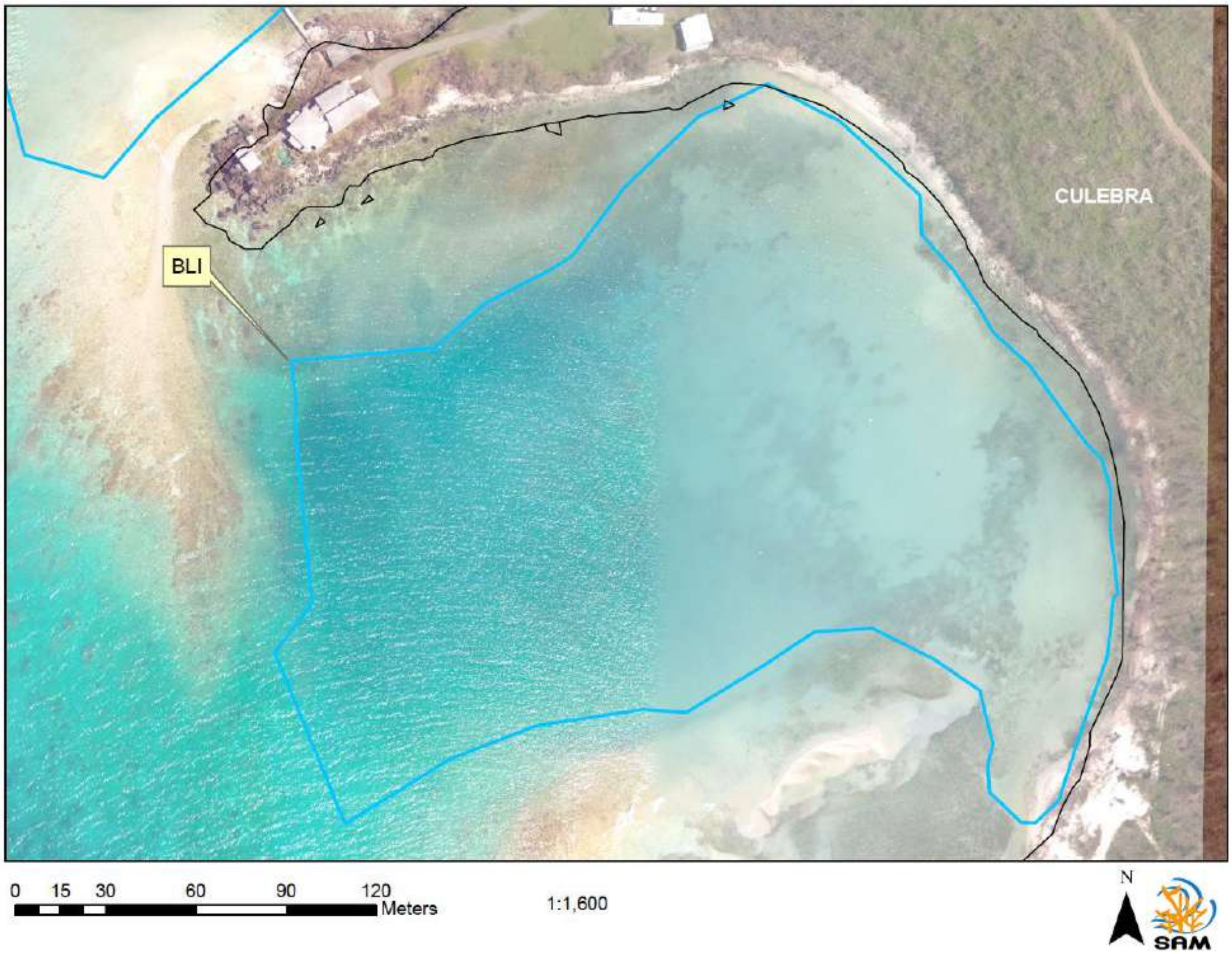

FIGURE 35. Surveyed polygon at BLI *after* hurricanes (2017).

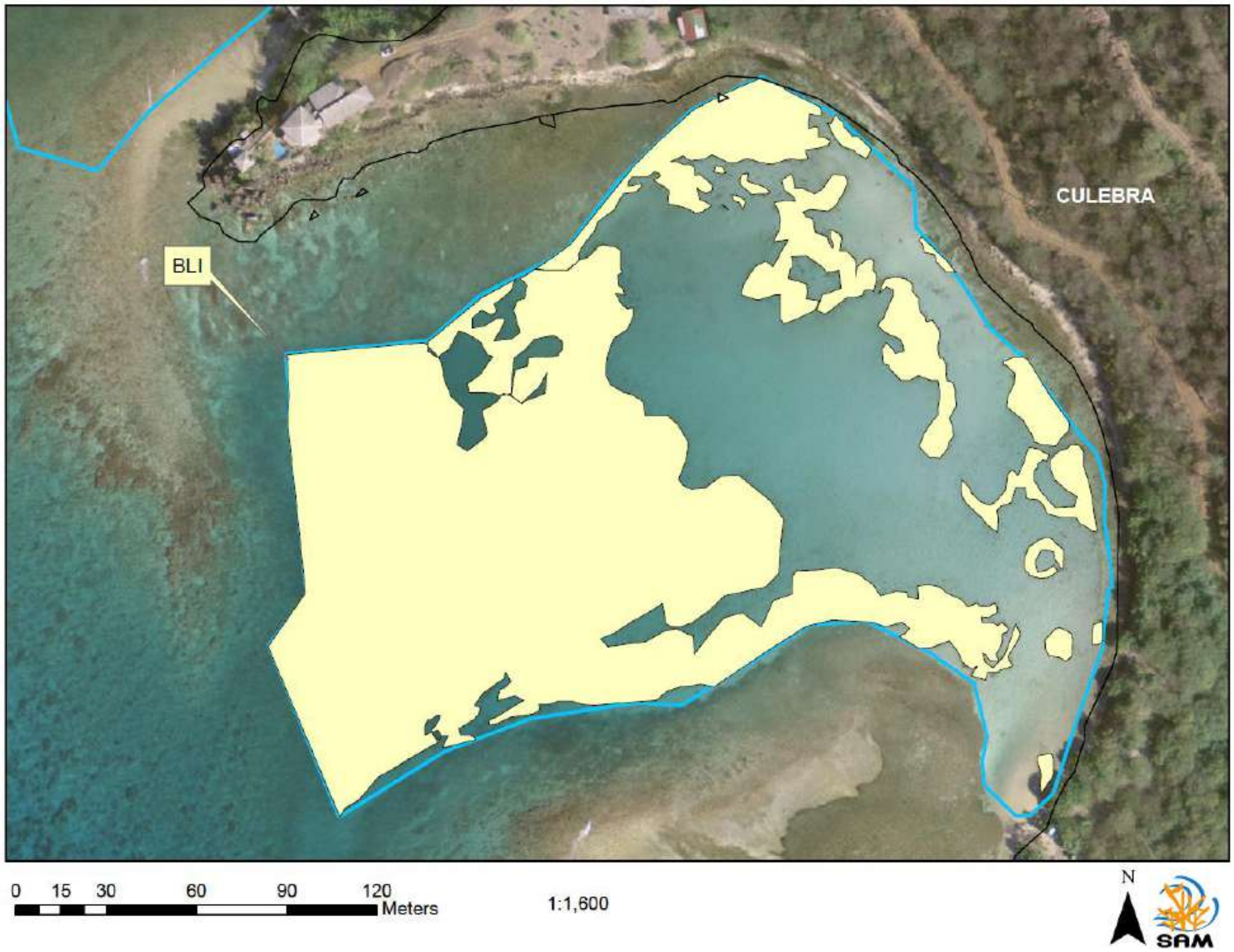

FIGURE 36. Spatial extension of seagrass habitats at BLI *before* hurricanes (2007).

Seagrass spatial extension at BLI in 2007 was 23,901.8 m^2 (57.1% cover) (***Tables 1-2***, ***Figure 36***). By 2010 declined to 23,437.0 m^2 (56.0% cover), or a 1.94% loss (***Figure 37***). However, after Hurricanes Irma and María in 2017 seagrass extension slightly dropped to 23,150.0 m^2 (55.3% cover). This represented a minimal 3.15% loss in comparison to 2007, and a 1.22% loss in comparison to 2010 (***Figure 38***). Playa Dátiles is a semi-enclosed bay. Therefore, due to its physical configuration, its protection by two shallow fringing reefs, and due to its narrow entrance, seagrass communities were largely protected from wave action during the hurricanes. Most of the observed impacts were in the form of minor sediment bedload and burial. Nevertheless, turtle grass, *Thalassia testudinum*, assemblages are being significantly displaced by extensive meadows of invasive Sea vine (*Halophila stipulacea*).

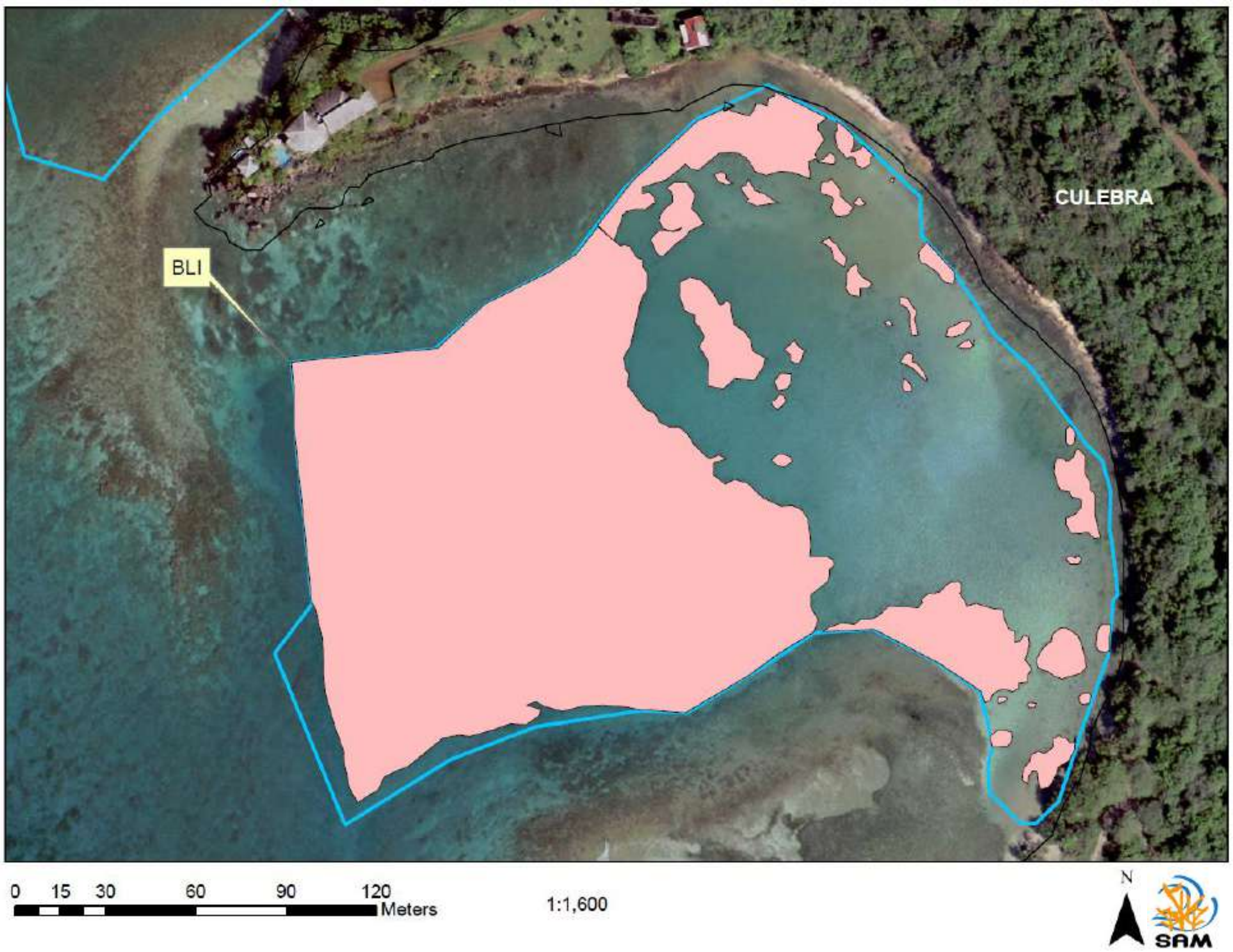

FIGURE 37. Spatial extension of seagrass habitats at BLI *before* hurricanes (2010).

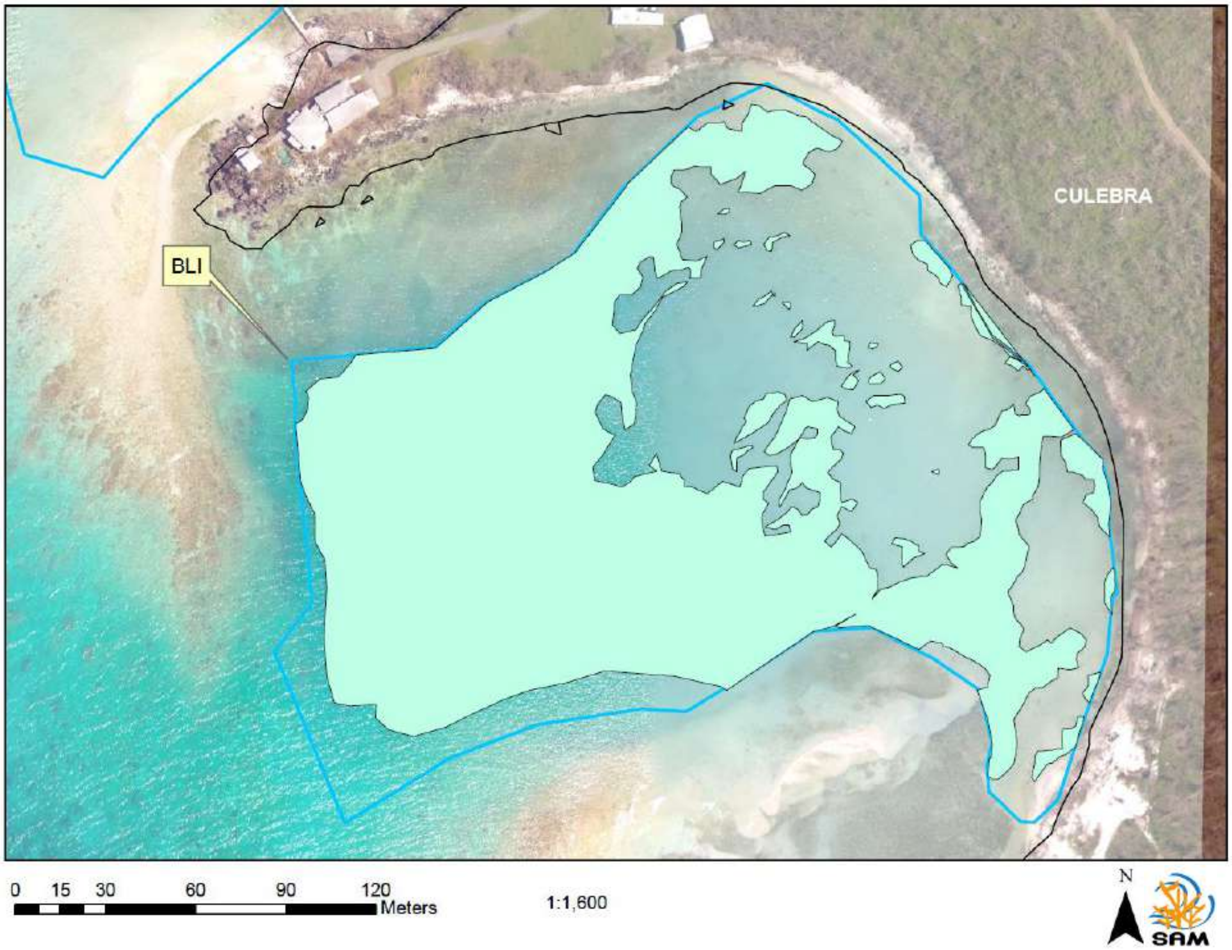

FIGURE 38. Spatial extension of seagrass habitats at BLI *after* hurricanes (2017).

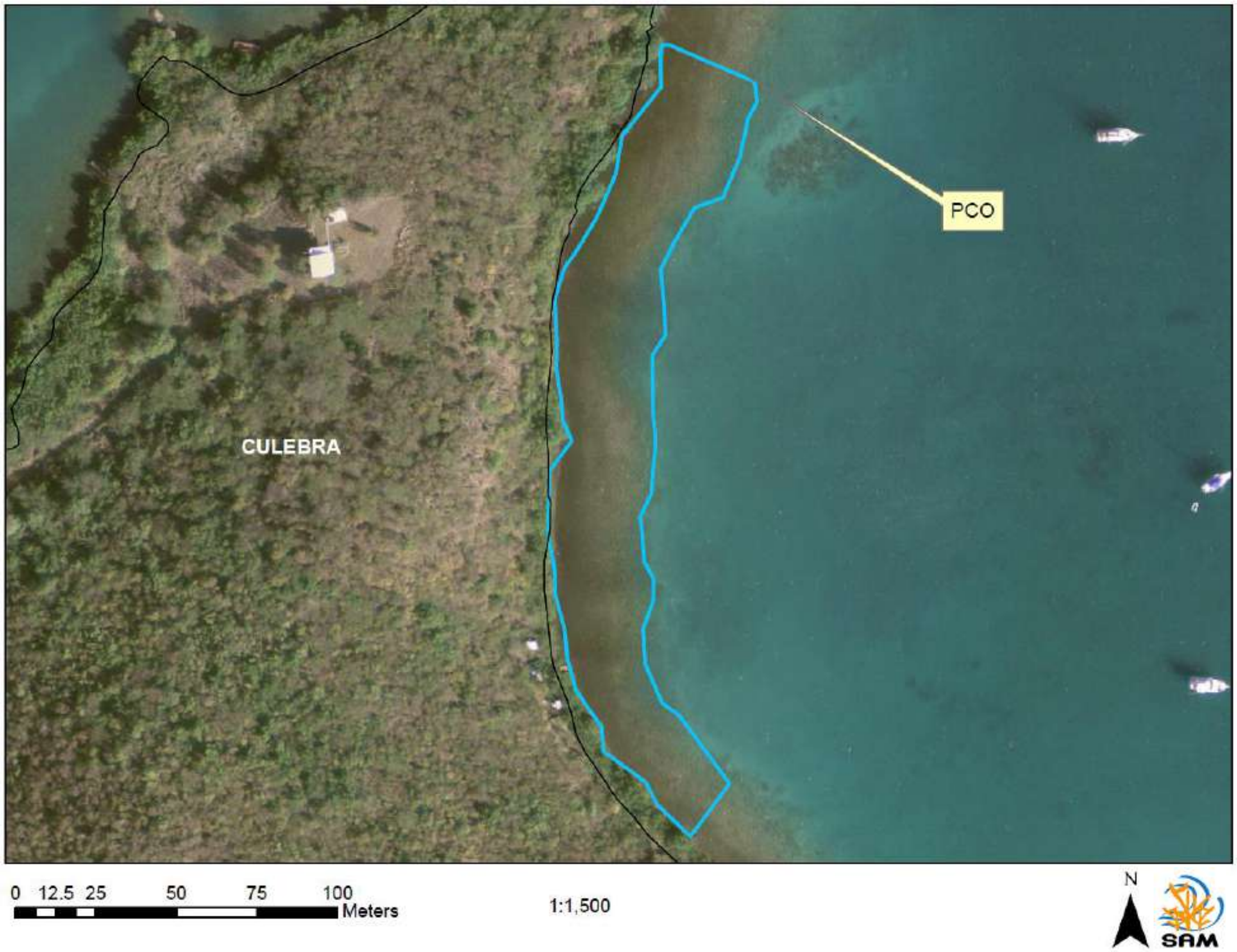

FIGURE 39. Surveyed polygon at PCO *before* hurricanes (2007).

4.1.7 Punta Colorada (PCO)

The surveyed polygon at PCO is representative of its seagrass community and supports the common visit of critically endangered Green turtle, *Chelonia mydas*. But it is under an increasing pressure of anchoring activities by recreational vessels (***Figure 39***). It is also frequently subjected to recurrent turbid, sediment-laden, nutrient-loaded runoff pulses from an adjacent Ensenada Fulladosa and from Ensenada Honda Bay. As this area is facing tradewinds from the southeast, recurrent stranded mats of *Sargassum fluitants* wash ashore along PCO. In addition, Invasive Sea vine (*Halophila stipulacea*) is rapidly spreading across the zone. ***Figures 39***, ***40***, and ***41*** show the extension and condition of the surveyed area *before* (2007, 2010) and *after* the hurricanes (2017). The surveyed polygon size was only 6,953.1 m^2.

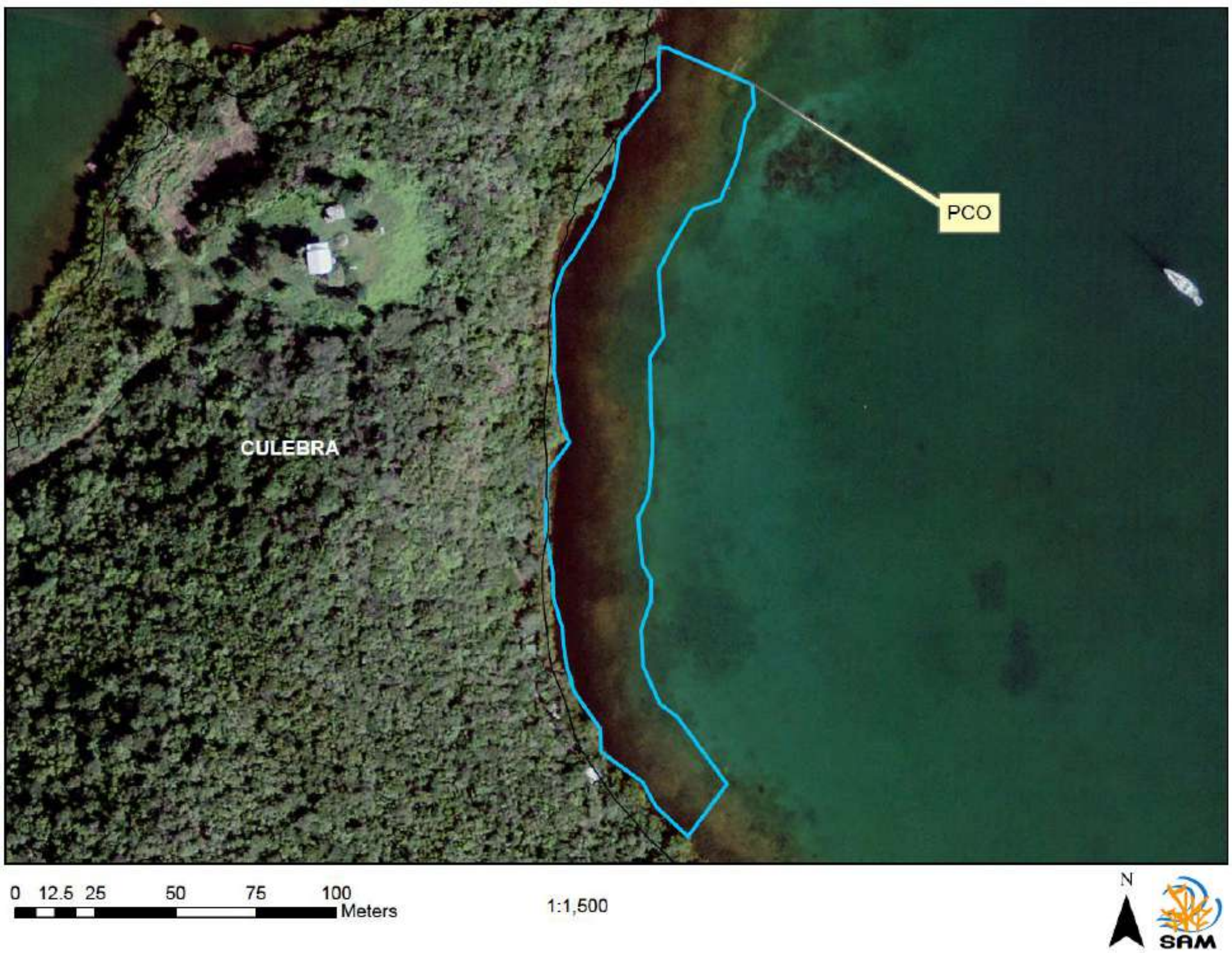

FIGURE 40. Surveyed polygon at PCO *before* hurricanes (2010).

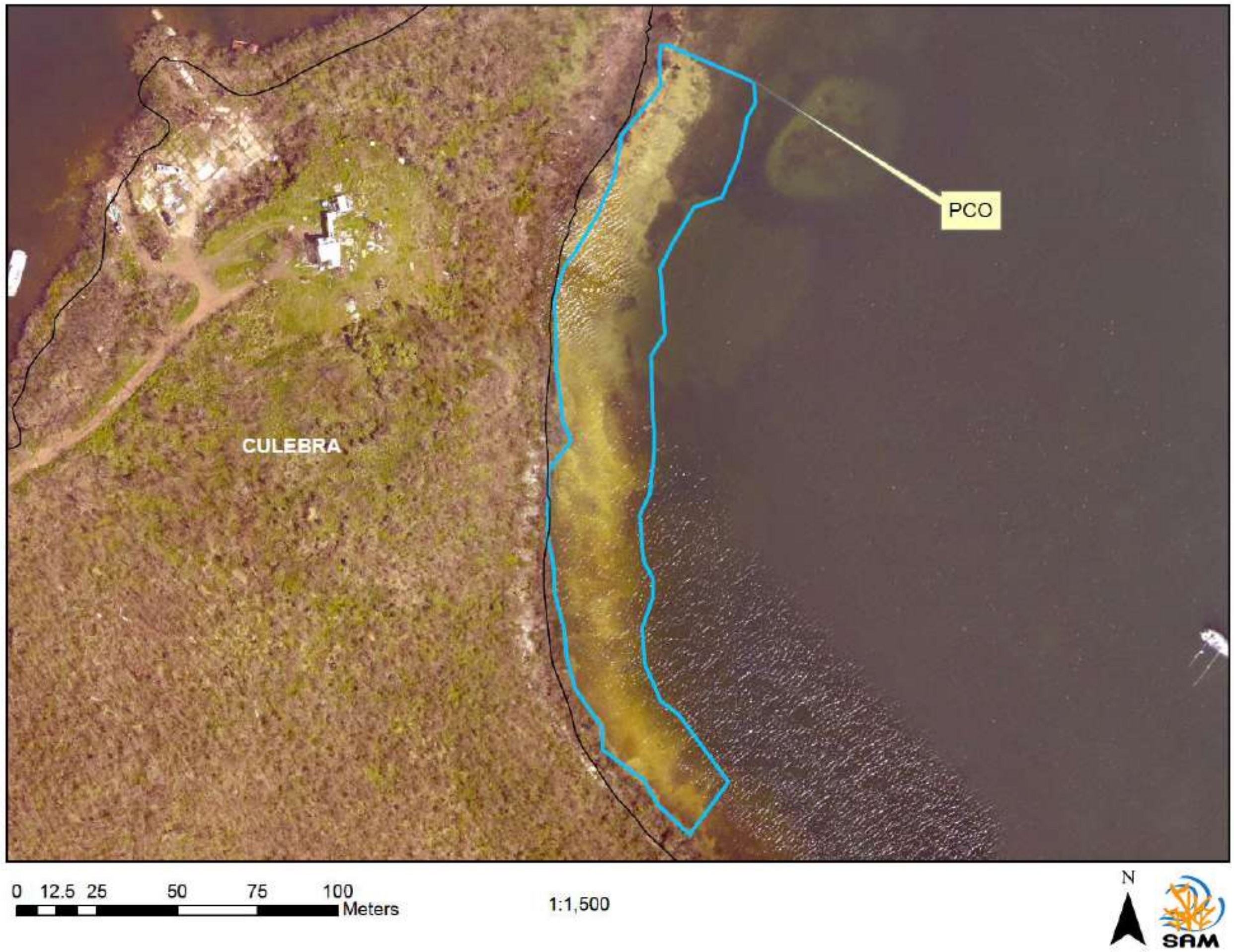

FIGURE 41. Surveyed polygon at PCO *after* hurricanes (2017).

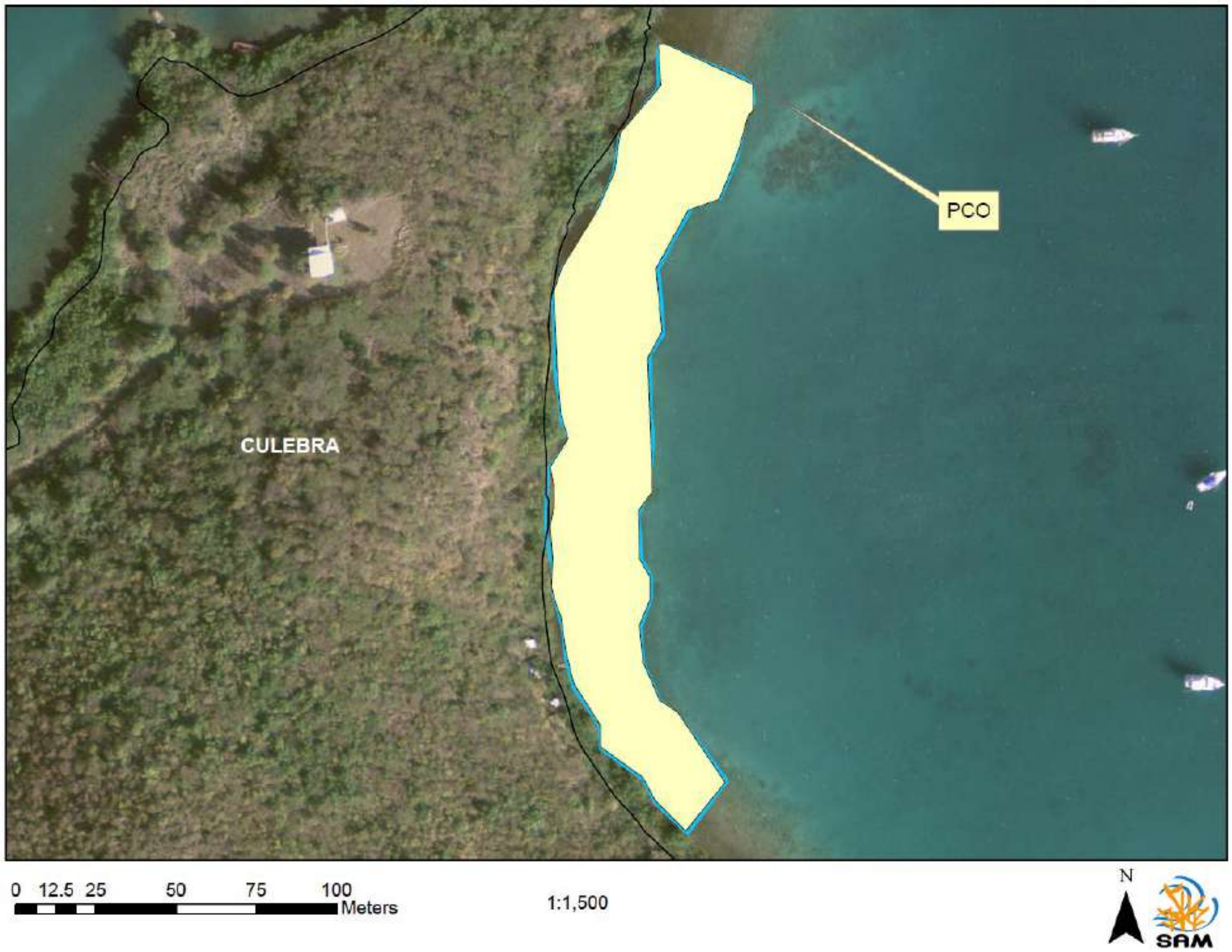

FIGURE 42. Spatial extension of seagrass habitats at PCO *before* hurricanes (2007).

Seagrass spatial extension at PCO in 2007 was 6,827.2 m^2 (98.2% cover) (***Tables 1-2***, ***Figure 42***). By 2010 it slightly declined to 6,808.8 m^2 (97.9% cover), or only a 0.27% loss (***Figure 43***). However, after Hurricanes Irma and María in 2017 seagrass extension sharply dropped to 3,408.0 m^2 (49.0% cover). This represented a substantial 50.1% loss in comparison to 2007, and a 50.0% loss in comparison to 2010 (***Figure 44***). Most of the observed impacts were in the form of mechanical dislodgment of very shallow seagrasses, with minor sediment bedload and burial. There was also evidence that turtle grass, *Thalassia testudinum*, assemblages are being also displaced by a combination of recurrent *Sargassum fluitans* stranded mats, followed by invasive Sea vine (*Halophila stipulacea*).

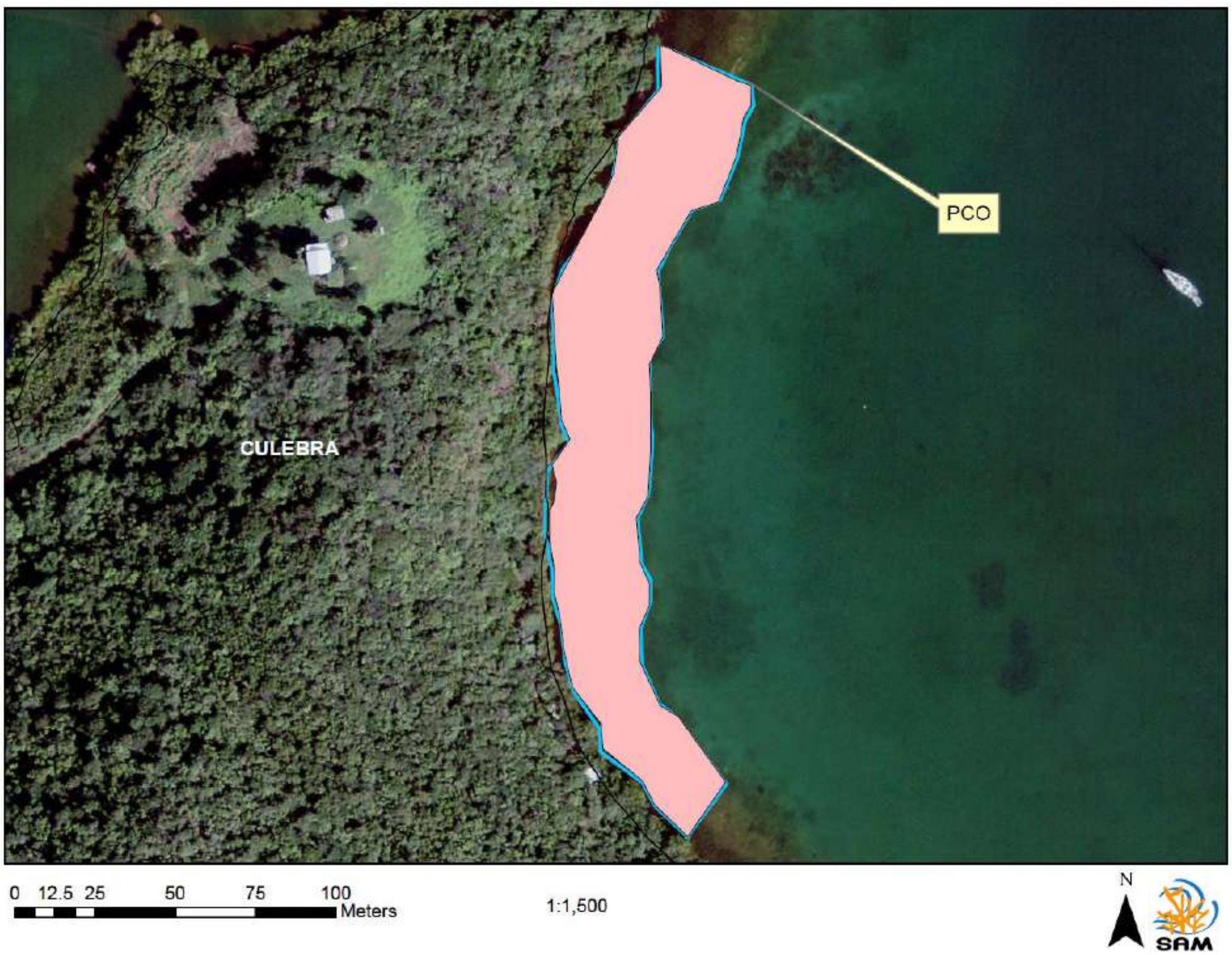

FIGURE 43. Spatial extension of seagrass habitats at PCO *before* hurricanes (2010).

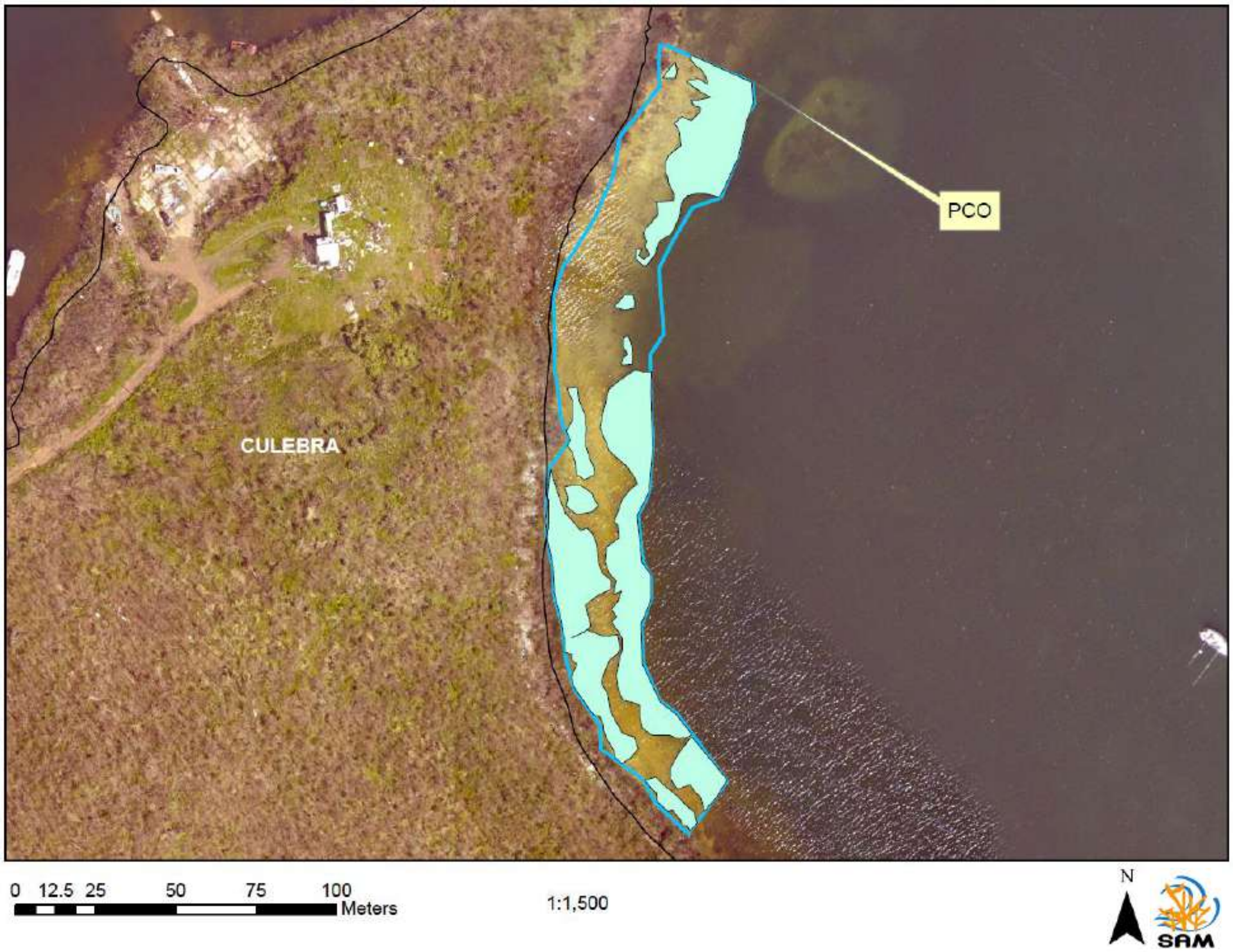

FIGURE 44. Spatial extension of seagrass habitats at PCO *after* hurricanes (2017).

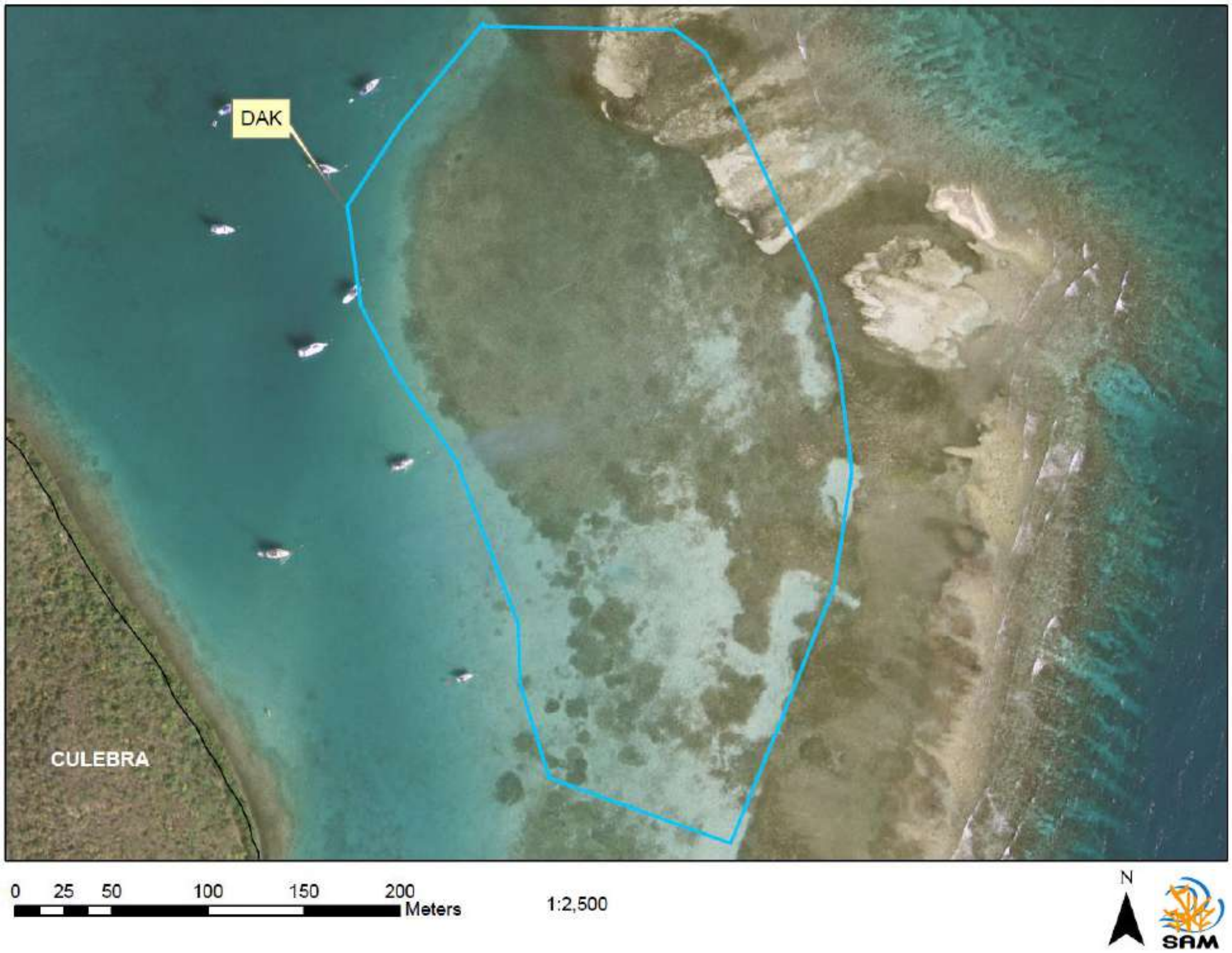

FIGURE 45. Surveyed polygon at DAK *before* hurricanes (2007).

4.1.8 Cayo Dákity (DAK)

The surveyed polygon at DAK is representative of local backreef seagrass communities and supports the common visit of critically endangered Green turtle, *Chelonia mydas*. But it is under an increasing pressure of anchoring activities by recreational vessels (***Figure 45***). It is also frequently subjected to recurrent turbid, sediment-laden, nutrient-loaded runoff pulses from an adjacent Ensenada Fulladosa and from Ensenada Honda Bay. Invasive Sea vine (*Halophila stipulacea*) is rapidly spreading across DAK. ***Figures 45-47*** show the extension and condition of the surveyed area *before* (2007, 2010) and *after* the hurricanes (2017). The surveyed polygon size was only 74,172.1 m^2.

FIGURE 46. Surveyed polygon at DAK *before* hurricanes (2010).

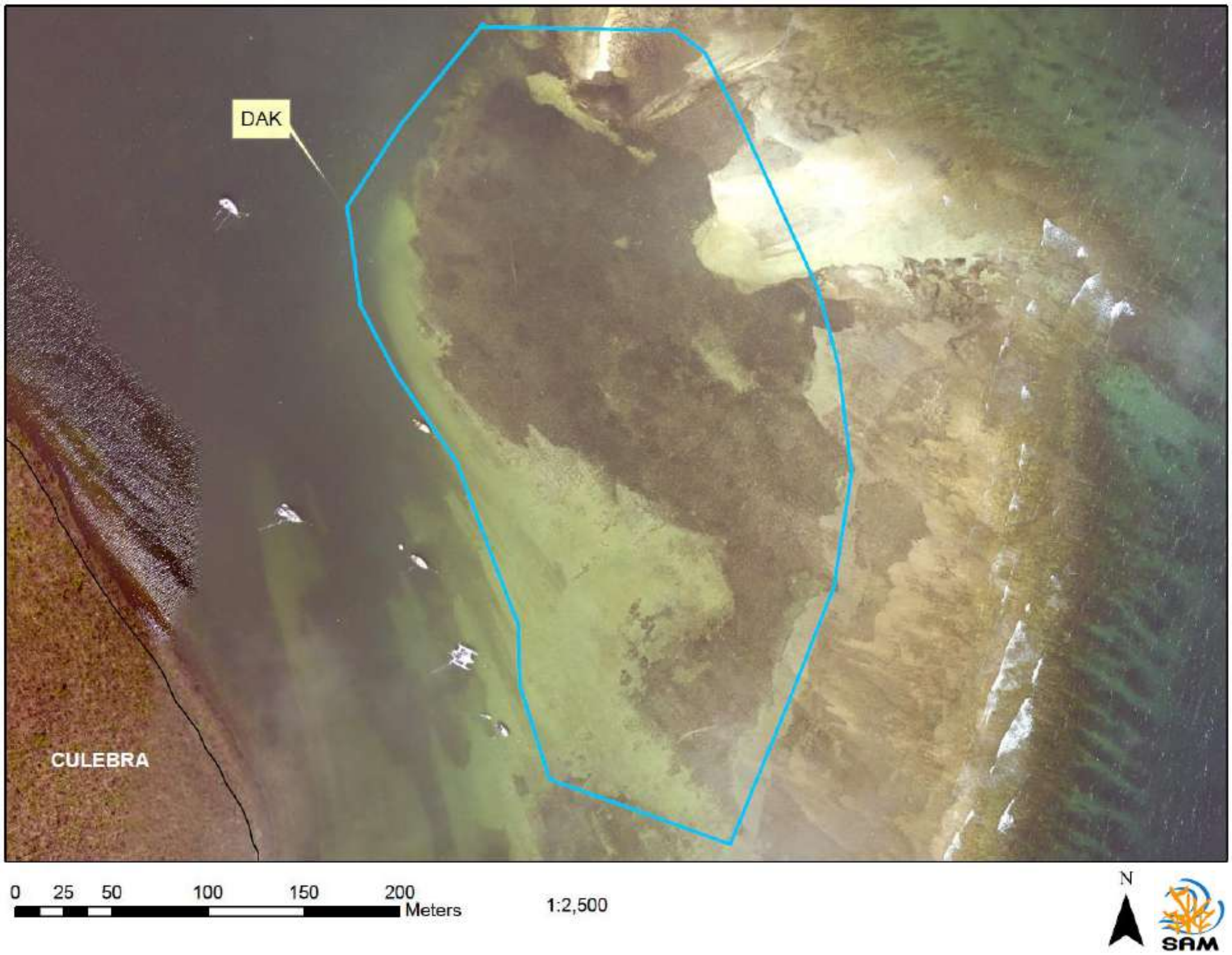

FIGURE 47. Surveyed polygon at DAK *after* hurricanes (2017).

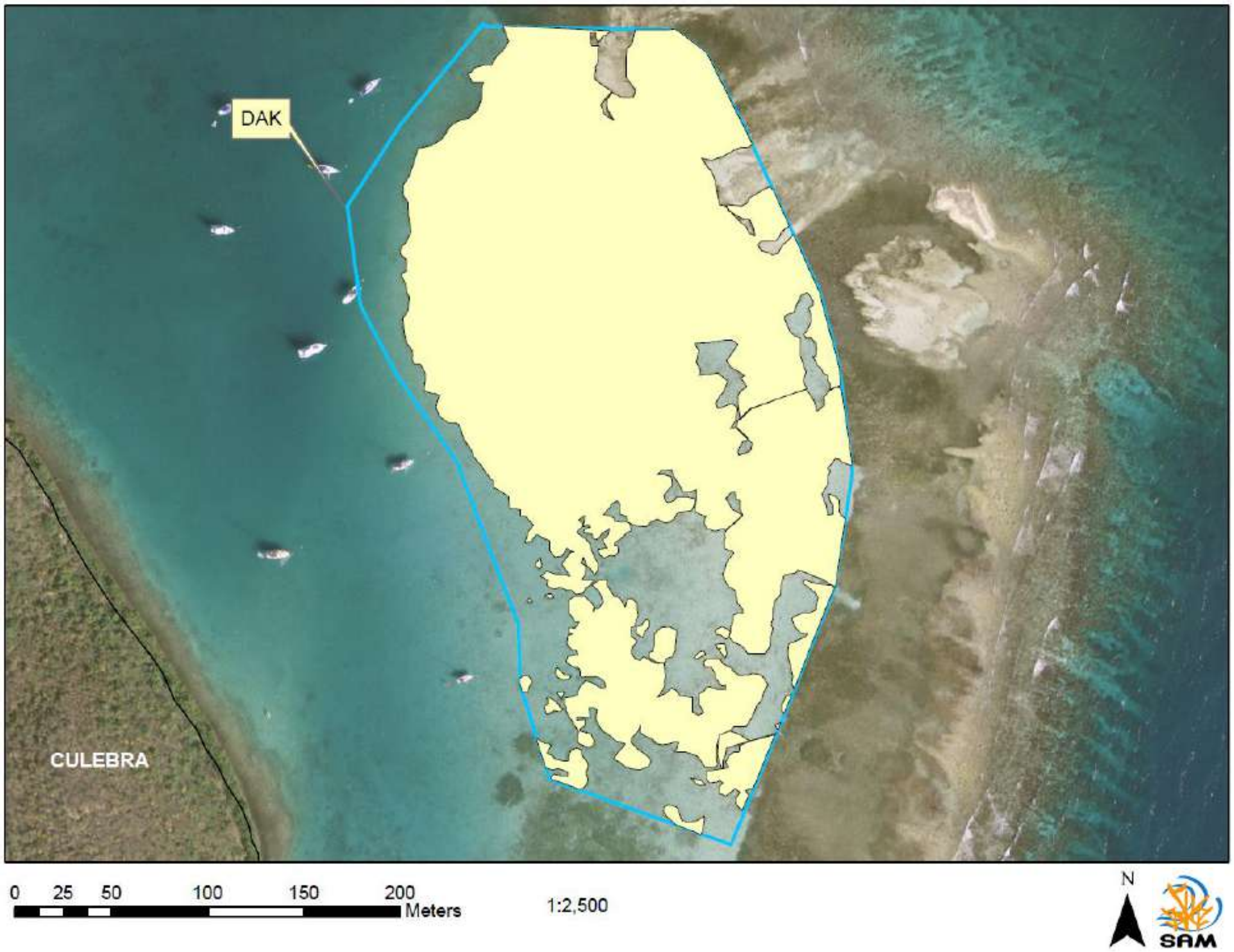

FIGURE 48. Spatial extension of seagrass habitats at DAK *before* hurricanes (2007).

Seagrass spatial extension at DAK in 2007 was 54,091.1 m^2 (72.9% cover) (***Tables 1-2***, ***Figure 48***). By 2010 it actually increased to 56,610.0 m^2 (76.3% cover), or a 4.7% gain (***Figure 49***). However, after Hurricanes Irma and María in 2017 seagrass extension dropped to 50,184.6 m^2 (67.8% cover). This represented a substantial 7.2% loss in comparison to 2007, and a 11.4% loss in comparison to 2010 (***Figure 50***). Most of the observed impacts were in the form of mechanical dislodgment of very shallow seagrasses, also with significant sediment bedload and burial, particularly along the southern segment of the surveyed polygon. In addition, dislodged coral fragments and rubble washed over seagrasses along the northern part of the polygon. There was also evidence that turtle grass, *Thalassia testudinum*, assemblages are being also displaced by invasive Sea vine (*Halophila stipulacea*).

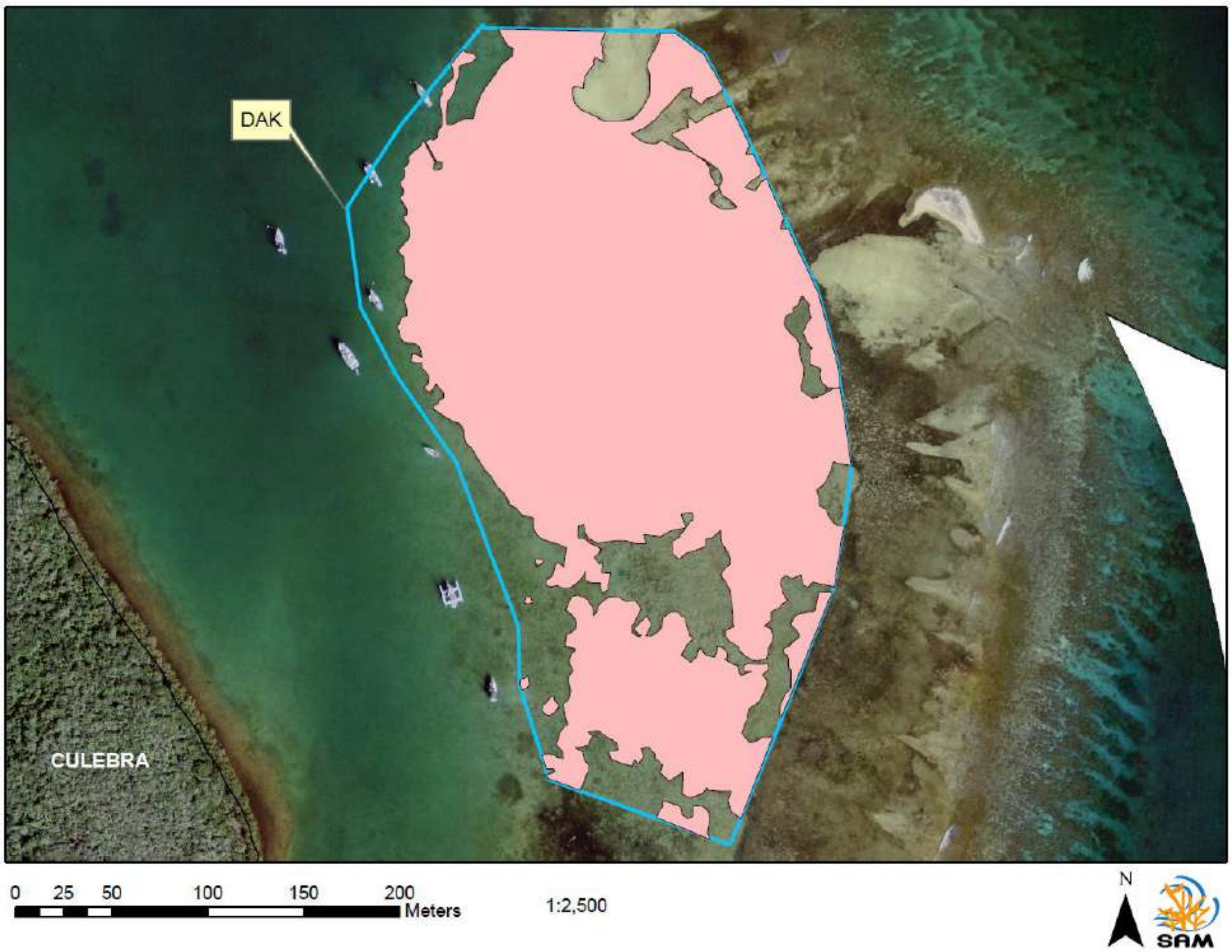

FIGURE 49. Spatial extension of seagrass habitats at DAK *before* hurricanes (2010).

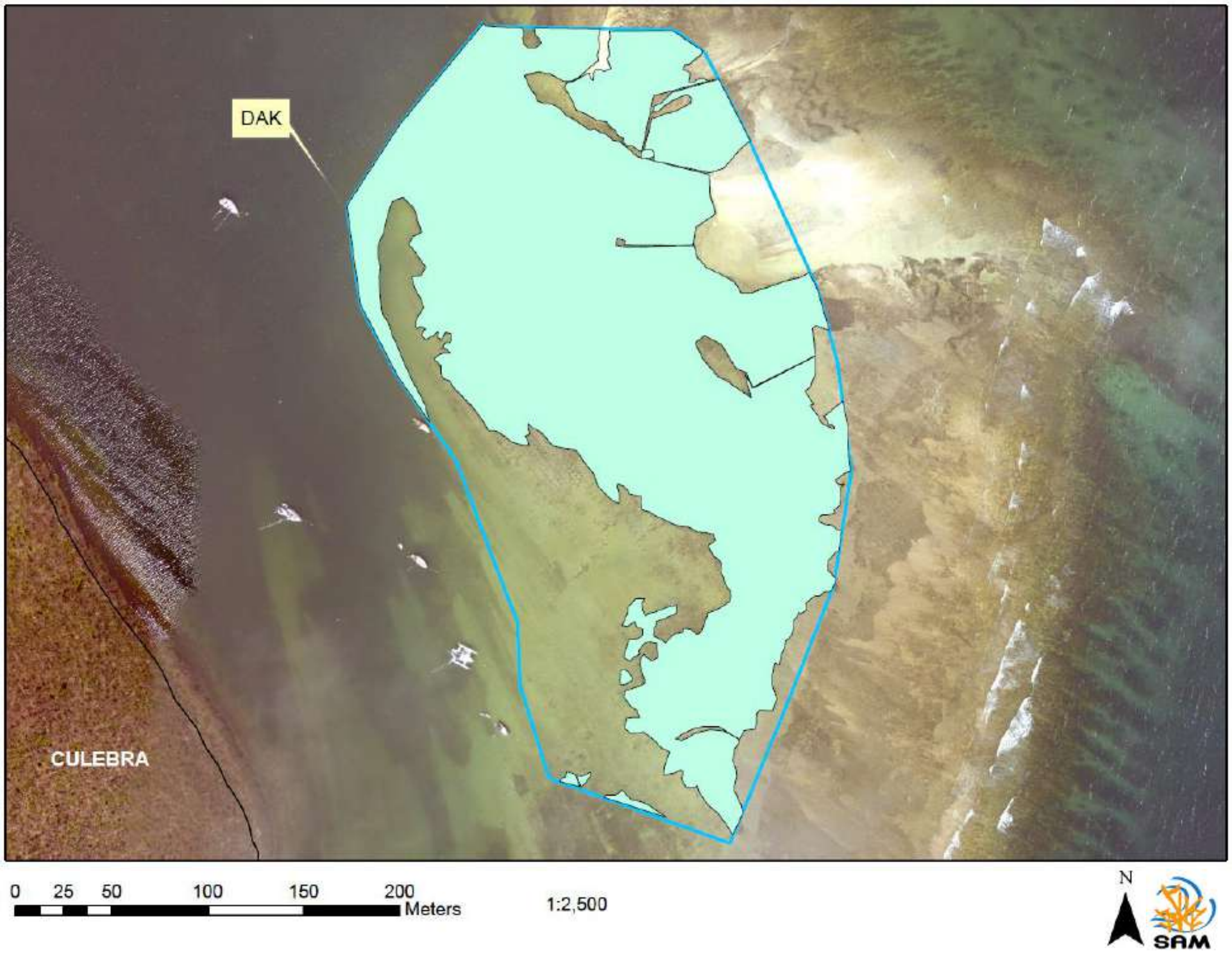

FIGURE 50. Spatial extension of seagrass habitats at DAK *after* hurricanes (2017).

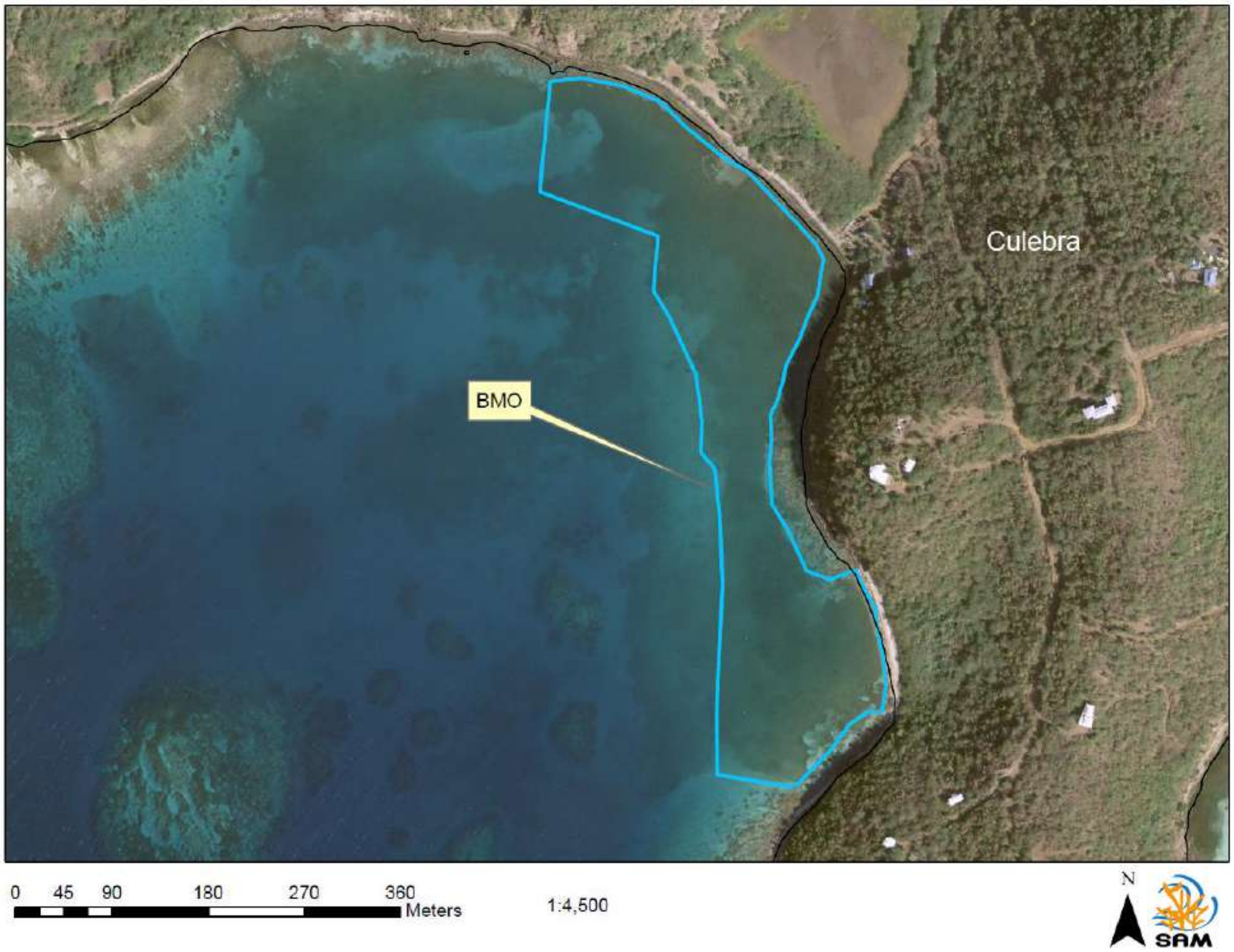

FIGURE 51. Surveyed polygon at BMO *before* hurricanes (2007).

4.1.9 Bahía Mosquito (BMO)

The surveyed polygon at BMO is representative of local backreef seagrass communities and supports the common visit of critically endangered Green turtle, *Chelonia mydas*. It is also occasionally subjected to recurrent turbid, sediment-laden, nutrient-loaded runoff pulses from Ensenada Honda Bay. Invasive Sea vine (*Halophila stipulacea*) is also spreading across BMO. In spite of that, BNO is a also a very important nursery and fishing ground for Queen conch (*Lobatus gigas*). ***Figures 51-53*** show the extension and condition of the surveyed area *before* (2007, 2010) and *after* the hurricanes (2017). The surveyed polygon size was only 76,986.7 m^2.

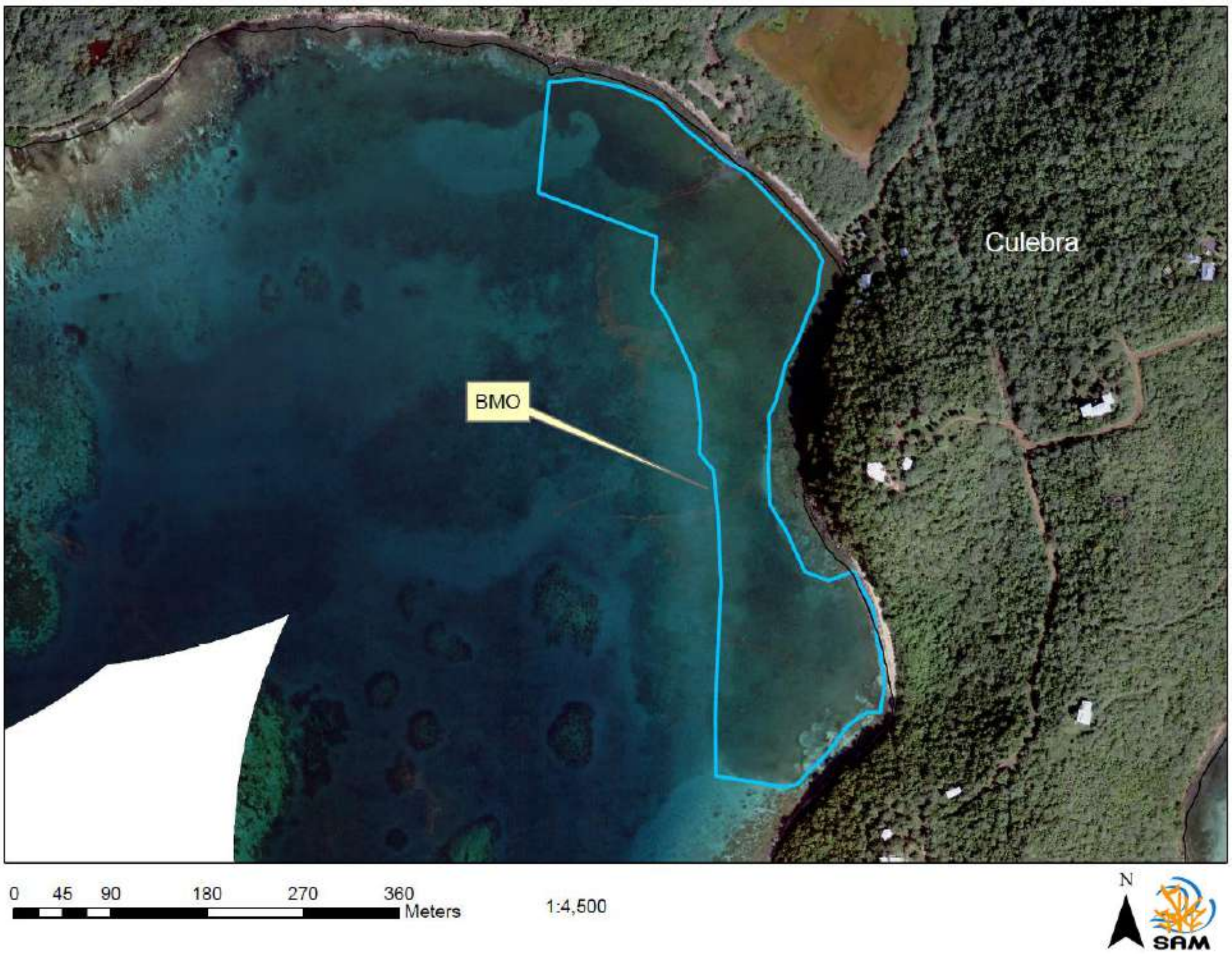

FIGURE 52. Surveyed polygon at BMO *before* hurricanes (2010).

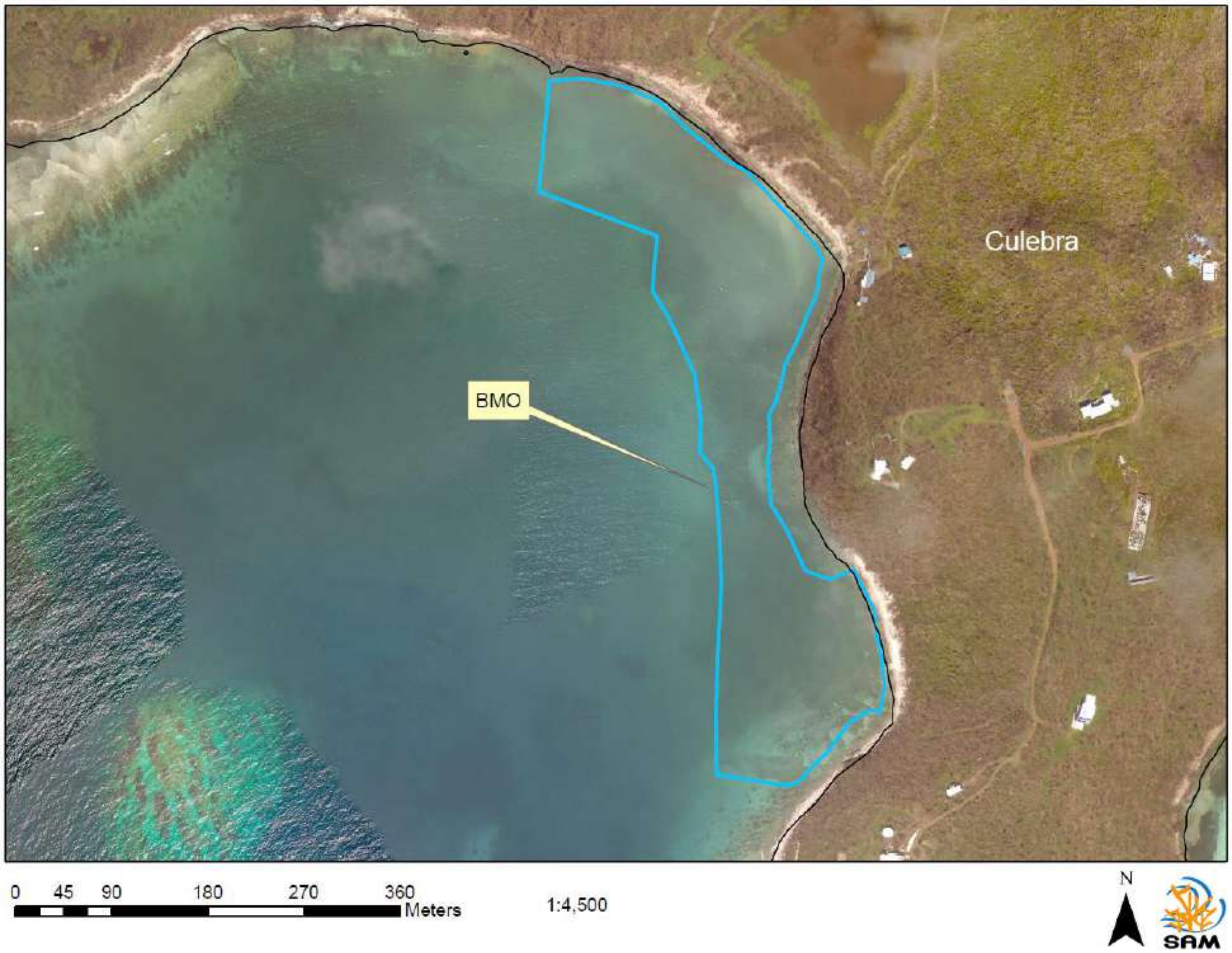

FIGURE 53. Surveyed polygon at BMO *after* hurricanes (2017).

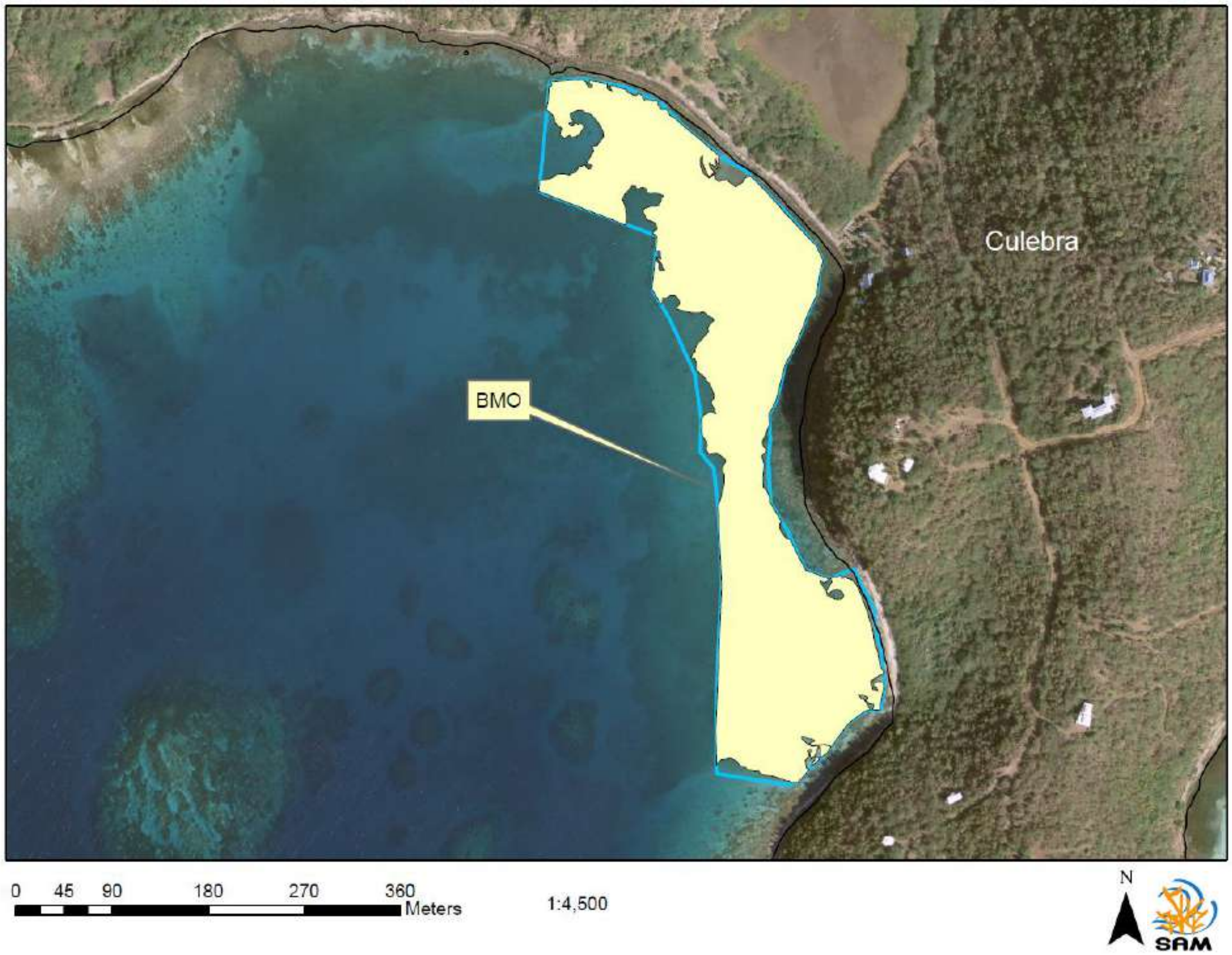

FIGURE 54. Spatial extension of seagrass habitats at BMO *before* hurricanes (2007).

Seagrass spatial extension at BMO in 2007 was 68,415.2 m^2 (88.9% cover) (***Tables 1-2***, ***Figure 54***). By 2010 it actually increased to 73,749.1 m^2 (95.8% cover), or a 7.8% gain (***Figure 55***). However, after Hurricanes Irma and María in 2017 seagrass extension dropped to 64,983.3 m^2 (84.4% cover). This represented a 5.0% loss in comparison to 2007, and a 11.9% loss in comparison to 2010 (***Figure 56***). Most of the observed impacts were in the form of partial sediment bedload and burial, particularly along the southern segment of the surveyed polygon. In addition, invasive Sea vine (*Halophila stipulacea*) is spreading through some areas of BMO.

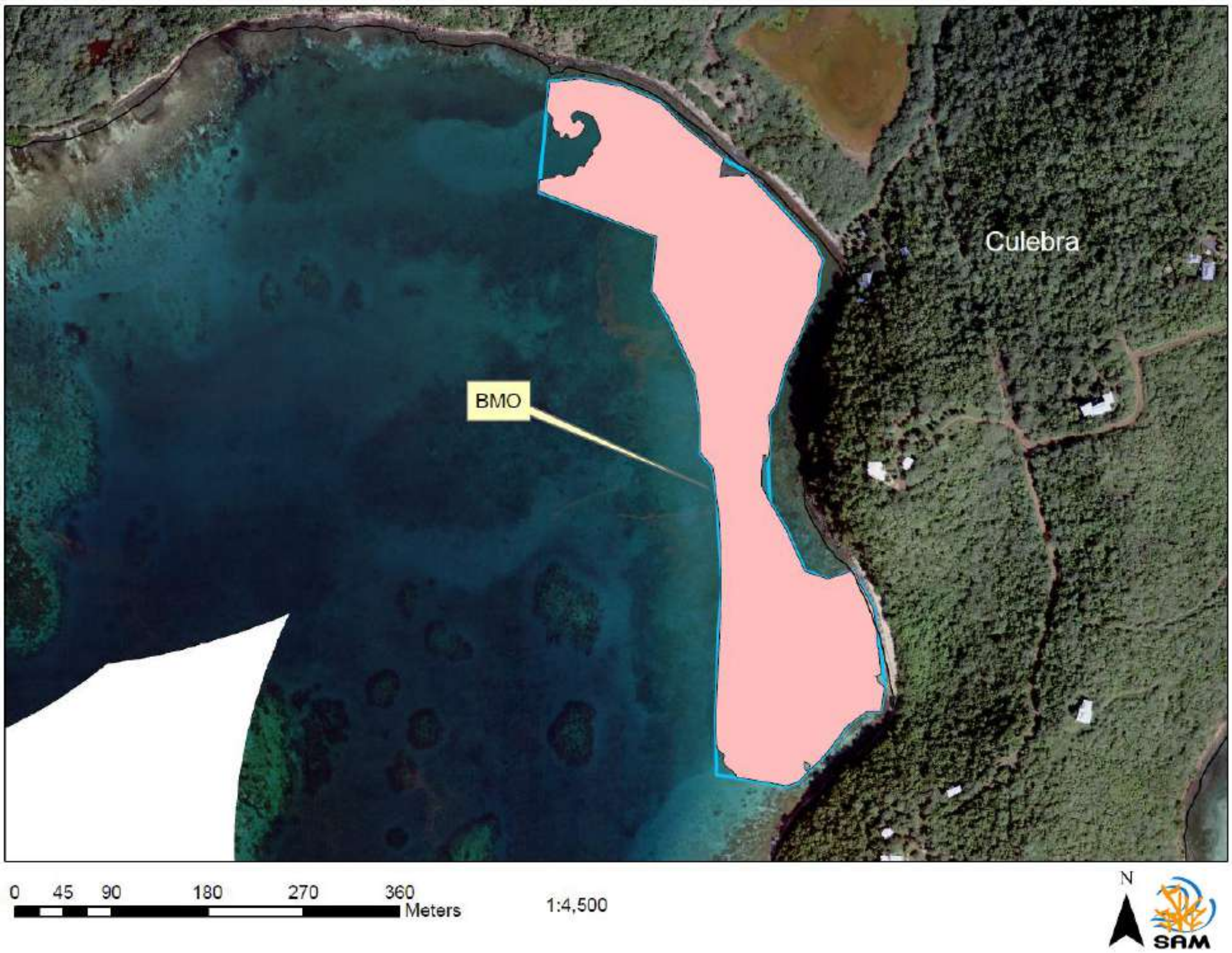

FIGURE 55. Spatial extension of seagrass habitats at BMO *before* hurricanes (2010).

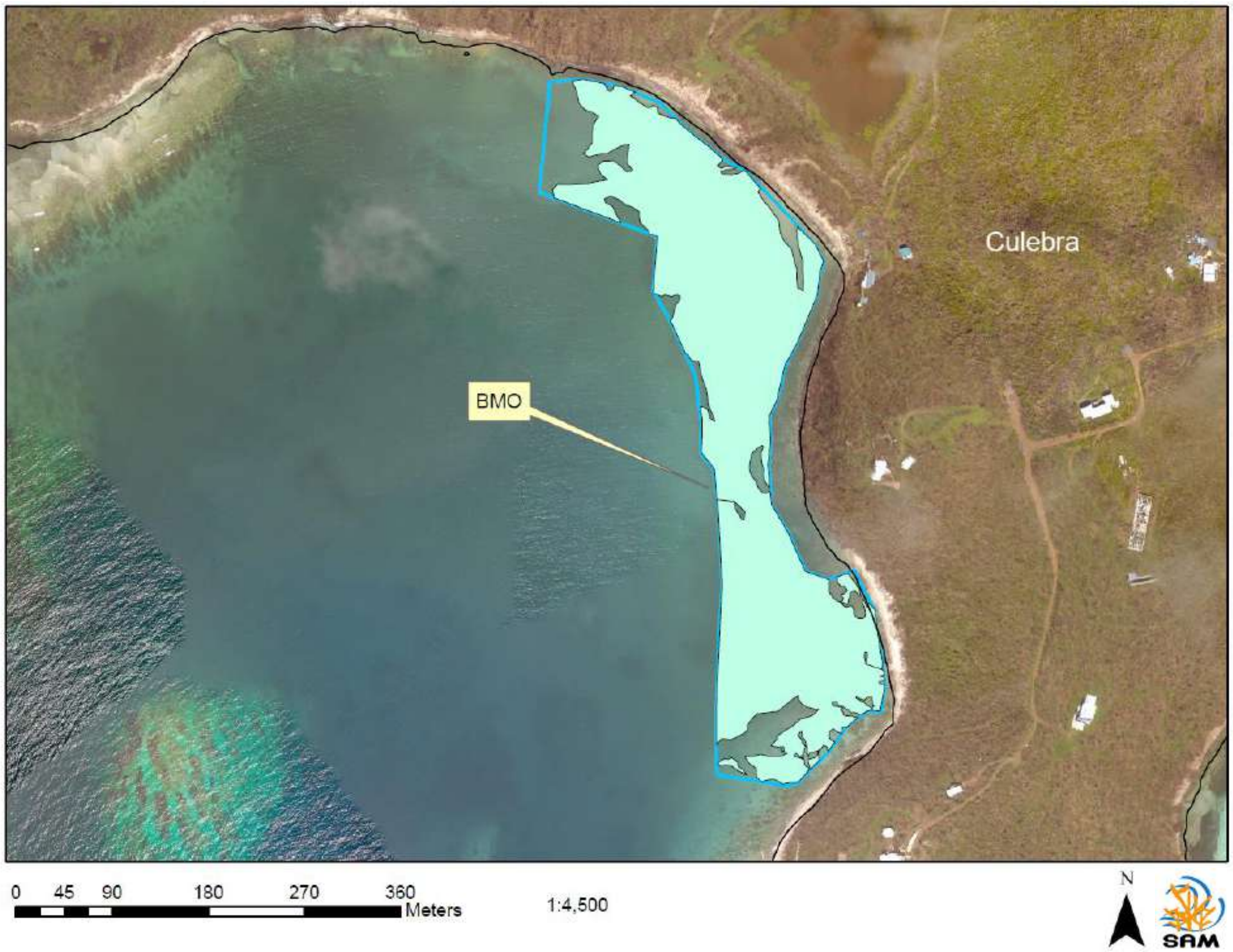

FIGURE 56. Spatial extension of seagrass habitats at BMO *after* hurricanes (2017).

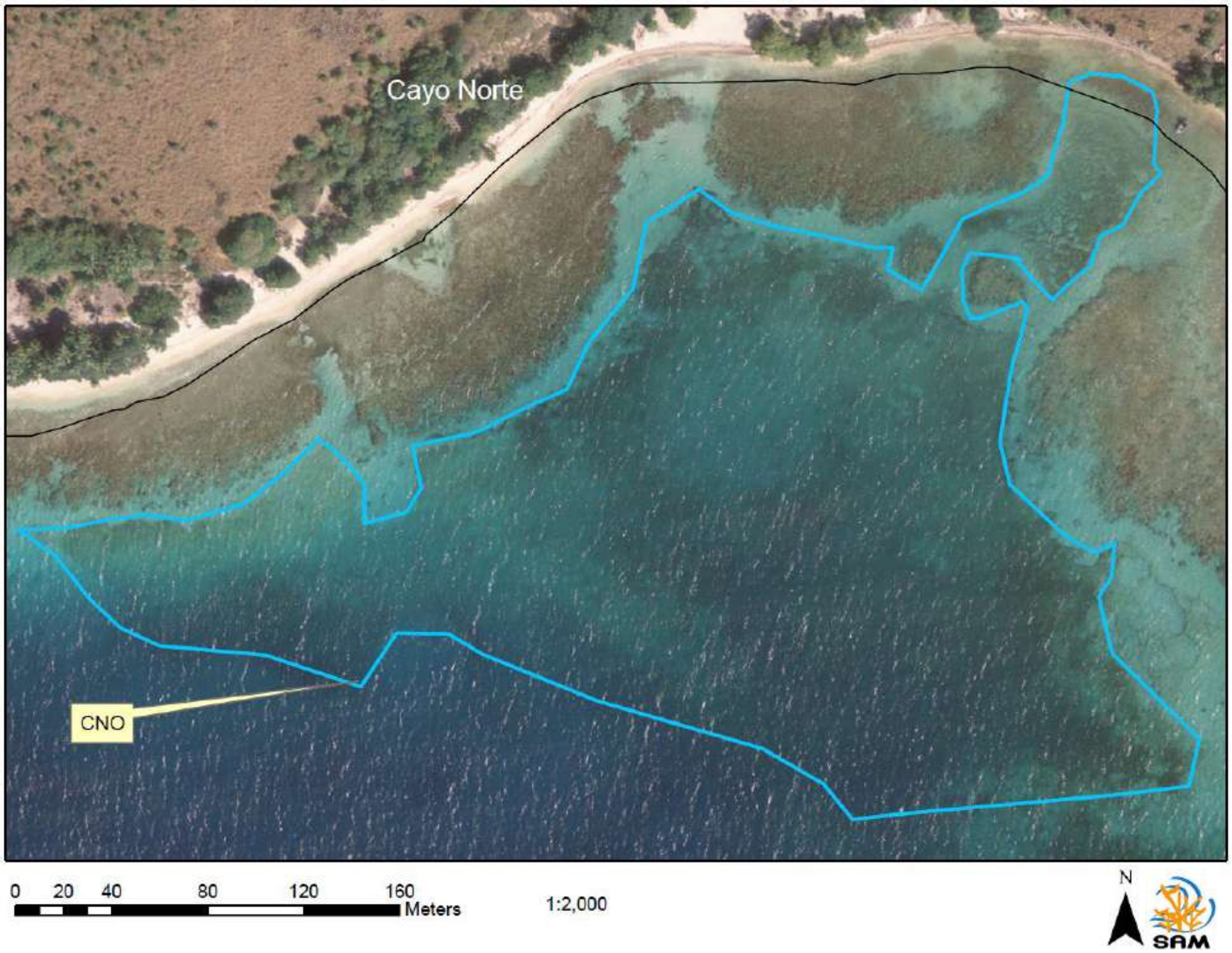

FIGURE 57. Surveyed polygon at CNO *before* hurricanes (2007).

4.1.10 Cayo Norte (CNO)

The surveyed polygon at CNO is representative of local seagrass communities and supports the common visit of critically endangered Green turtle, *Chelonia mydas*. CNO is a also a very important fishing ground for Queen conch (*Lobatus gigas*). Invasive Sea vine (*Halophila stipulacea*) is also spreading across CNO. ***Figures 57*-*59*** show the extension and condition of the surveyed area *before* (2007, 2010) and *after* the hurricanes (2017). The surveyed polygon size was only 64,054.2 m^2.

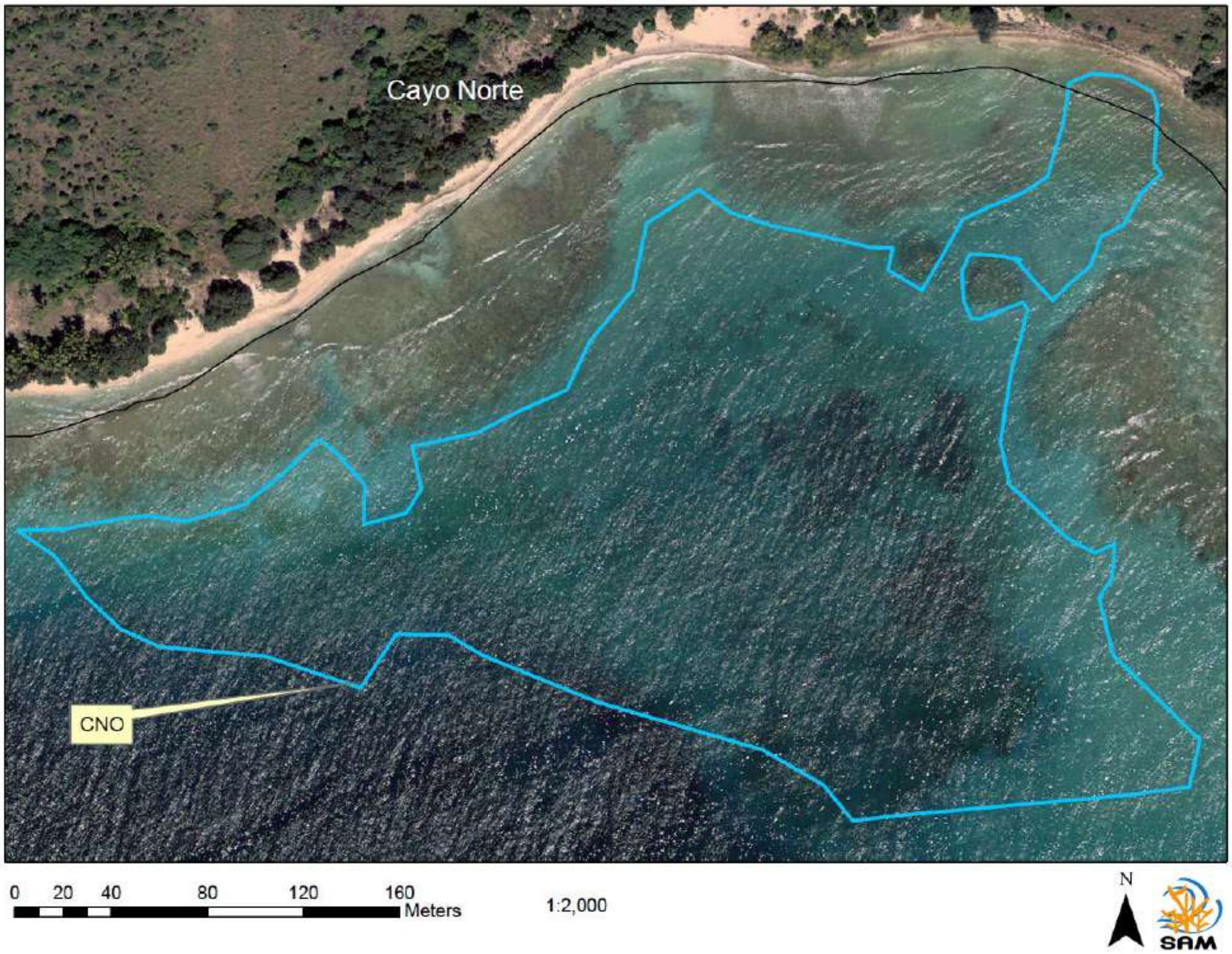

FIGURE 58. Surveyed polygon at CNO *before* hurricanes (2010).

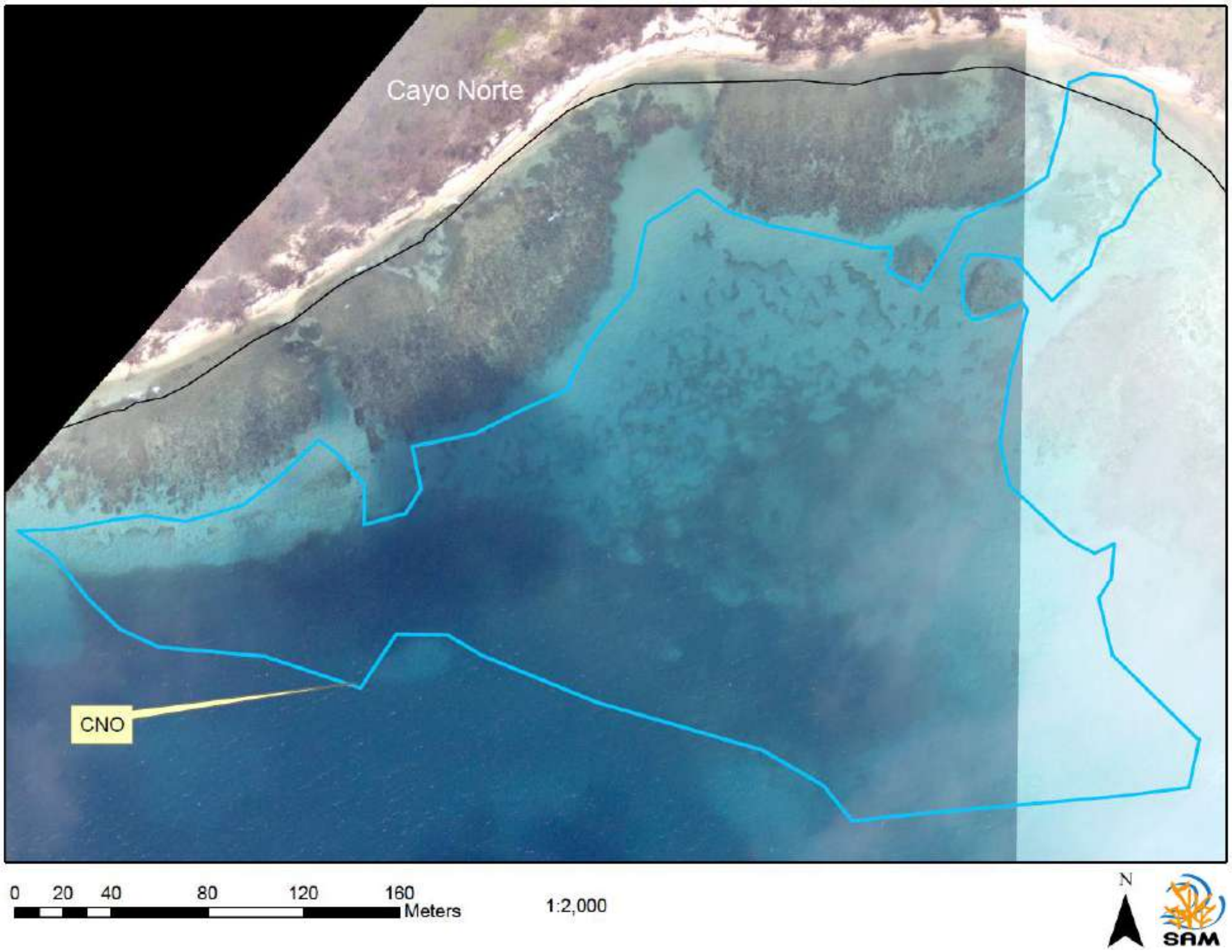

FIGURE 59. Surveyed polygon at CNO *after* hurricanes (2017).

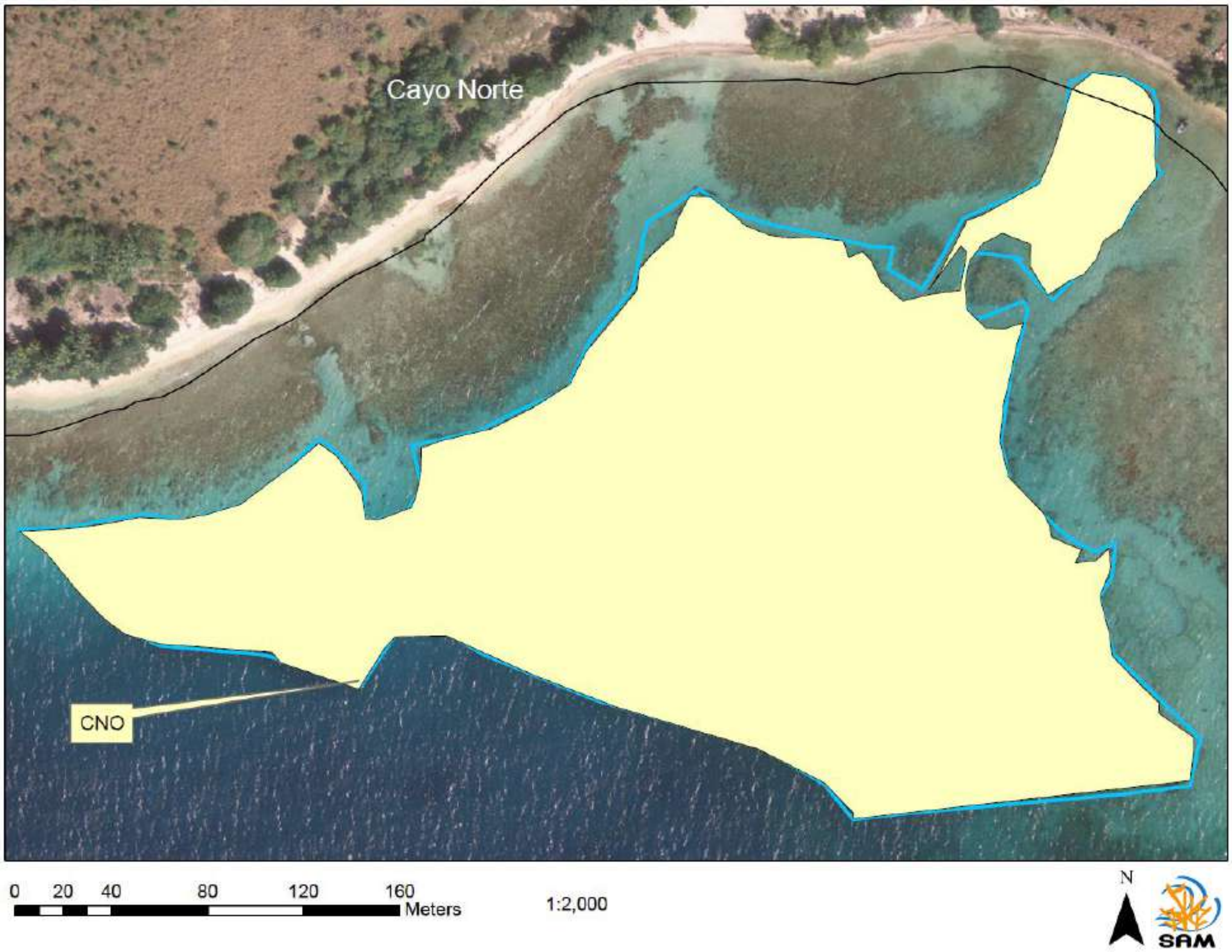

FIGURE 60. Spatial extension of seagrass habitats at CNO *before* hurricanes (2007).

Seagrass spatial extension at CNO in 2007 was 62,268.2 m^2 (97.2% cover) (***Tables 1-2***, ***Figure 60***). By 2010 it sharply dropped to 49,542.3 m^2 (77.3% cover), or a 20.4% loss (***Figure 61***). However, after Hurricanes Irma and María in 2017 seagrass extension further dropped down to 49,542.3 m^2 (51.1% cover). This represented a substantial 47.4% loss in comparison to 2007, and a 33.9% loss in comparison to 2010 (***Figure 62***). Most of the observed impacts were in the form of a significant sediment bedload and burial, with also partial seagrass matrix physical disruption by wave action. Innvasive Sea vine (*Halophila stipulacea*) is also spreading through some areas of CNO.

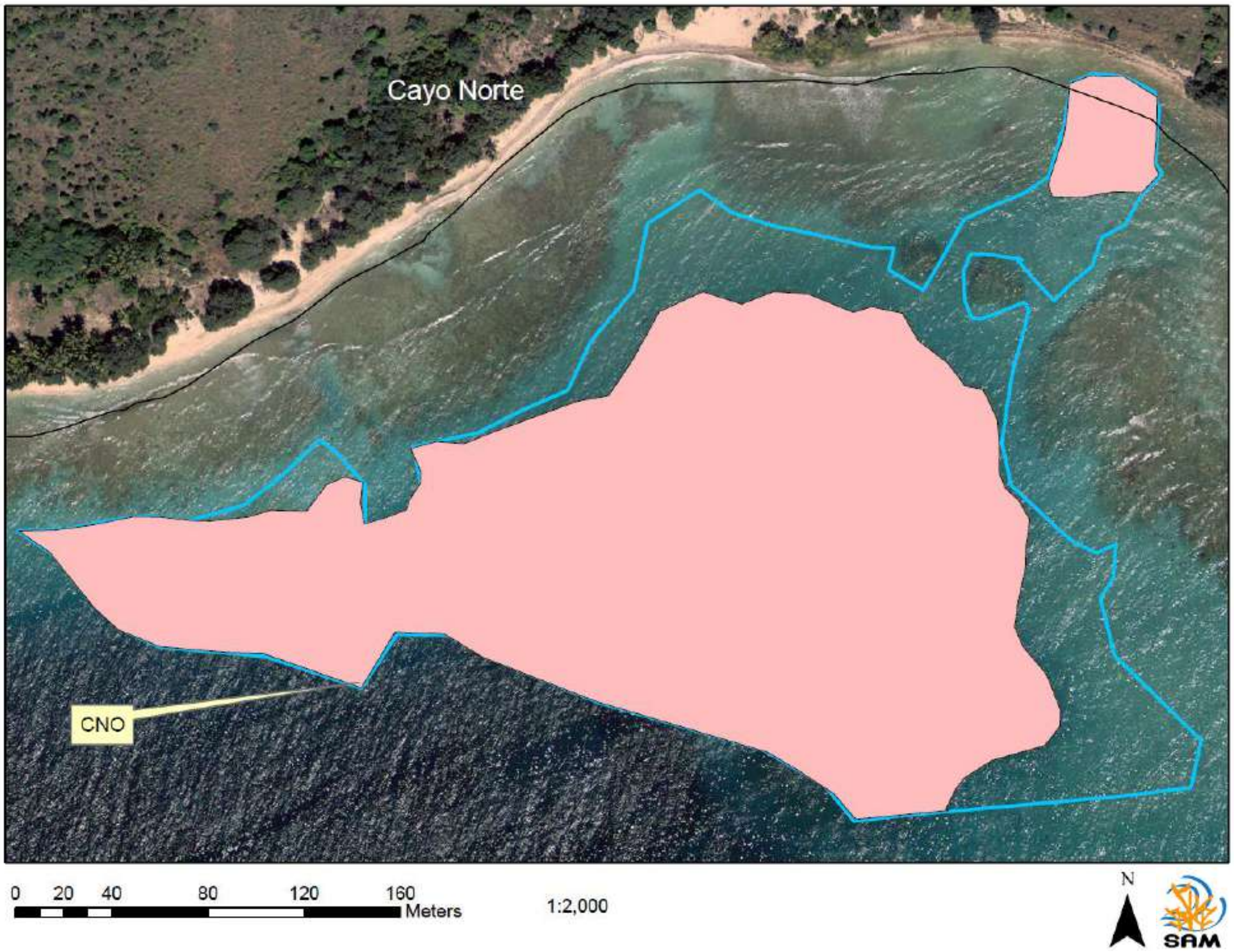

FIGURE 61. Spatial extension of seagrass habitats at CNO *before* hurricanes (2010).

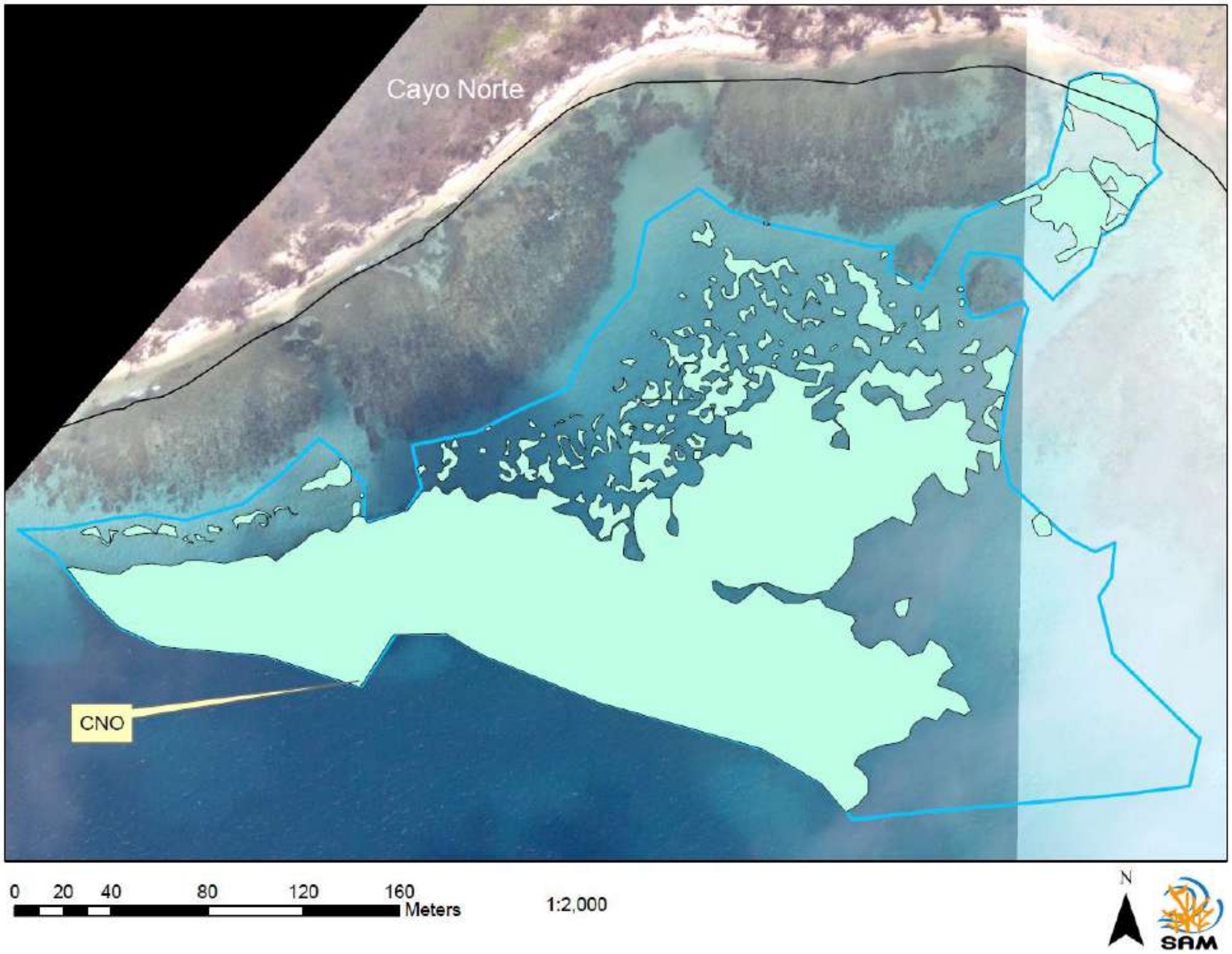

FIGURE 62. Spatial extension of seagrass habitats at CNO *after* hurricanes (2017).

4.2 Post-hurricanes ground-truthing assessment

Table 2 summarizes the 2-way PERMANOVA results of the *before* (2004) and *after* (2017) ground-truthing assessment of hurricanes impacts in Culebra's seagrass habitats. The assessment was limited only to BTA, PTC, PME, TAM, and BLI, which had previous comparison data from 2014, using a nearly similar sampling strategy to the one used in 2017.

TABLE 2. Summary of 2-way PERMANOVA results for seagrass community parameters.

Variable	d.f.	Pseudo-F	*p*
Benthic community structure			
Time	1,593	130.02	<0.0001
Location	4,590	26.50	<0.0001
Time x Location	4,590	11.49	<0.0001
Percent seagrass cover			
Time	1,593	63.74	<0.0001
Location	4,590	3.57	0.0050
Time x Location	4,590	2.94	0.0160
Percent *T. testudinum* cover			
Time	1,593	142.26	<0.0001
Location	4,590	17.76	<0.0001
Time x Location	4,590	10.88	<0.0001
Percent *S. filiforme* cover			
Time	1,593	144.67	<0.0001
Location	4,590	10.10	<0.0001
Time x Location	4,590	7.37	<0.0001
Percent *H. wrightii* cover			
Time	1,593	113.13	<0.0001
Location	4,590	4.75	0.0007
Time x Location	4,590	4.91	0.0010
Percent *H. stipulacea* cover			
Time	1,593	51.57	<0.0001
Location	4,590	31.20	<0.0001
Time x Location	4,590	31.20	<0.0001
Percent macroalgal cover			
Time	1,593	289.4	<0.0001
Location	4,590	39.77	<0.0001
Time x Location	4,590	36.53	<0.0001

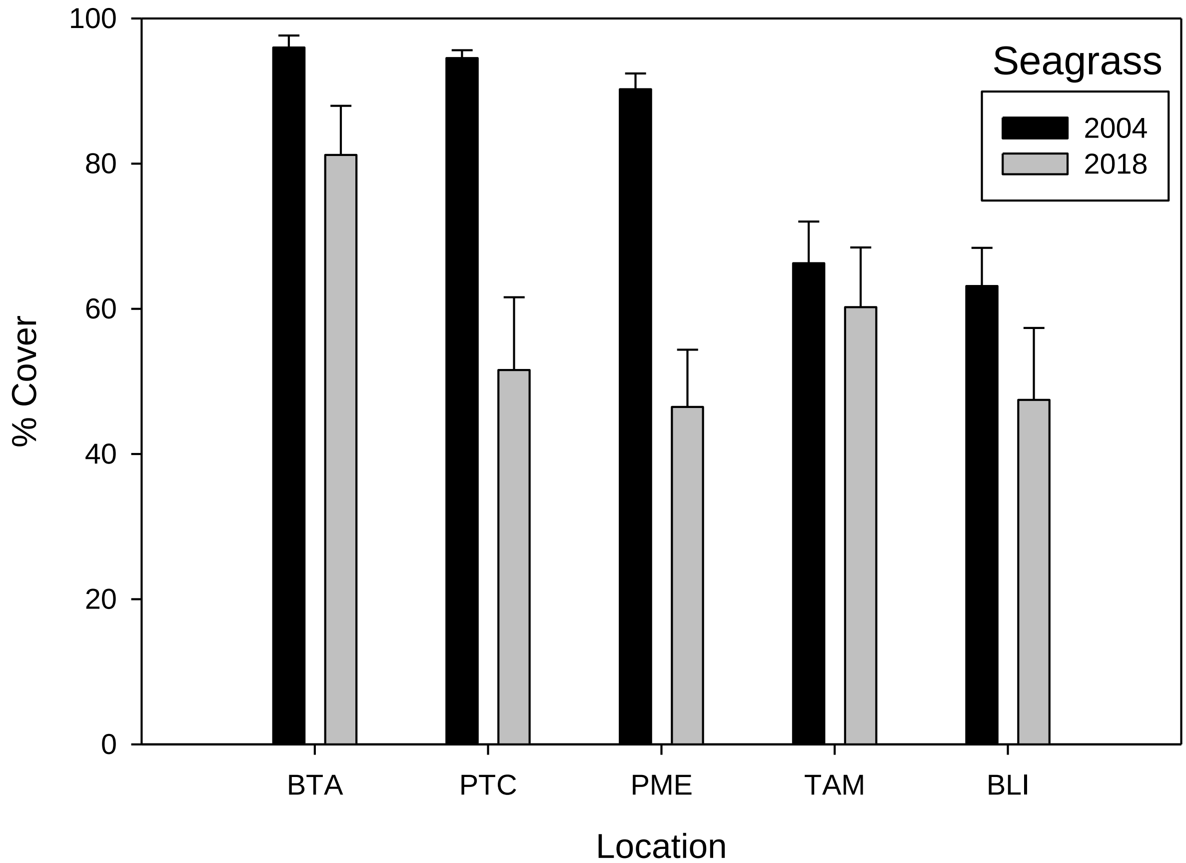

FIGURE 63. Percent total seagrass cover (mean±95% confidence intervals).

There was a highly significant spatial difference in seagrass benthic community structure either *before* or *after* hurricanes impacts, implying a gradient of variable environmental conditions *before* the hurricanes (***Table 2***). However, there was also a net temporal shift in benthic community structure following the hurricanes in 2018. This pattern is clearly reflected in a highly significant spatio-temporal decline in percent seagrass cover, which reflects both, an environmental stress gradient and the hurricanes impacts (***Figure 63***). Percent seagrass cover increased with increasing distance from urban-polluted waters and from physical disturbance from recreational vessel anchoring activities. But showed significant *after*-hurricanes decline.

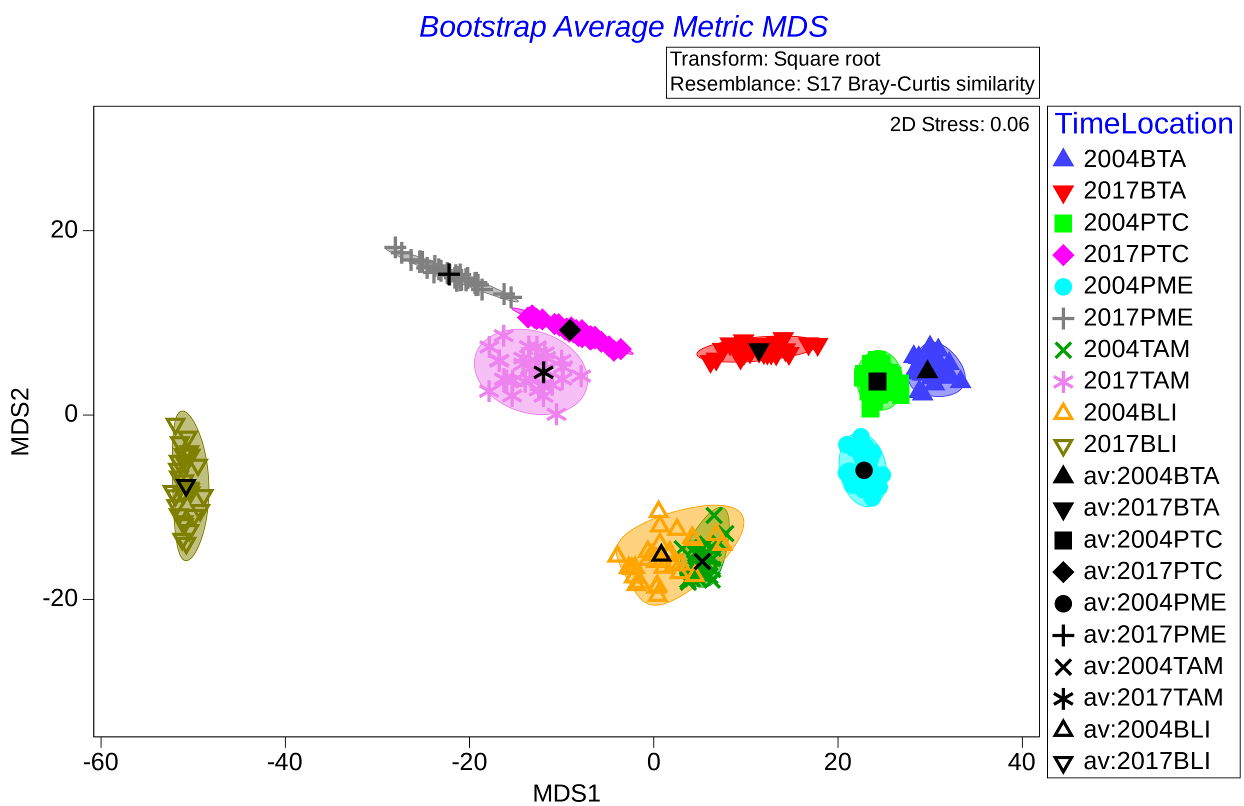

FIGURE 64. Bootstrap average metric multidimensional scaling (mMDS) analysis of spatio-temporal variation in seagrass community structure (2004 vs. 2018).

Spatio-temporal changes are also evidenced in a bootstrap average metric multidimensional scaling (mMDS) analysis (***Figure 64***). This shows the nature of spatio-temporal shifts in seagrass benthic assemblages in 2018 (*after* hurricanes) when compared to *before* data. In particular, TAM and BLI show a particular pattern of very large overlapping in 2004 and large divergence in 2018. In 2004 benthic assemblages showed very similar conditions, with lower percent seagrass cover (***Figure 63***), and widespread habitat fragmentation mostly resulting from anchoring. But benthic assemblages in 2018, not only showed impacts from hurricanes, but from the rapid invasion of Sea vine, *Halophila stipulacea*.

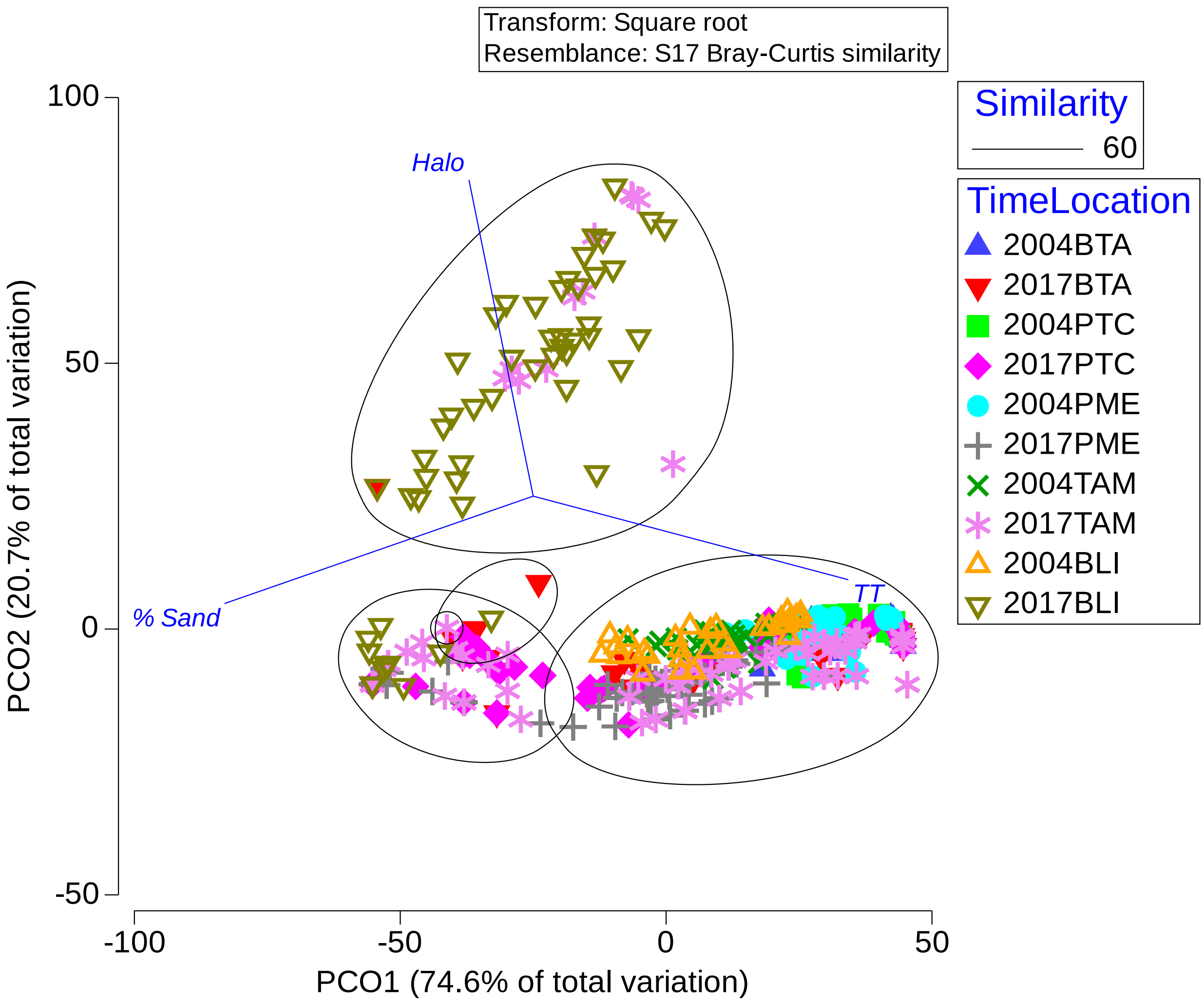

FIGURE 65. Principal coordinates ordination (PCO) analysis of spatio-temporal variation in seagrass community structure (2004 vs. 2018).

Principal coordinates ordination (PCO) analysis also confirmed the observed spatio-temporal variation in seagrass benthic assemblages, with five general clustering patterns (***Figure 65***). The cluster in the lower right shows sampling locations *before* hurricanes.

This cluster was mostly explained by *Thalassia testudinum* dominance. The group of three small clusters in the lower right of the image are reef locations in 2018 impacted by the hurricanes, and were largely explained by increasing percent sand cover due to a combination of both, sediment bedload (horizontal transport), burial and suffocation, and due to the mechanical destruction of the entire seagrass habitat matrix at some locations. The final cluster in the upper part of the image is composed by another group of locations in 2018 hurricanes impacts, but which also showed significant impacts of highly-resilience, invasive Sea vine, *Halophila stipulacea*.

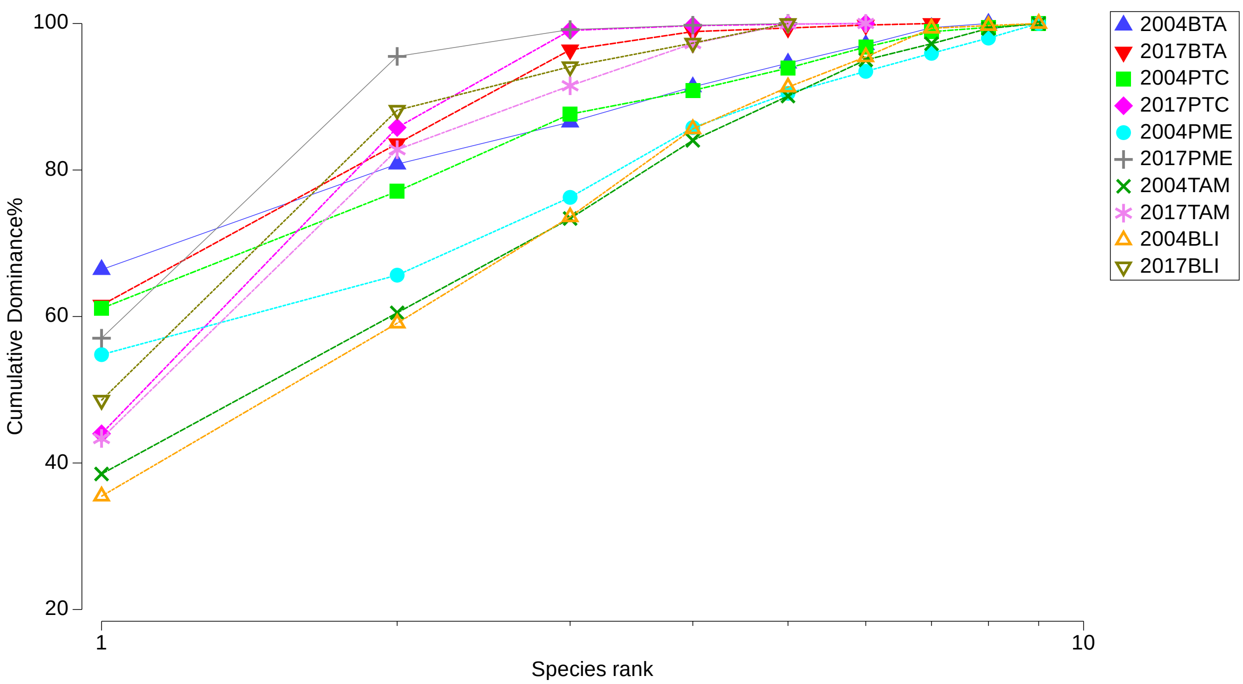

FIGURE 66. k-Dominance plot based on the spatio-temporal variation in seagrass benthic categories composition (2004 vs. 2018).

A k-dominance plot also showed a spatio-temporal shift towards the upper left corner of the image where the combined *after* effects of hurricanes impacts and the *H. stipulacea* invasions did drive cumulative dominance of seagrass habitats towards an altered state shifting to faster dominance accumulation, in comparison to *befiore* seagrass assemblages (***Figure 66***).

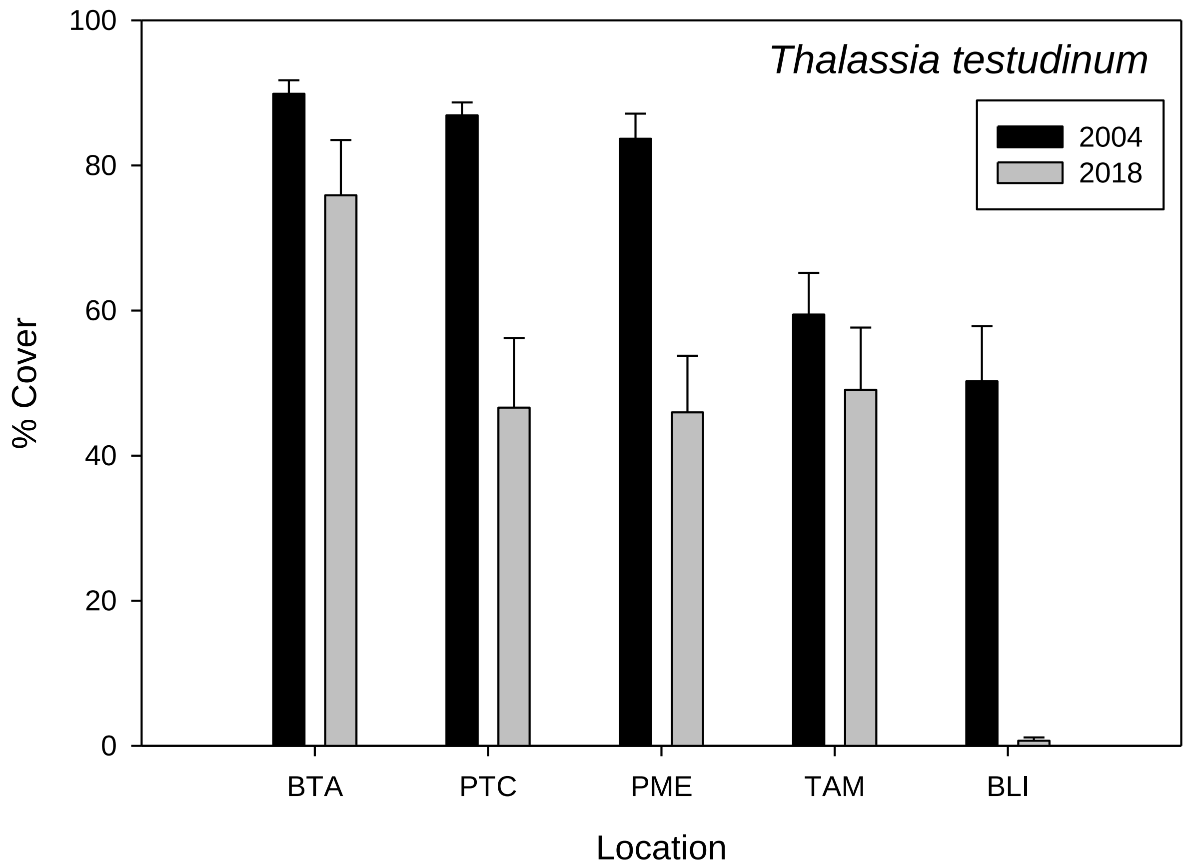

FIGURE 67. Percent *Thalassia testudinum* cover (mean±95% confidence intervals).

There was a highly significant spatio-temporal decline in percent *Thalassia testudinum* cover, which reflects both, an environmental stress gradient and the hurricanes impacts (***Figure 67***). Percent *T. testudinum* cover increased with increasing distance from urban-polluted waters and from physical disturbance from recreational vessel anchoring activities. But showed significant *after*-hurricanes decline.

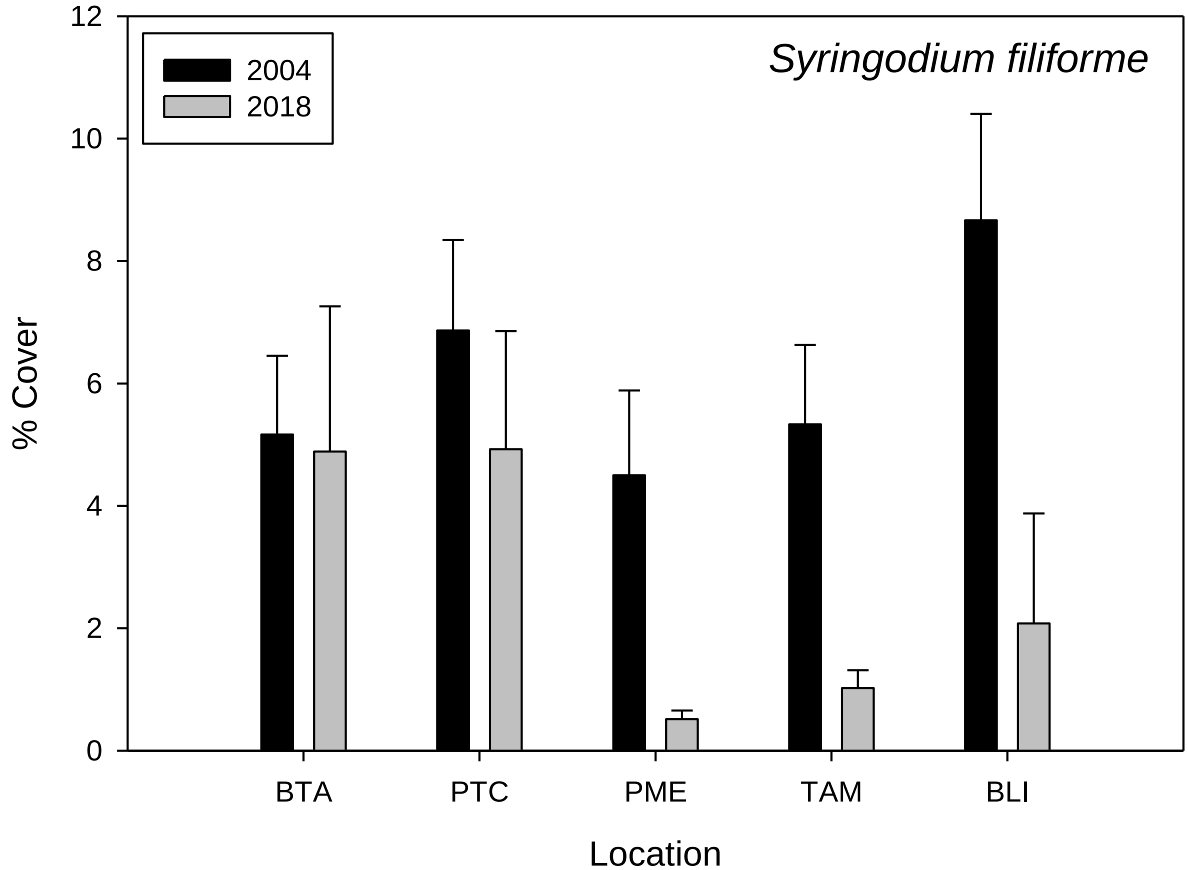

FIGURE 68. Percent *Syringodium filiforme* cover (mean±95% confidence intervals).

There was also a highly significant spatio-temporal decline in percent *Syringodium filiforme* cover, which reflects both, an indirect environmental stress gradient and the direct hurricanes impacts (***Figure 67***). Percent *S. filiforme* cover declined with increasing distance from urban-polluted waters, as a result of increasing dominance by *T. testudinum*. But showed significant *after*-hurricanes decline, particularly across those locations more exposed to S-SW winds and wave action (PME, TAM, BLI).

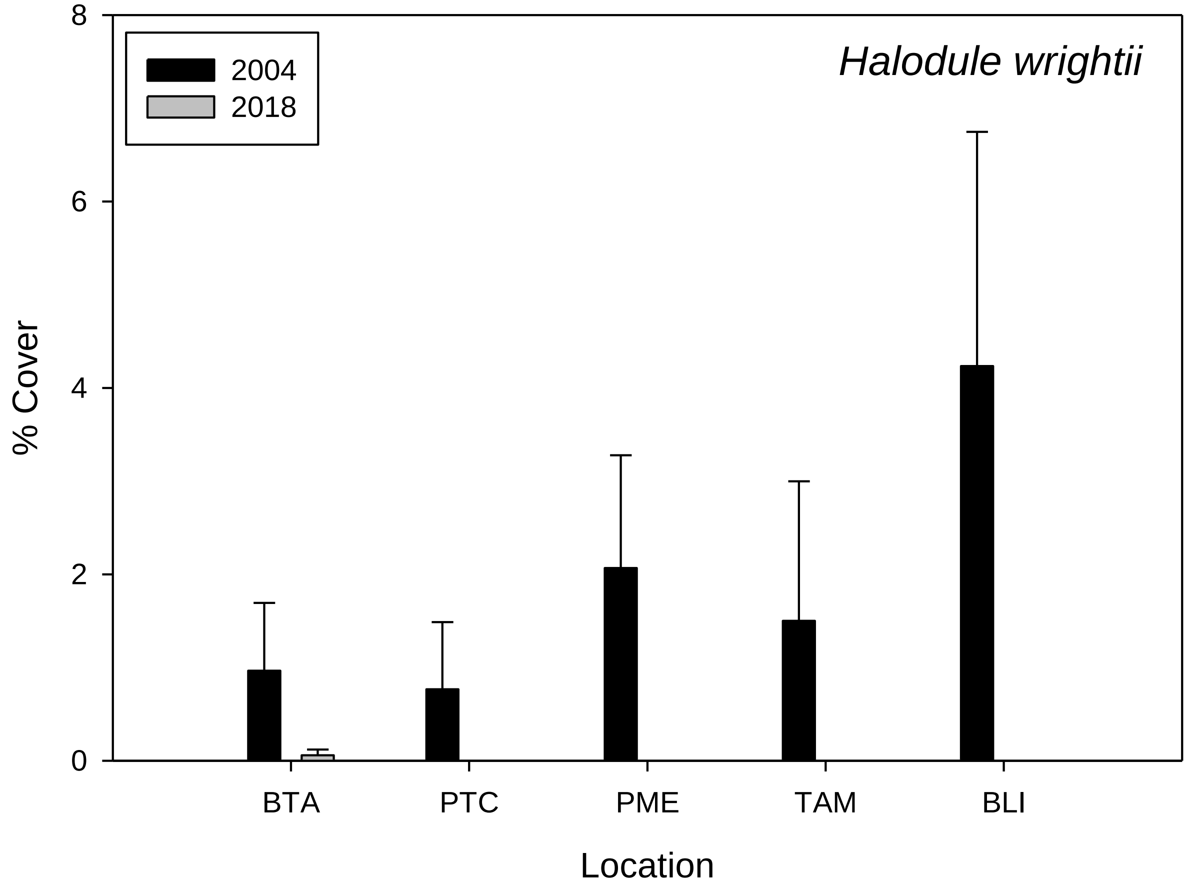

FIGURE 69. Percent *Halodule wrightii* cover (mean±95% confidence intervals).

There was also a highly significant spatio-temporal decline in percent *Halodule wrightii* cover, which reflects both, an indirect environmental stress gradient and the direct hurricanes impacts (***Figure 69***). Percent *H. wrightii* cover declined with increasing distance from urban-polluted waters, as a result of increasing dominance by *T. testudinum*, but increased across highly-disturbed locations. The species nearly disappeared in 2018 *after*-hurricanes, particularly across those locations more exposed to S-SW winds and wave action. Its presence is still limited and shows evidence of only sporadic, minor regrowth. This suggests that seagrass natural recovery processes are very slow.

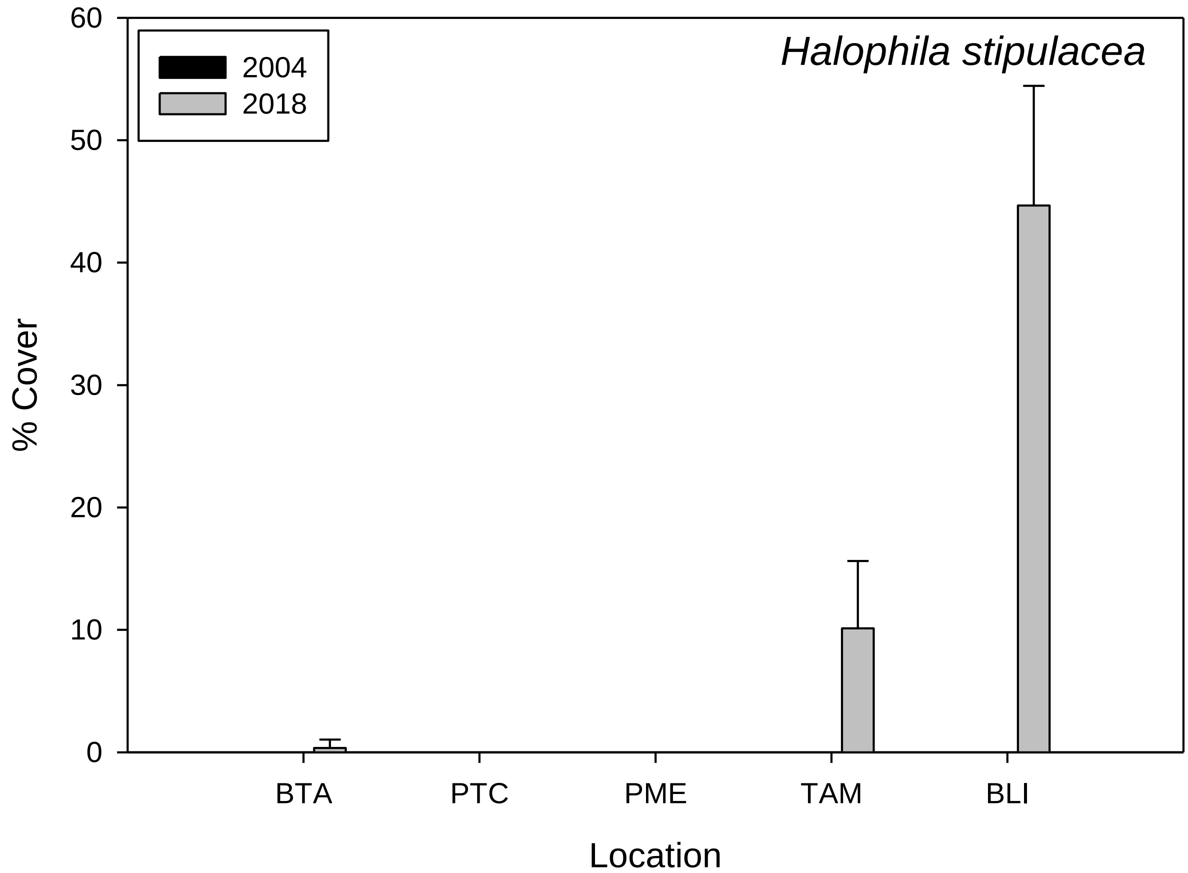

FIGURE 70. Percent *Halophila stipulacea* cover (mean±95% confidence intervals).

The invasive Sea vine, *Halophila stipulacea*, was totally absent in the 2004 surveys. Then, in spite of hurricane impacts, it showed a rapid increase in percent cover across TAM (~10%) and BLI (~45%) (***Figure 70***). This species has rapidly spread across chronically-disturbed seagrass habitats, taking over open reef substrates and displacing *Thalassia testudinum* and other native species. The fact that even *after* hurricanes impacts its cover remained high at both locations, and that for the first time it was informed growing within

Canal Luis Peña no-take Natural Reserve, at BTA, though at still a very low percent cover, it highlights its remarkable resilience to stochastic disturbances such as strong hurricanes.

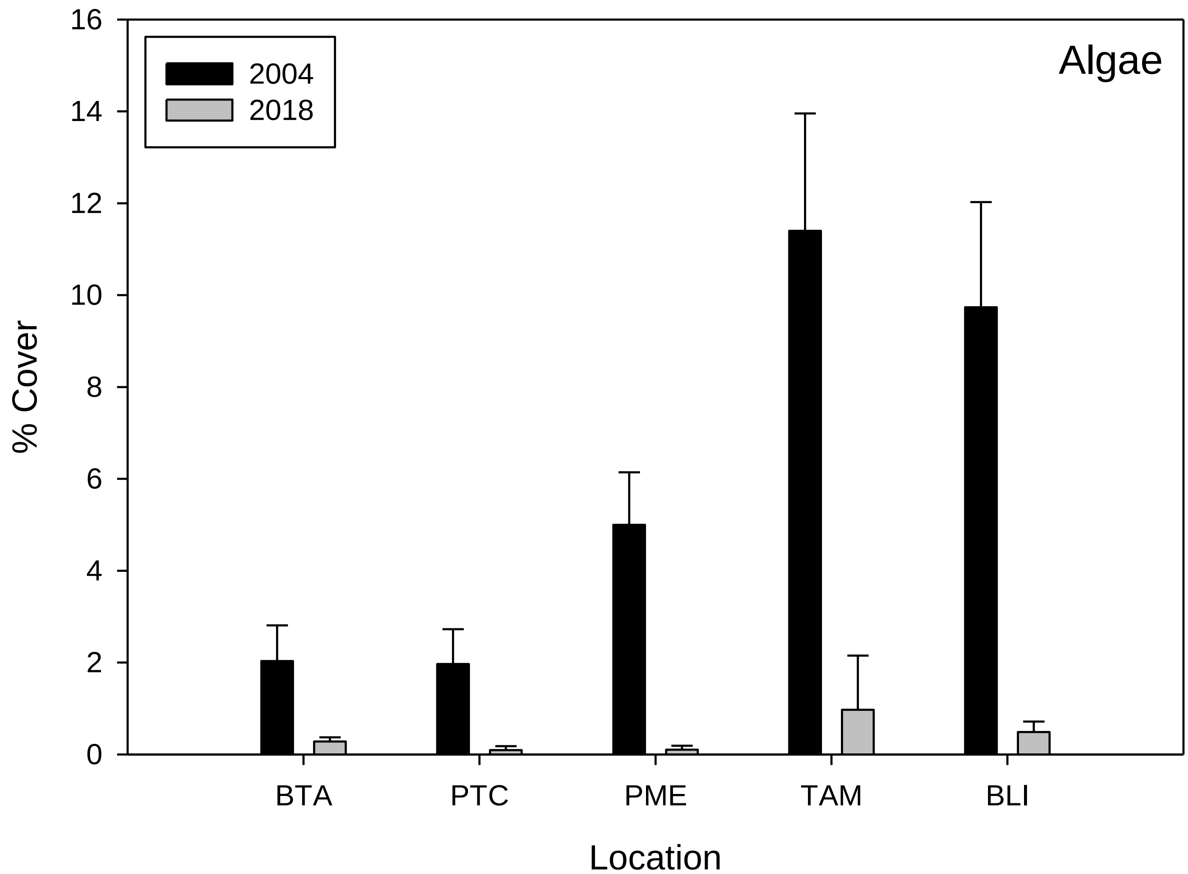

FIGURE 71. Percent total algal cover (mean±95% confidence intervals).

There was a highly significant spatio-temporal decline in percent algal cover, which reflects both, an indirect environmental stress gradient during 2004 and the direct hurricanes impacts (***Figure 71***). Percent macroalgal cover declined with increasing distance from urban-polluted waters but increased across highly-disturbed locations.

Many algal taxa nearly disappeared in 2018 *after*-hurricanes, particularly across those locations more exposed to S-SW winds and wave action. Many algal taxa are showing a slow recovery process.

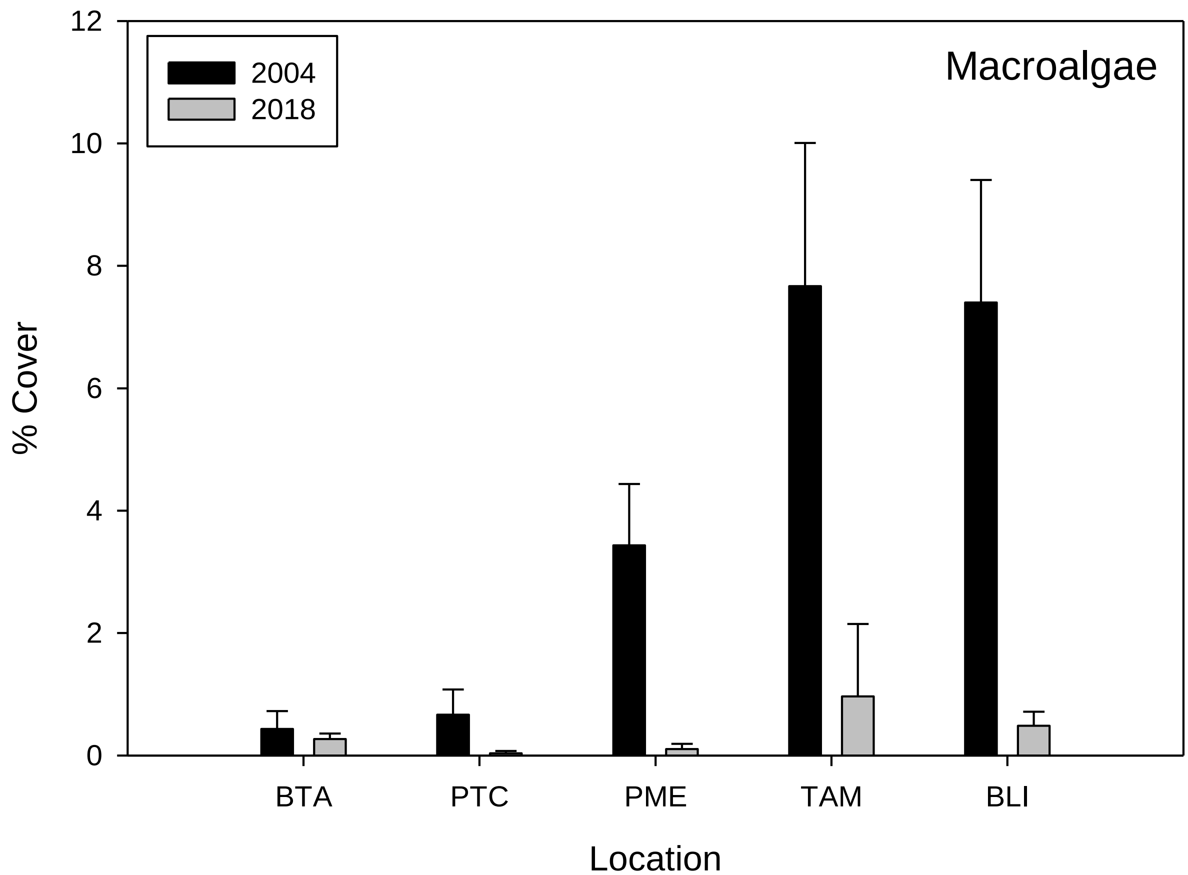

FIGURE 72. Percent macroalgal cover (mean±95% confidence intervals).

Spatio-temporal variation in macroalgae was highly similar to that documented for total algae, with a significant spatial gradient *before* hurricanes (2004), and then major *after*-hurricane loss across all locations, and still slow recovery (***Figure 72***).

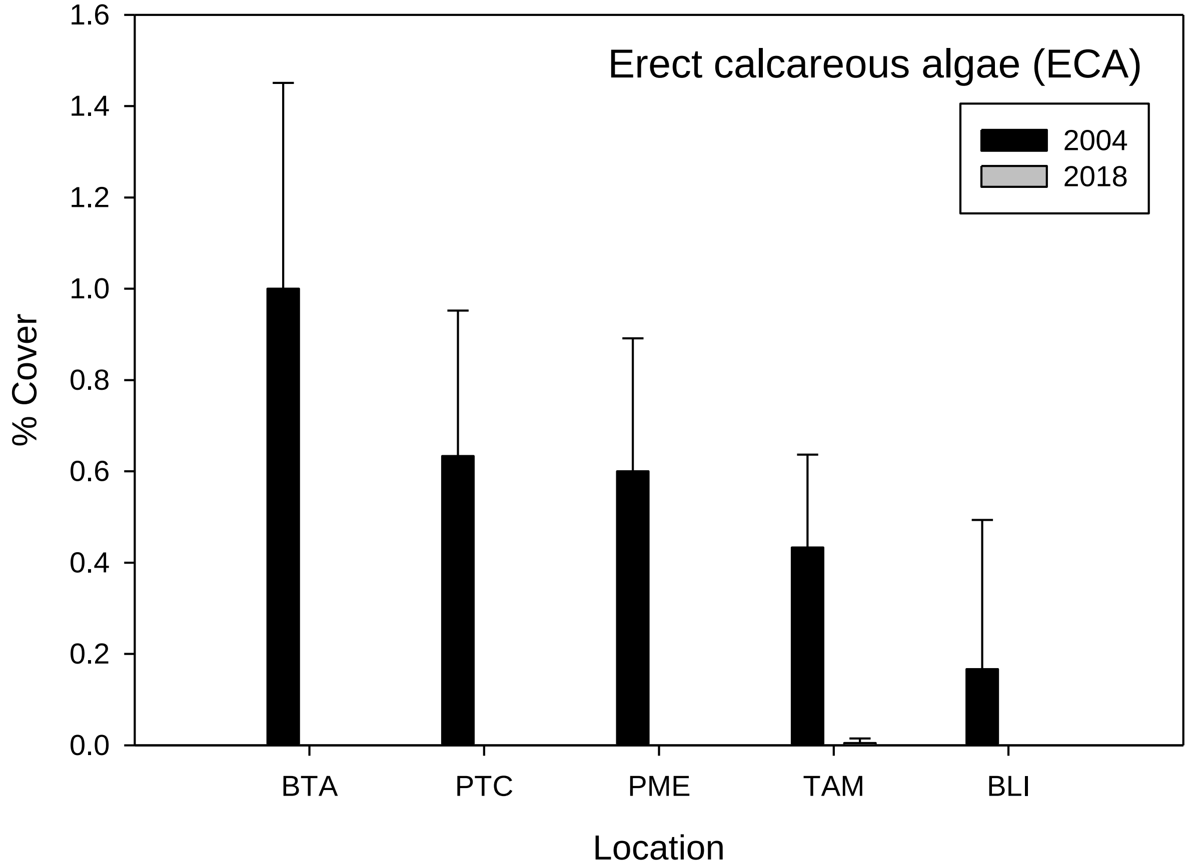

FIGURE 73. Percent erect calcareous algal (ECA) cover (mean±95% confidence intervals).

Spatio-temporal variation in erect calcareous algae (ECA) showed also a significant spatial gradient *before* hurricanes (2004), with declining cover under high water quality and physical disturbance, and then major *after*-hurricane loss across all locations, and still very slow recovery (***Figure 73***).

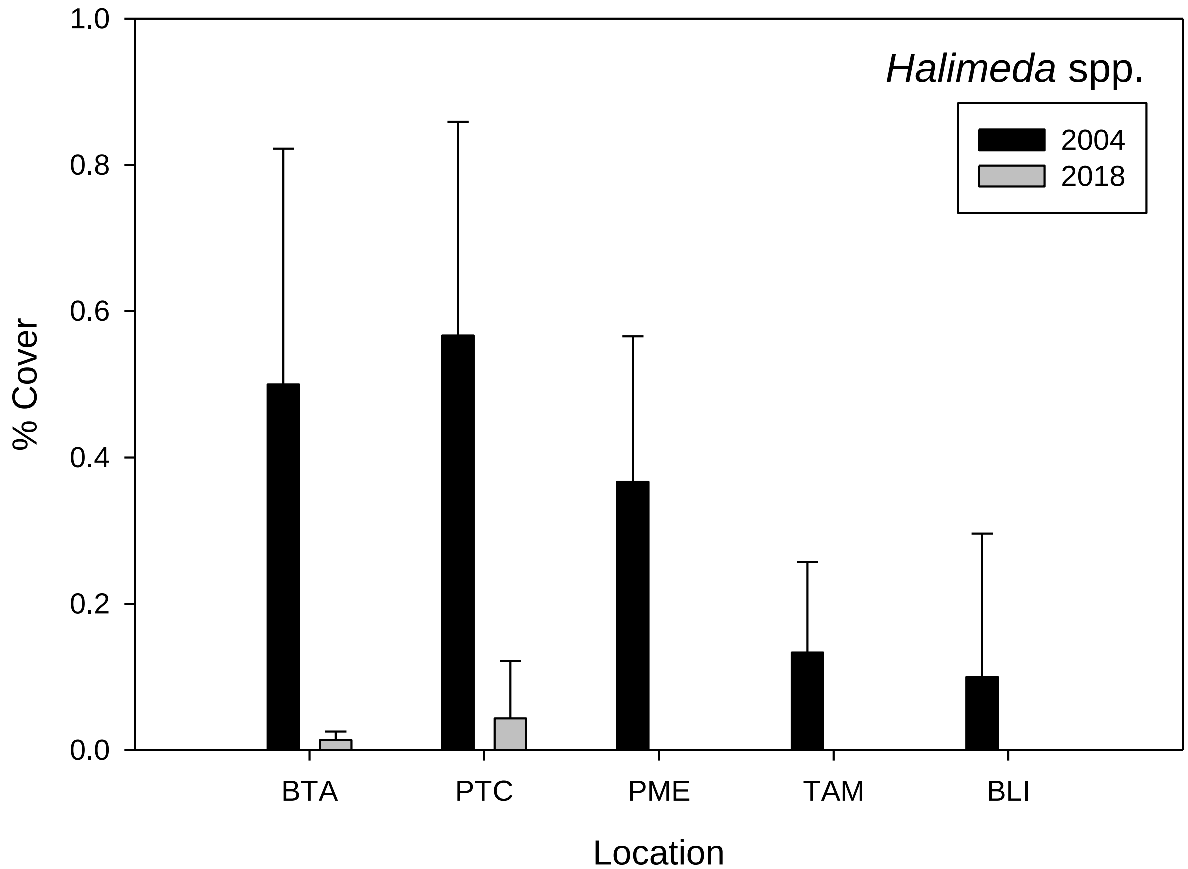

FIGURE 74. Percent *Halimeda* spp. cover (mean±95% confidence intervals).

Spatio-temporal variation in *Halimeda* spp. showed a nearly similar significant spatial gradient *before* hurricanes (2004), when compared to ECA, with declining cover under high water quality and physical disturbance, and then major *after*-hurricane loss across all locations, and still very slow recovery (***Figure 74***).

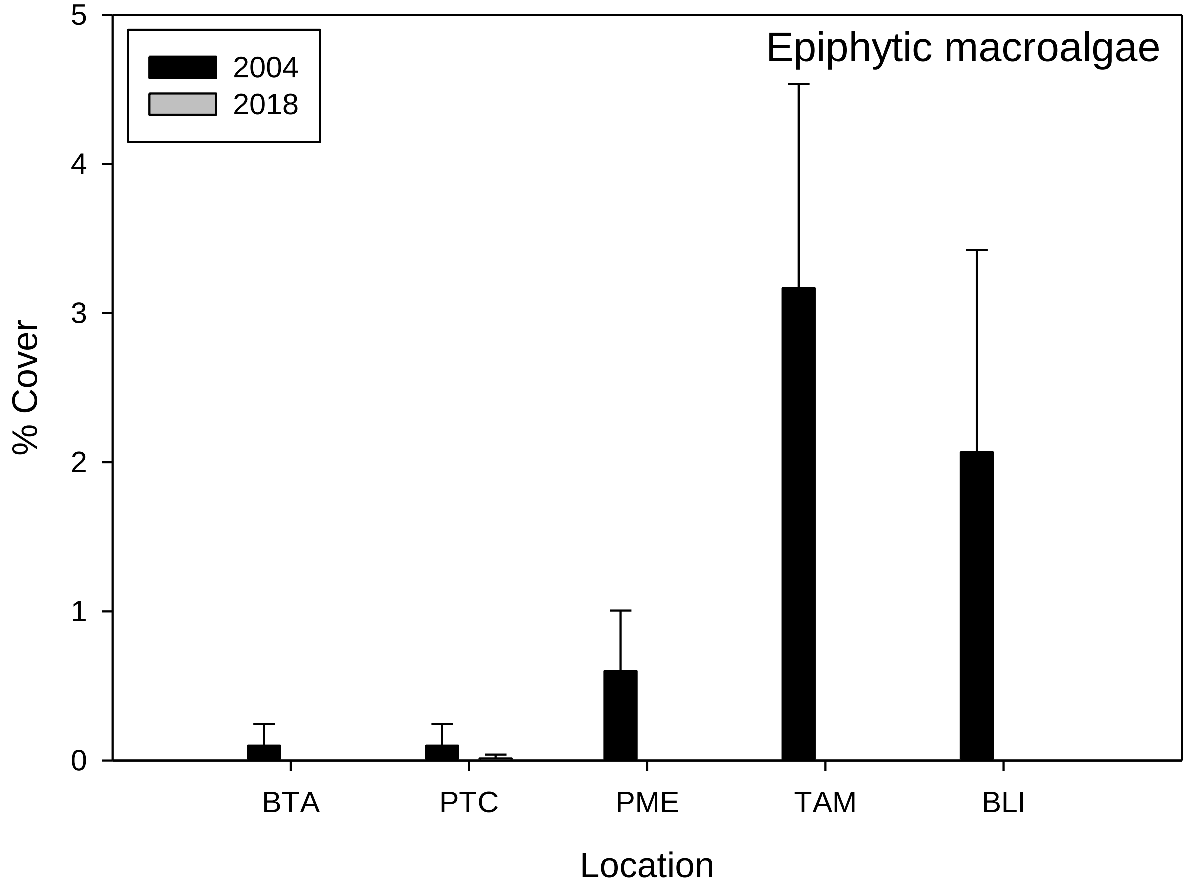

FIGURE 75. Percent epiphytic macroalgal cover (mean±95% confidence intervals).

Epiphytic macroalgae on seagrasses were significantly more abundant across disturbed and polluted habitats *before* hurricanes (2004), but largely declined *after*-hurricane impacts across all locations (***Figure 75***).

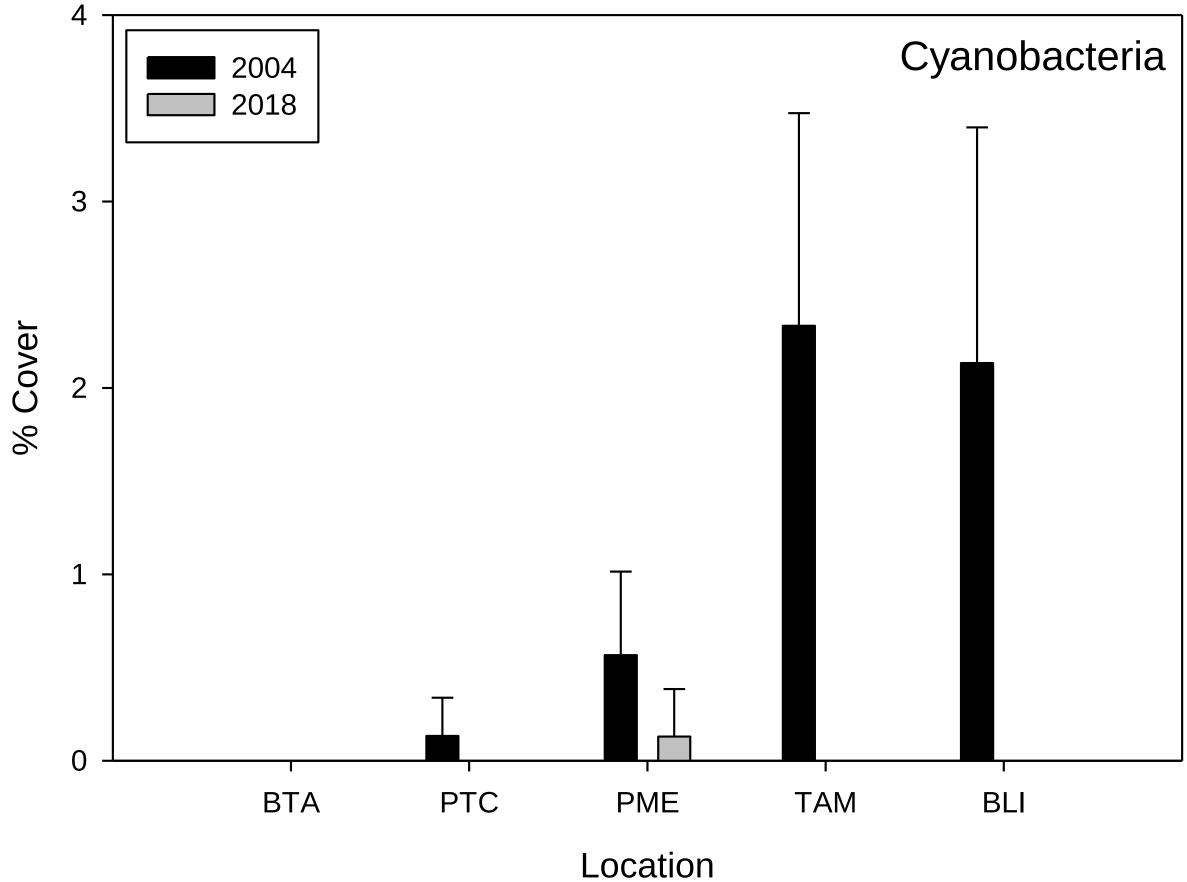

FIGURE 76. Percent cyanobacterial cover (mean±95% confidence intervals).

Cyanobacterial mats were significantly more abundant across disturbed and polluted habitats *before* hurricanes (2004), but largely declined *after*-hurricane impacts across all locations (***Figure 76***). Cyanobateria are also Hernández-Delgado et al., 2002

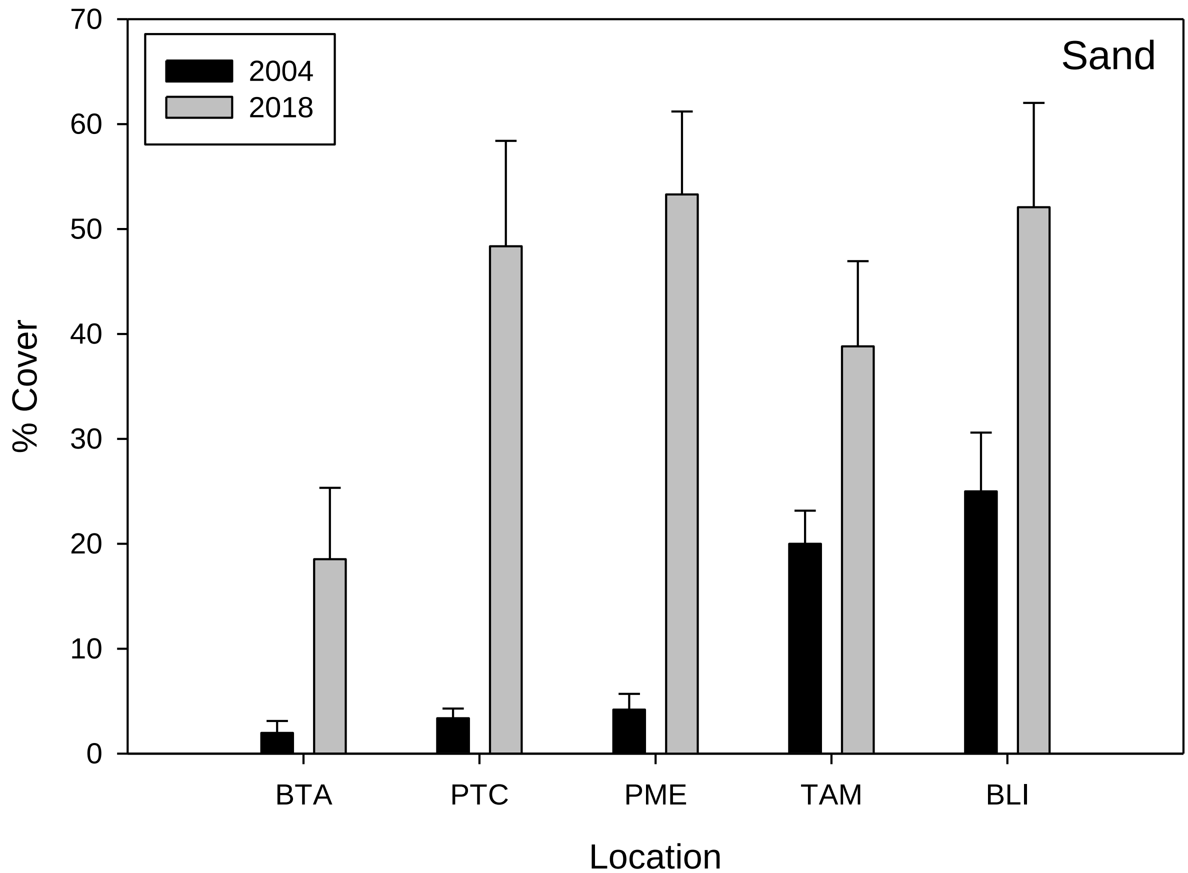

FIGURE 77. Percent sand cover (mean±95% confidence intervals).

Percent cover of sand showed a significant spatial pattern of increase in exposed seagrass bottom during *pre*-hurricane conditions across disturbed habitats exposed to recurrent turbid, sediment-laden, nutrient-loaded runoff, and in habitats impacted by frequent anchoring (***Figure 77***). However, by 2018 there was a highly-significant increase in percent sand cover due to sediment bedload, which caused seagrass habitat burial and suffocation, and due to the mechanical disruption of seagrass habitats from strong wave action.

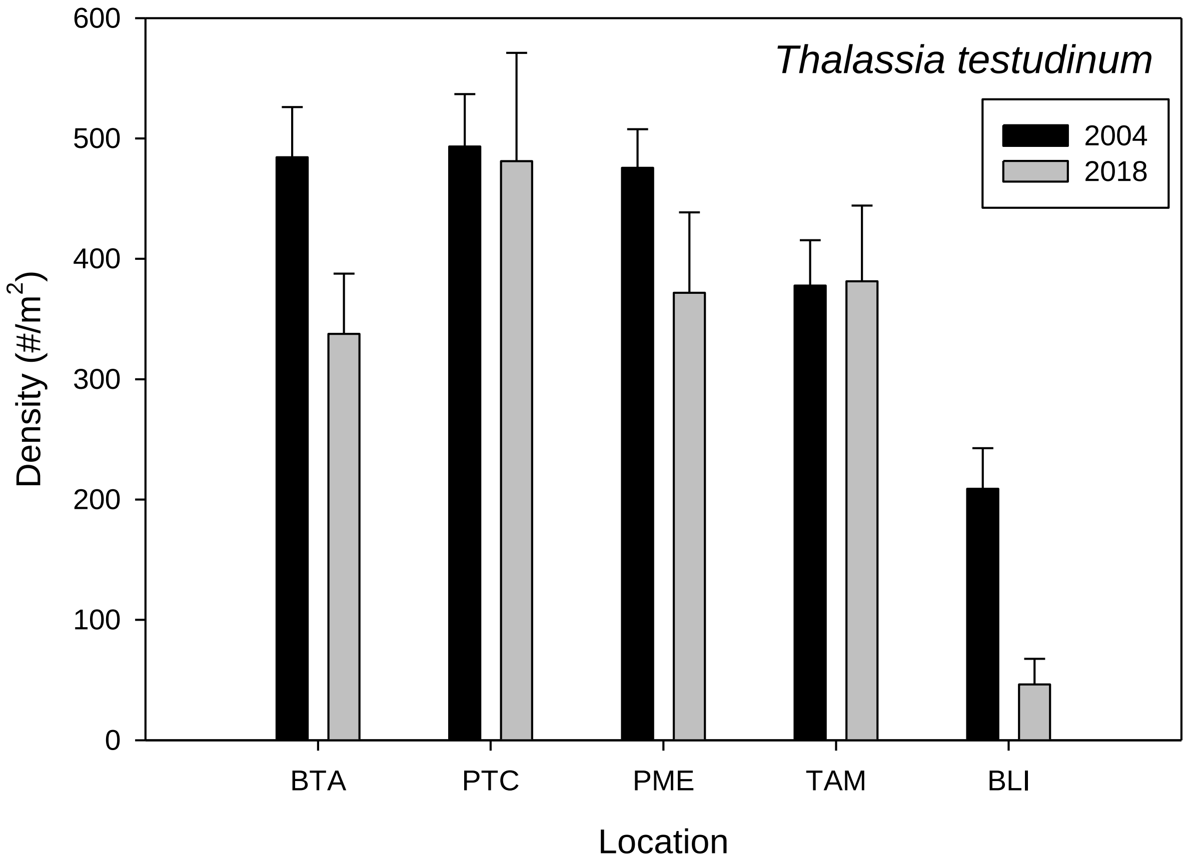

FIGURE 78. *Thalassia testudinum* density [#/m^2] (mean±95% confidence intervals).

Thalassia testudinum density showed a significant spatio-temporal decline, first in 2004 due to a gradient of water quality and physical disturbance associated to anchoring (***Figure 78***). During 2018, *after*-hurricane impacts were still evident, particularly BLI, BTA, and PME. Most of this effect was actually associated to a combination of factors, which included shifting sands, partial disruption of sea bottom, and the spreading of the invasive Sea vine, *Halophila stipulacea*.

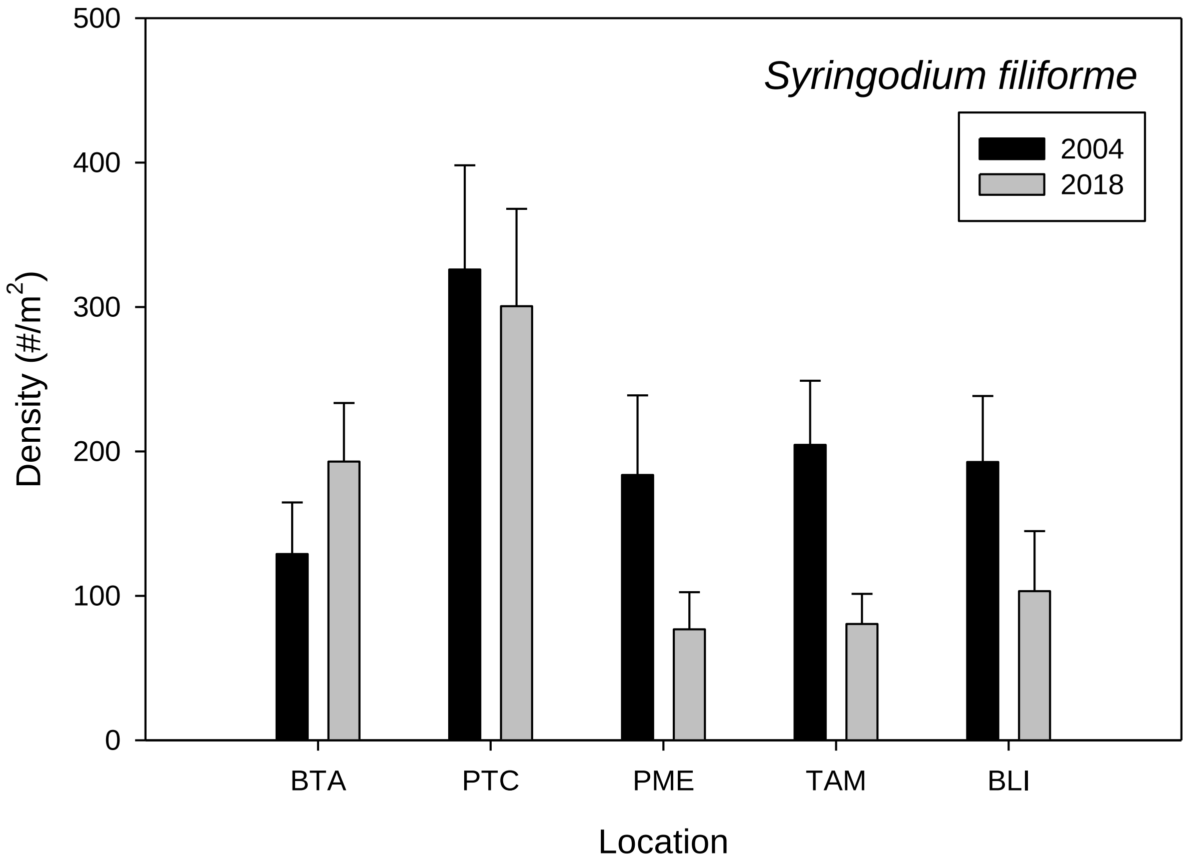

FIGURE 79. *Syringodium filiforme* density [#/m^2] (mean±95% confidence intervals).

Syringodium filiforme density showed a significant spatio-temporal decline at PME, TAM, and BLI, following hurricanes effects (***Figure 79***). Decline observed at PTC was minimal. It actually showed slightly higher density at BTA *after* hurricanes.

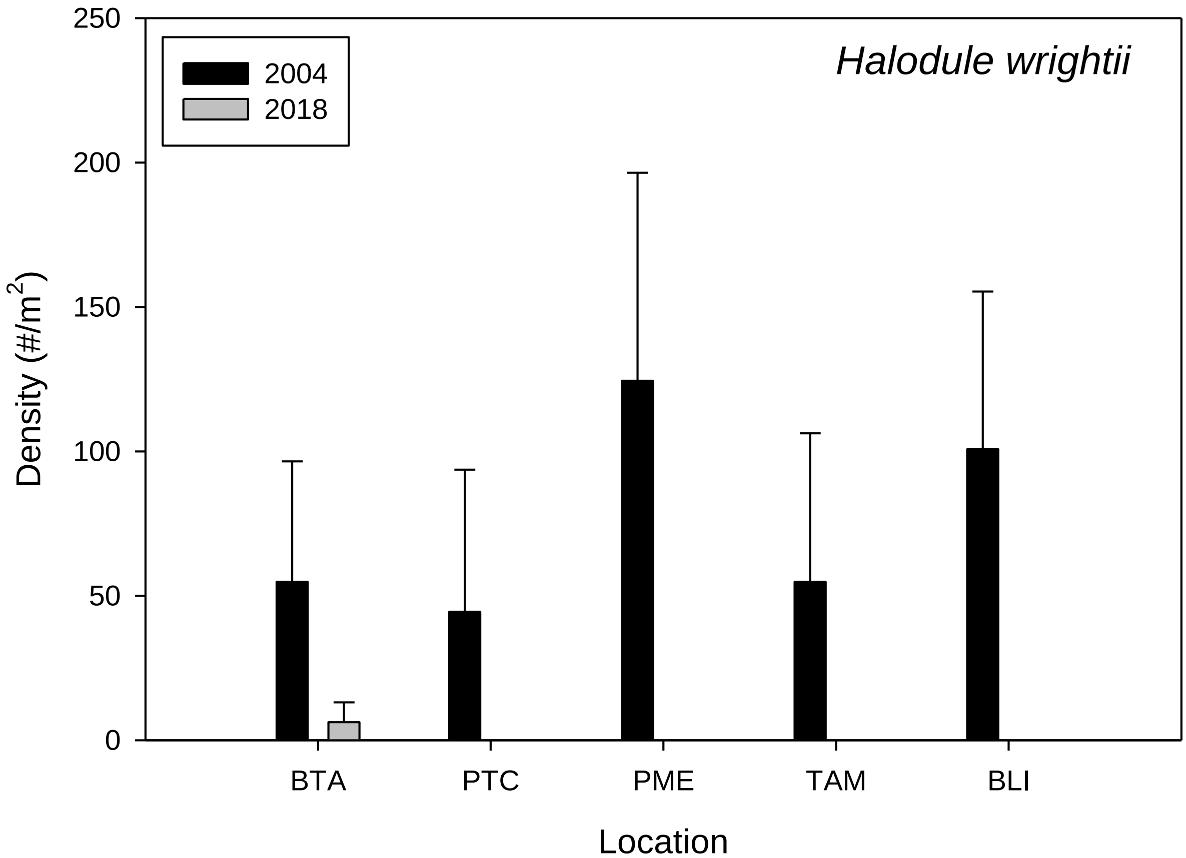

FIGURE 80. *Halodule wrightii* density [#/m^2] (mean±95% confidence intervals).

Halodule wrightii showd a highly-significant *after*-hurricane loss across almost all locations, with the exception of BTA (***Figure 80***). This species was more common in 2004 in physically-disturbed locations. It is an early-successional species, and a critical pioneer species during post-disturbance natural recovery. Its nearly total absence in 2018 implies that hurricane-impacted seagrass habitats are not showing rapid signs of natural recovery yet.

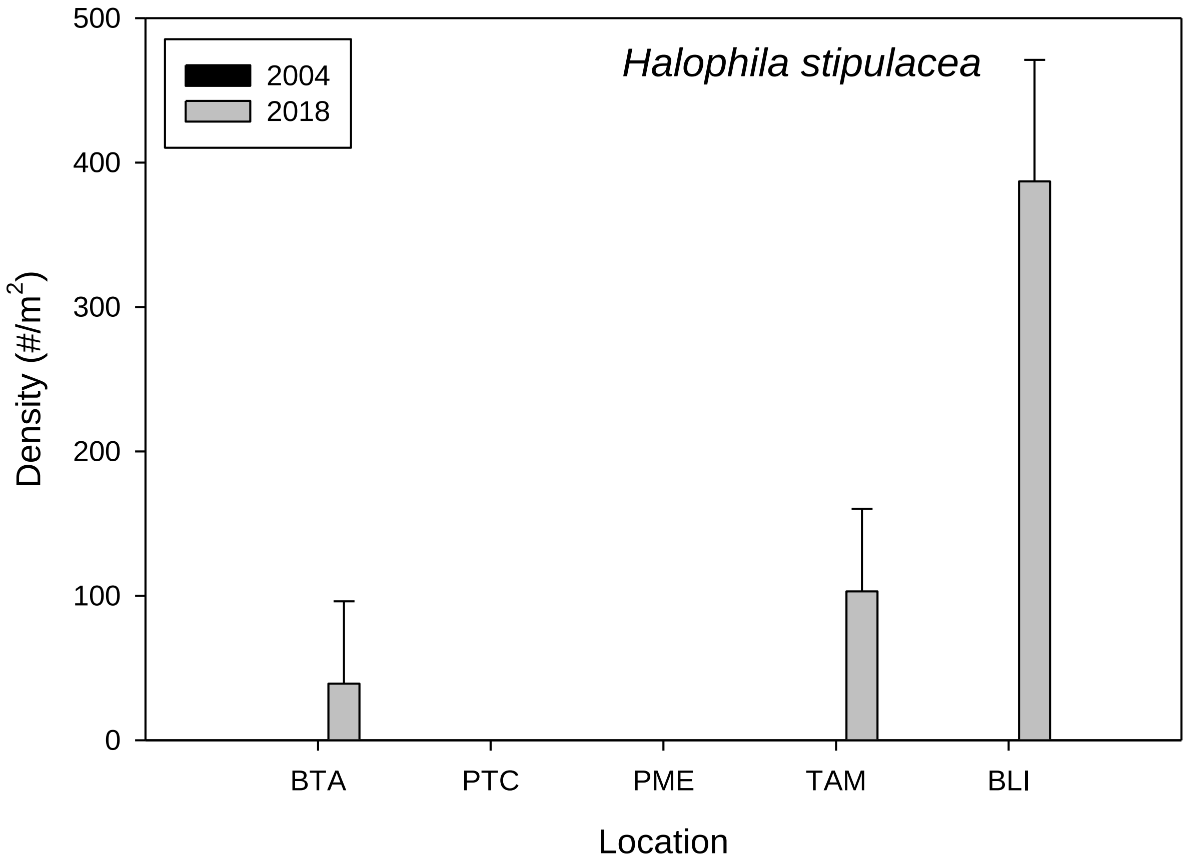

FIGURE 81. *Halophila stipulacea* density [#/m^2] (mean±95% confidence intervals).

The invasive Sea vine, *Halophila stipulacea*, was totally absent in the 2004 surveys. Then, in spite of hurricane impacts, it showed a rapid increase in density across TAM and BLI (***Figure 81***). This species has rapidly spread across chronically-disturbed seagrass habitats, taking over open reef substrates and displacing *Thalassia testudinum* and other native species. The fact that even *after* hurricanes impacts its density remained high at both locations, and that for the first time it was informed growing within Canal Luis Peña no-take Natural Reserve, at BTA, though at still a very low density and a very localized segment, highlights its remarkable resilience to stochastic disturbances such as strong hurricanes.

4.3 GIS-based interpolation analysis of post-hurricane seagrass condition

Inverse distance weighting (IDW) interpolation was used to address the spatial variation in seagrass habitat condition of groundtruthed polygons based on percent seagrass cover and on *Thalassia testudinum* density. Also, spatial variation in percent cover of invasive Sea vine, *Halophila stipulacea* was addressed at TAM and at BLI (Playa Dátiles). ***Figure 82*** shows that observed damage at BTA was patchy and most often across zones shallower than 4 m, and across the southern segment of the surveyed polygon. Nevertheless, moderately low to low *T. testudinum* shoot density was widespread across most of the polygon. ***Figure 83*** showed the most significant impact across deeper, but more exposed zone of PTC. The rocky peninsula and extended reef provided some partial protection to the shallower seagrass community from strong winds and waves. Deeper seagrasses were more exposed to winds, waves and swells. This is also reflected in the higher density of shallower *T. testudinum* segments. Most of the observed impacts were in the form of sediment bedload (horizontal transport) and seagrass burial.

Both, percent seagrass cover and *T. testudinum* density show a pattern of lower mean values at shallower polygon segments (***Figure 84***). These were mostly characterized by a combination of mechanical seagrass matrix destruction and sediment burial.

Inverse Distance Weigthing Interpolations at Bahía Tamarindo

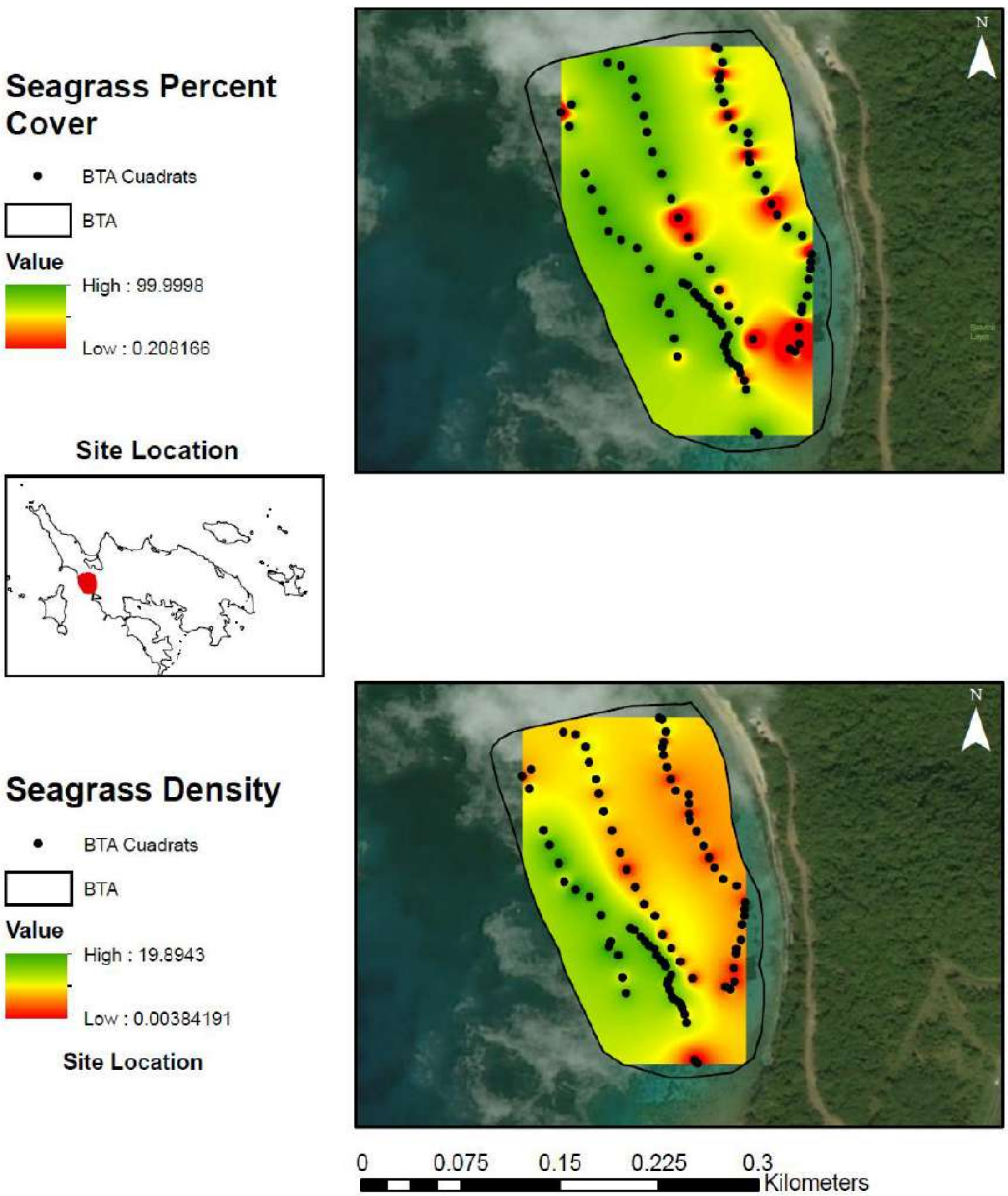

FIGURE 82. Inverse distance weighting (IDW) interpolation of percent seagrass cover and *Thalassia testudinum* density at Bahía Tamarindo (BTA).

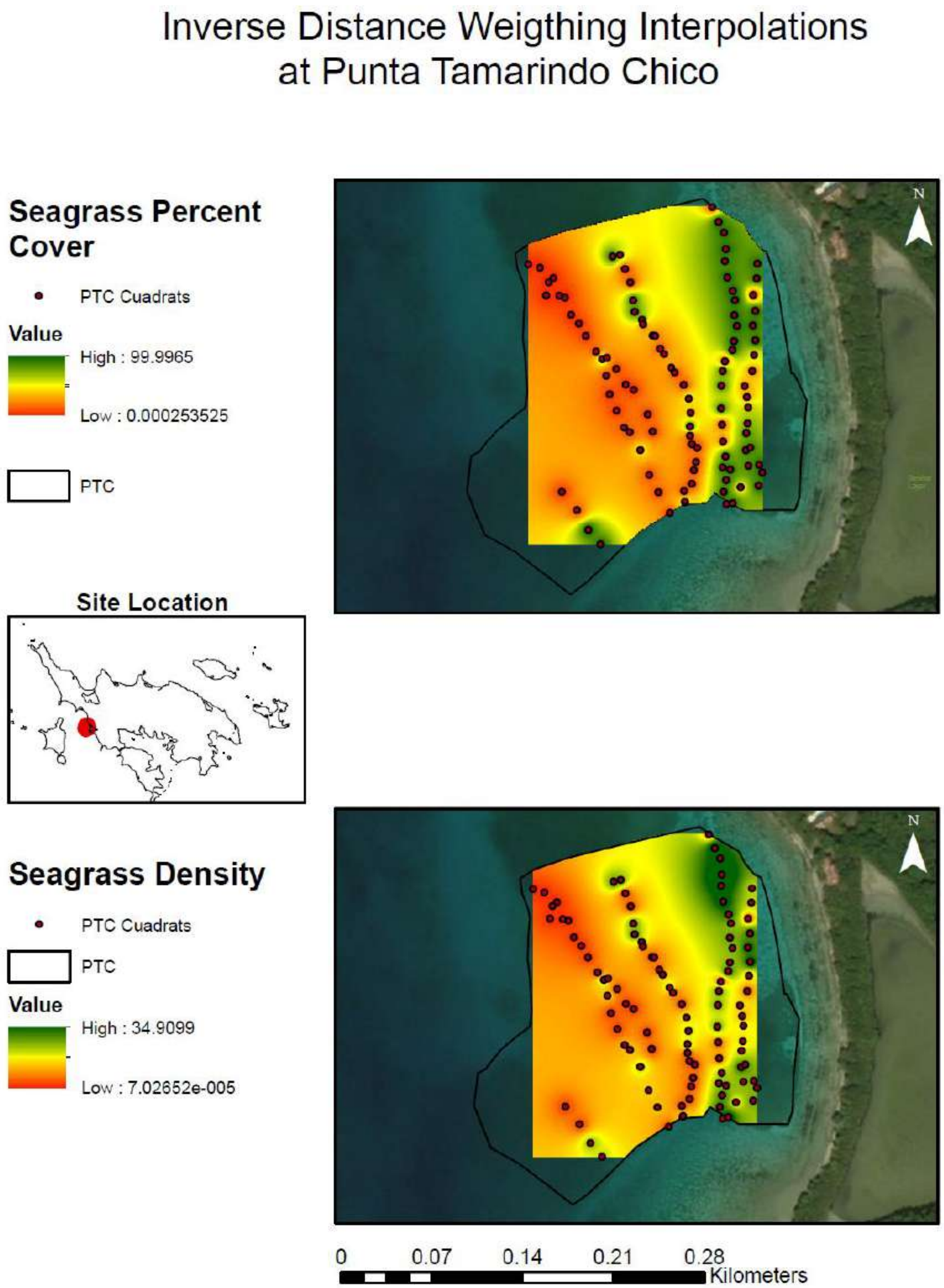

FIGURE 83. Inverse distance weighting (IDW) interpolation of percent seagrass cover and *Thalassia testudinum* density at Punta Tamarindo Chico (PTC).

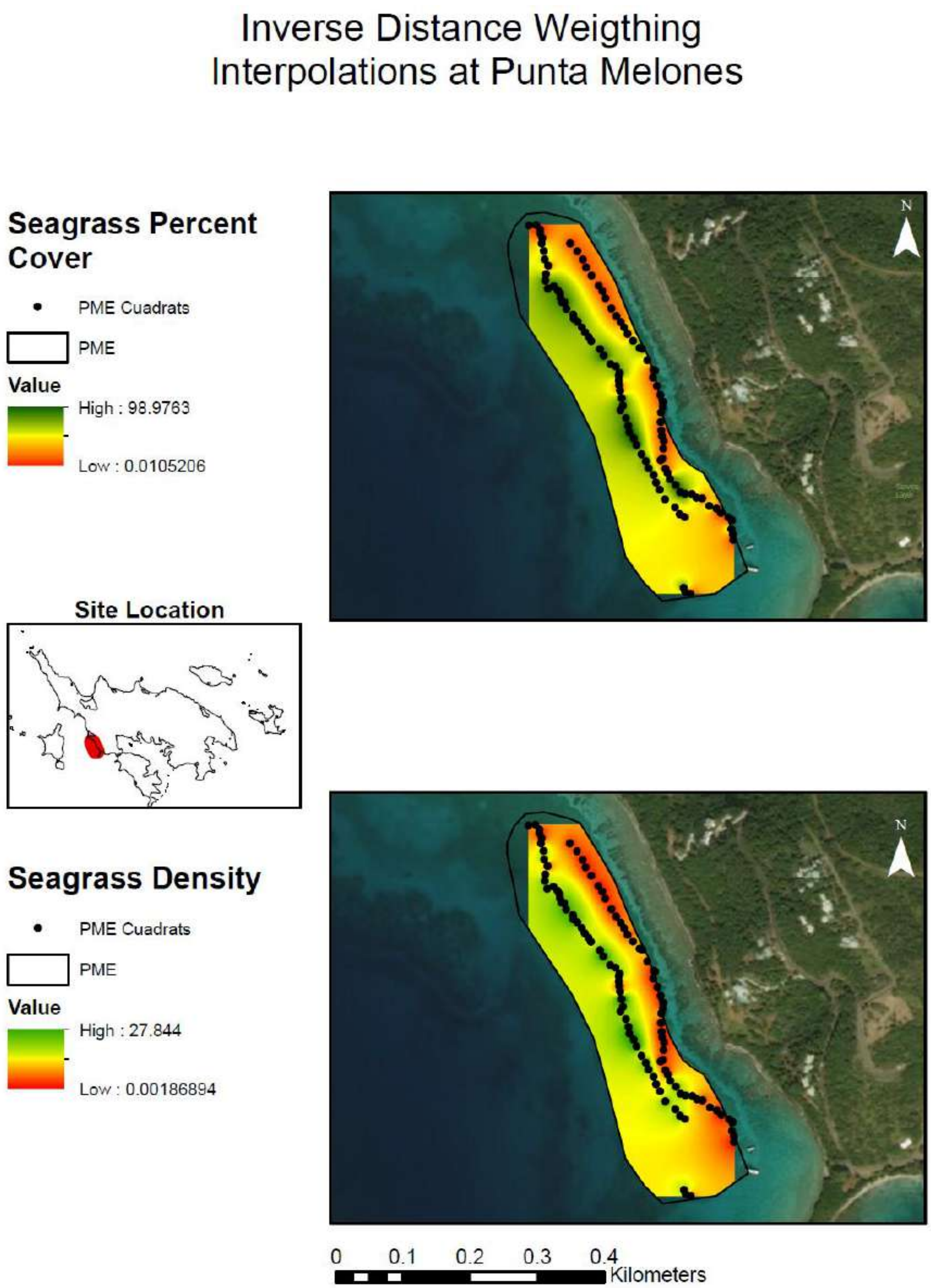

FIGURE 84. Inverse distance weighting (IDW) interpolation of percent seagrass cover and *Thalassia testudinum* density at Punta Melones (PME).

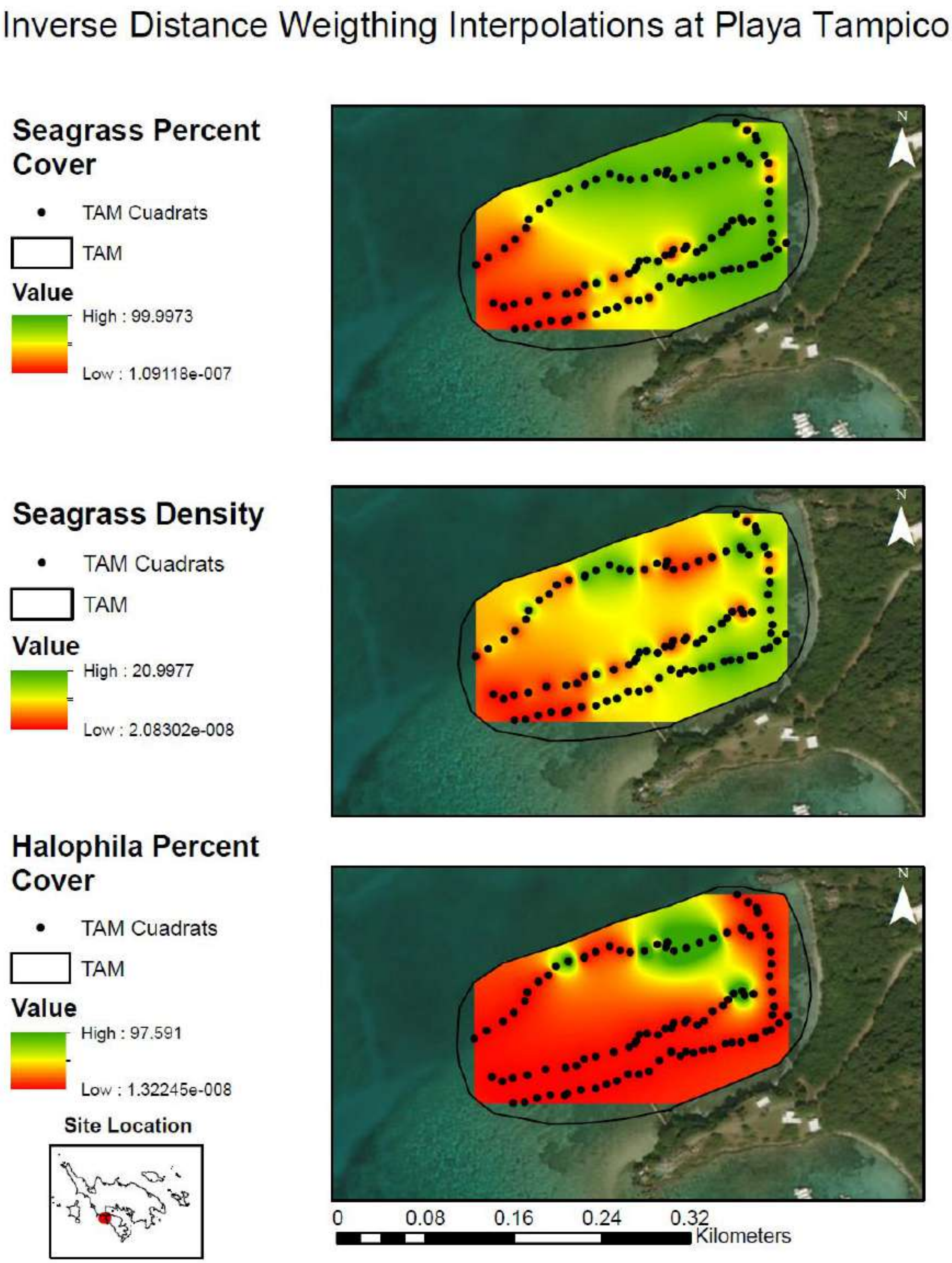

FIGURE 85. Inverse distance weighting (IDW) interpolation of percent seagrass cover, *Thalassia testudinum* density (#/m2), and percent *Halophila stipulacea* cover at Playa Tampico (TAM).

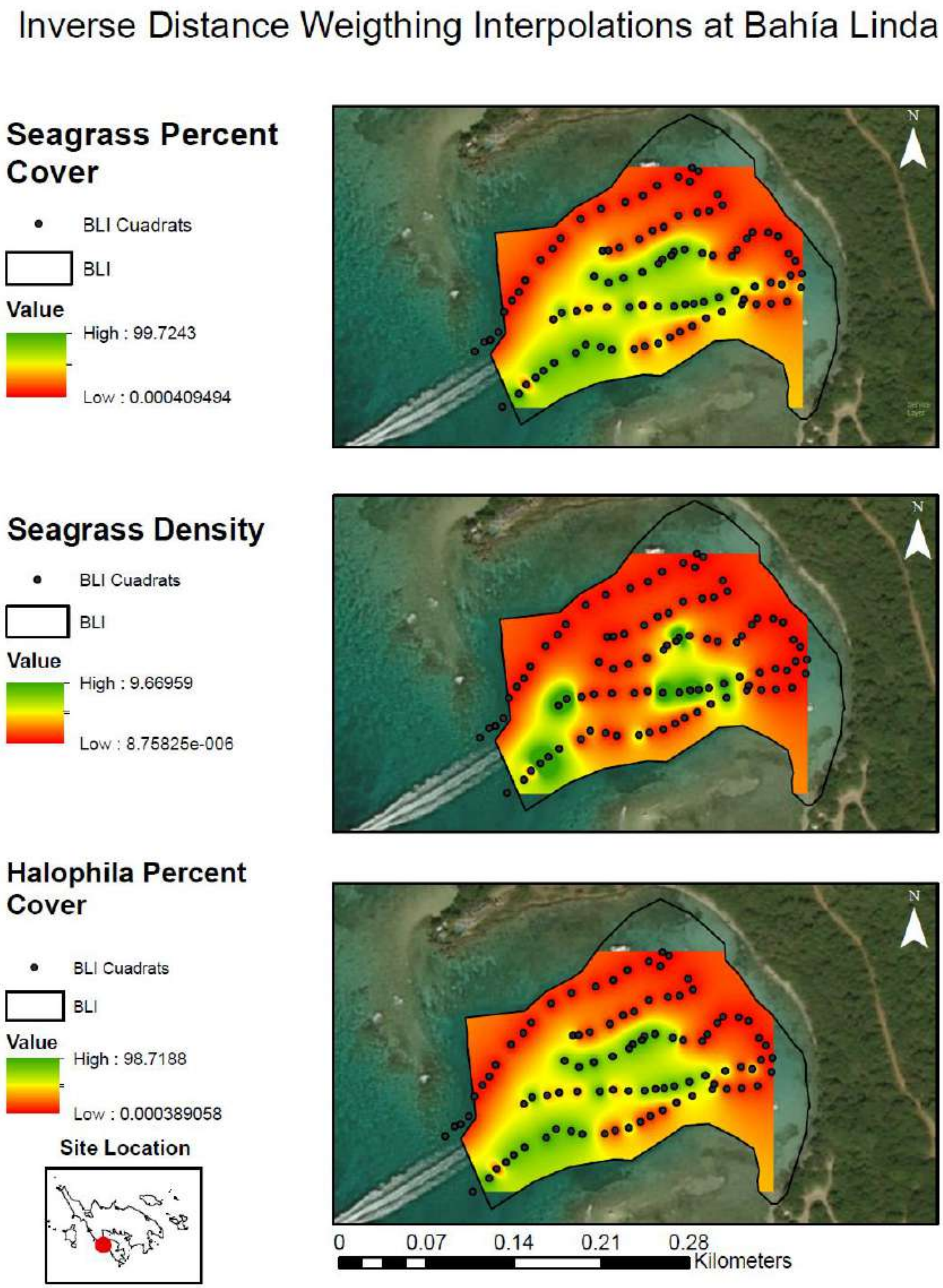

FIGURE 86. Inverse distance weighting (IDW) interpolation of percent seagrass cover, *Thalassia testudinum* density (#/m2), and percent *Halophila stipulacea* cover at Bahía Linda (BLI).

Percent seagrass cover at TAM showed a gradient of declining cover towards its western, and more exposed segment. Indeed, part of this segment was more exposed to wave action, winds, and was heavily impacted by rubble displacement from the adjacent shallow reef located halfway between TAM and BLI (***Figure 85***). *Thalassia testudinum* density followed a nearly similar spatial trend, with lower values or nearly total extirpation towards the western segment. But there were also low-density patches along the northern and northeastern sides of the segment in areas that were significantly overgrown and dominated by the invasive Sea vine, *Halophila stipulacea*. Percent cover of *H. stipulacea* was rapidly expanding along the northern segment of the surveyed polygon.

Percent seagrass cover at BLI (Playa Dátiles) showed mean higher values along the middle channel and the deepest part of the surveyed polygon (***Figure 86***). *Thalassia testudinum* density was higher only along two patches, one located at the outer, southwestern segment of the surveyed polygon, and along a second smaller patch along the middle section. This was the result of the extensive dominance and high cover by the invasive Sea vine, *H. stipulacea*. The shallowest, northeastern polygon segments showed very low seagrass cover resulting from a combination of hurricanes impacts and by the long-term decline associated to recreational boating anchoring.

5.0 DISCUSSION

5.1 Summary of major findings

This rapid assessment has shown important findings summarized below:

14. Seagrass communities in Culebra were significantly impacted by Hurricanes Irma and María in September 2017.

15. Most of the documented impacts were associated to sediment bedload (horizontal transport), which resulted in seagrass burial and suffocation. In a lesser extent there was also common to occasional physical disruption of the seagrass habitat matrix, creating major scars on the sea bottom, and exposing seagrass structure to further disintegration by future storm events.

16. Mechanical destruction of coral reef shallow grounds located between TAM and BLI, as well as in DAK, resulted in:

    a. Physical disruption shallow reef's framework, mostly along Finger coral, *Porites porites*, biotopes.
    b. Major stochastic reef flattening.
    c. Burial and suffocation of backreefs and seagrass habitats under displaced rubble.
    d. A continuous threat of potential spatial expansion of burial (moving substrate) during future storm/winter swells events.

17. Hurricane impacts resulted in a significant shift in seagrass benthic community structure, in a net decline in percent seagrass cover (all native species), in a net decline in multiple algal functional groups (e.g., macroalgae, erect calcareous algae, *Halimeda* spp.), and even in cyanobacteria. It also resulted in a net increase in exposed sand bottom.

18. This study also revealed the concerning increase in the spatial extent and localized dominance of invasive Sea vine, *Halophila stipulacea*, which has largely displaced native seagrasses at some extensive segments at least at BLI and TAM. It was also present at 7 of the 9 surveyed locations (78%). This has become a significant seagrass management concern, particularly due to its high resistance and resilience to hurricane disturbance.

19. Ground-truthing evidence also showed a significant decline in seagrass densities dependent on species assemblages and on location exposure to wave action. Particularly, it revealed that even as early as 2004, surveyed Culebra's seagrasses were being significantly impacted by an environmental stress gradient, characterized by localized turbid, sediment-laden, nutrient-loaded runoff pulses, and recurrent anchoring impacts, particularly at TAM and BLI.

20. The present study also revealed strong water quality impacts (TAM, BLI, PCO, DAK) associated to eutrophication from Ensenada Honda Bay and Lobina Channel. Culebra is still severely impacted by multiple non-point sources of land-based pollution, sedimentation, and illegal sewage dumping, previously documented in the literature (Hernández-Delgado et al., 2006, 2017; Otaño-Cruz et al., 2017). It also revealed significant impacts by anchors (TAM, BLI), in spite of previous efforts by DNER of establishing mooring buoys at BLI.

21. Locations not ground-truthed in this study also showed significant signs of post-hurricane decline, particularly, at PCO and CNO, with seagrass loss ranging from 33 to 50%. PCO has evidence of also being frequently impacted by stranded mats of *Sargassum fluitans*. CNO was also significantly impacted during 2008 by strong bottom swells associated to category 5 Hurricane Dean, which passed about 250 nm south of Puerto Rico in 2008.

22. There is an apparent synergy between *S. fluitans* stranded mats decay and the rapid expansion of invasive Sea vine, *H. stipulacea*. Areas along Cayo Dákity

which have been impacted by *S. fluitans* have shown a rapid spread of *H. stipulacea* over the last few years (***Figure 87***). Severe impacts by hurricane-generated wave action could further open more seagrass habitats which could expose open substrate to *H. stipulacea* invasions.

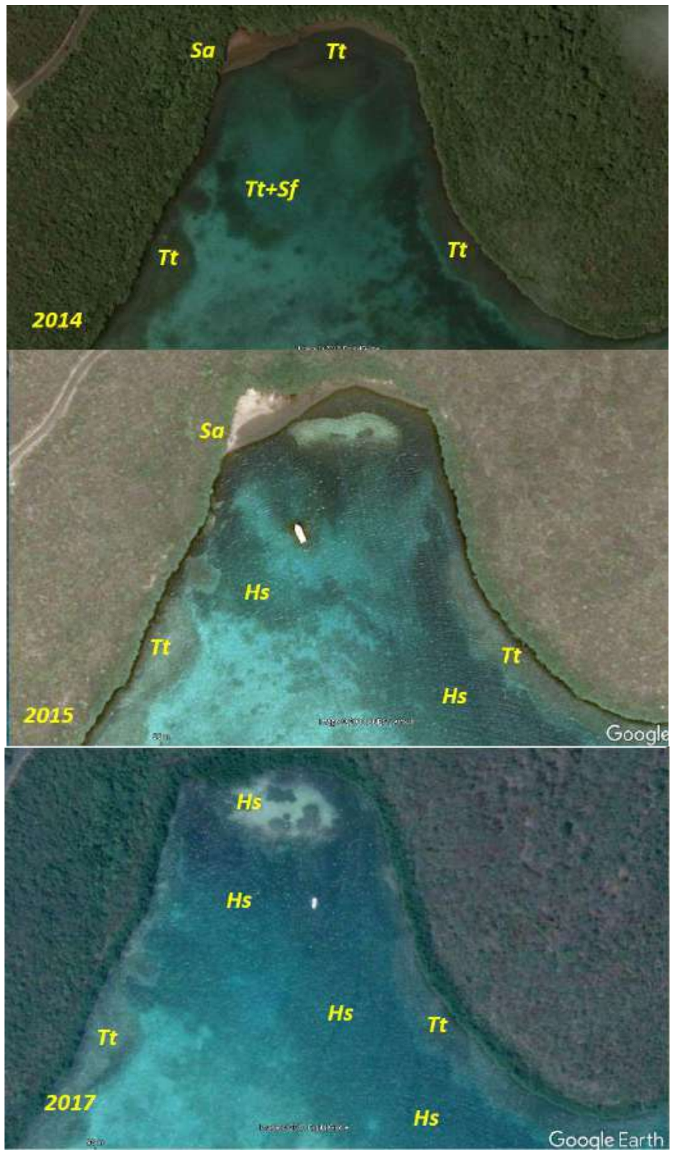

FIGURE 87. Spatio-temporal fluctuations in the distribution of *Thalassia testudinum* (Tt), *Syringodium filiforme* (Sf), *Sargassum fluitans* (Sa) stranded mats, and invasive Sea vine, *Halophila stipulacea* (Hs), observed at the western end of Cayo Dákity within 2014 and 2017. Image source: Google Earth.

23. The spatio-temporal implications of documented impacts in Culebra's seagrass communities are important. Impacted seagrass habitats are critical foraging grounds for a resident population of critically-endangered Green turtle, *Chelonia mydas*. Culebra's seagrasses up to 3 nm are designated as Resource Category 1 habitat and as DCH for *C. mydas*.

24. Sediment-buried seagrasses were also fundamental nursery and foraging grounds of multiple Federally-managed species, including Queen conch (*Lobatus gigas*), Spiny lobster (*Pannulirus argus*), Nassau grouper (*Epinephelus striatus*), Yellow-tail snapper (*Ocyurus chrysurus*), and Mutton snapper (*Lutjanus analis*), to mention some examples.

25. Some of the shallow seagrass locations, particularly those located within Canal Luis Peña no-take Natural Reserve, are fundamental for supporting local Culebra's municipality economy, as well as community-based livelihoods. Multiple nature-based tourism and recreation business operations were undertaken at locations such as BTA and PTC.

26. Observed impacts will require assisted restoration interventions to accelerate seagrass recolonization, and in some cases, may require localized benthic habitat reconstruction and stabilization, to foster the rapid recovery of ecological functions, benefits, and resilience.

5.2 Recommended management actions

A list of potential management actions important for each location is discussed below using a set of general call of actions (COAs) listed below:

SEAGRASS CoA Summary (NER-HFA)

5.2.1 Sector(s) Impacted

1. Infrastructure
2. Public buildings
3. Municipality of Culebra
4. Local and regional economy
5. Community-based livelihoods

5.2.2 Issue/Problem Being Solved

Hurricanes Irma and María had a severe impact on shallow coastal marine ecosystems in Culebra Island, including coral reefs and seagrass communities. Besides coral reefs, seagrass habitats contribute to provide wave energy and surface currents attenuation, and soft bottom stabilization which provide protection to coastal infrastructure. Seagrasses are also the habitat for multiple commercially important marine species and support a wide range of recreational activities, including SCUBA, snorkeling, kayaking, and swimming, being crucial for the sustainability of a long-term, strong ocean-dependent socio-economic activities. A better understanding of the health status and recovery ability of seagrass ecosystems, an expanded post-hurricane assessment of impacts, and addressing recovery of any lost resources will help ensure the sustainability of their economic and ecological contributions to the human and coral communities.

5.2.3 Short Description of CoA: Address landscape-scale seagrass data

gaps and restore degraded habitats

Actions to address seagrass data gaps and protect and restore seagrass resources will include create new marine habitat maps from high-resolution imagery, field assessments to determine seagrass community health, establish a seagrass permanent monitoring program, and implementation of recovery actions that improve or restore seagrass habitat damaged by hurricane, vessel grounding impacts, impacts from chronic disturbance (e.g., runoff), and coastal erosion. A specific recommendation for DNER include: strengthen conservation- and restoration-oriented management efforts of seagrasses within existing natural reserves, with particular emphasis on the NER-HFA, and on designated critical habitats for the critically-endangered Green turtle, *Chelonia mydas*, around Culebra Island.

5.2.4 Who is implementing the CoA?

The seagrass COA across the NER-HFA must be implemented by DNER, with the support of NOAA, and other important stakeholders, such the academia, mostly the University of Puerto Rico, NGOs (e.g. Sociedad Ambiente Marino), and any other private partners and collaborators.

5.2.5 How are they implementing the CoA?

COA must be implemented initially within existing natural reserves (e.g., NER-HFA). As such, it should be implemented through existing management plans, or through existing conservation- and restoration-oriented management plans for the NER-HFA.

5.2.6 What is the likely time scale to see benefits?

The likely time scale to see benefit will vary depending on the management action. Management activities such as expanded rapid assessments, and the implementation of seagrass long-term ecological monitoring can provide quick benefits (<1 yr). Mapping efforts will probably do it within 1-3 yr. Restoration efforts might likely produce benefits, depending on the magnitude and scale, within 3-5 yr. Managing invasive Sea vine, *Halophila stipulacea*, and restoring impacted areas may probably take longer (5-10 yr).

5.2.7 Location (if any) of CoA

No seagrass CoA has been implemented at this point. But proposed actions are focused to be implemented within NER-HFA, particularly, between Fajardo and Culebra Island.

5.2.8 Potential benefits

This will provide data for marine and emergency planning as well as strengthen seagrass resources. It will also provide important timely benefits to multiple small businesses that depend on seagrass conditions for their operations across the NER-HFA. It would also provide benefits to restore community-based livelihoods (e.g., artisanal fisher folks), and would contribute to enhanced protection from frequent anchoring impacts (e.g., by contributing to delineate special zoning schemes for safe anchoring, for the establishment and/or restoration of mooring buoys, to the restoration of navigational scars on very shallow seagrass habitats, and to controlling the widespread dispersal of the invasive Sea vine, *Halophila stipulacea*).

5.2.9 Potential spillover impacts to other sectors

Imagery and habitat maps can support various sectors' activities. Pollution reduction and coastal community restoration coordinated with multiple sectors can achieve this and others COAs' goals. Restoring seagrass habitats adjacent to existing coral farms operated by Sociedad Ambiente Marino and NOAA-Restoration Center in Culebra will provide additional bottom stabilization to areas adjacent to farms. It will also have a fundamental natural spillover effect on reef-based fisheries by rehabilitating the nursery ground function of shallow seagrass habitats, which would result in increased fish spillover to adjacent coral reefs.

5.2.10 Potential costs

Estimated costs are for field an extended field assessment across NER-HFA, for establishing a long-term permanent monitoring program, at least during an initial period of five years, and for conducting habitat restoration across selected locations may total $1,500,000.

5.2.11 Potential funding mechanisms

Funding mechanisms have not yet been identified for this COA, but should include a combination of public and private sources.

5.2.12 Potential pitfalls

Encountering adverse environmental or weather conditions during data collection and restoration. A critical pitfall that can also influence results might be out-competition by rapidly spreading invasive Sea vine, *Halophila stipulacea*. This needs to be put as a top management priority.

5.2.13 Likely Precursors

Planning such as methods and site selection for assessments and restoration, and planning for engaging other stakeholders and collaborators are likely.

5.3 Value added

This project has provided fundamental baseline information to inter-jurisdictional, and inter-agency managers and decision-makers in regards to hurricane impacts on seagrass habitats across the NER-HFA of Culebra Island. This has also provided the necessary baseline to address potential threats to the vulnerability of coastal community livelihoods, safety, properties, infrastructure, and to net ecosystem and socio-economic resilience in Culebra. This has served as a model project and has established basic metrics of hurricane impacts and the need of ecological restoration efforts applicable to other locations across Puerto Rico and the northeastern Caribbean. In addition, it has provided a critical assessment of needs and COAs aimed at the conservation and restoration of critical seagrass resources across the high priority NER-HFA.

6.0 REFERENCES

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Hernández Delgado, E.A., J.L. Medina-Muñiz, H. Mattei, & J. Norat-Ramírez. 2017. Unsustainable land use, sediment-laden runoff, and chronic raw sewage offset the benefits of coral reef ecosystems in a no-take marine protected area. *Env. Mgmt. Sust. Dev*. 6(2):292-333. http://www.macrothink.org/journal/index.php/emsd/article/view/10687

Otaño-Cruz, A., A.A. Montañez-Acuña, V.I. Torres-López, E.M. Hernández-Figueroa, & E.A. Hernández-Delgado. 2017. Effects of changing weather, oceanographic conditions, and land uses on spatio-temporal variation of sedimentation dynamics along near-shore coral reefs. *Front. Mar. Sci*. 4:249. http://dx.doi.org/10.3389/fmars.2017.00249

Appendix 1. Example of hurricane impacts on seagrass communities

FIGURE A1. Example of minimum to negligible impacts of wave action on Turtle grass, *Thalassia testudinum*, with <5% loss in living cover. Such level of minimum impacts was either present on deeper seagrasses (8-12 m or deeper), or in areas protected from direct wind and wave impacts due to variation in coastal morphology.

FIGURE A2. Example of moderate impacts of wave action on Turtle grass, *Thalassia testudinum*, with approximately 50% loss in living cover as a result of shifting sands and physical dislodgment. This type of damage can have a moderate to high potential of natural recovery, but in some cases it may warrant assisted recovery to accelerate natural recovery.

FIGURE A3. Example of severe impacts of wave action on Turtle grass, *Thalassia testudinum*, with approximately 95% loss in living cover as a result of shifting sands and physical dislodgment. Natural recovery in such cases will be very slow and will require assisted recovery.

FIGURE A4. Moderate and patchy seascape level impacts on seagrass communities are widespread across some locations. However, given the nature of the physical damage in such areas seagrass have a strong potential for natural recovery. Representative plots should be identified and monitored to address recovery trends. Natural recovery should be studied and compared to some experimental plots under assisted recovery.

FIGURE A5. Example of a small, rapidly recovering, remnant patch of Widgeon grass, *Halodule wrightii*. This species is a pioneer species with a critical bottom stabilizing role in early successional stages in seagrass communities. Some of the edges of moderately impacted seagrasses are showing modest signs of recovery by the rapid recolonization of bare substrate by *H. wrightii*. This species should be used as a pioneer re-colonizer during assisted recovery efforts.

FIGURE A6. Moderate to significant seascape level impacts on seagrass communities are frequent across some locations and may require significant recovery interventions to restore damage due to the physical disruption of the seagrass root/rhizome matrix.

FIGURE A7. Another example of moderate to significant seascape level impacts on seagrass communities. In this particular case, physical disruption was partial, and partially dislodged seagrass patches remained adjacent to the main matrix. This allows a high opportunity for slow natural recovery or for a combination of natural and assisted recovery.

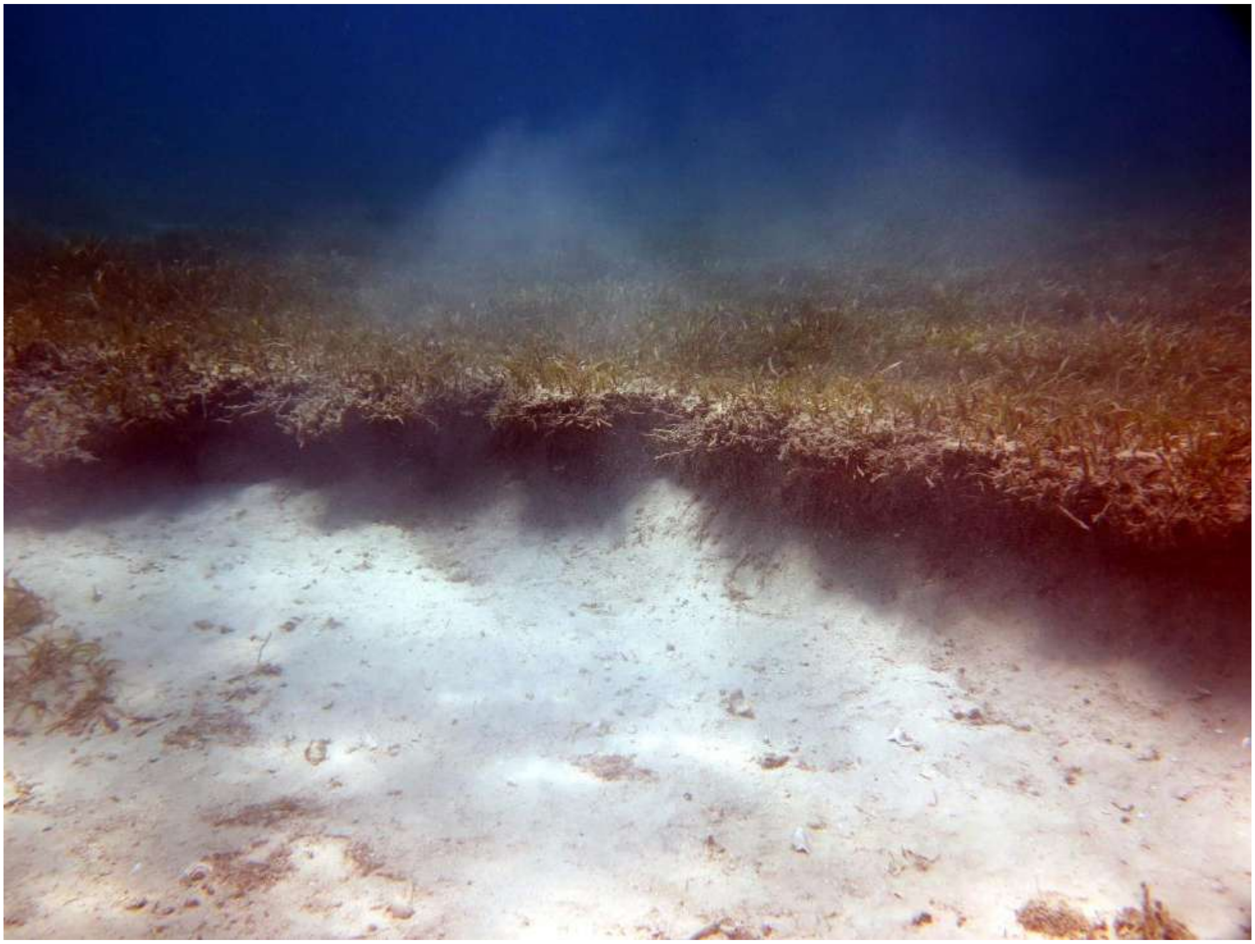

FIGURE A8. Seagrass habitat fragmentation was a common phenomenon of many shallow grounds. Such border effects should be rapidly repaired to minimize habitat vulnerability to future storm/hurricane events.

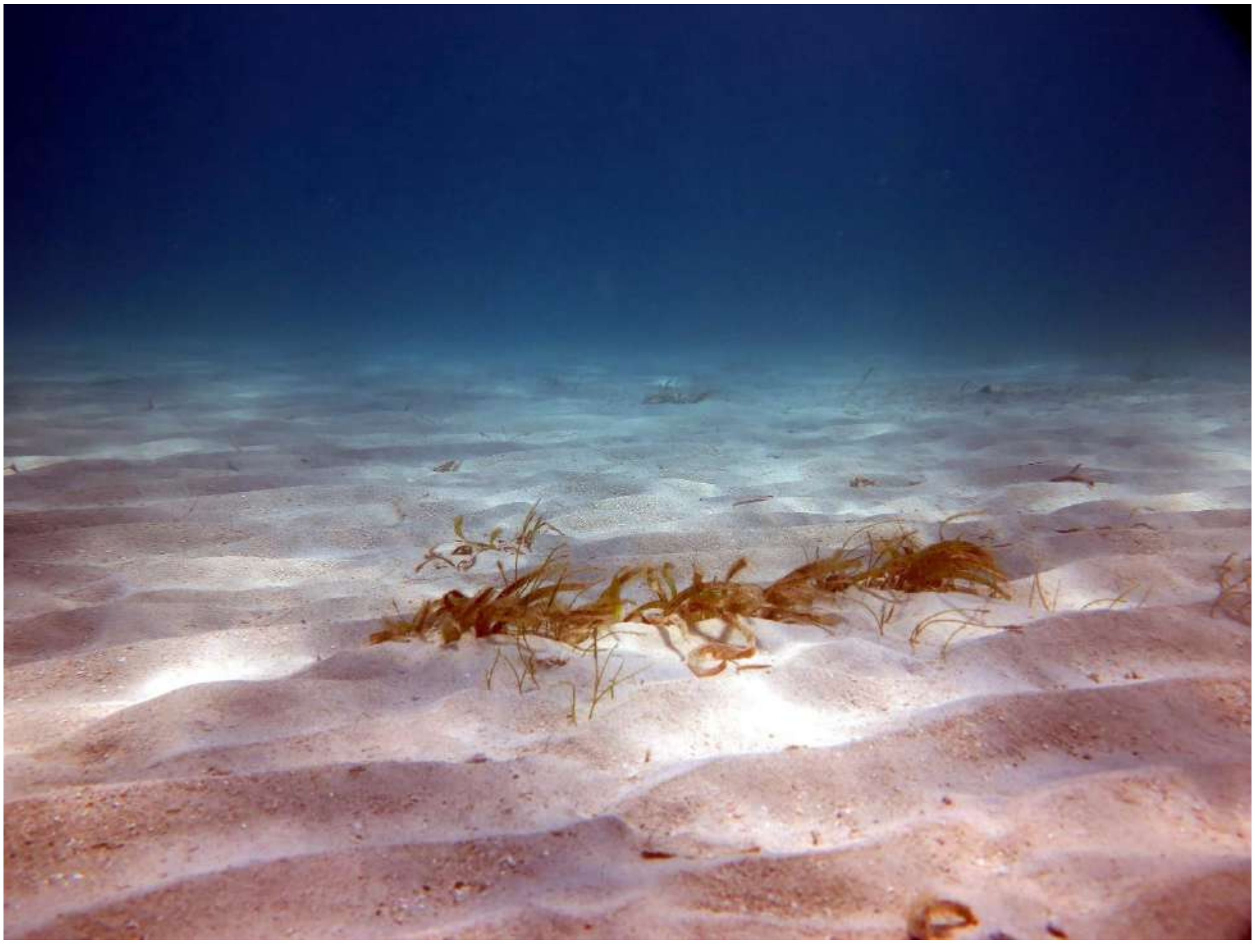

FIGURE A9. Severe seascape level impacts on seagrass communities are widespread across some locations and will require significant interventions to restore damage.

FIGURE A10. A particular form of severe seascape level impacts on seagrass communities was documented across extensive areas of the southern segment of the seagrass community at Playa Tampico (TAM). This involved a massive displacement of coral rubble from adjacent shallow reefs located between TAM and Bahía Linda (BLI). Such moving substrate caused the nearly total suffocation of seagrasses. A similar effect was observed at some areas of Cayo Dákity (DAK). It will require significant interventions through seagrass transplanting to restore damage and stabilize the rubble.

FIGURE A11. Extensive patches of invasive sea vine, *Halophila stipulacea*, remained nearly unblemished by hurricanes. This species showed remarkable resilience to hurricane impacts on depths below 8 m, which has allowed its rapid recovery across shallower zones where it was extirpated by waves disturbance. This species has completely substituted Turtle grass, *Thalassia tetudinum*, and Manatee grass, *Syringodium filiforme*, from extensive areas in Culebra and has become a critical management challenge, which can also interfere with post-hurricane natural recovery of native seagrasses. This is a particular phenomenon across Bahía Linda (BLI), and across multiple other locations in Culebra, particularly at Ensenada Honda Bay. It can be found at depths ranging from 0.5 to at least 30 m. Populations within the Bay and from bottoms deeper than 6-8 m remained unblemished. Populations from shallower habitats are showing remarkable recolonization rates.

FIGURE A12. The weedy dispersion strategy of invasive sea vine, *Halophila stipulacea*, shows a rapid and highly aggressive mechanism for natural recovery. This fosters the rapid recolonization of formerly-occupied shallow grounds where this species was decimated by hurricanes waves. But it can also allow it to colonize areas which were formerly dominated by native seagrasses which were dislodged by the hurricanes. This represents a critical management challenge. Fundamental research is necessary to address the potential interference role of invasive sea vines expansion on the natural recovery ability of native seagrasses.

FIGURE A13. Remnant unaltered seagrass patches still support sporadic populations of scleractinian corals, such as *Isophyllia sinuosa*. However, populations of this species were largely decimated across common grounds. Coral farming strategies should be implemented to restore its populations.

FIGURE A14. Remnant unaltered seagrass patches still support sporadic populations of scleractinian corals, such as *Manicina areolata*. However, populations of this species were largely decimated across common grounds. Coral farming strategies should be implemented to restore its populations.

FIGURE A15. Rare coral *Occulina diffusa*, which can be sporadically found across some seagrass communities in Culebra Island, has not been observed after Hurricanes Irma and María. An extensive search of this species must be conducted and propagation efforts should be immediately implemented to repopulate seagrass communities of this species. Image source: http://coralpedia.bio.warwick.ac.uk/sp/corals/oculina_diffusa.

FIGURE A16: Rare coral *Cladocora arbuscula*, which can be sporadically found across some seagrass communities in Culebra Island, has not been observed after Hurricanes Irma and María. An extensive search of this species must be conducted and propagation efforts should be immediately implemented to repopulate seagrass communities of this species. Image source: http://coral.aims.gov.au/factsheet.jsp?speciesCode=0567.

FIGURE A17. Marginal habitats at seagrass edges were also severely impacted by shifting sands. In this example, a colony of ESA-listed Laminar star coral, *Orbicella faveolata*, was significantly smothered by shifting sands, showing partial suffocation. A combination of colony removal and out-planting must be considered.

FIGURE A18. Marginal habitats at seagrass edges were also severely impacted by shifting sands. In this example, a colony of ESA-listed Pillar coral, *Dendrogyra cylindrus*, was significantly smothered by shifting sands, showing partial suffocation. A combination of colony removal and out-planting must be considered.

FIGURE A19. Marginal habitats at seagrass edges were also severely impacted by shifting sands. In this example, a colony of the Massive starlet coral, *Siderastrea siderea*, was significantly smothered by shifting sands, showing partial suffocation. This colony shows clear evidence that similar impacts occurred in the past, probably during Hurricane Georges (1998), as it has two different layers of skeletal growth.