TBEP Technical Report

#16-21a

December 2021

INTERTIDAL ELEVATION CHANGE ON CONSTRUCTED OYSTER REEFS IN TAMPA BAY FOLLOWING HURRICANE ETA (NOV. 2020)

Final Report

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Final Report Provided by the Florida Fish and Wildlife Conservation Commission to the Tampa Bay Estuary Program

30 September 2021

Revised 29 December 2021

Table of Contents

List of Tables

List of Figures

Appendix A

List of Figures (Cont.)

Appendix B

Abstract

Coastal development threatens natural shorelines through habitat loss, degradation of water quality, alteration of sedimentary and hydrologic regimes, and the addition of hardened structures. Living shorelines composed of planted vegetation in combination with a sediment sill, constructed oyster reef, or breakwater provide an alternative solution for shoreline protection while also restoring critical ecosystem services. This study examined elevation change surrounding 12 constructed oyster reefs composed of shell bags, oyster reef balls, or loose shell substrate, and 2 natural reefs acting as controls in Tampa Bay, Florida. These constructed reefs, sometimes accompanied by a back-reef vegetated marsh, did not have significantly different changes in elevation compared to the natural reef controls. During the project period, Hurricane Eta impacted Tampa Bay as a tropical storm and allowed comparison for pre- and post-storm elevation. Constructed reefs and surrounding areas monitored post-Eta changed in elevation by -0.012 ± 0.044 m while natural reefs changed by 0.018 ± 0.010 m over the survey areas. No hardened structures were included in this study; however, the living shorelines survived the storm with minimal to no damage.

Introduction

Sediment redistribution, whether erosional or depositional, is a constant process in all coastal environments, and with an ever-increasing coastal population the stabilization of shorelines is of major concern near developed areas. Shorelines in high-energy environments such as beaches or tidal channels are influenced by wave action, sea-level rise, and storms (Hayden 1975; Galgano et al. 1998). Lower-energy areas including estuaries, bayous, or embayments are impacted by wakes from boat traffic, modified hydrology, sediment starvation, and coastal development (Kennish 2001; Parnell et al. 2007). Like beaches and costal inlets, these sheltered environments may also be susceptible to sediment redistribution from storms or sea-level rise, the effects of which are often compounded by anthropogenic modifications such as coastal hardening and dredging (Tweel & Turner 2012; Ridge et al. 2017). Nearly 14 % of the United States shoreline is hardened and, while these structures can mitigate erosion over their lifespan, they require frequent upkeep costs and will be rendered ineffectual over time because of sea-level rise (Airoldi et al. 2005; Houser 2010; Gittman et al. 2015).

An alternative to coastal hardening is the development of a living shoreline composed of planted vegetation (e.g., mangroves, marsh grasses) and/or substrate suitable for oyster colonization. Coupled with an ecosystem restoration plan, living shorelines can have a significant impact on reducing shoreline erosion through the trapping of sediment (Boyd 2006; Leonard and Croft 2006) and wave attenuation (Knutson et al. 1982). In addition, living shorelines are able to keep pace with moderate rates of sea-level rise through an increase of belowground biomass (Morris et al. 2002), vertical growth of oysters and accumulation of shell on an established reef (Powell et al. 2006), and through the inclusion of accommodation space for transgression of intertidal species and habitats upslope (Ridge et al. 2015).

The dominant reef-building oyster species in the coastal Gulf of Mexico and Atlantic waters is the eastern oyster (hereafter, oyster), *Crassostrea virginica* (Gmelin 1791). Centuries of human development and economic activity in these regions resulted in widespread detrimental impacts to oyster populations because of altered hydrology (Camp et al. 2015), shell mining (Whitfield 1975), and commercial harvesting (Pine et al. 2015). Globally, oyster reefs have declined by 85% (Beck et al. 2011) making oyster restoration efforts increasingly important, as these organisms are not only a key economic species, but they also contribute to the overall health of estuarine habitats as a food and habitat resource for other species (Bahr and Lanier 1981;

Grabowski et al. 2012). Oyster restoration efforts date to the early 1900s, where cultch planting following harvesting aimed to replace lost substrate (Whitfield & Beaumariage 1977), however most artificial reefs along the Gulf of Mexico were constructed since 2000 (Hernandez et al. 2018). The primary focus of oyster reef restoration is on supplementing the native oyster population through substrate addition, with habitat improvements and erosion mitigation as secondary benefits (Hernandez et al. 2018).

Erosion effects from tropical storms and hurricanes are primarily a result of wave-topped storm surge, which increases inversely to the minimum central pressure of the system (Paine et al. 2017) and can vary drastically depending on approach vector or land interaction (Cahoon et al. 2006, Weisberg & Zheng 2006). In addition, areas with extensive coastal development or anthropogenic modifications, such as the hardened coastline within Tampa Bay, are prone to greater environmental damage that is also longer lasting and can include large scale releases of chemical or fecal pollutants, excessive nutrient loading, or spread of invasive species (Mallin & Corbett 2006). Living shorelines have demonstrated better resistance to storm-induced erosion than hardened structures or even natural marsh in a variety of settings and storm intensities (Gittman et al. 2014).

Hurricane Eta (2020 Atlantic hurricane season)

Hurricane Eta formed as a tropical depression on 31 October 2020 and subsequently became the 28th named storm of the 2020 Atlantic hurricane season as it rapidly intensified to a category-4 storm (Saffir-Simpson hurricane wind scale; Simpson & Riehl 1981) prior to impacting Central America near Puerto Cabezas, Nicaragua on 3 November. The storm then weakened to a remnant low over the Yucatan Peninsula before re-emerging over the Gulf of Honduras and regenerating into a tropical depression on 6 November. By 7 November, Eta regained tropical storm strength and made successive landfalls in central Cuba and near Lower Matecumbe Key in the Florida Keys before being steered south back toward Cuba. On 10 November, Tropical Storm Eta made a cyclonic loop in the Gulf of Mexico and began moving north-northwest toward central Florida, briefly strengthening to a category 1 hurricane on 11 November for approximately 6 hours before weakening to a tropical storm. Eta made a fourth landfall (second for the United States) as a tropical storm with sustained winds of 22.3 m s^{-1} near Cedar Key, Florida on 12 November before crossing the Florida peninsula and slowly weakening until it became extratropical and dissipated on 13 November (Fig. 1).

While Eta approached Tampa Bay with only tropical storm force winds (18.0 – 20.5 m s^{-1}; Pasch et al. 2021) and fetch in the Bay is relatively constricted compared to the coastal Gulf barrier islands, there was a reported storm surge of about 1 m (Pasch et al. 2021) so some amount erosion or deposition could be expected at more exposed locations. This study compares real-time kinematic global positioning system (RTK-GPS) elevation surveys of living shorelines and natural reefs in Tampa Bay pre- and post-Hurricane Eta to determine the effectiveness of these structures at erosion mitigation during storm events and over time.

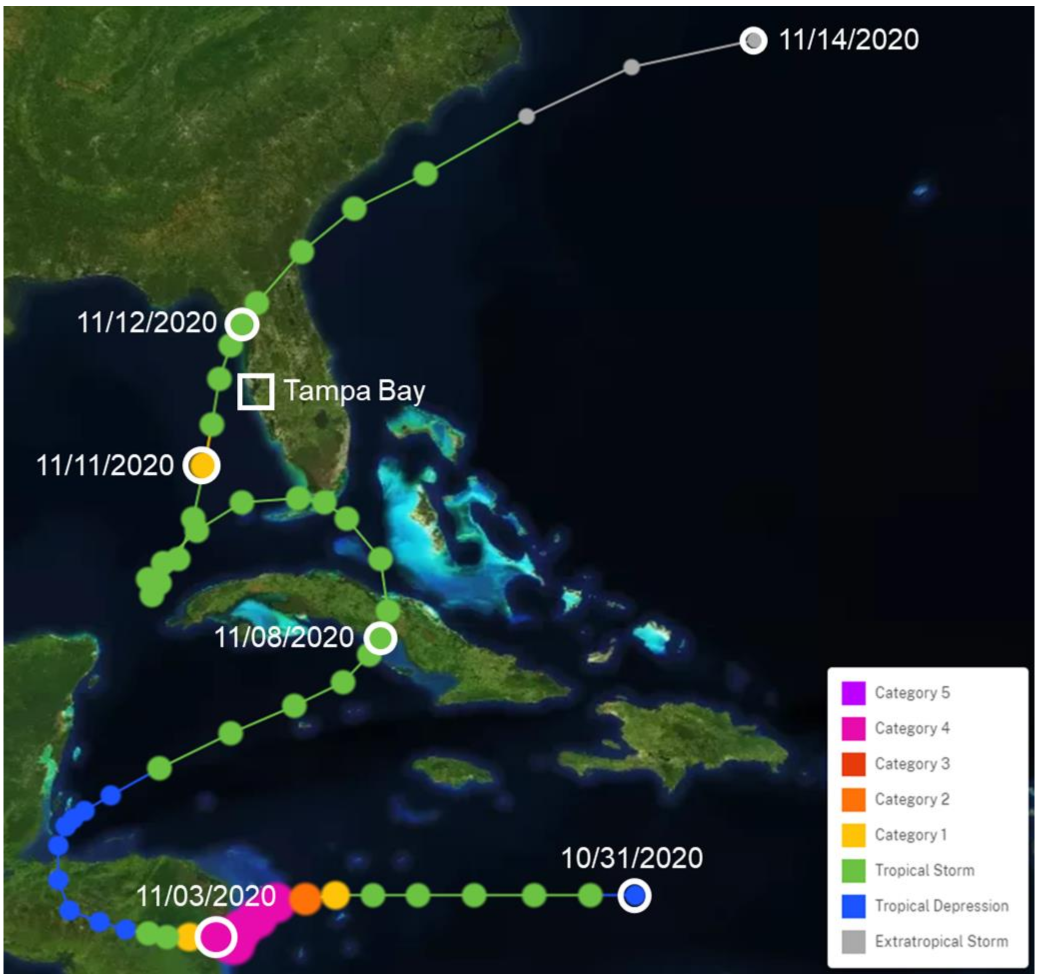

Figure 1. Map showing track and intensity history of Hurricane Eta during the 2020 Atlantic hurricane season. Eta passed north of Tampa Bay on 12 November 2020 as a tropical storm. Data and base image from the NOAA Historical Hurricane Tracks tool (https://coast.noaa.gov/hurricanes/).

Study Sites

Tampa Bay is located on the west-central coast of Florida and is a shallow subtropical estuary with seasonally varying freshwater contributions from four main rivers and many smaller tidal tributaries (Lewis & Estevez 1988). The estuarine system is open to the Gulf of Mexico and experiences additional fluctuations in salinity and temperature throughout the water column as the result of tidal mixing and shallow average depth (Weisberg & Zheng 2006). Natural oyster reefs are found throughout the bay, primarily in the intertidal zone, and often near freshwater inputs (Kaufman 2017). Restoration efforts in Tampa Bay focus on providing artificial substrate suitable for oyster settlement to compensate for the loss of natural reefs. At present, the majority of artificial oyster reefs in the bay are comprised of concrete oyster reef balls, mesh bags containing oyster or fossilized shells, loose shell, or a combination of these substrates (Fig. 2; Table 1). These projects have usually been constructed on public property, where access can more readily occur, and permits are more easily obtained. Multiple partners (including private, local, state, and federal organizations) restore and sporadically monitor constructed artificial reefs and natural reefs within Tampa Bay (Radabaugh et al. 2019). A total of 63 oyster restoration projects covering protecting approximately 8.4 linear miles of shoreline have been constructed within Tampa Bay since 2002 (Tampa Bay Restoration Data, https://tampabay.wateratlas.usf.edu/restoration/). Of the 63 oyster restoration projects, 12 constructed reefs (Fig. 2; Table 1) composed of shell bags (n = 7), oyster reef balls (n = 3), and loose shell (n = 2) were surveyed along with two natural reefs to evaluate net elevation changes over the 7- to 19-month timeframe encompassed by the surveys before and after Hurricane Eta impacted Tampa Bay as a tropical storm.

Methods

Real-time Kinematic GPS Elevation Surveys

An elevation survey of each oyster reef was completed using a Champion WR1 RTK-GPS receiver (Champion Instruments, Norcross, GA) paired with a Champion HC1 data collector running Carlson SurvCE v 5.07 (Carlson Software Inc., Maysville, KY) for Microsoft Windows Mobile v 6.1 (Microsoft Inc, Redmond, WA). Real-time base-station corrections were made via direct cellular data connection to the Florida Permanent Reference Network (FPRN) maintained

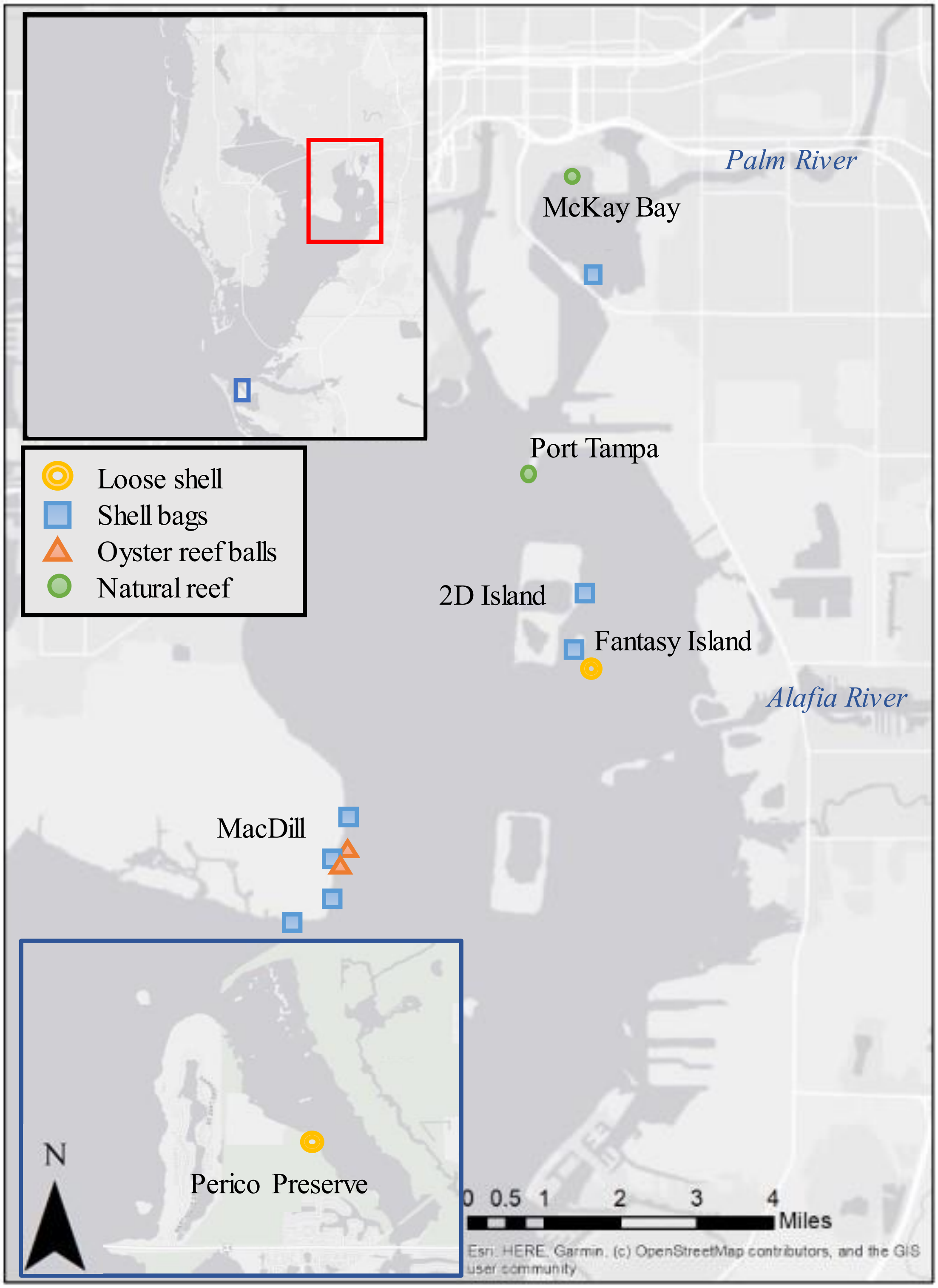

Figure 2. Oyster reefs evaluated for elevation changes due to the impacts of Hurricane Eta in Hillsborough Bay and Perico Preserve (inset at bottom left) in Tampa Bay, Florida (inset at top left). Open yellow circles indicate the location of loose shell reefs, blue squares are shell bag reefs, orange triangles are oyster reef balls, and filled green circles are natural reefs.

Table 1. Location, year of construction, and substrate type of monitored reefs across Tampa Bay. Fetch distance and angle were measured perpendicular to a line drawn from the start to end of each reef in the direction of the nearest open water. The exposure to waves designator of "protected" reflects the presence of a reef constructed offshore the selected reef or its location within a channel (i.e., Perico Preserve).

Reef location	Year constructed	Substrate type	Latitude	Longitude	Maximum fetch (km)	Maximum fetch angle (°)	Direct exposure to waves
2D Island	2018	Shell bag	27.874290	-82.425236	5.50	146	Exposed
Fantasy Island	2006	Loose shell	27.867834	-82.424517	47.65	218	Exposed
Fantasy Island	2008	Shell bag	27.868195	-82.426059	47.07	216	Exposed
MacDill	2007	Shell bag	27.822066	-82.473044	41.27	220	Protected
MacDill	2015	Shell bag	27.821304	-82.477788	9.03	20	Exposed
MacDill	2018	Shell bag	27.830693	-82.470921	9.42	185	Protected
MacDill	2019	Shell bag	27.842559	-82.469368	9.96	0	Exposed
MacDill	2007	Oyster reef ball	27.821574	-82.473722	41.33	220	Exposed
MacDill	2015	Oyster reef ball	27.831780	-82.470588	9.61	16	Exposed
MacDill	2018	Oyster reef ball	27.830514	-82.470796	9.45	185	Exposed
McKay Bay	2018	Shell bag	27.928640	-82.424487	2.38	29	Exposed
McKay Bay	--	Natural reef	27.946732	-82.427754	2.50	163	Exposed
Perico Preserve	2016	Loose shell	27.502676	-82.674681	0.37	53	Protected
Port Tampa	--	Natural reef	27.896449	-82.434353	25.82	201	Exposed

by the Florida Department of Transportation (https://www.fdot.gov/geospatial/fprn.shtm). Shore-perpendicular beach profile transects were surveyed from the back-reef (beach facing) to the fore-reef (open-water facing) area, with elevation recorded approximately every 2 – 5 m along each transect. Survey transects were spaced at 5-m intervals extending along the shore-parallel length of each reef. Elevations was also recorded along the top of the reef to serve as tie-lines for the survey grid. For reef-top elevations, the topo-foot of the survey rod was placed on the shell or oyster reef ball surface centered on the side of the reef closest to the shoreline. Horizontal geospatial locations were recorded in the Florida State Plane West coordinate system with metric vertical elevation measurements referenced to the North American Vertical Datum of 1988 (NAVD 88). Elevation measurements were assessed post-survey to remove duplicate points, make rod-height corrections, average points with high vertical errors (> 0.03 m; resulting from cloud or canopy cover), and to remove spurious measurements. Processed RTK-GPS survey data were then imported to NOAA vDatum (v. 4.1.2; National Oceanic and Atmospheric Administration, Washington DC; https://vdatum.noaa.gov/) to convert measured NAVD 88 elevations to the local mean tide level (MTL) tidal datum.

Survey Analysis

RTK GPS surveys with associated elevation data (m NAVD 88) were imported into Esri ArcGIS (Desktop Enterprise version 10.8.1) and interpolated using ordinary kriging following a spherical model of variable search radius with the Spatial Analyst tool. The difference in elevation between repeat surveys at each reef was visualized using the Raster Math tool, which calculated the difference between two cells on a cell-by-cell basis over the area of the survey. Visualization and calcuation of elevation differences was restricted to the area repeatedly surveyed during each monitoring event (using the Extraction tool, Extract by Mask). The minimum and maximum values for the stretched color ramps of the raster depicting elevation change were set to a range of either -0.3 to 0.3 m or -0.5 to 0.5 m, depending on the magnitude of elevation change at each location (MacDill, Fantasy Island, 2D Island, McKay Bay, Perico Preserve, and natural reefs), but the range of color ramps for multiple reefs within each location were kept consistent. Elevation differences from -0.03 to 0.03 m were set to white, indicating no change in elevation, as these values were within the instrumental error of the RTK GPS unit.

Elevation data with an interpolated point spacing of approximately 20 cm for each survey were exported from a kriged raster to an ASCII file format (using the Raster to ASCII tool) for statistical comparison in SAS and R. The mean and standard deviation were calculated for the interpolated elevation measurements on each reef for each date of survey. Elevation change was calculated as the difference between the means from each survey.

Statistical analyses were completed in SAS Enterprise Guide 7.1 for Windows (SAS Institute Inc., Copyright © 2017, SAS Institute Inc., Cary, NC) and R version 4.0.3 (R Core Team 2020). Significance was assessed at an alpha of 0.05. Data were examined for normality using Shapiro–Wilk tests. A two-tailed t-test was used to compared elevation changes between constructed and natural reefs. A one-way analysis of variance (ANOVA) was used to assess elevation changes across reef substrates. Pearson's correlation coefficient was used to examine the relationship between reef elevation change and reef elevation as well as time between surveys.

Results

Elevation survey data for each reef for the survey period spanning pre- to post-Eta are given in Table 2. The period between the surveys prior to and after Hurricane Eta varied on each reef and spanned 7 to 19 months across the 14 surveyed reefs. The kriged elevation-difference rasters (e.g., Fig. 3) for storm-derived changes are given in Appendix A and those reefs surveyed again in the month following Eta to provide information on elevation recovery are given in Appendix B. The mean elevation change (NAVD 88) for all constructed reefs (n = 12) surveyed prior to and after the storm was -0.012 ± 0.044 m, while natural reefs (n = 2) exhibited a mean elevation change of 0.018 ± 0.010 m (Fig. 4). There was no significant difference between pre- and post-Eta elevation changes for constructed vs. natural reefs (t_2 test value = 0.92, df = 12, p = 0.375). When examined by substrate type, the average pre- and post-Eta elevation change was -0.020 ± 0.024 m for reefs constructed with shell bags (n = 7), 0.019 ± 0.050 m for oyster reef balls (n = 3), and -0.032 ± 0.092 m for loose shell (n = 2) (Figs. 5 & 6). There was no significant difference in elevation change among the three constructed reef substrate types and natural reefs (F = 1.09, df = 3,10, p = 0.396). There was no significant correlation between net elevation change and the number of months between surveys for all constructed and natural reefs (Pearson's r = -0.080, n = 14, p = 0.787; Fig. 7).

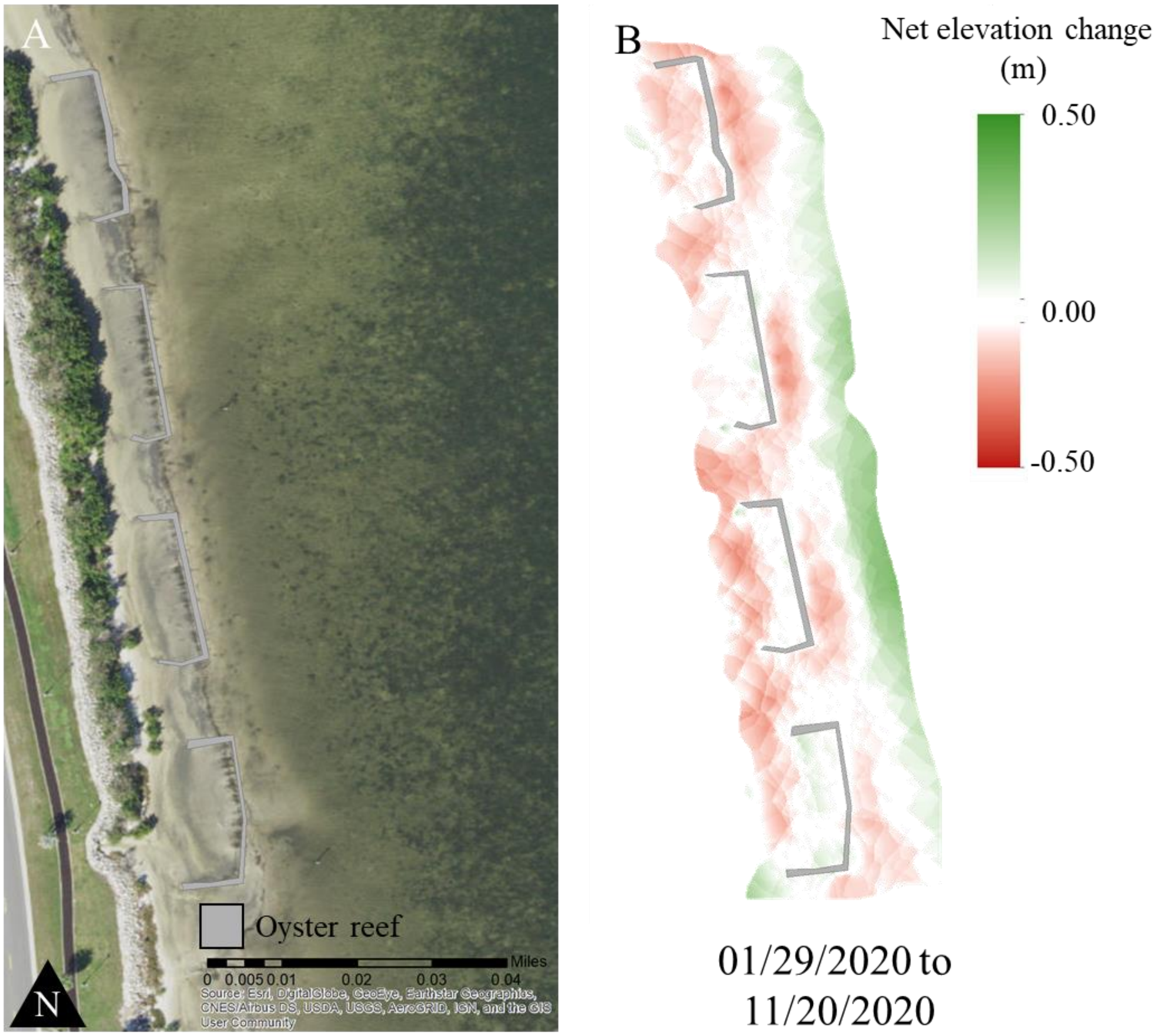

Figure 3. Aerial imagery (A) and net elevation change (B**)** of kriged RTK GPS survey data for the 2019 shell bag reef at MacDill Air Force Base from surveys before and after Hurricane Eta, which impacted Tampa Bay on 12 November 2020. White shading represents elevation changes between -0.03 to 0.03 m, which is the range of instrumental error and represents no elevation change.

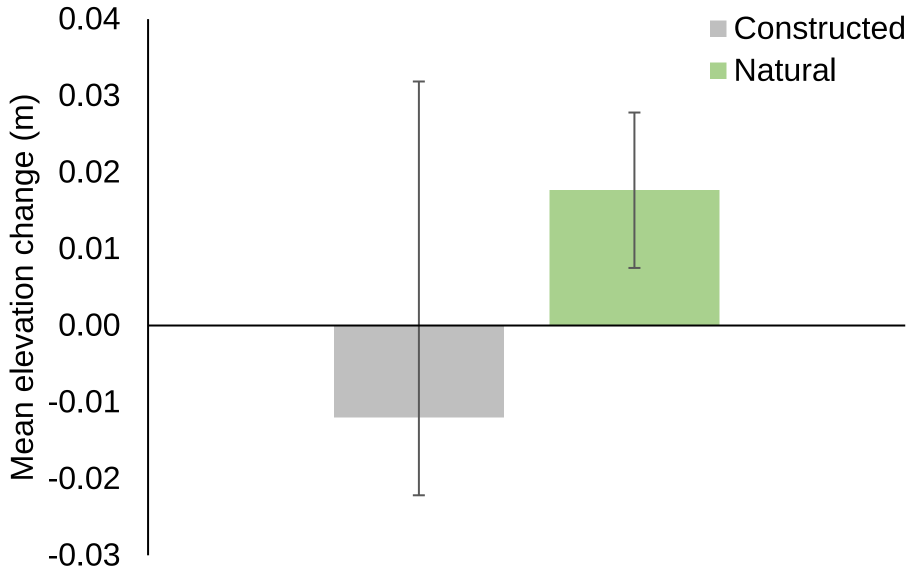

Figure 4. Mean elevation change (m) for constructed (n = 12) and natural (n = 2) oyster reefs from surveys conducted before and after Hurricane Eta.

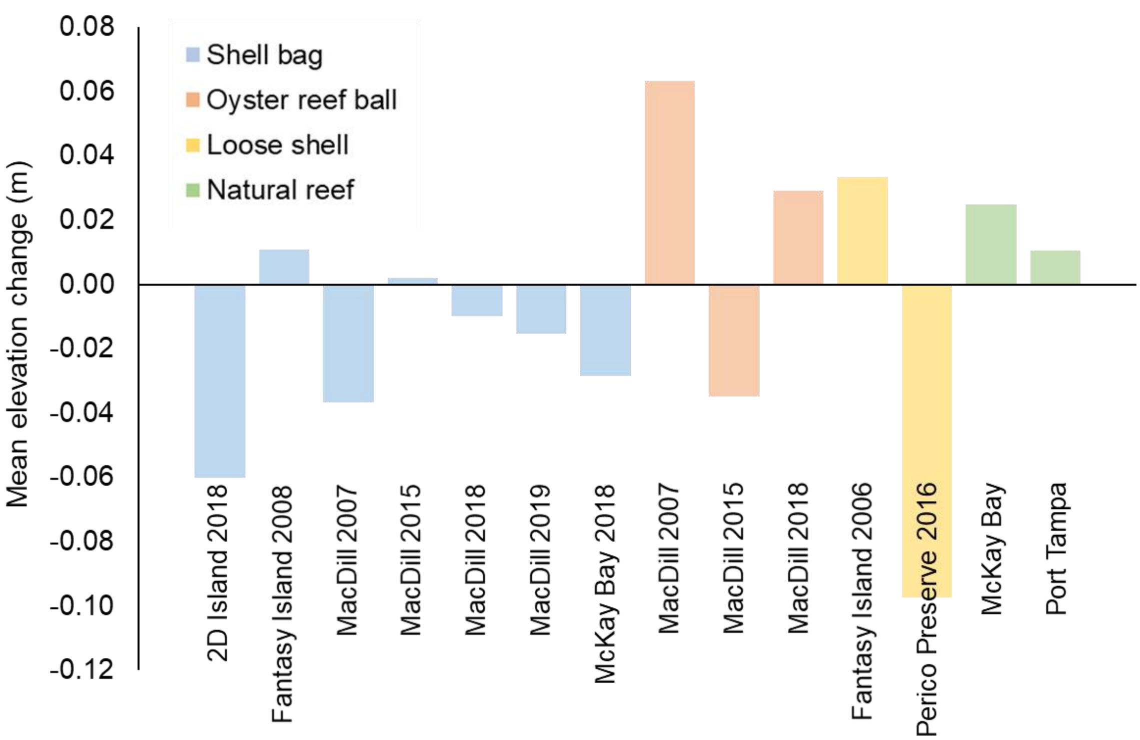

Figure 5. Mean elevation change (m) from surveys conducted before and after Hurricane Eta for constructed and natural oyster reefs in Tampa Bay. Reefs are identified by their location and year of construction.

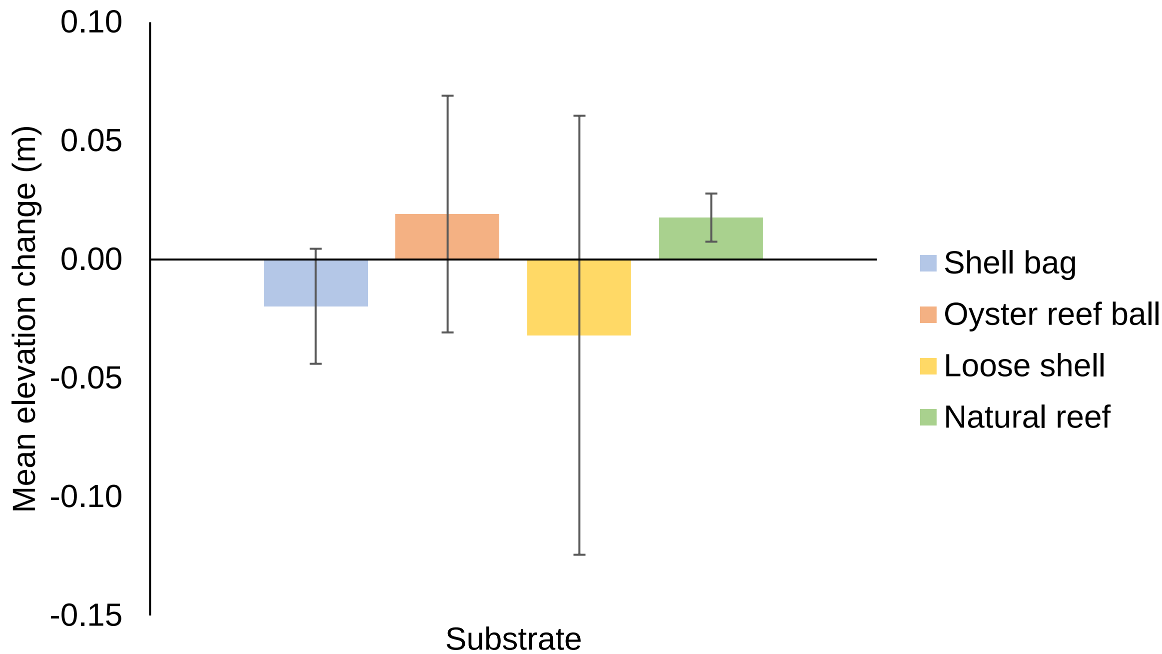

Figure 6. Mean elevation change by substrate type on constructed and natural oyster reefs from surveys conducted prior to and after Hurricane Eta. The total number of reefs represented by each substrate type were: shell bags, n = 7; oyster reef balls, n = 3; loose shell, n = 2; and natural reefs, n = 2.

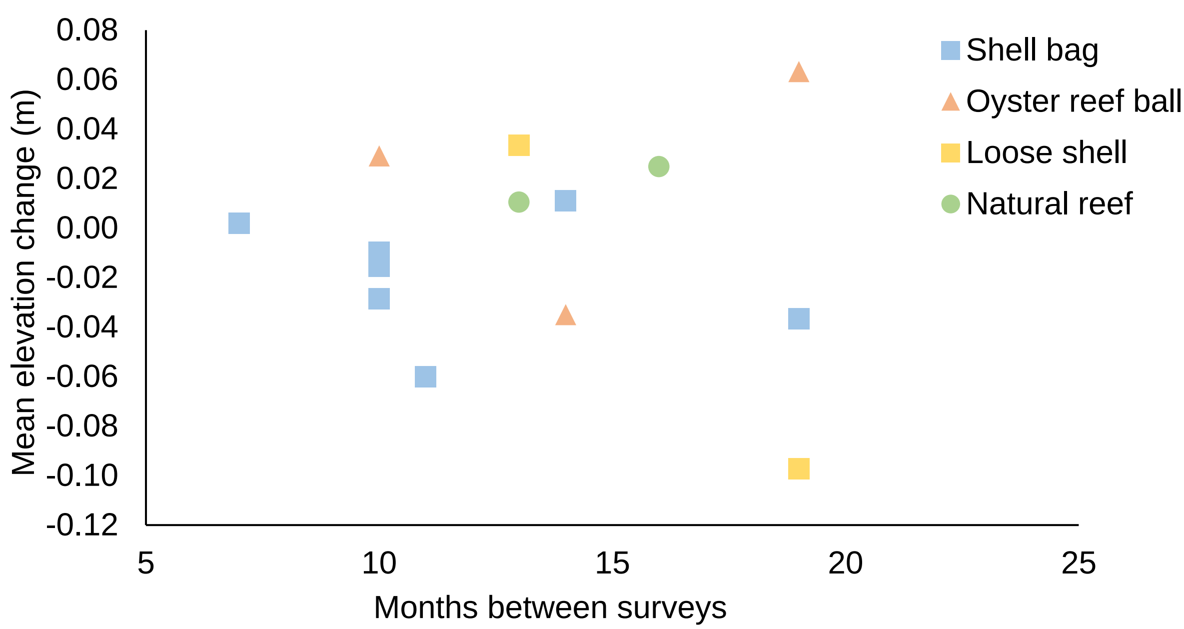

Figure 7. Relationship between net elevation change from kriged survey data and the number of months between pre- and post-Eta elevation surveys.

Table 2. Mean elevation change (m NAVD 88) for survey area of kriged RTK-GPS elevation data at each location pre- and post-Eta. Elevations are shaded green if elevation change was > 0.03 m, shaded red if elevation change was < -0.03 m, and unshaded if between those ranges, which was within instrumental error.

Reef location	Year constructed	Reef type	Pre-storm survey date	Post-storm survey date	Months between surveys	Pre-storm elevation (m NAVD 88)	Post-storm elevation (m NAVD 88)	Net storm elevation change (m)	Recovery survey date	Recovery elevation change (m)
2D Island	2018	Shell bag	1/28/2020	12/14/2020	11	-0.39 ± 0.16	-0.45 ± 0.15	-0.0602		
Fantasy Island	2006	Loose shell	11/1/2019	12/14/2020	13	-0.45 ± 0.25	-0.42 ± 0.26	0.0335		
Fantasy Island	2008	Shell bag	10/1/2019	12/15/2020	14	-0.45 ± 0.21	-0.43 ± 0.21	0.0110		
MacDill	2007	Shell bag	4/17/2019	11/20/2020	19	-0.18 ± 0.15	-0.21 ± 0.17	-0.0367	12/16/2020	0.0444
MacDill	2015	Shell bag	4/18/2019	11/20/2020	7	-0.23 ± 0.07	-0.23 ± 0.05	0.0019	12/4/2020	-0.0150
MacDill	2018	Shell bag	1/24/2020	11/20/2020	10	-0.21 ± 0.12	-0.22 ± 0.14	-0.0099		
MacDill	2019	Shell bag	1/29/2020	11/20/2020	10	-0.16 ± 0.22	-0.17 ± 0.18	-0.0155	12/4/2020	-0.0072
MacDill	2007	Oyster reef ball	4/17/2019	12/16/2020	19	-0.50 ± 0.12	-0.43 ± 0.07	0.0633		
MacDill	2015	Oyster reef ball	10/29/2019	11/20/2020	14	-0.37 ± 0.10	-0.40 ± 0.08	-0.0350	12/1/2020	-0.0309
MacDill	2018	Oyster reef ball	1/24/2020	11/20/2020	10	-0.47 ± 0.08	-0.44 ± 0.08	0.0292		
McKay Bay	2018	Shell bag	1/27/2020	11/17/2020	10	-0.41 ± 0.06	-0.44 ± 0.06	-0.0285		
McKay Bay	na	Natural	11/13/2019	3/1/2021	16	-0.48 ± 0.13	-0.45 ± 0.13	0.0248		
Perico Preserve	2016	Loose shell	4/30/2019	11/20/2020	19	-0.27 ± 0.09	-0.37 ± 0.10	-0.0973	12/18/2020	0.0910
Port Tampa	na	Natural	11/27/2019	12/15/2020	13	-0.61 ± 0.12	-0.60 ± 0.13	0.0105		

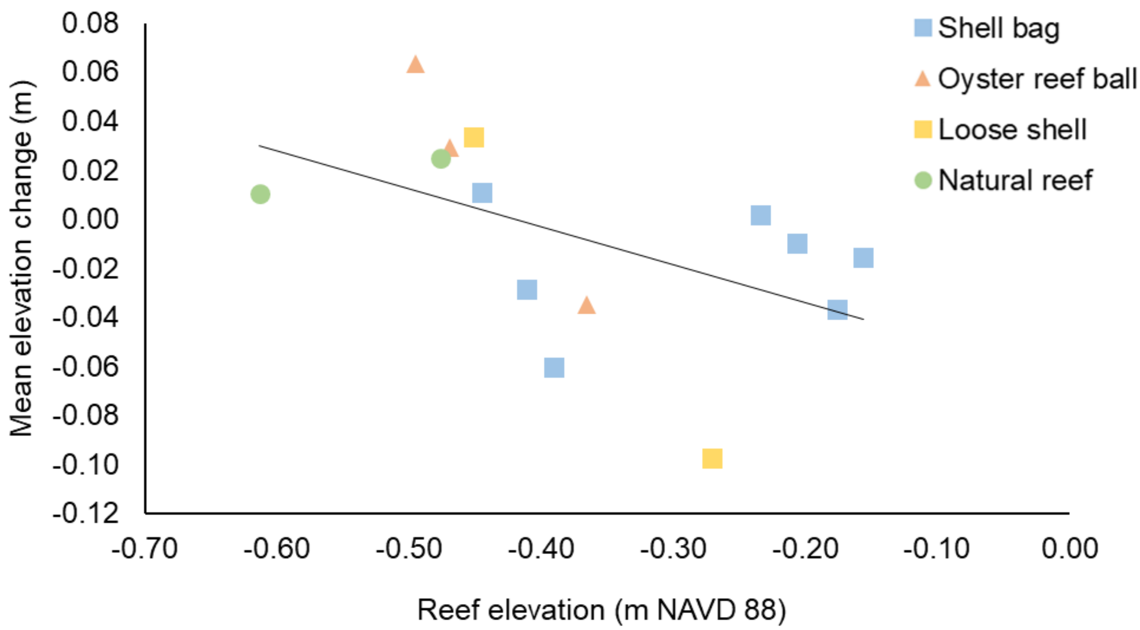

Figure 8. Mean reef elevation change following Hurricane Eta as a function of pre-Eta reef elevation for all reefs. The solid black line represents a least-squares regression model to describe the relationship between the two variables (correlation not significant).

There was no significant correlation between pre-Eta mean reef elevation and mean elevation change across all reef types (Pearson's r = -0.518, n = 14, p = 0.058; Fig. 8). There were also no significant correlations between these metrics for shell bags only (Pearson's r = 0.054, n = 7, p = 0.909) or oyster reef balls only (Pearson's r = -0.992, n = 3, p = 0.081). There was no significant difference between elevation change on exposed vs. protected reefs (t_2 test value = 2.11, df = 12, p = 0.057; see Table 2), and no significant correlation between maximum fetch and elevation change among the reefs (Pearson's r = 0.240, n = 14, p = 0.409).

Discussion

Living shorelines, such as constructed oyster reefs, can enable various habitat improvements and erosion mitigation, along with providing the hard substrate necessary to supplement native oyster populations even during tropical-storm events. The constructed oyster reefs that were surveyed immediately after the passing of Hurricane Eta did not have significantly different changes in elevation compared to two natural reefs (-0.012 m vs. 0.018 m; Fig. 4). Loose shell demonstrated the largest change in elevation (-0.032 m) after the surveyed interval, however both loose shell reefs included in this study (Perico Preserve and Fantasy Island) are geomorphically different (i.e., not shore parallel) or located in a protected bayou (Perico Preserve; Figs. 2 and 5). Two of the three reefs constructed of oyster reef balls experienced an increase in elevation post-storm, which may be a result of their placement further offshore and in deeper water to serve as wave attenuators for shell bag reefs located inshore of the oyster reef balls.

Unlike hardened structures, living shorelines have the capacity to recover from storm events without additional investment in maintenance or repair further highlighting their economic benefits (Smith et al. 2017). Hardened structures were not included in this study, but previous research has demonstrated landward elevation loss when they are overtopped by storm surge because the elevation behind these structures is often one meter or more above local mean sea level (Thieler & Young 1991; Smith et al. 2018). In addition, bulkheads and other retaining walls exposed to wave energy can experience scouring at the base, undermining structural integrity, leading to collapse during future storms (Camfield & Morag 1996). Inundation and over-topping are natural occurrences for living shorelines and, as such, sediment is often trapped on the back-reef side of these structures, in turn facilitating further growth of the reef and contributing to elevation gain in the back reef (Ganju 2019). Construction of intertidal oyster reefs will ultimately affect sediment dynamics in the local-to-regional environment, ideally with the benefit of improving shoreline stabilization. However, this stabilization may slow elevation gains in back-reef marshes or shorelines by reducing suspended sediment that would otherwise be deposited on the marsh surface by wave action (Ganju et al. 2017; Hopkinson et al. 2018). Sediment may be lost at higher elevations, then redistributed to deeper intertidal areas or transported out of the living shoreline system. Reef elevation may also impact the movement of sediment, as lower-elevation reefs will experience less wave-driven erosion day-to-day, but potentially higher wave energy with larger storm-derived waves having a deeper wave base.

Eta-associated storm surge in Hillsborough Bay peaked at 1.2 m above local mean sea level on 12 October 2020 (NOAA Station 8726674) and co-occurred with high tide, which normally inundates higher-elevation reefs. The extra depth caused by Hurricane Eta's storm surge, likely allowed for larger wave activity over a 12-hour period on 12 October. However, since storm events are brief, typically lasting less than a day and recurring only a few days per year at most, inundation due to storm surge has been shown to contribute minimally to erosion in marsh-planted living shorelines (Leonardi et al. 2016). However, since constructed oyster reefs are more rigid than a planted marsh, and do not have the sediment-baffling capacity of submerged marsh grasses, there is a higher likelihood that higher wave energy associated with storm-derived waves contributed to erosion on high-elevation constructed oyster reefs in Tampa Bay. Thus, there is a need to better understand the physical characteristics of daily (non-storm) and storm-related wave fields as they influence sediment dynamics on constructed oyster reefs.

The longer-term study by Leonardi et al. (2016), demonstrated that hurricane-strength storms account for less than 1 % of salt marsh erosion with average wave conditions being the overwhelming driving factor in salt marsh deterioration. The elevation surveys in this study encompassed a 7- to 19-month timeframe, thus average wave conditions likely influenced erosional patterns as much as, or more than, Hurricane Eta. While hardened structures may be able to endure daily wave energy, they are susceptible to failure during these strong storms resulting in drastic elevation loss, damage to property, and large costs to rebuild (Gittman et al. 2014; Smith et al. 2017). Other studies have shown that the presence of planted marshes in the back-reef zones of constructed oyster reefs reduced wave energy by 67 % (Manis et al. 2015), and that wave attenuation by oyster reefs and breakwaters reduced erosion by up to 40 % (Scyphers et al. 2011).

Of the 14 oyster reefs surveyed after Hurricane Eta, five were re-visited less than a month after the post-Eta survey (Table 2; "recovery survey"; Appendix B). These elevation surveys allowed for some insight into post-storm sedimentary dynamics over a shorter period (~1 month). However, only one reef (Perico Preserve) had a discernable net recovery elevation change (+0.10 m). It is worth noting that this gain over 1 month was equal to the elevation loss observed at the same site over the previous 19 months (Table 2). This highlights either the potential for some sites to regain storm losses, and the presence of large short-term changes in elevation that are not captured by surveys with long repeat intervals. However, since only Perico Preserve showed a recovery change, and that site is not reflective of other reefs surveyed in this study (protected inlet vs. exposure to open water; Fig. 2; Table 1), further investigation is needed to understand the observed change in recovery elevation. While the change is larger than the uncertainty of the RTK-GPS instrument, it is possible that this measured change is anomalous, rather than reflective of most constructed reefs with other shoreline configurations. More surveys at additional locations would be required to further elucidate the meaning of the large recovery of sediment at Perico Preserve.

A number of factors such as duration of wind across a given fetch, reef orientation, shoreline slope, or sediment type (to name a few) can affect the rates of erosion, especially during storms (Houser 2010; Gittman et al. 2014; Smith et al. 2017); these factors were not specifically accounted for in this study. Over the kriged areas surveyed on each reef before and after the storm, two of the three of oyster reef ball sites gained elevation following Hurricane Eta. Thus, those substrate types could be regarded as the best overall option to mitigate erosion where constructed oyster reefs are components of living shoreline projects. For shell bags, two sites recorded net elevation gain, while five lost elevation or did not change. It should be noted that while elevation gain is being perceived as erosion mitigation, the deposition of too much sediment may result in burial of the constructed reef, thereby stunting oyster growth and nullifying some ecosystem-service benefits provided by the reef.

Recommendations for future work

Due to the transient nature of sediment deposition and erosion in coastal systems, RTK-GPS elevation surveys should be performed more frequently than bi-annually or, ideally, immediately prior to and after storm events. Elevation surveys at more frequent intervals allow for a better understanding of short-term sediment dynamics at specific locations throughout the year. In addition, sediment samples should be retrieved from representative sites to determine median grain size for each location, which allows for the calculation of sediment volume lost or gained. This would provide useful information, as even small changes in elevation can represent large quantities of sediment lost or gained, and quantifying sediment volume allows for a better understanding of the economic benefits of living shorelines, such as constructed oyster reefs, since sediment is a tradeable commodity with a quantifiable free-market value.

While many living shoreline projects incorporate planting of marsh grasses behind the reef to further attenuate wave activity, baffle suspended sediments, and promote shoreline stabilization, most of the reefs surveyed did not have planted marshes. Thus, the combined effects of constructed oyster reefs in combination with planted living shorelines could not fully be evaluated in this study. However, there are several modeling tools that could be used in conjunction with elevation data and historical shoreline conditions (e.g., vegetated vs. non-vegetated) to determine combined effects of living shoreline components in ameliorating shoreline change. One such tool is the

Digital Shoreline Analysis System (DSAS; US Geological Survey; https://www.usgs.gov/centers/whcmsc/science/digital-shoreline-analysis-system-dsas). McClenachan et al. (2020) applied DSAS quantify the effects of living shorelines on shoreline change and recommended its use in addition to regular vegetation and elevation monitoring for living-shoreline projects.

Daily wave activity contributes overwhelmingly to coastal changes. While there was no discernable relationship between basic estimations of fetch and net elevation change in this study, no rigorous quantitative measurements or modeling of the prevailing wave field or storm waves were performed. Another open-source modeling platform, Simulation of the Waves Nearshore (SWAN; https://sourceforge.net/projects/swanmodel/files/swan/), has a long history (1993 to present) of being applied to model waves within enclosed systems such as estuaries. Future projects would benefit from the estimation of local (i.e., Hillsborough Bay or Old Tampa Bay segments) wind-driven wave fields, during both project planning and subsequent ecological and geomorphic monitoring.

Acknowledgments

This research was supported by the Tampa Bay Estuary Program through its annual work plan (EPA 620 funds). In-kind contributions included work conducted by the Florida Fish and Wildlife Conservation Commission.

Field assistance was provided by FWRI personnel Savanna Hearne, Emily Ritz, Christine Russo, and Sam Roussopoulos. Site access for MacDill Air Force Base was provided by Andy Lykens and Jason Kirkpatrick (PAE Inc., contractor to MacDill AFB) and at Perico Preserve by Damon Moore. Advice and assistance with statistical analysis was provided by Colin Shea. The use of any trade names does not imply endorsement by the State of Florida, or any organizations involved in this study.

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Appendix A – Net elevation change maps pre- and post-Eta

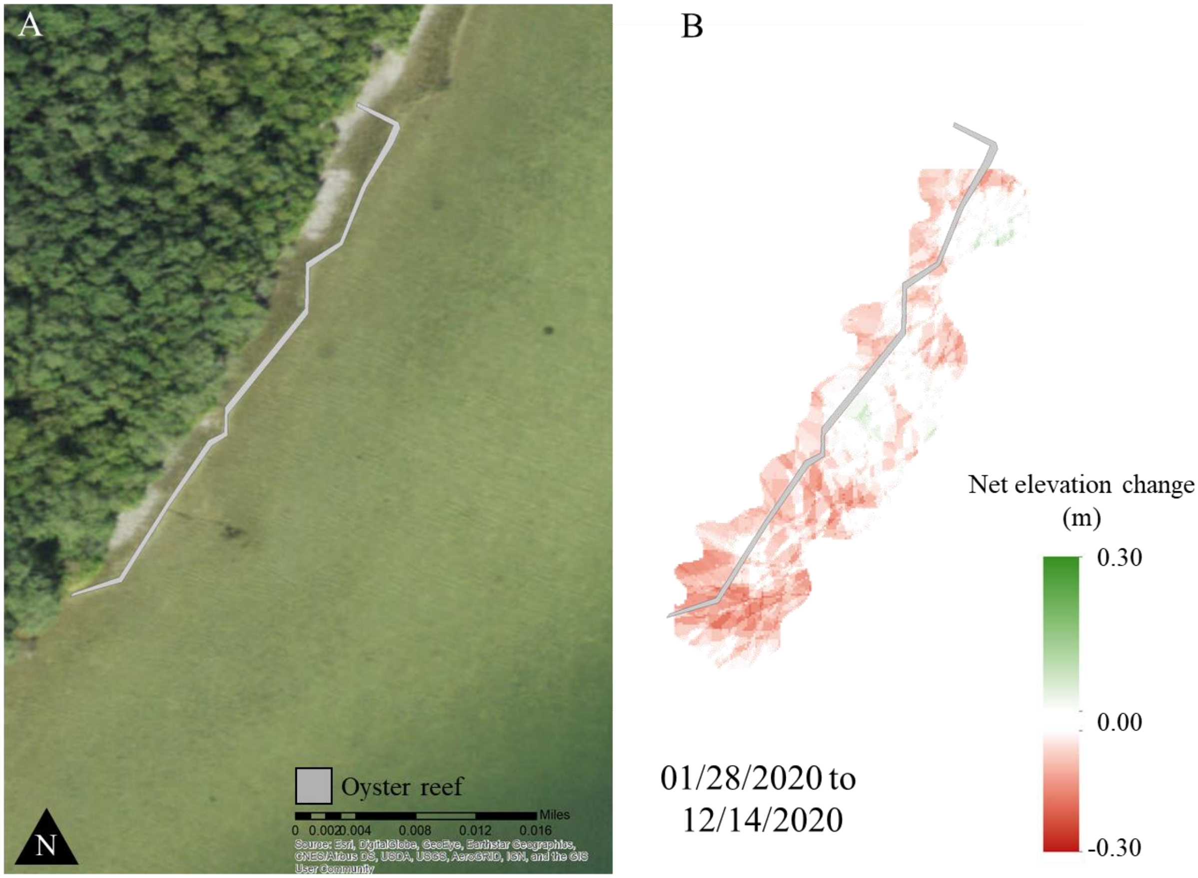

Figure A1. Aerial imagery (**A**) and net elevation change (**B;** scale -0.30 to 0.30 m) of kriged RTK GPS survey data for the 2018 shell bag reef on 2D Island from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

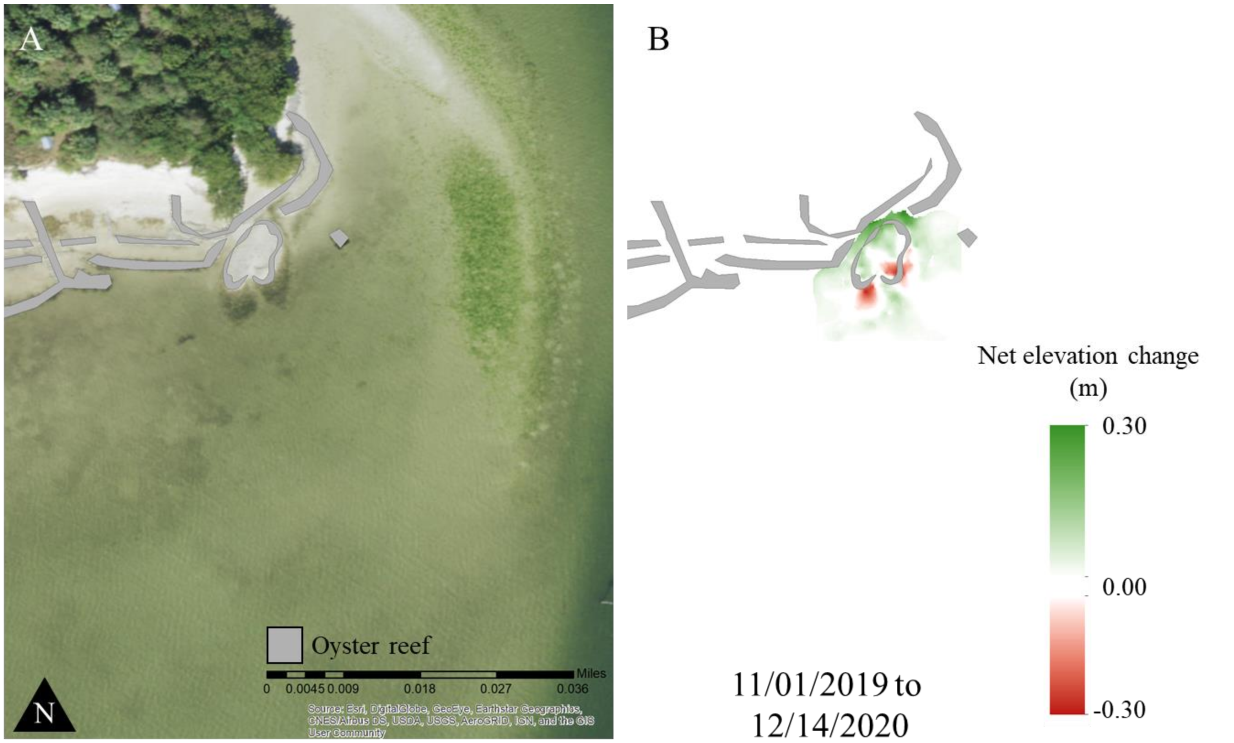

Figure A2. Aerial imagery (**A**) and net elevation change (**B;** scale -0.30 to 0.30 m) of kriged RTK GPS survey data for the 2006 loose shell reef on Fantasy Island from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

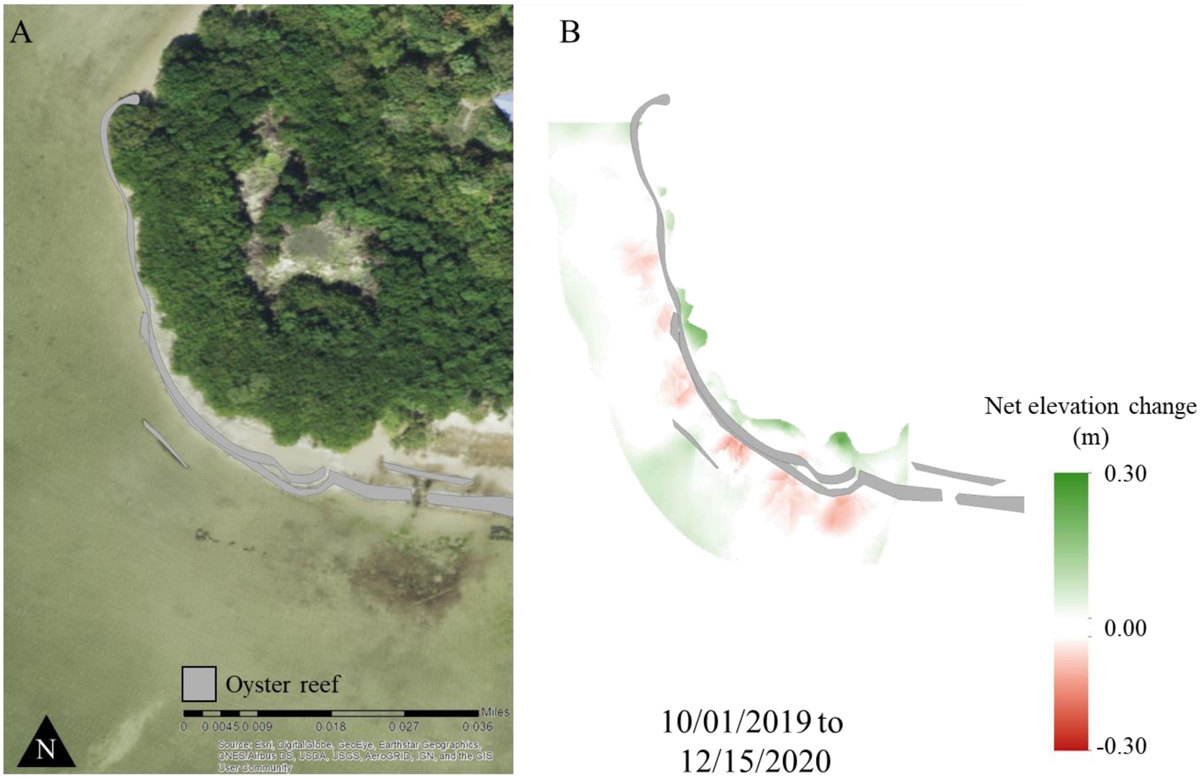

Figure A3. Aerial imagery (**A**) and net elevation change (**B;** scale -0.30 to 0.30 m) of kriged RTK GPS survey data for the 2008 shell bag reef on Fantasy Island from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

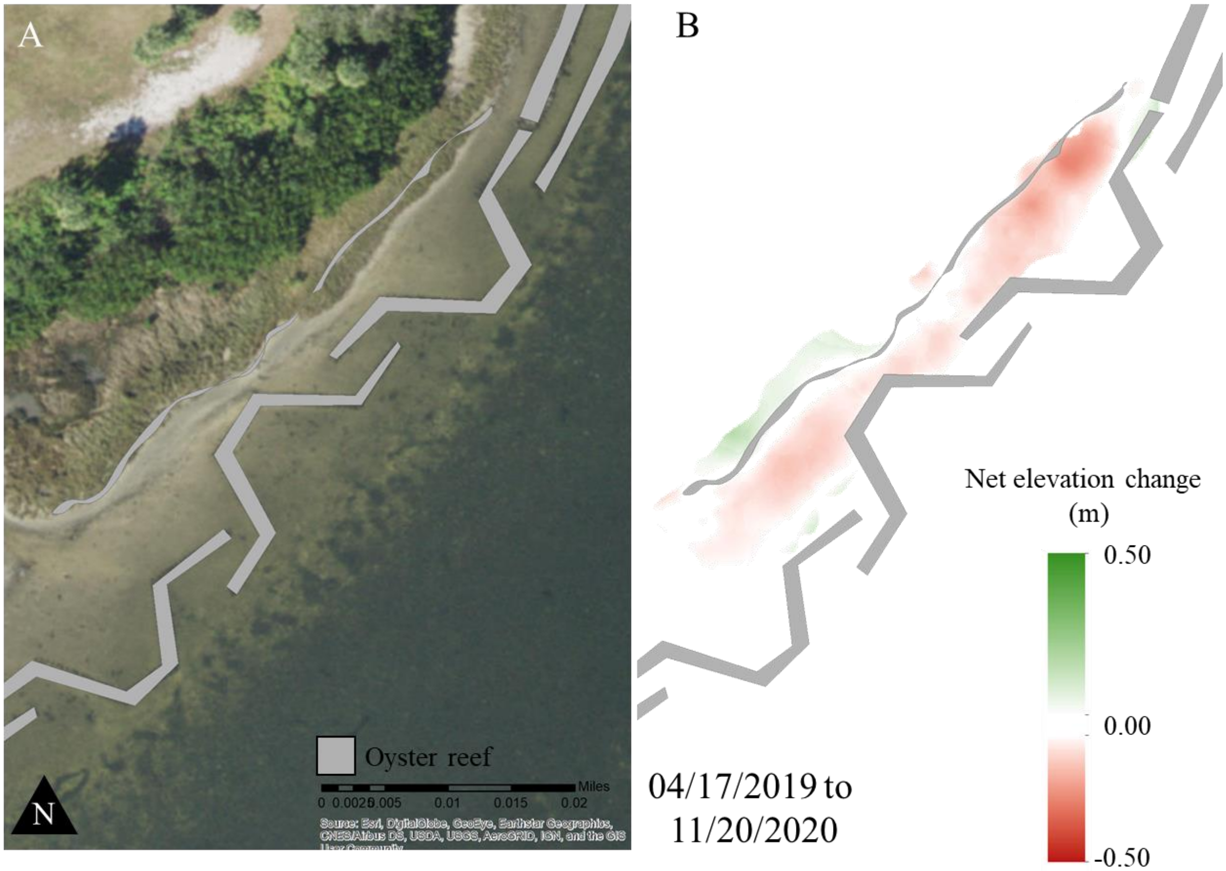

Figure A4. Aerial imagery (**A**) and net elevation change (**B;** scale -0.50 to 0.50 m) of kriged RTK GPS survey data for the 2007 shell bag reef at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

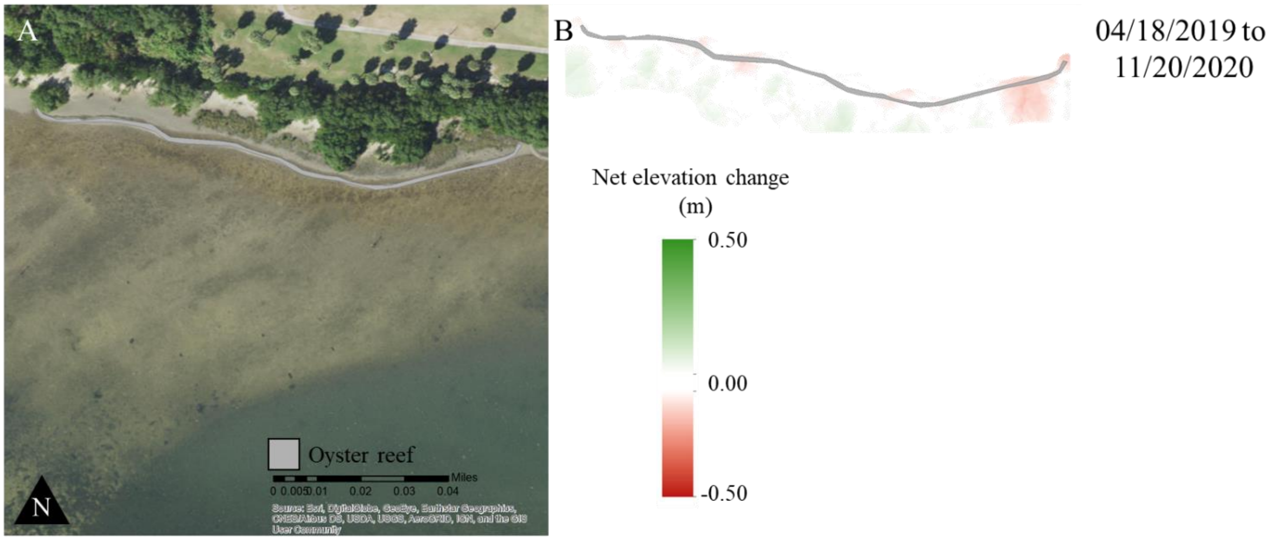

Figure A5 Aerial imagery (**A**) and net elevation change (**B;** scale -0.50 to 0.50 m) of kriged RTK GPS survey data for the 2015 shell bag reef at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

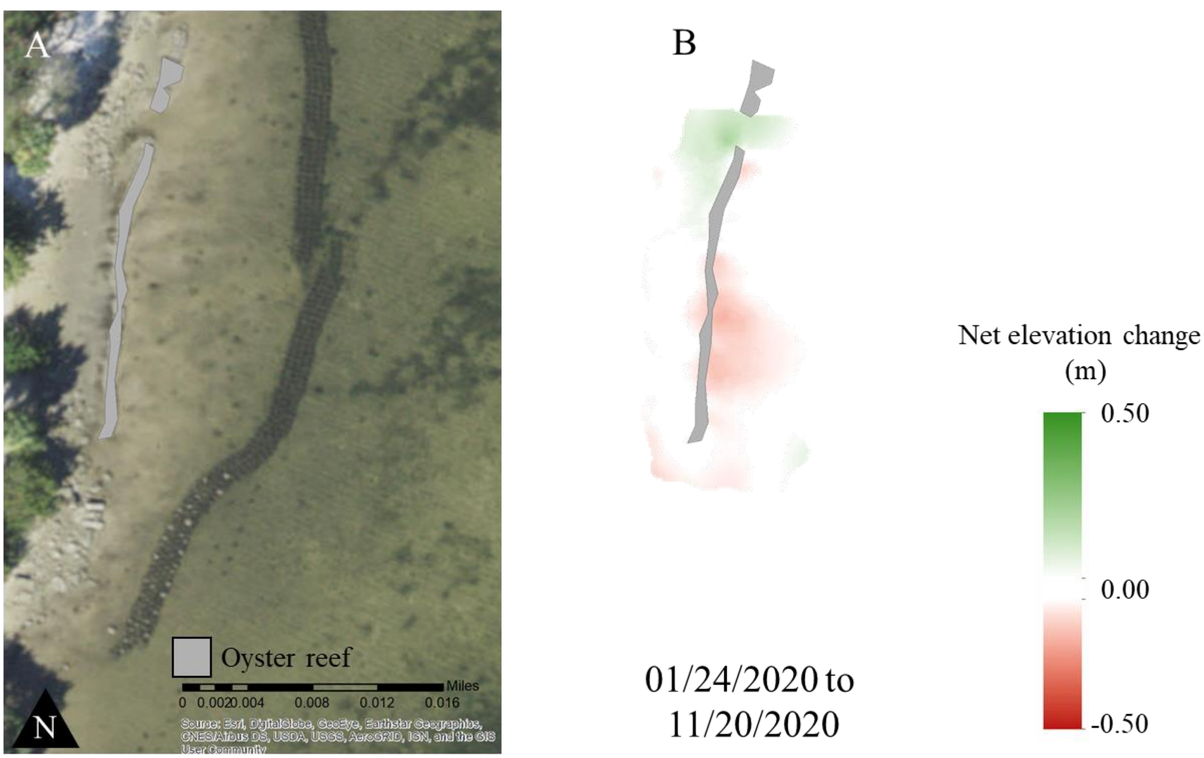

Figure A6. Aerial imagery (**A**) and net elevation change (**B;** scale -0.50 to 0.50 m) of kriged RTK GPS survey data for the 2018 bag reef at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

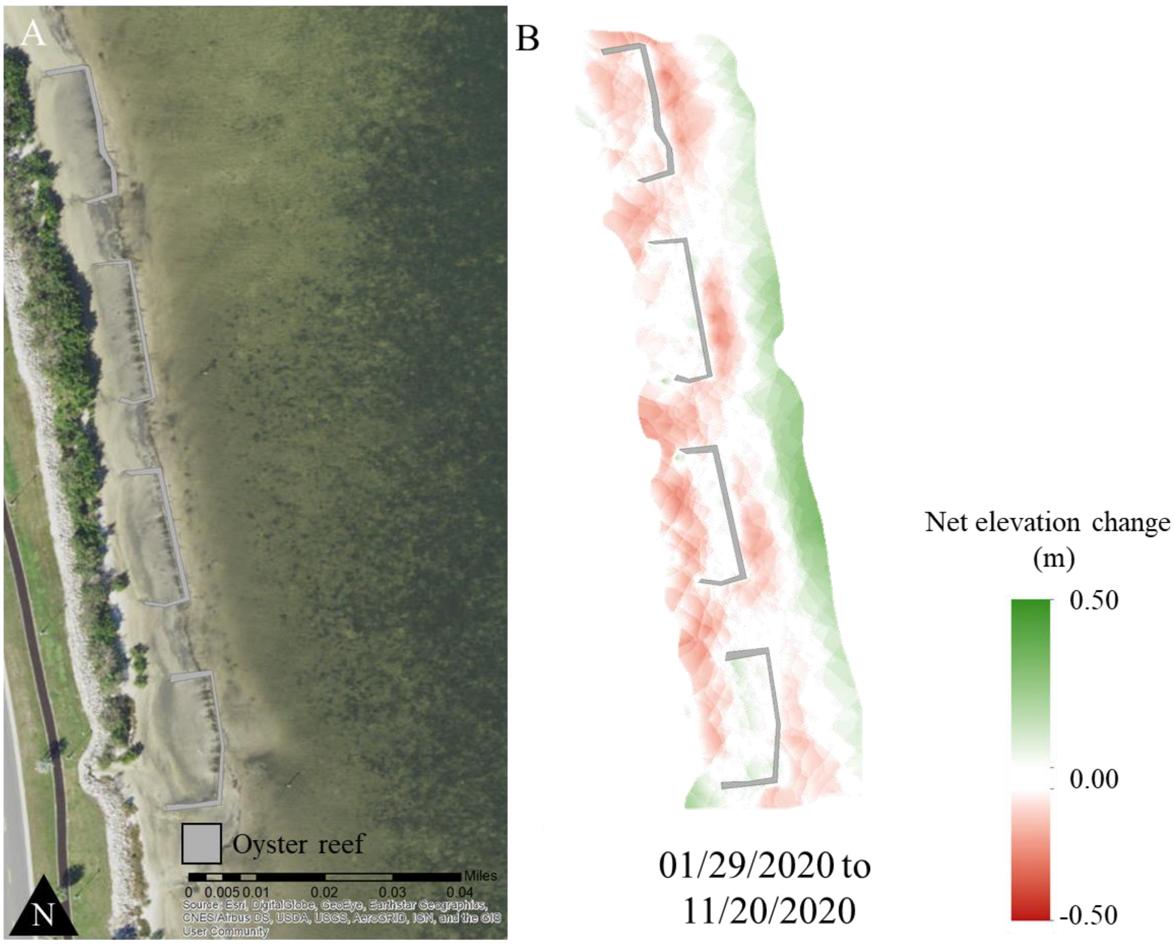

Figure A7. Aerial imagery (**A**) and net elevation change (**B,** scale -0.50 to 0.50 m) of kriged RTK GPS survey data for the 2019 shell bag reef at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

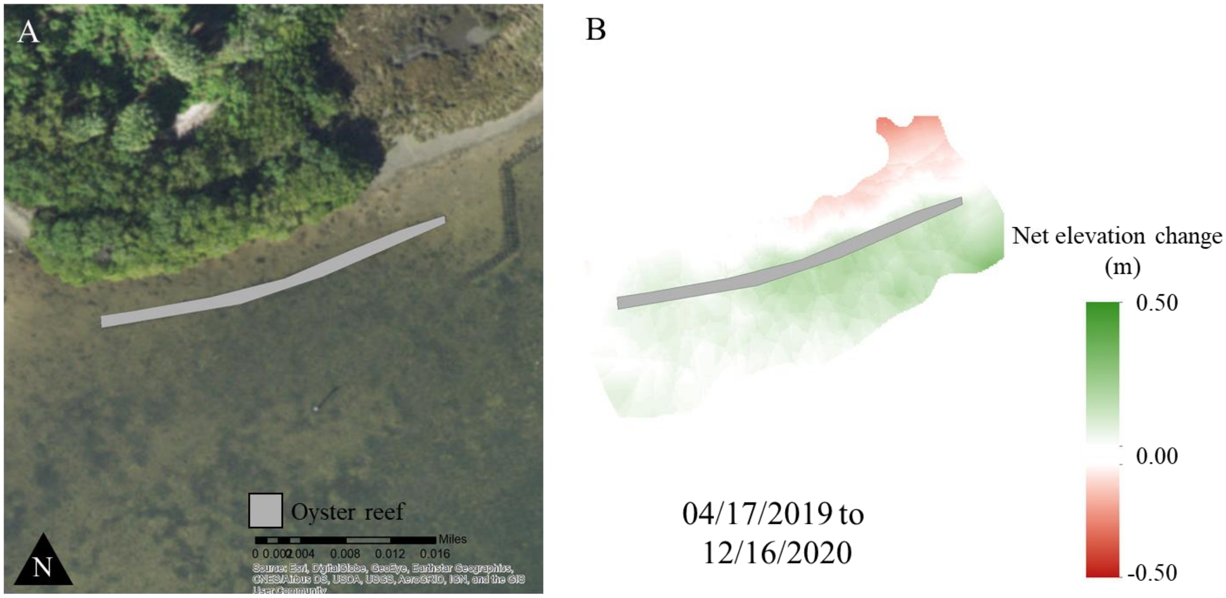

Figure A8. Aerial imagery (**A**) and net elevation change (**B;** scale -0.50 to 0.50 m) of kriged RTK GPS survey data for the 2007 oyster reef balls at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

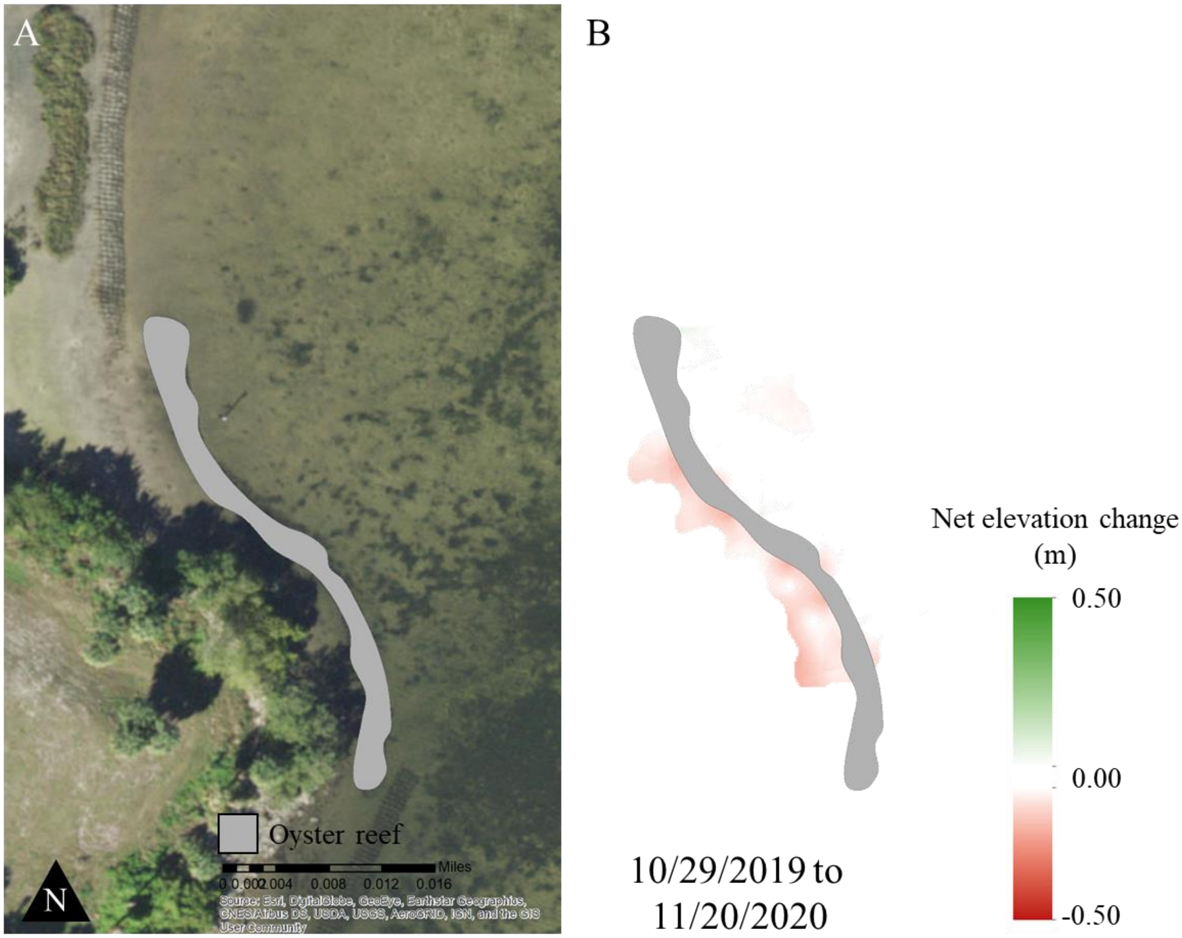

Figure A9. Aerial imagery (**A**) and net elevation change (**B;** scale -0.50 to 0.50 m) of kriged RTK GPS survey data for the 2015 oyster reef balls at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

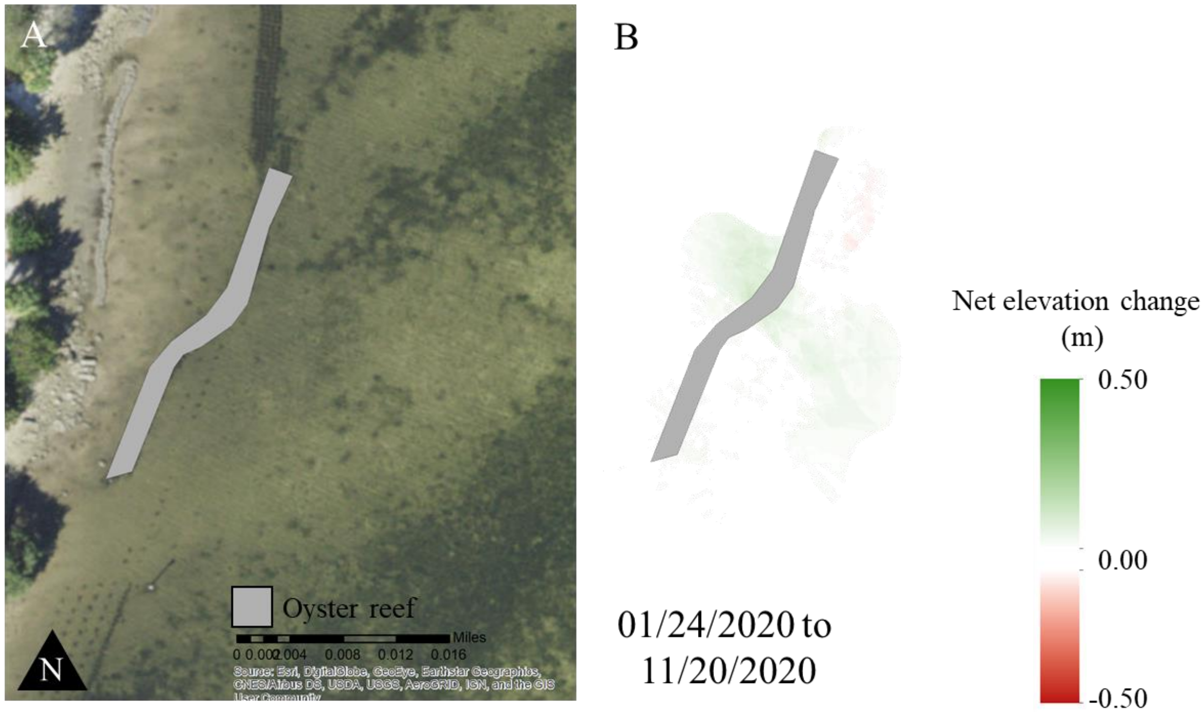

Figure A10. Aerial imagery (**A**) and net elevation change (**B,** scale -0.50 to 0.50 m) of kriged RTK GPS survey data for the 2018 oyster reef balls at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

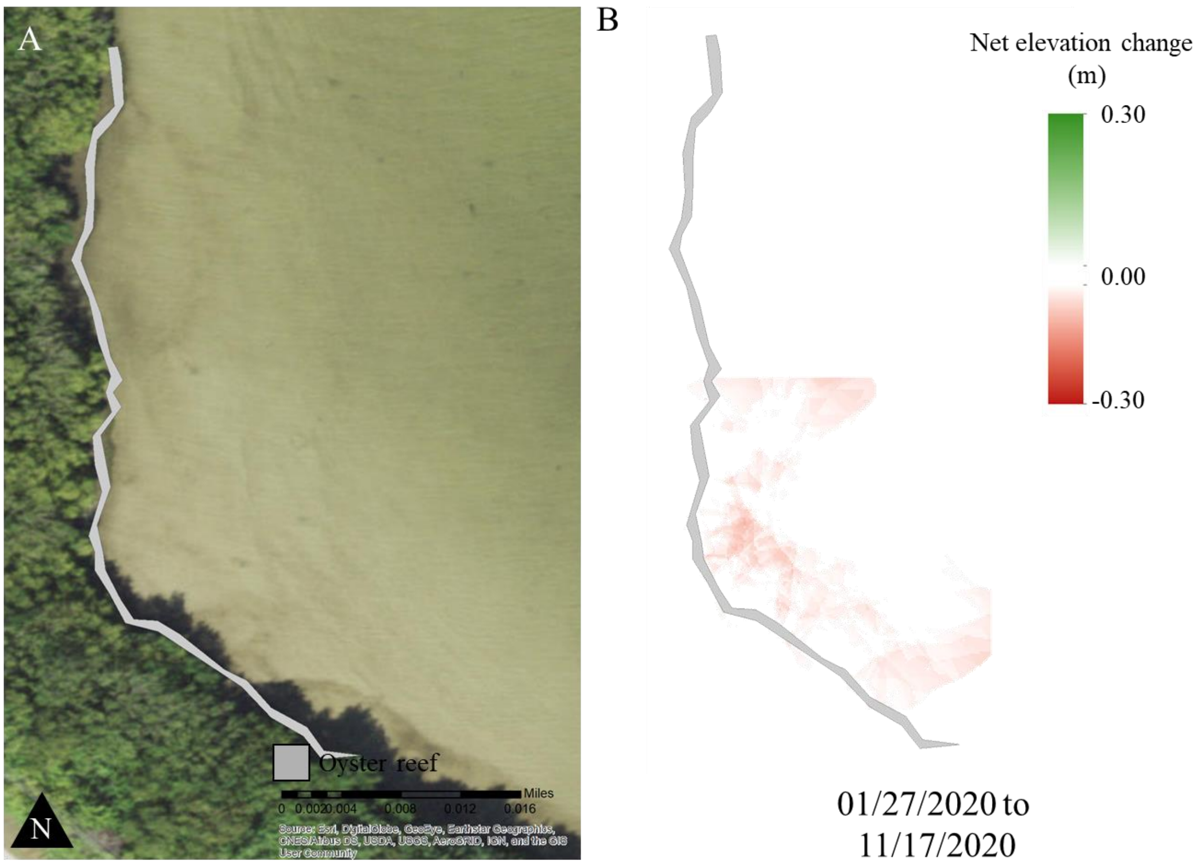

Figure A11. Aerial imagery (**A**) and net elevation change (**B;** scale -0.50 to 0.50 m) of kriged RTK GPS survey data for the 2018 shell bag reef at McKay Bay from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

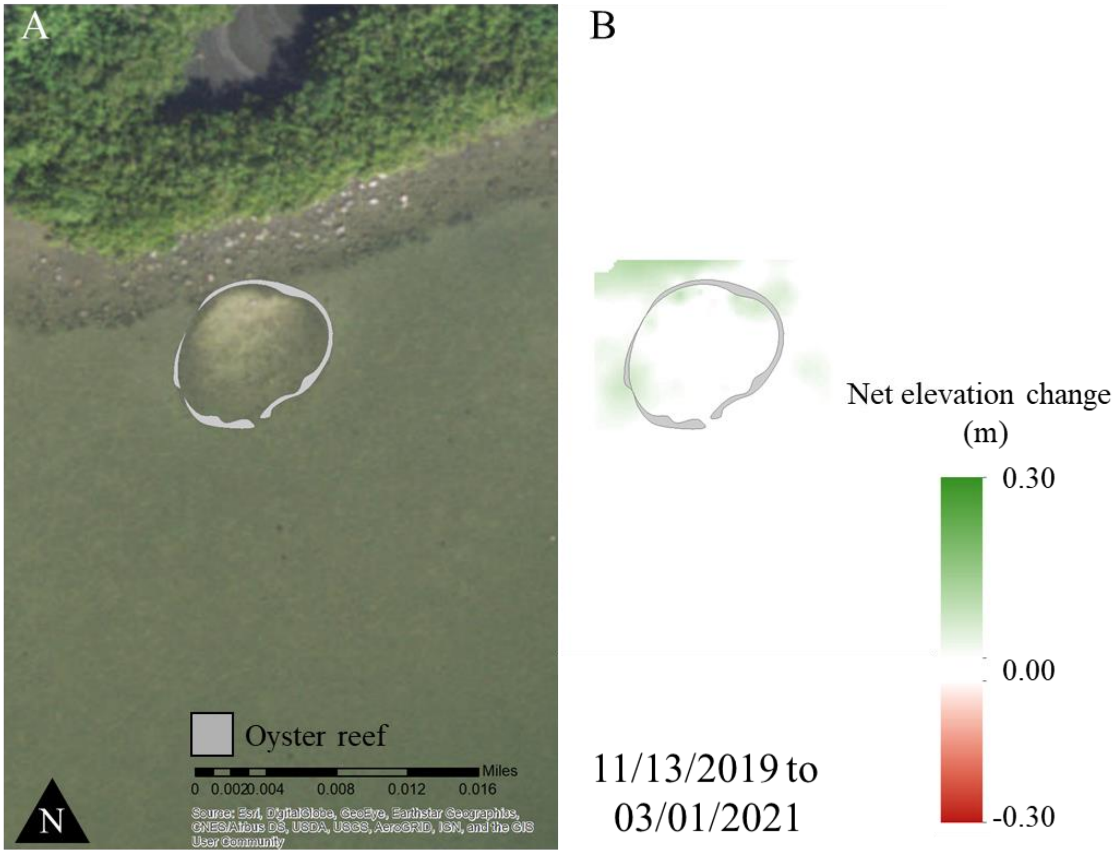

Figure A12. Aerial imagery (**A**) and net elevation change (**B**; scale -0.30 to 0.30 m) of kriged RTK GPS survey data for the McKay Bay natural reef from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

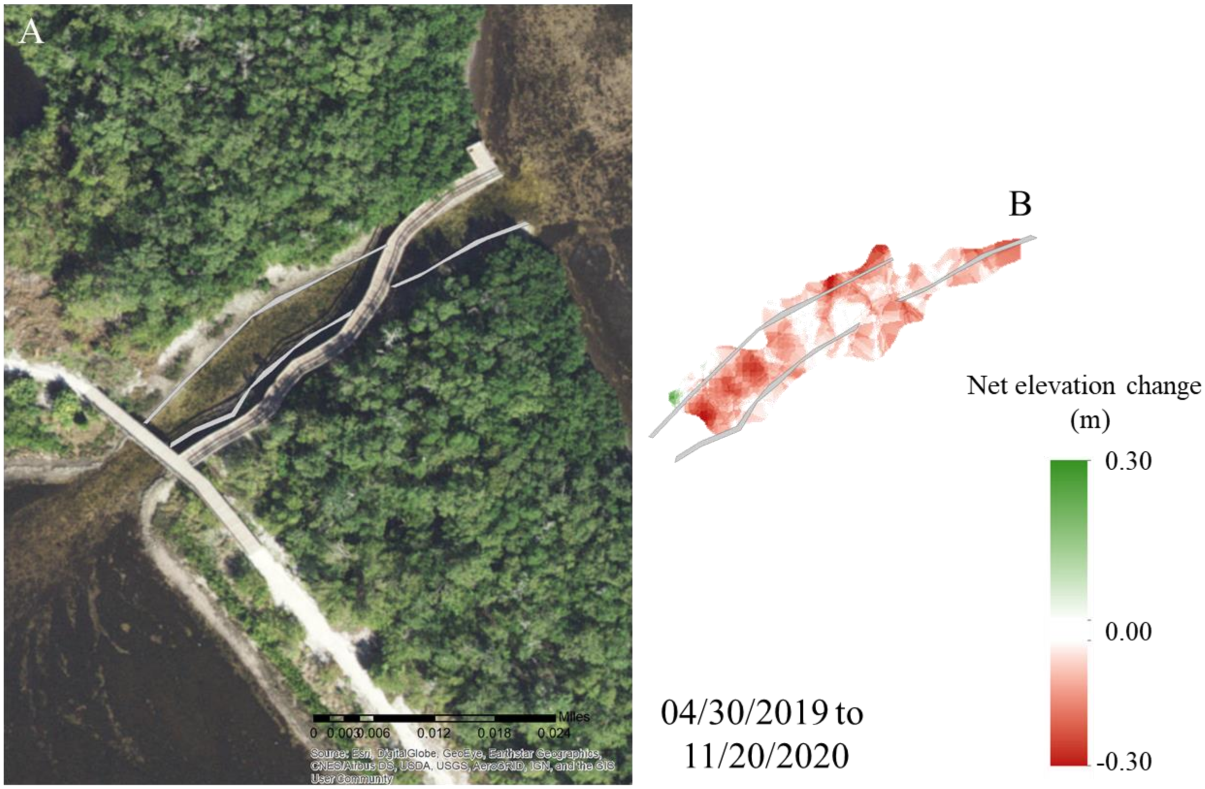

Figure A13. Aerial imagery (**A**) and net elevation change (**B;** scale -0.30 to 0.30 m) of kriged RTK GPS survey data for the 2016 loose shell reef in Perico Preserve surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m and is interpreted as 0 m of elevation change.

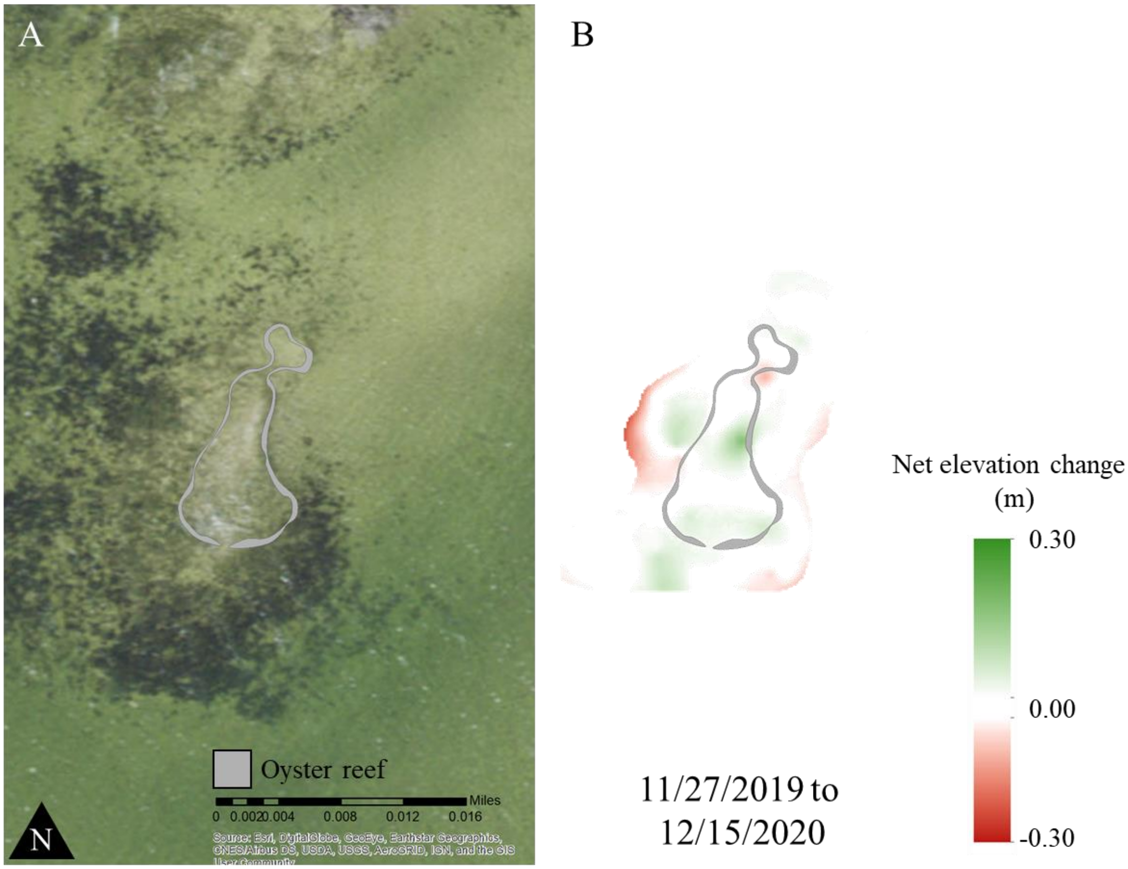

Figure A14. Aerial imagery (**A**) and net elevation change (**B;** scale -0.20 to 0.20 m NAVD 88) of kriged RTK GPS survey data for the natural reef outside the Port of Tampa from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m NAVD 88 and is interpreted as 0 m of elevation change.

Appendix B

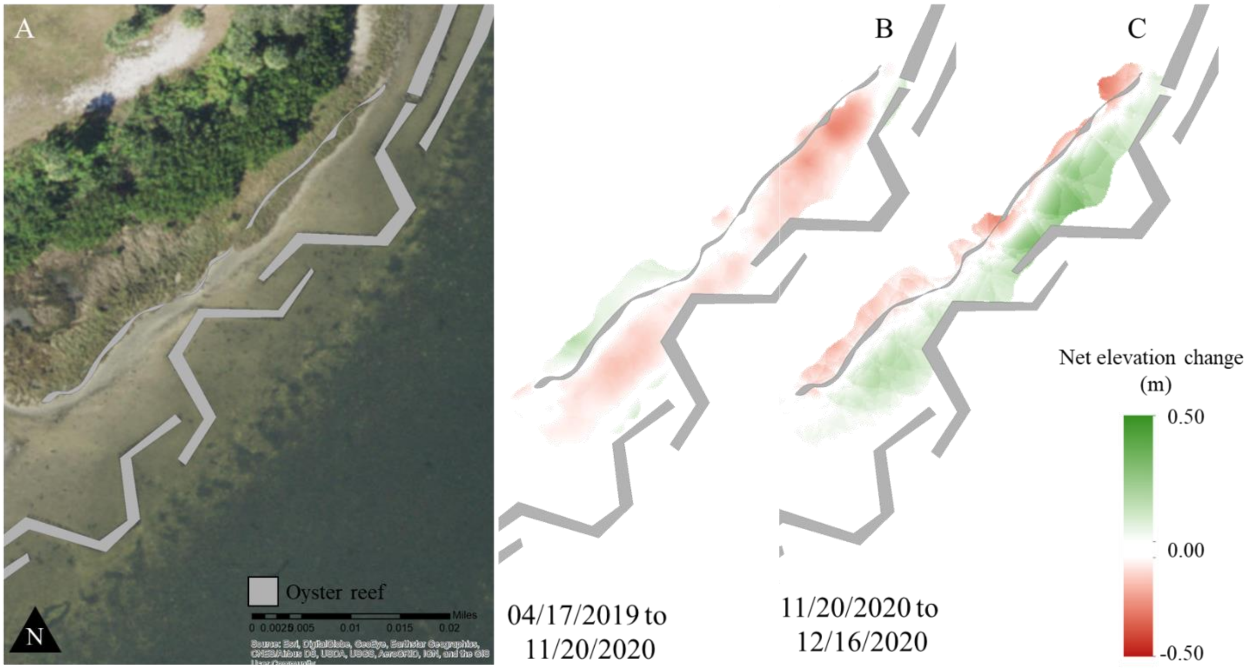

Figure B1. Aerial imagery (**A**) and net elevation change (**B, C;** scale -0.50 to 0.50 m NAVD 88) of kriged RTK-GPS survey data for the 2007 shell bag reef at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m NAVD 88 and is interpreted as 0 m of elevation change.

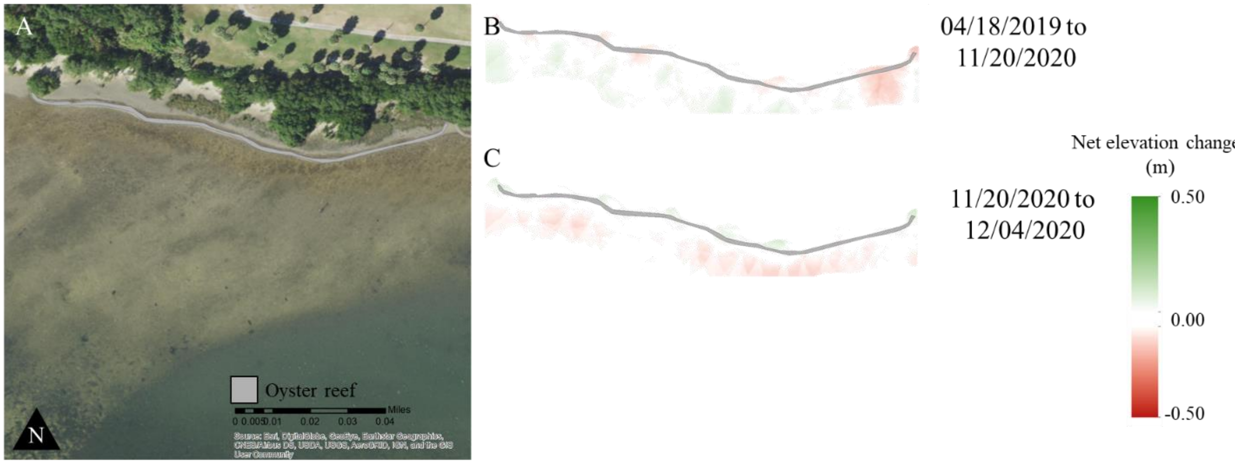

Figure B2. Aerial imagery (**A**) and net elevation change (**B, C;** scale -0.50 to 0.50 m NAVD 88) of kriged RTK-GPS survey data for the 2015 shell bag reef at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m NAVD 88 and is interpreted as 0 m of elevation change.

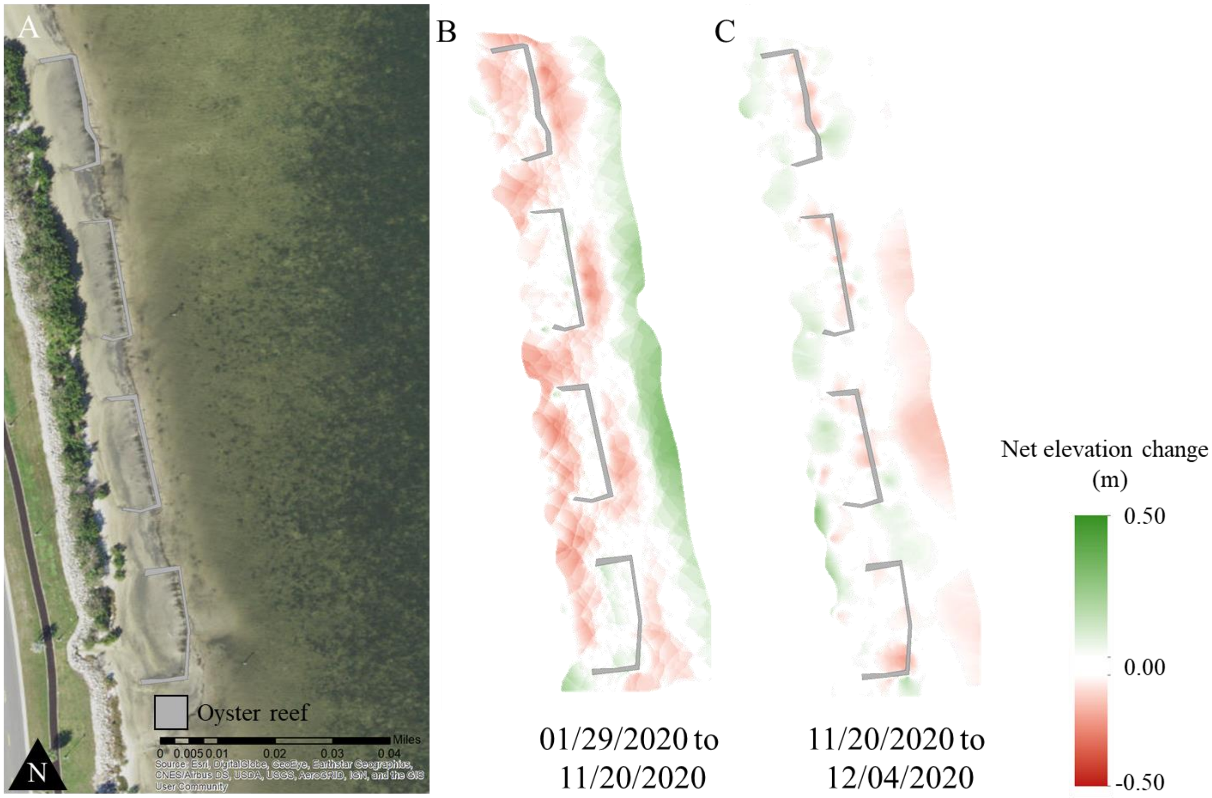

Figure B3. Aerial imagery (**A**) and net elevation change (**B, C;** scale -0.50 to 0.50 m NAVD 88) of kriged RTK-GPS survey data for the 2019 shell bag reef at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m NAVD 88 and is interpreted as 0 m of elevation change.

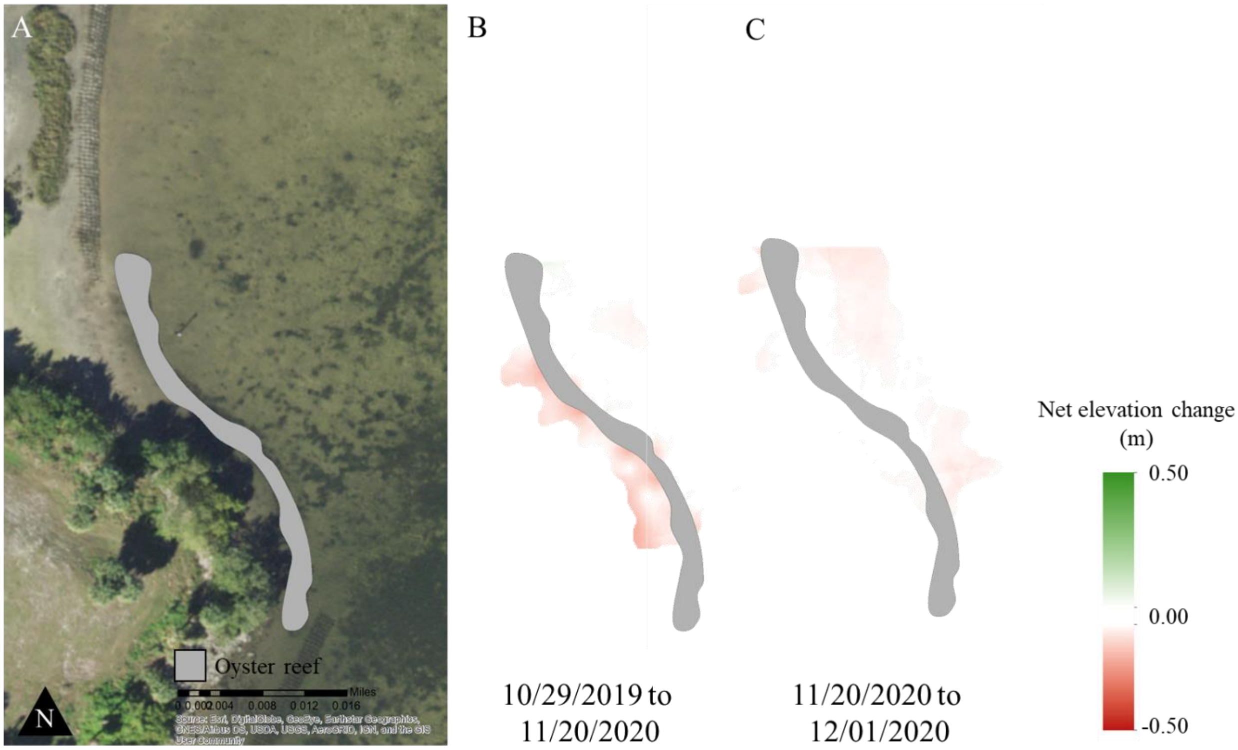

Figure B4. Aerial imagery (**A**) and net elevation change (**B, C;** scale -0.50 to 0.50 m NAVD 88) of kriged RTK-GPS survey data for the 2015 oyster reef balls at MacDill Air Force Base from surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020. White shading represents instrumental error or elevation changes between -0.03 to 0.03 m NAVD 88 and is interpreted as 0 m of elevation change.

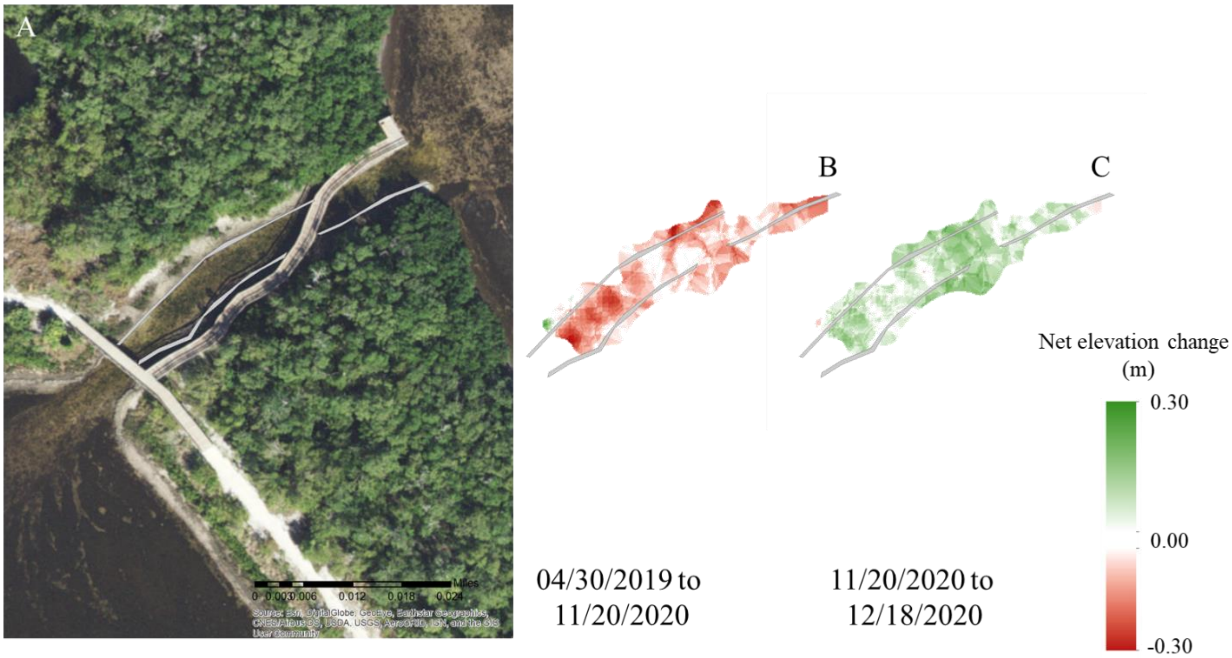

Figure B5. Aerial imagery (**A**) and net elevation change (**B, C;** scale -0.30 to 0.30 m NAVD 88) of kriged RTK-GPS survey data for the 2016 loose shell reef in Perico Preserve surveys pre- to post-Eta, which impacted Tampa Bay on 11/12/2020.White shading represents instrumental error or elevation changes between -0.03 to 0.03 m NAVD 88 and is interpreted as 0 m of elevation change.