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Reports

Ecology, 102(4), 2021, e03309

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Citation: Pennings, S. C., R. M. Glazner, Z. J. Hughes, J. S. Kominoski, and A. R. Armitage. 2021. Effects of mangrove cover on coastal erosion during a hurricane in Texas, USA. Ecology 102(4):e03309. 10.1002/ecy.3309

Abstract. We tested the hypothesis that mangroves provide better coastal protection than salt marsh vegetation using 10 1,008-m^2 plots in which we manipulated mangrove cover from 0 to 100%. Hurricane Harvey passed over the plots in 2017. Data from erosion stakes indicated up to 26 cm of vertical and 970 cm of horizontal erosion over 70 months in the plot with 0% mangrove cover, but relatively little erosion in other plots. The hurricane did not increase erosion, and erosion decreased after the hurricane passed. Data from drone images indicated 196 m^2 of erosion in the 0% mangrove plot, relatively little erosion in other plots, and little ongoing erosion after the hurricane. Transects through the plots indicated that the levee (near the front of the plot) and the bank (the front edge of the plot) retreated up to 9 m as a continuous function of decreasing mangrove cover. Soil strength was greater in areas vegetated with mangroves than in areas vegetated by marsh plants, or nonvegetated areas, and increased as a function of plot-level mangrove cover. Mangroves prevented erosion better than marsh plants did, but this service was nonlinear, with low mangrove cover providing most of the benefits.

Key words: *coastal protection; erosion; hurricane; mangrove; salt marsh; soil strength.*

Introduction

Vegetation canopies reduce water velocity, and roots increase soil shear strength, and both mechanisms protect against erosion in riverine (Allen et al. 2016) and coastal ecosystems (Gedan et al. 2011, Chen et al. 2012, Valentine and Mariotti 2019). As a result, the loss of vegetation, for example, after an oil spill, can lead to greatly increased erosion rates (Beland et al. 2017). The effect of vegetation on geomorphology is so important that the presence or absence of vegetation in an area can be inferred simply from a photograph, based on the nature of the geomorphological traces left by past water movement across the landscape (Davies and Gibling 2010*a*, *b*). However, almost all studies of how vegetation affects erosion are either small-scale experiments subject to experimental artifacts (Yang and Nepf 2018) or natural experiments affected by unknown confounding variables. Thus, although there is a consensus that vegetation stabilizes sediments, there is a need for field experiments that more rigorously quantify this process at ecologically relevant spatial and temporal scales.

The role of vegetation in shoreline stabilization is particularly important during large storms such as hurricanes. Environmental economists often assign a high value to tropical mangrove and temperate salt marsh habitats because of their capacity to attenuate storm surge and therefore reduce storm damage (Bao 2011). Variation among types of vegetation may lead to different levels of wave attenuation and sediment stabilization. For example, subtropical coastal wetlands can be dominated by either mangrove trees or salt marsh plants (Osland et al. 2013). Mangroves are common on tropical coasts, and are spreading to higher latitudes with global warming (Saintilan et al. 2014). At the same time, existing mangroves can be lost to severe freeze events (Osland et al. 2019), or to other disturbances such as clearing for

Manuscript received 30 June 2020; revised 24 November 2020; accepted 5 February 2021. Corresponding Editor: Edwin Grosholz.
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aquaculture (Pattanaik and Prasad 2011). Thus, the vegetation at a given site can alternate between salt marshes, dominated by grasses and succulents, and mangroves, dominated by woody vegetation. Within different types of mangrove stands, vegetation structure affects the extent to which mangrove forests dampen waves (Bao 2011, Sánchez-Núñez et al. 2019). Mangroves and marsh plants differ dramatically in morphology, with mangroves being taller and stiffer, but having lower stem density than stands of salt marsh plants, and this in theory should affect storm protection services (Barbier et al. 2013, Doughty et al. 2017); however, it is uncertain whether shoreline protection services provided by these two groups of species in fact differ. Published empirical comparisons (Gedan et al. 2011) have large, overlapping error bars, and are natural experiments, comparing different sites in different geographic contexts experiencing different types of wave and flow regimes; these differences obscure the effects of plant type. Laboratory and wave tank studies offer alternative approaches, but have a limited capacity to mimic the intensity of large storms.

The geographic transition zone between mangroves and marshes, where both vegetation types can occur, provides an opportunity to explore how shoreline protection services differ among coastal vegetation types while holding geomorphic setting and wave exposure constant (McKee and Vervaeke 2017). We conducted a large-scale experimental vegetation manipulation on the coast of Texas, USA. This area is near the current northern limit of mangroves in the United States, where mangroves have a short "scrub" morphology because of cold winter temperatures and summer salinity stress caused by the arid climate and low sea levels in summer. Many locations on the Texas coast have alternated between salt marsh and mangrove cover over the past 100 yr, as mangroves have gradually expanded during warm periods and abruptly contracted during severe freezes (Armitage et al. 2015). The most likely scenario for the next 100 yr, however, is widespread expansion of mangroves throughout the western Gulf Coast of the United States because of climate warming (Osland et al. 2013, Gabler et al. 2017), with largely unknown effects on the ecosystem services provided by coastal wetlands (Perry and Mendelsohn 2009, Guo et al. 2017, Kelleway et al. 2017).

We created large field plots that varied in cover of mangroves and salt marsh plants (Guo et al. 2017), and used these plots to test the hypothesis that reduced mangrove cover would increase shoreline erosion. A major hurricane came ashore over our plots during the study,

Fig. 1. Representative image of the 55% mangrove cover plot in October 2017, depicting plot boundaries and the erosion polygon at the front of the plot.

allowing us to also test the hypothesis that a severe storm would increase erosion.

Methods

Our study was conducted on Harbor Island, near Port Aransas, Texas (27.86° N, 97.08° W), within the domain of the Mission-Aransas National Estuarine Research Reserve. The vegetation at the site was initially dominated (90%–100% cover) by "scrub form" (canopy height ~ 1–2.5 m) black mangroves (*Avicennia germinans*) with patches (~10% cover) of salt marsh vegetation (mostly the succulents *Batis maritima* and *Sarcocornia* spp. at ~ 5% cover each and the grass *Spartina alterniflora* at <1% cover). In 2012, we established 10 plots, each 42 × 24 m (Fig. 1), with the shorter side of each plot facing open water (the Lydia Ann Channel). At the start of the study, plot elevation (based on publicly available LIDAR and NADV 1983) ranged from 0.2 m above mean lower low water (MLLW) along a small berm at the water's edge to 0.1 m above MLLW in the remainder of the plots, with low-relief topography in the middle and back portions of the plot. The higher elevation along the shoreline was likely due to the accumulation of sediment and wrack trapped by plant stems, trunks, and aerial roots (pneumatophores). We removed mangroves from the plots by cutting them at the soil surface to create a gradient of mangrove cover (nominally 0%, 11%, 22%, 33%, 44%, 55%, 66%, 77%, 88%, and 100% mangrove cover); mangrove treatments were maintained annually. The plots were arranged in three blocks, with each block containing at least one low (0%–22%), one intermediate (33%–66%), and one high (77%–100%) mangrove cover plot (Guo et al. 2017). To facilitate maintenance and to simulate the natural patchiness of the vegetation, mangroves were removed or left in place within 3 × 3 m cells in a stratified random checkerboard pattern. Marsh vegetation naturally colonized much of the cleared areas in following years (Guo et al. 2017), attaining cover values by 2019 of ~30% (*B. maritima*), ~20% (*Sarcocornia* sp.), and ~20% (*S. alterniflora*) averaged across all the plots. Some of the cleared cells, however, especially in plots with high mangrove cover, remained unvegetated over the course of this study, likely because of shading and root competition from mangroves in adjacent cells.

Hurricane Harvey, a Category 4 storm, came ashore on 25 August 2017, passing directly over the plots. The plots were exposed to hurricane-force winds exceeding 119 k/h for ~6 h, with gusts up to 225 k/h (National Oceanic and Atmospheric Administration [NOAA 2019]). A tide gauge at Port Aransas, ~3.5 km from the experimental plots, recorded a storm surge of 1.6 m above MLLW (NOAA 2019), and estimates of storm surge based on debris deposition and other flood evidence indicated a storm surge of up to 2.4 m (United States Geological Survey [USGS] 2019). Major flooding (0.8 m above MLLW) persisted for approximately 6 h.

We used three methods to characterize geomorphological changes in the plots over time as a function of mangrove cover. First, we obtained point measurements from each plot on multiple dates before and after Hurricane Harvey using erosion stakes. We inserted eight PVC pipes into the ground to refusal in the front third of each plot in March 2014. In March 2016, October 2017, and November 2019 we measured changes in how much of the pipe was exposed (vertical erosion) and the distance from the pipe to the front of the plot (horizontal erosion). Detailed methods are in Appendix S1: Section S1. Second, we obtained estimates of area eroded from each plot using three drone surveys, all after Hurricane Harvey. We collected aerial images of all plots with an unmanned aerial vehicle on 22 October 22 2017, 15 March 2018, and 13 October 2018. We estimated the area of the plot that was eroded from the images based on the location of the water–vegetation interface. Detailed methods are in Appendix S1: Section S2. Third, we measured the vertical profile of each plot along a single transect per plot using a theodolite in November 2018, after Hurricane Harvey. These measurements quantified how elevation changed throughout each plot and how the front of the plot and the levee varied as a function of mangrove cover. Detailed methods are in Appendix S1: Section S3. This suite of methods provided complementary insights into the geomorphological changes that have taken place in the plots since we established different levels of mangrove cover in 2012.

In addition, we measured soil strength to test one possible mechanism for erosion—that soil strength was a function of mangrove cover. To test the hypothesis that removal of mangroves altered soil shear strength, we measured the strength of surface (0–4 cm) soils in each plot on 28 November 2019, using a field shear vane (GEONOR model H-60). In each plot, we took readings in the front and back third of each plot in cells dominated by mangroves, each of the three most common marsh plant species at the site (*Batis maritima*, *Sarcocornia* sp., *S. alterniflora*), and nonvegetated cells where mangroves had been cleared but marsh vegetation had not yet colonized. We took up to five readings for each vegetation type in each location in each plot when present, for a total of 50 possible readings per plot (2 locations × 5 vegetation types × 5 replicates); actual replication was considerably less because not all vegetation types were present in each plot. Within each plot and each location (front and back), we averaged all mangrove readings, all marsh plant readings, and all nonvegetated readings, to give a single average strength for each of three vegetation types (mangrove, marsh, nonvegetated) in the front and in the back of each plot. Data were analyzed with ANCOVA in R (version 4.0.0), with location (front and back of the plot) and vegetation type as the main effects and mangrove cover as the covariate.

Results

Vertical erosion was most pronounced in the 0% mangrove plot (Fig. 2A). In the first 24 months of measurement, the front of the 0% mangrove plot lost ~17 cm of elevation, whereas no other plot lost or gained more than 3 cm of elevation. In the following 19 months, which included landfall of Hurricane Harvey, vertical erosion in the front of the 0% mangrove plot increased to 26 cm, with cumulative change in all other plots increasing to at most 9 cm. In the following 25 months, there was no additional vertical erosion in the front of the 0% mangrove plot (cumulative 25 cm), and little to no additional erosion in all other plots (cumulative change at most 9 cm). Horizontal erosion was greatest in the 0% mangrove plot, but all plots showed some shoreline retreat over time (Fig. 2B). In the first 24 months of measurement, the front of the 0% mangrove plot retreated by ~ 410 cm, the 11% and 22% mangrove plots retreated by 140–154 cm, and the other plots retreated by at most 103 cm. In the following 19 months, which included landfall of Hurricane Harvey, horizontal erosion in the front of the 0% mangrove plot increased to 970 cm, horizontal erosion in the 11% and 22% mangrove plots increased to 170–275 cm, and erosion in all other plots increased to at most 160 cm. In the following 25 months, the 0% mangrove recovered somewhat (826 cm), but horizontal erosion in the 11% and 22% mangrove plots continued to increase (212–425 cm), as it did in all the other plots (up to 267 cm).

Drone images (Appendix S1: Fig. S1) indicated that the plot area lost to erosion was substantially higher in the 0% mangrove plot than in the other plots (Fig. 2C). By October 2017 (2 months after Hurricane Harvey), the 0% mangrove plot had lost nearly 20% (196 m^2) of its original area, with losses in the other plots declining

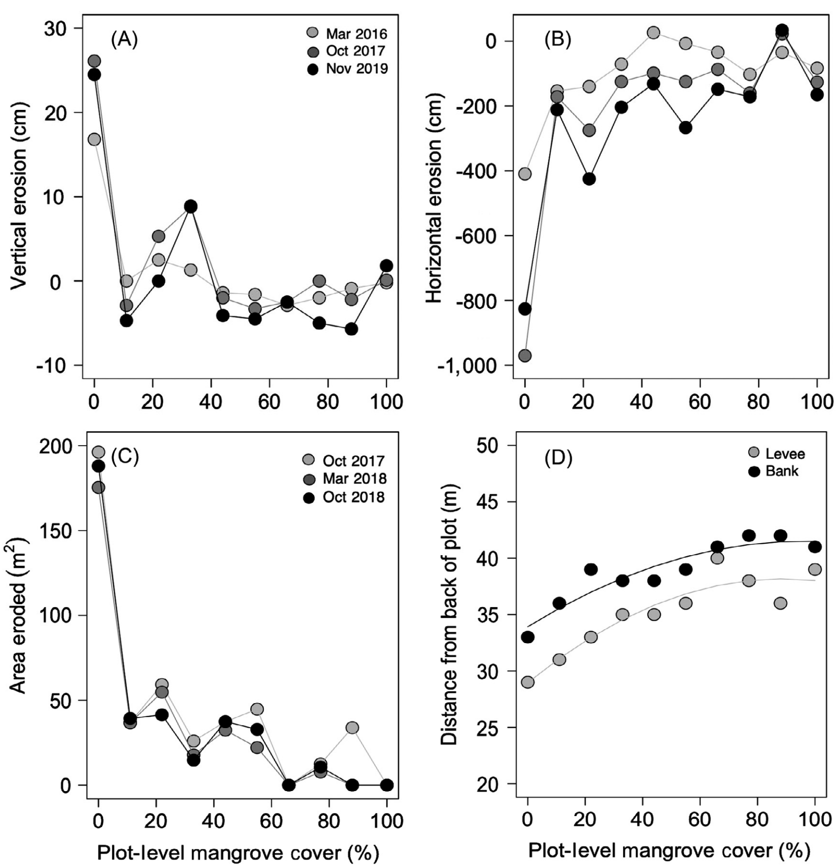

Fig. 2. Measures of erosion as a function of plot-level mangrove cover. (A) Vertical erosion measured with erosion stakes. Values greater than zero indicate erosion; values less than zero indicate accretion. Hurricane Harvey came ashore on 25 August 2017. ANCOVA, Cover $F_{1,26}$ = 8.68, P = 0.007; Date, $F_{1,27}$ = 1.31, P = 0.29. (B) Horizontal erosion measured with erosion stakes. Values greater than zero indicate progradation (i.e., an increase in plot area); values less than zero indicate regression (i.e., a loss of plot area). ANCOVA, Cover $F_{1,26}$ = 9.89, P = 0.004; Date, $F_{1,26}$ = 0.91, P = 0.42. (C) Cumulative area eroded from the plots on three dates (all after Hurricane Harvey). ANCOVA, Cover $F_{1,26}$ = 58.88, P < 0.0001; Date, $F_{2,26}$ = 0.86, P = 0.43. (D) Location (distance from back of the plot) of the levee peak (Distance = 0.21, Cover-0.001Cover^2 + 29, adjusted R^2 = 0.84, P < 0.001) and the front of the plot ("Bank", Distance = 0.16Cover-0.001Cover^2 + 34, adjusted R^2 = 0.84, P < 0.001) in November 2018. All regression model terms had P < 0.05 except Cover^2 for the bank, P = 0.08.

from ~ 6% (60 m^2) to zero as plot-level mangrove cover increased from 11% to 100% percent. Over the two following sampling periods, 7 and 14 months after Hurricane Harvey, the plots gained on average 8 m^2 in area (range −2.4 to 34 m^2), although these differences were not statistically significant, indicating no further erosion and perhaps modest recovery in the aftermath of the hurricane-driven erosion event.

Transects across the plots in November 2018 (6 yr after mangrove cover was manipulated) revealed that the back and middle of each plot was almost flat. The soil rose 10–25 cm to form a levee near the front of each plot, and then dropped 20–30 cm below the elevation of the plot in front of the plot (Appendix S1: Fig. S2). When we established the plots in 2012, they were all approximately the same size. Over the following 6 yr, however, the locations of the levee and of the front ("bank") of the plot had retreated as a function of decreasing mangrove cover, with the greatest retreat (~9 m) in the 0% mangrove plot (Fig. 2D).

Soil strength was highest in the back of the plots for all vegetation types, was greater in mangrove cells than in nonvegetated or marsh cells, and increased across plots as plot-level mangrove cover increased (Fig. 3). We did not have sufficient replication to compare among different plant species within the salt marsh vegetation type, but most of the data points (14 out of 20) were from succulents (*Batis maritima* and *Sarcocornia* sp. rather than *S. alterniflora*).

Discussion

Our results indicated that, at this site, mangroves were more effective at preventing erosion than marsh plants. At a first approximation, all three methods that we used to study geomorphological change in the plots gave the same result: Mangrove loss increased horizontal erosion, especially in the 0% mangrove plot, and led to migration of the levee even in plots without noticeable edge erosion. This result is consistent with modeling results that suggest that mangroves provide greater shoreline protection services than marshes (Doughty et al. 2017). Previous meta-analyses found large overlap in shoreline protection services between marshes and mangroves (Gedan et al. 2011), likely because of confounding effects of wave exposure, bathymetry, wetland width and sediment type. In our study, we were able to hold all these possible confounding effects constant, and found clear evidence that mangroves offer greater protection than salt marshes.

The most likely mechanisms explaining our results are twofold. First, mangroves likely buffer waves more effectively than marsh plants, because of their taller, stiffer stems. We did not measure this mechanism, but it is a fundamental assumption of physical models of how vegetation protects shorelines (Barbier et al. 2013, Doughty et al. 2017). That said, a natural experiment in a depositional environment in Louisiana found no difference in the trapping of hurricane sediment by marsh plants, *S. alterniflora*, and scrub mangroves, *A. germinans* (McKee et al. 2020), and an experimental study in Florida suggested that the most important mechanism by which wetland vegetation reduces erosion is by increasing soil strength, not buffering waves (Silliman et al. 2019). Second, mangrove root systems likely strengthen the soil more effectively than those of marsh plants. In general, soil strength in wetlands increases with root biomass (Wilson et al. 2012, Cahoon et al. 2020). In our plots,

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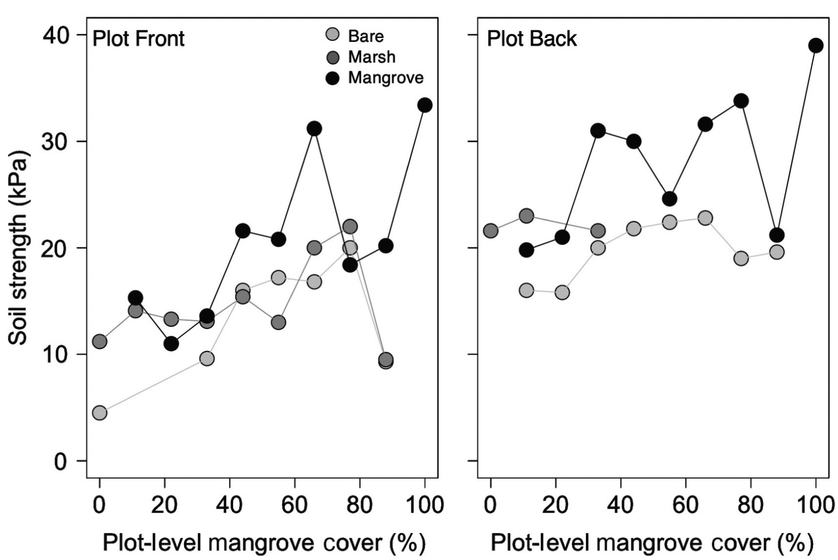

Fig. 3. Strength of surface soils as a function of location (front of plots versus back of plots, ANCOVA, $F_{1,33}$ = 30.4, P < 0.0001), vegetation types ($F_{2,33}$ = 10.3, P = 0.0003, "Bare" = nonvegetated), and plot-level mangrove cover ($F_{1,33}$ = 18.0, P = 0.0002). None of the interaction terms in the analysis were significant.

root biomass was twice as great in cells dominated by mangroves than in cells dominated by marsh plants (Charles et al. 2020). Direct measurements of soil strength also indicated that it was higher (i.e., that soils were less easily eroded) in areas dominated by mangroves than in areas dominated by marsh plants (Fig. 3). Moreover, soil strength increased in each habitat type as the plot-level cover of mangroves increased. This result could in part be due to mangrove roots extending beyond the mangrove canopy and increasing soil strength in adjacent vegetation types. Another possible mechanism for this result is that the increased erodability of soils in plots with low mangrove cover would lead to increased sediment transport through the plots because of wave action. These recently mobilized surface sediments would have lower strength than soils that experienced less transport because of wave action. The fact that the levee at the front of the plots has retreated in plots with lower mangrove cover is clear evidence that sediments are quite mobile in the plots with lower mangrove cover.

Salt marshes can be vegetated with many different plant species. At this site, the most common salt marsh plants were the succulents *Batis maritima* and *Sarcocornia* sp., relatively low-stature plants that have shallower and less extensive root systems than do mangroves at the same site (Charles et al. 2020). Buffering of waves increases with plant stature (Möller 2006, Möller et al. 2014), and soil strength increases with root density (Gedan et al. 2011, Wilson et al. 2012, Silliman et al. 2019), so a salt marsh plant like *S. alterniflora*, with taller stems and a more extensive root system than these succulents, might offer greater shoreline protection services in a given geomorphic setting. When *S. alterniflora* was present in the same location (front or back) of the same plot as succulents, the soil strength in that location was always greater than or equal to that of the succulents, but data were too limited for a formal comparison. *Spartina alterniflora* is slowly increasing in abundance in some of our experimental plots, and may in the future stabilize some of the plots that are currently eroding, but is not yet common enough to have an obvious effect. At the same time, mangrove stature varies geographically, and taller mangroves are also likely to provide more shoreline protection than the scrub mangroves found at this site. Thus, our results should be generalized to sites with markedly different vegetation types only with caution.

The effects of mangroves on plot erosion were strikingly nonlinear when measured using erosion stakes or drone photographs. Even a low cover of mangroves (11%) provided a high amount of shoreline protection compared to the absence of mangroves, with only incremental increases in protection at higher mangrove cover. In contrast, the transects through the plots suggested that the effect of mangroves on intertidal geomorphology was relatively continuous, although even here the relationship was curved (significant quadratic term) rather than a straight line, indicating a greater effect of mangrove cover when mangroves were rare. These results are consistent with previous measurements from these plots that found that the greatest effects of mangroves on the ecosystem were realized before mangroves attained 50% cover (Guo et al. 2017). In particular, as mangrove cover increased from 0% to 44%, average wind speed dropped by two-thirds, but wind speed was hardly affected at all by increases in mangrove cover from 44% to 100% (Guo et al. 2017). If the effects on waves follow the same pattern, the combination of reduced soil strength and increased wave action could explain why erosion was most pronounced in the plot with no mangroves. Similarly, loss of wetland vegetation in Louisiana following the Deepwater Horizon oil spill was nonlinear, with erosion modest at moderate oiling levels and greatest at heavy oiling levels that killed most plants (Lin et al. 2016, Silliman et al. 2016).

Hurricane Harvey did not appear to increase erosion rates in the plots greatly, in contrast to greater erosion following hurricanes elsewhere (Deis et al. 2019). Although there may have been some sediment reworking during the storm, vertical erosion in the 19-month period including Hurricane Harvey was less than in the 24 months previous. Horizontal erosion in the 19-month period including Hurricane Harvey was slightly more than that in the 24 months previous, but not dramatically different. It is likely that erosion in this case was mitigated by the 1.6-m storm surge, which submerged the wetland edge, in combination with the limited fetch at the study site, which limited wave height (Armitage et al. 2020). In both cases, however, erosion over the following 25 months was greatly reduced. Similarly, drone images indicated little additional plot erosion in the year after the hurricane. This could indicate that plot erosion has stabilized—given the spatial scale of the plots and clear edge effects on erosion (Appendix S1: Fig. S1), it is unlikely that they will erode away indefinitely—or it could reflect an increased sediment supply in the area that was mobilized from subtidal habitats by the hurricane (Browning et al. 2019) that is now balancing erosion at the front of the plots.

Our results indicate that even a few mangroves dramatically reduce erosion of intertidal habitats compared to no mangroves. Similarly, the width of coastal habitat affects wave height nonlinearly, with each additional unit of width providing incrementally less additional protection (Barbier et al. 2008). These results need to be replicated in other settings, and in landscape-scale experiments before they are used to guide management decisions. They suggest, however, that mixed-use approaches to mangrove habitats that retain a buffer of mangroves for coastal protection while converting some interior stands to other uses may allow economic development (e.g., shrimp ponds, wood harvesting) without greatly sacrificing coastal protection services. Whether such approaches would retain other important services, such as carbon sequestration or provision of nursery habitat, remains to be addressed.

ACKNOWLEDGMENTS

This research was funded in part by Institutional Grants (NA10OAR4170099, NA14OAR4170102, and NA18OAR4170088) from the Texas Sea Grant College Program from the National Sea Grant Office, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. All views, opinions, findings, conclusions, and recommendations expressed in this material are those of the authors and do not necessarily reflect the opinions of the Texas Sea Grant College Program or the National Oceanic and Atmospheric Administration. Additional funding was provided by the National Science Foundation (DEB-1761411, DEB-1761444, and DEB-1761428), the Gulf Research Program of the National Academies of Sciences, Engineering, and Medicine (award number 2000009307), and the Ecology and Evolutionary Biology program at Texas A&M University. We thank J. Goeke, S. Hall, W. Liu, J. Ruiz, J. Thompson, F. Wu, M. Zimmer, and everyone else who provided assistance in the field. We thank the editor and anonymous reviewers for helpful comments on the manuscript.

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Supporting Information

Additional supporting information may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/ecy.3309/suppinfo

Data Availability Statement

Data are available from the Environmental Data Initiative (Pennings et al. 2021): https://doi.org/10.6073/pasta/1b30a722e2e89177e6a217ad77bad74f.