Does vegetation prevent wave erosion of salt marsh edges?

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This study challenges the paradigm that salt marsh plants prevent lateral wave-induced erosion along wetland edges by binding soil with live roots and clarifies the role of vegetation in protecting the coast. In both laboratory flume studies and controlled field experiments, we show that common salt marsh plants do not significantly mitigate the total amount of erosion along a wetland edge. We found that the soil type is the primary variable that influences the lateral erosion rate and although plants do not directly reduce wetland edge erosion, they may do so indirectly via modification of soil parameters. We conclude that coastal vegetation is best-suited to modify and control sedimentary dynamics in response to gradual phenomena like sea-level rise or tidal forces, but is less well-suited to resist punctuated disturbances at the seaward margin of salt marshes, specifically breaking waves.

coast | hurricane | wave attenuation | wetland

After recent natural disasters such as Hurricane Katrina, the Indian Ocean tsunami, and Cyclone Nargis among others, several studies have purported that wetland vegetation can provide protection from erosion (1–4); however, the acceptance of such claims is far from universal (5–8). Previous studies on the protective capacity of wetland vegetation have focused solely on the ability of above-ground plant stems and leaves to reduce wave forces on the medial surface (9, 10) or retard through-flow underneath the vegetation canopy (11, 12). The restoration of these ecosystems has become a billion dollar industry (13), yet no studies have addressed the primary mechanism that causes the direct physical erosion of wetlands, a lateral erosion of the land-water edge by waves (14). Here, we show that the traditional paradigm needs to be revised. Salt marsh plants do not directly prevent all types of wave-induced erosion, in particular, erosion of the wetland edge.

To investigate erosion, we simulated a continuous, linear cliff-like marsh edge by placing several extracted marsh samples, side by side, into a wave flume. To correctly scale and quantify the relevant processes, we focused on the effect of a single plant on erosion. Samples were contained in square cross-section boxes, with 1 open side that was exposed to wave impact (see *Materials and Methods*). The waves simulated a windy, 18-h period in an estuary with significant breaking wave heights of 7.38 cm impacting the edge and a run-up of several tens of cm (a subset of the possible conditions that one may encounter in the field). We tested for differences in erosion rates between samples with plants and without plants, for differences among plant species, and for differences in soil types. We also recorded erosion along a steeply sloping marsh edge in the field, as it converted into a vertical edge over 462 days. Wave heights during this period generally corresponded with the conditions tested in the flume, yet exceeded flume conditions 10% of the time and included the passing of Hurricane Humberto within 50 km and Hurricane Ike within 10 km, and several winter storms.

Results

In a crossed 2-factor experimental design, the presence of plants and their live roots made no statistically significant difference to the amount of erosion in the wave flume portion of the study ($P = 0.569$, where P is measure of significance in ANOVA tests; see Tables S1–S5 for ANOVA and statistical summaries), although mean erosion was higher when plants were present (Fig. 1*A*). We visually observed that the roots moved when acted on by waves and that this movement released sediment. This phenomenon was also observed in the field (see below) and by Coops et al. (15), which is to the best of our knowledge the only other flume study on the effect of vegetation-wave interactions on soil erosion. Erosion appeared to be most prominent during the draw-down (backwash) of the wave cycle, rather than during the swash of an oncoming wave.

In this same experiment, we found that both vegetated and unvegetated samples from the marsh interior eroded much more quickly than those from the marsh edge ($P < 0.001$) (Fig. 1*B*). Although organic matter content of marsh edge samples was not significantly different from that of interior samples ($P = 0.609$), the marsh edge did have a significantly lower percentage of large detrital debris ($P = 0.012$); suggesting that there may be 2 categories of organic matter in terms of erosion, organic material that is humic and finely grained (reducing wave-induced erosion) and "coarse" organic material that includes roots, chunks of decaying stalks, or other large plant debris (enhancing wave-induced erosion). Similarly, soil strength is known to vary as a function of the size of embedded plant material (16).

We followed up on these initial results with 2 additional flume experiments. In the first, differences between *Spartina alterniflora* (extensive roots and prolific on marsh edges in areas exposed to moderate wave energy) and *Batis maritima* (weak, brittle root structure, and found in sheltered or more elevated areas) did not alter the observed erosion rates ($P = 0.978$) (Fig. 1*C*). In the second, mean erosion varied by a factor of 100 between restored marsh and natural marsh samples (log-transformed $P = 0.008$) (Fig. 1*D*). In general, the restored samples contained more sand and were less cohesive than the natural marsh cores. These results further support the contention that soil type is the primary variable influencing lateral erosion rates in coastal wetlands like those studied here, more significant than the amounts or types of vegetation present.

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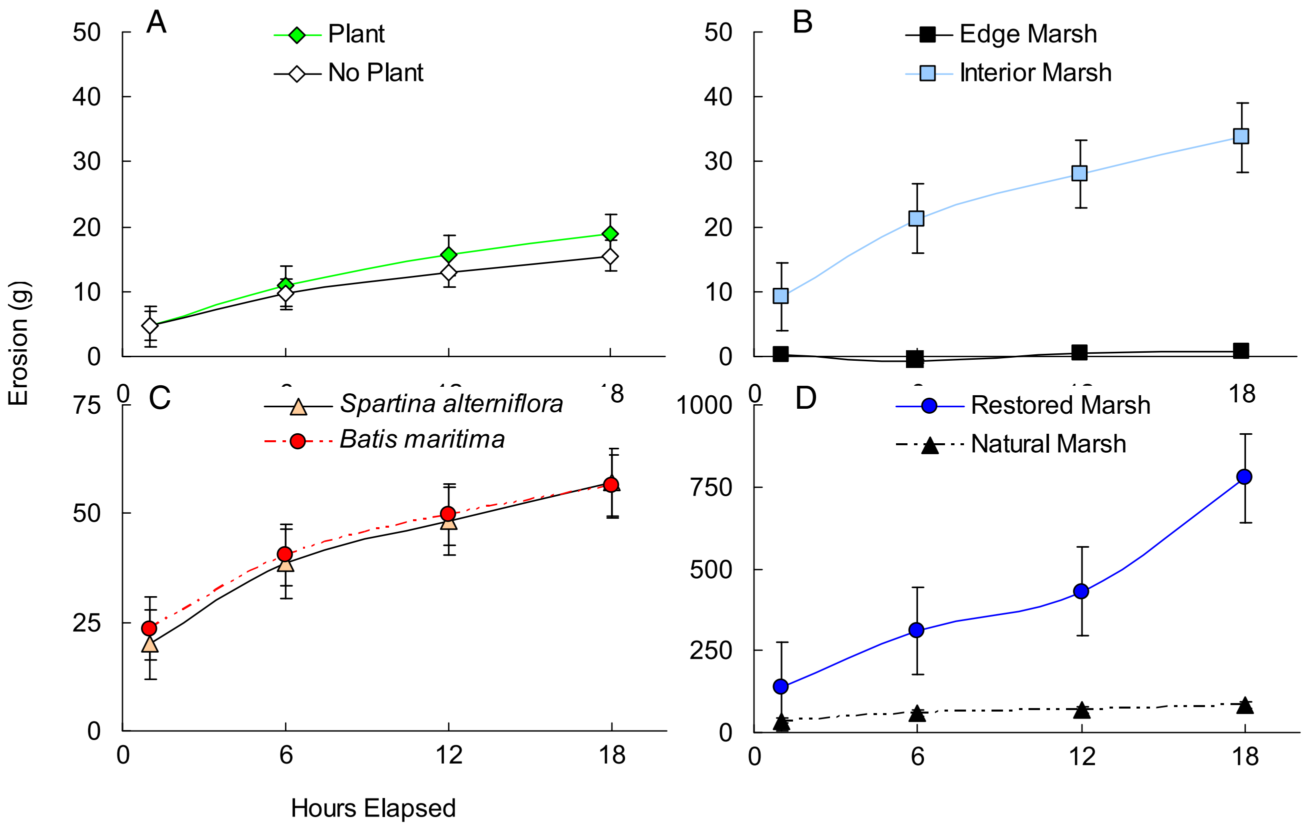

Fig. 1. Laboratory flume results. Erosion rates for plant versus no plant samples (*A*), marsh edge versus marsh interior samples (*B*), *S. alterniflora* versus *B. maritima* samples (*C*), and restored versus natural marsh samples (*D*). Data points represent the means, and error bars represent the standard errors.

For all samples in the flume experiments, we found that bulk density provided the best linear predictor for erosion ($r^2 = 0.721$, $P < 0.001$), while the percentage of organic matter ($r^2 = 0.390$, $P < 0.001$), the percentage of water ($r^2 = 0.578$, $P < 0.001$), and the percentage of coarse particles ($r^2 = 0.633$, $P < 0.001$) were also important predictors (Fig. 2). There was no apparent relationship between erosion rates and the percentage of silt or finer particles ($r^2 = 0.012$, $P = 0.544$), or the percentage of root cover ($r^2 = 0.018$, $P = 0.466$). When each parameter was added in a stepwise fashion to an overall regression model, they described 72.1%, 1.1%, 0.2%, 12.3%, 0.4%, and 0.1%, respectively, of the variation. These results are driven by the presence of sand, i.e., bulk density and percentage of coarse particles, particularly in the restored marsh samples. If the restored samples are removed from the analysis, then each respective parameter only described 21.1%, 1.9%, 24%, 1.1%, 1.9%, and 2.8% of the variation for the remaining samples. The findings suggest a threshold bulk density value of ≈ 0.9 g/cm^3 given the study wave conditions, above which erosion is strongly driven by the presence of sandy sediments. Below this threshold, erosion is much less rapid and is more related to the presence of coarse versus fine organic detritus (which is likely responsible for the remaining bulk density, percentage of water, and increasing importance of root cover variation that this second stepwise model describes relative to the first, but also was detected as the significant difference in the amount of large detritus debris between the edge marsh versus interior marsh described previously).

In a field experiment conducted at the top of an immediate marsh edge as a small cliff began to form, we found no significant difference in the amount of erosion between vegetated and unvegetated locations ($P = 0.3291$) (Fig. 3). Rather, all of the erosion appeared to be related to a spatial gradient along the shoreline, because the east-to-west grouping of experimental blocks showed significant differences ($P < 0.001$) and the east-to-west replicated plots showed differences when tested over a subsampling error term ($P < 0.001$). Moreover, erosion in the plots matched the "parabolic" shore outline with a quadratic trend ($P < 0.001$). This erosion gradient was likely caused by the interaction of wave energy, microtopography, and bathymetry at the sites and subsequent wave refraction and attenuation before striking the marsh edge (i.e., those sites with the greatest elevation loss were exposed to the greatest wave energy levels).

Although the physical presence of plants does not appear to make a significant difference in reducing marsh edge erosion, plants may have an indirect effect. For the samples in the flume experiment, the percentage of organic matter was significantly and negatively correlated with bulk density ($r = -0.788$, $P < 0.001$) and the percentage of very coarse sand or coarser particles ($r = -0.514$, $P = 0.003$). It was also significantly and positively correlated with the percentage of water ($r = 0.876$, $P < 0.001$).

Discussion

Although the inorganic mineral content is the most important influence on near-surface soil bulk density in salt marshes (17, 18), the input of organic detritus by plants lowers the bulk density (19). Moreover, plants alter the hydrodynamics and subsequently the spatial and temporal variability of inorganic sediment deposition throughout the wetland (e.g., refs. 20 and 21). As plants proliferate, detritus and finer-grained sediments become incorporated into the soil matrix through accretion, and soil becomes less dense, less coarse, and more cohesive. As our study shows, these sedimentary properties are associated with resistance to

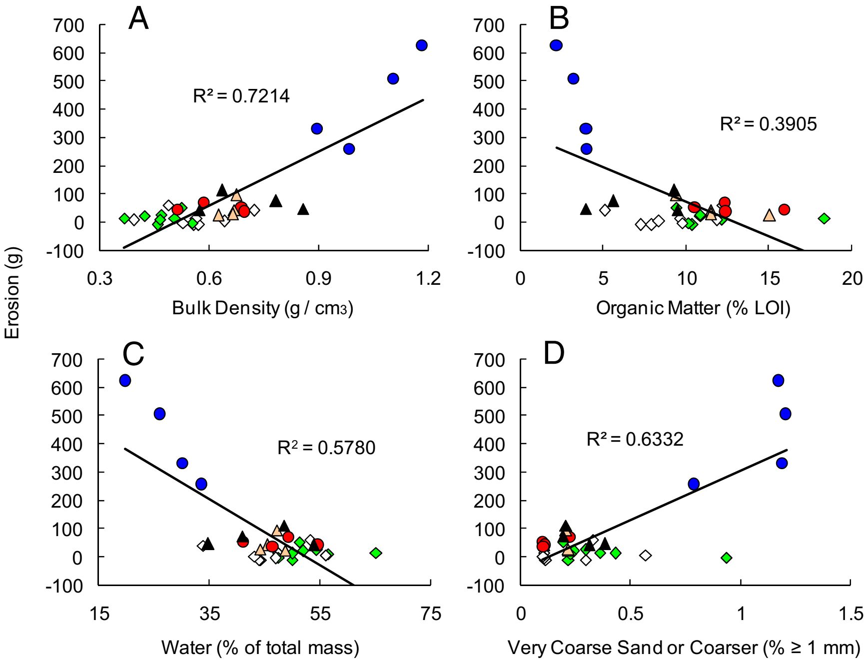

Fig. 2. Relationships between erosion and bulk density (*A*), percentage of organic matter (*B*), percentage water (*C*), and percentage of coarse particles (*D*). Data points represent sample replicates. Marker colors are the same as for Fig. 1.

lateral wave-induced erosion. Thus, plants may not directly reduce erosion on cliff-like edges by binding the soil with their live roots, but may do so indirectly by modifying soil properties before cliff formation. Indeed, coastal plants can build coastal landforms through a coupled process of ecological succession and sedimentary accretion (13, 22).

We conclude that coastal vegetation is best suited to modify and control sedimentary dynamics in response to gradual phenomena like sea-level rise or tidal forces (23, 24), but is less well-suited to resist punctuated disturbances (25, 26) at the seaward margin of salt marshes, specifically breaking waves. In addition, the soil type (27) and geographical setting (28) are the most important factors to consider when comparing erosion rates among sites. From this perspective, coastal vegetation management should not solely focus on erosion prevention and substrate stabilization during extreme events, rather management should move toward the goal of landscape-scale sedimentary modification over the long term.

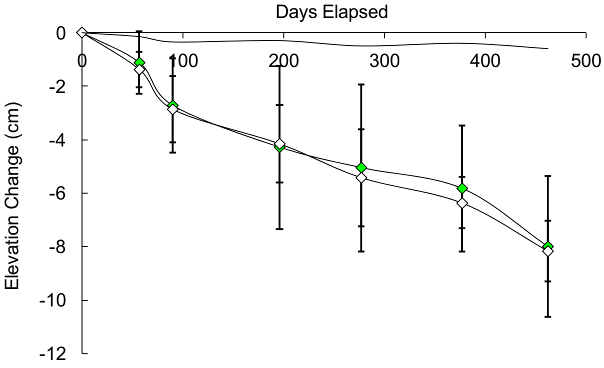

Fig. 3. Field experiment results. Elevation changes over time for control plots (plants present) and removal treatment plots (no plants present). Data points represent the means and errors bars the standard error. Marker colors are the same as for Fig. 1. The solid line just below *x* axis represents root zone compaction and expansion.

Our results also challenge the idea that coastal vegetation always provides protection. A priori, it is critical to distinguish between lateral (marsh edge) and medial (marsh interior) erosion, because the interaction between waves and the substrate is very different in each case (direct impact force in the case of the former, and attenuated orbital wave currents at the bed in the latter). Existing evidence for the medial erosion process suggests that above-ground portions of a plant attenuate orbital wave currents within relatively dense vegetated salt marshes, but it has also been shown in steady-flow conditions that these above-ground portions can result in surface scouring in adjacent locations that are less dense (29, 30). Moreover, it has been hypothesized that these above-ground portions can actually trigger the formation of the vertical cliff-like edge at the land–water interface (31, 32), as a result of relative differences in landward versus seaward flow velocities and wave stresses on either side of the edge (33). Waves can also typically force large block detachment, yet it is currently unknown whether such mass wasting events are likely to be mediated by plant roots.

The wave-height-to-water-depth ratio determines where waves break and the resulting cross-shore location of possible cliff formation. Raising the water level during an extreme event such as a hurricane submerges the vegetation and pushes this location landward. The threshold for erosion at preexisting marsh cliffs is very low, below the significant wave heights of 7.38 cm seen in this study, and the roots may even act as an erosive agent under the impact of breaking waves. Furthermore, roots have little effect on binding soil at sites that are converting from slopes to cliffs. Because shear stress thresholds are certainly exceeded during more extreme events (34), plants likely do not reduce soil erosion with their roots during these events either, at the location where the waves break. However, because their above-ground portions effectively reduce the wave height/water depth ratio by generating friction at the lower reaches of the water column, they may push this wave-breaking location further seaward, thereby reducing wave energy (and wave-induced bed shear stress) on landward-lying areas of the marsh. In contrast, removing vegetation shifts this location landward. However, it is important to note that even when waves are attenuated, the longer-period storm surge can still penetrate diffuse vegetative structures and backfill tidal distributaries.

Our empirical findings show that salt marsh vegetation does not reduce lateral erosion on wetland edges. Thus, we recommend that efforts toward salt marsh restoration, a multibillion dollar endeavor, should place the highest priority on obtaining the correct soil rather than on planting vegetation, in areas that are subject to high wave energy. Of secondary importance, vegetation should be used modify the soil, such that it may become more resistant to erosion over the long term.

Materials and Methods

Core Samples. We extracted samples directly from the salt marsh by using a custom stainless-steel coring device. The coring device used to obtain samples had a total length of 30.48 cm and square internal cross-section width of 10.16 cm. It was carefully inserted into the marsh surface to avoid sample compaction, and an intact core sample was removed. When samples contained plants, we placed their above-ground portions through the corer, and then slowly drove the corer through the sediment and roots. The resulting core samples were cohesive and roots were cleanly sliced. To account for the fact that the coring size and method isolates individual plants from a bank, we also present corroborative results from the field to show that the results are consistent regardless of whether one investigates individuals or groupings of plants (see below). Core samples were carefully extracted and placed directly into a fitted, stiff plastic sleeve with an opening on one longitudinal side and the top. No core compaction was observed during this process. Core samples were taken from 3 salt marshes on the bay side of Galveston Island: Sportsman's Road for the first experiment (29.254756, latitude; −94.919134, longitude), Old Port Industrial Boulevard for the second experiment (29.298942, −94.827504), and Galveston Island State Park for the third (29.200571, −94.966418).

Core samples were then placed into a single chamber within a 4-chambered, Plexiglas box. The box was then placed at one end of a wave flume. The box allowed 4 separate samples to be subjected to identical conditions during the experiment. This experimental design enabled the use of blocking during statistical tests of difference.

Wave Conditions. We aimed to simulate conditions during a minor storm event in an estuarine bay, with typical wave reflection at the water–marsh edge interface. Regular waves were produced by a small motor-run wave paddle at the far end of the flume (Dayton Adjustable Speed Drive, model 6K119; Dayton Electronic Manufacturing Company). The wave flume was 718 cm long, 39 cm wide, and 40 cm tall (Fig. S1). The water level was maintained at 19 cm. The water level intersected the core samples at their midpoint (i.e., ≈15 cm below the marsh surface). Water salinity was 12 ppt.

Following the method outlined in ref. 10, we used a camera to film the waves as they passed vertically oriented measuring sticks placed at a distance of 458 cm and 4 cm away from the interface with the water–marsh edge interface, then we reviewed the digital film and recorded water level as it passed each stick at a frequency of 4 hz. We then used a FFT algorithm to derive significant wave heights and total spectral energy, J/m^2. A second algorithm found individual wave heights. Waves became more irregular near the water-to-marsh edge interface because of reflection (Fig. S2). Average wave heights were 5.09 cm at 458 cm away from the interface and 4.71 cm at 4 cm away from the interface, yet there was much more variability at the 4-cm distance (i.e., significant wave heights were actually larger at the 4-cm distance than at the 458-cm distance, 7.38 cm versus 6.46 cm). At the interface itself, wave run-up was common and extended to the tops of the cores (tens of cm in swash height).

All core samples were subjected to waves for a total of 18 h. Samples were initially weighed on a balance before being placed into the wave flume. They were then taken out of the flume and reweighed at the following intervals of the test: 1, 6, 12, and 18 h. Weight loss was used as the measure of erosion.

Flume Study Statistical Approach. We first sought to test the relative effects of soil with plants versus soil without plants on erosion. We placed a single core sample from each of 4 treatments into the side-by-side chambers in the box: marsh edge with a *S. alterniflora* plant present, marsh edge without a plant present, marsh interior with a plant present, and marsh interior without a plant present. This test was replicated 4 times under identical wave conditions, for a total of 16 cores. A 2-factor randomized block ANOVA was conducted with treatments as plant versus no plant crossed by edge versus interior, with each box as a block (Table S1). SAS 9.1.3 software was used for all ANOVA tests of difference (SAS Institute).

Second, we sought to test the relative effect of 2 plant species on erosion. *S. alterniflora* is known for its extensive roots and below-ground production and is often prolific on marsh edges in areas exposed to moderate wave energy. *B. maritima* has a weak, brittle root structure, and is often found in sheltered or more elevated areas. We placed 2 replicate core samples of each species into the box. All core samples were taken from a relatively sheltered site. This test was replicated twice, for a total of 8 cores. A single-factor generalized block ANOVA was conducted with the treatments as *S. alterniflora* versus *B. maritima*, with each box as a block.

Third, we sought to test whether restored marsh soils erode faster than natural marsh soils. Core samples were collected with *S. alterniflora* present, from a restored site and an adjacent natural site. We placed 2 replicate core samples from each site into the box. This test was replicated twice, for a total of 8 cores. A single-factor generalized block ANOVA was conducted with the treatments as restored versus natural marshes, with each box as a block.

Sediment Properties. The sediment properties of each of the 32 marsh core samples were also investigated. At each field coring site, we extracted 1 surface sediment sample immediately adjacent to the core, halfway down the cored hole. These samples were bagged and transported to the laboratory.

In the laboratory, each sample was weighed in a dish of known volume, dried in an oven at 65 °C, and reweighed at its dry weight to obtain a measure of bulk density (g/cm^3). The percentage of water in samples was calculated as $(1 - \text{dry weight/wet weight}) \times 100$. Each sample was then heated in a muffle furnace for 18 h at 440 °C and reweighed to obtain the percentage of organic matter lost on ignition. Each sample was then sieved by using sieves ranging from ≥ 2 mm to < 15.6 μm (from gravel granules to fine silt and finer). Each subset of sieved particles was weighed and standardized by the total weight of the sample. This procedure yielded the percentage of each sample that was of a given grain size. The percentage of roots was separately estimated by examining the longitudinal side and bottom cross-section of each core sample, visually estimating the percentage cover of roots in each, and averaging the 2 estimates.

Sediment physical parameters were linearly regressed against the erosion rate measurements from the wave flume portion of the study (Table S2). Generally, linear relationships provided the lowest R^2 and best statistical fits for the parameters. Although some data visually appear to follow an exponential or polynomial curve, these relationships did not provide a better statistical fit, nor did a log transformation of the data. Because much of the trend in these regressions visually appeared to be a result of the restored marsh core response to erosion, we also removed these 4 samples and conducted the linear regression model on the remaining 28 samples without them. All R^2 and P values for the regression analyses are reported in these contexts, i.e., they are from regression models with a single independent variable. Stepwise linear regression was also conducted (both with the restored samples and without them), where all of the parameters were included into a single regression model, i.e., assuming 6 variables (Table S3). In these cases, we only state the percentage of variation (derived from R^2 values) that can be attributed to each parameter. SPSS 15 software was used for all regressions.

We also tested whether the percentage of organic matter in each sample was correlated with the other sediment parameters, using Fisher's exact test, with 2 tails (Table S4). SPSS 15 software was used for all correlations.

Field Experiments. In addition to the wave flume study, we conducted a controlled field experiment to assess the importance of vegetation in reducing marsh edge erosion. We established 4 stations along a steeply sloping *S. alterniflora* marsh edge at Jumbile Cove on Galveston Island, Texas. The 4 stations were located along an open bay with a fetch of ≈4 km; lateral erosion rates in this area can easily exceed 1 m per year (35). The stations were distributed along this relatively straight bay front, at the same elevation. At the beginning of the experiment, there was a linear slope to the bottom sediment in the cross-shore direction at each station. The microtopography of the bottom slopes was slightly heterogeneous, and we could visually see that when water levels were low (subsequent to experimental set-up), the water line would demarcate the relief such that the slope on stations 2 and 3 were slightly less and extended slightly further out into the bay, given the same elevation contour. We refer to this visual appearance as the parabolic shape of the shoreline, yet it is only categorical, i.e., the stations at locations 2 and 3 along the bay front are different from stations 1 and 4. On top of these bottom slopes, there was a transition of nearly 100% vegetation into 100% open water over a span of 2 m. All stations were set up at the cross-shore location where the 100% vegetation interface began, at the beginning of the experiment.

The average wave height seaward was 2 cm, as calculated following the methods of ref. 36. The wave conditions that we generated in the laboratory flume were exceeded ≈10% of the time at the field site, primarily as cold fronts blew winds across the 3-km fetch and generated waves, but also during Hurricane Humberto and Hurricane Ike (Fig. S3).

We placed a rod sediment elevation table (RSET) at each station to serve as a permanent elevation benchmark, on which the surface of the marsh edge was recorded (37). To establish this benchmark, a 10.16-cm diameter hole was dug and a 50-cm-long by 10.16-cm-diameter PVC pipe was inserted into the hole. Coupled stainless-steel rods (1.43 cm diameter) were then driven into the ground through the center of the PVC pipe, a connector rod was attached to the top rod, quick-drying concrete was poured into the PVC pipe, and a survey marker was set in the concrete, following U.S. Geological Survey methods (37). The marsh surface around these benchmarks can be surveyed and thus reflect total elevation change (integrating changes in elevation caused by deep subsidence to the bottom of the rods, root zone compaction/expansion, surface accretion, and surface erosion).

To separately record compaction and expansion in the root zones near each RSET station, we inserted 40-cm-long acrylic tubes into the surface, down to a depth of 30 cm. Any recorded difference between the elevation change at the surface and the elevation change at the bottom/top of a tube reflects compaction/expansion in the root zone. Several of these tubes became dislodged at different time periods as the erosion at the site was severe, so we only present an average value across the entire site for those tubes that survived from one sampling period to the next.

We also established G200 Feldspar clay marker horizons for the purpose of recording accretion. Any potential differences between elevation change at the surface and the amount of accretion above the marker horizon would have been attributed to accretion, but all of these marker horizons washed away because of the large amount of erosion at the site.

We then established 2 × 2-m plots on each side of the 4 stations (8 total), in the alongshore direction. We randomly assigned 1 of 2 treatments to either side of each station, so that each station represented both treatments: unvegetated (removal) and vegetated (control). We conducted side-by-side plots of unvegetated and vegetated conditions so that both treatments would experience nearly-identical wave conditions at each station. The removal plots were repeatedly inundated with 0.16% Imazapyr and 1.00% Glyphosate herbicide over the course of the experiment (Ortho GroundClear; Scotts Miracle-Gro). Within 30 days, all vegetation appeared dead, but dead stalks remained and dead roots could be seen at the surface. After 60 days, the percentage cover of all removal plots was 0% with very few roots remaining (dead materials appeared to have been removed by tidal and storm processes). The control plots were not manipulated and percentage cover remained nearly 100%.

During each sampling visit, we recorded the erosion of the marsh surface at 8 subsampled points within each plot. Records were taken at days 0, 57, 90, 196, 277, 377, and 462.

A single-factor randomized block ANOVA was conducted with the treatments as vegetated marsh edge versus unvegetated marsh edge, with each station as a block (Table S5). The 8 recorded points within a plot at a given sampling date were treated as subsamples; the plots were the replicates. Accordingly, tests of difference for the removal vs. control treatment and the blocking factor were conducted over the replicate experimental error term, while this replicate experimental error term was tested over the subsampling error term to determine whether replicate plots also differed. A posthoc contrast was also conducted to determine whether there was a quadratic spatial trend that followed the parabolic outline of the shore. Root zone compaction and expansion data are presented as a single average value with no statistical analysis, as mentioned above because of the large amount of erosion at the site.

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