Received: 31 August 2020 | Revised: 12 February 2021 | Accepted: 19 February 2021

DOI: 10.1002/esp.5108

RESEARCH ARTICLE

ESPL WILEY

Brackish marshes erode twice as fast as saline marshes in the Mississippi Delta region

Kendall Valentine[1,2] | Grayton Bruno[1] | Tracy Elsey-Quirk[1] | Giulio Mariotti[1,3]

[1]Department of Oceanography and Coastal Sciences, College of the Coast and Environment, Louisiana State University, Baton Rouge, Louisiana, USA

[2]Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, USA

[3]Center for Computation and Technology, Louisiana State University, Baton Rouge, Louisiana, USA

Correspondence
Kendall Valentine, Department of Oceanography and Coastal Sciences, College of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA.
Email: kvalen7@lsu.edu; kvalentine@vims.edu

Funding information
Gulf of Mexico Research Initiative; Louisiana Board of Regents

Abstract

Marsh soil properties vary drastically across estuarine salinity gradients, which can affect soil strength and, consequently, marsh edge erodibility. Here, we quantify how marsh erosion differs between saline and brackish marshes of the Mississippi Delta. We analyzed long-term (1932–2015) maps of marsh loss and developed an algorithm to distinguish edge erosion from interior loss. We found that the edge erosion rate remains nearly constant at decadal timescales, whereas interior loss varies by more than 100%. On average, roughly half of marsh loss can be attributed to edge erosion, the other half to interior loss. Based on data from 42 cores, brackish marsh soils had a lower bulk density (0.17 vs. 0.27 g/cm^3), a higher organic content (43% vs. 26%), a lower shear strength (2.0 vs. 2.5 kPa), and a lower shear strength in the root layer (13.8 vs. 20.7 kPa) than saline marsh soils. We then modified an existing marsh edge erosion model by including a salinity-dependent erodibility. By calibrating the erodibility with the observed retreat rates, we found that the brackish marsh is two to three times more erodible than the saline marshes. Overall, this model advances the ability to simulate estuarine systems as a whole, thus transcending the salinity boundaries often used in compartmentalized marsh models.

KEYWORDS

ecogeomorphology, estuarine, Louisiana, marsh loss, modeling

1 | INTRODUCTION

Coastal wetlands are one of the most valuable ecosystems in the world; they provide habitat for wildlife, protect coastal communities from storms (Möller et al., 2014), reduce nutrient loads to coastal waters (Deegan et al., 2012), and sequester carbon from the atmosphere (Chmura et al., 2003). Alarmingly, an estimated 30%–50% of wetlands have been lost globally (Finlayson, 2012; Hu et al., 2017), and this trend is predicted to continue (Roman, 2017). In coastal areas, sea-level rise and waves can contribute to wetland loss, which can be parsed into two main modes: lateral erosion of the marsh edge and interior marsh loss. As these two modes of land loss are driven by distinct processes, it is important to understand which is dominant in a given area in order to guide marsh restoration and protection.

Many marshes of the Mississippi River delta (Louisiana, USA) and Blackwater Bay (Maryland, USA) are experiencing interior loss associated with low sediment supply, high geologic subsidence rates, and high sea-level rise rates. These conditions lead to waterlogging of the marsh interior, which causes anaerobic conditions and high porewater sulfide concentrations, eventually leading to plant death (DeLaune et al., 1994; Kirwan et al., 2008; Reed, 1995; Reed & Cahoon, 1992; Scaife et al., 1983; Schepers et al., 2017; Wrayf et al., 1995). However, these mechanisms tend to be site-specific and not entirely predictable, making them difficult to implement in numerical models of marsh evolution at the landscape scale.

Edge erosion by wave impact is ubiquitous across marshes, given adequate fetch (Mariotti & Fagherazzi, 2010; Marani et al., 2011; Schwimmer, 2001; Stevenson et al., 1985). Other processes such as currents, soil creep (Mariotti et al., 2019), and biological processes such as crab burrows (Hughes et al., 2009) can also affect the lateral erosion, but are typically an order of magnitude smaller than the effect of waves. Worldwide marsh edge retreat rates have been shown to be proportional to wave energy (Leonardi et al., 2016), highlighting the dominant role of waves in lateral erosion processes. Local conditions such as sediment composition and vegetation properties affect erosion rates (Feagin et al., 2009) and are commonly combined and parameterized in marsh erosion models as an erodibility coefficient (Leonardi et al., 2016). This coefficient is often assumed constant over an entire marsh or model domain (Mariotti, 2020), and is typically used as a calibration parameter. This coefficient can be highly site-specific and remains one of the poorest constrained aspects, hampering the ability to predict marsh loss.

For models of marsh loss, marshes are often depicted as having similar sediment and vegetation characteristics. Only a few studies have examined the role of plant species or the presence of clonal patches of a single species, which show that spatially variable plant and soil properties can be important for predicting marsh loss (Bernik et al., 2018; Ford et al., 2016; Wang et al., 2017). Along estuaries, however, large heterogeneities caused by the presence of salinity gradients result in distinct plant zonation and differences in biogeochemical cycling and soil properties (Dausse et al., 2012, Silvestri et al., 2005; and citations therein).

Vegetation is crucial for the stabilization of marsh edges (Le Hir et al., 2007; Turner, 2011) and contributes to accretion, which maintains marsh elevation above sea level (Silliman et al., 2019). The plant root network provides strength to the soil depending on the physical structure and extent of the roots (Gillen et al., 2020; Wang et al., 2017). Along salinity gradients in estuaries, plant species composition, soil structure, and biogeochemical processes, all of which can affect erodibility, tend to vary. For example, fresh marshes have been found to be weaker than salt marshes, thus leading to enhanced erosion (Gillen et al., 2020; Howes et al., 2010). Plant stress, such as that due to salinity or salinity changes, can create differences in root structure for the same species of plant, potentially also changing the erodibility of the marsh edge (McHugh & Dighton, 2004).

In this study, we explore how erosion varies across marshes with different salinities within an estuary. We present a model that explores marsh edge loss as a function of salinity zone, as supported by field measurements. By applying this model to the rapidly eroding Barataria and Terrebonne basins in Louisiana, this study improves predictions of marsh erosion dynamics across different environments and salinity regimes.

2 | METHODS

2.1 | Case study: coastal Louisiana

The Mississippi River delta region has been rapidly losing land; since the 1930s, 5200 km^2 of coastal wetlands have been lost, accounting for ~80% of the wetland losses within the continental USA (Couvillion et al., 2011, 2017). The rapid land loss in this region has been attributed to a combination of sea-level rise and subsidence (González & Tornqvist, 2006; Jankowski et al., 2017)—causes of land loss that are found throughout the world but are exacerbated in this region due to exceptionally high rates of subsidence (Nienhuis et al., 2017), fluid withdrawal (Yuill et al., 2009), the leveeing of the Mississippi river, which disconnects the river water and sediment from the marshes (Kesel, 1989), the extensive canal networks (Scaife et al., 1983; Turner & McClenachan, 2018), and oil spills (McClenachan et al., 2013).

The Louisiana coastline is home to two million residents and houses $3.6 billion in infrastructure (Barnes & Virgets, 2017). Moreover, these regions support trade, playing significant roles in the oil and gas industry, and in fisheries and transportation of goods; and they provide storm surge protection for the large port city of New Orleans, Louisiana (Coastal Protection and Restoration Authority of Louisiana [CPRA], 2017). The total economic benefit of the Mississippi River delta region to the USA is valued at $330 billion to $1.3 trillion per year (CPRA, 2017). Because of the economic and cultural importance of coastal Louisiana, there have been great efforts to understand and mitigate land loss through coastal restoration and protection projects, including large-scale sediment diversions and marsh creation projects.

The LaFourche delta lobe, active ~2500–800 BP, formed Barataria and Terrebonne basins (Roberts, 1997). This delta lobe was abandoned, leaving these interdistributary basins with associated low-lying marshes and microtidal bays located to the west of the outlet of the Mississippi River (Figure 1). Now in the declining phase of the delta cycle, these basins have no major sediment source and are rapidly being reworked. Winds typically blow either from the south (fair weather) or the north (passage of cold fronts), creating water-level set up or set down (Perez et al., 2000; Valentine & Mariotti, 2019). These interdistributary basins are the most rapidly eroding areas of coastal Louisiana (Couvillion et al., 2017; Karimpour et al., 2013), likely due to large subsidence rates and minimal sediment inputs (Blum & Roberts, 2009; Day et al., 2007; Morton et al., 2002).

Both marsh edge erosion and interior marsh loss play important roles in Louisiana's land loss, and understanding the relative importance of these processes can provide cost-effective insight for restoration projects. Additionally, both estuaries host a range of salinity zones, with fresh marshes in the northern reaches grading to saline marshes in the south. These salinity differences may also affect the dominant mechanism of marsh erosion (i.e., via interior loss or edge erosion), and therefore a better understanding of these differences is necessary to inform the appropriate restoration and protection measures.

2.2 | Historical mapping and image analysis

We classified Barataria and Terrebonne basins into land and water categories following the procedure outlined in Valentine and Mariotti (2019). Marsh extent in 1932 was determined using historical survey data, in 1956 using aerial photography (National Wetlands Inventory), and in 1988 and 2015 using Landsat Imagery, with a resolution of 30 m by 30 m.

The amount of land lost from 1932 to 2015 was classified into two drivers of marsh loss in coastal Louisiana: edge erosion from waves and interior marsh loss (Penland et al., 2000). Edge erosion is the more straightforward and identifiable marsh loss mechanism, where waves impact the marsh edge and cause lateral retreat. Interior marsh loss, on the other hand, is a combination of processes that include subsidence, pond formation, man-made land change, and expansion of previous interior loss by wind waves. We classified the land lost between 1932 and 2015 by creating a buffer around the marsh edge from the 1932 dataset. The buffer was set at 420 m (approximately 5 m/yr loss between 1932 and 2015) from the marsh edge towards the interior. This represents an upper bound on edge erosion, as most estimates from these basins estimate a rate of ~2–5 m/yr (Allison et al., 2017; Sapkota & White, 2019). Additionally, for the marsh edge to retreat laterally via wave attack, we assumed that there was a minimum fetch (300 m, Ortiz et al., 2017) for waves to gain enough energy to cause erosion. Therefore, if the fetch was 300 m or less, the adjacent marsh edge was not given a buffer and any erosion that occurred in these locations was considered interior loss.

Marsh classification maps, as determined by vegetation, were downloaded from the CIMS website (https://cims.coastal.louisiana.gov/Viewer/GISDownload.aspx) and were digitized into three marsh categories: saline, brackish, and fresh (intermediate marshes were combined with fresh marshes). Individual maps of marsh classification were processed in this way for data from 1948, 1968, 1978, 1988, 1997, 2001, 2007, and 2013. From these data, we created a median marsh classification map for both Barataria and Terrebonne basins. First, the median value for marsh classification was determined, and then the maps were smoothed using a Weiner filter to create an overall median marsh classification map. For analysis, we analyzed the areas that were considered brackish or saline; fresh marshes were omitted from this study.

2.3 | Field sampling

We collected a total of 24 cores (35 cm long, 8 cm diameter) in saline marshes (four paired sites) and 18 cores (35 cm long, 8 cm diameter) in brackish marshes (three paired sites) in Barataria Bay, approximately 1–3 m from the marsh edge (Figure 1). Cores were analyzed for bulk density, and total organic matter through loss on ignition (LOI). Each core was sliced into 5-cm sections. A sub-core (5 cm long, 1.5 cm diameter) of each section was used to determine dry bulk density and LOI. LOI was determined by placing the samples in a muffler furnace at 550°C for 4 h (Dean, 1974). At each core location, we collected five profiles of soil shear strength using a Humbolt shear vane (all profiles approximately 1 m from the marsh edge). We also collected elevation profiles using an RTK-GPS (Leica GS14 GNSS).

2.4 | Wind wave model

We modified the marsh erosion model of Valentine and Mariotti (2019). This model uses a semiempirical formulation for wind waves based on wind speed, water depth, and fetch (Young & Verhagen, 1996) and was improved to allow for asymmetric erosion due to wind direction. The asymmetry in edge erosion has been associated with the correlation between wind direction and water level in coastal Louisiana (Valentine & Mariotti, 2019). When wind blows from the north the levels are low, and thus the waves impact the more erodible soils beneath the root mat. The opposite takes place when the wind comes from the south. Thus the model allows for the edge to be more erodible during northerly winds compared to southerly winds.

Using the height-correct wind from Southwest Pass station (NDBC Station BURL1) (Mariotti et al., 2018), wave height (Hs) and wave period (Tp) were calculated for each cell adjacent to a body of water assuming a depth of 0.8 m (Valentine & Mariotti, 2019). Wave power P is then calculated for each edge cell as

$$P = \frac{1}{16}\rho g H_s{}^2 c_g, \tag{1}$$

where ρ is water density, g is the gravitational constant, and c_g is the group velocity of the waves (calculated using Tp and the water depth). All wave power (from any direction) impacting a given edge cell was summed. To calculate the erosion rate (E), we assumed the relationship

$$E = \alpha P, \tag{2}$$

where α is an erodibility coefficient (Leonardi et al., 2016). Marsh edge cells were eroded using a probabilistic method (Mariotti & Canestrelli, 2017). Importantly, the erodibility coefficient (α) was described as

$$\alpha_i = \alpha_{0i}\,(1 + \mu_i \cos\theta) \tag{3}$$

following Valentine and Mariotti (2019), where i is the marsh type (saline or brackish), α_0 is a background erodibility, μ is the amplitude of variability (representing the asymmetry of erosion due to wind direction), and θ is the wind direction (north = 0). This effective erodibility, α_i, is calculated separately for each marsh type to allow this value to vary across salinity gradients.

This model was applied to two domains: Terrebonne and Barataria basins. The initial marsh extent from 1932 for both basins was used, and the total domain area was approximately 60 km by 55 km for Terrebonne and 60 km by 75 km for Barataria. To determine the erodibility coefficients for each marsh zone, the model was calibrated separately for each marsh type in each basin. The model was calibrated by salinity zone (salt or brackish), allowing for the

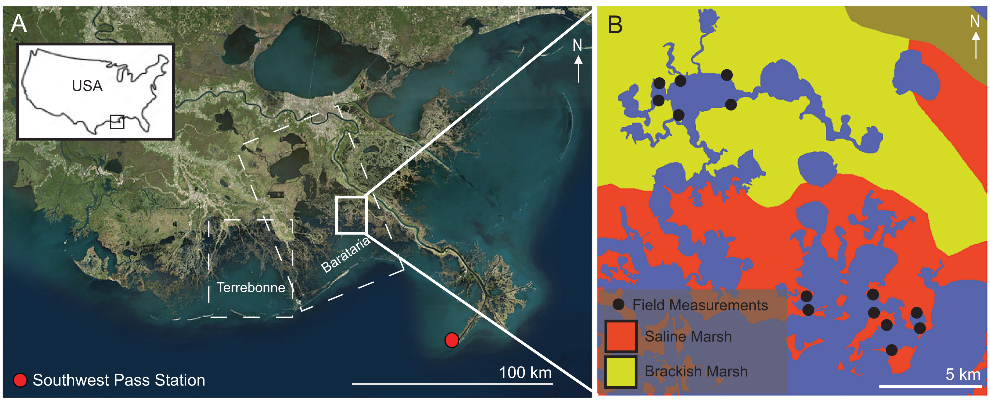

FIGURE 1 (A) Louisiana coast (imagery from CRMS). Model domains outlined in dashed white lines, study site outlined in solid white box, and wind station (southwest pass) noted by red circle. (B) Field locations for coring and sediment property analysis, spanning across modern-day salinity zones (data on salinity zones from CRMS) [Color figure can be viewed at wileyonlinelibrary.com]

baseline erodibility (α_{0i}) and asymmetry factor (μ_i) to differ across zones. This was calibrated to the portion of erosion attributed to edge erosion, as opposed to total erosion.

For calibration purposes, salinity zone was determined using the Louisiana Coastwide Reference Monitoring System (CRMS) dataset and taking the median salinity zone of a given location from all surveys (see Section 2.2 for full explanation). For each salinity zone, a calibration area that related to areas of fieldwork was selected (Figures 7 and 8). We determined a priori that these sites were likely largely influenced by wind wave erosion, and that they had no large obvious influence of man-made alterations or fault activity. Calibrations in Barataria Bay were done on the regions with fieldwork presented in this study, while calibrations for Terrebonne Bay were done for areas with minimal swell influence, as described from fieldwork by Everett et al., (2019). The model was calibrated to each of these areas, and the erodibility and asymmetry that achieved the best fit for a given salinity zone (saline and brackish) was used for the entire salinity zone domain.

2.5 | Model performance and statistical methods

Model performance was assessed as in Valentine and Mariotti (2019), where the intersection of the erosion matrices (modeled and measured) was divided by the union of these two matrices according to

$$\Pi = (X_{\text{model}} \cap X_{\text{measured}})/(X_{\text{model}} \cup X_{\text{measured}}) \times 100,$$

where X_{model} are the modeled eroded cells and X_{measured} are the areas that eroded in reality. The model was calibrated so that the value of Π was maximized. For statistical analysis of the sediment cores, we used a two-sample Kolmogorov–Smirnov test (K-S test) to compare variables at depth within the cores.

3 | RESULTS

3.1 | Field results

Marsh elevation profiles varied between sites, but there was no clear distinction between brackish and salt marshes (Figure 2). The profiles in brackish marshes were more variable. Likewise, there was no consistent difference between north-facing and south-facing marsh profiles. The majority of the profiles (all except one at a brackish site) exhibited a scarped marsh edge, with an abrupt elevation change at the marsh–water interface.

Soil parameters (shear strength, bulk density, and organic content) differed between saline and brackish marshes (Figure 3). While soil strength was only significantly different in the top 20 cm (i.e., in the root zone), bulk density and organic content were significantly different at all depths, except 15–20 cm.

3.2 | Land loss processes

Using the classification algorithm, we found that in Terrebonne 54% of the total land loss was due to edge erosion and 46% to interior loss

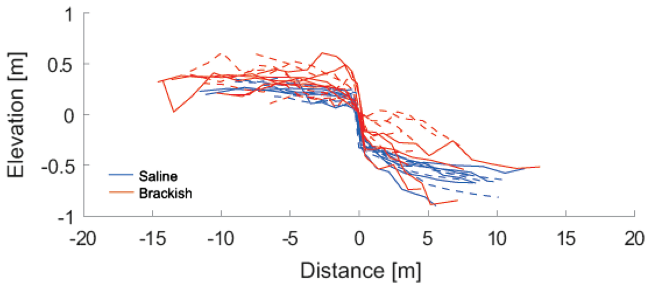

FIGURE 2 Marsh elevation (NAVD88) profiles for saline and brackish marshes. The majority of marshes have a cliffed edge (scarp) and generally show similar elevation trends across sites. Solid lines indicate south-facing sites; dashed lines indicate north-facing sites [Color figure can be viewed at wileyonlinelibrary.com]

(Table 1, Figure 4). Similarly, in Barataria 53% of the total land loss was due to edge erosion and 47% to interior loss.

Within Barataria Bay edge erosion was dominant in the saline marshes, while interior marsh loss was most common in the brackish marshes (Table 1). Likewise, within Terrebonne, the brackish marshes had the highest percentage of interior marsh loss. Edge erosion was the dominant loss mechanism between 1932 and 1956, whereas interior loss became the dominant loss mechanism in the subsequent periods (Figure 5). Even though the proportion of each land loss mechanism changed through time, the absolute rate of edge erosion remained relatively constant in both basins over time, with only a slight decrease for the time interval 1956–1988 in Barataria (Figure 5).

3.3 | Model results

3.3.1 | Barataria Basin

The optimal calibration of the model in Barataria Bay indicated that the erodibility was lowest in the saline marshes compared to brackish marshes (Table 2, Figure 6A), whereas the asymmetry (μ) of the edge erosion was equal across marsh types. The fit metric was lower for the saline marshes (72%) than for the brackish marshes (79%) (Table 2).

The model accurately predicted marsh edge erosion in semi-enclosed microbays that have had less human intervention (Figure 7C, D). Notable exceptions to the fit are in elongated bays in the northern part of the domain (Figure 7B). Allowing the erodibility to change depending on salinity zone increased the model fit (72% vs. 51% for saline, 79% vs. 43% for brackish) in regions that were dominated by edge erosion, such as semienclosed microbays (Table 3).

3.3.2 | Terrebonne Basin

As in Barataria Bay, erodibility in Terrebonne Bay was higher in the brackish than in the saline marshes (Figure 6B, Table 2). Likewise, the fit was better for the brackish marshes compared to the saline marshes (79% vs. 65%). The asymmetry was slightly greater in brackish marshes compared to saline marshes (70% vs. 80%). When considering the entire model domain, the model tended to underestimate

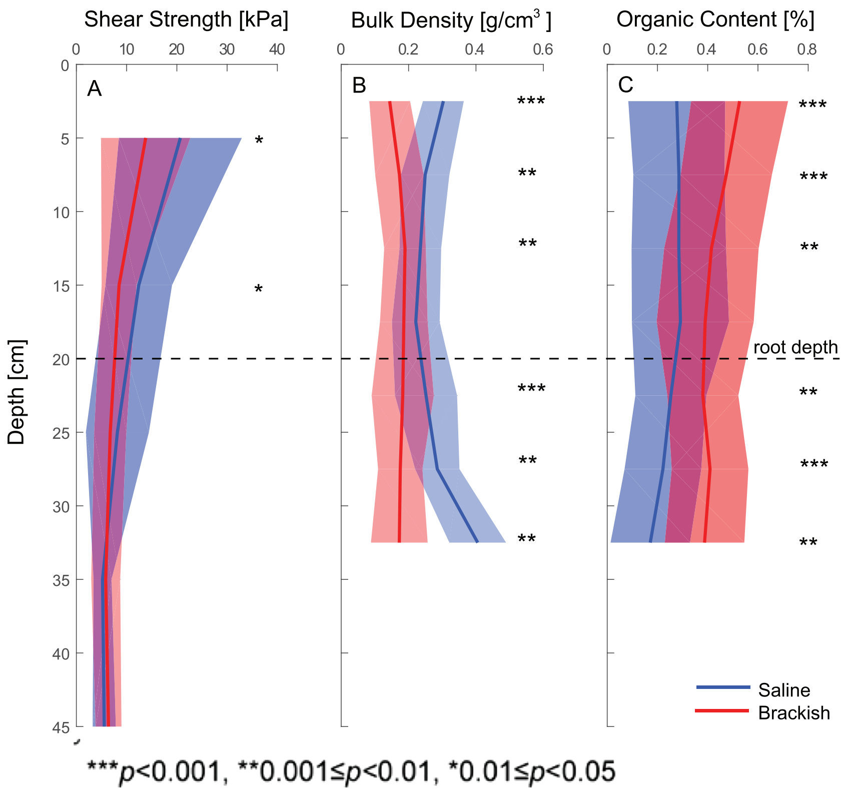

FIGURE 3 (A) Shear strength, (B) bulk density, and (C) organic content from sediment cores taken in Barataria Bay, LA, in both saline and brackish marshes. Root depth of 20 cm is marked and is from general field observations of where the dense, active root mat terminated. Significant differences are marked with asterisks. Shading indicates standard deviation [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Proportion of erosion from 1932 to 2015 attributed to edge processes and interior marsh loss in Barataria and Terrebonne basins

	Edge erosion	Interior marsh loss
Barataria	53%	47%
Saline	66%	33%
Brackish	36%	64%
Terrebonne	54%	46%
Saline	71%	29%
Brackish	24%	76%

marsh loss due to edge erosion (Figure 8). While the edge erosion of the smaller bays was generally well predicted, large areas adjacent to smaller bodies of water were not predicted well. Allowing erodibility to vary depending on salinity improved model fit in Terrebonne (Table 3), especially in the areas that were dominated by edge erosion (65% vs. 62% in the saline, 79% vs. 63% in the brackish).

4 | DISCUSSION

4.1 | Modes of marsh loss: edge versus interior

Our findings confirm that both edge and interior erosion are important drivers of land loss in coastal Louisiana. While these estimates give an objective metric as to the relative importance of each process, the classification between the two processes is not without error. For example, edge erosion of newly created marsh ponds is also incorporated into interior loss, so the total amount of edge erosion is likely underestimated. On the other hand, land loss due to direct human action and fault activity that occurred near the marsh edge was likely miscategorized as marsh edge erosion, leading to an over-estimation of this category (Figures 7C and 8C).

A previous study of edge versus interior erosion across the Louisiana coast (1932–1990) found that 70% of land loss was attributed to interior loss, while 30% was considered edge erosion (Penland et al., 2000). By including the active part of the Mississippi Delta (the "birdfoot"), which experiences extremely high rates of subsidence and interior loss, that study might have an excessive emphasis towards interior erosion compared to edge erosion. Our results highlight that in saline marshes a much higher percentage of marsh loss is occurring from edge erosion (66% in Barataria, 71% in Terrebonne) and that interior loss is the dominant mechanism of marsh loss only in brackish marshes.

4.2 | Changes in erodibility with salinity

Brackish marshes were more erodible than salt marshes, based on the model results (Table 2). Further, model results show that using different erodibility coefficients for saline and brackish marshes improves estimates of land loss, particularly in regions that are dominated by edge erosion (i.e., the calibration areas) (Table 3). This modeling result that brackish marshes are more erodible than saline marshes is consistent with the field measurements showing that saline marshes had greater soil strength, greater bulk density, and lower organic content (Figure 3). Other studies on marsh properties have demonstrated similar trends in soil bulk density and organic matter content across marsh salinity gradients. For example, Nyman et al., (2006) found higher bulk

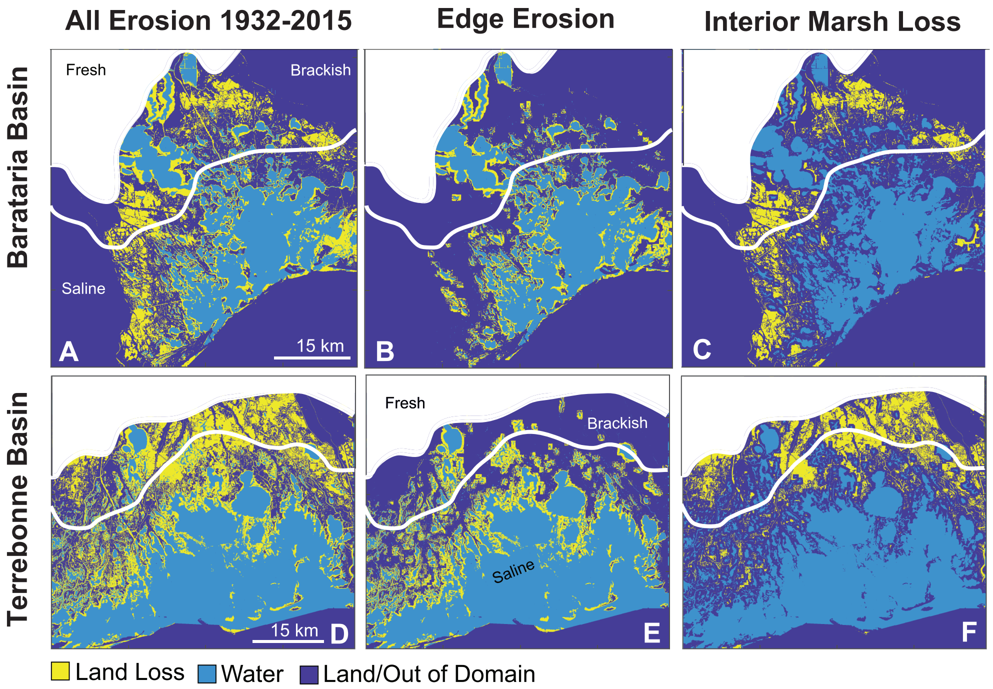

FIGURE 4 Marsh loss from 1932 to 2015 for Barataria Basin (A–C) and Terrebonne Basin (D–F). Panels A and D indicate all wetland losses; B and E show only edge erosion; C and F show only interior loss. White lines indicate boundary between marsh types (Figure 2) [Color figure can be viewed at wileyonlinelibrary.com]

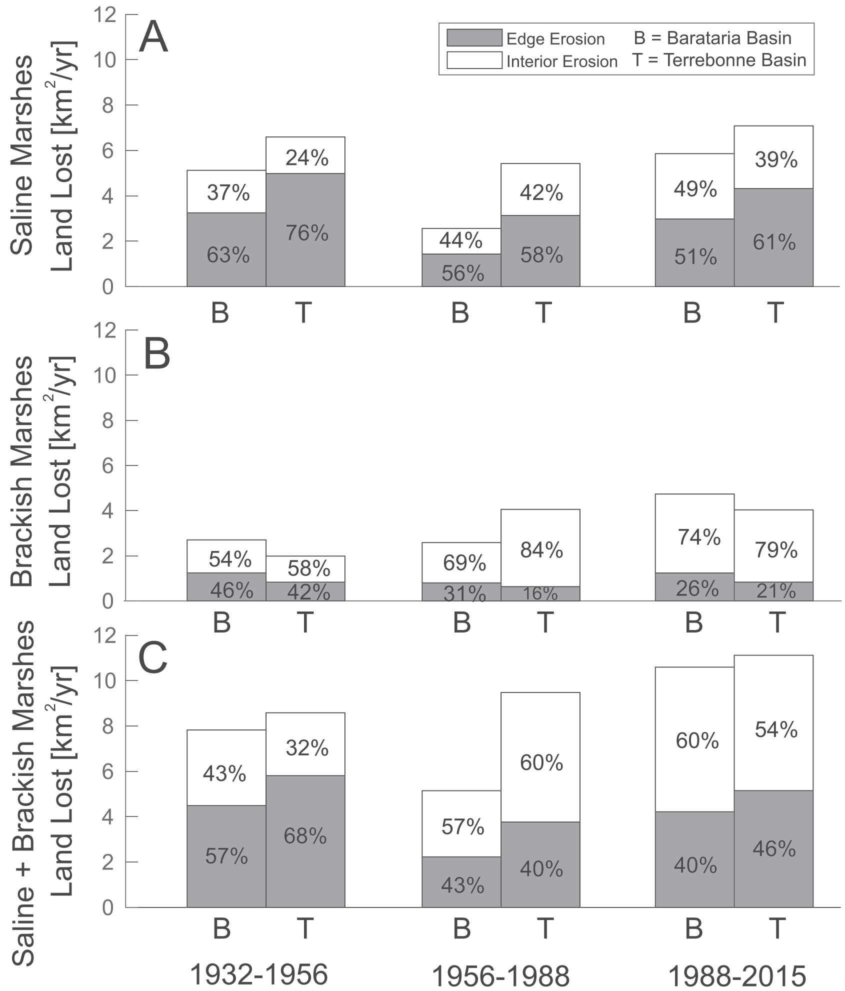

FIGURE 5 Land loss in (a) Barataria and (B) Terrebonne basins over time for brackish and saline marshes. Total land loss rates for edge (grey bar) and interior (white bar) marsh loss and the percentage of each type of land loss are shown over three time periods

density in saline marshes compared to brackish and fresh, in both stable and deteriorating marshes in coastal Louisiana. Likewise, field studies across US marshes have found higher bulk density in saline marshes compared to brackish and fresh, as well as higher organic carbon content in fresh and brackish marshes compared to saline (Craft, 2007). Saline marshes also tend to have higher soil strength compared to fresher marshes. Howes et al., (2010) reported a roughly twofold difference between fresh and saline marsh soil strength in Louisiana marshes, whereas Gillen et al., (2020) found that saline marshes were up to four times stronger than fresh marshes along the Atlantic coast. Previous work that explored rooting depth between marsh types in Louisiana found that fresh marshes had shorter rooting depths compared to saline marshes, which may explain the different erosional response to Hurricane Katrina (Howes et al., 2010).

4.3 | Differences between basins

Similar geometries, plant communities, and climates in Barataria and Terrebonne basins justify the use of the same model for the two systems. However, there are some important differences between these two basins, which may have led to different values for erodibility.

A major difference is the configuration of the barrier islands, and therefore the influence of swell within the bay. The barrier islands enclosing the south side of Terrebonne Bay are more fragmented compared to those in Barataria Bay, allowing more swell waves to enter the bay and leading to greater edge retreat. Previous studies have shown the importance of swell within Terrebonne, and how this is related to higher marsh edge retreat rates (Everett et al., 2019). On the other hand, only small areas within Barataria Bay are subject to swell wave energy. In the model used in this study, only locally generated wind waves were simulated. Therefore, this is more likely to affect the results and calibration of the model within Terrebonne compared to Barataria.

TABLE 2 Model calibration information for both Terrebonne and Barataria basins across salinity zones

Marsh type	Basin	α_{0i} (m/yr)/(W/m)	$\mu_i \times 100$ (%)	Π (%)
Saline	Barataria	0.364	60	72
	Terrebonne	0.539	70	65
Brackish	Barataria	1.01	70	79
	Terrebonne	1.23	80	79

As discussed, the classification of interior versus edge erosion (which was then used to calibrate the model) has some error associated with it. Ponding and interior marsh loss within Terrebonne was higher compared to that in Barataria Bay (51% vs. 48%), and through visual inspection we noticed that the ponds are close together and in many cases are closer to the marsh edge and to large (>300 m) bodies of water. Because of this difference in geometry in Terrebonne, substantial amounts of erosion are attributed to edge processes, but are in fact interior loss. To assess these different modes of erosion more accurately, the methodology would necessarily become more subjective and less automated. Therefore, the lower fit of the calibrations within Terrebonne compared to Barataria might be due to an erroneous classification of edge erosion.

4.4 | Model limitations

Beyond areas that were misclassified as edge erosion, there are other parts of the model domains that did not perform well. This indicates that wave-induced edge erosion is likely not the dominant process in these areas (i.e., Figure 8C) and that there are other important factors driving land loss.

The two elongated bays in the middle of Barataria Basin (Figure 7B) had higher erosion rates than expected. We suggest two reasons as to why the erosion pattern here does not match that of other edges throughout the basin. First, due to the geometry of these bays, currents could be higher and contribute to marsh erosion. Second, the Gulf Intracoastal Waterway is immediately adjacent to this area and might provide different sediments and nutrients, which could locally affect vegetation and soil. On the eastern side of Barataria Bay, there are several enclosed basins where the model overpredicted marsh edge erosion (Figure 7). Many of these are sites of marsh creation, restoration, and marsh edge protection (CPRA, 2017), which are currently not included in the model.

Other reasons for the model mismatch might be associated with a variety of processes that are not included in the model, which include faulting (Morton et al., 2002), erosion by storm surges associated with hurricanes (Howes et al., 2010), and anthropogenic modifications of the landscape such as canal building (Turner, 2014).

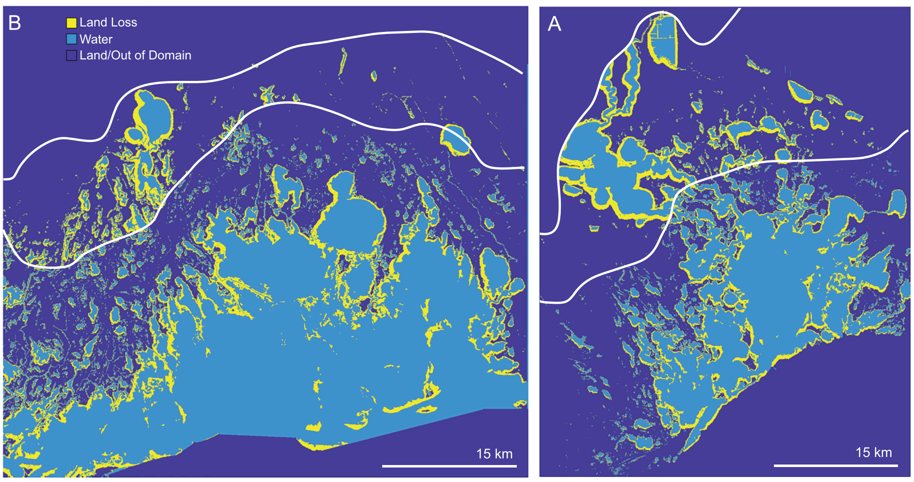

FIGURE 6 Calibrated model of marsh edge erosion for (A) Barataria and (B) Terrebonne basins. These models use the calibration parameters described in Table 2. White lines indicate boundary between marsh types (Figure 2) [Color figure can be viewed at wileyonlinelibrary.com]

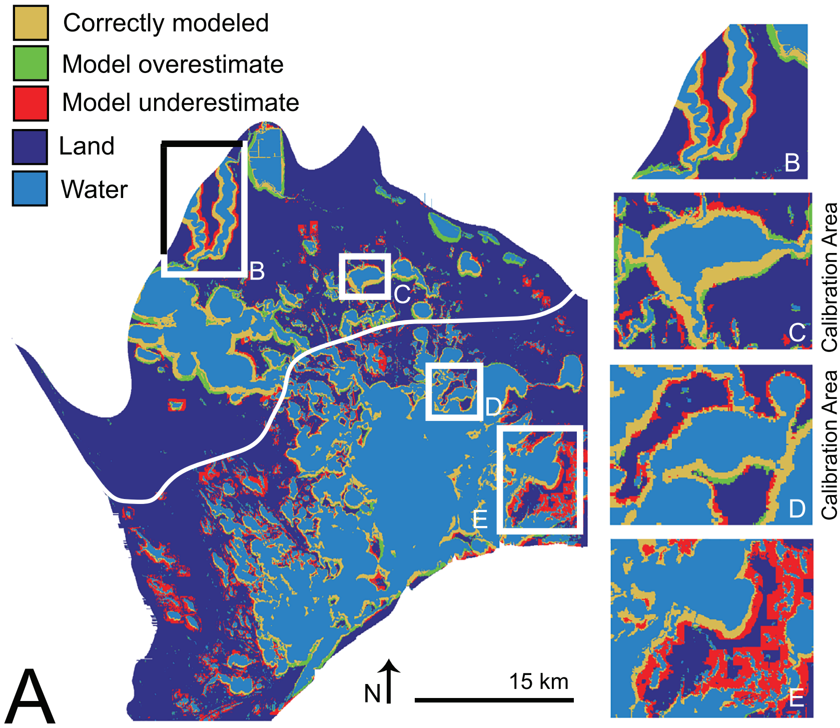

FIGURE 7 (A) Model fit for Barataria Basin. Yellow indicates correctly predicted marsh edge erosion, red indicates areas that the model did not erode but should have, and green indicates areas where the model overestimated erosion. (B) Example of an elongated basin that with significant mismatch. (C, D) Calibration areas for the brackish and saline marshes, respectively. (E) Area where there was likely a mis-categorization of erosion type, likely due to fault activity. White line indicates boundary between marsh types [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Model performance metric (Π) for calibration regions and salinity zones with and without different calibrations by salinity zone. Fit for areas that are dominated by wave erosion (calibration regions) were the highest, while the fit was substantially reduced in the wave erosion dominated areas when a general fit was used (i.e., not specific to the local salinity zone)

Marsh type	Barataria Basin	Π (%)	Terrebonne Basin	Π (%)
Saline	Calibration region	72	Calibration region	65
	Calibration region using brackish calibration	51	Calibration region using brackish calibration	62
	Saline region	50	Saline region	50
	Saline region using brackish calibration	53	Saline region using brackish calibration	62
Brackish	Calibration region	79	Calibration region	79
	Calibration region using saline calibration	43	Calibration region using saline calibration	63
	Brackish region	50	Brackish region	46
	Brackish region using saline calibration	38	Brackish region using saline calibration	30

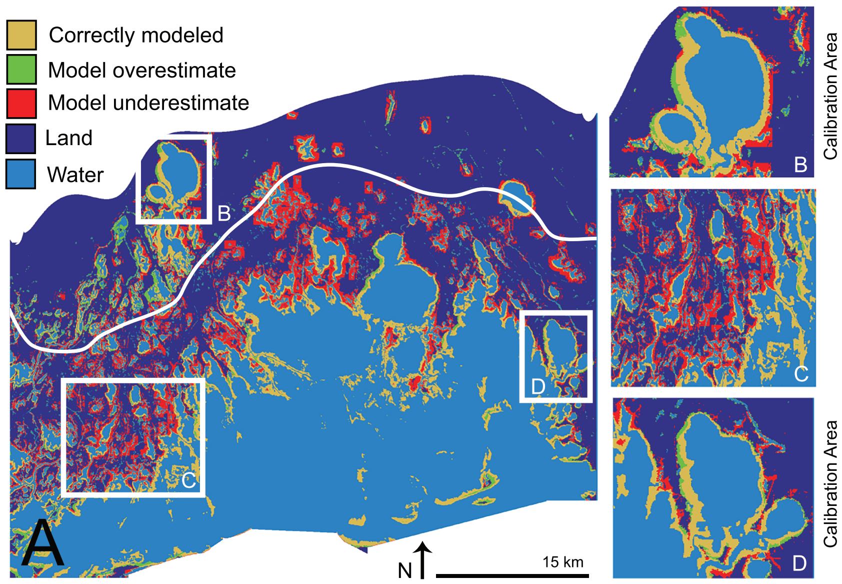

FIGURE 8 (A) Model fit for Terrebonne Basin. Yellow indicates correctly predicted marsh edge erosion, red indicates areas that the model did not erode but should have, and green indicates areas where the model overestimated erosion. (B, D) Calibration areas for brackish and saline marshes, respectively. (C) An area where there was likely a mis-categorization of erosion type. White lines indicate boundary between marsh types [Color figure can be viewed at wileyonlinelibrary.com]

5 | CONCLUSIONS

We propose a model for marsh edge erosion that accounts for salinity-dependent marsh erodibility. Model calibrations indicate that brackish marshes are more erodible than salt marshes. This finding is corroborated by our field observations, and it is attributed to differences in soil strength, vegetation, soil bulk density, and organic content. Marsh transgression by sea-level rise is expected to shift existing brackish marshes into salt marshes. Based on our results on marsh edge erodibility, this shift could decrease marsh loss by wave edge erosion. On the other hand, changes in salinity might also trigger vegetation die-off and interior loss, and thus the overall effect is uncertain.

The differences in erodibility with salinity also have implications for coastal restoration. Introduction of freshwater into the basins via river diversions will increase brackish marsh area and therefore increase basin-averaged erodibility unless sedimentation allows for marsh building and progradation.

We conclude that the salinity effect on marsh erodibility—which likely takes place by shifting vegetation and consequently soil properties—is another important aspect that needs to be considered when assessing system-wide responses to sea-level rise and to restoration projects.

ACKNOWLEDGEMENTS

We would like to thank V. Ford, M. Kelsall, S. Murshid, J. Robinson, and A. Cole for their help in the field. Thanks to G. Groseclose for helping with downloading data and to M. Miller for boat assistance and troubleshooting. This manuscript was greatly improved by the comments of C. Wilson, G. Turner, S. Bargu, and Z. Zhou. KV was funded by a Louisiana Board of Regents Fellowship. This research was made possible by a grant from the Gulf of Mexico Research Initiative.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

ORCID

Kendall Valentine https://orcid.org/0000-0002-5143-3266

REFERENCES

Allison, M.A., Chen, Q.J., Couvillion, B., Leadon, M., McCorquodale, A., Meselhe, E., *et al.* (2017) *Coastal Master Plan. Model improvement plan, attachment C3–2: Marsh edge erosion*. Coastal Protection and Restoration Authority of Louisiana.

Barnes, S.R. & Virgets, S. (2017) *Regional impacts of coastal land loss and Louisiana's opportunity for growth*. LSU EJ Ourso College of Business Economics and Policy Research Group, Environmental Defense Fund.

Bernik, B.M., Eppinga, M.B., Kolker, A.S. & Blum, M.J. (2018) Clonal Vegetation Patterns Mediate Shoreline Erosion. *Geophysical Research Letters*, 45(13), 6476–6484. https://doi.org/10.1029/2018GL077537

Blum, M.D. & Roberts, H.H. (2009) Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience*, 2(7), 488–491. https://doi.org/10.1038/ngeo553

Chmura, G.L., Anisfeld, S.C., Cahoon, D.R. & Lynch, J.C. (2003) Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles*, 17(4), 1111. https://doi.org/10.1029/2002GB001917

Coastal Protection and Restoration Authority of Louisiana (CPRA). (2017) *Louisiana's comprehensive master plan for a sustainable coast, coastal protection and restoration*. Baton Rouge, LA: Authority of Louisiana.

Couvillion, B.R., Barras, J.A., Steyer, G.D., Sleavin, W., Fischer, M., Beck, H., *et al.* (2011) Land area change in coastal Louisiana from 1932 to 2010, scale 1:265,000, U.S. Geological Survey Sci. Invest. Map, 3164, 12pp.

Couvillion, B.R., Beck, H., Schoolmaster, D. & Fischer, M. (2017) *Land area change in coastal Louisiana (1932 to 2016)* (USGS Numbered Series No. 3381). Scientific Investigations Map. Reston, VA: US Geological Survey.

Craft, C. (2007) Freshwater input structures soil properties, vertical accretion, and nutrient accumulation of Georgia and U.S. tidal marshes. *Limnology and Oceanography*, 52(3), 1220–1230. https://doi.org/10.4319/lo.2007.52.3.1220

Dausse, A., Garbutt, A., Norman, L., Papadimitriou, S., Jones, L.M., Robins, P.E. & Thomas, D.N. (2012) Biogeochemical functioning of grazed estuarine tidal marshes along a salinity gradient. *Estuarine, Coastal and Shelf Science*, 100, 83–92. https://doi.org/10.1016/j.ecss.2011.12.037

Day, J.W., Boesch, D.F., Clairain, E.J., Kemp, G.P., Laska, S.B., Mitsch, W.J., *et al.* (2007) Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science*, 315(5819), 1679–1684. https://doi.org/10.1126/science.1137030

Dean, W.E. (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. *Journal of Sedimentary Research*, 44, 242–248. https://doi.org/10.1306/74D729D2-2B21-11D7-8648000102C1865D

Deegan, L.A., Johnson, D.S., Warren, R.S., Peterson, B.J., Fleeger, J.W., Fagherazzi, S. & Wollheim, W.M. (2012) Coastal eutrophication as a driver of salt marsh loss. *Nature*, 490(7420), 388–392. https://doi.org/10.1038/nature11533

DeLaune, R.D., Nyman, J.A. & Patrick, W.H., Jr. (1994) Peat collapse, ponding and wetland loss in a rapidly submerging coastal marsh. *Journal of Coastal Research*, 10(4), 1021–1030.

Everett, T., Chen, Q., Karimpour, A. & Twilley, R. (2019) Quantification of swell energy and its impact on wetlands in a deltaic estuary. *Estuaries and Coasts*, 42(1), 68–84. https://doi.org/10.1007/s12237-018-0454-z

Feagin, R.A., Lozada-Bernard, S.M., Ravens, T.M., Möller, I., Yeager, K.M. & Baird, A.H. (2009) Does vegetation prevent wave erosion of salt marsh edges? *Proceedings of the National Academy of Sciences*, 106(25), 10109–10113. https://doi.org/10.1073/pnas.0901297106

Finlayson, C.M. (2012) Forty years of wetland conservation and wise use. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 22(2), 139–143. https://doi.org/10.1002/aqc.2233

Ford, H., Garbutt, A., Ladd, C., Malarkey, J. & Skov, M.W. (2016) Soil stabilization linked to plant diversity and environmental context in coastal wetlands. *Journal of Vegetation Science*, 27(2), 259–268. https://doi.org/10.1111/jvs.12367

Gillen, M.N., Messerschmidt, T.C. & Kirwan, M.L. (2020) Biophysical controls of marsh soil shear strength along an estuarine salinity gradient, Earth Surface Dynamics, doi.org/10.5194/esurf-2020-58.

González, J.L. & Tornqvist, T.E. (2006) Coastal Louisiana in crisis: Subsidence or sea level rise? *EOS. Transactions of the American Geophysical Union*, 87(45), 493–498. https://doi.org/10.1029/2006EO450001

Howes, N.C., FitzGerald, D.M., Hughes, Z.J., Georgiou, I.Y., Kulp, M.A., Miner, M.D., *et al.* (2010) Hurricane-induced failure of low salinity wetlands. *Proceedings of the National Academy of Sciences*, 107(32), 14014–14019. https://doi.org/10.1073/pnas.0914582107

Hu, S., Niu, Z., Chen, Y., Li, L. & Zhang, H. (2017) Global wetlands: Potential distribution, wetland loss, and status. *Science of the Total Environment*, 586, 319–327. https://doi.org/10.1016/j.scitotenv.2017.02.001

Hughes, Z.J., FitzGerald, D.M., Wilson, C.A., Pennings, S.C., Więski, K. & Mahadevan, A. (2009) Rapid headward erosion of marsh creeks in response to relative sea level rise. *Geophysical Research Letters*, 36(3), L03602. https://doi.org/10.1029/2008GL036000

Jankowski, K.L., Törnqvist, T.E. & Fernandes, A.M. (2017) Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. *Nature Communications*, 8(1), 1–7. https://doi.org/10.1038/ncomms14792

Karimpour, A., Chen, Q. & Jadhav, R. (2013) Turbidity dynamics in Upper Terrebonne Bay, Louisiana. In: Khan, A. & Wu, W. (Eds.), *Sediment Transport: Monitoring, Modeling, and Management*. Nova Science Publishers, Inc, pp. 339–360.

Kesel, R.H. (1989) The role of the Mississippi River in wetland loss in southeastern Louisiana, U.S.A. *Environmental Geology and Water Sciences*, 13(3), 183–193. https://doi.org/10.1007/BF01665368

Kirwan, M.L., Murray, A.B. & Boyd, W.S. (2008) Temporary vegetation disturbance as an explanation for permanent loss of tidal wetlands. *Geophysical Research Letters*, 35(5), L05403. https://doi.org/10.1029/2007GL032681

Le Hir, P., Monbet, Y. & Orgain, F. (2007) Sediment erodibility in sediment transport modelling: Can we account for biota effects? *Continental Shelf Research*, 27(8), 1116–1142. https://doi.org/10.1016/j.csr.2005.11.016

Leonardi, N., Ganju, N.K. & Fagherazzi, S. (2016) A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. *Proceedings of the National Academy of Sciences*, 113(1), 64–68. https://doi.org/10.1073/pnas.1510095112

Marani, M., D'Alpaos, A., Lanzoni, S. & Santalucia, M. (2011) Understanding and predicting wave erosion of marsh edges. *Geophysical Research Letters*, 38(21), L21401. https://doi.org/10.1029/2011GL048995

Mariotti, G. (2020) Beyond marsh drowning: The many faces of marsh loss (and gain). *Advances in Water Resources*, 144, 103710. https://doi.org/10.1016/j.advwatres.2020.103710

Mariotti, G. & Canestrelli, A. (2017) Long-term morphodynamics of muddy backbarrier basins: Fill in or empty out? *Water Resources Research*, 53 (8), 7029–7054. https://doi.org/10.1002/2017WR020461

Mariotti, G. & Fagherazzi, S. (2010) A numerical model for the coupled long-term evolution of salt marshes and tidal flats. *Journal of Geophysical Research - Earth Surface*, 115, F01004. https://doi.org/10.1029/2009JF001326

Mariotti, G., Huang, H., Xue, Z., Li, B., Justic, D. & Zang, Z. (2018) Biased wind measurements in estuarine waters. *Journal of Geophysical Research, Oceans*, 123(5), 3577–3587. https://doi.org/10.1029/2017JC013748

Mariotti, G., Kearney, W.S. & Fagherazzi, S. (2019) Soil creep in a mesotidal salt marsh channel bank: Fast, seasonal, and water table mediated. *Geomorphology*, 334, 126–137. https://doi.org/10.1016/j.geomorph.2019.03.001

McClenachan, G., Eugene Turner, R. & Tweel, A.W. (2013) Effects of oil on the rate and trajectory of Louisiana marsh shoreline erosion. *Environmental Research Letters*, 8(4), 044030. https://doi.org/10.1088/1748-9326/8/4/044030

McHugh, J.M. & Dighton, J. (2004) Influence of mycorrhizal inoculation, inundation period, salinity, and phosphorus availability on the growth of two salt marsh grasses, *Spartina alterniflora* Lois. and *Spartina cynosuroides* (L.) Roth., in nursery systems. *Restoration Ecology*, 12(4), 533–545. https://doi.org/10.1111/j.1061-2971.2004.03109.x

Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., van Wesenbeeck, B.K., *et al*. (2014) Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience*, 7(10), 727–731. https://doi.org/10.1038/ngeo2251

Morton, R.A., Buster, N.A. & Krohn, M.D. (2002) Subsurface controls on historical subsidence rates ad associated wetland loss in southcentral Louisiana. *Gulf Coast Association of Geological Societies Transactions*, 52, 767–778.

Nienhuis, J.H., Törnqvist, T.E., Jankowski, K.L., Fernandes, A.M. & Keogh, M.E. (2017) A new subsidence map for coastal Louisiana. *GSA Today*, 27, 60–61. https://doi.org/10.1130/GSATG337GW.1

Nyman, J.A., Walters, R.J., Delaune, R.D. & Patrick, W.H. (2006) Marsh vertical accretion via vegetative growth. *Estuarine, Coastal and Shelf Science*, 69(3–4), 370–380. https://doi.org/10.1016/j.ecss.2006.05.041

Ortiz, A.C., Roy, S. & Edmonds, D.A. (2017) Land loss by pond expansion on the Mississippi River Delta Plain. *Geophysical Research Letters*, 44(8), 3635–3642. https://doi.org/10.1002/2017GL073079

Penland, S., Wayne, L., Britsch, L.D., Williams, S.J., Beall, A.D. & Butterworth, V.C. (2000) Process classification of coastal land loss between 1932 and 1990 in the Mississippi River Delta Plain, southeastern Louisiana. *U.S. Geological Survey Open File Report*. No. 2000-417, Vol. 00-418. Washington D.C: US Department of the Interior, p. 1.

Perez, B.C., Day, J.W., Rouse, L.J., Shaw, R.F. & Wang, M. (2000) Influence of Atchafalaya River discharge and winter frontal passage on suspended sediment concentration and flux in Fourleague Bay, Louisiana. *Estuarine, Coastal and Shelf Science*, 50(2), 271–290. https://doi.org/10.1006/ecss.1999.0564

Reed, D.J. (1995) The response of coastal marshes to sea-level rise: Survival or submergence? *Earth Surface Processes and Landforms*, 20(1), 39–48. https://doi.org/10.1002/esp.3290200105

Reed, D.J. & Cahoon, D.R. (1992) The relationship between marsh surface topography, hydroperiod, and growth of *Spartina alterniflora* in a deteriorating Louisiana salt marsh. *Journal of Coastal Research*, 8, 77–87.

Roberts, H.H. (1997) Dynamic changes of the Holocene Mississippi river delta plain: The delta cycle. *Journal of Coastal Research*, 13(3), 605–627.

Roman, C.T. (2017) Salt marsh sustainability: Challenges during an uncertain future. *Estuaries and Coasts*, 40(3), 711–716. https://doi.org/10.1007/s12237-016-0149-2

Sapkota, Y. & White, J.R. (2019) Marsh edge erosion and associated carbon dynamics in coastal Louisiana: A proxy for future wetland-dominated coastlines world-wide. *Estuarine, Coastal and Shelf Science*, 226, 106289. https://doi.org/10.1016/j.ecss.2019.106289

Scaife, W.W., Turner, R.E. & Costanza, R. (1983) Coastal Louisiana recent land loss and canal impacts. *Environmental Management*, 7(5), 433–442. https://doi.org/10.1007/BF01867123

Schepers, L., Kirwan, M., Guntenspergen, G. & Temmerman, S. (2017) Spatio-temporal development of vegetation die-off in a submerging coastal marsh. *Limnology and Oceanography*, 62(1), 137–150. https://doi.org/10.1002/lno.10381

Schwimmer, R.A. (2001) Rates and processes of marsh shoreline erosion in Rehoboth Bay, Delaware, U.S.A. *Journal of Coastal Research*, 17, 672–683.

Silliman, B.R., He, Q., Angelini, C., Smith, C.S., Kirwan, M.L., Daleo, P., *et al*. (2019) Field experiments and meta-analysis reveal wetland vegetation as a crucial element in the coastal protection paradigm. *Current Biology*, 29(11), 1800–1806.e3. https://doi.org/10.1016/j.cub.2019.05.017

Silvestri, S., Defina, A. & Marani, M. (2005) Tidal regime, salinity and salt marsh plant zonation. *Estuarine, Coastal and Shelf Science*, 62(1-2), 119–130. https://doi.org/10.1016/j.ecss.2004.08.010

Stevenson, J.C., Kearney, M.S. & Pendleton, E.C. (1985) Sedimentation and erosion in a Chesapeake Bay brackish marsh system. *Marine Geology*, 67(3–4), 213–235. https://doi.org/10.1016/0025-3227(85)90093-3

Turner, R.E. (2011) Beneath the salt marsh canopy: Loss of soil strength with increasing nutrient loads. *Estuaries and Coasts*, 34(5), 1084–1093. https://doi.org/10.1007/s12237-010-9341-y

Turner, R.E. (2014) A synoptic examination of causes of land loss in southern Louisiana as related to the exploitation of subsurface geological resources (Discussion of: Olea, R.A., and Coleman, J.L., Jr., 2014). Journal of Coastal Research 30(6): 1330–1334. *Journal of Coastal Research*, 30(5), 1025–1044.

Turner, R.E. & McClenachan, G. (2018) Reversing wetland death from 35,000 cuts: Opportunities to restore Louisiana's dredged canals. *PLoS One*, 13(12), e0207717. https://doi.org/10.1371/journal.pone.0207717

Valentine, K. & Mariotti, G. (2019) Wind-driven water level fluctuations drive marsh edge erosion variability in microtidal coastal bays.

Continental Shelf Research, 176, 76–89. https://doi.org/10.1016/j.csr.2019.03.002

Wang, H., van der Wal, D., Li, X., van Belzen, J., Herman, P.M.J., Hu, Z., *et al*. (2017) Zooming in and out: Scale dependence of extrinsic and intrinsic factors affecting salt marsh erosion. *Journal of Geophysical Research - Earth Surface*, 122(7), 1455–1470. https://doi.org/10.1002/2016JF004193

Wrayf, R.D., Leatherman, S.P. & Nicholls, R.J. (1995) Historic and future land loss for upland and marsh islands in the Chesapeake Bay, Maryland, U.S.A. *Journal of Coastal Research*, 11, 1195–1203.

Young, I.R. & Verhagen, L.A. (1996) The growth of fetch limited waves in water of finite depth. Part 1. Total energy and peak frequency. *Coastal Engineering*, 29(1–2), 47–78. https://doi.org/10.1016/S0378-3839(96)00006-3

Yuill, B., Lavoie, D. & Reed, D.J. (2009) Understanding subsidence processes in coastal Louisiana. *Journal of Coastal Research*, 2009(10054), 23–36. https://doi.org/10.2112/SI54-012.1

How to cite this article: Valentine K, Bruno G, Elsey-Quirk T, Mariotti G. Brackish marshes erode twice as fast as saline marshes in the Mississippi Delta region. *Earth Surf. Process. Landforms*. 2021;46:1739–1749. https://doi.org/10.1002/esp.5108