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RESEARCH ARTICLE

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Fetch and distance from the bay control accretion and erosion patterns in Terrebonne marshes (Louisiana, USA)

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Abstract

Wetlands in the Mississippi River Delta are rapidly degrading. Sea level rise and low sediment supply are widely recognized as the two main factors contributing to land-to-water conversion. To determine what marsh areas are more resilient, it is fundamental to identify the drivers that regulate marsh accretion and degradation. In this study, a combination of field data and aerial images is used to determine these drivers in Terrebonne Bay, Louisiana, USA. We find that accretion and degradation patterns depend on whether the marsh is located inland in a sheltered area or facing open water. In the first case, the distance to the nearby channel is important, because during flooding of the marsh platform more sediment is deposited in the proximity of channel banks. The accretion rates of marshes facing open water are high and correlate to fetch, a proxy for the ability of waves to resuspend bottom sediment. These areas are more resilient to sea level rise, but waves are also the main mechanism of degradation, as these marshes tend to degrade by edge erosion. Consequently, we propose a bimodal evolution trajectory of the marshes in Terrebonne Bay: marshes close to the bay and facing open water accrete rapidly but are affected by lateral erosion due to waves, whereas sheltered marshes accrete slowly and degrade in large swathes due to insufficient sediment supply.

KEYWORDS
CRMS, marsh accretion, marsh erosion, Mississippi River Delta Plain, waves

1 | INTRODUCTION

Salt marshes are tidally regulated ecosystems found in the intertidal zone at the boundary between ocean and land. They are important coastal landforms as they are able to sequester carbon, protect unique wildlife, and act as a buffer against violent storm surges (Galbraith et al., 2002; Gedan et al., 2011; Mcleod et al., 2011). These ecosystems can bring economic benefit to local communities. For instance, Bergstrom et al. (1990) estimated that the recreational value of Louisiana's wetlands is around 145 million dollars per year. At the same time, salt marshes are often undervalued because the economic value of services associated with them is difficult to estimate and many uses are indirect (e.g. storm protection, shoreline stabilization; Barbier et al., 1997).

Sediment supply represents a fundamental parameter for estimating the resilience of a salt marsh (Fagherazzi et al., 2013; Ganju et al., 2017). If enough sediment is brought over the marsh platform during the flooding period, marshes can offset sea level rise (SLR) (Kirwan & Megonigal, 2013; Redfield, 1972; Reed, 1995; van Wijnen & Bakker, 2001). Marshes can adapt to SLR and survive as long as vertical accretion rates exceed rising water rates (Kirwan et al., 2010). Globally, the vulnerability to SLR has increased in recent decades because sediment fluxes are decreasing in many wetlands and deltas of the world, as a consequence of damming (Syvitski et al., 2005, 2009).

A reduction in sediment supply, combined with subsidence, is leading to rapid losses of deltaic wetlands in the Mississippi River Delta Plain (MRDP) (Day & Templet, 1989; Yu et al., 2012). Because of damming, between 1976 and 2006 the Mississippi suspended load has drastically decreased from about 400–500 MT/year to about 205 MT/year (Blum & Roberts, 2009), making the modern sediment load less than the value needed to build new land. Despite land gains made possible throughout various diversions and the application of marsh restoration and shoreline protection projects (Coastal Wetlands Planning, Protection and Restoration Act—CWPPRA), Barras et al. (2003) projected an 8.77% (1329 km^2) net land loss from 2000 to 2050.

The MRDP waters are microtidal, making the influence of astronomical tides of secondary relevance. For this reason, storms exert a high impact on sediment dynamics (Georgiou et al., 2005; Hiatt et al., 2019). Around 60% of tropical storms usually hit the coast between August and September (Stone et al., 1997). Cold fronts occurring during winter are extremely effective for erosion and sediment dynamics (Childers & Day, 1990). The wetland area is also subject to subsidence as a result of the natural compaction of the soil. Natural subsidence is enhanced by human activities like oil and water extraction (Törnqvist et al., 2008), which cause more compaction and act as additional degrading factors.

With the exception of the Atchfalaya Delta basin, which has experienced a growth of about 16 km^2, the remaining coastal land in Louisiana is currently undergoing a complex degradation process caused by rising sea level, subsidence, increased storminess, and wave erosion (Hiatt et al., 2019). Many studies and surveys along the Louisiana coast focused on the rate of land loss. For instance, Couvillion et al. (2017, 2011) used historical datasets, aerial photography, and Landsat images to detect land change and land loss. Twilley et al. (2016) adopted the 50% ratio land/water isopleths to measure coastal instability. These studies clearly show that the rate of land-to-water conversion is not homogeneous. Not only do different areas of the coast have different erosion rates, but even within the same marsh complex we find different deterioration rates, indicating that several drivers affect the wetlands.

Both erosional and depositional processes have been largely studied in coastal Louisiana. For instance, Valentine et al. (2021) found that in Terrebonne Bay, brackish marshes located inland tend to degrade as a result of drowning and collapse, while the saline marshes facing the bay tend to degrade due to edge erosion. Everett et al. (2018), by employing a wave spectral model, were able to relate wave power to edge retreat and quantify the contribution of swell and wind waves generated within Terrebonne Bay. Bendoni et al. (2019) used an improved version of the XBeach model to assess wave impact and morphological changes of the marsh edge profile. Likewise, several studies regarding marsh accretion have been published. Cahoon and Reed (1995) highlighted the importance of prolonged inundation periods to sediment deposition, generated by the passage of a storm surge. The importance of major events like hurricanes has been investigated by Cahoon et al. (1995b), who assessed the impact of Hurricane Andrew on the marsh surface, while Bianchette et al. (2016) considered the effect of Hurricane Isaac in 2012. Liu et al. (2018) used a numerical model to compute sediment fluxes on the marsh generated by Hurricane Gustav. All found that these events are able to bring a volume of sediment that surpasses the volume brought by tides alone. Despite describing the processes with accuracy, all these studies focus on either erosion or accretion, and do not consider how these two processes coexist and influence each other.

Novel studies of erosion–accretion feedback have recently been published. Valentine and Mariotti (2019) showed that the impact of wind waves is different depending on the direction a marsh faces. By measuring wave power, erosion, and soil strength in a restricted area of Barataria Bay (Louisiana), they showed that south-facing marshes, directly exposed to high water levels and waves, tend to accrete more because of waves bypassing the marsh boundary and higher availability of sediment due to wave resuspension; in contrast, north-facing marshes tend to erode more as they experience low water levels and higher rates of toe erosion. They extended the results to the entire bay using a 2D model. Mariotti (2020), by applying the MarshMorpho2D model in a microtidal and mesotidal marsh, showed that marsh edge and tidal flat erosion are a primary source of sediments and drive a faster accretion for seaward-facing marshes. Moreover, he highlighted the importance of channel widening and pond expansion as land loss mechanisms and suggested that the external sediment supply is a key factor for marsh survival. These studies, however, reached their conclusions either using very localized measurements or numerical models to infer physical mechanisms. Therefore, linking this feedback to measurements taken on a large scale can fill this knowledge gap.

In this study, we want to quantify how mechanisms of degradation and accretion work on a large scale in the deteriorating marshes of Terrebonne Bay (Louisiana). Specifically, we use processed sedimentation data collected across the entire bay, satellite images, and erosion maps. This is the first time that these spatially distributed data were combined to present a holistic view of erosion and deposition patterns in Terrebonne Bay.

2 | STUDY AREA

The study area is Terrebonne Bay (TB, Figure 1) in south Louisiana, located in the MRDP between the Atchafalaya and Mississippi rivers. TB is a microtidal environment, with an average tidal range around 40 cm, and lunar diurnal constituents K1 and O1 dominant. Saline marshes are *Spartina* spp. dominated, with *Spartina alterniflora* having a much higher presence than *Spartina patens*. One of the main aspects driving the drowning of Terrebonne marshes is the absence of riverine inputs and the isolation from the sediment-laden Mississippi River (Twilley et al., 2016). Specifically, in Terrebonne the sediment supply from the Mississippi River was diverted in 1903 (LBSE, 1904), and the bay has experienced a land loss of 1302 km^2 between 1932 and 2016, the greatest of all MRDP basins (Couvillion et al., 2017). Between 1932 and 2010, the landward migration rate was 216 m/year, and since 1949 saline marsh vegetation has increased its presence in the remaining wetlands by 25%, following an increase in salinity (Twilley et al., 2016). Moreover, as the bathymetry and topographic conditions changed, the wind fetch increased together with wave power, with a total increment of 50–100% in the Upper Terrebonne Bay (Twilley et al., 2016).

3 | DATA AND METHODS

All field data used in this study are obtained from the Coastwide Reference Monitoring System of Louisiana (CRMS, https://www.lacoast.gov/CRMS/) dataset. This programme monitors around 309 wetland sites along the Gulf of Mexico coast of Louisiana and offers a long-term and exhaustive dataset on hydrology and biology. For each station, water levels are provided at an hourly timescale, together with marsh elevation, salinity, soil bulk density, percentage organic content, and dominant vegetation species. Vertical accretion rates have been measured with feldspar horizons for several years and have already been processed by Jankowski et al. (2017). We compare these data to the following physical parameters derived from 2020 Google Earth satellite images: distance from the channel, channel width, distance

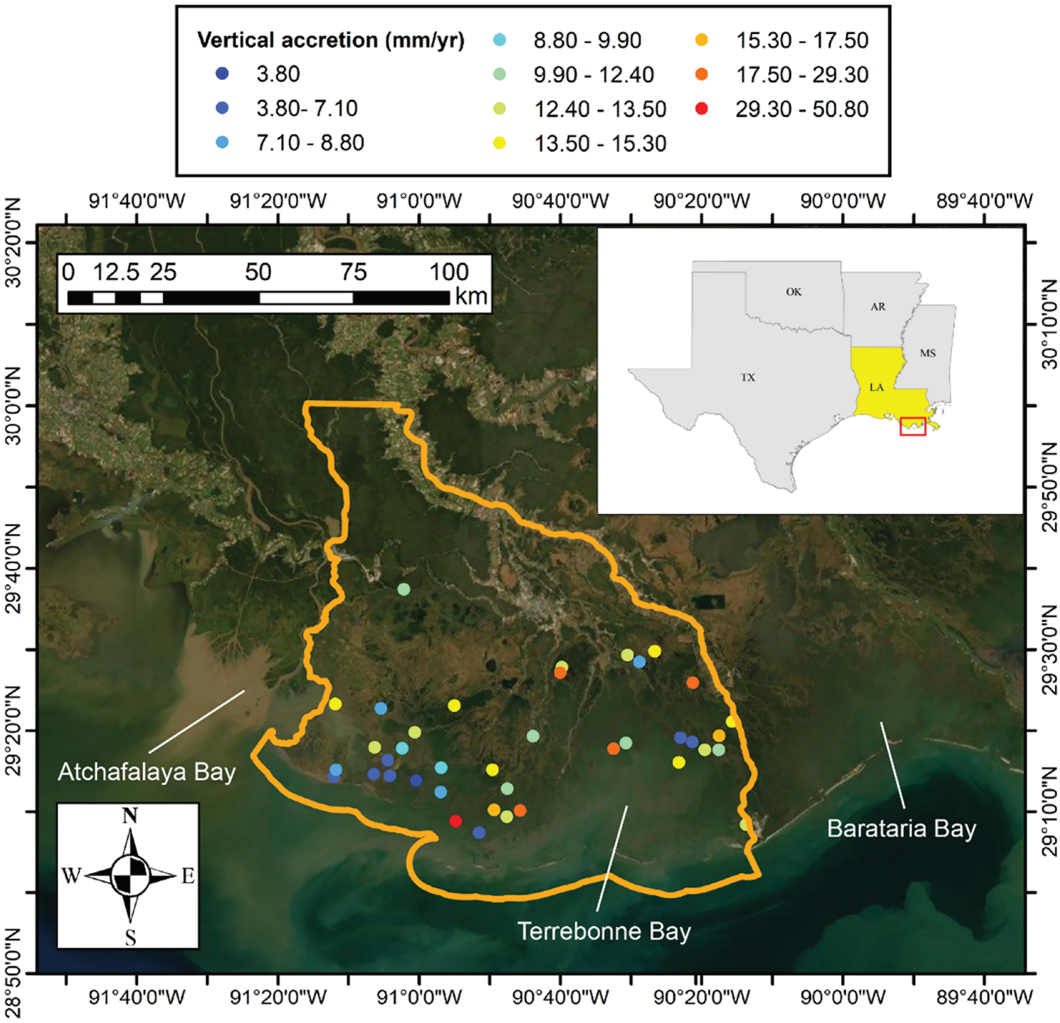

FIGURE 1 Aerial photograph of the Mississippi River Delta Plain in Louisiana, USA. The Terrebonne basin is highlighted with an orange contour. The dots are vertical accretion rates measured at CRMS wetland stations (see Jankowski et al., 2017) [Color figure can be viewed at wileyonlinelibrary.com]

from the bay, and maximum wind fetch. Distance from the channel bank is defined as the orthogonal distance between the point where accretion is measured and the nearest channel bank. Channel width is defined as the bank-to-bank distance in the nearby channel. Distance from the bay is computed in two ways: the shortest path length to open water (Terrebonne Bay or Gulf of Mexico), which we will refer to as 'distance to the bay', and the path length along the channel network. Finally, fetch is defined as the maximum water distance over which the wind can blow without encountering any obstacle. This parameter correlates directly with the energy of wind-generated waves (Young & Verhagen, 1996). Every station included in the CRMS network is found in the proximity of either the bay or a channel. Therefore, by taking the nearest point on the banks, we calculated the fetch by measuring the open water distance along eight possible directions (north, northeast, east, southeast, south, southwest, west and northwest) and then selecting the largest value.

In order to retrieve spatial data on erosion, the map of Couvillion et al. (2017) was used. The map shows land loss and gain for the entire MRDP from 1932 to 2016. The map was first converted into a TIF file and georeferenced using the Georeferencing tool available on ArcMap (version 10.7.1). The pixel size is 20 m. From the resulting map, three categories were defined: water, lost land, and existing land (Figure 2a). From the resulting map it is possible to observe areas where the land loss is confined and areas where the land loss is widespread (Figure 2b). To quantify the extent of land loss at each location, for each pixel identified as lost land the distance to the closest pixel identified as existing land was computed. Along a linear marsh boundary with uniform lateral erosion, the average of this distance is equal to half of the eroded marsh width.

Although the barrier islands system of Isles Dernieres and Timbalier Island is subject to land-to-water conversion, it is also highly affected by longshore transport. As a result, these islands are considered only for the computation of fetch, as they act as physical obstacles to wind and waves, but excluded for the land loss evaluation.

Finally, we computed the spatial distribution of the maximum fetch for each pixel that belonged to the water class and compared it to the extent of land loss map.

4 | RESULTS

4.1 | Extent of land loss as a function of fetch and distance from bay

The wind fetch is found to be highly variable, ranging from a few hundred metres to 80 km (Figure 3). We find the highest values for the

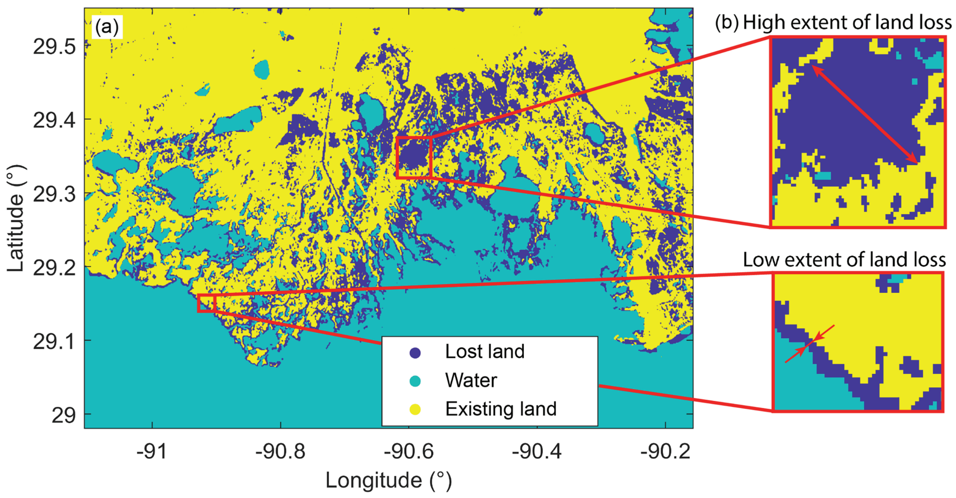

FIGURE 2 (a) Map indicating lost and existing marshland obtained from Couvillion et al. (2017). (b) Inset showing the extent of land loss. Note that it increases as the number of contiguous blue pixels increases [Color figure can be viewed at wileyonlinelibrary.com]

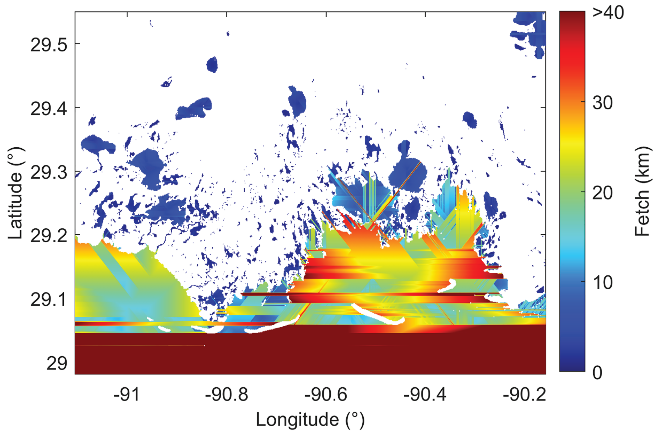

FIGURE 3 Maximum fetch for each point classified as water. The maximum fetch is selected from eight possible values (eight main wind directions). For clarity purposes, the colour bar is limited at 40 km [Color figure can be viewed at wileyonlinelibrary.com]

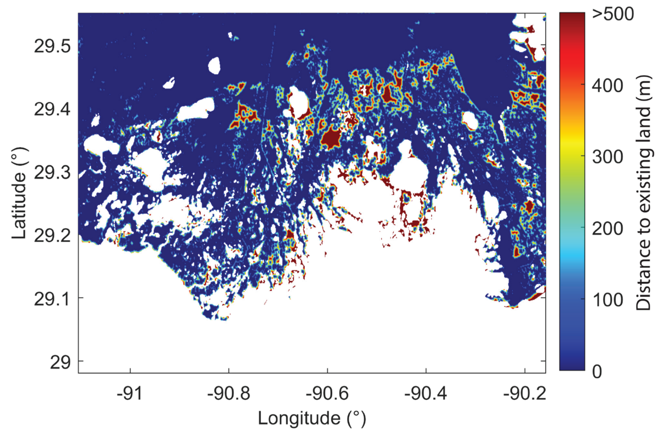

FIGURE 4 Extent of lost marshes in Terrebonne Bay. For each lost marsh pixel, the distance to the closest existing marsh pixel is calculated. For clarity purposes, the colour bar is limited at 500 m [Color figure can be viewed at wileyonlinelibrary.com]

areas facing TB and the Gulf of Mexico in the most western part, while in the inner marshes we find the highest values near large ponds and lakes, especially Caillou Lake, Lake Mechant, and Lost Lake.

From Figure 4 we can observe that the extent of land loss is very heterogeneous. In areas facing the bay we observe a limited loss confined at the edge of the marsh and in the proximity of large lakes. Degradation is more extensive in the proximity of the Houma Navigation canal outlet and in the central area, which has been converted almost completely to water. As we move northward, where the fetch is very limited, the areas affected by land-to-water conversion become larger. Here the loss of land appears more widespread, with many locations converted to ponds. In Figure 5 the distance from the bay for each lost land pixel is shown, while Figure 6 shows the distribution of the extent of land loss as a function of distance from the bay. The distribution is not normal and tends to be skewed towards medium–high values of distance. Outliers are also present, and for these reasons we used the median, instead of the mean, to describe the central tendency of the data, while we adopted the median absolute deviation to express the variability as it is also independent of the size of the sample (Huber, 2004). Figure 6 indicates the tendency of the system to increase the extent of land loss as the distance from the bay increases, with a peak at 27.5 km. After the peak the extent of land loss diminishes, although few lost land pixels are so distant, and this might affect the statistics (93.7% of the eroded pixels area between 0 and 27.5 km). For distances below 7.5 km, the median land loss does not exceed 180 m. We observe a significant jump for distances between 20 and 27.5 km, with a median extent of land loss of 1476 and 3330 m, respectively. Those are the values we see in the large patches in Figure 4 in the northern part of the bay. As we consider greater distances, the extent of land loss tends to decrease as the uppermost bay shows very small areas converted to water (see Figures 4 and 5). The comparison between lost area and fetch (Figure 7) displays a bimodal distribution, with the first and highest peak of 138 km^2 eroded area having small fetch (<10 km) and a second peak of 80 km^2 for a fetch within 40 and 45 km. We also note that the highest values of lost area are found for the two smallest ranges of fetch. It has to be noted that the fetch analysis presents some simplifications that could affect the relationship between fetch and lost area. The maximum fetch is computed by considering only eight directions and taking the maximum value, since we wanted to account for the most energetic waves. This choice led to a very fragmented map with abrupt jumps in fetch values even in close areas.

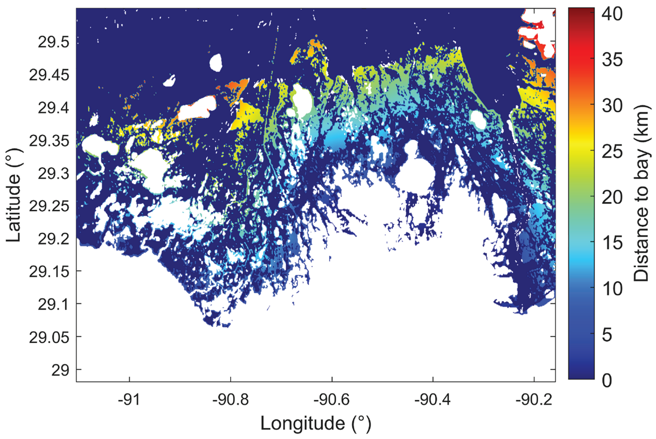

FIGURE 5 Distance of lost marshland from the bay [Color figure can be viewed at wileyonlinelibrary.com]

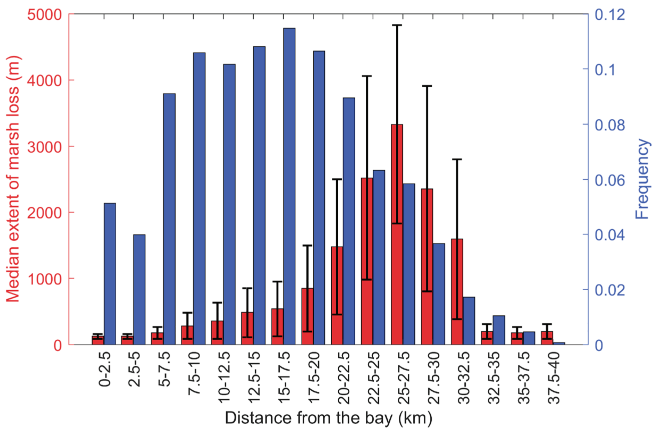

FIGURE 6 Distribution of the median value of extent of marsh loss as a function of distance from the bay (red bars). The black vertical error bar shows the median absolute deviation. Percentage of eroded pixels within each distance range (blue bars) [Color figure can be viewed at wileyonlinelibrary.com]

4.2 | Sediment accretion analysis

Of all stations considered, 31 out of 39 have as dominant vegetation species either *S. alterniflora* or *S. patens*, specifically 19 stations are *S. alterniflora* dominated. All *S. alterniflora* stations are located in the saline marsh, adjacent to the bay, while the *S. patens* stations are found in the brackish areas more inland.

For each of the variables used to find a correlation with vertical accretion rates, we ran a two-sample *t*-test to see whether the averages for the *S. alterniflora* and *S. patens* groups are different or not. We were able to reject the null hypothesis (of equal means) in two cases. We found that only elevation and salinity are statistically different between stations dominated by *S. alterniflora* and *S. patens*. We ran the test on vertical accretion also, and found no statistical difference.

Vertical accretion in Terrebonne Bay ranges from 3.80 to 50.80 mm/year. The highest value recorded in the region is at station 302 (the red dot in Figure 1), located very close to the Gulf of Mexico, 5 km northwest from Grand Pass des Ilettes. From Figure 1 we do not detect any large-scale geographic pattern. On the contrary, accretion rates are extremely heterogeneous, indicating that local factors and complex dynamics are controlling sedimentation. Figures 8a and b confirm the poor relationship between latitude, longitude, and vertical accretion. Elevation does not play a major role in predicting sedimentation rates ($R^2 = 0.0036$ and $p = 0.716$, Figure 8c). Vertical accretion is not related to salinity and bulk density of the sediments (Figures 8d and e). Vertical accretion appears correlated with channel width and distance from channel bank ($p < 0.05$, Figures 9a and b). Furthermore, vertical accretion is positively correlated with wind fetch ($R^2 = 0.64$ and $p < 0.05$, Figure 9c) and negatively correlated with distance from the bay ($R^2 = 0.57$ and $p < 0.05$, Figure 9d). Finally, we also found a relationship between the distance from the bay along the channel and the percentage of organic material in the sediments (Figure 9e). The regression gives a significant $R^2 = 0.55$.

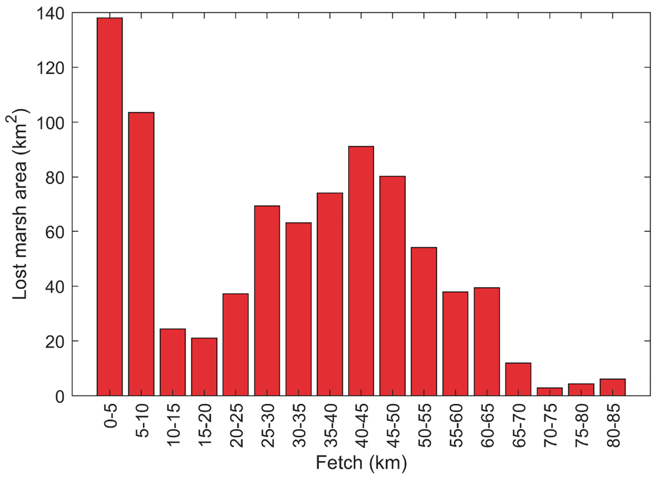

FIGURE 7 Lost marsh area for each fetch range [Color figure can be viewed at wileyonlinelibrary.com]

In addition to simple linear bivariate regressions, we used multiple regressions to determine what group of variables independently control vertical accretion. In order to find the combination of variables that explain the most variance, we first included all variables, and then excluded step by step those that were not significant. The results are summarized in Table 2. From the first regression, where all variables are counted, only elevation, distance from channel bank, distance from the bay, and fetch have a *p* value less than 0.05. Elevation and distance from the channel bank are then discarded in the last step, and distance from the bay and fetch are the only two significant variables. In the last regression all terms have $p < 0.05$ and global adjusted coefficient of determination $R^2 = 0.69$ with *F* statistic equal to 44.23. Since the critical value for *F* is 2.87, we have a regression variance much greater than the residual variance, so the coefficients are statistically different from zero. In Figure 10 the model results are compared to the observations. Due to the high value of R^2, the points are found close to the parity line, although some of them tend to be either under or over the line, indicating that missing processes are in some cases more relevant. Thus, the multiple regression confirms that distance from the bay and fetch are the two main drivers related to the rate of accretion. Of the four variables that have a meaningful relationship, only two are present in the final multivariate model.

5 | DISCUSSION

5.1 | Drivers of land loss

Terrebonne Bay is characterized by lack of sediment supply. The bay is located in an area highly impacted by storms (during both winter

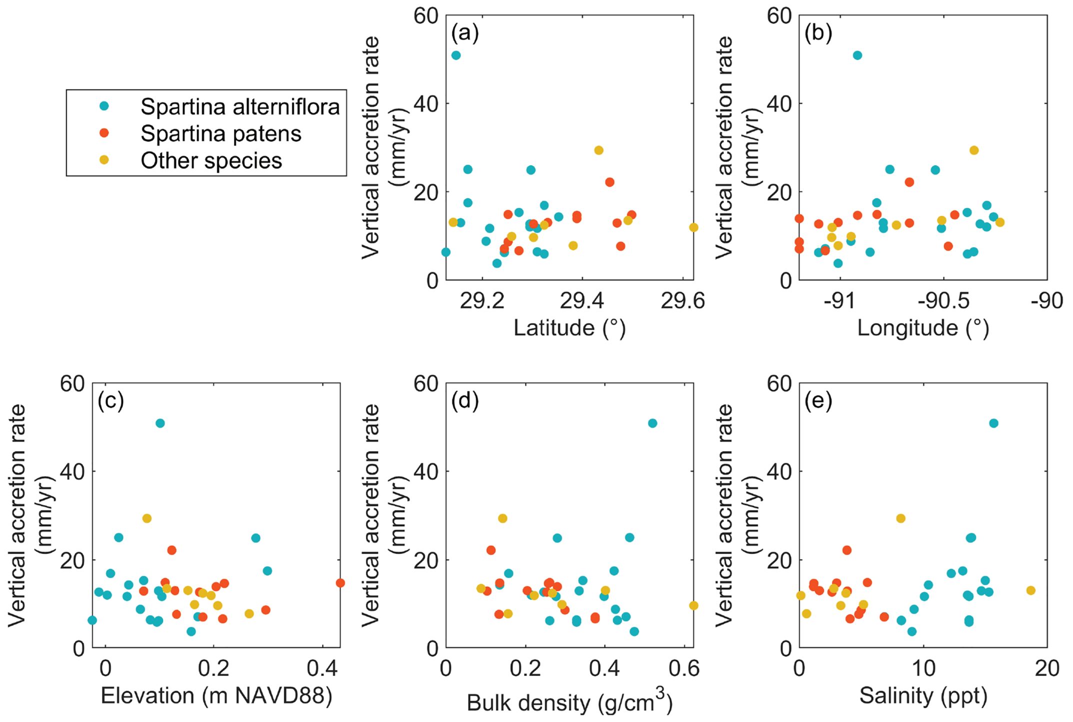

FIGURE 8 Scatterplots of accretion rates as a function of (a) latitude, (b) longitude, (c) marsh elevation, (d) soil bulk density, and (e) salinity. All variables show no correlation with vertical accretion rates. The dots are coloured as a function of the dominant plant species. For regression coefficients refer to Table 1 [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Coefficients of determination between physical variables and vertical accretion. The bold variables indicate a significant relationship ($p < 0.05$). The variables marked with an asterisk have a logarithmic relationship

Variable	R^2	*p* Value
Longitude (°)	0.0298	0.293
Latitude (°)	0.0030	0.741
Elevation (m)	0.0036	0.716
Channel width (m)	**0.5340**	**1.27e-07**
Distance from channel bank (m)*	**0.3050**	**2.64e-04**
Distance from the bay (km)*	**0.5653**	**3.45e-08**
Salinity (ppt)	0.0751	0.0913
Bulk density (g/cm^3)	0.0392	0.227
Fetch (km)*	**0.6000**	**7.18e-09**

and summer), which contribute to the degradation of the marsh by enhancing lateral erosion due to waves (Leonardi & Fagherazzi, 2014; Marani et al., 2011; McLoughlin et al., 2015). As previously noted, fetch is correlated with wave energy and here is found to have an impact on the lost marsh area. The bimodal distribution displayed in Figure 7 indicates that two groups can be identified: lost marsh areas with a limited fetch, found in the marsh interior or near channels and small ponds, and degraded areas bordering the bay or large lakes. The mechanism of erosion changes as the fetch increases, switching from widespread drowning and pond expansion for small fetches, to confined edge erosion for high fetches. From Figure 7 we deduce that the transition happens between the 10–15 and 15–20 km fetch bands, for which we see an abrupt decrease in lost area. Leonardi et al. (2016) showed that erosion due to waves has a positive linear relationship with the power of waves, which in turn increases with fetch. Areas included in those bands are mainly located around the western large lakes. Here fetch is high enough to develop waves and resuspension, but not high enough to produce lateral erosion. This range is optimal for marsh stability. Sheltered marshes with fetch <10 km are not impacted by waves, but at the same time they cannot rely on the enhanced resuspension of sediment and degrade as a result of poor sediment supply. Marshes facing the bay and with fetch >25 km degrade by lateral erosion triggered by wave action. The separation between exposed and interior marshes is also found in Figure 6: marshes close to the bay show a limited extent of land loss, while the extent of land loss increases for marshes far away. We interpret this difference as the effect of storm surges. During a storm, marshes near the bay receive a higher volume of mineral sediment, which allows them to accrete more (Figure 9d). Marshes far away from the bay receive less sediment and are more prone to large-scale collapse.

In the second half of the 20th century, coastal Louisiana marshes far from the bay have been subject to enhanced subsidence rate due to water and hydrocarbons extractions (Morton et al., 2002, 2005). The combination of subsidence with a lack of sediment supply made them more prone to drowning. Another driver of marsh interior loss is pond expansion. Mariotti (2016) and Schepers et al. (2020) showed that pond deepening and enlarging can be an irreversible form of land loss in a marsh with poor sediment supply and high rates of relative SLR. Moreover, when ponds become wide enough, waves can develop and trigger the mechanism of lateral erosion.

5.2 | Drivers of accretion rates

Our results indicate that multiple factors control accretion rates in Terrebonne Bay. When water reaches the top of channel banks

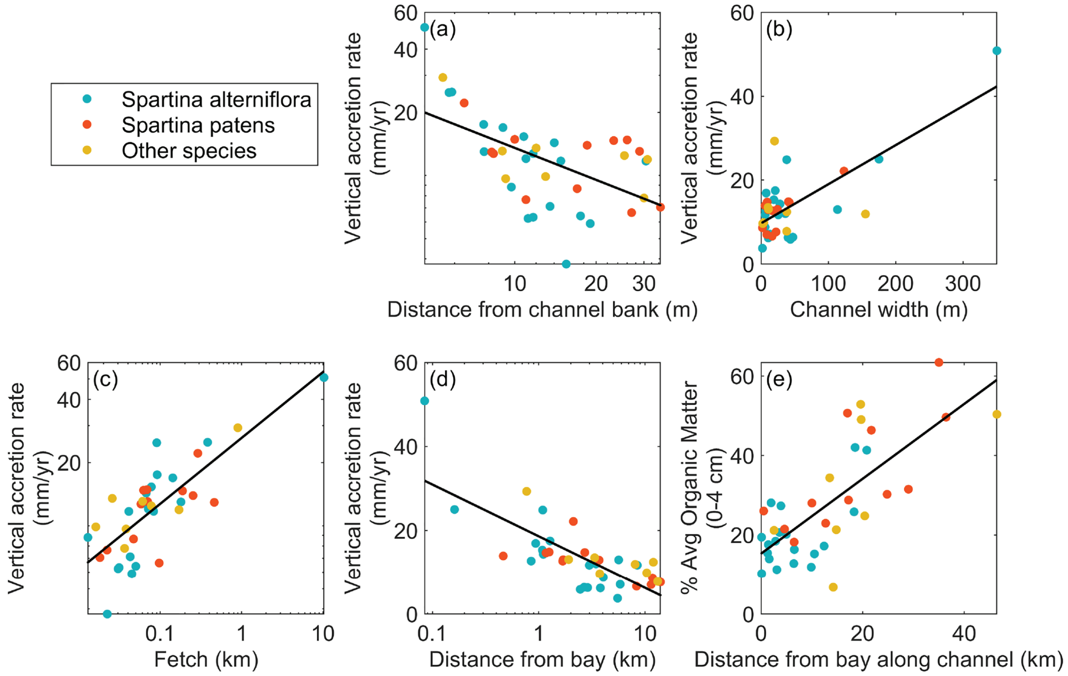

FIGURE 9 Accretion rate as a function of (a) distance from channel bank, (b) channel width, (c) maximum fetch, and (d) distance from the bay. All variables show significant correlation with vertical accretion rates. Subplot (e) shows percentage organic matter as a function of distance from the bay along the channels. The dots are coloured on the basis of the dominant plant species. For regression coefficients refer to Table 1. Note that subplots (a) and (c) have *y*-axis with logarithmic scale [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Summary of the multivariate linear regression. The intercept and slope term for each variable are specified for each step. The values with $p < 0.05$ are highlighted in bold

Step	Variable	Coefficient value	*p* Value
First	Intercept	4660.590	0.541
	Longitude	2.361	0.635
	Latitude	−7.949	0.560
	Elevation	**19.771**	**0.019**
	Distance to channel	**−0.205**	**0.048**
	Channel width	0.035	0.088
	Distance to bay	**−0.506**	**0.012**
	Distance to bay along channel	0.074	0.528
	Salinity	−0.081	0.824
	Bulk density	−9.496	0.413
	% Avg. organic matter	0.053	0.695
	Fetch	**2.641**	**0.001**
Second	**Intercept**	**15.829**	**3.09e-11**
	Elevation	12.918	0.119
	Distance to channel	−0.193	0.07
	Distance to bay	**−0.580**	**0.008**
	Fetch	**3.498**	**5.15e-09**
Third	**Intercept**	**15.005**	**2.20e-15**
	Distance to bay	**−0.664**	**0.001**
	Fetch	**3.625**	**2.70e-09**

and floods the marsh surface, it tends to deposit more sediment near the channel, often creating a natural levee (Christiansen et al., 2000; Neubauer et al., 2002). In our multivariate model, the distance from the bank is not included, meaning that when all variables are considered together, the distance from the bank does not provide unique information and results in a redundant variable. Yet locally the distance from the channel exerts some control on accretion.

The positive relationship between channel width and vertical accretion (Figure 9b) could be explained by looking at the typical

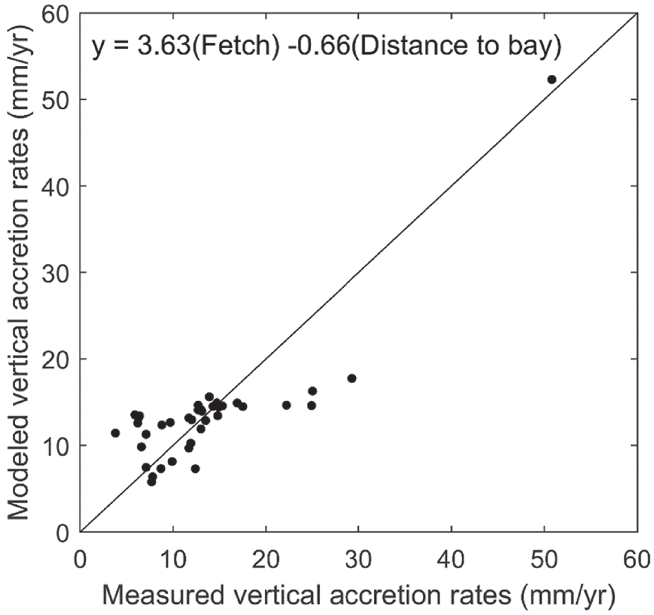

FIGURE 10 Model results compared to the measured values of vertical accretion

organization of a tidal channel network. The stream order is usually higher near the coast, where the channels are wide, and progressively decreases inland, where the channels become narrow (Hughes, 2012). This means that water and sediment are first conveyed in wide channels and then in small ones. The sediment load might decrease while propagating within the channel network, because sediment is constantly deposited at the bottom of the channels and in nearby marshes. As a result, small channels might receive less sediment. Channel width is not accounted for in the multivariate model, indicating that this variable is of less importance with respect to fetch and distance to the bay. The correlation between accretion rate and channel width is also affected by the large leverage of station 302, which has a very high value of accretion rate associated with a large channel (350 m wide). We therefore conclude that channel width exerts a secondary effect on accretion rate. The weak influence of channel width can also be justified by the small tidal range of Terrebonne Bay, where wind-driven storm surges are a fundamental source of sediment (Day et al., 1995). When a storm hits the marsh, it usually submerges the entire platform for a longer period compared to the tidal cycle, making tidal channels less relevant for deposition. Moreover, sediments are likely to be deposited in bands paralleling the outline of the marsh (Friedrichs & Perry, 2001). Therefore, storm deposition can weaken the correlation between accretion, distance to channel bank, and channel width.

Vertical accretion is positively correlated with wind fetch (Figure 9c) and negatively correlated with distance from the bay (Figure 9d), which means that areas more exposed to surface waves tend to increase their elevation faster, while sheltered areas in the marsh interior—where the action of winds and waves is limited—tend to accrete slowly. Waves enhance bottom shear stress and can resuspend sediments, thus increasing the concentration in the bays (Green & Coco, 2014). This sediment is then advected by tides and storm surges on the nearby marshes (Fagherazzi & Priestas, 2010). Sedimentation is also favoured by the prolonged marsh submergence time, due to the increased water levels during a surge (Cahoon & Reed, 1995). From our statistical model, fetch and distance from the bay are the two most important drivers of marsh accretion, explaining almost 70% of the accretion variability. Furthermore, as we increase the distance from the bay, the organic content increases (Figure 9e), indicating that accretion in salt marshes close to open water is mainly caused by mineral sediment coming from Terrebonne Bay and the Gulf of Mexico. In the inner marshes, organic deposition is more important, indicating that mineral sediment is less available as we move inland. This is consistent with findings from Mariotti et al. (2020), as they measured an organic matter content of 28±14% in internal brackish marshes compared to 17±7% in salt marshes.

Overall, we see that locations far from channels in sheltered areas are prone to accrete slowly with a higher contribution of organic matter, while marsh banks exposed to open water tend to grow faster with a higher inorganic fraction.

5.3 | Implications for marsh evolution and deterioration

Despite the positive accretion rates, it has been well documented that in Terrebonne the land-to-water conversion is an ongoing process (Couvillion et al., 2017). In this bay, marsh surface elevation is considerably affected by sediment compaction (Cahoon et al., 1995a). Recently, it has been proposed that the marshes might be unstable with current rates of relative SLR (Törnqvist et al., 2020). Marshes facing open bays are more subject to wind-waves effects. In Terrebonne, Everett et al. (2018) showed that rates of edge retreat are correlated with wave power. Waves resuspend sediments from the bottom by applying shear stress (Booth et al., 2000; Fagherazzi & Priestas, 2010; Green & Coco, 2014) and erode marsh edges at the same time (Leonardi & Fagherazzi, 2014; Marani et al., 2011; Priestas et al., 2015). These two processes have positive feedback: edge erosion exerted by waves enhances the creation of tidal flats, which in turn promote higher waves and sediment resuspension (Li et al., 2019; Mariotti & Fagherazzi, 2013). In Terrebonne, marshes facing open bays accrete faster because waves resuspend and bring over the marsh platform a higher volume of sediment. Moreover, not only the sediment from the bottom of the bay is resuspended, but also the eroded material from the marsh edge itself represents a considerable contribution to total vertical accretion (FitzGerald & Hughes, 2019; Hopkinson et al., 2018). These marshes experience high rates of lateral erosion (Couvillion et al., 2017) (Figure 11a). Because Terrebonne is microtidal, this mechanism can be further enhanced by SLR (Spencer et al., 2016).

Marshes that are found in sheltered areas are not affected by waves. Here the vertical accretion is a function of the flooding regime. As there is less sediment resuspension by waves, in normal conditions the tidal currents might not bring significant volumes of material to the marsh platform. Storm surges can increase the volume of sediment carried on the top of the marsh, but a large part of this sediment is often returned to the bays during the following ebb tide (Fagherazzi & Priestas, 2010). This mechanism is active during the passage of cold winter fronts. Winds that hit the coast from the south and the east enhance the inundation of the wetlands and the resuspension of sediments (Murray et al., 1993; Wang et al., 1993). As the front passes, the wind direction changes to the north and the

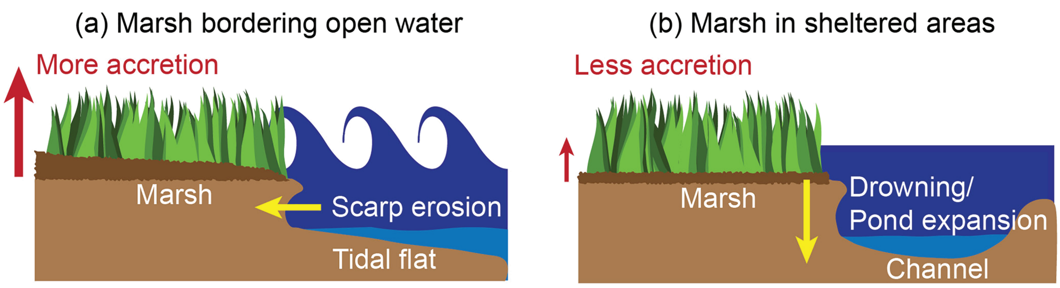

FIGURE 11 Styles of marsh degradation. (a) Marshes facing open water are affected by waves that lead to scarp erosion and high accretion rates on the platform. (b) Marshes in sheltered areas where the waves effect is negligible receive less sediment and might drown due to subsidence and pond expansion driven by sea level rise [Color figure can be viewed at wileyonlinelibrary.com]

west, accelerating the drainage of the wetlands (Childers & Day, 1990). Compared to marshes facing the bay and the ocean, marshes located in the interior and drained by channels are consequently accreting less. Despite the fact that they degrade less at the boundaries (Couvillion et al., 2017), they can drown because of the high subsidence rates and SLR (Törnqvist et al., 2008; see Figure 11b).

6 | CONCLUSIONS

In this study, we analysed the drivers that determine accretion and erosion patterns in the degrading marshes of Terrebonne Bay, Louisiana, USA, by coupling field data derived from the CRMS database and image processing of maps. Although previous studies described the same feedback between degradation and erosion, for the first time we used here large-scale spatial data of both accretion and land loss to explain the processes, without employing numerical modelling. Edge retreat is often studied by means of wave spectra analysis (e.g. Everett et al., 2018), derived wave gauge data, installed pressure sensors and numerical modelling, or from wave model outputs. Here, we showed that fetch, which can be spatially computed at any point of the bay, can be used to quantify the effect of waves on marsh boundaries and be related to the extent of marsh loss. Moreover, we showed that a reliable estimate of accretion rates can be simply obtained using fetch and distance from the bay, both of which are easily retrievable parameters.

A statistical analysis indicates that marshes facing open areas tend to aggrade at higher rates with respect to marshes located inland. The data analysis provides an additional insight on the main drivers regulating sedimentation. Initially we found that channel width, distance from the channel bank, distance from the bay, and wind fetch are the main drivers correlated with vertical accretion. When considered in a multivariate model, we found that distance from the bay and fetch are the most important variables, as they affect more this microtidal system in which channels play a secondary role in the distribution of sediments. An analysis of the erosion map of Couvillion et al. (2017) allows us to investigate how erosion is correlated with the distance from the bay and fetch. We found that marshes closer to the bay tend to have a more limited land loss, while sheltered marshes located in the north part of the bay are affected by large-scale land loss. Moreover, the distribution of land loss area as a function of fetch is bimodal, with peaks for small fetch values, indicating the vertical collapse of sheltered marshes in the interior, and for a fetch of 40 km, indicating horizontal edge erosion by waves.

Using our results, we propose a twofold, unifying conceptual model that explains the patterns of sedimentation and erosion and related feedback. Marshes facing the open bay are directly affected by the action of storm waves that trigger marsh retreat by edge erosion while enhancing the resuspension of sediment. During storms, the increased water levels and higher sediment concentrations allow high volumes of sediment to deposit on the marshes. In marshes facing open water, the degradation is more persistent but also confined to the edge. Marshes located in sheltered areas and fed by one or more channels are highly affected by the sediment volume carried by the channels. Their vertical accretion is regulated by flooding events during high tide and storm surges, but due to reduced sediment supply, the volume of sediment imported in these areas is limited. The degradation mechanism is therefore bulk drowning and pond expansion as a consequence of subsidence and SLR.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Coastwide Reference Monitoring System at https://lacoast.gov/crms/.

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