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The concept of land bridge marshes in the Mississippi River Delta and implications for coastal restoration

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ABSTRACT

Louisiana has high coastal wetland loss rates due to natural processes such as subsidence and anthropogenic activities such as construction of river levees and dams, pervasive alteration of surface hydrology by local industries such as oil and gas, and navigation. With the exception of the Atchafalaya River discharge area, most of Louisiana's marsh coastline is retreating and coastal marshes are degrading. In the inactive degrading delta regions, there exists a previously uncharacterized landform referred to colloquially as coastal 'land bridge' marshes. Land bridge marshes are saline or brackish marshes fronting large estuarine bays or lakes with sufficient fetch and wave energy to supply high levels of resuspended sediments to the marsh surface. They are generally linear features that are oriented parallel to the coast and the shoreline front retreats landward due to erosion from wave energy. These marshes persist over time vertically due to input of resuspended sediments but are experiencing rapid edge erosion due to wave attack. Comparison of data from Louisiana's Coastal Reference Monitoring System (CRMS) sites show that land bridge marshes have a greater frequency of higher soil surface elevation and higher soil bulk density than non-land bridge marshes. Because land bridges are vertically stable relative to other coastal wetlands, identification of measures to sustain these landscape features is important. Simulations using MarshMorpho2D, a process-based reduced-complexity morphology model, suggest that protection barriers installed on the seaward side of land bridge marshes will attenuate wave energy and, thus, edge erosion. Shoreline protection that can reduce wave energy but still allow sediment input to marshes include living shorelines, rock barriers, and/or breakwaters. Periodic thin layer nourishment of the marsh surface may be necessary to help sustain vertical growth. Further, marsh creation projects directly landward of land bridge marshes may benefit from their protection from waves and as a source of sediment. Consideration of land bridge marshes as distinct marsh types in the State Master Plan and integrated modeling could help to identify measures to sustain these landscape features.

Introduction

The Mississippi River Delta lost about 25% of its coastal wetlands during the 20th century primarily due to river engineering designs that reduced Mississippi River sediment input and pervasively altered wetland hydrology [1–4]. In addition, coastal flooding to communities has become more common, and was disastrous during Hurricane Katrina [5,6] and later storms such as Hurricanes Laura, Delta [7] and Ida [8]. In response to such crises, the State of Louisiana is currently involved in the largest coastal restoration and protection effort globally, specifically the Louisiana Coastal Master Plan (CMP). The 50-year CMP utilizes a variety of restoration approaches, including river diversions, marsh creation using dredged sediments, levees for flood risk reduction, and shoreline protection [4,9]. For the CMP to be most effective, it is important to understand why some coastal marshes have been resilient and exhibit significantly lower rates of wetland loss and shoreline migration than other coastal marshes. As expected, areas along the coast receiving significant river discharge such as the Atchafalaya River and Wax Lake deltas have lower rates of wetland loss, and even wetland gain, and stationary shorelines [3,10,11]. Inactive delta basins including Terrebonne, Barataria and Breton Sound experience inland migration of shorelines due to wave erosion [11] as younger geomorphic phases of the Mississippi River Delta retreat in response to river abandonment. We suggest that the shoreline of these more stable marshes in younger

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inactive delta basins reach a position where sufficient open water and fetch produce sufficiently strong wave action and input of resuspended sediment to create a stabilized coastal landscape feature of the delta cycle known as ‘Land Bridges’ attributable to their general linear shape and orientation parallel to the coast. There are other inactive delta areas with older more stable marginal deltaic features such as the Biloxi marshes that also represent land bridges resulting from input of resuspended sediment as a result of wave activity [12]. However, the concept and extent of land bridge marshes as a landscape feature of the delta cycle has not been carefully defined or quantified. The objectives of this paper are to describe both land bridge marshes as a feature of the delta cycle and coastal restoration projects that would sustain these important landscape features. Given the demise of deltas globally, it is important to consider this important feature of the delta cycle when identifying measures to protect and conserve delta resources and communities in times of declining sediment delivery and accelerated sea level rise.

The land bridge as a feature of the delta cycle

A land bridge is a saline or brackish coastal marsh fronting a large bay or large estuarine lake with sufficient fetch and wave energy to supply resuspended sediments that stabilize it vertically but that also causes shoreline erosion during the degradation phase of the delta lobe cycle (Fig. 1). The shoreline front of a land bridge marsh retreats over time in inactive basins as part of the degradation phase of the delta lobe cycle associated with river abandonment [13] (Fig. 1). The inland migration of wetland shorelines in geologically recent inactive deltas can be plotted using marsh to water ratios of 50% as proposed by [14] (Fig. 2; [11]). The movement of the 50% marsh:water isopleth was nearly 18 km between 1932 and 2010 in both Terrebonne and Barataria basins. The water areas (area <50% marsh:water) in the Terrebonne Basin increased 1545 km^2 during this time period, almost doubling over 78 years. As water areas enlarge, fetch and wave energy increase. In Terrebonne Bay, where the largest landward migration of the <50% marsh:water ratio isopleth has occurred, and Breton Sound the wave power has increased by 50 to 100% from 1932 to 2010 [11,15,16]. The marsh erosion rate was 53% lower with small fetch marshes compared with marshes facing a large, open water fetch in Barataria Bay [17].

Wetland loss in land bridges is primarily due to wave-induced shoreline erosion on the seaward side of the marshes whereas in more interior marshes degradation is caused by surface elevation deficits and excessive inundation. As a result, land bridge marshes can be identified using historical images of wetland loss such as that created by [3]. Wetlands with lower rates of land loss and fronting large water bodies of inactive delta basins are identified as land bridges compared to more interior wetland areas with higher rates of land loss [3] (Fig. 3). Increased fetch contributes to wave energy that may de-stabilize fringe marshes of land bridges, but eroded and re-suspended sediments are deposited on the land bridge marshes, primarily during high energy events such as frontal passages and hurricanes (e.g., [18]). Thus, sediment input is not directly from riverine input, as in the active Atchafalaya delta complex, but resuspended from bay bottoms or the nearshore Gulf of Mexico. It is important to note that active delta basins connected to the Mississippi River are not associated with land bridge marshes as this is a feature resulting from river abandonment and delta degradation.

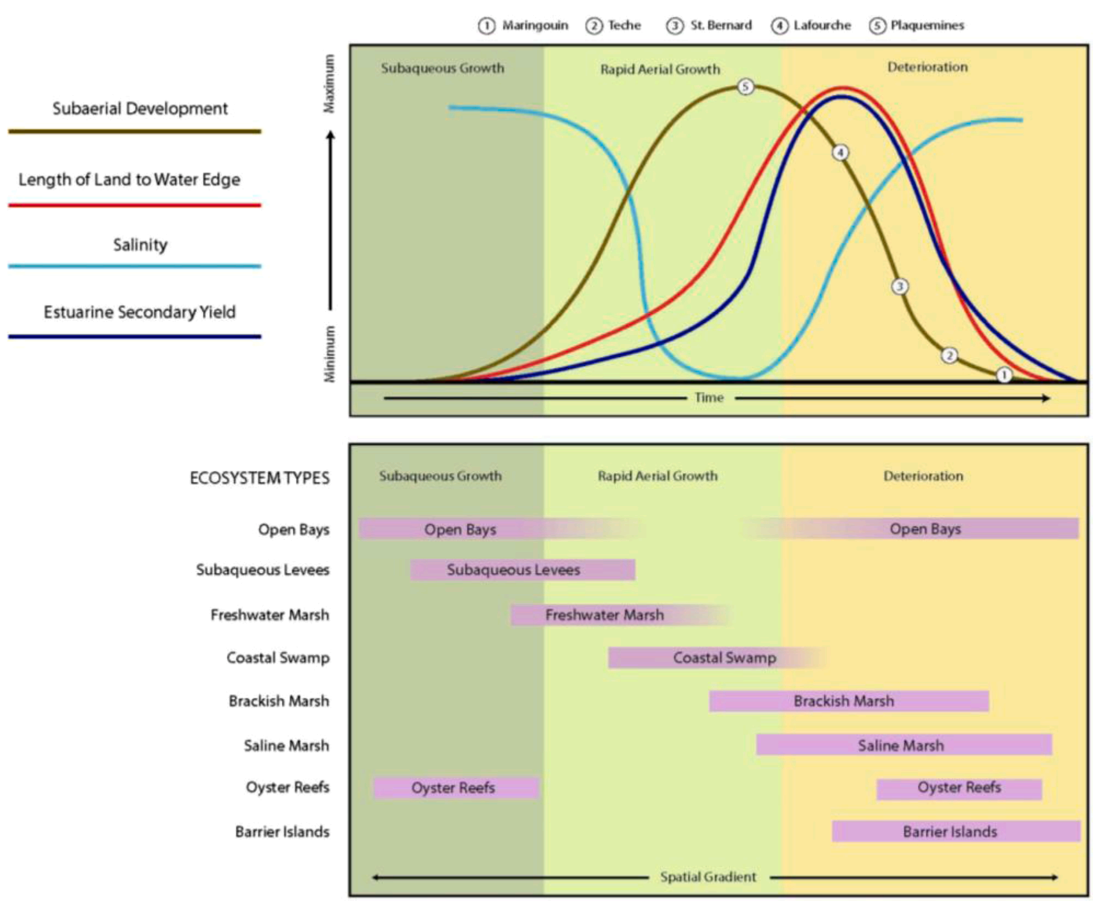

Fig. 1. Ecosystem development along the spatial and temporal gradients of delta cycle associated with magnitude of sediment delivery to coastal basins including specific attributes of coastal basins (subaerial development, length of land to water edge, salinity, estuarine secondary productivity) and distribution of ecosystem types in a coastal basin with magnitude of river input (modified from [20,21]). Numbers refer to different delta lobes over the last 6000 years formed from river avulsions in the Mississippi River Delta [11].

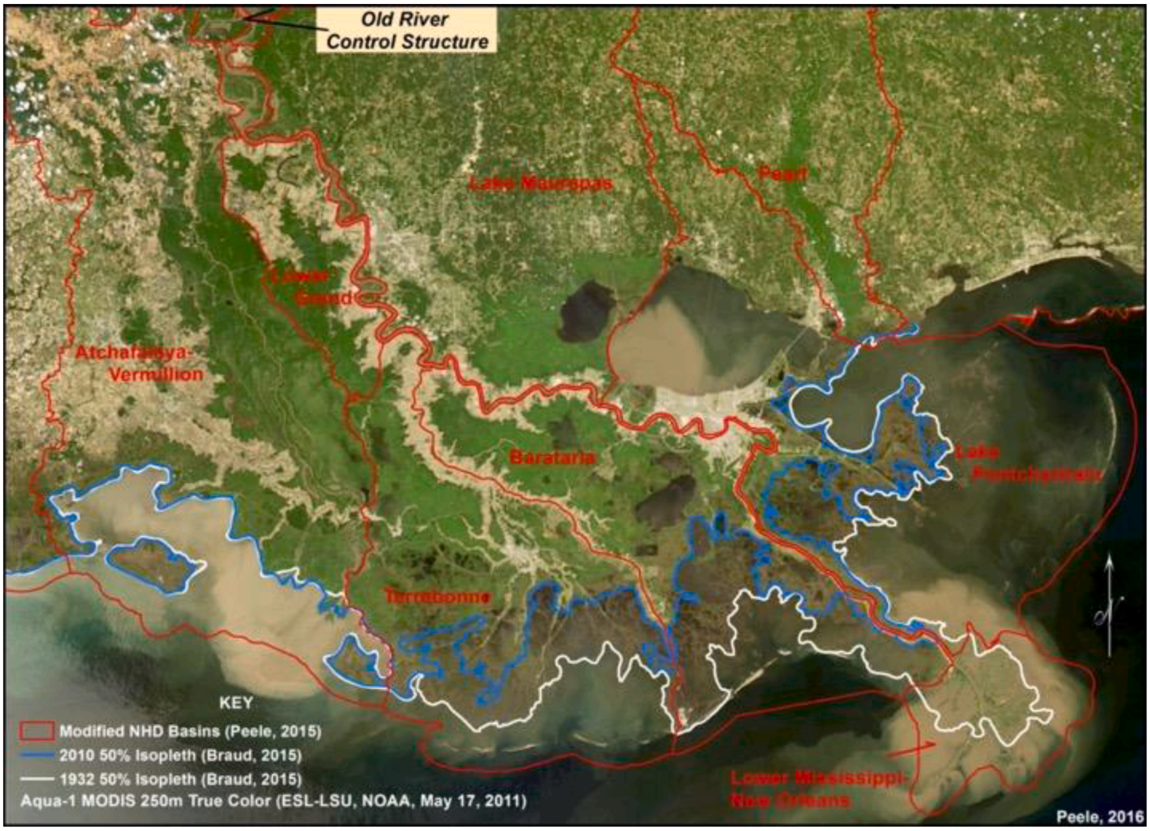

Fig. 2. Map of Mississippi River Delta showing progressive position of the 50% land:water isopleth along the coastal basins using a 1932 land vs. water composite image compiled from 1930s USGS topographic quadrangles compared with a 2010 land vs. water composite image compiled from LANDSAT satellite imagery. Isopleths were overlaid on a 2011 MODIS satellite image showing distribution of sediment during the 2011 major flood event. The Atchafalaya coastal basin receives direct riverine input while the Terrebonne, Barataria, and Breton Sound (just east of the Mississippi River) basins have little direct riverine input. Modified from [11]. R. H.Peele and D.Braud made the indicated changes to the figure in 2015. The map key lists the GIS data layers Peele and Braud creatd. The references to Peele and Braud in 2015 and 2016 do not refer to publications. The cartographer and creation date are cited in the lower right corner of the figure.

Mapping of coastal wetland loss shows the broad zone of more intact marshes in land bridges in the inactive basins of the deltaic plain [3,19] (Fig. 3). To determine the characteristics of land bridge marshes in the Mississippi River Delta, marshes adjacent to open bays and more inland marshes were identified and then ecosystem characteristics were evaluated using Coastwide Reference Monitoring System (CRMS) data. Marsh sites in the vicinity of the Atchafalaya River delta complex and on Marsh Island were also included for comparison to more stationary shorelines. A total of 118 CRMS stations in coastal deltaic plain marshes were classified *a priori* as either land bridge or non-land bridge marsh (Fig. 4). After classification in either of these two categories, site characteristics of the respective CRMS sites were compiled, including vegetation, elevation, long-term and short-term accretion rates, surface elevation change rates, soil salinity, soil bulk density, and organic matter content. Land bridge marshes were mostly mesohaline to polyhaline while non-land bridge marshes located in the interior were primarily fresh to oligohaline.

A comparison of elevation dynamics and soil characteristics was conducted for marsh types and basins with greater than two CRMS sites in each land bridge and non-land bridge category (Tables 1 and 2). There were not enough data for fresh, fresh/brackish, fresh/intermediate, intermediate/brackish/saline, and brackish marshes for a robust comparison. For brackish/saline marshes, there was no significant difference in elevation, long-term and short-term accretion rates, surface elevation change rates, soil salinity, soil bulk density, and organic matter content between land bridge and non-land bridge marshes.

Using brackish and intermediate salinity marsh types combined, elevations were not statistically different between land bridge and non-land bridge sites, but a comparison of elevation frequency distributions illustrates that land bridge marshes have a greater frequency of higher elevations than non-land bridge marshes (Fig. 5). Mean soil bulk density in land bridge marshes was also significantly greater than non-land bridge marshes in Terrebonne basin ($p = 0.0461$; Fig. 6) and likely contributed to the resilience of these marshes. The greater frequency of higher soil surface elevation and surface elevation change rate may explain the lower surface accretion rates in land bridge sites compared to non-land bridge marshes (Figs. 7 and 8, respectively). Sapkota and White [17] found that marsh edge erosion rates were negatively correlated with bulk density which demonstrates mineral-amended marshes are more resistant to erosion.

Land bridge marshes tend to have higher salinity and a higher soil surface (platform) elevation than non-land bridge marshes but also have lower rates of accretion and elevation increases over time due to their higher elevation. Land bridge marshes also have lower soil organic matter content that non-land bridge marshes (Fig. 8).

Mechanisms maintaining wetland sustainability in land bridge marshes

As noted above, marshes in land bridges are maintained by mineral sediment input resuspended from adjacent bay bottoms and the near-shore Gulf of Mexico. The passage of cold fronts and hurricanes often results in high rates of sediment deposition on the surface of coastal wetlands, especially those adjacent to large water bodies [22,23]. Winter storm fronts generally pass every 7 to 10 days from November through March, resulting in frequent flooding and draining of marshes [24]. The strong frontal winds resuspend shallow bottom sediments

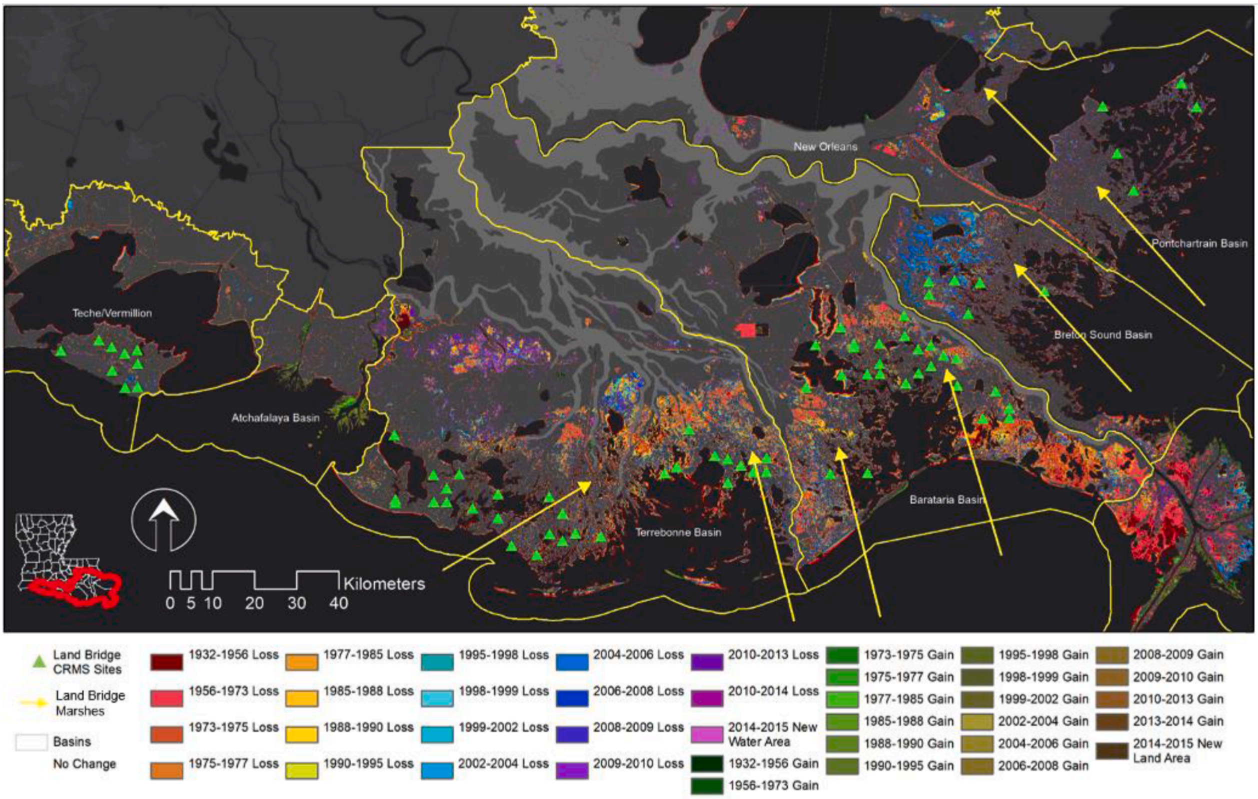

Fig. 3. Wetland loss in the Mississippi River Delta [3] (Couvillion et al. 2017). Different colors represent land loss during different time periods. Yellow arrows indicate the position of marshes identified *a priori* as Land Bridge marshes in the Deltaic Plain (as indicated by low wetland loss). These marshes have experienced lower loss rates than marshes further inland and in the Birds Foot delta. Edge erosion due to wave attack is the major mechanism of wetland loss in land bridge marshes. Green triangles are CRMS stations used in the analysis of land bridge and non-land bridge marshes. The marshes in the Atchafalaya discharge-influenced area are similar to land bridge marshes but with the additional direct input of Mississippi River water via the Atchafalaya River. Note that wetland loss does not increase with distance from open bays in the area influenced by Atchafalaya River discharge. See Fig. 4 for marshes identified either as land bridge or non-land bridge marshes.

resulting in total suspended sediment (TSS) concentrations often between 400 and 600 mg/L to as high as 2000 mg/L (Fig. 9; [18]) and high deposition of mineral sediments in wetlands [25–28]. Roberts et al. [24] found a mean of 1.9 cm of mineral sediment deposited 100 m from the marsh edge from cold fronts. Land bridge marshes occur in inactive delta basins without riverine sediment inputs, but still can have extremely high TSS concentrations in association with meteorologically driven events that resuspend bottom sediments. For example, Bayou Chitigue of northern Terrebonne Bay is an inactive delta basin, yet [29] recorded sediment concentrations over 2000 mg/L during a severe winter storm and attributed the high levels to channel scour and resuspension of bay bottom sediment. TSS concentrations up to 1840 mg/L have been recorded in lower Barataria Bay during cold front passages [30]. Hurricanes-driven waves have the potential for significant distribution of bay muds into the interior of marsh platforms. The eye of Hurricane Ida passed over the town of Lafitte, Louisiana on August 26, 2021 and deposited a layer of mud throughout the town (Fig. 10).

Sediment deposition during Hurricane Andrew was much greater on coastal marshes located within land bridges that were hydrologically connected to Barataria and Terrebonne bays than those that were not within a land bridge and had no direct bay connection (Fig. 11; [31]). A simulation of hurricane impacts of sediment transport in Terrebonne and Barataria basins demonstrated that the source of sediment deposited on marsh surface during storm events is from resuspended sediment in the bay rather than from the nearshore region [28]. Up to 12 cm of sediment was deposited on Barataria Bay land bridge marshes during the 2008 hurricane season, which was strongly related to marsh primary production (Fig. 12; [22]). *S. alterniflora* productivity showed a strong linear relationship with the depth of hurricane sediment deposition, with plant production increasing by a factor of three with deposition up to 9 cm. Other species showed a relative doubling of production. Thus, hurricane sediment deposition is an important mechanism of sediment delivery to land bridge wetlands along open water bays and lakes helping to offset relative sea level rise in inactive delta basins. In active delta basins, such as Wax Lake Delta, deposition from river floods can contribute more sediment than storm events, particularly when the frequency of these two types of events is considered [23].

The impact of Hurricane Ida in Sept. 2021 demonstrates the relative stability of land bridge marshes in the Barataria Basin with respect to hurricane impact. Land bridge marshes had significantly less land loss rates than marshes inland of these marshes east and north of Little Lake (Fig. 13). Hurricane impacts to marshes are very distinct in oligohaline dominated marshes of active delta basins compared to more saline marshes in inactive delta basins. In active basins, salinity impacts associated with storm surge during hurricanes have short-term disturbances to oligohaline marshes such as in Wax Lake Delta [23,28,32].

Total suspended sediments in breton sound

TSS observations in the Breton Sound estuary from 2000 to 2002 demonstrate the two sources of TSS for the upper Breton Sound where most wetlands occur (Fig. 14). The main source of sediments to the northern part of the basin is from the Caernarvon diversion in winter and spring when the diversion structure is most often open. TSS concentrations when the structure is operating generally range from 50 to over 200 mg/L. TSS concentrations decline down basin as sediments settle from the water column and are deposited in wetlands when water flows

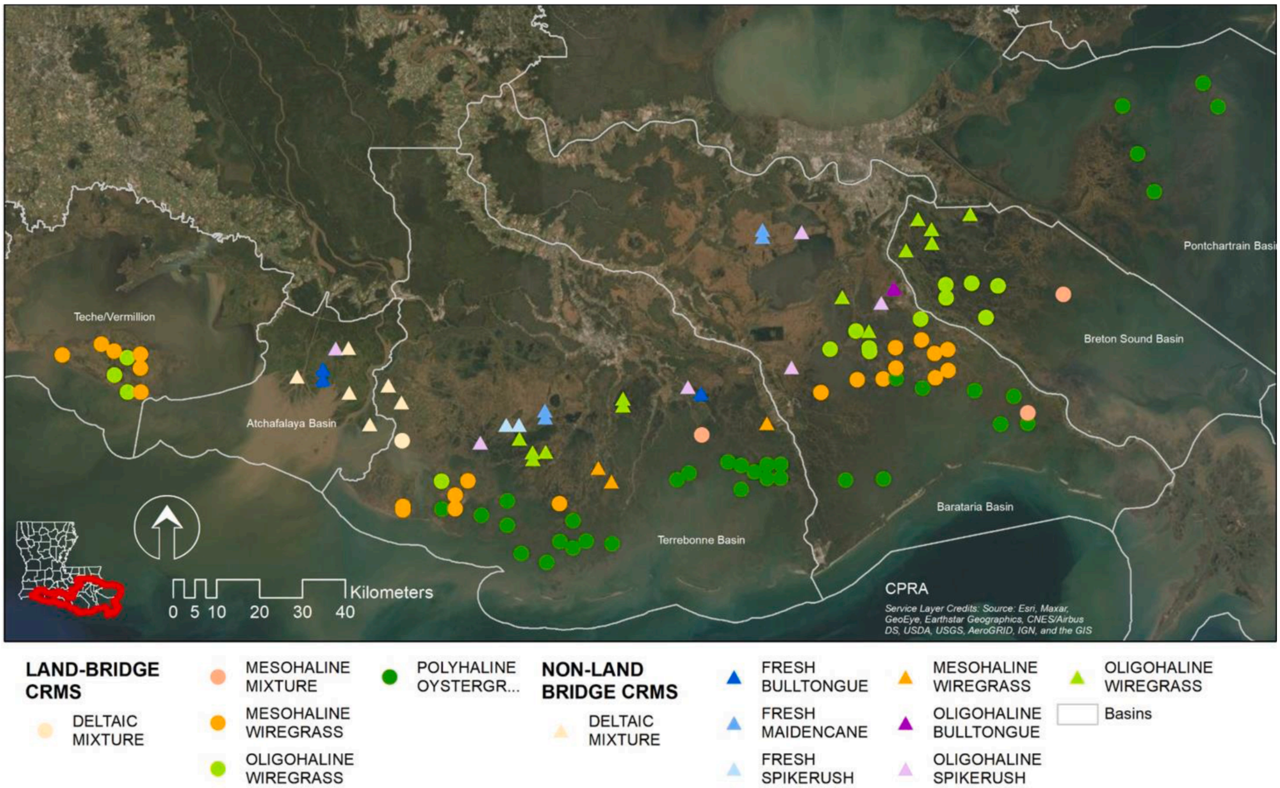

Fig. 4. Vegetation types of marshes classified *a priori* as land bridge (circles) and non-land bridge (triangles) marshes in the Mississippi River Delta. Marshes at coastwide reference monitoring system (CRMS) stations classified as land bridge marshes are primarily mesohaline or polyhaline. Marshes at CRMS stations classified as non-land bridge marshes are primarily fresh to oligohaline.

Table 1
Number of coastwide reference monitoring system (CRMS) stations in land bridge and non-land bridge marshes classified by marsh type.

Marsh type	Land bridge	Non-land bridge
Fresh	0	16
Fresh/Intermediate	1	14
Intermediate	11	5
Intermediate/Brackish	10	4
Intermediate/Brackish/Saline	1	2
Brackish	6	0
Brackish/Saline	6	3
Saline	39	0
Total number of sites	74	44

Table 2
Number of coastwide reference monitoring system (CRMS) stations in land bridge and non-land bridge marshes classified by hydrologic basin of the Mississippi River Delta.

Basin	Land bridge	Non-land bridge
Atchafalaya	0	10
Barataria	23	10
Breton Sound	6	5
Pontchartrain	5	0
Teche/Vermillion	9	0
Terrebonne	31	19
Total number of sites	74	44

over the marsh surface. TSS from the diversion generally settle and deposit between 10 and 20 km from the diversion.

A second source of suspended sediments comes from the south, and this source is important to maintaining land bridge marshes. These sediments are resuspended from bottom sediments in the open waters of upper Breton Sound. Upper Breton Sound is regularly supplied with riverine sediments via overbank flooding through channels from the Mississippi River. The highest concentrations were in excess of 200 mg/L and decrease up basin. Because of the inability of sampling during high energy events, this sampling did not capture the high TSS concentrations associated with these events. Because of the high sediment input, the marshes closest to the open waters of Breton Sound are very stable and most wetland loss is due to edge erosion caused by waves [33].

These two sources of sediments, one from the diversion and another from Breton Sound, result in high sediment availability in the upper and lower parts of the wetland-dominated part of upper Breton Sound but lower sediment availability in the middle portion of Breton Sound marshes.

Sedimentation and accretion

The regional rate of geologic subsidence in the Mississippi River Delta averages about 10 mm per year, primarily due to consolidation of Holocene sediments [1,35]. In sustainable wetlands, this subsidence is offset by mineral sediment and organic matter accretion. Sedimentation is the mass of sediments deposited and accretion leads to an increase in surface elevation of the marsh platform. A reduction of sediment delivery into marshes, especially interior marshes and those impounded by canal spoil banks leads to decreases in soil accretion, enhanced subsidence, increased inundation, and vegetation water logging stress [1,2,10,36–38]. Accretion of both mineral and organic matter helps offset relative sea level rise (RSLR) while healthy plant roots stabilize the marsh platform to minimize soil erosion and lead to organic soil formation from root production. Sedimentation in impounded and non-impounded coastal Louisiana wetlands, resulting from vertical features such as levees and spoil banks that reduce sedimentation, demonstrates the significance of slight changes in mineral sedimentation rates to the ability of the wetlands such as land bridges to offset shallow subsidence. The mean sedimentation in impounded areas averaged 0.75

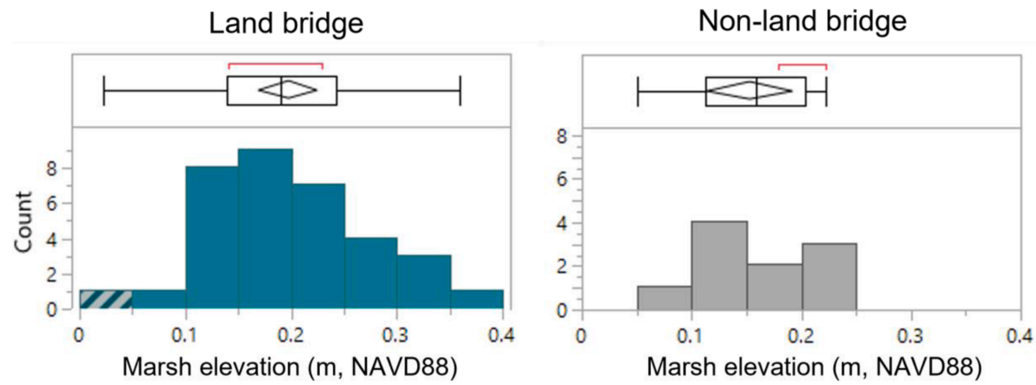

Fig. 5. Elevation frequency distributions illustrate that land bridge marshes have a greater frequency of higher elevations than non-land bridge marshes. Marsh elevations were based on 2014 CRMS data (NAVD88, GEOID 12A).

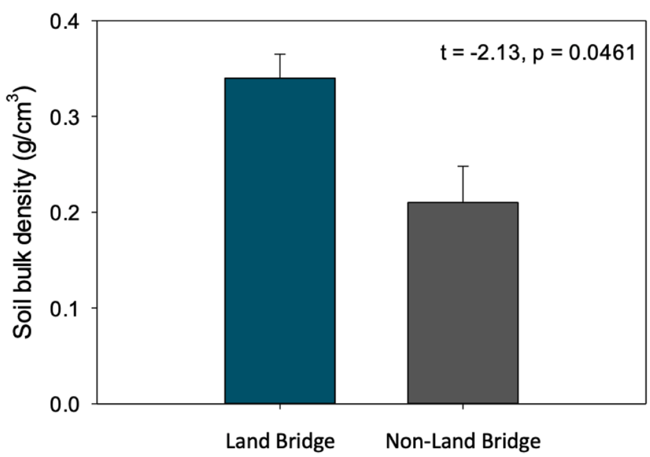

Fig. 6. Mean soil bulk density in land bridge and non-land bridge marshes in Terrebonne basin, Louisiana. Means include both intermediate and brackish marshes.

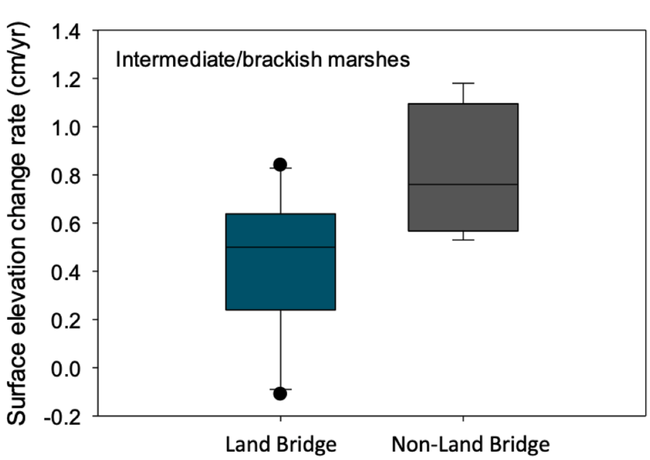

Fig. 7. Surface elevation change rate in intermediate/brackish salinity land bridge (n = 10) and non-land bridge (n = 4) marshes in the Mississippi River Delta.

g m^{-2} yr^{-1} compared to 2.28 g m^{-2} yr^{-1} in non-impounded wetlands [39–42]. Similarly, accretion rates in impounded and non-impounded coastal Louisiana wetlands showed that accretion rates in impounded wetlands averaged 3.40 mm yr^{-1} compared to 9.15 mm yr^{-1} in non-impounded wetlands [43–46]. These data demonstrate that spoil banks significantly reduce sediment inflow and decrease processes important for soil accretion and that open access to TSS when the marsh is flooded results in healthier marshes.

Studies showing features that reduce hydrologic exchange and sediment input, such as spoil banks, demonstrate the importance of connection between land bridge marshes and adjacent water bodies. Surface marsh accretion rates were 9.9 ± 2.0, 6.6 ± 2.5, and 6.0 ± 1.2 mm yr^{-1} in natural marshes, marshes with a continuous spoil bank, and marshes with a discontinuous spoil bank, respectively, in Cameron Parish, Louisiana [43]. Sedimentation rates are lower in marshes impounded by spoil banks than marshes without impoundments [47]. Surface accretion rates were 1.5 times higher in marshes along natural waterways when compared to marshes impounded by spoil banks in coastal Louisiana [48]. Surface accretion rates and organic matter accumulation in managed, impounded marshes in coastal Louisiana, were about five times lower than in unmanaged marshes without impoundments (Fig. 15; [45]). Similarly, sediment deposition at impounded marshes and unimpounded reference marshes in the Barataria and Terrebonne Basins, Louisiana, was two to five times higher at reference marshes with unimpeded access to suspended sediments than those that were impounded (Fig. 16; [27]).

Studies of structural marsh management compared semi-impounded and natural sites at the Rockefeller State Wildlife Refuge and Game Preserve [26,45]. Accretion over marker horizons was about 10 times higher in the natural marshes near the coast compared to semi-impounded marshes (Fig. 17; [45]). Short-term sedimentation rates were significantly higher in unmanaged marshes (1 ± 0.7 g m^{-2}d^{-1}) compared to managed marshes (0.6 ± 0.8 g m^{-2}d^{-1}) that had natural hydrology [26]. Organic short-term sedimentation was also higher at the unmanaged site (0.9 g m^{-2}d^{-1}) compared to the managed site (0.5 ± 0.6 g m^{-2}d^{-1}). In essence, land bridge marshes have a high availability of TSS input that makes them analogous to unimpounded marshes with unrestricted access to suspended sediments.

Shear strength in the root zone of land bridge marshes

The shear strength in the root zone “defines the ability of soils to resist displacement or deformation when subjected to shear stress” and is indicative of soil resistance to erosion [49]. Shear strength is influenced by soil composition (including vegetation root biomass), void ratio, water content, pore water chemistry, soil structure, mineral content, and loading conditions [10,49,50]. In Louisiana coastal marshes, shear strength generally increases with an increase in live belowground biomass because roots add strength due to the tensile force required to break roots and rhizomes (Fig. 18; [49,51,52]). Thus, factors that affect vegetation belowground productivity will directly impact root shear strength and susceptibility to erosion and uprooting. The higher elevation of land bridge marshes leads to better drainage and higher above

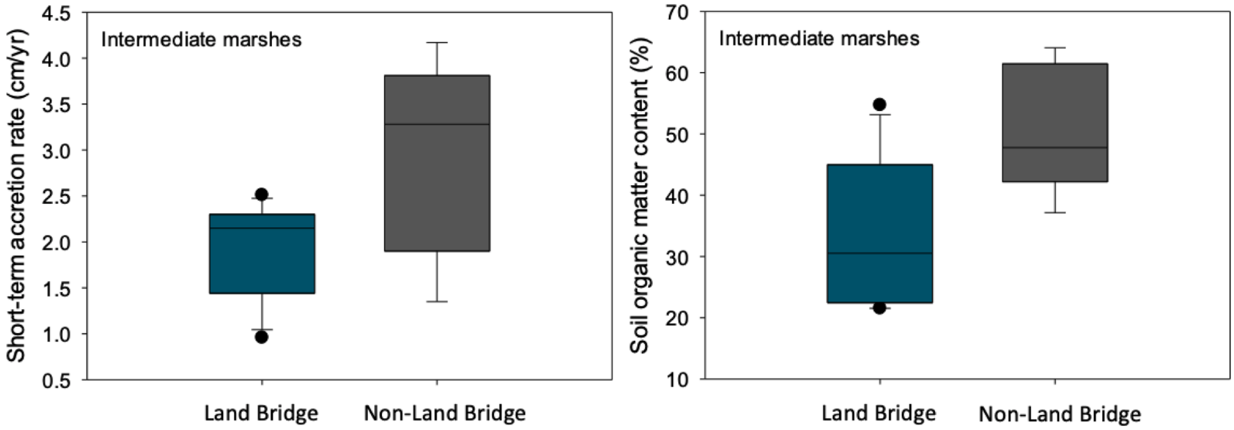

Fig. 8. Short-term accretion rate and soil organic matter content in intermediate salinity land bridge ($n = 11$) and non-land bridge ($n = 5$) marshes in the Mississippi River Delta.

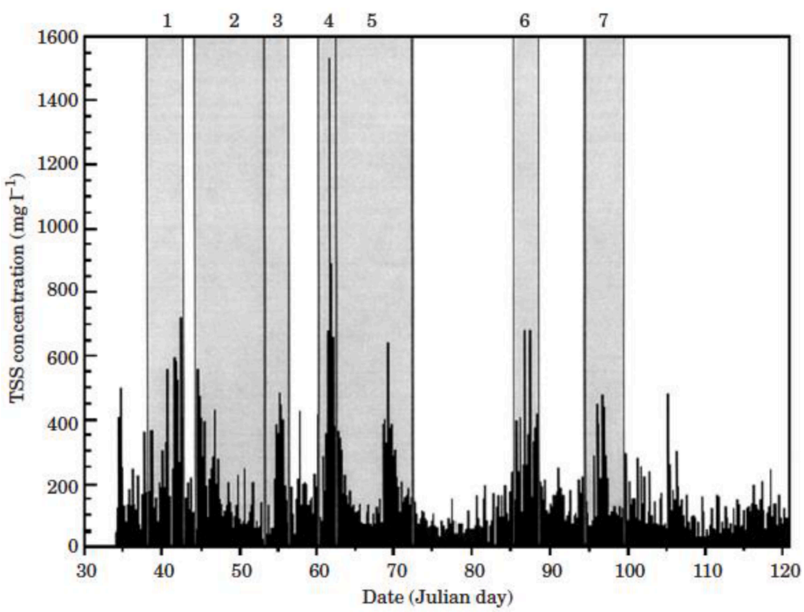

Fig. 9. Total suspended sediment (TSS) concentration in Fourleague Bay, LA during Feb. – April 1994. The shaded areas are frontal passages. Strong frontal winds result in TSS concentrations generally between 400 and 600 mg/L and as high as 1500 mg/L [18].

Fig. 10. Resuspended mud deposition in Lafitte LA during the passage of Hurricane Ida. The eye passed directly over the town.

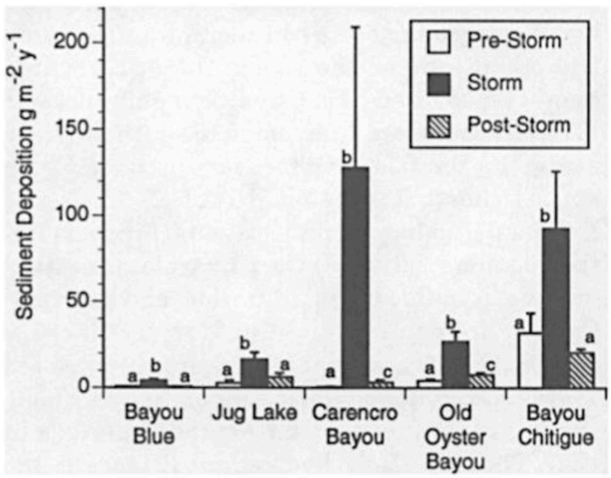

Fig. 11. Sediment deposition during 12-wk sampling intervals before, during and after Hurricane Andrew. Means ± 1 SE. Means with a site followed by a different letter are significantly different at p =0.05. Carenco Bayou and Bayou Chitigue are land bridge marshes connected to a bay via a 1st order channel. Bayou Blue and Jug Lake are not located within a land bridge marsh and have no direct hydrologic connection to a bay. Old Oyster Bayou is strongly influenced by Atchafalaya River discharge [31]. Reproduced and modified with permission from the Coastal Education and Research Foundation, Inc.

and belowground productivity [10,22,53] leading to conditions that support increased soil strength.

Soil strength measured with a cone penetrometer demonstrates variation among marsh edge, interior, and mudflat zones in a land bridge marsh in Terrebonne Bay (Fig. 19; [50]). The edge and interior marshes exhibited similar sleeve resistances to a depth of 15 cm, where the marsh edge reached a peak resistance of 127 kPa at a depth of 25 cm and the interior marsh peaked at 15 cm with a value of 113 kPa. By a depth of 50 cm, the sleeve resistances approached a constant minimum of ~70 kPa and ~30 kPa for the marsh edge and interior marsh, respectively. In comparison, the unvegetated mudflat showed an approximate sleeve resistance of 30 kPa, which matched the interior marsh because of the close proximity of the two sites. This pattern of decrease in soil strength from the marsh edge to the interior marsh, as well as with depth, is replicated on a larger scale from land bridge marshes to marshes further inland.

Modeling dynamics of land bridge marshes

To test the effectiveness of installation of shore protection in front of land bridge marshes, we performed simulations using MarshMorpho2D, a numerically-efficient marsh evolution model that includes a variety of hydrodynamic and sedimentary processes [54,55]. The model calculates a tidal flow map representative of the whole tidal cycle based on a balance between pressure gradient and bed friction and considering a tide-averaged water depth for each cell. Tidal velocities are used to estimate tidal dispersion [56], which is used to transport sediment in suspension. Only fine sediment (mud, silt and clay) is included in the model. Organic material produced *in situ* by plants is also modeled as mud once it gets eroded. The sediment substrate is the same composition as the sediment that is input from the model boundaries. Marsh vegetation parameters are modeled as a function of the hydroperiod which, in turn, is a function of bed elevation and water levels. The lower limit for plant growth, i.e., the elevation below which marsh plants drown, is set equal to 0.1 m below MSL [57]. We acknowledge that marsh loss due to inundation is a complex topic that remains to be a topic of active research. We adopt this simple approach for the purpose of this analysis and we intend to add more complexity to this approach in the future. The presence of vegetation increases bed drag (which affects the flow), soil creep (which drives bank erosion), and organic accretion by *in situ* plant production. Ponding dynamics include pond formation by random seeding and impoundment, pond lateral expansion and deepening, and pond merging [55,58]. Wind waves are calculated with a smoothed-fetch approach [59]. Waves contribute to resuspension of bed sediments (thus driving spatially and temporally variable suspended sediment concentrations throughout the domain) as well as edge erosion, which is implemented through a probabilistic approach [54].

The model is set to recreate an analogue for the land bridge marshes in Breton Sound (LA) (Fig. 20A). We considered an idealized domain, 8 km long and 5 km wide, plus a 2 km mudflat on the seaward side. An additional fetch at the edge of the mudflat is set equal to 20 km, to simulate the portion of Breton Sound not directly included in the domain. We used the wind speed from Southwest Pass station (NOAA)

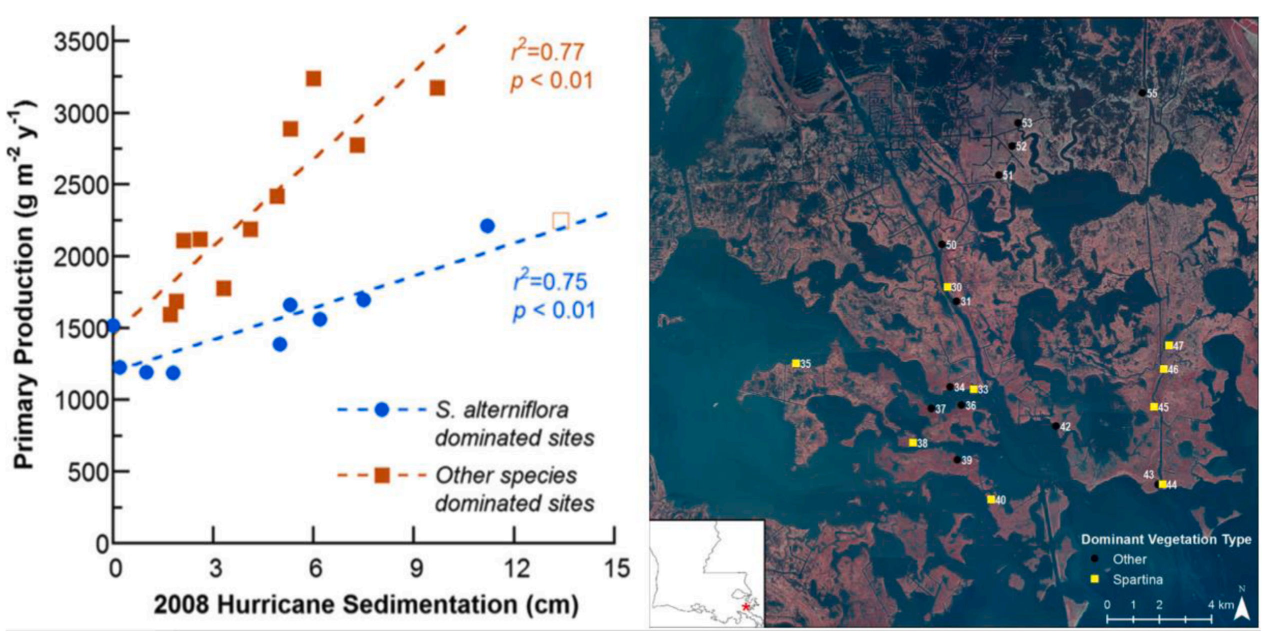

Fig. 12. Left - Relationship of aboveground primary production in land bridge marshes to 2008 hurricane sedimentation in Barataria Bay land bridge marshes. The open square (Site 42) was identified as an outlier and omitted from the regression. Right – Location of marshes sampled for the study [22].

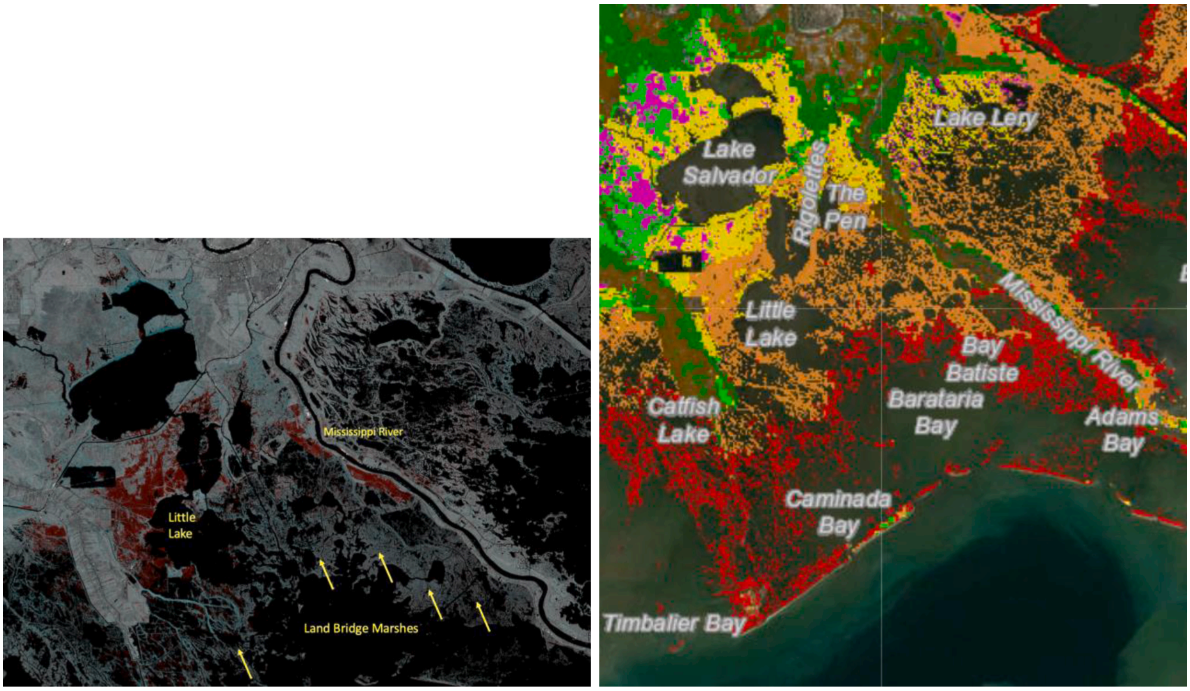

Fig. 13. Left. Image of the mid Barataria Basin showing the stability of land bridge marshes (yellow arrows) during Hurricane Ida. Land bridge marshes had low land loss compared to marshes west and north of Little Lake (loss shown in red). Right. Marsh types in the Barataria Basin. Colors indicate marsh types: red - saline marsh, orange - brackish marsh, yellow – intermediate marsh, green and purple – fresh marshes. The white north-south line indicates the track of the eye of Ida. Note that saline marshes and more seaward brackish marshes had low rates of loss, while more inland brackish marshes and intermediate marshes had high rates of loss.

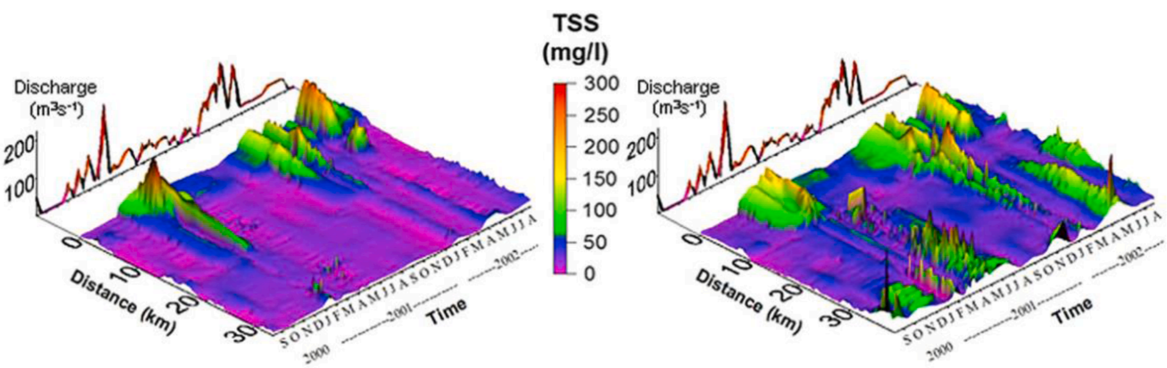

Fig. 14. Total suspended sediment (TSS) along the western (left) and eastern (right) routes in the Breton Sound estuary from 2000 to 2002 (modified from [34]). Distance is from the diversion structure. TSS varied from less than 10 mg/L to over 200 mg/L. The graph shows the two major sources of sediments to the upper Breton Sound where most wetlands occur.

[60] and the water levels from the Grand Isle station (USGS), simplified through a method that accounts for both time variable tidal ranges and MSL anomalies, and that includes both astronomical and meteorological constituents [61]. Tidal range is assumed to remain uniform over the 10 $\times$ 5 km domain.

We first created a healthy marsh by setting RSLR rate to 5 mm yr^{-1} and a sediment supply concentration at the seaward end (c_o) to 120 mg l^{-1} (thus, without any sediment input from the landward end), running the model for 500 years starting from a gently sloping bed. Then, we increased RSLR rate to 10 mm yr^{-1} and decreased c_o to 60 mg l^{-1}, and ran the model for 100 years. The resulting marsh morphology was taken as representative for present time (Fig. 20B). Starting from this configuration, the model was run for another 100 years under two scenarios: one in which no human modification was made (Fig. 20C), and one in which wave barriers were included in front of the marsh edge (Fig. 20D). The wave barriers are assumed to resist erosion, were set at a height of 0.1 m above MSL, and were assumed to completely stop the incoming waves while they allowed some water and sediment transport. Gaps were included to allow for tidal currents.

When the marsh evolved naturally, two major types of marsh loss were present (Fig. 20C). At the landward side, the marsh drowned, ponds expanded and created 1–2 km wide mudflats, which further expanded through wave erosion. On the seaward side, the marsh edge retreated by about 2–5 m per year due to wave attack. Marsh elevation was relatively high (0.3–0.4 m above MSL) closer to the seaward marsh edge and on the (natural) levees of the main channels. When the protective barriers were included, marsh edge erosion on the seaward side was absent, and new marsh colonized between the marsh edge and the barriers (Fig. 20D), as was demonstrated by [12] for protected marshes in Lake Borgne about 20 km northeast of the Breton Sound marshes. Within the landward portion of the domain, no major difference in marsh loss was present when the protective barriers were present compared to the no-action scenario (Fig. 20E). The marsh elevation on the levees and the marsh edge was about 0.05–0.1 m lower than for the

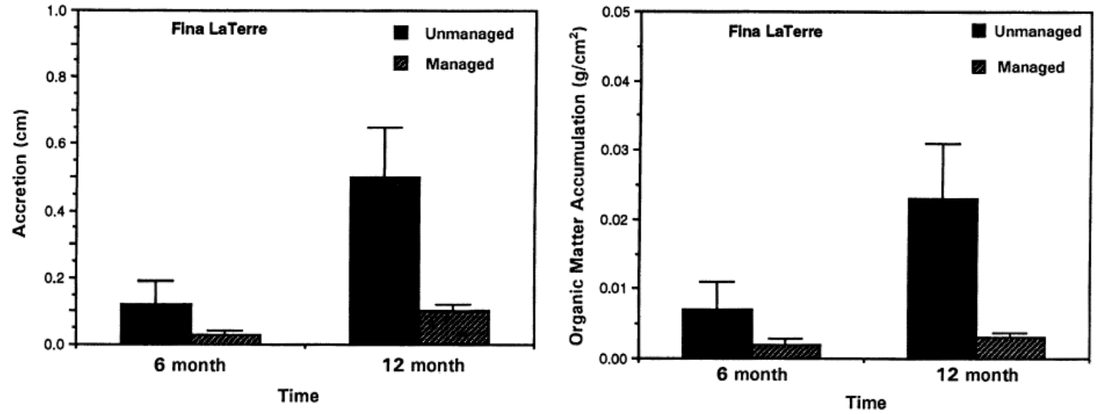

Fig. 15. Rates of vertical accretion (left) and organic matter accumulation (right) in managed and unmanaged marshes at Fina LaTerre, Louisiana (means and 1 SE; from [45]).

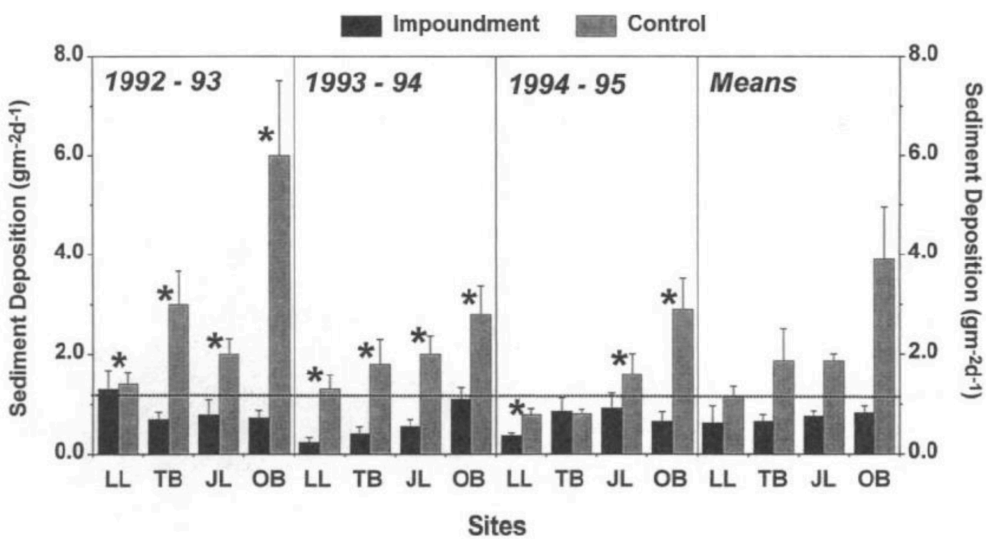

Fig. 16. Comparison of marsh surface sediment deposition rates between impounded and reference sites by management year (means ± 1 SE) and means for all years. Stars indicate statistically significant differences at $p = 0.05$. The horizontal line indicates the 1.1 g/m^2/day of inorganic accumulation required for fresh marsh soils (from [27]). The highest rates of sediment deposition occurred during frontal passages.

no-action case, but the elevation was still high compared to the tidal frame (i.e., ~0.3 m above MSL). These results differ from those of the Coastal Master Plan Integrated Compartment Model (ICM) modeling that predicts complete loss of land bridge marshes after fifty years (Fig. 20F).

Management, restoration and protection of land bridges

Management, restoration and protection of land bridge marshes must counter two processes leading to wetland loss; edge erosion and elevation deficits compared to relative sea-level rise. Given the increased water surface area and bathymetry of degrading inactive delta basins, edge erosion is the dominant cause of wetland loss in the fringe zone of land bridge marshes, with most loss occurring along south-facing shores bordering large coastal bays and lakes. To protect against wave erosion along these shorelines, structures such as stone breakwaters or living shorelines can be used to reduce wave energy as shown for Lake Borgne [12]. Land bridge marshes are more stable than interior marshes due to higher levels of sediment deposition and surface elevation gain as result of wave resuspension of sediments. Thus, there is a complex trade-off in land bridge marshes between surface sediment nourishment that can provide elevation gain to offset RSLR and increased marsh edge erosion. Shoreline protection should be designed to reduce wave energy while maintaining sediment input to marshes by creating regularly spaced openings to allow tidal exchange and built low enough so that tidal flooding is not blocked.

Periodic synoptic sampling does not capture the highest TSS levels that occur in large coastal waterbodies during frontal passages and hurricanes (see Fig. 9). This indicates that there is a much larger availability of suspended sediments that are advected over land bridge marshes during these energetic events. Thus, although land bridge marshes generally have high sediment input, high soil strength, and are higher in elevation, they may need to be nourished periodically. “Thin-layer placement,” also known as “thin-layer sediment addition” and “marsh nourishment,” is a process where dredged sediment is transported to a marsh by pipeline or barge and applied to the surface of the marsh by spraying a slurry of water, sand, and silt [63]. The term thin-layer placement itself has been used to describe thicknesses ranging from less than 1.0 cm to >30 cm. Since the ecological impact of sediment thickness differs among habitats, [64] concluded that the best definition of thin-layer placement would be placement of a thickness of dredged material that does not transform the receiving habitat’s ecological functions [65]. Proper thickness can be determined by calculating how much sediment needs to be added to return the deteriorated marsh back

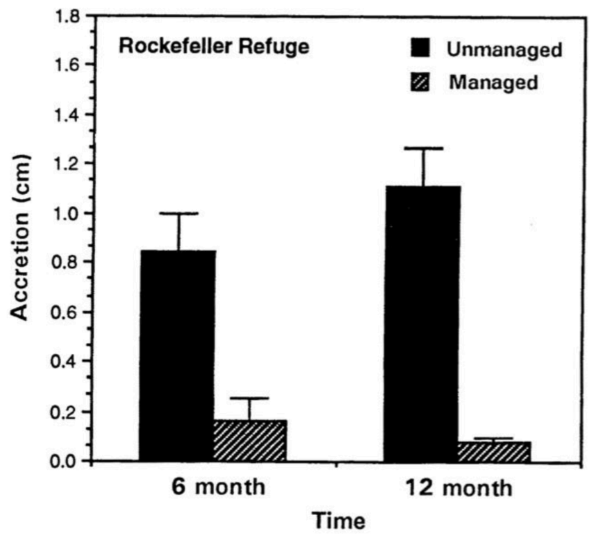

Fig. 17. Rates of accretion after 6 and 12 months at managed and unmanaged marshes at Rockefeller Wildlife Refuge (means and standard error). Managed marshes were surrounded by spoil banks and water exchange was controlled by water control structures [45].

to the elevation of nearby healthy marsh [66]. When done correctly, dredged sediment addition to marshes can be beneficial as a mechanism for increasing marsh resilience [63]. Thin-layer placement of dredge material is used to increase soil surface elevation to reduce waterlogging and porewater H_2S and to increase soil redox potential and vegetation stem density, productivity and nutrient uptake [67–70].

Living shorelines are created or enhanced shorelines that reduce edge erosion by strategic placement of plants, stone, sand fill, and other structural or organic materials [71,72]. Living shorelines stabilize coastal sediments and support the persistence or recovery of coastal wetlands (e.g., salt marsh, mangrove forests), the ecosystem services they provide and the infrastructure they protect [73–75]. In Louisiana, oyster reefs constructed with either loose shell or precast concrete structures were effective at reducing erosion of the marsh edge behind them by as much as 1 m/yr [76]. Stricklin et al. [77] found that the ecological function of constructed reefs, as measured by reduction in marsh edge erosion, was equivalent or exceeded the function of nearby natural oyster reefs. In addition, oyster bag reef breakwaters have been found to increase survivability of plantings behind the reef [78]. An oyster reef used for shoreline protection can respond to changing conditions including subsidence and sea level rise [71,79], and intertidal reefs have the potential to match even the highest predictions of sea level rise by the year 2100, provided sea level rise does not coincide with or create additional stresses on oyster reefs that reduce productivity [80].

Land bridge marshes receive the majority of their sediment input from bay bottoms and the coast during higher energy wave and storm events. The sediment received fosters root growth, soil strength, and higher elevation capital than marshes further inland. While the land bridges can protect landward wetlands from wave erosion, as efficient sediment traps, they may also limit sediment delivery from the coast to interior wetlands. For coastal restoration, a strategy may be to extend the landward extent of these land bridge marshes by providing sediment to marshes directly landward (i.e., thin-layer deposition).

The coastal master plan and land bridge marshes

Land bridges in coastal Louisiana have been recognized as important landscape features in numerous planning efforts, beginning with Coast 2050, a strategic plan approved in 1998. The 2007, 2012, and 2017 Coastal Master Plans have all included projects to restore land bridges [9,81,82]. These land bridge features in the coastal landscape connect landmasses, such as the New Orleans East Land Bridge (NOELB), which separates Lake Pontchartrain and Lake Borgne. The Manchac Land Bridge, between Lake Maurepas and Lake Pontchartrain, was created by the formation of Lake Maurepas several thousand years ago [83]. Formation and persistence of the land bridge is likely due to its site at a historic distributary network for the Mississippi River, since larger and heavier sediment is deposited at the mouths of distributaries making these areas more stable and resistant to erosion [84,85]. Restoration projects for land bridges include hydrologic restoration, marsh creation, shoreline protection, and hurricane protection projects. Based on the evidence presented in this paper, restoration should not in any way interfere with input of suspended sediment to the marsh surface during high energy storm events. The use of various types of shoreline protection approaches (living shorelines, breakwaters, etc.) must allow

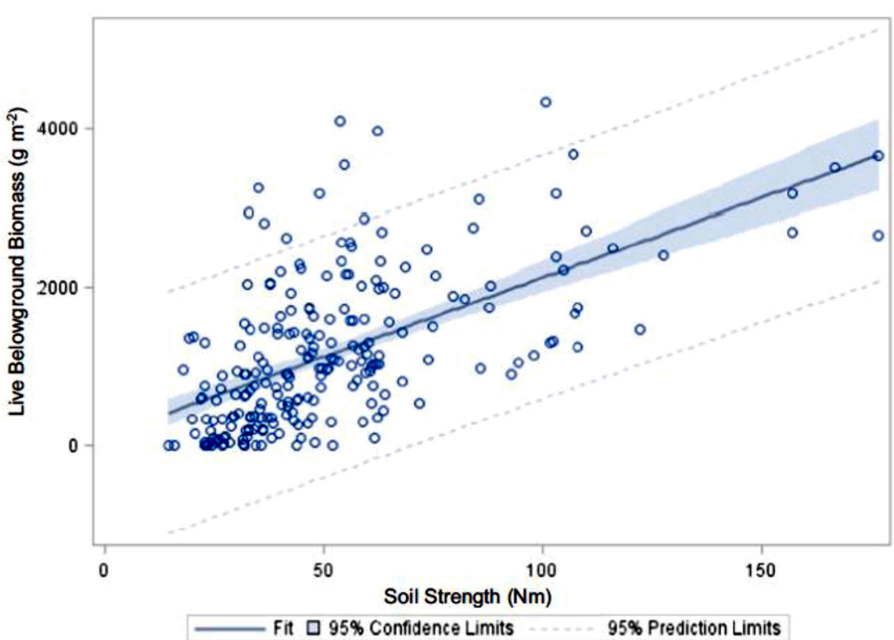

Fig. 18. Relationship of soil strength versus live belowground biomass for Louisiana coastal marshes ($R^2 = 0.35$, $p < 0.0001$; from [52]).

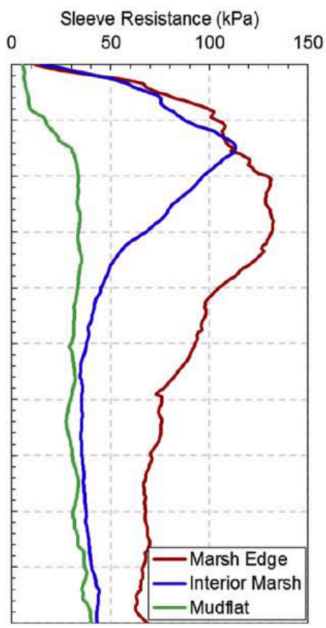

Fig. 19. Penetrometer sleeve resistance in cores from edge (10 m) and interior (50 m) marshes and a mudflat in a land bridge marsh facing Terrebonne Bay (from [50]).

maximum input of suspended sediments (e.g., [7,12]).

Land bridge marshes have additionally been recognized by 2023 CMP regional working groups as an area of focus for shoreline protection and marsh stabilization and creation for the CMP. These projects build on 2017 CMP restoration projects such as the East Bank Land Bridge Marsh Creation Project (001.MC.104) and the Spanish Lake Marsh Creation Project (001.MC.105) (Fig. 21). Both of these projects are in the second 2017 CMP implementation period, from Years 11–30, with estimated costs of $159,800,000 and $58,200,000. The East Bank Land Bridge Marsh Creation is predicted to create approximately 2300 acres of marsh in Plaquemines Parish between Grand Lake and Lake Lery and the Spanish Lake Marsh Creation is predicted to create approximately 800 acres of marsh in Plaquemines Parish along the eastern shore of Spanish Lake [9].

The Biloxi Marsh Complex, which contains land bridge marshes (Fig. 1), is an area where local subsidence and accretion factors may result in the area performing better and being more sustainable than surrounding areas [9,12]. The Louisiana Coastal Protection and Restoration Authority (CPRA) recently began construction on a $67 million project to create an oyster reef living shoreline to reduce shoreline retreat and stabilize marshland along a 7-mile stretch of the southeastern shoreline of Lake Borgne and the Biloxi Wildlife Management Areas in St. Bernard Parish, Louisiana (Fig. 21).

Model predictions for the coastal master plan

The predictions used in the CMP are based on the ICM [86,87]. The ICM includes sediment resuspension during wave events and, thus, should in theory be able to recreate the high vertical accretion experienced by land bridge marshes. However, it is not clear whether this process is accurately reproduced [62] for at least two reasons. First, it is unclear if the sediment resuspension model implemented in the ICM has been appropriately calibrated – primarily because of the lack of TSS data, especially during energetic events. Second, it is unclear if the sediment transport mechanism from the open water to the marsh is appropriately represented. For example, the ICM uses a maximum thickness of bed sediment available for resuspension, which in practice creates a constraint to the amount of sediment that can be transferred to the marsh platform during strong wave events. In addition, the hydrodynamics (and thus the currents responsible for sediment advection) are calculated between "compartments" whose size is of the order of 10 km by 10 km. This resolution might be too coarse to correctly reproduce the fluxes at the boundary between open water and land bridge marshes. The interested reader is referred to [88] regarding how some of the aforementioned processes affected the uncertainty of the ICM output.

The ICM also includes the process of marsh edge erosion, even though the rates are imposed as a spatially-variable time-constant value based on historical trends [86]. ICM predictions suggest that edge erosion is generally less important than marsh inundation [62], and that land bridge marshes are mostly lost by marsh drowning rather than edge erosion. This prediction contrasts with that from our idealized model, in which the land bridge marshes do not drown. We speculate that the main discrepancy between the two models is not edge erosion but rather inorganic sediment accretion, given that the former likely differs by a factor of two, while the latter might differ by an order of magnitude. A detailed comparison between the two models in which RSLR trends, subsidence, plant characteristics, and all other relevant parameters are matched is needed to clarify this issue.

Summary and recommendations

Land bridge marshes are saline or brackish marshes fronting large estuarine bays or lakes with sufficient fetch and wave energy to supply high levels of resuspended sediments to the marsh surface. They are generally linear features that are oriented parallel to the coast and the shoreline front retreats landward due to erosion from wave energy. These marshes persist over time vertically due to input of resuspended sediments but are experiencing rapid edge erosion due to wave attack. Comparison of data from long-term monitoring sites show that land bridge marshes have a greater frequency of higher soil surface elevation and higher soil bulk density than non-land bridge marshes.

Because land bridges are vertically stable relative to other coastal wetlands, identification of measures to sustain these landscape features is important. These important coastal features have been recognized in the Louisiana CMP and hydrologic restoration, marsh creation, shoreline protection, and hurricane protection projects have been planned for these areas. However, while the model used to inform the CMP does in theory include all the relevant processes present in land bridge marshes, it is unclear whether those processes are adequately implemented and calibrated. Hence, sustainability of some of the most valuable marshes in coastal Louisiana is highly uncertain. We recommend implementing a sediment monitoring program during energetic events such as frontal passages, hurricanes, and waves in the immediate nearshore zone fronting beach-dune systems. These data would be useful to better calibrate the model but also to improve the understanding of sediment dynamics in general. We also recommend that further analyses be performed on the ICM, testing its ability to reproduce inorganic sediment accretion on land bridge marshes. If correct values of sediment accretion cannot be achieved through parameter calibration, some structural modification of the model (e.g., changes in the equations) might be needed. If land bridge marshes can keep pace with RSLR, edge erosion would be their primary cause of conversion to open water. Structures for marsh edge protection have the potential to stop and even reverse shoreline retreat. Selective protection of the edges of land bridge marshes would be cost-effective relative to marsh creation or restoration. Consideration of land bridge marshes as distinct marsh types in the State Master Plan and integrated modeling could help to identify measures to sustain these landscape features.

While the application in this manuscript focuses on the coast of Louisiana, USA, coastal land-loss is a global challenge requiring a variety of restoration and protection initiatives. Natural and nature-based solutions, similar to the restoration of land-bridge marshes presented here, are explored in numerous coastal systems including Indonesia [89,90], the Mekong Deltaic system [91], and the Mediterranean zone, Egypt

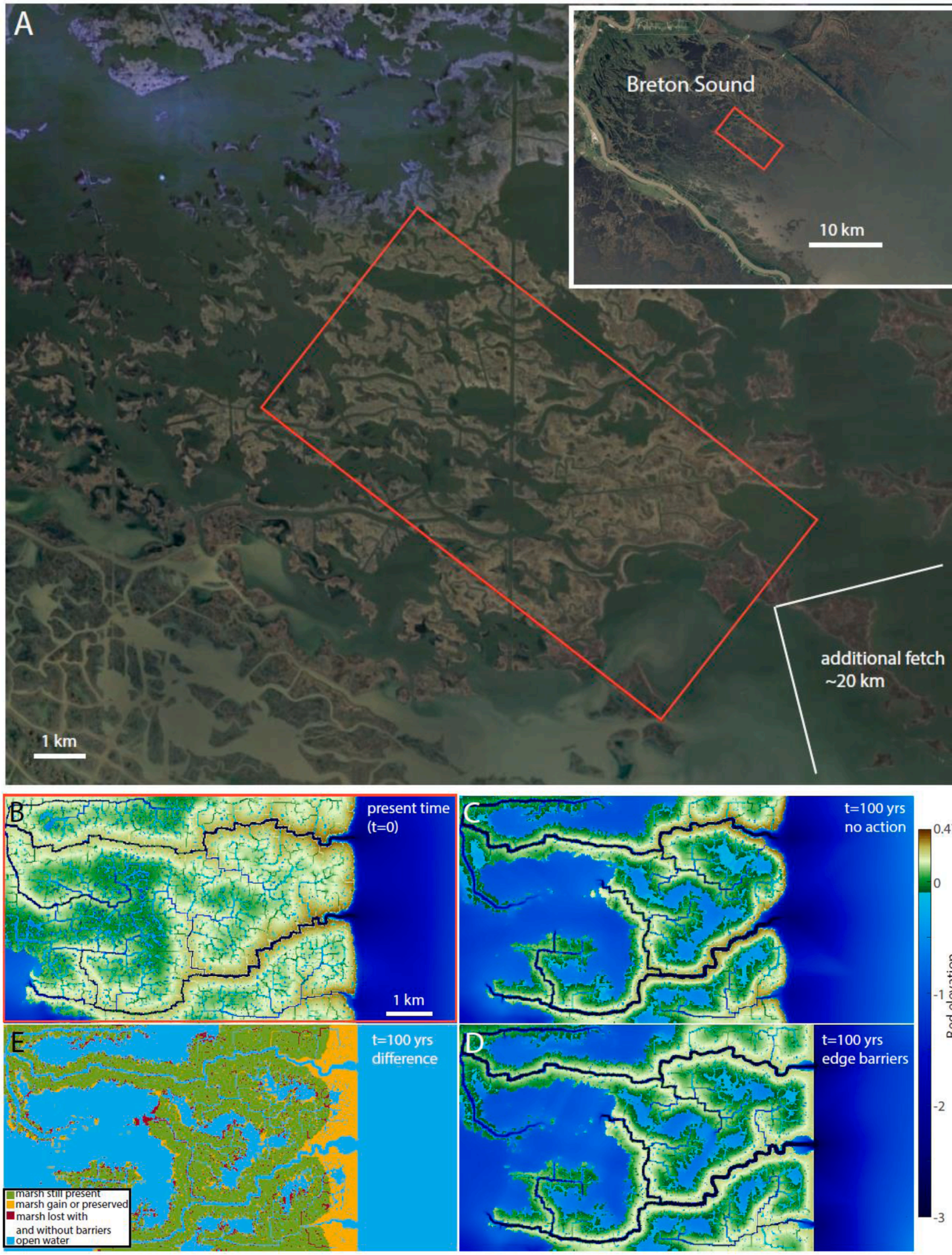

Fig. 20. Top Figure: (A) Location modeled in the Breton Sound, LA. Middle Figure: Model predictions with MarshMorpho2D for an idealized marsh, considering a RSLR rate of 10 mm yr^{-1} over 100 years, comparing a scenario without action and a scenario in which the marsh edge facing the open water is protected. (B) Land bridge marsh at the $t = 0$; (C) Land bridge marsh in 100 years with no action; (D) Land bridge marsh shown in B after 100 years with edge barriers; (E) The difference in marsh area between C and D. These model results support the empirical results presented above and the restoration suggestion that breakwaters of some kind will greatly reduce or stop marsh edge erosion. Bottom Figure: (F) Model prediction from the 2017 Coastal Master Plan Integrated Compartment Model (ICM) showing cumulative land loss over 50 years for the Breton Sound Basin for low, medium and high RSLR scenarios. Pink line shows basin boundary [62].

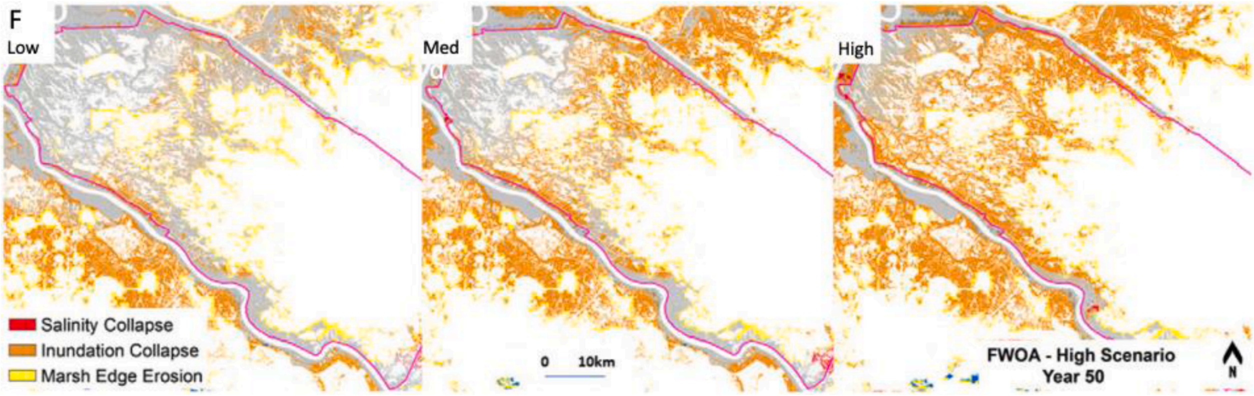

Fig. 20. (*continued*).

Fig. 21. 2017 Coastal Master Plan projects to be implemented in the Southeast Coast region, including 38 restoration projects, 6 structural protection projects, and 18 nonstructural risk reduction projects [6]. Projects 001.MC.104 and 001.MC.105 east of the Mississippi River are representative of land bridge marsh restoration projects being designed for the 2023 Coastal Master Plan.

[92] among others. The focus of this manuscript to encourage the restoration and sustenance of land-bridge marshes is consistent with the global promotion of nature-based solutions as effective restoration strategies [93,94].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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NBS Impacts and Implications

With the exception of the Atchafalaya River discharge area, most of Louisiana's marsh coastline is retreating and coastal marshes are degrading. In the inactive degrading delta regions, there exists a previously uncharacterized landform referred to colloquially as coastal 'land bridge' marshes. Land bridge marshes are important because they persist over time and are stable relative to other coastal marshes. However, sufficient management of these marshes has not been addressed in the Louisiana Coastal Master Plan. We summarize characteristic of land bridge marshes using data from the CPRA Coastal Reference Monitoring System monitoring sites. By using simulation from the Marsh Morpho2D process-based reduced-complexity morphology model, we show how land bridges are not sufficiently modeled with the CPRA ICM model. Our paper also identifies strategies to manage and maintain land bridge marshes in coastal Louisiana.

References

[1] J. Day, N. Psuty, B. Perez, The role of pulsing events in the functioning of coastal barriers and wetlands: implications for human impact, management and the response to sea level rise, in: M. Weinstein, D. Dreeger (Eds.), Concepts and Controversies in Salt Marsh Ecology, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2000, pp. 633–660.

[2] J. Day, H. Clark, C. Chang, R. Hunter, C. Norman, Life cycle of oil and gas fields in the Mississippi River Delta: a, Review. Water. 12 (2020) 1492, https://doi.org/10.3390/w12051492.

[3] B.R. Couvillion, H. Beck, D. Schoolmaster, M. Fischer, Land area change in coastal Louisiana 1932 to 2016, U.S. Geolo, Surv. Sci. Investig. Map 3381 (2017) 16, https://doi.org/10.3133/sim3381, pamphlet.

[4] A.M. Freeman, J.W. Pahl, E.D. White, S. Langlois, D.C. Lindquist, R.C. Raynie, L. A. Sharp, A review of how uncertainties in management decisions are addressed in coastal louisiana restoration, Water (Basel) 13 (11) (2021) 1528, https://doi.org/10.3390/w13111528.

[5] J. Day, D. Boesch, E. Clairain, P. Kemp, S. Laska, W. Mitsch, K. Orth, H. Mashriqui, D. Reed, L. Shabman, C. Simenstad, B. Streever, R. Twilley, C. Watson, J. Wells, D. Whigham, Restoration of the Mississippi Delta: lessons from Hurricanes Katrina and Rita, Science 315 (2007) 1679–1684.

[6] S. Laska, Louisiana's Response to Extreme Weather: A Coastal State's Adaptation Challenges and Successes, Springer Nature, Cham, Switzerland, 2020.

[7] J.A. Cadigan, J.H. Bekkaye, N.H. Jafari, L. Zhu, A.R. Booth, Q. Chen, B. Raubenheimer, B.D. Harris, C. O'Connor, R. Lane, G.P. Kemp, J.N. Day, J. W. Day, H.O. Ulloa, Impacts of coastal infrastructure on shoreline response to major hurricanes in Southwest Louisiana, Front. Built Environ. 8 (2022), 885215, https://doi.org/10.3389/fbuil.2022.885215.

[8] M. Kozlov, Hurricane Ida forces researchers to rethink their future, Nature 597 (2021) 313–314.

[9] [80]CPRA, Louisiana's Comprehensive Master Plan for a Sustainable Coast, Coastal Protection and Restoration Authority, Baton Rouge, LA, USA, 2017. Retrieved from, http://coastal.la.gov/wp-content/uploads/2017/04/2017-Coastal-Master-Plan_Web-Book_CFinal-with-Effective-Date-06092017.pdf. Accessed 15 October 2022.

[10] J. Day, A. Yáñez-Arancibia, J.M. Rybczyk, Climate change: effects, causes, consequences: physical, hydromorphological, ecophysiological, and biogeographical changes, in: E. Wolanski, D. McLusky (Eds.), Treatise of Estuarine and Coastal Science, Elsevier, Oxford, 2011, pp. 303–315.

[11] R.R. Twilley, S.J. Bentley, Q. Chen, D.A. Edmonds, S.C. Hagen, N.S.-N. Lam, C. S. Willson, K. Xu, D. Braud, R.H. Peele, Co-evolution of wetland landscapes, flooding, and human settlement in the Mississippi River Delta Plain, J. Sustainability Sci. Manage. 11 (4) (2016) 711–731, https://doi.org/10.1007/s11625-016-0374-4.

[12] G.P. Kemp, E.C. McDade, J.W. Day, R.R. Lane, N.H. Dawers, J.N. Day, Recovery and Restoration of Biloxi Marsh in the Mississippi River Delta, Water (Basel) 13 (2021) 3179, https://doi.org/10.3390/w13223179.

[13] H.H. Roberts, Dynamic changes of the Holocene Mississippi River delta plain: the delta cycle, J. Coastal Res. 13 (3) (1997) 605–627.

[14] S.M. Gagliano, J.L. Van Beek, An Approach to Multiuse Management in the Mississippi Delta System, Houston Geological Society, 1975, pp. 223–238.

[15] Q. Chen, L. Wang, R. Tawes, Hydrodynamic response of northeastern Gulf of Mexico to hurricanes, Estuar. Coast. 31 (2008) 1098–1116, https://doi.org/10.1007/s12237-008-9089-9.

[16] A. Karimpour, Q. Chen, A simplified parametric model for fetch-limited peak wave frequency in shallow estuaries, J. Coastal Res. 32 (4) (2016) 954–965. http://www.jstor.org/stable/43843064.

[17] Y. Sapkota, J.R. White, Marsh edge erosion and associated carbon dynamics in coastal Louisiana: a proxy for future wetland-dominated coastlines world-wide, Estuar. Coast. Shelf Sci. 226 (2019), https://doi.org/10.1016/j.ecss.2019.106289.

[18] B. Perez, J. Day, L. Rouse, R. Shaw, M. Wang, Influence of Atchafalaya River discharge and winter frontal passage on suspended sediment concentration and flux in Fourleague Bay, Louisiana, Estuar. Coast. Shelf Sci. 50 (2000) 271–290, https://doi.org/10.1006/ecss.1999.0564.

[19] J.B. Dunbar, L.D. Britsch III, Geology of the New Orleans area and the canal levee failures, J. Geotech. Geoenviron. Eng. 134 (5) (2008) 566–582, https://doi.org/10.1061/(ASCE)1090-0241(2008)134:5(566).

[20] S.M. Gagliano, H.J. Kwon, J.L. Van Beek, Deterioration and restoration of coastal wetlands, Coast. Eng. Proceed. 12 (1970) 107. -107.

[21] J. Gosselink, W. Conner, J. Day, R. Turner, Classification of wetland resources: land, timber, and ecology, in: B.D. Jackson, J.L. Chambers (Eds.), Timber Harvesting in Wetlands, LSU Division of Continuing Education, 1981, pp. 29–48.

[22] J.J. Baustian, I.A. Mendelssohn, Hurricane-induced sedimentation improves marsh resilience and vegetation vigor under high rates of relative sea level rise, Wetlands 35 (2015) 795–802.

[23] A.E. Bevington, R.R. Twilley, C.E. Sasser, G.O. Holm Jr., Contribution of river floods, hurricanes, and cold fronts to elevation change in a deltaic floodplain, northern Gulf of Mexico, USA, Estuar. Coast. Shelf Sci. 191 (2017) 188–200.

[24] H.H. Roberts, R.D. DeLaune, J.R. White, C. Li, C.E. Sasser, D. Braud, et al., Floods and cold front passages: impacts on coastal marshes in a river diversion setting (wax lake delta area, Louisiana), J. Coastal Res. 31 (5) (2015) 1057–1068, https://doi.org/10.2112/JCOASTRES-d-14-00173.1.

[25] R. Baumann, J. Day, C. Miller, Mississippi deltaic wetland survival: sedimentation vs coastal submergence, Science 224 (1984) 1093–1095.

[26] R. Boumans, J. Day, Effects of two marsh management plans in the Mississippi delta on water and materials flux and short-term sedimentation, Wetlands 14 (2) (1994) 247–261.

[27] D.J. Reed, N. De Luca, A.L. Foote, Effect of hydrologic management on marsh surface sediment deposition in coastal Louisiana, Estuaries 20 (1997) 301–311.

[28] K. Liu, Q. Chen, K. Hu, K. Xu, R.R. Twilley, Modeling hurricane-induced wetland-bay and bay-shelf sediment fluxes, Coastal Eng. 135 (2018) 77–90.

[29] S. Murray, N. Walker, J. Adams, Impacts of winter storms on sediment transport within the Terrebonne Bay marsh complex, in: Processes of Coastal Wetlands Loss in Louisiana, Coastal Zone '93, New Orleans, 1993, pp. 56–70.

[30] A.R. Payandah, D. Justic, G. Mariotti, H. Huang, K. Valentine, N.D. Walker, Suspended sediment dynamics in a deltaic estuary controlled by subtidal motion and offshore river plumes, Estuar. Coast. Shelf Sci. 250 (2020), 107137, https://doi.org/10.1016/j.ecss.2020.107137.

[31] D. Cahoon, D. Reed, J. Day, G. Steyer, R. Boumans, J. Lynch, D. McNally, N. Latif, The influence of hurricane Andrew on sediment distribution in Louisiana coastal marshes, J. Coast. Res. Special Issue 18 (1995) 280–294.

[32] A.E. Bevington, C.E.Sasser R.R.Twilley, Deltaic Floodplain Wetland Vegetation Dynamics Along the Sediment Surface Elevation Gradient and in Response to Disturbance from River Flooding and Hurricanes in Wax Lake Delta, 398, Geomorphology, Louisiana, USA, 2021, 108011, https://doi.org/10.1016/j.geomorph.2021.108011.

[33] B.R. Couvillion, J.A. Barras, G.D. Steyer, W. Sleavin, Fischer, Land area change in coastal Louisiana from 1932 to 2010. U.S, Geolo. Surv. Sci. Investig. (2011) 12, https://doi.org/10.3133/sim3164, pamphlet.

[34] R. Lane, J.W. Day, B. Marx, E. Reyes, E. Hyfield, J.N. Day, The effects of riverine discharge on temperature, suspended sediments, and chlorophyll a in a Mississippi delta estuary measured using a flow-thorough system, Estuar. Coast. Shelf Sci. 74 (2007) 145–154.

[35] T.E. Tornqvist, D.J. Wallace, J.E.A. Storms, J. Wallinga, Mississippi Delta subsidence primarily caused by compaction of Holocene strata, Nat. Geosci. 1 (2008) 173–176.

[36] D.J. Reed, D.R. Cahoon, The relationship between marsh surface topography and vegetation parameters in a deteriorating Louisiana *Spartina alterniflora* salt marsh, J. Coastal Res. 8 (1992) 77–87.

[37] I.A. Mendelssohn, J.T. Morris, Eco-physiological Controls On the Primary Productivity of Spartina alterniflora, in: press. Concepts and Controversies in Tidal Marsh Ecology, Kluwer Academic Publishers, Amsterdam, The Netherlands, 2000, pp. 59–80.

[38] J.C. Jarvis, Vertical Accretion Rates in Coastal Louisiana: A review of the Scientific Literature, U.S. Army Engineer Research and Development Center, Vicksburg, MS, 2010.

[39] L.G. Nichols, Erosion of Canal Banks On the Rockefeller Wildlife Refuge, LA Wildlife and Fisheries Comm, New Orleans, LA, 1961.

[40] L.N. Doiron, C.A. Whitehurst, Geomorphic processes active in the Southeast Louisiana Canal, LaFourche Parish, Louisiana. Res. Monographs, Division of Eng. Rese.–RM 5 (1974) 48.

[41] N. Craig, R. Turner, J. Day, Land Loss in Coastal Louisiana, Environ. Manage. 3 (2) (1979) 133–144.

[42] W.B. Johnson, J.G. Gosselink, Wetland loss directly associated with canal dredging in the Louisiana coastal zone, in: D. Boesch (Ed.), Proceedings of the Conference On Coastal Erosion and Wetland Modification in Louisiana: causes, consequences, and Options, Office of Biological Services, U.S. Fish and Wildlife Service, Slidell, Louisiana, 1982, pp. 60–72.

[43] D.R. Cahoon, R.E. Turner, Accretion and canal impacts in a rapidly subsiding wetland: II. Feldspar marker horizon technique, Estuaries 12 (4) (1989) 260–268.

[44] N. Taylor, J. Day, G. Neusaenger, Ecological characterization of Jean Lafitte National Historical Park: basis for a management plan, in: W. Duffy, D. Clark (Eds.), Marsh Management in Coastal Louisiana: Effects and Issues 89(22), U.S. Fish and Wildlife Service, Biological Rep, Washington, USA, 1989, pp. 247–277.

[45] D.R. Cahoon, Recent accretion in two managed marsh impoundments in coastal Louisiana, Ecol Appl 4 (1994) 166–176.

[46] J.C. Bryant, R.H. Chabreck, Effects of impoundment on vertical accretion of coastal marsh, Estuaries 21 (1998) 416–422.

[47] C. Neill, R.E. Turner, Backfilling canals to mitigate wetland dredging in Louisiana coastal marshes, Environ. Manage. 11 (6) (1987) 823–836.

[48] N.C. Taylor, Ecological Characterization of Jean Lafitte National Historical Park, Louisiana: Basis for a Management Plan, Louisiana State Univ., Baton Rouge, Louisiana, USA, 1988, p. 160. Master's Thesis.

[49] J.M. Teal, R. Best, J. Caffrey, C.S. Hopkinson, K.L. McKee, J.T. Morris, S. Newman, B. Orem, et al., Mississippi River Freshwater Diversions in Southern Louisiana: effects on Wetland Vegetation, Soils, and Elevation, in: A.J. Lewitus, M. Croom, T. Davison, D.M. Kidwell, B.A. Kleiss, J.W. Pahl, et al. (Eds.), Final Report to the State of Louisiana and the U.S. Army Corps of Engineers through the Louisiana Coastal Area Science & Technology Program, National Oceanic and Atmospheric Administration, 2012, p. 49.

[50] N.H. Jafari, B.D. Harris, J.A. Cadigan, J.W. Day, C.E. Sasser, G.P. Kemp, C. Wigand, A. Freeman, L.A. Sharp, J. Pahl, G.P. Shaffer, G.O. Holm Jr., R.R. Lane, Wetland shear strength with emphasis on the impact of nutrients, sediments, and sea level rise, Est. Coast. Shelf Sci. 229 (2018), 106394, https://doi.org/10.1016/j.ecss.2019.106394.

[51] J.A. Nyman, Integrating successional ecology and the delta lobe cycle in wetland research and restoration, Estuaries Coasts 37 (6) (2014) 1490–1505, https://doi.org/10.1007/s12237-013-9747-4.

[52] C.E. Sasser, E. Evers-Hebert, B. Milan, G.O. Holm Jr, Relationships of marsh soil strength to belowground vegetation biomass in Louisiana coastal marshes, Wetlands 38 (2) (2018) 401–409, https://doi.org/10.1007/s13157-017-0977-2.

[53] J. Day, J. Cable, J. Cowan, R. DeLaune, K. de Mutsert, B. Fry, H. Mashriqui, D. Justic, P. Kemp, R. Lane, J. Rick, S. Rick, L. Rosas, G. Snedden, E. Swenson, R. Twilley, B. Wissel, The impacts of pulsed reintroduction of river water on a Mississippi delta coastal basin, J. Coastal Res. 54 (2009) 225–243. Special Issue.

[54] G. Mariotti, Marsh channel morphological response to sea level rise and sediment supply, Estuar. Coast. Shelf Sci. 209 (2018) 89–101, https://doi.org/10.1016/j.ecss.2018.05.016.

[55] G. Mariotti, A.C. Spivak, S.Y. Luk, G. Ceccherini, M. Tyrrell, M.E. Gonneea, Modeling the spatial dynamics of marsh ponds in New England salt marshes, Geomorphology 365 (2020), 107262, https://doi.org/10.1016/j.geomorph.2020.107262.

[56] G. Di Silvio, C. Dall'Angelo, D. Bonaldo, G. Fasolato, Long-term model of planimetric and bathymetric evolution of a tidal lagoon, Cont. Shelf Res. 30 (8) (2010) 894–903, https://doi.org/10.1016/j.csr.2009.09.010.

[57] G.A. Snedden, K. Cretini, B. Patton, Inundation and salinity impacts to above- and belowground productivity in Spartina patens and Spartina alterniflora in the Mississippi River deltaic plain: implications for using river diversions as restoration tools, Ecol. Eng. 81 (2015) 133–139, https://doi.org/10.1016/j.ecoleng.2015.04.035.

[58] G. Mariotti, Beyond marsh drowning: the many faces of marsh loss (and gain), Adv. Water Resour. 144 (2020), 103710, https://doi.org/10.1016/j.advwatres.2020.103710.

[59] Y.R. Young, L.A. Verhagen, The growth of fetch limited waves in water of finite depth .1. Total energy and peak frequency, Coastal Eng. 29 (1996) 47–78.

[60] G. Mariotti, H. Huang, Z. Xue, B. Li, D. Justic, Z. Zang, Biased wind measurements in estuarine waters, J. Geophys. Res.: Oceans 123 (5) (2018) 3577–3587, https://doi.org/10.1029/2017JC013748, b.

[61] S.M. Zapp, G. Mariotti, Evaluating direct and strategic placement of dredged material for marsh restoration through model simulations, Shore Beach 89 (4) (2021) 33–40.

[62] D. Reed, Y. Wang, E. Meselhe, E. White, Modeling wetland transitions and loss in coastal Louisiana under scenarios of future relative sea-level rise, Geomorphology 352 (2020), https://doi.org/10.1016/j.geomorph.2019.106991.

[63] Virginia Institute of Marine Science, Thin-layer Sediment Addition of Dredge Material For Enhancing Marsh Resilience, Virginia Institute of Marine Science, College of William and Mary, 2014, https://doi.org/10.21220/V5X30S.

[64] P. Wilber, Managing Dredged Material Via Thin-Layer Disposal in Coastal marshes. Environmental Effects of Dredging Technical Bulletin, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 1993.

[65] G.L. Ray, Thin Layer Placement of Dredged Material On Coastal wetlands: A review of the Technical and Scientific literature, ERDC/EL Technical Notes Collection (ERDC/EL TN-07-1), U.S. Army Engineer Research and Development Center, Vicksburg, MS, 2007.

[66] M.K. La Peyre, B. Gossman, B.P. Piazza, Short- and long-term response of deteriorating brackish marshes and open-water ponds to sediment enhancement by thin-layer dredge disposal, Estuaries Coasts 32 (2009) 390–402.

[67] R.D. DeLaune, S.R. Pezeshki, J.H. Pardue, J.H. Whitcomb, W.H. Patrick Jr, Some influences of sediment addition to a deteriorating salt marsh in the Mississippi River Deltaic Plain: a pilot study, J. Coastal Res. 6 (1990) 181–188.

[68] I.A. Mendelssohn, N.L. Kuhn, Sediment subsidy: effects on soil-plant responses in a rapidly submerging coastal salt marsh, Ecol. Eng. 21 (2003) 115–128.

[69] A.L. Croft, L.A. Leonard, T. Alphin, L.B. Cahoon, M. Posey, The effects of thin layer sand renourishment on tidal marsh processes: masonboro Island, North Carolina, Estuaries Coasts 29 (2006) 737–750.

[70] C.M. VanZomeren, J.F. Berkowitz, C.D. Piercy, J.R. White, Restoring a degraded marsh using thin layer sediment placement: short-term effects on soil physical and biogeochemical properties, Ecol. Eng. 120 (2018) 61–67, https://doi.org/10.1016/j.ecoleng.2018.05.012.

[71] D.M. Bilkovic, M. Mitchell, P. Mason, K. Duhring, The role of living shorelines as estuarine habitat conservation strategies, Coast. Manag. 44 (3) (2016) 161–174.

[72] M.K. La Peyre, S.C.L. Buie, R.E. Rossi, B.J. Roberts, Long-term assessments are critical to determining persistence and shoreline protection from oyster reef nature-based coastal defenses, Ecol. Eng. 178 (2022), 106603, https://doi.org/10.1016/j.ecoleng.2022.106603.

[73] C.A. Currin, J. Davis, A. Malhotra, Response of salt marshes to wave energy provides guidance for successful living shoreline implementation, in: Living Shorelines, 2017, pp. 211–234.

[74] C.A. Currin, Living shorelines for coastal resilience, in: G.M.E. Perillo, E. Wolanski, D.R. Cahoon, C.S. Hopkinson (Eds.), Coastal Wetlands: An Integrated and Ecosystem Approach, 2nd edition, Elsevier, Amsterdam, The Netherlands, 2019, pp. 1023–1053.

[75] I. Safak, P.L. Norby, N. Dix, R.E. Grizzle, M. Southwell, J.J. Veenstra, A. Acevedo, T. Cooper-Kolb, L. Massey, A. Sheremet, C. Angelini, Coupling breakwalls with oyster restoration structures enhances living shoreline performance along energetic shorelines, Ecol. Eng. 158 (2020), 106071, https://doi.org/10.1016/j.ecoleng.2020.106071.

[76] M.K. La Peyre, K. Serra, T.A. Joyner, A. Humphries, Assessing shoreline exposure and oyster habitat suitability maximizes potential success for sustainable shoreline protection using restored oyster reefs, PeerJ 3 (2015) 1317, https://doi.org/10.7717/peerj.1317.

[77] A.G. Stricklin, M.S. Peterson, J.D. Lopez, C.A. May, C.F. Mohrman, M.S. Woodrey, Do small, patchy, constructed intertidal oyster reefs reduce salt marsh erosion as well as natural reefs? Gulf Caribbean Res 22 (1) (2010) 21–27.

[78] R.M. Fillyaw, M.J. Donnelly, J.W. Litwak, J.L. Rifenberg, L.J. Walters, Strategies for successful mangrove living shoreline stabilizations in shallow water subtropical estuaries, Sustainability 13 (2021) 11704, https://doi.org/10.3390/su132111704.

[79] S.M. Casas, J.La Peyre, M.K. La Peyre, Restoration of oyster reefs in an estuarine lake: population dynamics and shell accretion, Mar. Ecol. Prog. Ser. 524 (2015) 171–184.

[80] A.B. Rodriguez, F.J. Fodrie, J.T. Ridge, N.L. Lindquist, E.J. Theuerkauf, S. E. Coleman, J.H. Grabowski, M.C. Brodeur, R.K. Gittman, D.A. Keller, M. D. Kenworthy, Oyster reefs can outpace sea-level rise, Nat. Clim. Chang. 4 (6) (2014) 493–497.

[81] CPRA, Integrated Ecosystem Restoration and Hurricane protection: Louisiana's comprehensive Master Plan For a Sustainable Coast, Coastal Protection and Restoration Authority, Baton Rouge, LA, USA, 2007. Retrieved from, https://cims.coastal.louisiana.gov/RecordDetail.aspx?Root=0&sid=670#. Accessed 15 October 2022.

[82] CPRA, Louisiana's Comprehensive Master Plan for a Sustainable Coast, Coastal Protection and Restoration Authority, Baton Rouge, LA, USA, 2012. Retrieved from, http://sonris-www.dnr.state.la.us/dnrservices/redirectUrl.jsp?dID=4379731. Accessed 15 October 2022.

[83] R.T. Saucier, Geomorphology and Quaternary geologic History of the Lower Mississippi Valley, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS, 1994. Volume 1.

[84] S. Penland, R. Boyd, J.R. Suttor, Transgressive depositional systems of the Mississippi Delta Plain: a model for barrier shoreline and shelf sand development, J. Sediment. Petrol. 58 (6) (1988) 932–949.

[85] D.M. Thomson, G.P. Shaffer, J.A. McCorquodale, A potential interaction between sea-level rise and global warming: implications for coastal stability on the Mississippi River deltaic plain, Global and Planetary Changes 32 (2002) 49–59.

[86] E.D. White, E. Meselhe, A. McCorquodale, B. Couvillion, Z. Dong, S.M. Duke-Sylvester, Y. Wang, in: *2017 Coastal Master Plan: Attachment C3–22: Integrated Compartment Model (ICM)* Development. Version Final, Baton Rouge, Louisiana, Coastal Protection and Restoration Authority, 2017, p. 49. Retrieved from, http://coastal.la.gov/wp-content/uploads/2016/04/Attachment-C3-22-ICM-Development_10-5-16.pdf.

[87] White, E.D., Reed, D.J., Meselhe, E.A., 2019. Modeled sediment availability, deposition, and decadal land change in coastal Louisiana marshes under future relative sea level rise scenarios. Wetlands 1-16. https://doi.org/10.1007/s13157-019-01151-0.

[88] E. Meselhe, E.D. White, Y. Wang, D.J. Reed, Uncertainty analysis for landscape models used for coastal planning, Estuar. Coast Shelf Sci. 256 (2021), 107371. https://www.sciencedirect.com/science/article/pii/S0272771421002249.

[89] J.C. Winterwerp, T. Albers, E.J. Anthony, D.A. Friess, A.G. Mancheno, K. Moseley, A. Muhari, S. Naipal, J. Noordermeer, A. Oost, C. Saengsupavanich, S.A.J. Tas, F. H. Tonneijck, T. Wilms, C. Van Bijsterveldt, P. Van Eijk, E. Van Lavieren, B.K. Van Wesenbeeck, Managing erosion of mangrove-mud coasts with permeable dams—Lessons learned, Ecol. Eng. 158 (2020), https://doi.org/10.1016/j.ecoleng.2020.106078.

[90] I.S. Bumi, Widyaningtias, M.B. Adityawan, Coastal erosion management by implementing concept of building with nature (bwn) in demak regency, Central Java, Indonesia, IOP conference series. Earth environ. sci. 698 (1) (2021) 12005, https://doi.org/10.1088/1755-1315/698/1/012005.

[91] E. Meselhe, D. Roelvink, C. Wackerman, F. Xing, Q.T. Vo, Modeling the process response of coastal and deltaic systems to human and global changes, Focus on the Mekong Syst. Oceanograph. 30 (3) (2017), https://doi.org/10.5670/oceanog.2017.317.

[92] A. Masria, M. Iskander, A. Negm, Coastal protection measures, case study (Mediterranean zone, Egypt), J. Coast Conserv. 19 (2015) 281–294, https://doi.org/10.1007/s11852-015-0389-5.

[93] D. Reed, B. van Wesenbeeck, P.M.J. Herman, E. Meselhe, Tidal flat-wetland systems as flood defenses: understanding biogeomorphic controls, Estuar. Coast. Shelf Sci. 213 (2018) 269–282. https://www.sciencedirect.com/science/article/pii/S0272771418301057.

[94] Ankita Singhvi, Arjen P. Luijendijk, Alexander P.E. van Oudenhoven, The grey – green spectrum: a review of coastal protection interventions, Environ. Manage. 311 (2022) 114824.