Estuarine, Coastal and Shelf Science 227 (2019) 106341

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Ecogeomorphology of coastal deltaic floodplains and estuaries in an active delta: Insights from the Atchafalaya Coastal Basin

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ARTICLE INFO

Keywords:
Coastal delta geomorphology
Ecogeomorphology
Coastal deltaic floodplain
Deltaic wetlands
Large river delta estuaries

ABSTRACT

We present here an integrated analysis of coastal deltaic floodplains in the active Atchafalaya Coastal Basin coupled to downstream deltaic estuaries to review how ecosystem properties self-organize around fluvial processes during river re-occupation as part of the delta cycle. The flood pulse of the river is critical to providing autogenic feedbacks between flow patterns, sediment delivery, vegetation productivity, and organic/inorganic accretion that produce spatial patterns of land elevation, habitat diversity, and estuary dynamics. Coastal deltaic floodplains form in the proximal region of an active delta as bar-shaped islands with interdistributary bays shape hydrogeomorphic zones influenced by both geophysical and ecological processes. Hydrogeomorphic zones in coastal deltaic floodplains of the proximal sedimentation zone can also be defined by time since subaerial emergence accounts for variability in vegetation community composition and soil successional development. The reduction in sedimentation and increase in both above- and belowground biomass associated with formation of hydrogeomorphic zones results in significant increase in organic matter density in soils, with higher N:P ratios reflecting the biotic feedback of ecological succession on delta floodplain development. In both the proximal and distal sedimentation regions, episodic events, such as river floods and cold fronts, control seasonal water levels, marsh platform inundation, and increase in elevation capital. In coastal deltaic floodplains, an increase in vegetation height and density has a twofold effect: it favors trapping of sediment on the islands; whereas an increase in roughness deflects water flow and sediment into the channels thus bypassing the marsh surface. There is evidence that this is in contrast to more constant positive feedback of vegetation on sedimentation in distal estuarine marsh platforms. Delta estuaries go through a transformation from a near-riverine estuary in the winter-spring season to a near-marine lagoon in the summer-fall season. Geomorphological displacement of vegetation types occurs as platform elevation increases in the proximal sedimentation zone as delta landform emerges, with specific vegetation dominating the respective subtidal, intertidal and supratidal hydrogeomorphic zones. This does not occur in the distal sedimentation zone that lack sediment input as marsh platform elevation decreases. This is due to presence of salinity and H_2S that limit the capacity of biotic feedbacks to contribute to marsh stability. The growth of a coastal deltaic floodplain in the proximal sedimentation region of Atchafalaya Coastal Basin along with stable estuarine marshes in distal sedimentation region demonstrate the value of long-term riverine influence by preventing loss of wetland platform elevation.

1. Introduction

The Mississippi River Delta is a highly engineered landscape whereby river engineering plans have historically focused on flood control and navigation to promote the economic development of the Mississippi River under the guidance of project design flood (Twilley et al., 2016). This engineering design of the Mississippi River has enabled ports and waterborne transportation systems to move commerce

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https://doi.org/10.1016/j.ecss.2019.106341
Received 18 April 2019; Received in revised form 9 August 2019; Accepted 11 August 2019
Available online 14 August 2019
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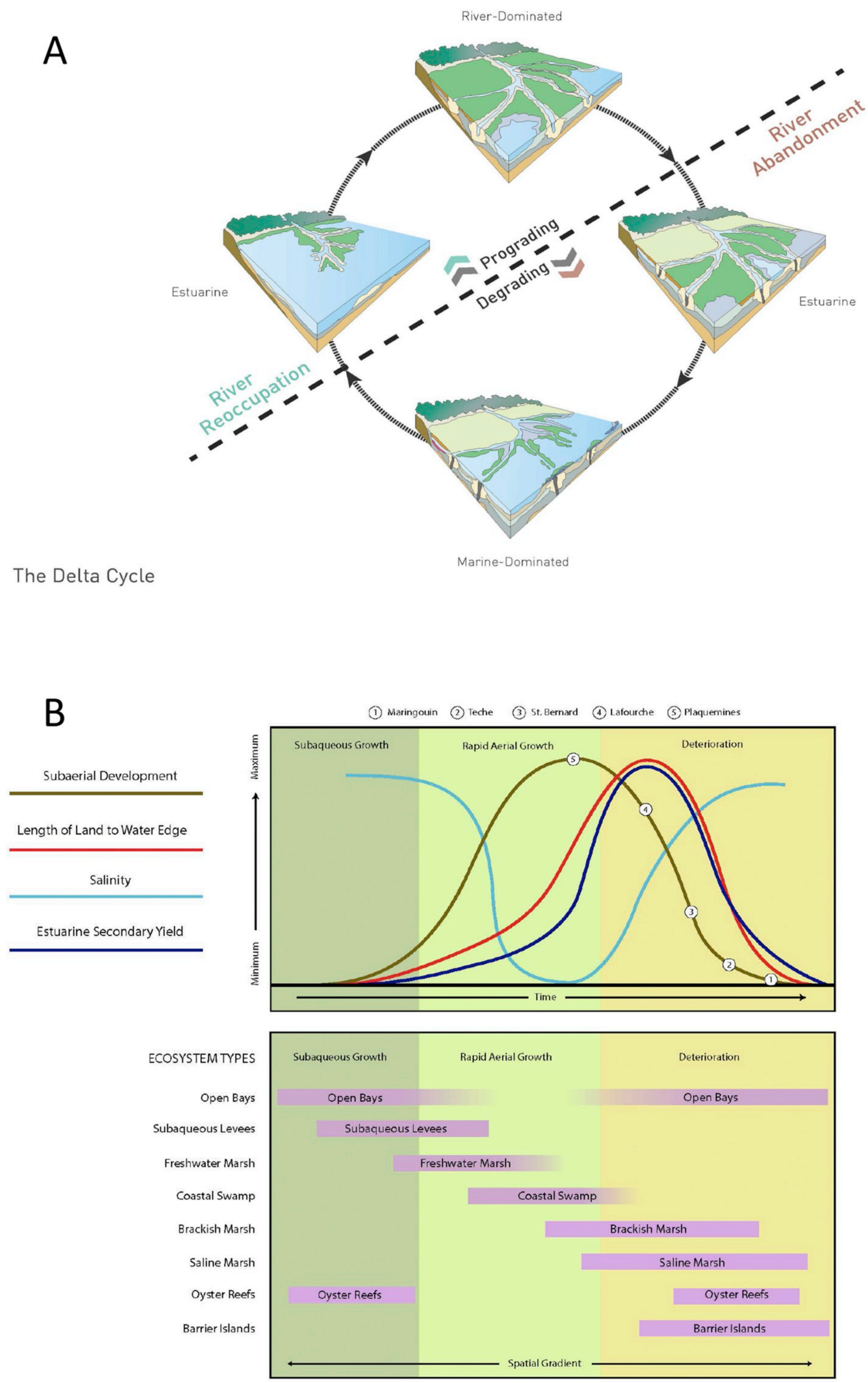

Fig. 1. **(A)** Landscape changes of delta cycle associated with river occupation (prograding active delta) compared to stages with river abandonment (degrading inactive delta) modified from Penland et al. (1988). **(B)** Ecosystem development along the spatial and temporal gradients of delta cycle associated 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 Gagliano and Van Beek, 1975; Gosselink et al., 1998). Numbers on the subaerial development line correspond to delta lobes in Mississippi River Delta.

through 41% of the conterminous nation, realizing economic benefits by providing safety to communities and industries located along the river floodplains (Carney et al., 2018). Project design flood was the impetus to initiate a national program to control the Mississippi River (USACOE, 2008) as designs were modified over two decades following the great flood of 1927 (Barry, 2007; Day et al., 2018). The final design was a combination of reservoirs, levees and flood-control structures that serve as either storage or conveyance of flood waters and sediment within managed channels to the Gulf of Mexico (Reuss, 2004). This engineering design is in striking contrast to historical processes of forming crevasses and overbank flooding into active floodplains during major river floods (Fisk et al., 1954; Day et al., 2016).

1.1. Engineering the delta cycle

In the deposition zone at the river's mouth, river engineering designs to convey flood waters past the active delta floodplain have essentially replicated the equivalent of river abandonment in the delta cycle (Fig. 1A). The delta cycle, which is a series of delta morphologies and ecosystem types (Fig. 1B) associated with the degree of river occupation and abandonment to coastal delta floodplains, describes the impacts of present river engineering approaches to flood-pulses in a major river basin (Penland et al., 1988; Roberts, 1997; Gosselink et al., 1998). The lack of sediment input to formerly active coastal basins has replicated the wetland retreat emblematic of a degrading delta where

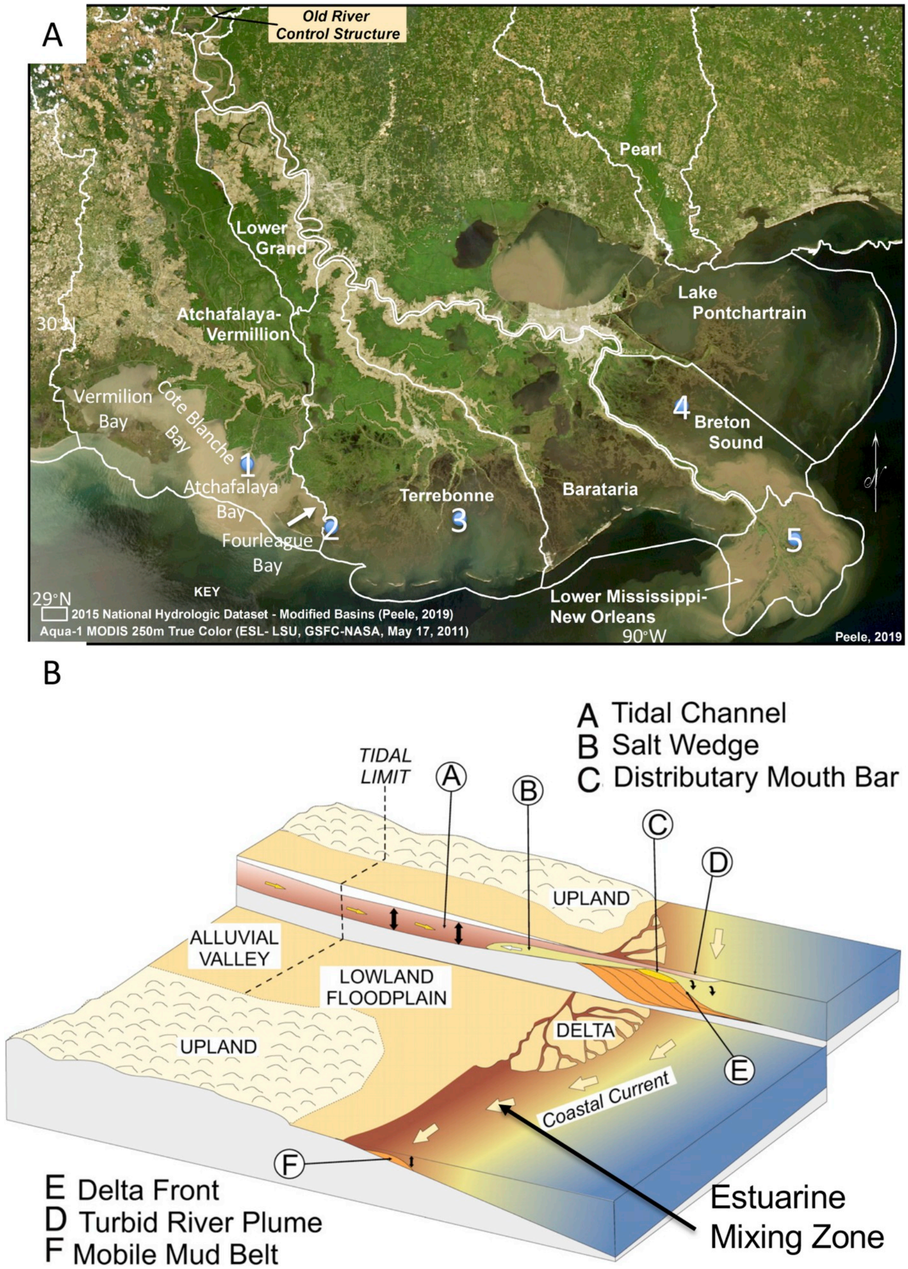

Fig. 2. (A) Coastal basins of the Mississippi River Delta including Atchafalaya, Terrebonne, Barataria, Breton, Lake Pontchartrain, and Lower Mississippi (Balize Delta). Numbers represent study sites that will be described in this review representing active and inactive delta processes. (B) Regional geomorphogical boundaries and associated sedimentary deposits within a large delta estuary (Bianchi and Allison, 2009).

coastal waters migrate inland, with annual wetland loss ranging from a high of 100 $km^2 yr^{-1}$ in the 1970s to more recent values of 44 $km^2 yr^{-1}$ (Couvillion et al., 2011). River abandonment of an active deltaic coastal basin results in salinity increases as the Gulf of Mexico migrates inland, converting wetlands to open water and increasing distribution of brackish and salt marshes where flood control designs restrict river floods (Gosselink et al., 1998). River abandonment increases bay areas with higher salinities, which expands the zones of productive estuarine fisheries such as oysters and shrimp (Fig. 1B). The accumulated impact of coastal deltaic basins abandoned by river processes and sediment supply over the entire Mississippi River Delta from 1932 to present is 5200 km^2 of wetland loss. This immense loss of wetland landscape to the seventh largest delta in the world has raised concerns over increased flood risks and decreased ecosystem services to communities and industries that inhabit an unsustainable landscape (Twilley et al., 2016; Carney et al., 2018). Presently there is a 50-yr, $50 billion plan for projects to provide ecosystem restoration and protection measures for public safety compensating for negative impacts of the engineering design to flood control (Peyronnin et al., 2013).

The process-based approach to delta restoration over recent decades for Mississippi River Delta relies upon the principles of river re-occupation of the delta cycle that will transform coastal basins from inactive to active coastal deltas (Gagliano and Van Beek, 1975; Day et al., 2007; Paola et al., 2011). Reintroducing riverine sediments into coastal basins will help to offset subsidence and sea level rise that is contributing to land loss in much of coastal Louisiana (Paola et al., 2011; Nyman, 2014; Blum and Roberts, 2012; Day et al., 2018). The concept of reconnecting river processes to deltaic floodplains as a means of restoring wetlands is rooted in the flood-pulse concept of enhancing biological productivity and biogeochemistry in a river-floodplain ecosystem (Junk et al., 1989; Bayley, 1995; Odum et al., 1995; Sparks, 1995; Day et al., 2009; Buijse et al., 2002; Wolski and Murray-Hudson, 2005). Flood pulses occur along the entire longitudinal gradient of a major river basin controlling floodplain hydrogeomorphology, which is a dynamic equilibrium of the physical environment with ecosystem processes (Johnson et al., 1995; Noe et al., 2013). The flood pulse of the river is believed to be critical to providing autogenic feedbacks between flow patterns, sediment delivery, vegetation productivity, and organic/inorganic accretion that produce spatial patterns of land elevation, habitat diversity, and aquatic dynamics (Larsen, 2019). In deltaic floodplains, these patterns of hydrogeomorphology are remarkably consistent among active deltas and exhibit a predictable sequence of succession (Fig. 1A). Thus, the manipulation of fluvial connectivity in coastal deltaic floodplains using river diversion structures are an essential tool for restoring inactive deltas that have been abandoned from sediment delivery, and offer opportunity to link sustainable ecosystem services with human activities at the land-ocean interface (Odum et al., 1995; Day et al., 1997, 2009; Batker et al., 2014; Pont et al., 2017; Rutherford et al., 2018).

1.2. Coastal basins as experimental units

Ecosystem design (Koenig and Tummala, 1972; Ross et al., 2015) using the delta cycle concept is based upon strategies associated with re-connecting river processes that control the self-organization of coastal morphology and ecosystem dynamics, or ecogeomorphology (Day et al., 2007; Paola et al., 2011; Blum and Roberts, 2012; Ma et al., 2018). The effectiveness of restoring an active delta basin depends on process-based ecosystem design approaches to recreate the hydrologic conditions of functional deltaic floodplains (Shaffer et al., 1999; Ross et al., 2015; Day et al., 2018; Wiegman et al., 2017; Rutherford et al., 2018). Coastal deltaic floodplains are coupled to downstream estuarine ecosystems, which are also considered part of an active delta (Madden et al., 1988; Perez et al., 2000; Lane et al., 2011; Day et al., 2011). The resultant coastal morphology and ecological community dynamics in this outfall region of coastal deltaic floodplains and estuaries using engineered structures to re-connect river processes is shaped by the hydrogeomorphology of the flood pulse (Heiler et al., 1995; Passalacqua, 2017). Therefore, sedimentation processes in both the proximal and distal regions of the outfall region of river diversions control ecosystem design of active deltaic coastal basins.

River control structures and levees in the lower Mississippi River Delta (Fig. 2A) constructed as part of river engineering approaches to flood control represent different degrees of river occupation within coastal deltaic floodplains (Day et al., 2007, 2016; Paola et al., 2011). Essentially, these river engineering structures manipulate the delta cycle defined above with different regimes of flood pulses. Such control of flood pulses offers the opportunity to experimentally test how varying processes of freshwater and sediment delivery will control basin level processes and coastal deltaic floodplain dynamics as defined by the delta cycle (Fig. 1A; Paola et al., 2011; Twilley et al., 2016). Observations of how coastal basins self-organize as river re-occupation drives processes provides insights into how to calibrate ecosystem design with increments of hydrologic connectivity (Paola et al., 2011; Day et al., 2011; Ross et al., 2015; Ma et al., 2018). Modeling such self-organization between river processes, coastal morphology and ecosystem attributes has not been well established. Such models are needed to more specifically develop ecosystem design specifications for all sediment enrichment techniques, from river diversions and pipeline conveyance to beneficial dredging.

The Atchafalaya Coastal Basin represents the largest river diversion along the lower Mississippi River that controls alluvial processes forming the emergence of an active coastal basin in the Mississippi River Delta (Fig. 2A). During the 1950's it became clear that a natural delta-switching event was occurring, and the Mississippi River would soon take the course of the Atchafalaya River. Congress authorized the construction of the Old River Control Structure in the upper region of Atchafalaya Coastal Basin in 1954, designed to prevent the Mississippi River from changing its course, serving as a river diversion that enhanced sediment supply to the Atchafalaya Coastal Basin (Reuss, 2004, Fig. 2A). The Old River Control Structure represents the only location where a distributary outlet has been maintained in the lower deltaic plain of the Mississippi River, emptying 30% of the combined flow of the Red and Atchafalaya Rivers into Atchafalaya River down to Atchafalaya Bay (Roberts, 1998; Roberts et al., 2003; Wellner et al., 2005). The Atchafalaya River has a mean flow of 5100 $m^3 s^{-1}$ with a flood peak from December to June with a mean of about 11,000 $m^3 s^{-1}$ (Lane et al., 2002). On an annual basis this diversion design delivers about 40 Mt/yr of sediment (estimates for 2008–2010), which represents ~31% of total Atchafalaya and Mississippi discharge (Allison et al., 2012).

The focus of this review is to present a synthesis of gradients in floodplain hydrology, fluvial geomorphology, and ecosystem dynamics (ecogeomorphology) in the Atchafalaya Coastal Basin as an example of a restored active deltaic basin re-connected to riverine processes. There is a hierarchy of processes that control the ecogeomorphology of coastal deltaic floodplains and delta estuaries from province to basin to marsh scale (Boesch et al., 1994; Larsen, 2019). This review is organized around two hierarchies of the active deltaic basin: (1) proximal vs distal regions of sedimentation that define ecosystem processes in the outfall area; (2) basin vs marsh scale processes that control accretion and ecological succession of wetland platforms (Fig. 3). This hierarchy is important in establishing details in processes and models of expected outcomes as specific designs for ecosystems are considered in delta restoration. The following sections present the organizational structure of longitudinal processes in the outfall region, and how models at the

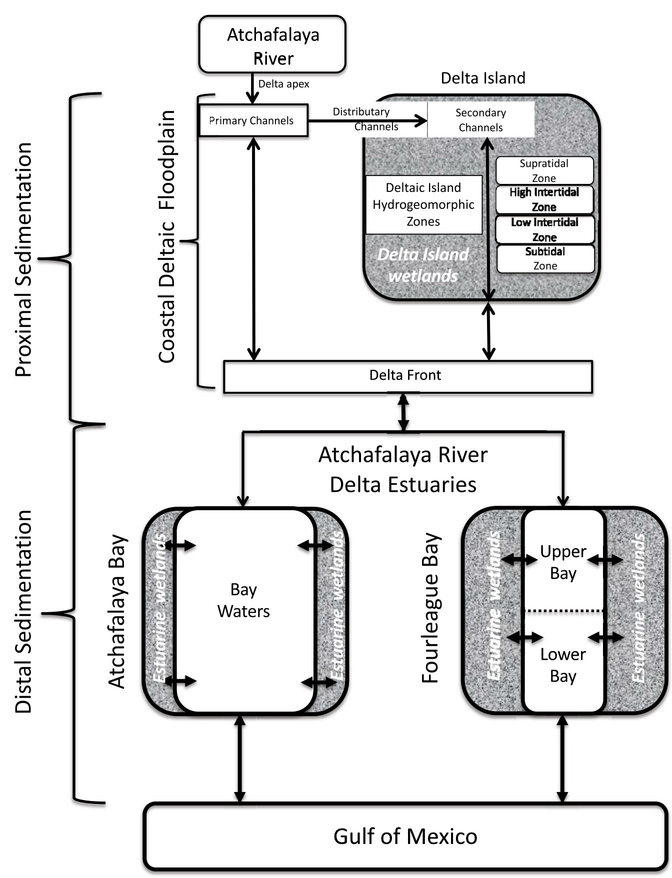

Fig. 3. Diagram describing the fate of freshwater, sediment and nutrients from Atchafalaya River as it passes through ecosystems of the lower coastal basin. The proximal ecosystems include Coastal Deltaic Floodplains coupled to the distal ecosystems of the Atchafalaya River Delta Estuary. The Atchafalaya River Delta Estuaries consists Atchafalaya Bay and Fourleague Bay with different ratio of wetlands to bay water areas.

basin and marsh levels link process of ecogeomorphic patterns driven by sediment supply. We present here an integrated analysis of coastal deltaic floodplains in the active Atchafalaya Coastal Basin coupled to downstream deltaic estuaries to review how ecosystem properties self-organize around fluvial processes during river re-occupation as part of the delta cycle along the entire salinity gradient of an active delta region (Fig. 3). We propose that the self-organization principles of this coastal basin serve as an analog of processes that can be used to calibrate how longitudinal and lateral connectivity by river reoccupation can restore active deltaic coasts around the world (Edmonds et al., 2011).

2. Ecosystems of an active delta

2.1. Large river delta estuaries

Large river delta estuaries (Fig. 2B) are recognized as part of delta-fronts extending from the upper influence of tides or salt in the river channel to the edge of river plume on the continental shelf (Hart, 1995). This mixing zone of river and gulf waters is a function of currents, tides and waves, controlling the deposition of sediments forming subaqueous and subaerial deposits shaping the ecosystems in active deltas (Neill and Allison, 2005; Gosselink et al., 1998). These regions are described as large river delta estuaries (Bianchi and Allison, 2009), which include the active coastal deltaic floodplain in the proximal sedimentation region, and large delta estuaries in the distal sedimentation zone (Figs. 2B and 3). It has been argued that fluxes of materials from large river basins to the ocean in active delta zones have significant ecosystem processes disproportionate to other types of estuaries on continental margins (Bianchi and Allison, 2009). The Atchafalaya River empties into an active coastal basin forming both coastal deltaic floodplains and delta estuaries meeting the definition of large river delta estuaries as proposed by Bianchi and Allison (2009) (see also Perillo, 1995; Hart, 1995). The alluvial and coastal deltaic floodplains along with large delta estuaries of the Atchafalaya Coastal Basin (Fig. 3; Fig. 4A) demonstrate self-organization of ecosystems of an active delta.

A majority of the mean (6400 $m^3 s^{-1}$) discharge from Atchafalaya River discharges into Atchafalaya Bay, which is a 150-km-wide shelf area with shallow water extending 40 km offshore to shelf edge (Fig. 4A). The Atchafalaya Bay is a broad, shallow (< 2–3 m) embayment coupled to a shallow and broad low-gradient shelf (10-m isobath is more than 40 km offshore of the delta), which is exposed to episodically energetic storms (Allison et al., 2000). The river plume from the Atchafalaya River extends out beyond the shelf edge during high flow, generating physical and biogeochemical impacts in the coastal and deep-water ocean mostly westward to the Texas shelf. This easily identifiable turbid water plume at high discharge defines the large river delta estuary seaward boundary (Figs. 2A and 4A; Bianchi and Allison, 2009). The nearshore coastal plume covers Atchafalaya Bay, and adjacent Cote Blanche and Vermillion Bays, and extends southwest along the coastal boundary zone flowing towards Texas. Discharge into the Atchafalaya Bay system is highly seasonal, and the estuary receives most of its sediment input and high loadings of nutrients during spring (Roberts and Doty, 2015).

Fourleague Bay is a 95-km^2 coastal waterbody located ~10 km southeast of the mouth of the Atchafalaya River bounded by a vast coastal wetland complex of about 380 km^2 (Fig. 4A), that formed several thousand years ago when the Mississippi River flowed into the region (Coleman and Gagliano, 1964; Roberts, 1997). The bay has a mean depth of ~1.5 m, with a well-mixed water column and a tidal range of about 0.30 m. The bay receives river water from the Atchafalaya through a 2.5-km wide opening to the north and is influenced by the Gulf of Mexico through a 180-m wide, 4-km long tidal channel to the south, referred to as Oyster Bayou (average depth ~ 5.5 m). Seasonal salinity and nutrient gradients, controlled by the relative influence of river input in the upper bay compared to tidal exchange in the lower bay, have extreme daily variation depending on changes in physical boundary conditions.

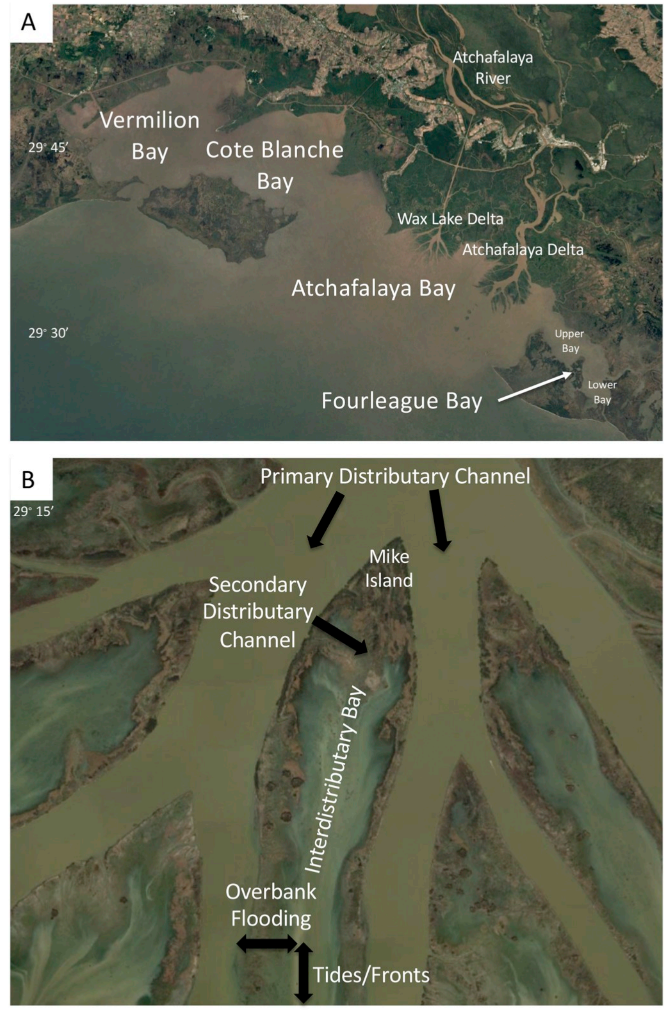

Fig. 4. **(A)** Map of the large delta estuaries of the Atchafalaya River that include Fourleague Bay, Atchafalaya Bay, Cote Blanche Bay and Vermilion Bay. **(B)** Morphologic features of coastal deltaic floodplain that defines the connectivity between primary and secondary channels with delta islands that include wetlands defined by hydrogeomorphic zones and interdistributary bay that is coupled to Gulf of Mexico by tides and fronts.

2.2. Coastal deltaic wetlands

Wetlands of an active delta include coastal deltaic floodplains that develop along the proximal sedimentation region, and estuarine deltaic wetlands that colonize the distal sedimentation region (Fig. 3; Fig. 5A). Coastal deltaic floodplains form in the proximal region of an active delta as bar-shaped islands that prograde and change in topography influenced by both geophysical and ecological processes (Fig. 4B; Fagherazzi et al., 2015; Ma et al., 2018). These wetlands are similar to tidal freshwater wetlands that have been identified as part of the upper boundary of river-dominated estuaries (Fig. 5A; Simpson et al., 1983; Megonigal and Neubauer, 2019). Estuarine deltaic wetlands colonize the intertidal platform that forms adjacent to large delta estuaries where large fluctuations in salinity are associated with mixing of river pulse and tidal prism of coastal waters, forming salt marshes similar to river dominated estuaries (Fig. 5A). Estuarine wetlands in the distal region of the Atchafalaya Coastal Basin represent salinity transition zones to the west along the shorelines of Atchafalaya Bay, Cote Blanche Bay, Marsh Island, and Vermilion Bay (Figs. 3 and 5A). To the

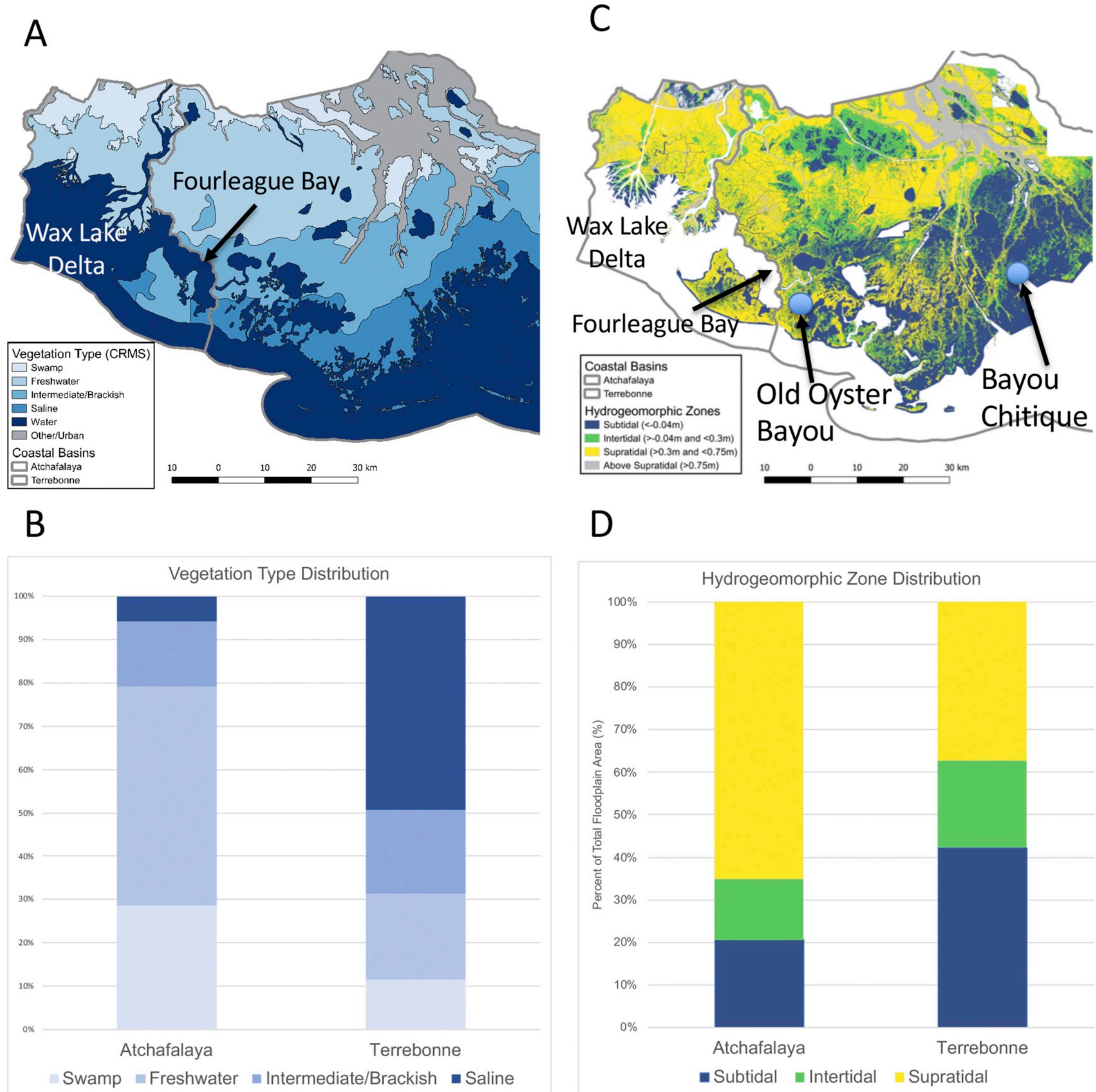

Fig. 5. (A) Map describing the distribution of wetland vegetation types in the portions of the Atchafalaya and Terrebonne Coastal Basins. (B) Bar graph describing the relative distribution of wetland vegetation type in Atchafalaya and Terrebonne Basins based on map (A). (C) Map describing the distribution of hydrogeomorphic zones in portions of the Atchafalaya and Terrebonne Coastal Basins. Study sites at Old Oyster Bayou and Bayou Chitique that are discussed later in this review. (D) Bar graph describing the relative distribution of hydrogeomorphic zones in Atchafalaya and Terrebonne Basins based on map (C). (Data sources include: vegetation types are based on Coastal Protection and Restoration Authority, Coastwide Vegetation layer (https://cims.coastal.louisiana.gov/Viewer/GISDownload.aspx); hydrogeomorphic maps from 2012 LIDAR DEM, United States Geological Survey, 2015, The National Map. (viewer.nationalmap.gov).

southeast, Fourleague Bay has estuarine wetlands that are hydrologically connected via several large bayous along the bay perimeter, such as Mosquito Bayou, Carencro Bayou, and Blue Hammock Bayou (Fig. 4A).

Wax Lake Delta (WLD, Fig. 4A and B) is a bayhead delta forming at the mouth of the Wax Lake Outlet (a flood control channel constructed in 1942) located in the Wax Lake-Atchafalaya Delta lobe complex (Roberts and Sneider, 2003; Blum and Roberts, 2009), which is the most recent of the Mississippi River early Holocene delta lobes (Roberts and Coleman, 1996). The hydrogeomorphology of coastal deltaic floodplains within WLD include turbulent jet deposition (Wellner et al., 2005), hydrological processes such as winds, tides, storms and river flooding (Bevington and Twilley, 2018), and soil formation by vegetation that trap sediment and deposit organic matter (Cahoon et al., 2011; Nardin and Edmonds, 2014; Nardin et al., 2016). Deltaic islands represent all land within the delta floodplain, defined as the land area that is subaerial above MLLW (-0.14 m, NAVD88), including deltaic island subtidal wetlands (Shaw et al., 2013, 2016; Fagherazzi et al., 2015).

The resultant delta islands have a planform morphology generally characterized by narrower upstream ends, with widening downstream newly emergent landscapes (Fig. 4B). Primary distributary channels, which are the major distributary channels that bifurcate below the delta apex, separate distinct deltaic islands. Upstream ends, nearest to primary distributary channels, exhibit higher elevation, which decreases both in a downstream direction and towards the interior of islands (Wagner et al., 2017). Secondary channels are smaller channels that usually flow into the interior of deltaic islands, such as on Mike Island in WLD, whereas other secondary channels also separate upper and lower portion of islands. Island interiors are characterized by shallow open water interdistributary bays that are generally open at the downstream end of islands (Fig. 4B). River energy decreases while tidal and wind influences increase along this gradient towards the delta front boundary (Hiatt et al., 2014; Geleynse et al., 2015; Shaw et al., 2016; Rossi et al., 2016). The downstream end of the interdistributary bays are open to the marine system and influenced by tides, coastal fronts

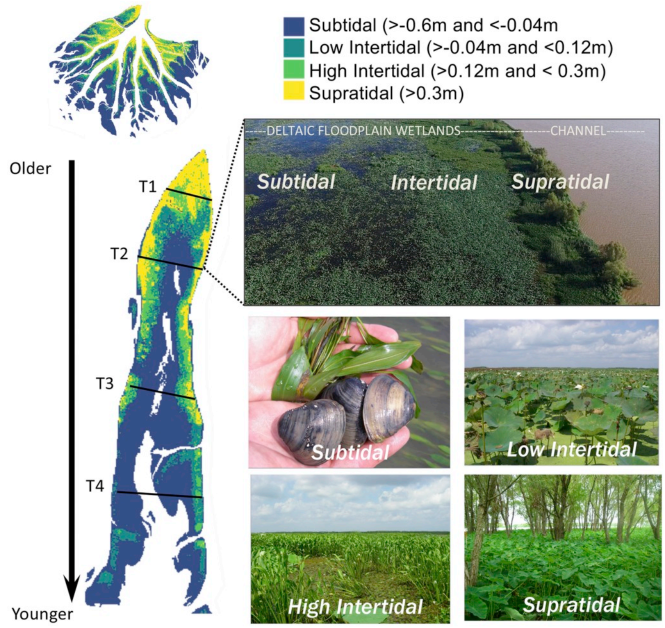

Fig. 6. Illustration of deltaic island cross-sectional elevation profile morphology from four transects across Mike Island at Wax Lake Delta. Elevations are extracted from a 2012 USGS LIDAR DEM. These patterns were used to develop a conceptual model that describes how differences in morphology and elevation range of island elevation profiles are related to island age. Younger, more recently deposited islands at the distal portions of the delta have lower overall elevation, wider levees, and more gradual interior slope; as deposition patterns change in response to elevation gain, intermediate age islands begin to develop a pronounced levee ridge that increases in elevation over time. In the oldest islands with high overall elevation, interior infilling occurs, with the interior of the islands achieving an elevation very close to the highest levee edges (Bevington and Twilley, 2018).

and hurricanes (Roberts et al., 2015; Bevington et al., 2017). Therefore, the transition from interdistributary bay to delta front is somewhat unclear but could be defined as the end of the vegetated subaqueous wetland.

Deltaic floodplain and estuarine wetlands can be defined by the elevation of the wetland platform that controls the frequency and duration of flooding (hydroperiod; Figs. 5C and 6). Distinct hydrogeomorphic zones are defined by soil elevation relative to a tidal datum to describe some of the complex interactions of physical and ecological processes that shape floodplain formation (Fig. 6; Wagner et al., 2017; Bevington and Twilley, 2018). Subtidal zones are those described as below mean low water (MLW, −0.04 m NAVD88), intertidal zones as those between MLW and mean high water (MHW, 0.30 m NAVD88), and supratidal as those above MHW (> 0.30 m NAVD88) (Fig. 6). The subtidal zone is generally vegetated by subtidal emergent herbaceous vegetation and submerged aquatic vegetation (SAV). Maximum vegetated depth is not known, most likely depending on water turbidity, however a maximum depth of interdistributary bays of approximately −1.0 m below MLLW was observed by Shaw et al. (2016). Supratidal hydrogeomorphic zones occur mainly along the natural levees and may limit inundation from primary distributary channels to island interiors.

Wetlands in the proximal and distal sedimentation regimes of an active delta can be classified into salinity zones in addition to hydrogeomorphic zones (Fig. 5A–D). Both proximal and distal wetland types are influence by tides, but the freshwater floodplain wetlands are diverse with several freshwater species differentiated by island topography, since tolerance to salinity is not a stress (Figs. 5 and 6). In the distal sedimentation region, salinity gradients result from mixing of river discharge with saline tidal waters, resulting in intermediate, brackish, and saltmarsh zones (Visser et al., 1998; Sasser et al., 2008).

In an active delta the river provides sediment that controls topography of wetland platforms and salinity regimes, controlling the distribution of both hydrogeomorphic and salinity zones of the deltaic floodplain and estuarine wetlands. In the active delta region of the Atchafalaya Coastal Basin, most of the wetlands are freshwater marshes and swamps, making up nearly 80% of the wetlands around Atchafalaya and Fourleague Bay (Fig. 5B). In contrast, to the east in the inactive Terrebonne Coastal Basin, nearly 70% of the wetlands are saline, intermediate and brackish marshes. In the active Atchafalaya Coastal Basin, the freshwater wetlands are mostly supratidal and intertidal hydrogeomorphic zones, while the subtidal and intertidal hydrogeomorphic zones dominate in the inactive Terrebonne Coastal Basin (Fig. 5D).

Hydrogeomorphic zones in coastal deltaic floodplains of the proximal sedimentation zone can also be defined by time since subaerial emergence to account for variability in vegetation community composition and soil successional development (Fig. 6). The amount of time that each zone has existed at a given elevation controls the geomorphology and formation of deltaic wetlands and contributes to patterns in vegetation community composition and other ecosystem processes such as nutrient biogeochemistry, organic matter composition, and nutrient sequestration rates (Bevington and Twilley, 2018). The younger stage of island development in deltaic floodplains is dominated by subtidal hydrogeomorphic zones, and as the islands age there is an infilling of the interdistributary bay resulting in decrease in subtidal zone and increase in intermediate hydrogeomorphic zones. Older areas of deltaic floodplains are often supratidal resulting from the collective effects of physical and organic sediment deposition and ecological processes contributing to infilling of these regions (Bevington and Twilley, 2018). In addition, there is no chronosequence applied to defining ecological processes on marsh platforms of estuarine wetlands in the distal sedimentation zone. Most of the estuarine wetlands in distal region of active coastal basin are supratidal hydrogeomorphic elevation.

3. Coastal basin dynamics

The recent continuous supply of new sediment from Old River Control structure to the Atchafalaya Coastal Basin allows us to experimentally describe the mass-balance equation for delta dynamics (Fig. 7A). The sustainable land area *(L)* of a coastal floodplain within a coastal basin (*A*) is determined by elevation gains associated with sediment supply and organic production relative to elevation loss due to local relative rise in sea level (accounting for subsidence) as follows:

$$L = \frac{Q_s f_r (1 + r_0)}{C_0(\sigma + H)} \quad \text{EQ (1)}$$

where Q_s is volumetric sediment discharge, f_r is the fraction of sediment delivered that is retained for land building, r_0 is the fraction of sediment volume contributed by organic production, C_0 is solids volume fraction, σ is local subsidence rate, and H is the rate of eustatic sea level rise (Fig. 7A). The sum of H and σ represent the relative sea level rise (RSLR, mm/yr) to which landscape surfaces must respond (by vertical accretion) to maintain a constant land area (*L*) in deltaic coastal basins (*A*). The Atchafalaya Coastal Basin exemplifies many of the functions and feedbacks of an active delta that demonstrate the principles of this mass balance equation (Day et al., 2007; Blum and Roberts, 2009; Syvitski et al., 2009; Twilley et al., 2016).

The dynamics of delta landscape behavior over the last six decades in the Atchafalaya Coastal Basin, with continued sediment delivery, is in striking contrast to landform dynamics to the east in the Terrebonne Coastal Basin, which represents the delta stage of river abandonment resulting from engineering projects that have reduced sediment delivery (Fig. 7B). A shoreline isopleth using a 50% *L:W* (land:water) ratio was used to measure delta instability in coastal deltaic basins as a

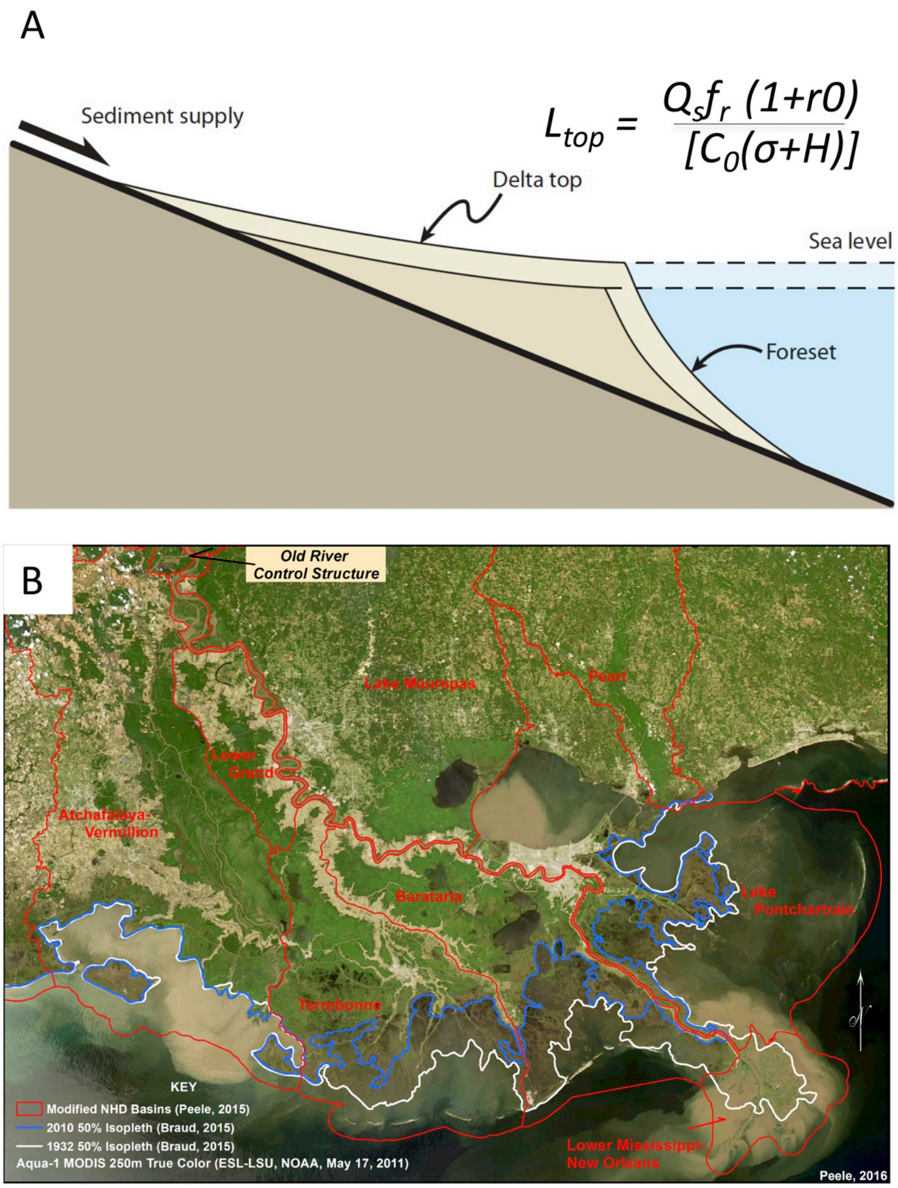

Fig. 7. (A) The longitudinal clinoform shape of a river delta subject to relative sea level rise (sea level plus subsidence) comparable to its overall surface relief; the trajectory of the shoreline (transgression or regression) depends on the balance between relative sea level rise rate and sediment supply based on equation where L is area of delta top, Q_s is volumetric sediment discharge, f_r is the fraction of sediment delivered that is retained for land building (Fig. 1), r_0 is the fraction of sediment volume contributed by organic production, C_0 is solids volume fraction, σ is local subsidence rate, and H is the rate of eustatic sea level rise (Paola et al., 2011). **(B)** Atchafalaya and Terrebonne Coastal Basins comparing shorelines in 1932 (white line) and 2010 (blue line) that demonstrates migration of Gulf of Mexico in the coastal basin with reduced sediment input (Twilley et al., 2016). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

function of reduced sediment supply from river flooding (Gagliano et al., 1970; Neill and Deegan, 1986; Twilley et al., 2016). Assumptions of how coastal basins respond to river management over the last 75 years are analyzed by noting landward migration rate of 50% *L:W* isopleths (landward migration of Gulf of Mexico) between 1932 and 2010 (Fig. 7B). The average landward migration for Terrebonne Coastal Basin was nearly 17 km compared to only 0.02 km in Atchafalaya Coastal Basin over the last 78 yrs. The resulting annual migration rates average 218 m/yr in Terrebonne Coastal Basin compared to < 0.5 m/yr in the active delta of Atchafalaya Coastal Basin. Given that both basins have similar H and σ in equation (1) above, this difference in migration of Gulf of Mexico inland is the result of sediment delivery to these two respective coastal basins (Twilley et al., 2016).

The lack of isopleth migrations in the Atchafalaya Coastal Basin over the last eight decades are explained by patterns of land area emergence above mean sea level as result of both lacustrine and coastal deltaic floodplain formations (Fig. 8). The natural processes of lacustrine delta sedimentation and succession occurring in Grand Lake has been accelerated through natural and anthropogenically induced hydrologic modifications of the Atchafalaya River (Fig. 8B) (Tye and Coleman, 1989; Hupp et al., 2008). During the decades of the 1930's and 1940's a significant fraction, perhaps 20–40%, of the suspended sediment load entering the Atchafalaya Basin remained in the basin and was unavailable for delta accretion in Atchafalaya Bay. Grand Lake was transformed into a lacustrine deltaic floodplain reducing open water area from 768 km^2 in 1863 to 371 km^2 in 2006 resulting in the expansion of 397 km^2 of floodplain wetlands (Mossa, 2016). The average accretion rate of wetlands in the basin ranged from 2.2 to 3.3 cm/yr from 1917 to 1978. As Grand Lake filled, and a sediment storage sink was exhausted within the Atchafalaya River Basin, a larger fraction of the sediment load has discharged to a proximal sedimentation region of the Atchafalaya Bay. As the sediment trapping efficiency of Grand Lake declined to near zero, nearly all suspended sediment entering Grand Lake was delivered to Atchafalaya Bay.

The Wax Lake Outlet was completed in 1942 and conveys ~30% of the Atchafalaya flow since the canal was expanded in the 1970s (Roberts et al., 1997). As the Wax Lake Outlet emptied into the proximal sedimentation region of Atchafalaya Bay, the resulting bed friction and decreasing flow velocities resulted in the formation of distributary mouth bars and bifurcating distributary channels (Wellner et al., 2005). The Atchafalaya-Wax Lake delta complex began developing subaqueously in the early 1950's, but subaerial land exposure was achieved by elevated sand transport during the flood of 1973 (van Heerden, 1994; Roberts, 1998). The present sediment load to the delta is

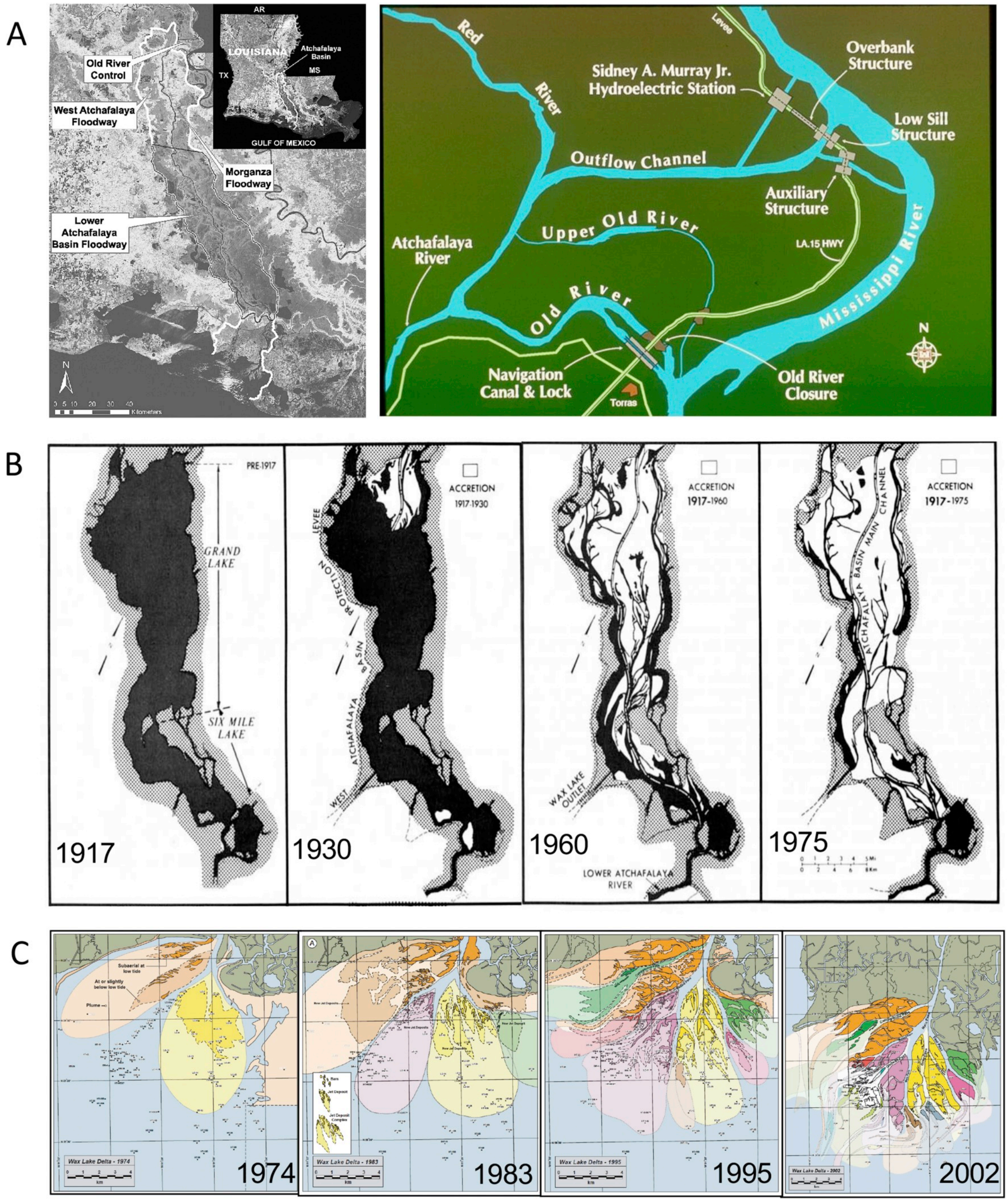

Fig. 8. (**A**) Location of the Atchafalaya Coastal Basin in the lower Mississippi River Basin. Right panel shows flood gates at Old River Control structure (ORCS) that controls flow to Atchafalaya River. (**B**) Formation of lacustrine deltaic floodplain in Grand Lake (Grand Lake Delta) from 1917 to 1975 within the Atchafalaya Coastal Basin (from Roberts and Adams, 1980). (**C**) Formation of the coastal deltaic floodplain at mouth of Wax Lake Outlet (Wax Lake Delta) from 1974 to 2002 (from Wellner et al., 2005).

25–38 Mt yr^{-1} of which 18% is sand (Kim et al., 2009). WLD subaerial land growth rate is estimated to be 2.62 km^2 yr^{-1} with a current areal extent of 70 km^2 (Kim et al., 2009; Xu, 2010; Edmonds et al., 2011; Paola et al., 2011). The WLD, in contrast to the Atchafalaya Delta forming to the east, had very little maintenance dredging during its growth and none after the early 1980's. Therefore, its growth has proceeded “naturally” as the result of river re-occupation with a maximum sediment retention efficiency of ~19% during 1981–1989 (van Heerden, 1994; Majersky et al., 1997). The rapid and unusually well documented development of Grand Lake Delta and WLD provides a model of coastal sedimentation patterns and primary ecological succession in an active coastal basin demonstrating the self-organizing principles of delta mass balance in Fig. 7A (Esposito et al., 2013). The formation of delta islands and coastal deltaic floodplains as described above (Figs. 4 and 5) in the proximal sedimentation region will be used to describe hydrologic connectivity and ecological succession in the following sections of this review.

The self-organization of ecological succession linked to the hydrogeomorphology of active deltaic processes is also demonstrated in basin level observations of marsh vegetation colonizing the landscapes formed on the lacustrine and deltaic floodplains in the Atchafalaya Coastal Basin (Fig. 9). Freshwater vegetation expanded in the

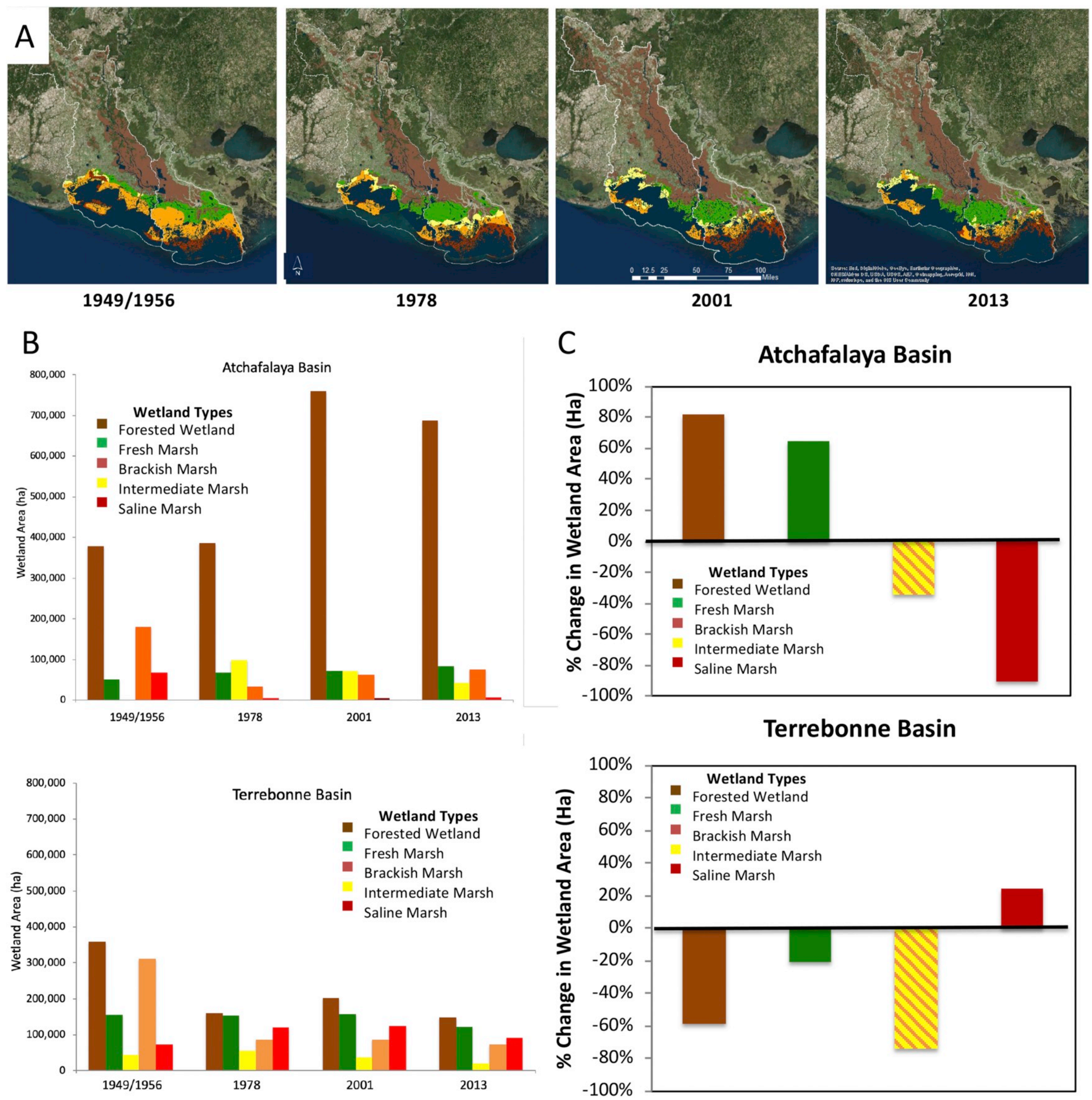

Fig. 9. **(A)** Vegetation maps and wetland distribution for Atchafalaya and Terrebonne Basins from 1949 to 2013 showing shifts in forested wetlands, freshwater marsh, brackish marsh, intermediate marsh and salt marsh over time in each basin. **(B)** Bar graphs of data shown in maps (A). **(C)** Change in area of wetland types. The hashed yellow bars represent combination of area for brackish and intermediate marshes. *Description of datasets used: (1)* 1949/1956 map (O'Neil, 1949; Habitat zones 1956; U.S. Geological Survey, 1978); (2) 1978 map (Chabreck and Linscombe, 1978; U.S. Geological Survey, 1978); (3) 2001 map (Linscombe and Chabreck, 2001; U.S. Geological Survey, 2003); (4) 2013 map (Sasser et al., 2014; U.S. Geological Survey, 2011). From Twilley et al. (2016). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Atchafalaya Coastal Basin since 1949 on newly emergent landscapes in contrast to migration of intermediate and brackish marshes landward in the Terrebonne Coastal Basin (Twilley et al., 2016). Salt marsh vegetation increased by 25% in the Terrebonne Coastal Basin compared to a 90% decrease in the Atchafalaya Coastal Basin since 1949. The marsh and delta landscape dynamics in these two coastal basins with contrasting sediment delivery define how river management controls land area and vegetation types within coastal basins (*L,* in Fig. 8A). The balance of land relative to water, changes in vegetation type, and processes of marsh instability in these two coastal basins demonstrate the contrast in processes of an active versus inactive coastal deltaic floodplain as predicted in the delta cycle concepts in Fig. 1.

The present distribution vegetation types and hydrogeomorphic zones in the proximal and distal sedimentation zones of the Atchafalaya and Fourleague Bay regions, in contrast to the Terrebonne Coastal Basin, demonstrates the distinct landscape features of an active vs inactive deltaic coastal basins (Fig. 5A–D). Both the dominance of freshwater vs estuarine vegetation, along with the hydrogeomorphic zone, depict coastal basin features in transition as function of sediment supply associated with river re-occupation vs river abandonment. The following sections of this review will focus on hydrologic connectivity and marsh wetland productivity associated with marsh platform elevations (hydrogeomorphic zones) to explain processes that may be responsible for these basin level patterns observed in Fig. 5. The succession of floodplain hydrology, fluvial geomorphology, and ecosystem dynamics in the Atchafalaya Coastal Basin in contrast to Terrebonne Basin provides insights into patterns of self-organization of an active deltaic basin re-connected to riverine processes.

4. Hydrologic connectivity

4.1. Proximal sedimentation region

River stage in primary channels strongly influences the hydrology of coastal deltaic floodplains by establishing flow in secondary distributary channels that deliver water, sediment and nutrients directly to interior of islands that flow downstream to delta front (Fig. 4B). In addition, water stage in primary channels will determine overbank flooding of island levees and hyporheic exchange via groundwater discharge with island interior (O'Connor and Moffett, 2015). These three pathways of flow control water, sediment, and nutrient exchange between channels and floodplain, with maximum exchange occurring during flood stages of river source, similar to flood pulse observed in alluvial floodplains. However, in coastal deltaic floodplains, marine forcings, such as tides and waves, also control exchange of water, sediment and nutrients with primary distributary channels and interior of islands (Fig. 4B).

Deltaic floodplain connectivity with primary channels is similar to alluvial floodplains as a function of river stage and bank/island topography; thus, geomorphology of the floodplain and the hydrologic forcings control inundation patterns of deltaic islands. Simulation techniques of water exchange at WLD demonstrate that 23–54% of water at the delta apex will enter the floodplains, indicating the strong hydrologic connectivity with deltaic islands (Hiatt and Passalacqua, 2015). Coastal deltaic floodplains have much more complex hourly, daily and seasonal exchange of water, sediment and nutrients compared to alluvial floodplains given the multi-directional gradients resulting from tides vs river stage that can be modified by pulsed disturbance events including river floods, meteorological fronts, and tropical storms.

Episodic events, such as hurricanes and cold fronts, force water upstream and downstream in islands, depending on southerly pre-frontal and northerly post-frontal wind conditions, respectively (Roberts et al., 2015). These events can play a significant role in the hydrology and sediment transport of coastal deltaic floodplains (Fig. 10A; Bevington et al., 2017). At WLD, extremely high peak discharge of river floods occurring in 2008 and 2011 resulted in a mean net elevation gain of 4.9–5.4 cm over each flood season, respectively (Fig. 10B). This is similar to patterns observed at Atchafalaya River Delta where the growth of the delta only occurred during floods with mean monthly discharge > 14,000 m^3/s (Rejmánek et al., 1987). While large floods add a considerable amount of sediment, Bevington et al. (2017) found that lower discharge floods also contributed sediment to the deltaic floodplain wetlands and that the total sediment subsidy from both large and small floods was likely necessary to maintain land building due to a large amount of elevation loss that occurred as a result of annual winter cold front passages (most likely due to erosion, Liu et al., 2018). Hurricanes have also been observed to result in net elevation gain, as demonstrated for WLD when Hurricanes Gustav and Ike resulted in a total net elevation gain of 1.2 cm. However, the long-term contribution of hurricane-derived sediments to deltaic wetlands was estimated to be just 22% of the long-term contribution of large river floods (Bevington et al., 2017). It is likely that measured over a larger temporal scale that sediment subsidies resulting from hurricanes is even less.

The resuspension of sediment occurs as a result of the waves, currents, and storm surge associated with hurricane passage (Walker, 2001), which is then redeposited as the surge moves inland into coastal wetlands, resulting in the measurable elevation gain attributed to hurricanes (Baumann et al., 1984; Rejmanek et al., 1988; Nyman et al., 1995; Cahoon, 2006; Turner et al., 2006; McKee and Cherry, 2009; Morton and Barras, 2011; Tweel and Turner, 2012). However, if elevation gains fail to also quantify erosion, thus essentially reporting gross deposition (i.e., positive elevation change), then landscape scale values overestimate the total sediment attributable to hurricanes along the northern Gulf of Mexico coast (Turner et al., 2006; Tweel and Turner, 2012). While sediment deposition during hurricanes is still an appreciable sediment subsidy for coastal wetlands, especially in abandoned delta lobes that receive very little riverine sediment input (McKee and Cherry, 2009; Baustian et al., 2012), it only represents a small contribution in coastal wetlands with appreciable riverine sediment delivery such as in an active coastal basin where WLD is located (Tornqvist et al., 2007; Bevington et al., 2017).

4.2. Distal sedimentation region

Both Atchafalaya and Fourleague Bays respond to seasonal stage of Atchafalaya River discharge and seasonal frontal passages (Fig. 11). Atchafalaya River discharge peaks from November to May (based on 40 yr average flow) and dominates the hydrology of both delta

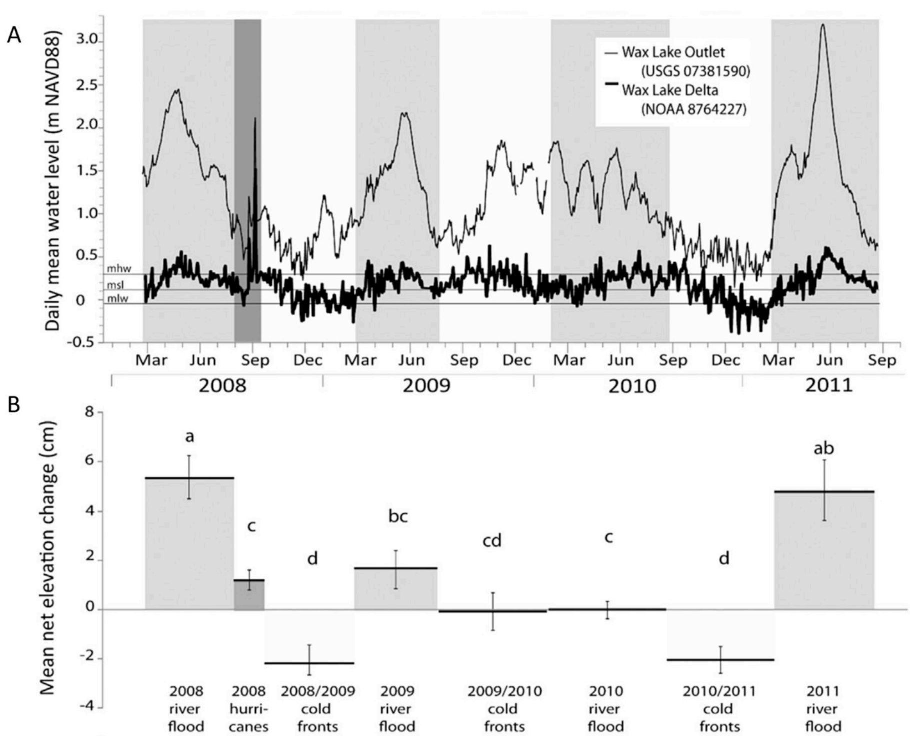

Fig. 10. (A) Water levels reported relative to NAVD88, measured at Wax Lake Outlet gauge (USGS 07381590) shown with thin line and Amerada Pass gauge (NOAA 8764227) represented by thicker line that describe river and tidal forcings at Wax Lake Delta. **(B)** Mean ± 1 standard error (SE) net elevation change (cm) across all the measured plots in Wax Lake Delta for each seasonal interval with results of one-way ANOVA (Tukey's pairwise comparison significant differences at $p < 0.05$, indicated by letters). From Bevington et al. (2017) (Needs copyright permission).

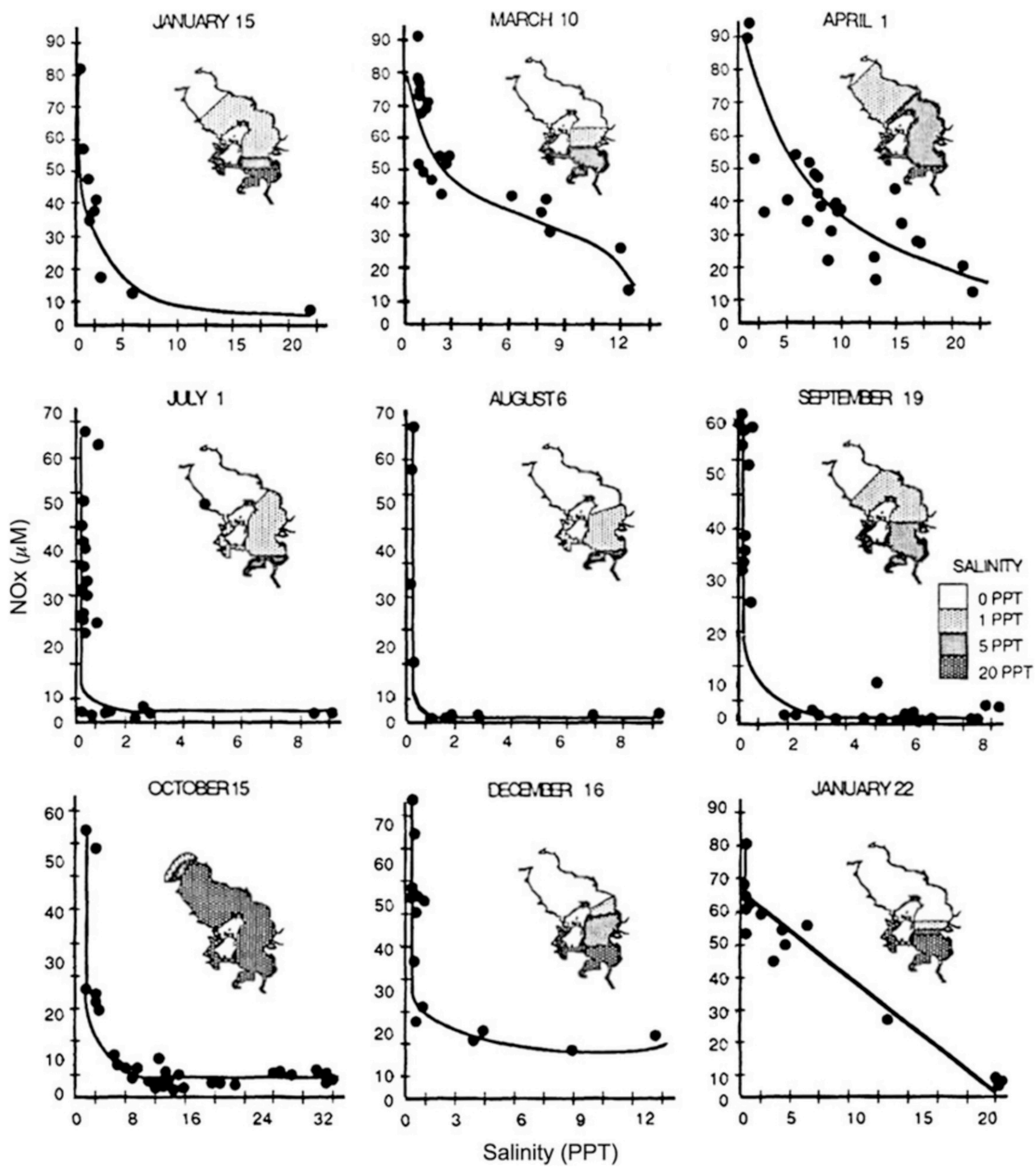

Fig. 11. Salinity mixing diagrams for nitrate ? nitrite (NOx) from January 1981 to January 1982. Inset maps show the 1, 5, and 15 ppt isohalines in Fourleague Bay (from Lane et al., 2011) (Needs Copyright Permission).

estuaries. River discharge represents nearly 98% of the freshwater into both delta estuaries and only 2% from local precipitation and runoff (Roberts and Doty, 2015). The resulting strong spring flood is considered a flood-pulse to both delta estuaries, similar to the proximal sedimentation region. Less than 5% of Atchafalaya River discharge enters Fourleague Bay but it exerts a strong influence on material fluxes and biogeochemistry in both wetland and tidal channel systems on the time scale of days to weeks (Caffrey and Day, 1986). Higher river stage from November to May is also a season of more frequent frontal passages, with fronts occurring nearly every 3–5 days in February (Wiseman et al., 1990). Southerly winds dominate several days prior to a frontal passage and push Gulf and bay waters against the shore, that along with higher river stage, raise water levels in both estuaries, but more pronounced in Fourleague Bay. As the front passes, northwesterly winds predominate that push water towards the Gulf, rapidly lowering water levels (Moeller et al., 1993; Day et al., 1995). Water level changes during switching of winds from south to north can be 1–2 m differences, increasing the inundation of adjacent marshes in Fourleague Bay, leading to sheet flow and sedimentation on the marsh surface.

Calm winds during July to October (summer to fall), when river discharge is low, results in hydrology controlled by tide-dominated circulation. The diurnal astronomical tidal amplitude is only 0.30 m and is influenced by ENSO events, such that during 1986–1988 there were few tides in summer that inundated wetlands in Fourleague Bay (Childers et al., 1990). These seasonal fluctuations of water levels in Fourleague Bay control the exchange with surrounding wetlands rather seasonal inundation with tides, as found in many tidally driven estuaries and salt marshes. The sequential passage of cold fronts when peak river discharge occurs during winter–spring, followed by lower water stands from calm winds and low river discharge in summer-fall form a cyclic hydrological pattern in the Atchafalaya River delta estuaries (Perez et al., 2000, 2003). Basically, Fourleague Bay undergoes a transformation from a near-riverine estuary in the winter-spring season to a near-marine lagoon in the summer-fall season (Wang et al., 1995).

Shifts in salinity in the upper and lower bays of Fourleague Bay follow this transformation from riverine to marine dominated estuary with seasons (Fig. 11). Passing of cold fronts during high river discharge can move low salinity waters from 0 to 5 ppt across the upper and lower bays. At lower river stage in late summer and fall, salinities of 20 ppt can dominate upper and lower bays by October (Fig. 11). This seasonal shift from oligohaline salinities during high river stage to mesohaline salinities in summer and fall is common in delta estuaries, referred to as estuarine recovery as river discharge decreases (Eyre and Balls, 1999).

Water levels in the marshes surrounding Fourleague Bay are particularly sensitive to seasonal changes in wind and river stage, forming three seasonal patterns of marsh-estuary exchange as follows: (1) north winds during frontal passage that decrease water levels and drain marshes in the upper bay; (2) east-southeast winds occurring in spring diverting Atchafalaya River water into Fourleague Bay raising bay water levels and inundating local marshes; (3) light north winds during the summer-fall causing the delta estuary to drain upper bay marshes (Madden et al., 1988; Lane et al., 2011; Miller, 1983; Baumann et al., 1984; Caffrey and Day, 1986). This mechanism of marsh flooding from increased bay water levels after prolonged southerly winds enhances resuspension of bay bottom sediments, which occurs most predominately during the winter–spring period (Booth et al., 2000; Wang et al., 2018, Fig. 12). The contribution of riverine and/or resuspended benthic sediment to adjacent wetlands in a study by Wang et al. (2018) was highly related to the seasonal relationship between river discharge and wind directions ($> 3\,m\,s^{-1}$). They refined the seasonal bay-wetland exchange patterns as follows: 1) limited sediment contribution during fall and winter seasons (‘bypassing’ season); 2) increasing sediment contribution in spring and summer seasons (resuspension-accumulation season); 3) abnormal high river discharge with pervasive northwesterly-northeasterly winds season (combined ‘bypassing’ and resuspension-accumulating season) (Wang et al., 2018, Fig. 12). The combination of high volumes of water originating from the northern bay and the restricted outlet to the Gulf often cause increased water levels and inundation of the surrounding marshes and potential advection of sediments onto the marsh surface.

Sedimentation in both proximal and distal delta wetlands are influenced by river discharge in combination with meteorological and astronomical tides. There seems to be some comparisons as function of channel vs bay morphologies, sand vs fine sediment deposition and resuspension, and distribution of wetland hydrogeomorphic zones, forming intricate networks of exchange among initial sources and sinks, respectively. Proximal wetlands are dominated by subtidal hydrogeomorphic zones in developing bay head delta islands in contrast to proximal wetlands in mostly supratidal hydrogeomorphic zones. Sediments in the proximal are sands and silts that dominate a series of resuspension and deposition across primary fluvial channels connected to vegetated delta islands. This is in contrast to proximal sedimentation zone which relies almost exclusively on cycles of fine sediment resuspension and exchange between bay floor and supratidal estuarine wetlands. There seems to be a different pattern described in proximal sedimentation region (Roberts et al., 2015; Bevington et al., 2017) compared to how fine sediment is exchanged with bay floor and marshes in response to local waves and currents during periods of minimal river discharge and energetic atmospheric conditions. In the distal region, riverine sediments may aggregate directly onto the bay floor (Restreppo et al., 2018; Wang et al., 2018) or bypasses the bay floor and delivered directly to the wetlands during periods of high river discharge. Connectivity in proximal and distal sedimentation regions will require more analyses and modeling efforts to determine if there are distinctions in how ecogeomorphology of these regions may differ in active coastal basin.

5. Ecological succession and biotic feedbacks

5.1. Ecological succession

Coastal deltaic floodplains first emerge as subaqueous deltas and increase in elevation forming hydrogeomorphic zones described above, with vegetation community composition controlled by elevation (Ma et al., 2018). This pattern follows the model of alluvial floodplains where primary ecological succession on newly formed land (emergence as subaerial delta) undergoes rapid shifts in elevation, hydrology, soil development, and plant succession, leading to the development of diverse wetland habitats (Roberts, 1997; Shaffer et al., 1992; Holm and Sasser, 2001; Cahoon et al., 2011; Roberts et al., 2015; Ma et al., 2018). Older and higher elevation lobes of the WLD tend to have a mixed community composed of *Colocasia esculenta*, *Phragmites australis*, *Polygonum punctatum*, *Typha spp*., *Schoenoplectus spp*., and *Zizaniopsis miliacea*. *Salix nigra* is the dominant woody vegetation present at levees of the older lobes, with an understory of *C. esculenta* and *P. punctatum* (Johnson et al., 1985; Shaffer et al., 1992; Holm and Sasser, 2001; Bevington, 2016). Previous work has helped to define and clarify the expected vegetation community that will occur on prograding deltaic islands in regard to the composition and zonation (Johnson et al., 1985; DeLaune et al., 1987; Rejmánek et al., 1987; Visser, 1989; Shaffer et al., 1992; White, 1993; Cahoon et al., 2011; White and Visser, 2016). Recent updates to this work from the Balize delta (site 5 in Fig. 2A) indicate that there may have been a shift in community composition to the invasive phenotype of *P. australis* in 2008 (White and Visser, 2016). Other shifts in dominance from species previously described have also occurred in the Wax Lake and Atchafalaya Deltas (site 1 in Fig. 2A), where *Sagittaria latifolia* is no longer dominant and *S. platyphylla* and increasingly *Nelumbo lutea* have taken its place (Carle et al., 2013; Carle and Sasser, 2016; Ma et al., 2018).

Temporal dynamics of herbaceous vegetation in coastal deltaic floodplains also respond to hurricane disturbance, which may respond differently than vegetation in inactive deltaic floodplains given the difference in soil texture. In WLD the passage of Hurricanes Gustav and Ike in 2008 expanded the coverage of invasive *C. esculenta* at elevations greater than MSL and exhibited an increase in percent cover within sampled plots in the years following hurricane passage. Lower elevation communities exhibited much greater diversity prior to the hurricanes and while the percent cover was higher than pre-storm levels, they had not yet returned to pre-storm species richness or diversity in three years following the storms. Therefore, it is likely that complex interactions of factors such as elevation, disturbance, and interspecific competition control vegetation patterns and community composition within deltaic floodplain wetlands (Bevington, 2016). Vegetation community cover in mineral dominated wetlands such as WLD demonstrate an ability to recover to pre-disturbance levels within one year, indicating that the loss of this type of wetlands has been overstated in previous analyses. There are many examples of how hurricanes have a selective effect on freshwater wetlands following hurricane passage, with general pattern of marsh surfaces forming ‘mats’ in zones formed by scouring out zones that become ponds with no vegetation (Chabreck and Palmisano, 1973). This pattern is less obvious in intertidal and salt marsh vegetation zones. However, in those cases where vegetation monitoring was continued for three years following disturbance, even the freshwater vegetation zones show signs of recovery following disturbance (Chabreck and Palmisano, 1973).

One of the conceptual models that is similar between alluvial and coastal deltaic floodplains is the transition from mineral sedimentation control to more visible increase in biotic control of accretion as time since emergence influences organic-dominated soil development (Noe and Hupp, 2005; Milner et al., 2007; Naiman et al., 2010; Larsen, 2019). In upstream alluvial floodplains, models of soil development and biogeochemistry are characterized in early stages by young, mineral rich soils with limited nitrogen availability. Vegetation cover influences

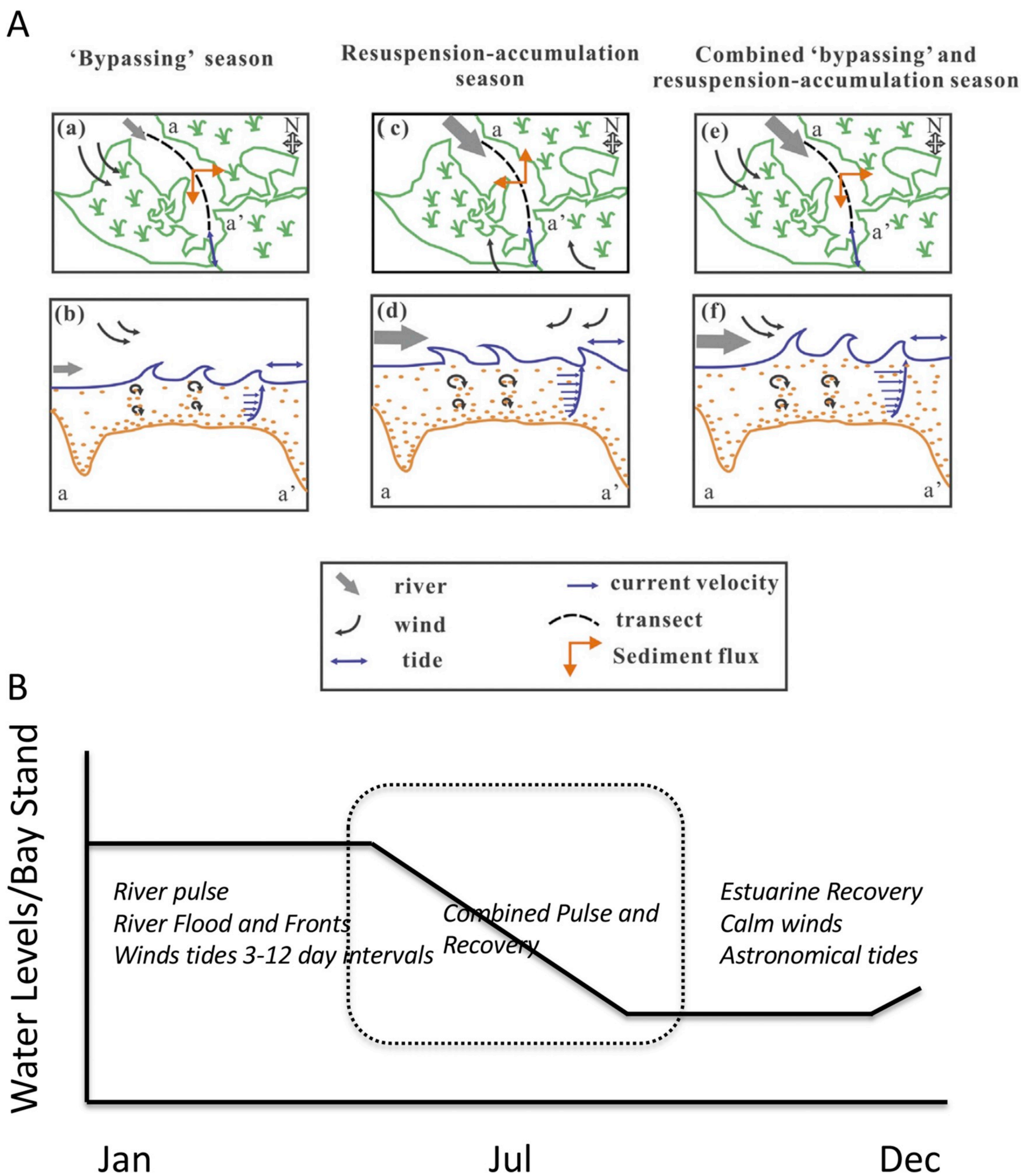

Fig. 12. (A) Three sediment transport regimes in Fourleague Bay system: (a–b) 'Bypassing' season: low river discharge and pervasive northwesterly-northeasterly winds; (c–d) Resuspension-accumulation season: high river discharge and pervasive southwesterly-southeasterly winds; (e–f) Combined 'bypassing' and resuspension-accumulation season: high river discharge and pervasive northwesterly-northeasterly winds. (a), (c), and (e) are in a plain view; (b), (d) and (f) are in a vertical profile view of transect a-a' (Wang et al., 2018). **(B)** Water levels in bounded delta estuary as function of the three seasonal forcings to describe sediment transport (based on Wang et al., 2018).

geomorphic processes and contributes to land formation via a range of physical and chemical mechanisms including altering surface hydrology, stimulating soil production, as well as sediment trapping and altering soil erodibility. The chronosequences associated with island formation observed in WLD (Figs. 13 and 14) represent shifts in floodplain morphology from geomorphic control by sediment deposition to ecological control by infilling with organic matter production (Bevington and Twilley, 2018). The younger chronosequence (IV) of deltaic floodplain (Fig. 13) is dominated by subtidal hydrogeomorphic zones with extensive interdistributary bays dominated by SAV. As the deltaic floodplain ages to older chronosequence (III), natural levees along fringe of islands increase, reducing connectivity with primary channels, intertidal hydrogeomorphic zones expand, interdistributary bay decreases and vegetation is a mix of SAV, lower and higher intertidal emergent vegetation. The interdistributary trough becomes a minor hydrogeomorphic zone of older chronosequence (II), with both low and high intertidal zones dominating the floodplain, along with emergence of a significant supratidal zone that restricts lateral connectivity with primary channel (Fig. 13).

The reduction in sedimentation and increase in both above- and belowground biomass from intertidal vegetation associated with formation of hydrogeomorphic zones results in significant increase in organic matter density in soils, with higher N:P ratios reflecting the biotic feedback of ecological succession in this chronosequence of delta floodplain development (Fig. 14). Older, supratidal zones are sheltered from frequent riverine mineral sediment inputs by high natural levees

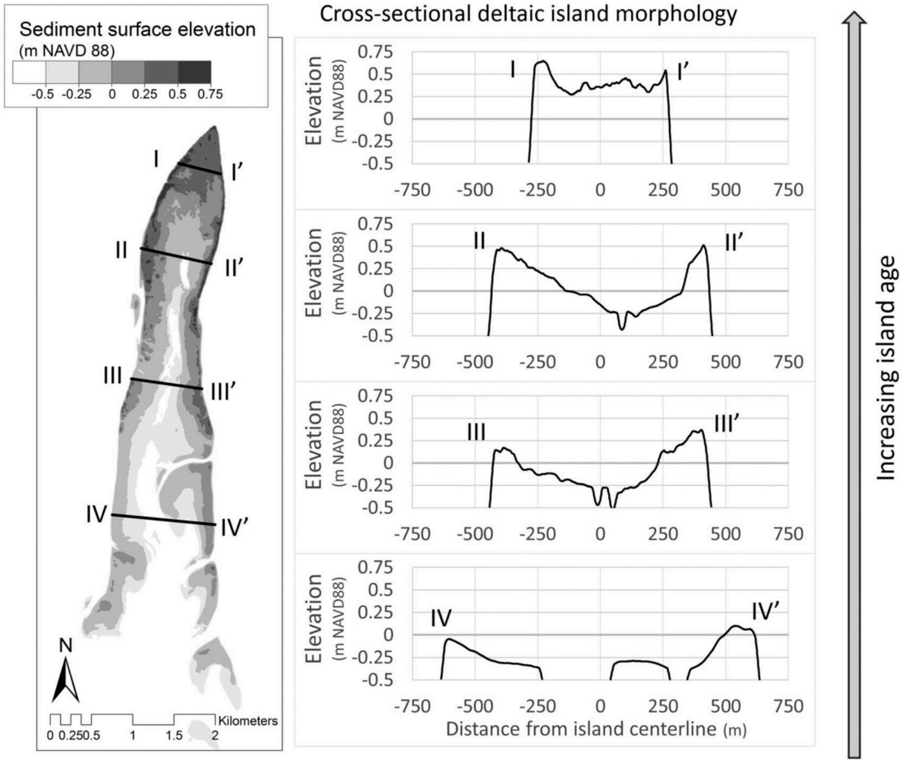

Fig. 13. Illustration of deltaic island cross-sectional elevation profile morphology from four transects across Mike Island. See Fig. 1 for location within delta. Elevations are extracted from a 2012 USGS LIDAR DEM. These patterns were used to develop a conceptual model that describes how differences in morphology and elevation range of island elevation profiles are related to island age. Younger, more recently deposited islands at the distal portions of the delta have lower overall elevation, wider levees, and more gradual interior slope; as deposition patterns change in response to elevation gain, intermediate age islands begin to develop a pronounced levee ridge that increases in elevation over time. In the oldest islands with high overall elevation, interior infilling occurs, with the interior of the islands achieving an elevation very close to the highest levee edges. (From Bevington and Twilley, 2018).

leading to vertical accretion driven by infilling from organic matter production (Bevington and Twilley, 2018), where future peat formation is expected to occur (Frazier, 1967; Lorenzo-Trueba et al., 2012). Throughout the 35-year chronosequence in WLD, soil nitrogen and organic matter content significantly increased by an order of magnitude, whereas phosphorus exhibited a less pronounced increase (Henry and Twilley, 2014; Aarons, 2019). This succession is characterized by a shift from mineral deposition with low soil total carbon (TC) and total nitrogen (TN) pools to rooted vegetation colonization as newly emerged landscapes stimulate wetland productivity that adds organic matter to soil. Since TN rapidly accumulates with OM while TP is primarily mineral-sourced, the soil atomic N:P ratios demonstrate the relative contributions of biological to physical controls during delta development and ecological succession (Fig. 14; Craft, 1997; Cleveland and Liptzin, 2007; DeLaune et al., 2016). Consequently, as biological feedback to soil development increases, OM concentration and N:P ratios increase over time and indicate feedback of ecological succession in the delta (Fig. 14). This is also evident when comparing the older marshes along Hog Island Channel compared to island sites on WLD (DeLaune et al., 2016), and when comparing sites along WLD of different chronosequences (Henry and Twilley, 2014; Aarons, 2019).

These patterns of self-organization with time of emergence associated with subaerial islands of WLD are similar to earlier studies of young successional stages of bar formation and ecological succession in the Atchafalaya River and Balize deltas (sites 1 and 5, respectively, Fig. 2A; Johnson et al., 1985; Rejmánek et al., 1987; Shaffer et al., 1992; White, 1993; Cahoon et al., 2011). A series of studies on the Brant splay at the mouth of the Mississippi River (site 5, Fig. 2A) exhibited shifts from allogenic to autogenic processes controlling elevation during seven years of island development (Fig. 15; White, 1993; Cahoon et al., 2011). Marsh net primary production (NPP) of islands showed sharp increase in above and below ground biomass from $< 200\,g\,m^{-2}$ to nearly $1000\,g\,m^{-2}$ in just three years (White, 1993). In WLD, mean aboveground live biomass at marsh study sites range from $892 \pm 590\,g\,m^{-2}$ on shoreline sites to $507 \pm 228\,g\,m^{-2}$ at island sites, correlated to greater soil carbon (DeLaune et al., 2016). Soil composition at WLD shifts from mineral to organic matter during this time frame, as indicated on the Brant splay by the shift in root:shoot ratio from 0.70 to 1.8 by year seven. The belowground biomass remained above $700\,g\,m^{-2}$ after the third year of marsh growth on these newly formed islands (White, 1993). Cahoon et al. (2011) described the concept of elevation capital in the self-organization of early successional stages of island formation, transitioning from mineral sedimentation to higher inputs of organic matter from plant production, with the additional contribution of plants to enhancing sedimentation. This transition is described in three distinct stages to the accrual of elevation capital and wetland formation in the splay: sediment infilling, vegetative colonization, and development of a mature wetland community (Cahoon et al., 2011).

Successional patterns associated with shifts from mineral to organic contributions linked to sedimentation with delta chronosequence are indicated by measuring rates of organic carbon sequestration in coastal deltaic floodplain soils. Accretion rates in marshes of WLD were greater at fringe sites most proximal to active sediment channels, with a decrease in accretion at more inland sites. Feldspar accretion rates ranged from 0.1 to 4.8 cm over a 6-month period at the marsh sites under the influence of the Wax Lake Outlet and ranged from < 0.1 to 2.0 cm at more isolated island sites (DeLaune et al., 2016). Based on ^{137}Cs, accretion is 1.43 cm/yr in marshes of this active delta (DeLaune et al., 2016), which is close to earlier estimates of 1.4 cm/yr for WLD (DeLaune et al., 1987). Based on these accretion rates, C sequestration rates ranged from 131 to $342\,g\,m^{-2}\,yr^{-1}$ for marsh surface profiles. These C sequestration rates are comparable to the decadal value reported by Simpson et al. (1983) for Louisiana deltaic freshwater marsh ($224\,g\,m^{-2}\,yr^{-1}$). For the WLD representing 60 years of delta formation, the organic carbon accumulation rate was $250\,g\,m^{-2}\,yr^{-1}$ (Shields et al., 2017; Aarons, 2019). One of the mechanisms of preferential carbon storage in deltas is the interaction with iron that is high in this active delta (Shields et al., 2016).

Ecological succession on mouth bar formations and subsequent islands of subaerial deltas not only contributes organic matter to elevation capital, but also directly enhances sediment deposition. This

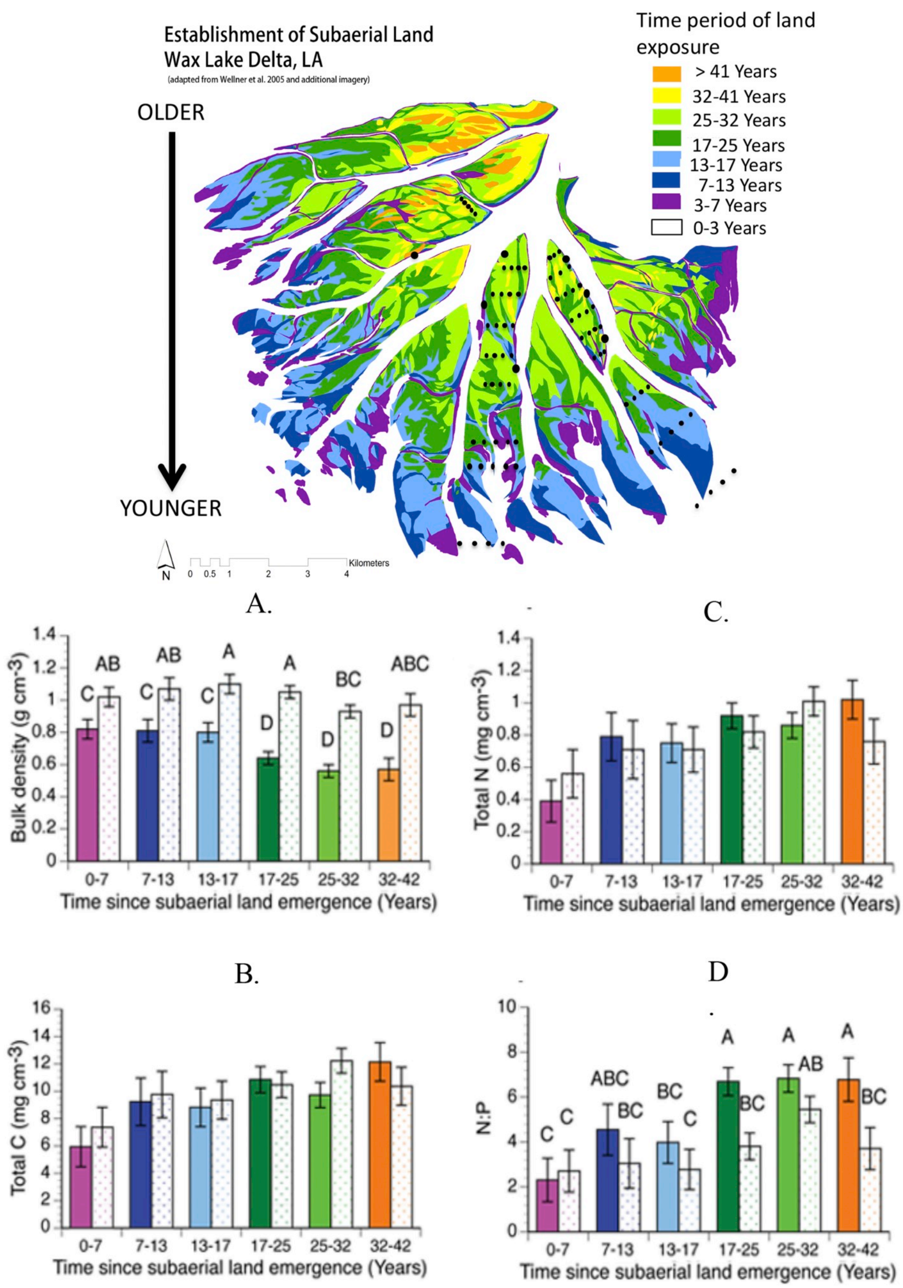

Fig. 14. Chronosequence map illustrating the age range over which land establishment occurred for the 2012 extent of Wax Lake Delta used to establish sampling sites to measure trends in soil characteristics since subaerial delta emergence (year in which land was first reported at or near subaerial, defined as above mean low water; Bevington and Twilley, 2018). Trends in soil characteristics include the following: **(A)** bulk density, **(B)** total C, **(C)** total N and **(D)** N:P. Values are given at both of the 0–15 cm (solid bars) and 15–30 cm (dotted bars) depths in each SDE zone (Aarons, 2019).

feedback effect on sedimentation in salt marshes was summarized by Fagherazzi et al. (2012), including direct particle trapping on wetland plants and indirect effects by enhancing the drag coefficient of emergent vegetation. These processes include both field measurements, mesocosm studies and simulations that test model assumptions. The connectivity of channels to marsh platforms of deltaic islands at WLD have also demonstrated these biotic feedbacks during ecological succession (Nardin and Edmonds, 2014; Nardin et al., 2016; Hiatt, 2013; Hiatt et al., 2018). Connectivity is a function of vegetation density on delta islands, representing important feedback of connectivity, whereby sediment deposition increases elevation, which decreases connectivity of overbank flow (Nardin and Edmonds, 2014; Nardin et al., 2016). During high river stage when connectivity peaks, vegetation density increases in the supratidal and intertidal hydrogeomorphic zones compared to the subtidal zone. Vegetation has less influence on sedimentation patterns during this season. However, vegetation is dense throughout the islands during the peak growing season (August–September), yet river stage is lower during this season and less connectivity occurs.

These results and others by Nardin and Edmonds (2014) and Nardin et al. (2016) suggest that proximal wetlands in an active delta might behave differently from distal estuarine wetlands in how biotic feedbacks influence sedimentation as a function of vegetation height and density. In proximal wetlands of coastal deltaic floodplains, an increase in vegetation height and density has a twofold effect: it favors trapping of sediment on the islands; whereas, the increase in roughness deflects water flow and sediment into the channels thus bypassing the marsh surface (Nardin et al., 2016). The presence of vegetation does enhance

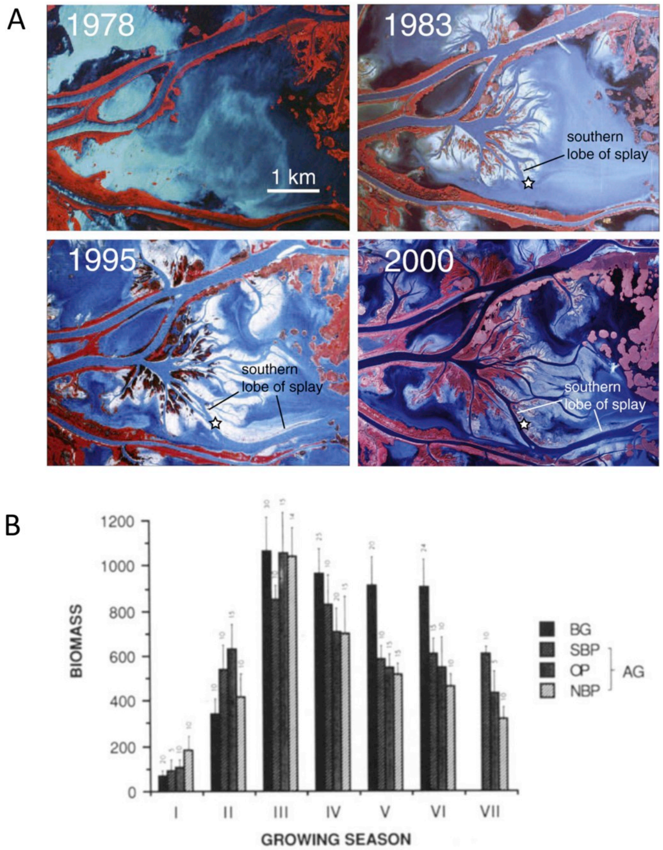

Fig. 15. **(A)** A time series of false-color aerial winter photographs of the study region showing the large, shallow pond adjacent to Brant Pass in 1978 and the growing crevasse splay in 1983, 1995, and 2000. The southern lobe of the splay, where this study was conducted, grew to over 3 km in length between 1983 and 2000. The red color indicates willow (*Salix nigra*) forest canopy and the white to lightest blue color indicates mud surfaces during the winter senescence when aboveground marsh vegetation is absent. The star indicates where D. White collected accretion and vegetation data from 1984 to 1990. In 1983, the star marked the location of mudflat habitat, which by 1988 had become high marsh habitat. (Cahoon et al., 2011). **(B).** Peak total dry weight plant biomass (g m^{-2}) on 'lower' mudflat sites within the Mississippi River active delta, Louisiana for seven growing seasons after emergence from shallow ponds. AG, aboveground biomass, i.e. the average of the biomass at SBP (South Brant Pass site), OP (Octave Pass site), and NBP (North Brant Pass site); BG, below-ground biomass (White, 1993). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

deposition at the edge of deltaic islands because of the reduced velocities and increased residence time (Hiatt, 2013; Christensen, 2016; Hiatt et al., 2018). Yet this deposition gives rise to sandy levees, which further confine the flow in the channels, bypassing proximal wetlands (Nardin et al., 2016). This change in sedimentation patterns as marsh islands increase in elevation and vegetation density was also observed by Cahoon et al. (2011) on the Brant splay at mouth of Mississippi River. In a tidal salt marsh, which represent the distal wetlands of an active delta, an increase in vegetation biomass may always favor sediment deposition and hence marsh resilience against sea level rise (see review in Fagherazzi et al., 2012). This is also evident in marsh sedimentation of estuarine wetlands of Fourleague Bay associated with combination of river stage and meteorological fronts (Fig. 12). This suggests that proximal and distal wetlands in an active large river delta estuary may have different functions under certain conditions of vegetation density and fluvial dynamics in response to seasonal river-pulse and coastal fronts. Mechanisms of biotic feedbacks control the relative amounts of sediment bypassing wetlands by constraining flow in channels in the proximal wetlands, compared to sediment re-suspension and transport from bay bottoms to marsh surfaces in the distal wetlands.

5.2. Model of marsh level processes

The stability of marshes within a coastal basin of the Mississippi River Delta reflect the local factors of sediment delivery, sea level rise, subsidence, and wave energy (Boesch et al., 1994; Day et al., 2011; Blum and Roberts, 2012). These detailed processes at the marsh scale explain the patterns described above for delta landscapes observed at the coastal basin scale (Twilley et al., 2016) (Figs. 7–9). We used the delta mass balance model by Paola et al. (2011) in the previous section to compare landscape dynamics of active and inactive coastal deltaic basins based on relative rates of sediment delivery. At the marsh level, we will use the marsh equilibrium model (Morris, 2006) to describe wetland vegetation response to flooding based on geomorphic platform elevations (hydrogeomorphic zones). Hydrogeomorphology at the basin scale controls the distribution of hydrogeomorphic zones at the marsh scale, which are distinct in the active Atchafalaya Coastal Basin compared to the inactive Terrebonne Coastal Basin (see Fig. 5). The marsh equilibrium model predicts plant net productivity based on depth of a hydrogeomorphic zone below mean high water (MHW, Morris et al., 2002; Morris, 2006, Fig. 16), which also controls biotic feedback to soil formation contributing to the elevation of a hydrogeomorphic zone. Maximum production (aboveground and belowground) of wetland vegetation occurs at a specific elevation of the marsh platform (hydrogeomorphic zone) below MHW. As sea level, subsidence and sediment deposition change this relative depth, there are feedbacks on net primary production and thus contribution of organic matter to platform elevation, as well as feedback effects of plant density on mineral sedimentation. The following equation is used to describe how wetland vegetation biomass may respond to the depth, D, of a marsh platform relative to MHW (Fig. 16):

$$B = aD + bD^2 + c \qquad \text{EQ (2)}$$

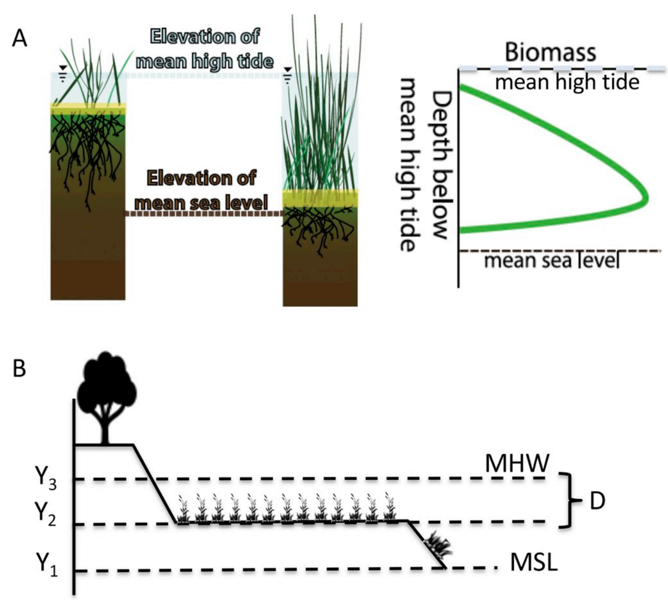

Fig. 16. **(A)** Schematic showing the relationship between mean high tide and biomass based on elevation of marsh platform relative to mean high water (MHW). The cartoons are based on measurements at North Inlet, South Carolina (Morris et al., 2002; Mudd et al., 2004). **(B)** Diagram of marsh platform illustrating the elevation of marsh surface relative to mean high water (MHW) and mean sea level (MSL), demonstrating the variable D, which is the depth of marsh platform below MHW. From Fagherazzi et al., 2012. (Needs copyright permission).

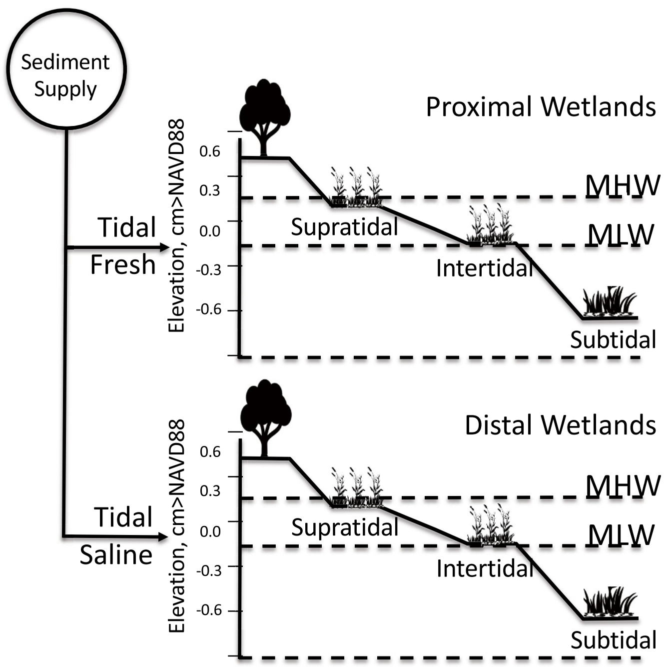

Fig. 17. Diagrams of marsh platforms illustrating the hydrogeomorphic zones in the proximal and distal wetlands of an active coastal basin, such as described for the Atchafalaya River Delta Estuaries. Distributions of hydrogeomorphic zones in the tidal freshwater region of the proximal wetlands and tidal estuarine wetlands in the distal wetlands is shown in Fig. 5.

where the parameters a, b, and c depend on vegetation type and marsh location. This equation is a simple representation of ecogeomorphology by combining the quantitative feedback between wetland ecology (vegetation biomass) and morphology (marsh platform elevation) by defining how flood duration impacts the ability of plants to influence geomorphic processes (Fagherazzi et al., 2012).

As noted by Fagherazzi et al. (2012), this ecogeomorphic model has formed the basis for several models of salt marsh evolution (Mudd et al., 2004; D'Alpaos et al., 2005; Morris, 2006; Kirwan and Murray, 2007; Mariotti and Fagherazzi, 2010). This review will use this model to compare the ecogeomorphic processes at the marsh level in the proximal and distal sedimentation regions of the Atchafalaya Coastal Basin; and compare those processes in the inactive Terrebonne Coastal Basin. Marsh vegetation typically occupies elevations approximately between mean sea level and mean high tide (Redfield, 1972; Morris et al., 2002; McKee and Patrick, 1988; Kirwan and Guntenspergen, 2010) (Fig. 16). The proximal and distal wetlands of the large river delta estuary of the Atchafalaya River have been described using subtidal, intertidal and supratidal hydrogeomorphic zones (Fig. 17). Both the proximal and distal wetlands have connectivity to sediment supply and are tidal, but there is a distinction defined by salinity gradients (fresh, brackish and salt marshes, Fig. 5). The biomass and productivity of macrophytes in the Mississippi River Delta have been noted to vary within the elevation range of marsh platforms (Spalding and Hester, 2007; Elsey-Quirk et al., 2019). While the model of Morris et al. (2002) is based on observations for tidal marshes in South Carolina dominated by *Spartina* spp., it has been tested in the Mississippi River Delta (e.g., Snedden et al., 2015; Wiegman et al., 2017) to explain the relation between elevation of hydrogeomorphic zones, percent time of inundation, and response of wetland productivity. The ecogeomorphology of proximal and distal sedimentation regions of the Atchafalaya Coastal Basin are distinct as to how marsh platform elevations control wetland net productivity, and how biotic feedbacks affect platform morphology (Fig. 17).

The equilibrium marsh model assumes a response of marsh

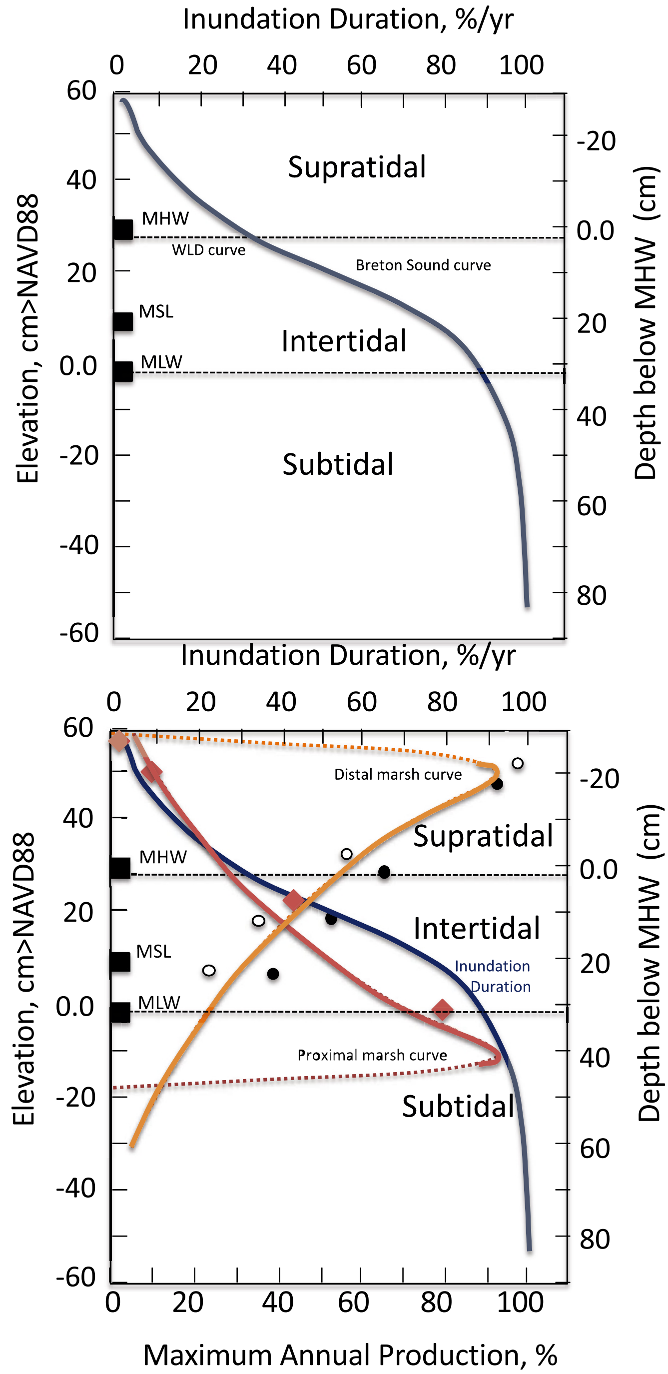

Fig. 18. (A) Inundation duration composite for Wax Lake Delta and Breton Sound relative to elevation for three hydrogeomorphic zones. **(B)** Estimates marsh production for proximal and distal wetlands as function of depth of hydrogeomorphic zones based on inundation duration for proximal wetlands in the Wax Lake Delta (unpublished data by Rovai and Twilley) and estuarine wetlands based on Snedden et al., (2015).

production with depth of marsh platform relative to MHW, which can also be explained by change in inundation duration with platform elevation (Morris et al., 2002, Fig. 16). Duration of flooding for the proximal wetlands in the coastal deltaic floodplain of WLD was calculated based on annual measures of water elevation in the field during 2014 and 2015 (Fig. 18A). A very similar inundation curve with marsh platform depth was generated by data provided in Snedden et al. (2015) for two marsh sites in Breton Sound, colonized by *S. patens* and *S. alterniflora* (site 4 in Fig. 2A; Fig. 18A). In addition, the inundation profiles for WLD fit the inundation durations measured in the emerging delta islands at the mouth of Mississippi River (site 5 in Fig. 2A; Cahoon et al., 2011). We compared these curves also to an inundation curve developed with platform depths (NAVD) provided in Kirwan and Guntenspergen (2015) for *S. paten* marshes in Chesapeake Bay (Fig. 1B in that publication). These inundation profiles with marsh elevation depth across three hydrogeomorphic zones in Fig. 18A (subtidal, intertidal, supratidal) will be used to compare and contrast plant production with depth relative to MHW and test the assumptions of the marsh equilibrium model for proximal and distal wetlands in active and inactive coastal delta basins.

Empirical evidence of how distal estuarine wetlands respond to marsh platform elevation is provided by experimental manipulations of marsh production for *S. alterniflora* and *S. patens* in two sites in Breton Sound (Snedden et al., 2015). Generalized curves for marsh production plotted against time inundated (%) provides insight into how estuarine wetlands in a distal sedimentation region respond to platform elevations (Fig. 18B). This response, as noted in Snedden et al., (2015), is distinct from the marsh equilibrium model anticipated in Fig. 16 as observed in salt marshes along the Atlantic coast. Aboveground and belowground net production decreased as elevation decreased in all inundation durations tested (a generalized curve in Fig. 18B is modified from Snedden et al., 2015). The results in Breton Sound are similar to responses of *S. patens* in field manipulations at Blackwater Marsh in eastern shore Maryland, where net production decreased for all elevations tested (Kirwan and Guntenspergen, 2015). This response is different than the curves for *S. americanus* in Chesapeake Bay that actually fit the model expected based on Morris et al. (2002) described above in Fig. 16. Given the assumptions in the marsh equilibrium model, there is speculation (using dotted line for distal marsh production in Fig. 18B) that marsh production may also decrease at higher platform elevations that were not tested for estuarine wetlands in Breton Sound.

There is preliminary evidence that marsh production of proximal wetlands has a very distinct response to platform elevation in contrast to distal estuarine wetlands. Vegetation from intertidal zone of delta islands was placed at fixed elevations across a gradient from high supratidal to subtidal hydrogeomorphic zones (Rovai, unpublished data). Net primary production of *C. esculenta* increased across all platform elevations tested (proximal wetlands in Fig. 18B). Again, assuming a response with marsh equilibrium, net production may decrease at lower elevations (dotted line for proximal wetlands in Fig. 18B). These divergent responses of marsh production to platform elevation between proximal (*C. esculenta*) and distal (*S. patens*) vegetation is limited to two vegetation types that colonize intermediate hydrogeomorphic zones in fresh and brackish salinity zones, respectively. Other vegetation types will need to be tested to build a more robust generalization of marsh production responses to platform elevations in the proximal and distal sedimentation regions of an active coastal delta basin. However, these patterns do fit other observations of marsh production with either newly emergent delta islands in proximal region (Cahoon et al., 2011; Elsey-Quirk et al., 2019) and studies of distal estuarine wetlands at modified elevations to simulate submergence (Wilsey et al., 1992; Webb and Mendelssohn, 1996; Mendelssohn and McKee, 2006).

Insights into the processes of sedimentation patterns and platform elevation to marsh productivity and stability in the active delta of Atchafalaya Coastal Basin were developed in a comprehensive analysis of salt marshes along the Old Oyster Bayou (OB) channel of Fourleague Bay (Day et al., 2011). Sedimentation, inundation frequency, and marsh elevation were compared with estuarine marshes in an inactive delta of the Terrebonne Coastal Basin at Bayou Chitique (BC). These two study sites in an active (sediment rich) and inactive (sediment poor) coastal basins of the Mississippi River Delta (Fig. 19A) demonstrate processes at the marsh level that can explain patterns previously described at the basin level of delta dynamics (Fig. 7B, Twilley et al., 2016). The marsh platform elevation is higher at OB in the active delta site compared to the marsh platform elevation at BC in the inactive delta. Since BC is at

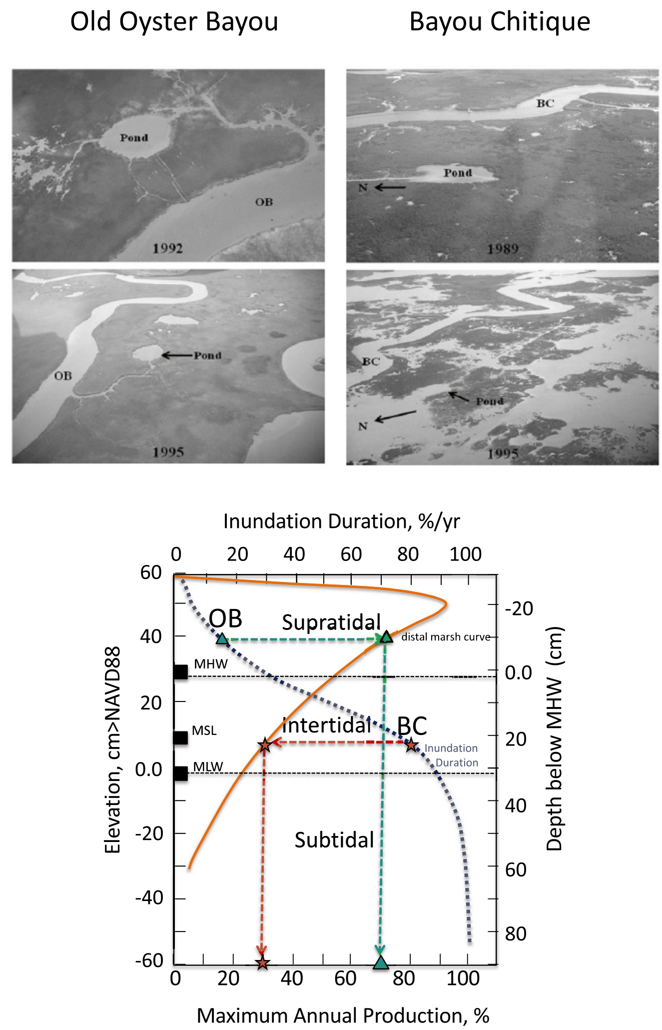

Fig. 19. **(A)** Photos of two study sites in active delta (Old Oyster Bayou, OB) and inactive delta (Bayou Chitique, BC). The ponds at OB remained stable during the study and remained a landscape feature of 2008. The BC pond opened up considerably by 1995 and surrounding marsh has disappeared by 2008. **(B)** Estimates of marsh net primary productivity for a site in an active delta (Oyster Bayou, OB, green line) and an inactive delta (Bayou Chitique, BC, red line) based on hydroperiods of both sites provided in Day et al. (2011) and marsh production model in Fig. 18B. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the lower end of the tidal prism, there is a low rate of sediment capture and soils do not drain and consolidate and remain fluid. OB marsh is well drained, particularly during summer when water levels are lower (as described above for distal hydrology and morphology section), and this allows consolidation and increased soil strength.

The production model for distal marshes proposed in Fig. 18B in response to platform elevation support the field observations at OB and BC based on platform depth relative to MHW. The flood frequency of both sites is based on annual measurements of water levels during 1993 (Day et al., 2011). If we use the production model for distal estuarine wetlands based on Breton Sound (Snedden et al., 2015), we can use inundation times for OB (15%) and BC (85%) to estimate marsh production values for each platform (Fig. 19B). Marsh production at OB is estimated at 80% maximum annual production (which is estimated to be about 4000 $g\,m^{-2}$) compared to only 30% for estuarine marshes at BC. Lower platform elevation, and thus increased depth to MHW and increased flood duration, contributes to poor soil strength as a result of decreased belowground production. This increased depth to MHW leads to lethal concentrations of H_2S in the BC marsh, compared to lower H_2S in the well-drained marsh site at OB. This stressed condition of the lower marsh platform also prevents revegetation, contributing to an accretion deficit for these interior marshes of an inactive delta site (Baumann et al., 1984; Hatton et al., 1983; DeLaune et al., 1994). Because BC elevation is lower, soil collapse occurred due to metabolic effects of prolonged inundation for the marsh platform in the inactive delta site. The marsh at OB in the active delta has a higher marsh platform which leads to higher sediment capture, consolidation and soil strength, and organic matter content (Day et al., 2011).

As explained in Day et al. (2011), accretion deficit is not the same as sediment deficit. As the elevation of the marsh platform decreases, the lack of mineral sediment accumulation increases the void volume in the rooting zone. They describe how increased void volume of soils in the lower tidal frame reduces upward displacement of the marsh surface by root development and other biogenic processes, leading to an accretion deficit. In the active delta estuarine marshes at OB, mineral sediment accumulation and expansion of the upper sediment column contributed almost half of the total sedimentation potential, compared to only 12% at BC. The accretion deficit and elevation loss in the inactive delta marsh is decades long and could likely be stabilized by increased sediment input as suggested by streamside salt marsh accretion rates (Hatton et al., 1983). But it ultimately leads to a point where several years without significant storm sediment input results in rapid loss of elevation and positive feedback of flood duration that continues to decrease NPP. Just before collapse the marsh is reduced to individual clumps of stressed vegetation floating in a fluid mud substrate. The stage is then set for rapid marsh deterioration and mortality over a matter of months.

As hydrogeomorphology controls platform elevation, vegetation types that are adapted to specific flooding duration dominate in the respective subtidal, intertidal and supratidal hydrogeomorphic zones, noted by Morris (2006) as geomorphological displacement. There seems to be distinct successional patterns between proximal and distal sedimentation zone in how the geomorphological displacement of vegetation (Morris, 2006; Cahoon et al., 2011) with hydrogeomorphic zones in active vs inactive delta coastal basins. In the proximal wetlands of the coastal deltaic floodplain, platform elevation increases with sediment deposition over time, species colonize marsh platforms converting interdistributary bays into vegetated intertidal and supratidal wetlands. As described by Cahoon et al. (2011), invading species modify their environment and raises the elevation to a level that excludes the original species. The upper limit to the acquisition of elevation capital is determined by the optimum growth range of the vegetation at a site (Morris et al., 2002), which is directly related to the tidal range at that site (McKee and Patrick, 1988; Kirwan and Guntenspergen, 2010).

However, in distal wetlands of inactive basins geomorphological displacement of vegetation is limited as marsh production decreases as hydrogeomorphic zones shift from supratidal to intertidal and subtidal, reducing biotic feedbacks on marsh stability. Why does geomorphological displacement of vegetation occur in proximal wetlands as sediment input to floodplains shift subtidal to supratidal hydrogeomorphic zones, but biotic feedbacks decreased in distal wetlands as marsh platforms decrease in elevation with lack of sediment supply? Both proximal and distal wetlands are tidal, but the presence of salt in distal wetlands with the formation of H_2S with increased flood duration is a stressor to marsh production (Mendelssohn and McKee, 2006). The reduction in sediment supply to inactive coastal deltaic wetlands reduces the input of fine sediment to estuaries and bays of distal sedimentation region that limits marsh sedimentation processes as described in this review. The decrease in marsh platform elevation (increase in depth to MHW) in the presence of H_2S limits geomorphological displacement in these distal wetlands.

6. Ecosystem design implications based on Atchafalaya Coastal Basin

The Atchafalaya Coastal Basin represents an active deltaic basin as a result of an engineered river diversion and thus provides insights to how self-organizing processes of geomorphology coupled to ecological succession generate distinct patterns of marsh stability in both proximal and distal wetlands. The formation of wetlands in coastal deltaic floodplains can be compared to alluvial floodplains in the proximal sedimentation zone, where sediments of lower cohesion form fan shaped patterns of deltaic islands in both the Atchafalaya River Basin (Piazza, 2014) and the Wax Lake Delta (Roberts et al., 2003). These delta islands form hydrogeomorphic zones that represent marsh platforms that change in elevation resulting in predictive vegetation patterns with increased levels of above and below ground production. This ecological succession results in biotic feedbacks that include increased organic accumulation that shifts the elevation capital from mineral to more organic based soils. As ecological succession increases vegetation density on delta islands, connectivity between primary and secondary channels as well as overbank flooding is reduced in response to increased drag coefficient of vegetation. The seasonality of vegetation density and river stage may control this dynamic, and together with meteorological fronts, control sediment deposition patterns and continued successional patterns as delta islands age. The combined effect of sediment type and vegetation on how cohesive forces control the patterns of ecogeomorphology of coastal deltaic floodplains has contributed significantly to how we can understand ecosystem design using the concepts of river reoccupation to inactive coastal basins (Edmonds and Slingerland, 2010). The challenge is to improve ecogeomorphic models to more accurately associate designs of fluvial processes to ecological outcomes.

Estuaries in the distal region of active coastal basins are dominated by fine sediments compared to coarser sediments in the proximal sedimentation zone of coastal deltaic floodplains. Estuarine marshes also have salinity, which includes the presence of sulfate (and thus production of H_2S), which is distinct from the freshwater tidal wetlands in the proximal sedimentation region that lacks this stressor with increased flooding (Fig. 17). The seasonality of sedimentation is similar in both the coastal deltaic floodplain platforms and distal estuarine platforms as a function of river stage and meteorological fronts. There is evidence that biotic feedbacks on sedimentation reduce connectivity with vegetation density in the proximal wetlands, where primary channels convey sediment past delta islands as marsh platform elevation increases. Estuarine bays in the distal region serve as reservoirs of fine sediments that are resupplied in flood-pulse season and redistributed to wetland platforms when water elevations are maximum during combination of river flood and meteorological fronts. Biotic feedbacks to sedimentation are positive in distal estuarine wetlands, as observed for most salt marshes. During the calm season of late summer and fall, lower water levels drain wetland platforms that consolidates sediment deposited during the winter season. This seasonal decrease in water levels relative to marsh elevation reduces the negative feedback of flooding with lower marsh platforms. The presence of H_2S in estuarine wetlands reduces vegetation diversity and establishes thresholds of flood duration that restrict the range of marsh platform elevations that can remain stable in these distal sedimentation regions of an active deltaic floodplain.

The combination of sediment supply during flood stage of the river, along with increased water elevations during meteorological fronts, helps explain how the estuarine-marsh systems survive elevated RSLR scenarios in micro-tidal environments. Most models assume that high sediment concentrations along with high tidal range are necessary for tidal marshes to reach critical stages under accelerated scenarios of sea level rise (Kirwan and Guntenspergen, 2010; Kirwan and Temmerman, 2009; Kirwan et al., 2010). These thresholds have been developed for estuaries in drowned river valleys with higher tidal amplitudes, in

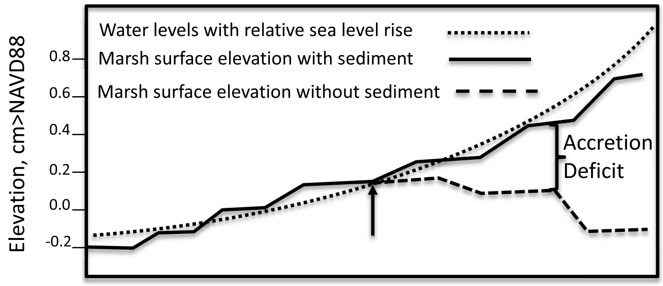

Fig. 20. Conceptual model of platform elevation changes proportional to relative sea level rise demonstrating point (shown by arrow) where river abandonment of delta cycle generates accretion deficit compared to marsh platform that continues to receive sediment supply.

contrast to large river delta estuaries, which have sediment supply to marsh platforms controlled by water levels as function of meteorological fronts and river stage, rather than inundation controlled only by tidal amplitude. In addition, suspended sediment concentrations in Fourleague Bay can range from about 400 to nearly 2000 mg L^{-1} during frontal passages (Perez et al., 2003). The combination of high suspended load and elevated water elevations during the spring river pulse-cold front season generates a sediment load that can build marsh surface elevation. This important contrast provides knowledge on the natural feedback mechanisms that could aid in the engineering design of future restoration strategies using delta estuaries as model for ecosystem design. Most sediment transport to and deposition on the marsh apparently occurs during weather-induced flooding events during flood river stage (Baumann et al., 1984; Rejmanek et al., 1988; Restreppo et al., 2018).

Insights into the stability of coastal deltaic floodplains and distal estuarine marshes can be explained using the concept of marsh platform accretion relative to sediment supply (Fig. 20). This review used results of vegetation dynamics in WLD to describe changes in vegetation types with hydrogeomorphic zones and disturbances. Response of estuarine marshes in active and inactive coastal basins provide insights into what processes are associated with marsh deterioration as waterlogging stress increases with a lack of sediment input (Day et al., 2011). The longer duration of marsh flooding as marsh platform elevation decreases in an inactive coastal basin along with low sediment capture efficiency establishes an accretion deficit as the coastal basin is abandoned from seasonal river-pulse. Even though there has been long-term relative sea-level rise at both sites, the active coastal basin remains stable as result of continued sediment supply that increased elevation compensating for RSLR.

These findings have important implications for wetland management using the operations of river diversions and the use of dredged sediments in delta stability. High sediment input will be necessary on a large scale if Mississippi River Delta marshes are to survive high rates of sea-level rise in a delta with high rates of subsidence. River diversions for regional-scale wetland restoration (Boesch et al., 1994; Day et al., 2007; Paola et al., 2011; Blum and Roberts, 2012) can utilize the flood-pulse season, along with coastal fronts, to distribute sediments on proximal and distal marsh platforms during high water level stands during winter and spring. The growth of coastal deltaic floodplains in the proximal sedimentation region of Atchafalaya Coastal Basin along with stable estuarine marshes in the distal sedimentation region demonstrate the value of long-term riverine influence by preventing loss of wetland platform elevation.

The key management question relative to ecosystem design for an inactive coastal basin is how to overcome accretion deficits that have accumulated for decades causing marsh instability. This is particularly problematic in areas where sulfate can produce H_2S that limits the ability of marsh production to overcome several decades of elevation deficits for marsh platforms. Another way to provide sediment input is via dredged sediments (Mendelssohn and Kuhn, 2003), but this is expensive and energy-intensive and likely unsustainable in the long-term (Wiegman et al., 2017). However, the use of diversions to overcome the accretion deficit requires flood-pulse operations that extend beyond the normal winter-spring flood pulse season. Some combination of marsh creation and beneficial use of dredge materials may offer limited recovery to elevation deficits; but the long-term maintenance of elevation platforms in both the proximal and distal sedimentation regions will require large sediment plumes from river diversions that can have large basin impacts.

Acknowledgement

Support was provided by the Louisiana Coastal Protection and Restoration Authority Interagency Agreement No. 4400008905 – Task Order 2. This research was partially supported by the National Science Foundation via the National Center for Earth-Surface Dynamics (EAR-0120914), Frontiers of Earth Surface Dynamics (FESD, OCE-1135427), and the Coastal SEES program at LSU (EAR-1427389).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2019.106341.

References

US Geological Survey, 2003. Louisiana land cover data set, UTM zone 15 NAD83, USGS. Online. http://lagic.lsu.edu/data/losco/landcover_la_nlcd_usgs_2001.zip accessed 7/15/15.
US Geological Survey, 2011. NLCD 2011 land cover (2011 edition, amended 2014) – national geospatial data asset (NGDA) land use land cover. Online. http://www.mrlc.gov accessed 7/23/15.
Aarons, A., 2019. Spatial and Temporal Patterns of Ecological Succession and Land Development along a Coastal Deltaic Floodplain Chronosequence. PhD dissertation. Louisiana State University, pp. 210.
Allison, M.A., Kineke, G.C., Gordon, E.S., Goni, M.A., 2000. Development and reworking of a seasonal flood deposit on the inner continental shelf off the Atchafalaya River. Cont. Shelf Res. 20 (16), 2267–2294.
Allison, M.A., Demas, C.R., Ebersole, B.A., Kleiss, B.A., Little, C.D., Meselhe, E.A., Powell, N.J., Pratt, T.C., Vosburg, B.M., 2012. A water and sediment budget for the lower Mississippi-Atchafalaya River in flood years 2008-2010: implications for sediment discharge to the oceans and coastal restoration in Louisiana. J. Hydrol. 432, 84–97.
Barry, J.M., 2007. Rising Tide: the Great Mississippi Flood of 1927 and How it Changed America. Simon and Schuster.
Batker, D., de la Torre, I., Costanza, R., Day, J., Swedeen, P., Boumans, R., Bagstad, K., 2014. 155-174. In: Day, J., Kemp, P., Freeman, A., Muth, D. (Eds.), Perspectives on the Restoration of the Mississippi Delta. Springer, New York.
Baumann, R.H., Day Jr., J.W., Miller, C.A., 1984. Mississippi deltaic wetland survival: sedimentation versus coastal submergence. Science 224, 1093–1095.
Baustian, J.J., Mendelssohn, I.A., Hester, M.W., 2012. Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob. Chang. Biol. 18, 3377–3382.
Bayley, P.B., 1995. Understanding large river: floodplain ecosystems. Bioscience 45, 153–158.
Bevington, A.E., 2016. Dynamics of Land Building and Ecological Succession in a Prograding Deltaic Floodplain, Wax Lake Delta, LA, USA. PhD Dissertation. Louisiana State University.
Bevington, A.E., Twilley, R.R., 2018. Island edge morphodynamics along a chronosequence in a prograding deltaic floodplain wetland. J. Coast. Res. 34 (4), 806–817.
Bevington, A.E., Twilley, R.R., Sasser, C.E., Holm, G.O., 2017. 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, 188–200.
Bianchi, T.S., Allison, M.A., 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proc. Natl. Acad. Sci. 106 (20), 8085–8092.
Blum, M.D., Roberts, H.H., 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nat. Geosci. 2 (7), 488–491.
Blum, M.D., Roberts, H.H., 2012. The Mississippi delta region: past, present, and future. Annu. Rev. Earth Planet Sci. 40 (1), 655–683. https://doi.org/10.1146/annurev-earth-042711-105248.
Booth, J., Miller, R., McKee, B., Leathers, R., 2000. Wind-induced bottom sediment resuspension in a microtidal coastal environment. Cont. Shelf Res. 20 (7), 785–806.
Boesch, D.F., Josselyn, M.N., Mehta, A.J., Morris, J.T., Nuttle, W.K., Simenstad, C.A., Swift, D.J.P., 1994. Scientific assessment of coastal wetland loss, restoration and management in Louisiana. J. Coast. Res. Spec. 20, 1–103.
Buijse, A.D., Coops, H., Staras, M., Jans, L.H., Van Geest, G.J., Grift, R.E., Ibelings, B.W., Oosterberg, W., Roozen, F., 2002. Restoration strategies for river floodplains along

large lowland rivers in Europe. Freshw. Biol. 47 (4), 889–907.
Caffrey, J.M., Day Jr., J.W., 1986. Control of the variability of nutrients and suspended sediments in a Gulf Coast estuary by climatic forcing and spring discharge of the Atchafalaya River. Estuaries 9, 295–300.
Cahoon, D.R., 2006. A review of major storm impacts on coastal wetland elevations. Estuar. Coasts 29 (6A), 889–898.
Cahoon, D.R., White, D.A., Lynch, J.C., 2011. Sediment infilling and wetland formation dynamics in an active crevasse splay of the Mississippi River delta. Geomorphology 131, 57–68.
Carle, M.V., Sasser, C.E., 2016. Productivity and resilience: long-term trends and storm-driven fluctuations in the plant community of the accreting Wax Lake Delta. Estuar. Coasts 39 (2), 406–422.
Carle, M.V., Sasser, C.E., Roberts, H.H., 2013. Accretion and vegetation community change in the Wax Lake Delta following the historic 2011 Mississippi River flood. J. Coast. Res. 31 (3), 569–587.
Carney, J.A., Twilley, R.R., Agre, C., Hird, J., Georgiou, I., Shelden, J., 2018. The giving delta. In: Mossop, E. (Ed.), Sustainable Coastal Design and Planning. Taylor & Francis, Boca Raton, FL9781498774543, LCCN 2018014032.
Chabreck, R.H., Linscombe, G., 1978. Vegetative Type Map of the Louisiana Coastal Marshes: Baton Rouge. Louisiana Department of Wildlife and Fisheries 1978 Data.
Chabreck, R.H., Palmisano, A.W., 1973. The effects of Hurricane Camille on the marshes of the Mississippi River delta. Ecology 54, 1118–1123.
Christensen, A., 2016. Hydrodynamic Modeling of Newly Emergent Coastal Deltaic Floodplains. MS Thesis. Louisiana State University, Baton Rouge, LA.
Childers, D.L., Day, J., John, W., Muller, R.A., 1990. Relating climatological forcing to coastal water levels in Louisiana estuaries and the potential importance of El Niño-southern oscillation events. Clim. Res. 1, 31–42.
Cleveland, C.C., Liptzin, D., 2007. C:N:P stoichiometry in soil: is there a "Redfield ratio" for the microbial biomass? Biogeochemistry 85, 235–252.
Coleman, J.M.M., Gagliano, S.M.M., 1964. Cyclic sedimentation in the Mississippi River deltaic plain. Transactions, Gulf Coast Association Geological Societies XIV, 67–80.
Couvillion, B.R., Barras, J.A., Steyer, G.D., Sleavin, W., Fischer, M., Beck, H., Trahan, N., Griffin, B., Heckman, D., 2011. Land area change in coastal Louisiana from 1932 to 2010. U.S. Geol. Surv. Sci. Investig. Map 3164, 12.
Craft, C.B., 1997. Dynamics of nitrogen and phosphorus retention during wetland ecosystem succession. Wetl. Ecol. Manag. 4, 177–187.
Day Jr., J.W., Pont, D., Hensel, P.F., Ibanez, C., 1995. Impacts of sea-level rise on deltas in the Gulf of Mexico and the Mediterranean: the importance of pulsing events to sustainability. Estuaries 18 (4), 636–647.
Day Jr., J.W., Martin, J.F., Cardoch, L., Templet, P.H., 1997. System functioning as a basis for sustainable management of deltaic ecosystems. Coast. Manag. 25, 115–153.
Day Jr., J.W., Boesch, D.F., Clairain, E.J., Kemp, G.P., Laska, S.D., Mitsch, W.J., Orth, K., Mashriqui, H., Reed, D.J., Shabman, L., Simenstad, C.A., Streever, B.J., Twilley, R.R., Watson, C.C., Wells, J.T., Whigham, D.F., 2007. Restoration of the Mississippi delta: lessons from hurricanes katrina and rita. Science 315, 1679–1684.
Day, J.W., Cable, J.E., Cowan, J.H., DeLaune, R., de Mutsert, K., Fry, B., Mashriqui, H., Justic, D., Kemp, P., Lane, R.R., Rick, J., Rick, S., Rozas, L.P., Snedden, G., Swenson, E., Twilley, R.R., Wissel, B., 2009. The impacts of pulsed reintroduction of river water on a Mississippi delta coastal basin. J. Coast. Res. 10054, 225–243.
Day, J.W., Kemp, G.P., Reed, D.J., Cahoon, D.R., Boumans, R.M., Suhayda, J.M., Gambrell, R., 2011. Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: the role of sedimentation, autocompaction and sea-level rise. Ecol. Eng. 37, 229–240.
Day, J.W., Cable, J.E., Lane, R.R., Kemp, G.P., 2016. Sediment Deposition at the Caernarvon Crevasse during the Great Mississippi Flood of 1927: Implications for Coastal Restoration, vol 8 Water, Switzerland.
Day, J.W., Lane, R.R., D'Elia, C.F., Wiegman, A.R., Rutherford, J.S., Shaffer, G.P., Brantley, C.G., Kemp, G.P., 2018. Large Infrequently Operated River Diversions for Mississippi Delta restoration Mississippi Delta Restoration. Springer, pp. 113–133.
DeLaune, R.D., Smith, C.J., Patrick, W.H., Roberts, H.H., 1987. Rejuvenated marsh and bay-bottom accretion on the rapidly subsiding coastal plain of U. S. Gulf Coast: a second-order effect of the emerging Atchafalaya Delta. Estuar. Coast Shelf Sci. 25, 381–389.
DeLaune, R.D., Nyman, J.A., Patrick, W.H., 1994. Peat collapse, ponding and wetland loss in a rapidly submerging coastal marsh. J. Coast. Res. 10 (4), 1021–1030.
DeLaune, R., Sasser, C., Evers-Hebert, E., White, J., Roberts, H., 2016. Influence of the Wax Lake Delta sediment diversion on aboveground plant productivity and carbon storage in deltaic island and mainland coastal marshes. Estuar. Coast Shelf Sci. 177, 83–89.
D'Alpaos, A., Lanzoni, S., Marani, M., Fagherazzi, S., Rinaldo, A., 2005. Tidal network ontogeny: channel initiation and early development. J. Geophys. Res. 110, F02001. https://doi.org/10.1029/2004JF000182.
Edmonds, D.A., Slingerland, R.L., 2010. 'Significant effect of sediment cohesion on delta morphology', Nature Geoscience. Nature Publishing Group 3 (2), 105–109. https://doi.org/10.1038/ngeo730.
Edmonds, D.A., Paola, C., Hoyal, D.C., Sheets, B.A., 2011. Quantitative metrics that describe river deltas and their channel networks. J. Geophys. Res.: Earth Surf. 116 (F4).
Elsey-Quirk, T., Graham, S.A., Mendelssohn, I.A., Snedden, G., Day, J.W., Shaffer, G., Sharp, L.A., Twilley, R.R., Pahl, J., Lane, R.R., 2019. Mississippi river sediment diversions and coastal wetland sustainability: synthesis of responses to freshwater, sediment, and nutrient inputs. Estuar. Coast Shelf Sci. 221, 170–183.
Esposito, C.R., Georgiou, I.Y., Kolker, A.S., 2013. Hydrodynamic and geomorphic controls on mouth bar evolution. Geophys. Res. Lett. 40 (8), 1540–1545.
Eyre, B., Balls, P., 1999. A comparative study of nutrient behavior along the salinity gradient of tropical and temperate estuaries. Estuaries 22 (2), 313–326.
Fagherazzi, S., Kirwan, M.L., Mudd, S.M., Guntenspergen, G.R., Temmerman, S., D'Alpaos, A., van de Koppel, J., Rybczyk, J.M., Reyes, E., Craft, C., Clough, J., 2012. Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors. Rev. Geophys. 50, 28.
Fagherazzi, S., Edmonds, D.A., Nardin, W., Leonardi, N., Canestrelli, A., Falcini, F., Jerolmack, D.J., Mariotti, G., Rowland, J.C., Slingerland, R.L., 2015. Dynamics of river mouth deposits. Rev. Geophys. 53 (3), 642–672.
Fisk, H.N., McFarlan Jr., E., Kolb, C.R., Wilbert, L.J., 1954. Sedimentary framework of the modern Mississippi Delta. J. Sediment. Petrol. 24 (2), 76–99.
Frazier, D.D.E., 1967. Recent deltaic deposits of the Mississippi river: their development and chronology. Gulf Coast Assoc. Geol. Soc. Trans. 17, 287–315.
Gagliano, S.M., Van Beek, J.L., 1975. An approach to multiuse management in the Mississippi delta system. In: Broussard, M.S. (Ed.), Deltas, Models for Exploration. Houston Geological Society, Texas, pp. 223–238 555 pp.
Gagliano, S.M., Kwon, H.J., Van Beek, J.L., 1970. Deterioration and restoration of coastal wetlands. In: Coastal Engineering Proceedings 1. pp. 1767–1781. https://doi.org/10.1061/9780872620285.107. (12).
Geleynse, N., Hiatt, M., Sangireddy, H., Passalacqua, P., 2015. Identifying environmental controls on the shoreline of a natural river delta. J. Geophys. Res. F: Earth Surf. 120, 877–893.
Gosselink, J.G., Coleman, J.M., Stewart Jr., R.E., 1998. "Coastal Louisiana." Status and trends of the nation's biological resources. 2, 385–436.
Hart, B.S., 1995. "Delta Front estuaries." Geomorphology and Sedimentology of Estuaries. Elsevier, New York, pp. 207–226.
Hatton, R., DeLaune, R., Patrick, W., 1983. Sedimentation, accretion, and subsidence in marshes of Barataria Basin, Louisiana. Limnol. Oceanogr. 28 (3), 494–502.
Heiler, G., Hein, T., Schiemer, F., Bornette, G., 1995. Hydrological connectivity and flood pulses as the central aspects for the integrity of a river-floodplain system. Regul. Rivers Res. Manag. 11, 351–361.
Henry, K.M., Twilley, R.R., 2014. Nutrient biogeochemistry during the early stages of delta development in the Mississippi River deltaic plain. Ecosystems 17, 327–343.
Hiatt, M.R., 2013. A Network-Based Analysis of River Delta Surface Hydrology : an Example from Wax Lake Delta. PhD Dissertation. University of Texas.
Hiatt, M., Passalacqua, P., 2015. Hydrological connectivity in river deltas: the first-order importance of channel-island exchange. Water Resour. Res. 51 (4), 2264–2282.
Hiatt, M., Wagner, R.W., Geleynse, N., Minton, B., Passalacqua, P., 2014. Network Flow Partitioning, Island Hydrodynamics, and Environmental Controls at Wax Lake Delta, Louisiana. Water Resources Research.
Hiatt, M., Castañeda-Moya, E., Twilley, R., Hodges, B.R., Passalacqua, P., 2018. Channel-island connectivity affects water exposure time distributions in a coastal river delta. Water Resour. Res. 54 (3), 2212–2232.
Holm, G.O., Sasser, C.E., 2001. Differential salinity response between two Mississippi river subdeltas: implications for changes in plant composition. Estuaries 24, 78.
Hupp, C.R., Demas, C.R., Kroes, D.E., Day, R.H., Doyle, T.W., 2008. Recent sedimentation patterns within the central Atchafalaya Basin, Louisiana. Wetlands 28 (1), 125–140.
Johnson, W., Sasser, C., Gosselink, J., 1985. Succession of vegetation in an evolving river delta, Atchafalaya Bay, Louisiana. J. Ecol. 973–986.
Johnson, B.L., Richardson, W.B., Naimo, T.J., 1995. Past, present, and future concepts in large river ecology: how rivers function and how human activities influence river processes. Bioscience 45, 134–141.
Junk, W.J., Bayley, P.B., Sparks, R.E.R., 1989. The flood pulse concept in river-floodplain systems. Can. Spec. Publ. Fish. Aquat. Sci. 106, 110–127.
Kim, W., Mohrig, D., Twilley, R., Paola, C., Parker, G., 2009. Is it feasible to build new land in the Mississippi river delta ? Eos 90, 373–384.
Kirwan, M.L., Guntenspergen, G.R., 2010. Influence of tidal range on the stability of coastal marshland. J. Geophys. Res. Earth Surf. 115, 11.
Kirwan, M.L., Guntenspergen, G.R., 2015. Response of plant productivity to experimental flooding in a stable and a submerging marsh. Ecosystems 18, 903–913.
Kirwan, M.L., Murray, A.B., 2007. A coupled geomorphic and ecological model of tidal marsh evolution. Proc. Natl. Acad. Sci. U. S. A 104, 6118–6122.
Kirwan, M., Temmerman, S., 2009. Coastal marsh response to historical and future sea-level acceleration. Quat. Sci. Rev. 28 (17,Äì18), 1801–1808.
Kirwan, M.L., Guntenspergen, G.R., D'Alpaos, A., Morris, J.T., Mudd, S.M., Temmerman, S., 2010. Limits on the adaptability of coastal marshes to rising sea level. Geophys. Res. Lett. 37.
Koenig, H.E., Tummala, R.L., 1972. Principles of ecosystem design and management. IEEE Trans. Syst. Man Cybern. 2, 449–459.
Lane, R.R., Day, J.W., Marx, B., Reves, E., Kemp, G.P., 2002. Seasonal and spatial water quality changes in the outflow plume of the Atchafalaya River, Louisiana, USA. Estuaries 25, 30–42.
Lane, R.R., Madden, C.J., Day Jr., J.W., Solet, D.J., 2011. Hydrologic and nutrient dynamics of a coastal bay and wetland receiving discharge from the Atchafalaya River. Hydrobiologia 658 (1), 55–66.
Larsen, L.G., 2019. Multiscale flow-vegetation-sediment feedbacks in low-gradient landscapes. Geomorphology 334, 165–193.
Linscombe, G., Chabreck, R., 2001. Task III.8—Coastwide Aerial Survey, Brown Marsh 2001 Assessment: Salt Marsh Dieback in Louisiana—Brown Marsh Data Information Management System. 2001 Data.
Liu, K., Chen, Q., Hu, K., Xu, K., Twilley, R.R., 2018. Modeling hurricane-induced wetland-bay and bay-shelf sediment fluxes. Coast Eng. 135, 77–90.
Lorenzo-Trueba, J., Voller, V.R.V.R., Paola, C., Twilley, R.R.R.R., Bevington, A.E.A.E., 2012. Exploring the role of organic matter accumulation on delta evolution. J. Geophys. Res.: Earth Surf. 117.
Ma, H., Larsen, L.G., Wagner, R.W., 2018. Ecogeomorphic feedbacks that grow deltas. J. Geophys. Res.: Earth Surf. 123 (12), 3228–3250.
Madden, C.J., Day Jr., J.W., Randall, J.M., 1988. Freshwater and marine coupling in estuaries of the Mississippi River deltaic plain. Limnol. Oceanogr. 33 (4 (part 2)),

982–1004.
Majersky, S., Roberts, H.H., Cunningham, R., Kemp, G.P., John, C.J., 1997. Facies development in the Wax Lake outlet delta: present and future trends. Basin Res. Inst. Bull. 7, 50–66.
Mariotti, G., Fagherazzi, S., 2010. A numerical model for the coupled long-term evolution of salt marshes and tidal flats. J. Geophys. Res. 115, F01004.
McKee, K.L., Cherry, J.A., 2009. Hurricane Katrina sediment slowed elevation loss in subsiding brackish marshes of the Mississippi River Delta. Wetlands 29 (1), 2–15.
McKee, K., Patrick, W., 1988. The relationship of smooth cordgrass (*Spartina alterniflora*) to tidal datums – a review. Estuaries 11, 143–151.
Megonigal, J.P., Neubauer, S.C., 2019. Biogeochemistry of tidal freshwater wetlands. In: Perillo, G.M.E., Wolanski, E., Cahoon, D.R., Hopkinson, C.S. (Eds.), Coastal Wetlands. Elsevier, pp. 641–683 (Chapter 19).
Mendelssohn, I.A., Kuhn, N.L., 2003. Sediment subsidy: effects on soil-plant responses in a rapidly submerging coastal salt marsh. Ecol. Eng. 21 (2–3), 115–128.
Mendelssohn, I.A., McKee, K.L., 2006. Spartina alterniflora die-back in Louisiana: time-course investigation of soil waterlogging effects. J. Ecol. 76 (2), 509. https://doi.org/10.2307/2260609.
Miller, C.A., 1983. Sediment and nutrient inputs to the marshes surrounding Fourleague Bay, Louisiana. MS. thesis. State Univ, La 68 p.
Milner, A.M., Fastie, C.L., Chapin, F.S., Engstrom, D.R., Sharman, L.C., 2007. Interactions and linkages among ecosystems during landscape evolution. Bioscience 57 (3), 237–247.
Moeller, C.C., Huh, O.K., Roberts, H.H., Gumley, L.E., Menzel, W.P., 1993. Response of Louisiana coastal environments to a cold front passage. J. Coast. Res. 9, 434–447.
Morris, J.T., 2006. Competition among marsh macrophytes by means of geomorphological displacement in the intertidal zone. Estuar. Coast Shelf Sci. 69 (3,Äì4), 395–402.
Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B., Cahoon, D.R., 2002. Responses of coastal wetlands to rising sea level. Ecology 83 (10), 2869–2877.
Morton, R.A., Barras, J.A., 2011. Hurricane impacts on coastal wetlands: a half-century record of storm-generated features from southern Louisiana. J. Coast. Res. 275, 27–43.
Mossa, J., 2016. The changing geomorphology of the Atchafalaya River, Louisiana: a historical perspective. Geomorphology 252, 112–127.
Mudd, S.M., Fagherazzi, S., Morris, J.T., Furbish, D.J., 2004. Flow, sedimentation, and biomass production on a vegetated salt marsh in South Carolina: toward a predictive model of marsh morphologic and ecologic evolution. In: Fagherazzi, S., Marani, A., Blum, L.K. (Eds.), The Ecogeomorphology of Tidal Marshes. American Geophysical Union, Washington, DC, pp. 165–187.
Naiman, R.J., Bechtold, J.S., Beechie, T.J., Latterell, J.J., Van Pelt, R., 2010. A process-based view of floodplain forest patterns in coastal river valleys of the Pacific Northwest. Ecosystems 13 (1), 1–31.
Nardin, W., Edmonds, D.A., 2014. Optimum vegetation height and density for inorganic sedimentation in deltaic marshes. Nat. Geosci. 7 (10), 722.
Nardin, W., Edmonds, D., Fagherazzi, S., 2016. Influence of vegetation on spatial patterns of sediment deposition in deltaic islands during flood. Adv. Water Resour. 93, 236–248.
Neill, C.F., Allison, M.A., 2005. Subaqueous deltaic formation on the Atchafalaya shelf, Louisiana. Mar. Geol. 214 (4), 411–430.
Neill, C., Deegan, L.A., 1986. The effect of Mississippi River Delta lobe development on the habitat composition and diversity of Louisiana coastal wetlands. Am. Midl. Nat. 116, 296–303.
Noe, G.B., Hupp, C.R., 2005. Carbon, nitrogen, and phosphorus accumulation in floodplains of Atlantic Coastal Plain rivers, USA. Ecol. Appl. 15 (4), 1178–1190.
Noe, G.B., Hupp, C.R., Rybicki, N.B., 2013. Hydrogeomorphology influences soil nitrogen and phosphorus mineralization in floodplain wetlands. Ecosystems 16 (1), 75–94.
Nyman, J.A., 2014. Integrating successional ecology and the delta lobe cycle in wetland research and restoration. Estuar. Coasts 37, 1490–1505.
Nyman, J.A., Crozier, C.R., DeLaune, R.D., 1995. Roles and patterns of hurricane sedimentation in an estuarine marsh landscape. Estuar. Coast Shelf Sci. 40, 665–679.
Odum, W.E., Odum, E.P., Odum, H.T., 1995. Nature 's pulsing paradigm. Estuaries 18, 547–555.
O'Connor, M.T., Moffett, K.B., 2015. Groundwater dynamics and surface water–groundwater interactions in a prograding delta island, Louisiana, USA. J. Hydrol. 524, 15–29.
O'Neil, T., 1949. The Muskrat in Louisiana Coastal Marshes: New Orleans. Louisiana Wildlife and Fisheries Commission, pp. 28 1949 Data.
Paola, C., Twilley, R.R., Edmonds, D.A., Kim, W., Mohrig, D., Parker, G., Viparelli, E., Voller, V.R., 2011. Natural processes in delta restoration: application to the Mississippi delta. Annu. Rev. Mar. Sci. 3, 67–91.
Passalacqua, P., 2017. The Delta Connectome: a network-based framework for studying connectivity in river deltas. Geomorphology 277, 50–62.
Penland, S., Boyd, R., Suter, J.R., 1988. Transgressive depositional systems of the Mississippi Delta Plain: a model for barrier shoreline and shelf sand development. J. Sediment. Petrol. 58, 932–949.
Perez, B.C., Day Jr., J.W., Rouse, L.J., Shaw, R.F., Wang, M., 2000. Influence of Atchafalaya River discharge and winter frontal passage on suspended sediment concentration and flux in Fourleague Bay, Louisiana. Estuar. Coast Shelf Sci. 50, 271–290.
Perez, B.C., Day, J.W., Justic, D., Twilley, R.R., 2003. Nitrogen and phosphorus transport between Fourleague Bay, LA, and the Gulf of Mexico: the role of winter cold fronts and Atchafalaya River discharge. Estuar. Coast Shelf Sci. 57 (5–6), 1065–1078.
Perillo, G.M., 1995. Definitions and Geomorphologic Classifications of estuaries. In: Geomorphology and Sedimentology of Estuaries. Developments in Sedimentology, vol 53. pp. 17–47.
Peyronnin, N., Green, M., Richards, C.P., Owens, A., Reed, D., Chamberlain, J., Groves, D.G., Rhinehart, W.K., Belhadjali, K., 2013. Louisiana's 2012 coastal master plan: overview of a science-based and publicly informed decision-making process. J. Coast. Res. 67 (sp1), 1–15.
Piazza, B., 2014. The Atchafalaya River Basin: History and Ecology of an American Wetland. Texas A&M University Press, College Station, TX, 9781623490393pp. 305.
Redfield, A.C., 1972. Development of a New England salt marsh. Ecol. Monogr 42, 201–237.
Pont, D., Day, J., Ibáñez, Carles, 2017. The Impact of Two Large Floods (1993-1994) on Sediment Deposition in the Rhone Delta: Implications for Sustainable Management. Science of the Total Environmenthttps://doi.org/10.1016/j.scitotenv.2017.07.155.
Rejmánek, M., Sasser, C.E., Gosselink, J.G., 1987. Modeling of vegetation dynamics in the Mississippi River deltaic plain. Vegetatio 69 (1–3), 133–140.
Rejmanek, M., Sasser, C.E., Peterson, G.W., 1988. Hurricane-induced sediment deposition in a Gulf coast marsh. Estuar. Coast Shelf Sci. 27 (2), 217–222.
Restreppo, G.A., Bentley, S.J., Wang, J., Xu, K., 2018. Riverine sediment contribution to distal deltaic wetlands: Fourleague bay, LA. Estuar. Coasts 1–13.
Reuss, M., 2004. Designing the Bayou: the Control of Water in the Atchafalaya Basin 1800-1995. Texas A&M Press, College Station TX, pp. 473.
Roberts, H.H., 1997. Dynamic changes of the Holocene Mississippi River delta plain: the delta cycle. J. Coast. Res. 605–627.
Roberts, H.H., 1998. Delta switching: early responses to the Atchafalaya River diversion. J. Coast. Res. 14, 882–899.
Roberts, H.H., Adams, R.D., 1980. Evolution of sand-dominant subaerial phase, Atchafalaya delta, Louisiana. AAPG (Am. Assoc. Pet. Geol.) Bull. 64 (2), 264–279. https://doi.org/10.1306/2F918964-16CE-11D7-8645000102C1865D.
Roberts, H.H., Coleman, J.M., 1996. "Holocene evolution of the deltaic plain: a perspective—from Fisk to present. Eng. Geol. 45, 113–138.
Roberts, B.J., Doty, S.M., 2015. Spatial and temporal patterns of benthic respiration and net nutrient fluxes in the Atchafalaya River Delta Estuary. Estuar. Coasts 38 (6), 1918–1936.
Roberts, H.H., Sneider, J.B., 2003. Guidebook Series No. 6: Atchafalaya-Wax Lake Deltas: the New Regressive Phase of the Mississippi River Delta Complex.
Roberts, H.H., Walker, N., Cunningham, R., Kemp, G.P., Majersky, S., 1997. Evolution of sedimentary architecture and surface morphology: Atchafalaya and Wax Lake deltas, Louisiana (1973-1994). Gulf Coast Assoc. Geol. Soc. Trans. 47, 477–484.
Roberts, H., Coleman, J., Bentley, S., Walker, N., 2003. An embryonic major delta lobe: a new generation of delta studies in the Atchafalaya-Wax Lake Delta system. In: Gulf Coast Association of Geological Societies Transactions. vol 52. pp. 690–703.
Roberts, H.H., DeLaune, R.D., White, J.R., Li, C., Sasser, C.E., Braud, D., Weeks, E., Khalil, S., 2015. Floods and cold front passages: impacts on coastal marshes in a river diversion setting (Wax Lake Delta Area, Louisiana). J. Coast. Res. 31 (5), 1057–1068.
Ross, M.R.V., Bernhardt, E.S., Doyle, M.W., Heffernan, J.B., 2015. Designer ecosystems: incorporating design approaches into applied ecology. Annu. Rev. Environ. Resour. 40, 419–443.
Rossi, V.M., Kim, W., Leva López, J., Edmonds, D., Geleynse, N., Olariu, C., Steel, R.J., Hiatt, M., Passalacqua, P., 2016. Impact of tidal currents on delta-channel deepening, stratigraphic architecture, and sediment bypass beyond the shoreline. Geology 44 (11), 927–930.
Rutherford, J.S., Day, J.W., D'Elia, C.F., Wiegman, A.R., Willson, C.S., Caffey, R.H., Shaffer, G.P., Lane, R.R., Batker, D., 2018. Evaluating trade-offs of a large, infrequent sediment diversion for restoration of a forested wetland in the Mississippi delta. Estuar. Coast Shelf Sci. 203, 80–89.
Sasser, C.E., Visser, J.M., Mouton, E., Linscombe, J., Hartley, S.B., 2008. Vegetation types in coastal Louisiana in 2007. Estuaries 21, 818–828.
Sasser, C.E., Visser, J.M., Mouton, Edmond, Linscombe, Jeb, Hartley, S.B., 2014. Vegetation types in coastal Louisiana in 2013: U.S. In: Geological Survey Scientific Investigations Map 3290, 1 Sheet, scale 1:550, 000. 2013 Data.
Shaffer, G.P., Sasser, C.E., Gosselink, J.G., Rejmanek, M., 1992. Vegetation dynamics in the emerging Atchafalaya delta, Louisiana, USA. J. Ecol. 677–687.
Shaffer, P.W., Kentula, M.E., Gwin, S.E., 1999. Characterization of wetland hydrology using hydrogeomorphic classification. Wetlands 19, 490–504.
Shaw, J.B., Mohrig, D., Whitman, S.K., 2013. The morphology and evolution of channels on the Wax Lake Delta, Louisiana, USA. J. Geophys. Res.: Earth Surf. 118 (3), 1562–1584.
Shaw, J.B.B., Mohrig, D., Wagner, R.W.W., 2016. Flow patterns and morphology of a prograding river delta. J. Geophys. Res.: Earth Surf. 121, 372–391.
Shields, M.R., Bianchi, T.S., Gelinas, Y., Allison, M.A., Twilley, R.R., 2016. Enhanced terrestrial carbon preservation promoted by reactive iron in deltaic sediments. Geophys. Res. Lett. 43, 1149–1157.
Shields, M.R., Bianchi, T.S., Mohrig, D., Hutchings, J.A., Kenney, W.F., Kolker, A.S., Curtis, J.H., 2017. Carbon storage in the Mississippi River delta enhanced by environmental engineering. Nat. Geosci. 10 (11), 846.
Simpson, R.L., Good, R.E., Leck, M.A., Whigham, D.F., 1983. The ecology of freshwater tidal wetlands. Bioscience 33, 255–259.
Snedden, G.A., Cretini, K., Patton, B., 2015. 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, 133–139.
Spalding, E.A., Hester, M.W., 2007. Interactive effects of hydrology and salinity on oligohaline plant species productivity: implications for relative sea-level rise. Estuar. Coasts 30 (2), 214–225.
Sparks, R.E., 1995. Need for ecosystem management of large rivers and their floodplains. Bioscience 45 (3), 168–182.
Syvitski, J.P., Kettner, A.J., Overeem, I., Hutton, E.W., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., 2009. Sinking deltas due to human activities. Nat. Geosci. 2 (10), 681–686.

Tornqvist, T.E., Paola, C., Parker, G., Liu, K., Mohrig, D., Holbrook, J.M., Twilley, R.R., 2007. Comment on "wetland sedimentation from hurricanes katrina and rita. Science 316 (5822).
Turner, R.E., Baustian, J.J., Swenson, E., Spicer, J.S., 2006. Wetland sedimentation from hurricanes katrina and rita. Science 314, 449–452.
Tweel, A.W., Turner, R.E., 2012. Landscape-scale analysis of wetland sediment deposition from four tropical cyclone events. PLoS One 7 (11), e50528.
Twilley, R.R., Bentley, S.J., Chen, Q., Edmonds, D.A., Hagen, S.C., Lam, N.S.N., Willson, C.S., Xu, K., Braud, D.W., Peele, H.R., McCall, A., 2016. Co-evolution of wetland landscapes, flooding, and human settlement in the Mississippi River Delta Plain. Sustain. Sci. 11, 711–731.
Tye, R.S., Coleman, J.M., 1989. Evolution of Atchafalaya lacustrine deltas, south-central Louisiana. Sediment. Geol. 65 (1–2), 95–112.
US Geological Survey, 1978. Land Use and Land Cover and Associated Maps for Hattiesburg, Mississippi; Alabama. Louisiana Online. https://pubs.er.usgs.gov/publication/ofr788 accessed 06/29/15.
US Army Corps of Engineers (USACOE), 2008. The Mississippi river & tributaries project: designing the project flood. https://www.mvd.usace.army.mil/Portals/52/docs/Designing%20the%20Project%20Flood%20info%20paper.pdf.
van Heerden, I.L., 1994. Natural and dredged material sedimentation in Atchafalaya delta, Louisiana. In: Roberts, H.H. (Ed.), Critical Physical Processes of Wetland Loss, pp. 9.1–9.40.
Visser, J.M., 1989. The Impact of Vertebrate Herbivores on Primary Production of Sagittaria Marshes in the Wax Lake Delta, Atchafalaya Bay, Louisiana. Louisiana State University.
Visser, J.M., Sasser, C.E., Chabreck, R.H., Linscombe, R., 1998. Marsh vegetation types of the Mississippi River deltaic plain. Estuaries 21 (4), 818–828.
Wagner, W., Lague, D., Mohrig, D., Passalacqua, P., Shaw, J., Moffett, K., 2017. Elevation change and stability on a prograding delta. Geophys. Res. Lett. 44 (4), 1786–1794.
Walker, N.D., 2001. Tropical storm and hurricane wind effects on water level, salinity, and sediment transport in the river-influenced Atchafalaya-Vermilion Bay system, Louisiana, USA. Estuaries 24 (4), 498–508.
Wang, F.C., Ransibrahmanakul, V., Tuen, K., Wang, M., Zhang, F., 1995. Hydrodynamics of a tidal inlet in Fourleague bay/atchafalaya bay, Louisiana. J. Coast. Res. 733–743.
Wang, J., Xu, K., Restreppo, G.A., Bentley, S.J., Meng, X., Zhang, X., 2018. The coupling of bay hydrodynamics to sediment transport and its implication in micro-tidal wetland sustainability. Mar. Geol. 405, 68–76.
Webb, E.C., Mendelssohn, I.A., 1996. Factors affecting vegetation dieback of an oligohaline marsh in coastal Louisiana: field manipulation of salinity and submergence. Am. J. Bot. 83 (11), 1429–1434. https://doi.org/10.2307/2446098.
Wellner, R., Beaubouef, R., Van Wagoner, J., Roberts, H.H., Sun, T., Wagoner, J.V., 2005. Jet-plume depositional bodies; the primary building blocks of Wax Lake Delta. Trans. Gulf Coast Assoc. Geol. Soc. 55, 867–909.
White, D.A., 1993. Vascular plant community development on mudflats in the Mississippi River delta, Louisiana, USA. Aquat. Bot. 45, 171–194.
White, D.A., Visser, J.M., 2016. Water quality change in the Mississippi River, including a warming river, explains decades of wetland plant biomass change within its Balize delta. Aquat. Bot. 132, 5–11.
Wiegman, R., Day, J., D'Elia, C., Rutherford, J., Morris, J., Roy, E., Lane, R., Dismukes, D., Snyder, B., 2017. Modeling impacts of sea-level rise, oil price, and management strategy on the costs of sustaining Mississippi delta marshes with hydraulic dredging. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2017.09.314.
Wilsey, B.J., Mckee, K.L., Mendelssohn, I.A., 1992. Effects of increased elevation and macro- and micronutrient additions on Spartina alterniflora transplant success in salt-marsh dieback areas in Louisiana. Environ. Manag. 16 (4), 505–511. https://doi.org/10.1007/BF02394126.
Wiseman, W., Swenson, E.M., Power, J., 1990. Salinity trends in Louisiana estuaries. Estuaries 13 (3), 265–271.
Wolski, P., Murray-Hudson, M., 2005. Flooding dynamics in a large low-gradient alluvial fan, the Okavango Delta, Botswana, from analysis and interpretation of a 30-year hydrometric record. Hydrol. Earth Syst. Sci. Discuss. 2, 1865–1892.
Xu, Y.J., 2010. Long-term sediment transport and delivery of the largest distributary of the Mississippi River, the Atchafalaya, USA. Sediment Dyn. Changing Future 337, 282–290.