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Authors: Bevington, Azure E., and Twilley, Robert R.

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Island Edge Morphodynamics along a Chronosequence in a Prograding Deltaic Floodplain Wetland

Azure E. Bevington[†]* **and Robert R. Twilley**[‡]

[†]Department of Oceanography and Coastal Sciences
Louisiana State University
Baton Rouge, LA 70803, U.S.A.

[‡]Louisiana Sea Grant
Department of Oceanography and Coastal
Sciences and Coastal Studies Institute
Louisiana State University
Baton Rouge, LA 70803, U.S.A.

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ABSTRACT

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Much of the previous research on coastal deltaic land building has focused on the planform delta dimensions; whereas this research focuses on shifts in vertical elevation and deltaic island edge cross-sectional morphology in relation to a proposed conceptual model of deltaic island edge morphological development. This study was conducted using data collected from the Wax Lake Delta in the northern Gulf of Mexico. Island edge cross-sectional elevation profiles were extracted from a 2012 LIDAR elevation survey. Four morphometric variables (levee width, interior slope, mean elevation range, and total elevation range) were selected to describe the shape of each of these profiles, and each profile was also assigned to an age class, which was determined based on mapping of historic deltaic island extent from aerial imagery. Multivariate analysis of variance was used to test the effect of age class and distance from the upstream end of the island on these four morphometric variables. Results indicated that both age and the distance within age were statistically significant predictors of island edge cross-sectional morphology. Field-surveyed elevation transects also followed the predicted pattern of morphologic change and illustrated that the shifts in morphology can occur very rapidly within this system—over a matter of a few months—as the result of a single large river flood. High soil percent organic matter was also found to correlate to high elevation in field-surveyed transects, indicating that biological processes such as organic matter production and accretion may also play an important role in morphological development of deltaic floodplain wetlands.

ADDITIONAL INDEX WORDS: *Elevation profiles, coastal delta geomorphology, ecogeomorphology, soil organic matter*.

INTRODUCTION

A thorough understanding of the morphological development of deltaic floodplain wetlands will allow for better predictions of how these critical habitats, associated with the depositional environments of major rivers, will respond to regional subsidence and rising global sea level. Worldwide, more than 500 million people currently occupy coastal deltaic plains, many of which are in peril from changes in sediment and water delivery patterns (Ericson *et al*., 2006; Syvitski *et al*., 2009). Major coastal restoration projects designed to lessen land loss, such as those in the Mississippi River Delta, are predicated on the ability of sediment delivery from river discharge to sustain and build new wetlands (CPRA, 2012). The ability of the Mississippi River to build new land has been demonstrated numerous times (Cahoon, White, and Lynch, 2011; Kolker, Miner, and Weathers, 2012; Majersky *et al*., 1997; Roberts and Adams, 1980; Rouse, Roberts, and Cunningham, 1978); however, most recent research on prograding delta morphodynamics has focused on the planform delta dimensions (Allen, Couvillion, and Barras, 2011; Edmonds and Slingerland, 2009; Kim *et al*., 2009; Kolker, Allison, and Hameed, 2011; Shaw, Mohrig, and Whitman, 2013), with less emphasis on the three-dimensional morphology of these systems. In an investigation of morphological change within deltaic distributary channels and low elevation distal mouth bars, Shaw and Mohrig (2013) found that significant channel incision occurred even during low river discharge. Seasonal and annual comparisons of elevation change across subtidal, intertidal, and supratidal vegetated mouth bars have demonstrated that most elevation gain occur as a result of large river floods, with very little annual net elevation gain in mean and low discharge flood years (Bevington *et al*., 2017). These findings help to inform models of deltaic morphodynamics, but they leave out the contribution of accumulated organic matter (Lorenzo-Trueba *et al*., 2012; Paola *et al*., 2011). This process is likely a strong driver of elevation change in the heavily vegetated islands during latter stages of deltaic wetland succession and may result in a positive feedback, in which higher elevation wetland vegetation communities have higher primary production, resulting in increased organic matter accumulation and therefore increased accretion rates. The transition from mineral sedimentation to organic accretion that occurs as a result of the infilling of interdistributary bays has been illustrated across a number of temporal and spatial scales (Coleman and Gagliano, 1964; Frazier, 1967; Lorenzo-Trueba *et al*., 2012; Nyman, DeLaune, and Patrick, 1990). However, there has been little work on coastal deltaic morphodynamics over intermediate decadal time scales, nor has it been

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*Corresponding author: azure.bevington@gmail.com

incorporated into predictive land building models over these shorter timescales.

Here, coastal deltaic floodplain wetlands are defined as those that receive river and sediment inflow during natural hydrologic conditions, including river flooding and does not include deltaic wetlands that are no longer in an active floodplain, such as those that have been disconnected from river inflow by avulsions and constructed flood control levees. In the Mississippi River Delta Plain, the freshwater deltaic floodplain wetlands are found in locations of active sediment deposition and land building, including the Atchafalaya Delta, Wax Lake Delta (WLD), and the main outlet of the Mississippi River (Couvillion *et al*., 2011). These wetlands are vegetated by emergent, floating leaved and submerged vegetation throughout the intertidal and shallow subtidal portion. The vegetation communities are dominated by freshwater-adapted species, and zonation and composition are controlled to a large extent by the elevation gradient, as well as by interspecific competition (Bevington, 2016; Cahoon, White, and Lynch, 2011; Johnson, Sasser, and Gosselink, 1985; Shaffer *et al*., 1992).

Previous research conducted at WLD found a pattern of high soil organic matter (OM) in older portions of the WLD (Henry and Twilley, 2014). It is not known what processes account for this pattern and whether there are environmental or biological controls on when and where high OM sequestration occurs. Deltaic islands within progradational deltas of the Mississippi River system are defined by a consistent morphology in which the island edges along distributary channels are higher in elevation than the island interiors (Cahoon, White, and Lynch, 2011; Johnson, Sasser, and Gosselink, 1985; Kolker, Miner, and Weathers, 2012; Shaw, Mohrig, and Wagner, 2016; Shaw, Mohrig, and Whitman, 2013). The cross-sectional elevation gradient resulting from this morphology defines the zonation of the vegetation community due to flooding stress (Bevington, 2016). The processes that control the morphological development of these elevation gradients include hydrodynamics, sediment transport, and biomass production and sediment trapping. While many of these processes vary over small spatial and temporal scales, this research study aims to look at trends in island edge morphology with time over the entire spatial extent (100 km^2) of the WLD (Figure 1). The chronosequence of the prograding WLD over time was used to test whether a predictable change in deltaic island edge morphology took place with island age and distance from the upstream end of island. A chronosequence experimental design, often used in ecological succession studies, allowed for a space-for-time substitution in sampling, where islands of different ages were sampled at the same time to test hypotheses related to island development (Walker *et al*., 2010). This approach has been used in the past in the WLD to look at the development of soil characteristics and biogeochemical fluxes over time (Henry and Twilley, 2014; Shields *et al*., 2016). The WLD has been expanding outward from the mouth of the Wax Lake Outlet (WLO) since 1973 at a rate of 1–3.3 km^2 yr^{-1} (Allen, Couvillion, and Barras, 2011; Majersky *et al*., 1997). The known starting point of subaerial land emergence and outward growth rate of the WLD makes this an ideal location for use of the chronosequence method (Pickett, 1989; Walker *et al*., 2010).

Conceptual Model

On the basis of previous work in which the authors investigated seasonal controls on elevation change along deltaic islands at the WLD (Bevington *et al*., 2017), as well as other studies of delta development (Cahoon, White, and Lynch, 2011; Esposito, Georgiou, and Kolker, 2013; Johnson, Sasser, and Gosselink, 1985; Kolker, Allison, and Hameed, 2011; Kolker, Miner, and Weathers, 2012), a hypothesized conceptual model of island morphologic change over time was developed. It was hypothesized that differences in morphology and total elevation range of island edges were primarily controlled by the age of the island and that the rate of elevation change was primarily controlled by allogenic physical processes, particularly sedimentation (Figure 2). Younger, more recently deposited islands at the distal portions of the delta have lower overall elevation, wider levees, and more gradual interior slopes (see elevation profiles from Mike Island in Figure 2, transect IV–IV'). 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 (see Figure 2 transects III–III' and II–II'). In the oldest islands (near the delta apex) with the highest overall elevation, interior infilling occurs, with the interior of the islands increasing in elevation until it is nearly equal to that of the levees, as in the example elevation profile in Figure 2 transect I–I'. Processes driving this infilling may be related to the relative degree of mineral sediment delivery and organic production, as well as protection from strong currents, allowing for finer grain sediment deposition in island interiors.

To test the validity of the conceptual model across the delta, four morphometric variables were selected that described the shape of the island edge cross-sectional profiles. Analysis of the combined morphometric variables tested whether island edge cross-sectional shape changed in a consistent way with island age. The morphologic trends were also investigated to better understand mechanisms that may explain ecosystem processes, such as wetland succession and soil development, as active deltas prograde over coastal landscapes.

Site Description and Timeline of Delta Development

The WLD is forming at the terminus of the WLO, a constructed distributary channel of the Atchafalaya River, which is in turn a main distributary of the Mississippi River (Figure 1). The discharge into the Atchafalaya River is maintained at 30% of the combined flows of the Mississippi and Red Rivers and is controlled by the Army Corps of Engineers at the Old River Control Structure completed in 1963. The WLO was originally constructed in 1942 as a flood control conduit on the Lower Atchafalaya River (Shlemon, 1975). As the WLO empties into the shallow (2–3 m) Atchafalaya Bay, the resulting bed friction results in the formation of distributary mouth bars and bifurcating distributary channels (Wellner *et al.,* 2005; Wright, 1977).

Prodelta deposits and subaqueous expansion of the WLD in Atchafalaya Bay were first observed in 1952, the majority of the fine grain sediment bypassed the bay and was deposited on the continental shelf (Shlemon, 1975). Small subaerial bars first began to appear in the WLD in 1972 on top of the large (1–5 km

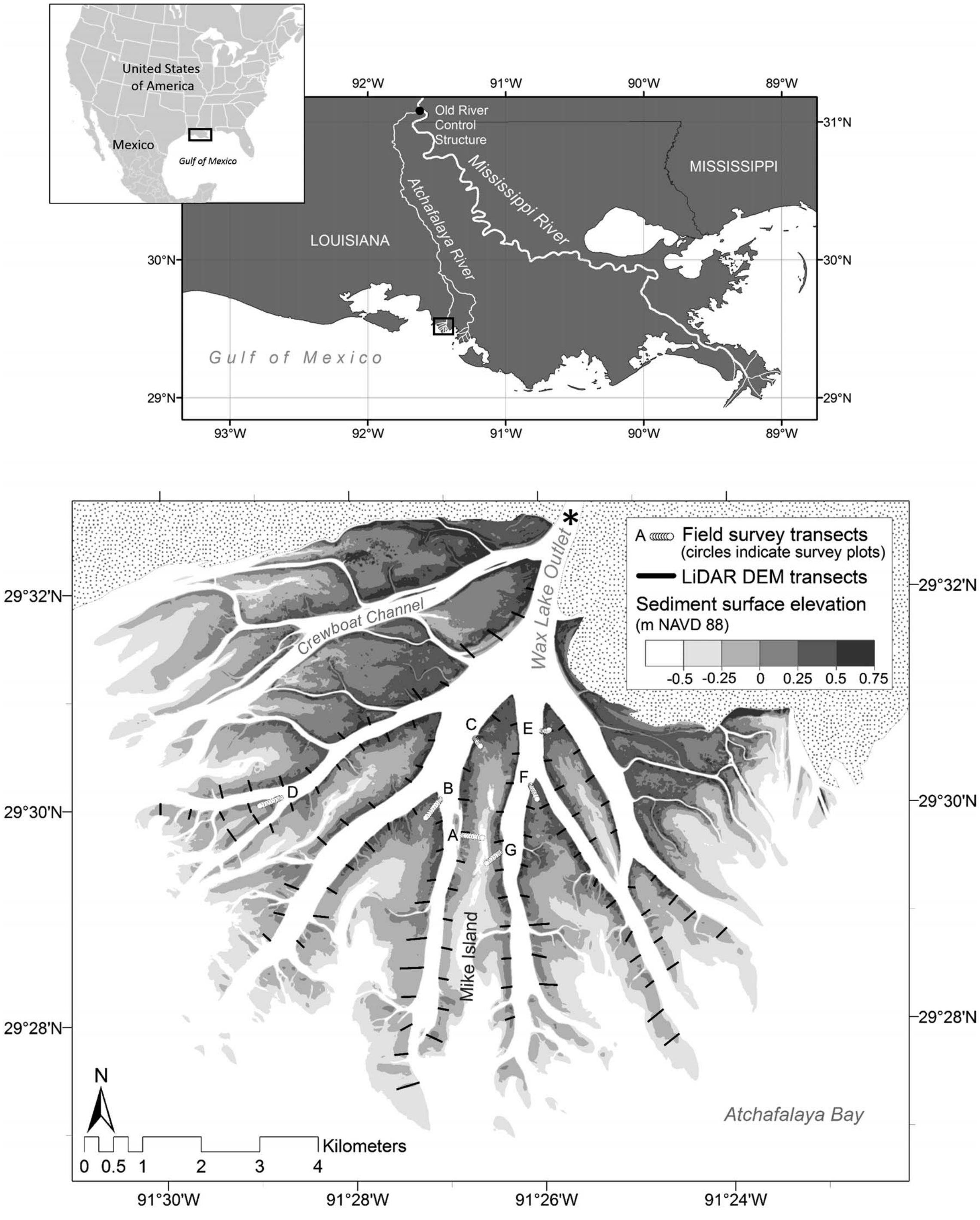

Figure 1. Study site map of the Wax Lake Delta, Louisiana, with location of the site along the Louisiana coast and the Gulf of Mexico shown in the inset maps at top. The field-surveyed transects are delineated by a series of overlapping white dots (each dot indicates a surveyed plot) and are labeled A–G. The 109 LIDAR transects are delineated by black lines that represent the location and length of all LIDAR-extracted elevation profiles. Mike Island, which is used in the conceptual model, is labeled in the center of the delta. The delta apex, defined as the location of the first bifurcating distributary channel, is indicated by an asterisk (*). The sediment surface elevations indicated by shading are from the 2012 USGS Atchafalaya 2 Project LIDAR survey digital elevation model.

long and 1–2 km wide) subaqueous deposits, which increased in elevation rapidly following high river flooding and infilling of shallow lakes upstream and adjacent to the WLO (Roberts and Adams, 1980; Wellner *et al.,* 2005). As the surfaces of the subaqueous bars build toward the water surface, they are colonized by submerged and emergent vegetation, becoming

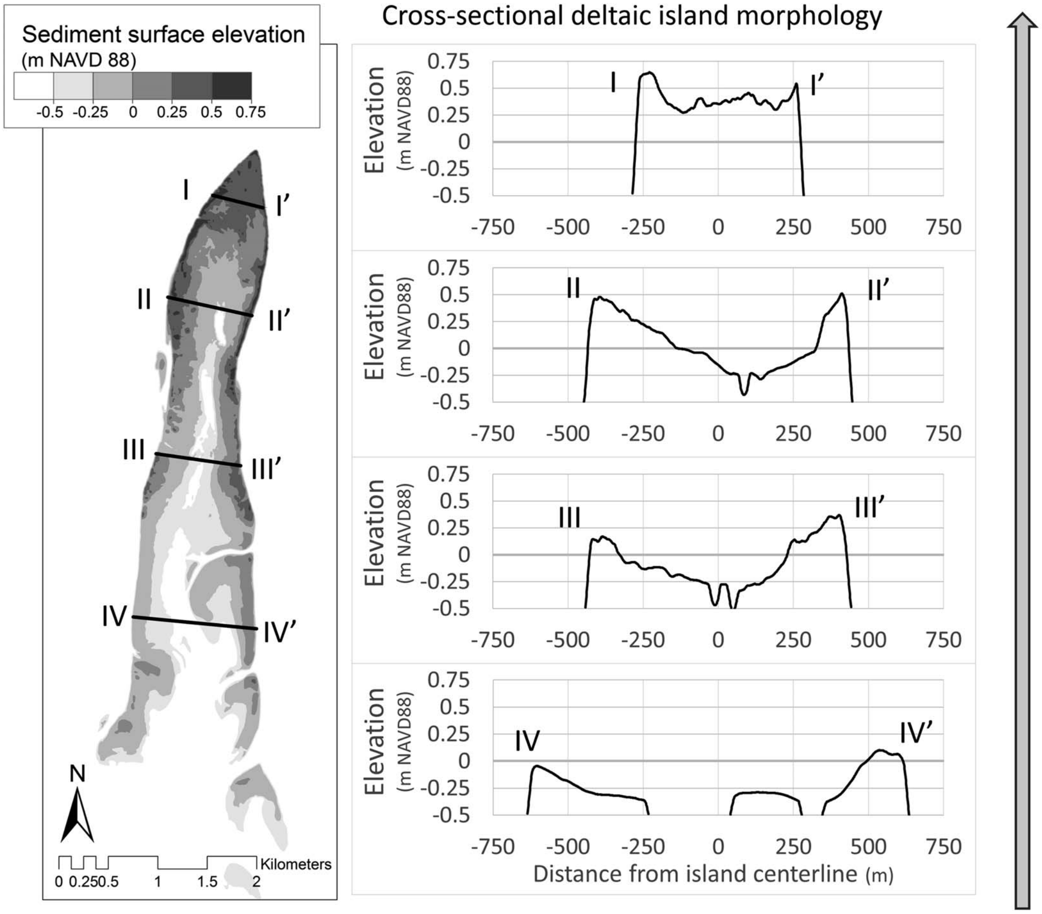

Figure 2. Illustration of deltaic island cross-sectional elevation profile morphology from four transects across Mike Island. See Figure 1 for location within delta. Elevations are extracted from a 2012 USGS LIDAR DEM. These patterns were used to develop a conceptual model that describes how differences 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.

delta islands, which along with the distributary channels, make up the delta top ecosystem (Fagherazzi *et al.*, 2015). The delta islands are primarily arrowhead shaped with a subtidal interdistributary bay surrounded by relatively narrow higher elevation (intertidal and supratidal) levees. The interdistributary bays generally widen and deepen in the downstream direction, and often have a deeper interdistributary trough down the center (Shaw, Mohrig, and Wagner, 2016). These features seem to be consistent across islands and can be clearly seen on elevation contours of the delta (Figure 1). The delta islands are primarily composed of mineral sediments; however, increasing soil organic content has been observed in older islands (Henry and Twilley, 2014).

Channel dredging has been limited in the WLD, mainly constrained to the northwestern channel called Crewboat Channel (Figure 1). Therefore the majority of the channel and island formation closely resembles natural undisturbed delta morphology (Wellner *et al.,* 2005). Accordingly this system represents an extremely valuable analog to many deltaic wetland restoration strategies, which propose diverting river water and sediment into shallow coastal basins to counteract coastal wetland loss (Allison and Meselhe, 2010; CPRA, 2012; Kim *et al.*, 2009; Paola *et al.*, 2011; Parker and Sequeiros, 2006).

METHODS

A combination of field surveys and remote sensing data were used to measure island elevation profiles and test for the effects of age. These methods are outlined below.

Deltaic Island Age Range Estimation

Deltaic island age was estimated from a number of data sources. In previously published maps from Wellner *et al.* (2005) of subaerial deltaic island extent for the years 1974, 1983, 1990, 1995, 1998, 2000, and 2002, the subaerial island extent, defined as the portion "at or near the minimum low tide

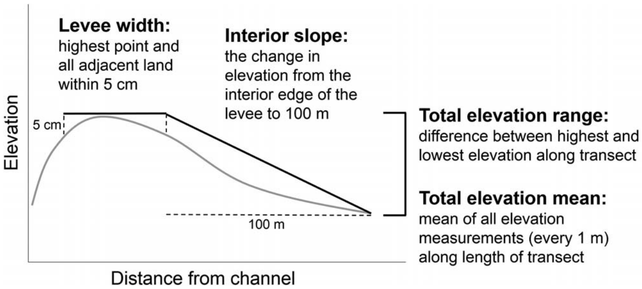

Figure 3. Illustration of four morphometric variables used in statistical analysis of elevation profile shape and how they were quantified on an idealized deltaic island cross-sectional elevation profile.

of sea level," was interpreted to be consistent with the common definition of subaerial, which is all land above mean low water (MLW), defined as –0.04 m NAVD 88 in this system (Roberts and Adams, 1980; Rouse, Roberts, and Cunningham, 1978). These published maps were georectified using ArcMAP 10.2 (ESRI, Redlands, California, U.S.A.) and manually digitized at 1:121,500 m resolution to create shapefiles of the extent of subaerial land. The extent of subaerial land was also digitized from U.S. Geological Survey High Resolution State Orthoimagery for the Coastal Wetlands collected October 2008 (USGS, 2015). The imagery was downloaded as digital orthophoto quarter quadrangles for the desired study site and processed using ERDAS Imagine 11 (Hexagon Geospatial, Norcross, Georgia, U.S.A.). The extent of land reported in 2012 was estimated by creating a layer of elevations greater than -0.5 m NAVD 88 from a December 2012 digital elevation model (DEM) of the WLD derived from the U.S. Geological Survey (USGS) Atchafalaya 2 LIDAR Survey (NOAA, 2015). The shapefiles of deltaic island extent for each year were then overlain and clipped using the most recent channel shape from the 2012 survey. This map allowed for age range classifications for all deltaic islands within the system and illustrated geographically how the current planform delta built over time, allowing for the use of a chronosequence experimental design.

Field Surveyed Elevation Transects and Soil Organic Matter Sampling

Surveys of sediment surface elevation were completed along seven transects, labeled A–G in Figure 1, two times per year between February 2008 and August 2011 in winter (February to early March) and summer (July and August). The original intention of the sampling intervals was to capture the effects of spring river flooding and cold front passage on change in elevation. During each survey, the sediment surface elevation along seven transects was measured over a total length of 1950 m. Transects were established perpendicular to the channel edge to capture the geomorphic gradient that includes near-channel, levee, and interior wetlands. The detailed field survey methods and results of the initial analyses related to seasonal elevation change are outlined in Bevington *et al*. (2017). As part of this sampling campaign, 2.5-cm-diam sediment cores were also collected during the summer of 2010 at all field-surveyed plots to a depth of 10 cm. These 87 cores were oven dried to constant mass at 60°C and weighed to determine bulk density, calculated as the total dry weight divided by the core volume. They were then homogenized and ground to 250 μm with a Wiley Mill. Total organic matter was determined by loss on ignition after combusting samples of known mass at 550°C for 2 hours (Davies, 1974).

LIDAR Elevation Profile Extraction and Morphometric Variable Determination

One hundred and nine elevation profiles were extracted from a December 2012 airborne LIDAR DEM of the WLD derived from the USGS Atchafalaya 2 LIDAR Survey (NOAA, 2015) using ArcGIS 10.2 (ESRI). The original 1-m horizontal resolution DEM with ±12.5 cm vertical root mean square error was resampled using bilinear interpolation over 15 m to fill in missing data pixels using the 3D analyst toolbar and exported as a text file to calculate morphometrics. The profiles were spaced at 500-m intervals starting from the upstream end and extending along all non-dredged island edges within the WLD (Figure 1). Each transect was extracted perpendicular to the channel edge with a starting channel-side depth of –0.3 m NAVD88 and extending into the interior of the island. The final length of each transect used in the analysis was determined by defining the levee extent and then extending 100 m from the interior terminus of the levee (Figure 3). Transects ranged from 121 to 356 m in length.

The shape of each of the cross-sectional profiles extracted from the LIDAR DEM was described using four morphometric variables. A similar method has been used for stream bank profiles in riparian restoration studies (Gurnell *et al*., 2006). The chosen morphometric variables included: (1) levee width, defined as the highest point along the transect and all adjacent points (measured every 1 m) on either side that were $\leq$5 cm lower in vertical elevation; (2) interior slope to 100 m, defined as the slope of the elevation gradient starting at the interior edge of the levee extending into the interior of the island 100 m; (3) total elevation range, defined as the difference of the highest and lowest elevation values on the transect; and (4) mean elevation, the sum of each individual 1-m elevation value divided by the length of the transect (Figure 3).

Statistical Analyses

The pattern of change of the four morphometric variables with island age and distance from the upstream end was tested using PROC GLM multivariate analysis of variation (MANOVA) in SAS 9.4 (SAS Institute, Cary, North Carolina, U.S.A.). The two-way nested MANOVA tested a model of cross-sectional morphometric parameters equal to the age and distance within age. PROC GLM in SAS 9.4 was also used to test the relationship of percent organic matter and elevation, using a simple linear regression. PRIMER 7 (PRIMER-E Ltd., Plymouth, U.K.) was used for principal components analysis (PCA) to visualize the trends in island edge morphology with age and to better understand the relationship between individual morphometrics and island age.

RESULTS

The results of the island age mapping and analysis of the pattern of cross-sectional elevation profile shape are reported here. The relationship of island morphology to patterns

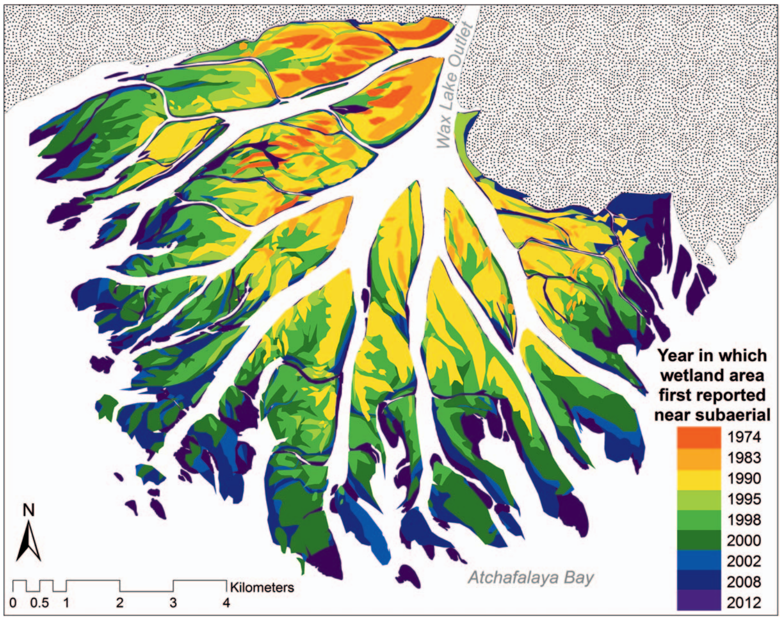

Figure 4. Chronosequence map, illustrating the age range over which land establishment occurred for the 2012 extent of Wax Lake Delta. The colors indicate the year in which land was first reported at or near subaerial, defined as above mean low water (–0.04 m NAVD88).

observed in the field-surveyed transects in relation to seasonal river flooding and organic matter are also given.

Deltaic Island Chronosequence Map

The chronosequence map of the WLD clearly delineates the age range categories across all the deltaic islands and geographically represents the planform development of the delta over time (Figure 4). Older areas, with subaerial establishment before 1990, are found in the upstream portion of the delta near the apex at the mouth of the WLO. The intermediate aged island areas were established between 1990 and 2000, and the young islands were established between 2000 and 2012. The resolution and methods used to create this map do not allow for a quantitative estimate of land building rate, as has been done in other analyses of WLD and Atchafalaya Delta (Allen, Couvillion, and Barras, 2011; Majersky *et al.*, 1997; Rouse, Roberts, and Cunningham, 1978).

Comparisons of Cross-Sectional Island Profiles

The two-way nested MANOVA of cross-sectional morphometric parameters equal to the age and distance within age indicated that age and distance within age were both statistically significant predictors of island edge cross-sectional morphology, as described by the four morphometric variables. For age, the Wilk's Lambda F statistic was 2.86 with $p < 0.0001$, and for distance within age, the Wilk's Lambda F statistic was 1.29 with $p = 0.0361$. Therefore, age is the strongest predictor of morphology, but distance from the upstream end of islands is also an important factor in describing island edge morphology. This result supports the initial hypothesis that island edge morphology varied in a consistent way with age; however, it also shows that predictable variation in morphology occurs along the downstream axis of delta islands and that age is not the sole predictor of morphology. The different morphologies seen within similarly aged islands are likely due to the widening and deepening of interdistributary bays and troughs in a downstream direction, which has been previously described for this system (Shaw, Mohrig, and Wagner, 2016). The morphologic expression of this trend is observed as greater steepness of interior slope with distance downstream.

The PCA results of all cross-sectional profile morphometric variables also reflected the patterns that were identified in the MANOVA. When the multivariate morphometric data describing the elevation profiles were plotted on the first two principal components, which accounted for a total of 87.5% of the variation (Figure 5), there was a pattern of increasing island age from right to left along the axis of PC1. Spread was greater throughout the distribution of the transects from locations of intermediate age (1995, 1998), but with a clearer distinction between the oldest (1973, 1983, 1990) and youngest (2002, 2008, 2012) land, likely because of the variable rates of geomorphic development throughout the delta. It is also possible that this difference is related to the distance from the upstream end of the islands, which was found to be significant as a nested factor in the MANOVA. Each of the four morphometric parameters were plotted as lines on the PCA, and the parameter of interior slope increases in roughly the same direction as PC2. Therefore it is likely PC2, with 21.2% of the variation, was related to distance down the island, because this is the morphometric variable that varies the most in relation to the depth of the interdistributary bay, which increases in depth in a downstream direction (Shaw, Mohrig, and Wagner, 2016).

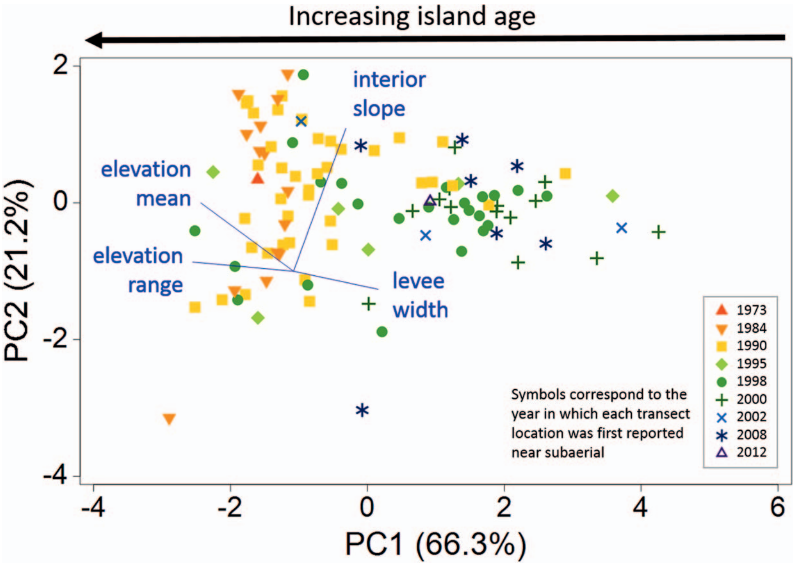

Figure 5. Results of principal components analysis of morphometrics, which describe the island cross-sectional elevation profile shape. Each transect plotted on the first two principal components (PC1 and PC2) accounts for 87.5% of the variation. Colors and symbols correspond to the year in which the land at the location of each transect was first reported to be subaerial (see map in Figure 2). The general trend is of increasing age along first principal component, particularly with distinction between the oldest (1973, 1983, 1990) and youngest (2002, 2008, 2012) land; intermediate age land (1995, 1998) spread more evenly throughout the distribution.

Field-Surveyed Elevation Profiles

The change in morphology measured at transect D from winter 2008 through summer 2011 is illustrated in Figure 6a–h. The daily mean water level within the WLO is also shown over the entire sampling period, and the transect sampling dates are indicated by a solid black line and correspond to the letters of each of the graphs in Figure 6. Transect D is located on the distal portion of the delta and is in the youngest age class of the field-surveyed transects (Figures 1 and 4). A change from the flat, low-relief, low-elevation topography of the cross-sectional elevation profile initially measured in winter of 2008 (Figure 6a) to the slight levee edge profile shape in the summer of 2008 (Figure 6b) can be attributed to the large river flood that was observed during the spring of 2008. The morphology of the profile remained relatively consistent during subsequent years (Figure 6c–g). But in the spring of 2011 when another very large river flood occurred (Figure 6i), the profile morphology rapidly shifted to a very pronounced levee formation accompanied by cut bank erosion along the channel edge (Figure 6h).

Soil OM Content Relative to Elevation

High soil percent OM was observed at all stations along transect E, which occurs near the upstream end of an older island (Figure 7). Higher elevation levee stations along transects C and F also had higher percent OM. However, the percent OM decreased at lower elevations in the island interiors of these transects. Overall, the simple linear regression analysis indicated that there was a significant positive relationship between soil percent OM and elevation ($R^2 = 0.39$, $p < 0.001$), as can be seen in Figure 7. It appears that percent OM content increases when elevation exceeds about 0 m NAVD 88, which is above MLW (about –0.04 m NAVD 88) and may be related to controls on primary productivity by the duration of tidal flooding.

DISCUSSION

The patterns of deltaic island growth over time that are evident in the chronosequence map (Figure 4) are consistent with jet plume deposit formation that was clearly laid out in Wellner *et al.* (2005), as well as models of shallow bayhead delta building (Wright, 1977). The additional analysis of cross-sectional profile shape allows for a better understanding of vertical land building in this prograding delta.

Conceptual Model of Deltaic Floodplain Wetland Development

The development of island edge morphology over time is consistent with the hypothesized conceptual model, wherein the initial low-elevation island edge with relatively flat morphology increases in elevation over time, first with a more pronounced levee edge and then with gradual infilling of the interior and interdistributary bay wetlands (Figure 2). These results indicate that the infilling of island interiors and interdistributary bays in upper regions of islands is occurring over time and that the concurrent increase in soil OM content observed is potentially driven by the ecological succession of deltaic island wetland vegetation communities. However, there was also a significant effect of distance from the upstream end of the island, resulting in different cross-sectional morphology than would be predicted solely based on age. This pattern is evident in field-surveyed transects A and G, which have lower mean elevation and a narrower range of elevation than transects within the same age range found closer to the

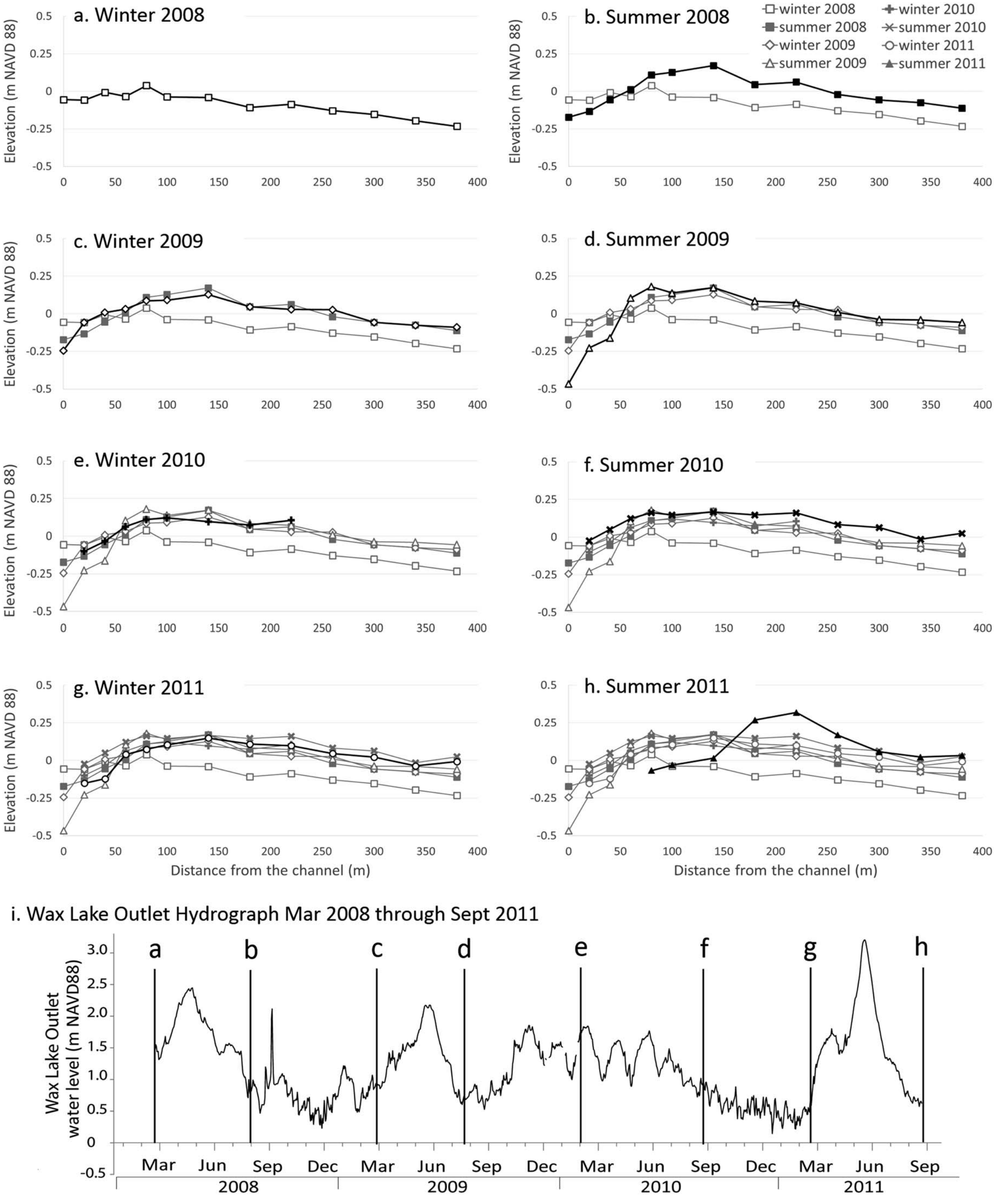

Figure 6. Changes in transect D cross-sectional morphology over time, from (a–h) winter 2008 through summer 2011. This period included two large river floods in the springs of 2008 and 2011 (i). These large river floods resulted in large amounts of deposition along the island edges and, in 2011, seem to have changed the cross-sectional morphology from that of a younger island (flat and low) to that of an intermediate aged island (distinct high elevation levee).

upstream ends of islands such as C and F (Figure 7). This is likely related to the depositional dynamics of the jet plume delta formation, where coarser sediments are deposited at the upstream ends of jet deposits with finer grain sediments further downstream (Wellner *et al.*, 2005). As the distributaries continue downstream, the islands widen and interdistributary bays are deeper, which results in a steeper interior slope for island edge cross-sectional profiles that are located further

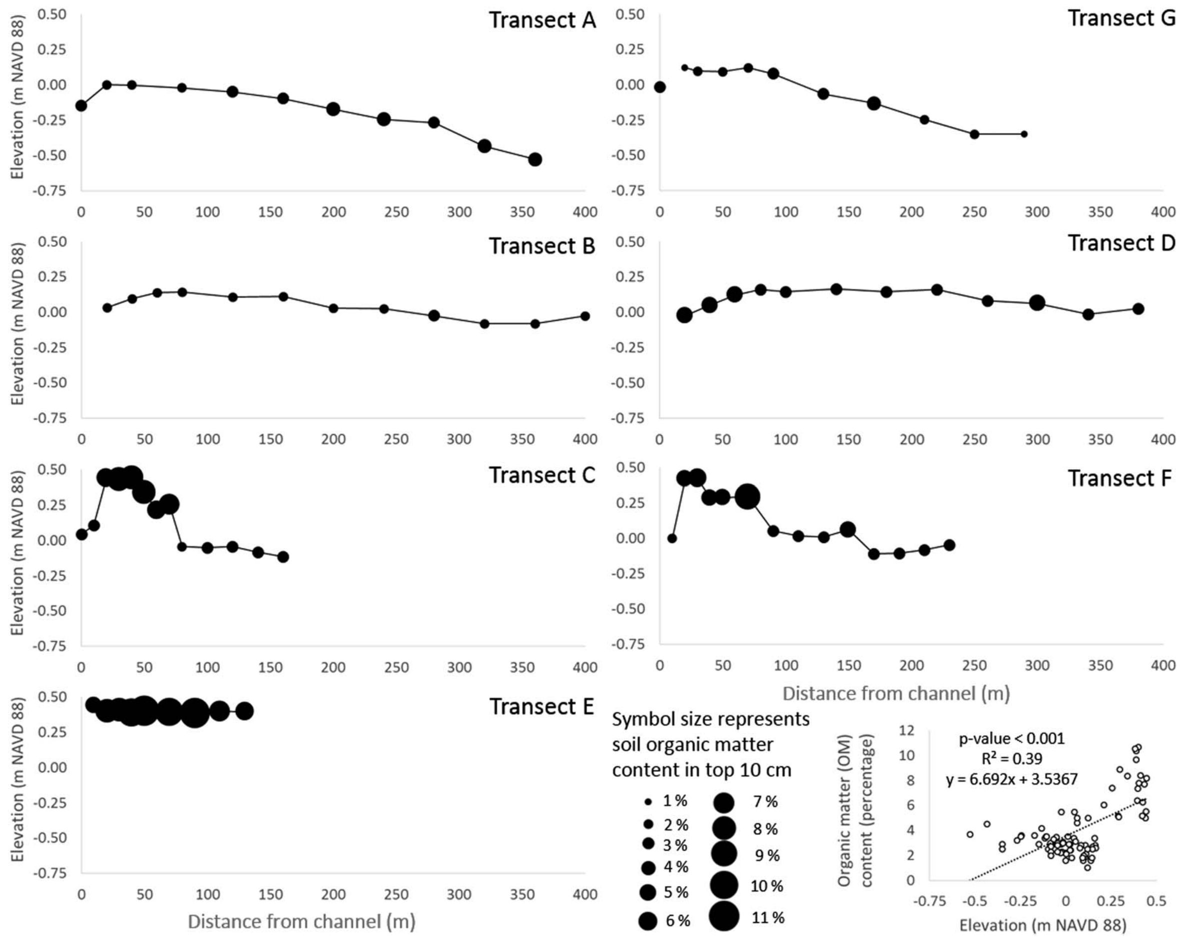

Figure 7. Plots of field-surveyed transects from summer 2010, with sediment surface elevation over distance from channel edge (m); each plot where elevation was measured is represented by a black circle, and the size of the circle is determined by the percent organic matter (OM) measured from homogenized sample from the top 10 cm. Regression analysis of percent OM over elevation showed a significant relationship, with $p < 0.0001$ and $R^2 = 0.39$.

downstream. The effect of both astronomically and meteorologically driven tidal exchange that occurs over the relatively low levees and the open distal ends of the interdistributary bays may serve to resuspend fine-grain sediments and limit elevation gain (Hiatt and Passalacqua, 2015). This experimental design limits any perspectives about how vegetation community change may increase accretion in island interiors; however, there is evidence of a significant increase in percent OM in older and higher elevation islands (Figure 7). Deltaic vegetation zonation is strongly controlled by elevation (Bevington, 2016; Cahoon, White, and Lynch, 2011; Johnson, Sasser, and Gosselink, 1985; Shaffer *et al.*, 1992). Therefore, it can be hypothesized that infilling is at least partially controlled by increased organic accretion in interior wetlands resulting from a positive feedback of increasing elevation, resulting in a successional shift toward vegetation communities that have higher belowground production rates. Deltaic floodplain wetland vegetation communities in the WLD have been shown to exhibit a shift in dominant species assemblage at soil surface elevations between MLW and mean sea level, in which lower elevation subtidal and intertidal communities composed of *Nelumbo lutea*, *Sagittaria platyphylla*, and *Potamogeton nodosus* transition to a dense emergent community dominated by *Colocasia esculenta* at higher intertidal and supratidal elevations (Bevington, 2016). It is possible that the morphological and functional differences between these dominant species could result in differing rates of belowground production, therefore controlling the percent OM that is sequestered in wetland soils at different elevations.

Possible Mechanism for Island Edge Development

The timing of spring river floods, which often result in large accumulations of sediment, may control the morphology of island edges and initiate morphologic development by changing the flat morphology of an island to the pronounced levee edge seen in intermediate age transects. Evidence for this comes from the field-surveyed transects collected from 2008 to 2011. Transect D, which was first reported subaerial in 1995 (Figures 1 and 4), exhibited flat, low elevation with very little apparent levee when it was first surveyed in the winter of 2008 (Figure 6a). As a result of the spring flood in 2008, which had the eighth

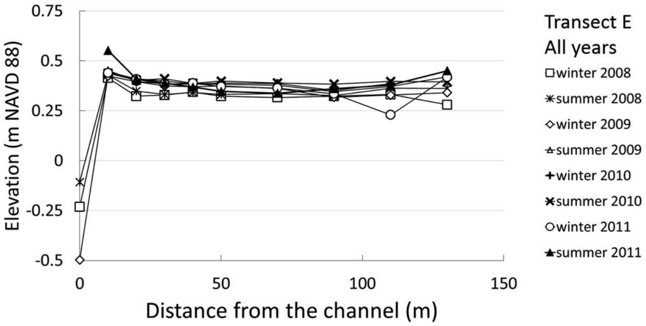

Figure 8. Elevation profiles of transect E from all sampling years, winter and summer. This transect, which has the highest overall elevation and organic matter, also had very little change in elevation over the 3.5 y of sampling. Variation is only seen in limited instances, such as a drop of about 10 cm measured in winter of 2011 at the second-most interior plot; however, this drop did not persist through the following summer.

highest water levels recorded for the Atchafalaya River at Simmesport, Louisiana (USGS 07381490), between 1932 and 2015, rapid elevation gain occurred across the transect (Figure 6b). Over subsequent years, repeated sampling in both winter and summer showed small elevation gain across the entire transect but very little change in the overall morphology (Figure 6c–g). In the spring of 2011, the third highest water levels were recorded at Simmesport in the last 83 years, resulting in very high water and sediment discharge in the WLD (Bevington *et al.*, 2017). As a result of this extremely large flood, the overall morphology of this transect changed dramatically: the location of the channel edge cut into the island by 80 m from its previous location, and a distinct high-elevation levee was deposited (Figure 6h). This shift from the relatively flat morphology of a younger deltaic island to that of an intermediate aged island occurred very rapidly as the result of a single large river flood in the spring of 2011. This evidence supports the role of large, high-energy river floods as a strong driver of island edge morphological development; thus, periods of rapid development over relatively short timescales as observed in the WLD are also controlled by the frequency and timing of these types of events.

Relationship between Island Age, Elevation, and Soil OM

A similar pattern of higher OM content in wetland soils on older islands at the WLD has been shown in other studies (Henry and Twilley, 2014; Shields *et al.,* 2016). Increased percent OM within intertidal soils compared with subtidal sediment indicates a difference in organic production, decomposition rates, or both, as well as in mineral sediment input. Differing rates of OM production could be related to a shift in the dominant vegetation community with increasing elevation, which has been found to occur in deltaic floodplain wetlands (Bevington, 2016; Cahoon, White, and Lynch, 2011; Johnson, Sasser, and Gosselink, 1985; Shaffer *et al.*, 1992). However, no work has yet shown differences in production rates between these communities, and it is possible that if production rates are similar across vegetation communities, the differences in the soil percent OM could be related to the lower input of inorganic sediment from frequent flooding at higher elevations.

Transect E, which exhibited both higher elevation and soil percent OM in interior wetland plots represents the later stage of island interior infilling (Figure 8). This same morphology can also been seen in the transect (I–I') most upstream from Mike Island in the conceptual model used to develop the hypothesis (Figure 2). On the basis of observations of all four years of the field survey data for transect E, the interior island elevations were persistent, with only small increases in elevation along the levee edge and some seasonal fluctuations in island interior elevation (Figure 8). This transect located on an older upstream portion of an island is consistent with the hypothesis based on the conceptual model of increasing elevation, organic content, and infilling of interdistributary bays with increasing island age. On the basis of the location of transect E, which was reported as subaerial in 1990 (Figures 1 and 4), the infilling and successional establishment of stable high elevation interior wetlands can be estimated to have occurred rapidly, within fewer than 20 years.

Implications for Coastal Restoration

Infilling of interior wetlands and interdistributary bays near the upstream end of islands has been shown to occur in the WLD within 40 years of subaerial delta emergence. Therefore, the timescale over which these natural processes have occurred has implications for restoration goals that have 50- to 100-year time frames. The conceptual model and results presented here lay the groundwork to gain a better understanding of when, how, and why this infilling occurs, because it is critical to improving predictions of deltaic wetland development and land building, particularly in regards to proposed sediment delivery diversions (Nyman, 2014). Much of the current research related to use and land building capacity of river diversions is based on numerical modeling of sediment delivery. However, organic accretion, which is not included in most models of delta morphodynamics, can be an equal if not greater driver of elevation gain in coastal wetlands, and understanding at what elevation and under what conditions the ecosystem switches from mineral sedimentation to mainly organic accretion will allow for more accurate and reliable predictions for land building in the future.

CONCLUSIONS

There was a clear statistically significant trend in cross-sectional elevation profile shape over time. This trend was consistent with the proposed conceptual model, in which a gradual increase in overall elevation occurs with the establishment of a distinct, high-elevation levee edge with a steep interior slope, followed by gradual infilling of the interior until an elevation similar to the levee edge is achieved. The distance from the upstream end of the islands also had a significant effect on the shape of the island cross-sectional profile, with steeper interior slopes occurring in more downstream portions of the delta where the interdistributary bay is deeper. Soil percent OM content showed a significant positive trend with higher elevations, which also corresponded to older deltaic island areas; however, the mechanism of this has not been determined. These results are consistent with the conceptual model of deltaic island edge development with age presented here and provide a description of deltaic island morphology over time on which to build further process-based hypotheses to better understand coastal deltaic development.

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