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Accretion and Vegetation Community Change in the Wax Lake Delta Following the Historic 2011 Mississippi River Flood

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ABSTRACT

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During the 2011 Mississippi River flood, discharge to the lower river exceeded that of the 1927 and 1937 floods and the lower river remained above flood stage for nearly 2 months. A combination of WorldView-2 and Land Satellite 5 Thematic Mapper (Landsat 5 TM) imagery was used to assess the impact of this flood event on the Wax Lake Delta, one of few areas where the river is building new land. Vegetation community change was mapped from 2010 to 2011 and related to elevation change using plant species elevation distributions calculated from light detection and ranging (LIDAR) data. Changes in the land area in the delta were also assessed by regressing land area against water level for a series of pre- and postflood Landsat 5 TM images. The results indicate a net growth of 6.5 km^2 at mean water level and 4.90 km^2 at mean sea level. Areal gains were greatest at high water levels, indicating substantial vertical accretion across the subaerial delta. At least 8.7 km^2, or 31.8%, of the area studied converted to a higher-elevation species. The most change occurred at low elevations with conversion from fully submerged aquatic vegetation to *Potamogeton nodosus* and *Nelumbo lutea*. Conversion to lower-elevation species occurred across 3.4 km^2, or 12.8% of the study area, while 55.5% remained unchanged. The results highlight the importance of infrequent, large flood events in the maintenance of river deltas and provide a reference for estimating the impact of proposed large-scale river diversions on the Mississippi River Delta.

ADDITIONAL INDEX WORDS: *Coastal land change, river deltas, tidal freshwater marsh, plant species distributions, zonation, flood events, sedimentation.*

INTRODUCTION

River deltas are geologically ephemeral features that occur throughout the world wherever river sediment is delivered to a coast faster than it is removed by marine processes (Day and Giosan, 2008; Wright, 1985). New sediment delivery to deltas is essential to maintain sediment accumulation despite marine erosional forces and subsidence caused by a variety of processes, including the dewatering and compaction of sediments and isostatic sediment loading (Blum *et al.,* 2008; Meckel, Ten Brink, and Williams, 2006; Morton and Bernier, 2010; Törnqvist *et al.,* 2008; Yuill, Lavoie, and Reed, 2009). Because extreme river floods deliver a disproportionate amount of sediment to coasts, they play a critical role in the creation and maintenance of deltas (Müller and Förstner, 1968; Nittrouer, Allison, and Campanella, 2008; Nittrouer, Mohrig, and Allison, 2011).

The quantity and size distribution of sediments delivered during a flood event are direct functions of watershed geomorphology, land cover, land use practices, and the amount of upstream sediment capture that occurs (Chakrapani, 2005). Watershed geomorphology largely determines the type of sediment that is available for transport and its inherent erodability, whereas relief determines the grain sizes that a river can transport (Chakrapani, 2005; Orton and Reading, 1993). Watershed land cover, particularly land use, influences the amount of sediment that is actually eroded from the land surface. Urbanization and increased agricultural activity resulted in a steady increase in sediment loads to many of the world's rivers throughout the early to mid-1900s (Syvitski and Kettner, 2011). For many rivers, sediment supply later rapidly decreased to rates at or below natural levels due to large-scale dam construction and riverbank hardening that trapped sediment upstream (Blum and Roberts, 2009; Syvitski and Kettner, 2011; Yang *et al.,* 2003). By controlling sediment availability, these factors constrain the rate of river delta growth.

The ability of a river to transport the sediment that is available from its watershed increases exponentially as a function of water discharge (Müller and Förstner, 1968). Extreme floods generate much of the disproportionately high sediment delivery that has been observed in rivers with small, mountainous or tectonic watersheds (Chakrapani, 2005; Inman and Jenkins, 1999; Meybeck *et al.,* 2003; Milliman and Syvitski, 1992) but have also been shown to be important drivers of sediment delivery in larger, low-relief river basins such as the Mississippi (Nittrouer *et al.,* 2012). Large floods mobilize sediments that are deposited in river channels during low-flow conditions and are able to transport larger grain sizes, which provide a stable platform

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for delta building (Nittrouer, Allison, and Campanella, 2008; Nittrouer, Mohrig, and Allison, 2011; Nittrouer *et al.,* 2012). Under natural conditions, extreme floods result in rivers overflowing or breaking through their banks to form crevasse splays and activating former distributaries, spreading sediment deposition over a larger area of the deltaic plain than occurs during a normal annual flood (Coleman, 1988; Kesel, 1989; Mossa and Roberts, 1990; Syvitski *et al.,* 2005). Sediment that is not retained within the delta is deposited in the nearshore environment, where it is available to be reworked onshore by waves, tides, and storms (Allison *et al.,* 2000; Mossa and Roberts, 1990; Reed, 1989).

However, there is an inherent conflict between floods' critical role in nourishing deltas and people's desire to live and work in and near deltas. Many of the earliest human civilizations arose on deltas, where rich alluvial sediments supported early developments in agriculture (Cao *et al.,* 2006; Pope *et al.,* 2001; Stanley and Chen, 1996; Wang *et al.,* 2010; Weng, 2000). Today, river deltas occupy less than 1% of the Earth's land area but are home to more than 500 million people (Ericson *et al.,* 2006), supporting population densities 10 times higher than the global average (Ericson *et al.,* 2006). As a result, many of the world's deltas have been hydrologically altered to prevent flooding of communities and infrastructure (Ericson *et al.,* 2006; Syvitski, 2008; Syvitski *et al.,* 2009). This modification of the hydrology removes the primary source of sediment input to the delta, often leading to subsidence through the compaction and dewatering of existing sediments (Day and Giosan, 2008; Meckel, Ten Brink, and Williams, 2006; Morton and Bernier, 2010; Törnqvist *et al.,* 2008). It can result in dramatic land loss as deltaic wetlands are no longer able to accrete vertically at a sufficient rate to keep pace with relative sea level rise (Syvitski, 2008).

One of the best studied examples is the Mississippi River Delta, which was cut off from the river by the construction of an extensive levee system following the catastrophic flood of 1927 and is losing land at a rate of about 40 km^2 per year (Barras, Bernier, and Morton, 2008; Couvillion *et al.,* 2011; Dixon *et al.,* 2006). Relative sea level rise in the Mississippi River Delta is the highest in the United States because of subsidence rates that range from 1 to 2 mm per year at the inland boundary near Baton Rouge to as high as 6 to 8 mm per year in areas with the thickest fluvial Holocene deposits (Blum and Roberts, 2009; Morton and Bernier, 2010). Engineered large-scale river diversions have been proposed to reverse land loss by restoring the hydrologic connection between the Mississippi River and its deltaic plain (Coastal Protection and Restoration Authority of Louisiana Staff, 2012; Paola *et al.,* 2011), but there are limited data available to test and calibrate deltaic models to predict how quickly such projects would build land.

The Wax Lake Delta

The Wax Lake Outlet, a flood control diversion of the Atchafalaya River, is of a similar order of magnitude as the proposed Mississippi River diversions and provides a good reference system for studying the land-building potential of such projects. The Atchafalaya River is the only remaining distributary of the Mississippi River and carries a fixed 30% of the combined flows of the Mississippi and Red Rivers as managed by the U.S. Army Corps of Engineers at the Old River Control Station upriver from Baton Rouge, Louisiana (Roberts, 1998). It travels 160 km through a narrow basin consisting of 5670 km^2 of freshwater swamps and shallow lakes before discharging into Atchafalaya Bay approximately 216 km west of the main channel (Hupp *et al.,* 2008). Constructed in 1941, the Wax Lake Outlet was designed to divert approximately one-third of the normal flow of the lower Atchafalaya River. Recent measurements (2008–10) indicate that that the channel has enlarged and carries 46% of the river's flow (Allison *et al.,* 2012). Average monthly discharges range from 1250 cubic meters per second (cms; September) to 3625 cms (April), with a long-term average of 2677 cms measured from 1995 to 2012 (USGS, 2013). It carries an average suspended sediment load of 20.5 metric tons per year, which represents 42% of the total suspended sediment discharge from the Atchafalaya Basin (Allison *et al.,* 2012).

While not originally designed to build land, construction of the Wax Lake Outlet resulted in the growth of a new bayhead river delta, the Wax Lake Delta (Figure 1). The Wax Lake Delta emerged from Atchafalaya Bay following record flooding in 1973 and has formed as a silt-and-sand-rich wedge with numerous elongating, bifurcated channels separating sandy lobe islands (Roberts, 1998; Roberts *et al.,* 1997; Van Heerden and Roberts, 1980). As of 1997, the river had built 51.1 km^2 of new land above the –0.6-m contour of the National Geodetic Vertical Datum of 1929 (NGVD29) in the Wax Lake Delta (Roberts *et al.,* 1997). While local dredging and spoil disposal have altered the natural development of the neighboring Atchafalaya Delta, the Wax Lake Delta has developed largely free of human intervention. The only major human impact is reduced sediment supply to the Mississippi River, an issue that affects the entire Mississippi River deltaic plain. The sediment load of the Mississippi River has decreased by as much as 50% since the early 1900s because of the construction of dams on upstream tributaries (Blum and Roberts, 2009). This has reduced the rate of delta development compared to natural conditions, although it is impossible to know by how much. However, as one of few areas of the Mississippi River deltaic plain where the river is actively building new land (Couvillion *et al.,* 2011; Roberts *et al.,* 1997), the Wax Lake Delta can provide insight into the river's delta-building processes and the land-building potential of the diversions that have been proposed to restore wetlands in other parts of the Mississippi River deltaic plain.

Plant Communities of the Wax Lake Delta

Wetland plants are extremely sensitive to slight variations in the frequency, depth, and inundation of flooding, making them useful indicators of hydrologic conditions (Albert and Minc, 2004; Goslee, Brooks, and Cole, 1997). Strong elevation-based zonation is common in coastal wetlands (Bertness and Ellison, 1987; Eleuterius and Eleuterius, 1979; Kershaw, 1976; Pielou and Routledge, 1976; Sánchez, Izco, and Medrano, 1996; Wilcox, 2004). Within river deltas, plant communities respond to a variety of riverine and coastal drivers, including

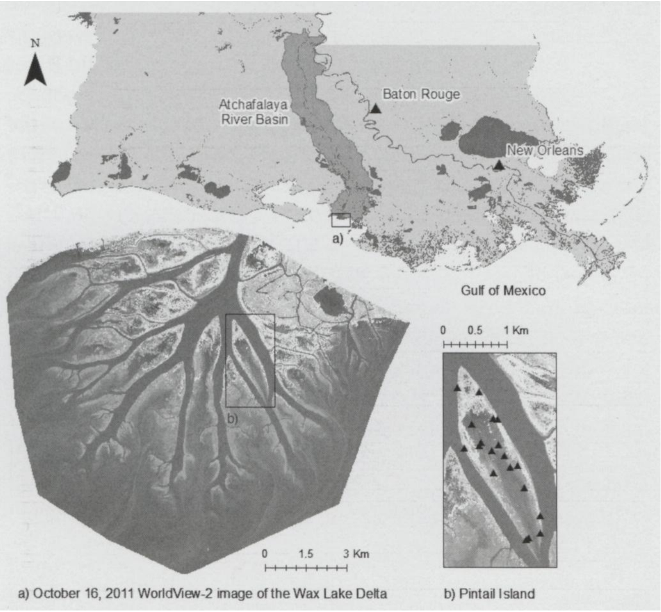

Figure 1. Location of the Wax Lake Delta and reference plots on Pintail Island.

sedimentation, river currents and associated erosion, lunar and wind-driven tides, coastal storms, and changes in salinity, but elevation remains the most important predictor of plant species distributions (Holm and Sasser, 2001; Johnson, Sasser, and Gosselink, 1985). Shifts in plant community composition and the distribution of individual species are a normal part of the life cycle of a delta (Neill and Deegan, 1986; Rejmánek, Sasser, and Gosselink, 1987). As a river delta accretes vertically and matures, the plant community changes and undergoes allogeneic succession over time. In temperate, river-dominated deltas such as the Wax Lake Delta, submerged aquatic vegetation (SAV) may first establish on newly formed shallow mudflats only to be replaced by floating-leaved vegetation, emergent vegetation, diverse high-marsh meadow communities, and eventually canopies of small trees and shrubs as elevation increases over time (Johnson, Sasser, and Gosselink, 1985; Kandus and Malvarez, 2004; Shaffer *et al.*, 1992). Changes in the vegetation community can, therefore, often be indicative of geomorphological changes occurring within the delta.

The wetland vegetation in the Wax Lake Delta exhibits such sharp zonation along the elevation gradient. Dominant plant species within the Wax Lake Delta include black willow *(Salix nigra)* and elephant ear *(Colocasia esculenta),* which occur along the natural channel levees; dense meadows of mixed grasses and forbs, which are found at intermediate elevations; emergent forbs such as *Sagittaria* species and American lotus *(Nelumbo lutea),* which colonize periodically exposed mudflats; and floating-leaved vegetation and SAV, which are found at the lowest elevations in the distal interior of the islands and on newly formed shallow deposits. Most species dominant within the delta are common in freshwater wetlands throughout coastal Louisiana. *Sagittaria* species have been particularly important components of the lower-elevation communities in both the Wax Lake and the Atchafalaya Deltas since their formation. However, their dominance at the Wax Lake Delta has waned in recent years, with the floating-leaved and submerged *Potamogeton nodosus* and the emergent *N. lutea* spreading over much of the lower-elevation areas of the delta previously dominated by the *Sagittaria* species. The expansive stands of *N. lutea* that are now found in the interior of the islands in the Wax Lake Delta are unique in coastal Louisiana. This species is not present in such high abundance in any other Louisiana marshes, but coastwide vegetation surveys conducted approximately every 5 to 10 years suggest that its presence is gradually increasing coastwide (C.E. Sasser, personal observation). It is unclear why this species is increasing in distribution or what impact its displacement of other species may have on ecosystem dynamics within tidal freshwater marshes in coastal Louisiana.

The 2011 Mississippi River Flood

In May 2011, high rainfall in the upper Mississippi River basin combined with spring snowmelt to generate a record flood on the lower Mississippi River (Figure 2). Discharge and river stage along parts of the lower river below Vicksburg, Mississippi, exceeded that of the catastrophic floods of 1927 and 1937, as well as the more recent floods of 1973 and 1993 (USGS, 2013). The lower river remained above flood stage for nearly 2 months—from early May to late June 2011. To prevent inundation of the cities of Baton Rouge and New Orleans, the U.S. Army Corps of Engineers diverted a portion of the floodwaters into the Atchafalaya Basin through the Morganza Spillway, a flood control structure located upstream of Baton Rouge. At the flood's crest on May 18, the Morganza Spillway diverted approximately 4870 cms into the Atchafalaya Basin. This flow joined the approximately 18,860 cms of combined Mississippi River and Red River flow that was diverted into the Atchafalaya River upstream at the Old River Control Station at the peak of the flood, as measured by the U.S. Geologic Survey (USGS) at Simmesport, Louisiana. In total, a peak discharge of approximately 23,730 cms of water flowed through the Atchafalaya River Basin, of which, 8860 cms was discharged into the Wax Lake Delta (USGS, 2013). This represents approximately 11% of the total peak flood discharge on the lower Mississippi River system.

In this study, we used high- and moderate-resolution satellite remote sensing to measure the response of the vegetation community in the Wax Lake Delta to this historic flood event. We measured the increase in the vegetated surface of the delta by comparing the relationship between the water level and the vegetated area before and after the flood. We also used light detection and ranging (LIDAR) data to test the relationship between the elevation and the spatial distribution of the six dominant plant species in the delta to ascertain the degree to which changes in species distribution may be attributable to flood-induced sedimentation and erosion. Ideally, LIDAR data obtained before and immediately following the flood event would be used to map elevation change across the surface of the delta. However, the high cost of LIDAR data

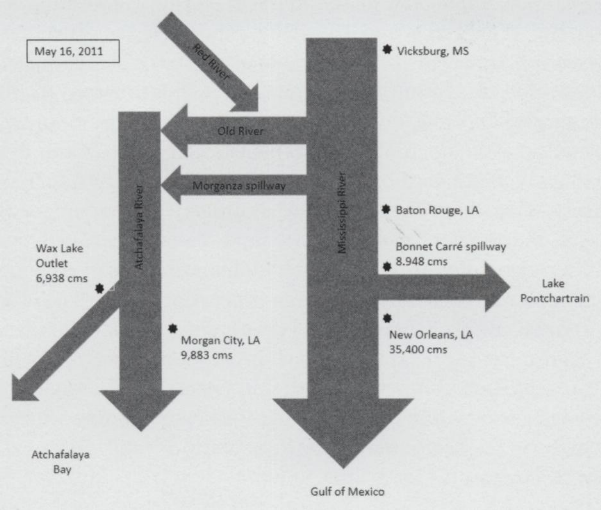

Figure 2. Peak discharge on the lower Mississippi River system during the historic 2011 flood.

acquisition limits frequent and event-driven acquisitions. To the extent that the sensitivity of wetland vegetation to slight changes in elevation can be exploited to identify areas of potential elevation change using high-resolution satellite imagery, such an approach could provide a lower-cost option for assessing landscape-scale geomorphic change where LIDAR data are unavailable.

In this case, quantifying the extent of vertical accretion and horizontal expansion in the Wax Lake Delta following the 2011 flood will enhance our understanding of the land-building capabilities of extreme flood events and assist in optimizing the operation of other large-scale river diversions within the Mississippi River system. It also provides a baseline to help project managers set realistic expectations for the amount of land that such large-scale diversion projects may be able to create or restore over time. Studying the response of the vegetation community to flood pulses also provides a reference for expected wetland plant community development associated with large river diversions.

The objectives of this study are threefold: (1) to measure the gain in the vegetated surface area of the Wax Lake Delta following the 2011 flood, (2) to quantify the extent of vegetation community change following the flood, and (3) to determine the degree to which changes in plant species distribution following the flood relate to changes in elevation and use this information to map areas of estimated elevation change.

METHODS

Measuring Change in the Vegetated Area of the Delta

We used a threshold of the normalized difference vegetation index (NDVI) to separate open water from vegetated areas of the Wax Lake Delta for a series of cloud-free or nearly cloud-free Land Satellite 5 Thematic Mapper (Landsat 5 TM) images from summer and early fall 2010 and 2011. The NDVI is a weighted ratio of reflectance in the red and near-infrared (NIR) regions of the light spectrum and is calculated according to the following formula (Rouse *et al.,* 1974):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}$$

Healthy vegetation tends to absorb light in the red region while strongly reflecting light in the NIR region, leading to positive values of NDVI that increase with the strength of photosynthetic activity. Water absorbs light in both of these regions but absorbs most completely in the NIR region, giving deep water its characteristic negative NDVI values. The NDVI threshold method has been shown to successfully separate land and water in shallow coastal environments and is especially useful for reducing misclassification of suspended sediments as land (Ryu, Won, and Min, 2002). For this study, we used a stepping method at 0.005 intervals to identify the optimum NDVI threshold to separate land and water for each image and selected the lowest value of NDVI that resulted in classification of all deepwater pixels as water. The NDVI thresholds selected varied from –0.07 to –0.02.

This classification method differs from methods that have been used for previous studies, which have relied on a threshold method applied to the NIR band alone (Landsat band 5). In its coastwide studies of land loss in Louisiana, the USGS limits images used for coastal land loss analysis to those acquired during the winter, when submerged and floating-leaved plants are absent, and taken within 0.15 m of mean water level, as measured at the tide gauge near Grand Isle, Louisiana (Couvillion *et al.,* 2011). We were unable to reproduce that method for this study due to a lack of suitable winter postflood imagery as a result of failure of the Landsat 5 TM satellite in November 2011. Our work represents the extent of the vegetated surface of the delta, a measure that we believe may hold more ecological significance but is not necessarily directly comparable to land area estimates made in previous studies. In particular, our estimate of vegetated area includes shallow areas dominated by floating-leaved vegetation and SAV. These areas are difficult to separate from adjacent emergent or high marsh vegetation during the growing season and obscure the location of the water line. However, given the important role that rooted vegetation plays in increasing sediment cohesion, trapping sediments, resisting erosion, and providing organic matter that contributes to vertical accretion (Edmonds and Slingerland, 2009; Nyman, Delaune, and Patrick, 1990; Serodes and Troude, 1984; Stumpf, 1983), we feel that its distribution warrants consideration independent of the area of the delta above high tide.

Land area in the Wax Lake Delta varies considerably with water level as a function of river discharge, tidal stage, and meteorological events (Allen, Couvillion, and Barras, 2012; Roberts, 1998). To account for this variability in land area, we used linear regression to quantify the relationship between the water level and the vegetated area before and after the flood. Vegetated area gain was determined based on the difference between the pre- and the postflood regression lines. Water levels at the time of image acquisition were obtained from hourly measurements of water level relative to the North American Vertical Datum of 1988 (NAVD88) taken at the

Louisiana Office of Coastal Protection and Restoration and USGS Coastal Reference Monitoring System (CRMS) station in the Wax Lake Delta (Coastal Protection and Restoration Authority of Louisiana, 2012). A weighted average was used to estimate water level at the exact time of Landsat 5 TM image acquisition. Five images from summer and early fall 2010 were used to determine the relationship between water level and vegetated area before the flood, and four images from summer and early fall 2011 were used to determine the postflood relationship. The analysis for 2011 was complicated by Tropical Storm Lee, which made landfall in the delta on September 6, 2011, and altered the relationship between water level and vegetated area by pushing a pulse of saltwater into the delta that killed most SAV and floating-leaved vegetation. Comparison of preliminary classifications for dates before and after the storm suggested that consistently less vegetated land was mapped using poststorm images, independent of water level, due to the loss of this vegetation. For consistency, we added areas that had been dominated by vegetation prior to the storm to the poststorm vegetated area maps so that only changes in vegetated area related to water level fluctuations were considered. Because the water level was lower for the poststorm images than it was for the prestorm images, we believe that it is valid to assume that these areas would have still been vegetated at the later dates were it not for the interference of the storm.

The relatively coarse resolution of Landsat 5 TM imagery (30 m) prohibits precise aerial estimates at the scale of the Wax Lake Delta. To develop a more precise estimate of change in the vegetated area of the delta following the flood, we compared the Landsat 5 TM results to those obtained using a WorldView-2 (WV-2) image from October 16, 2011 (2-m spatial resolution). For this analysis, we selected a small area of the delta where the mapped area did not appear to be affected by the loss of SAV and floating vegetation following Tropical Storm Lee. We determined land area for this region using each of the 2011 Landsat 5 TM images and determined the exponential function describing the relationship between water level and land area. We then calculated an NDVI using band 7 (NIR1) of the WV-2 image and mapped the vegetated area using the same method that we applied to the Landsat 5 TM imagery. We used the exponential relationship between water level and vegetated area to predict the amount of land that would have been mapped using Landsat 5 TM imagery for the same water level and developed a correction factor as the ratio of the area measured using the WV-2 image to the area predicted by the Landsat 5 TM–based equation.

To determine how our vegetated land area estimates for the Wax Lake Delta compare to those obtained using the NIR threshold technique used by the USGS for coastwide land loss studies, we mapped delta land area in a December 1, 2010, Landsat 5 TM image using the USGS method and compared the results to the area that would be predicted using our NDVI-based vegetated area model at the same water level. We also directly applied the NDVI method to this image to separate the variability in land area attributable to the choice of classification method from that associated with our use of growing-season imagery and the inclusion of SAV and floating-leaved vegetation.

Vegetation Mapping

We used vegetation maps produced by maximum likelihood supervised classification of high-resolution (2-m) WV-2 and moderate-resolution (30-m) Landsat 5 TM satellite imagery obtained before and after the 2011 Mississippi River flood to measure the flood's impact on wetland vegetation communities in the delta. We obtained preflood WV-2 imagery from June 15, 2010, and postflood imagery from October 16, 2011. These images were supplemented with Landsat 5 TM imagery to account for the effects of Tropical Storm Lee, which killed much of the vegetation at lower elevations (especially *N. lutea, Sagittaria* spp., and *P. nodosus*). We used Landsat 5 TM images of Wax Lake Delta from August 27, 2010, and August 30, 2011, to measure the postflood, prestorm vegetation change in these areas of the delta. These species typically form large monotypic stands and can be mapped with reasonable accuracy using Landsat 5 TM imagery.

All images were converted to at-satellite reflectance values prior to classification. Several small clouds, roads, and buildings in the NE corner of the 2010 WV-2 image were manually digitized, and a mask was created to extract them from the image. Clouds were removed from the Landsat 5 TM images using a threshold for the difference between reflectance in the visible portion of the spectrum (blue, green, and red bands) in the target image and a second, cloud-free image from the same time of year. Training areas for the 2010 WV-2 and Landsat 5 TM classifications were derived from a reference map of vegetation communities in the delta that was created by visual interpretation of November 2009 satellite imagery and extensively ground truthed during summer 2010 (D.E. Hebert, unpublished data). Training areas for the 2011 WV-2 and Landsat 5 TM classifications were collected in the field during late August and early September 2011 using a Trimble GeoXH differential global positioning system (DGPS) with submeter accuracy. To account for phenologic differences in the reflectance values of each class, individual signature sets were developed for each image before performing maximum likelihood supervised classification on all images in Earth Resources Data Analysis Systems (ERDAS) Imagine 2010 (ERDAS, 2010).

Initial classification runs indicated an overclassification of the trees class in the 2010 WV-2 image compared to the 2011 image, including many pixels classified as trees in open water areas. To correct for this classification error, the trees class was limited to the area of trees mapped in the 2011 WV-2 image, which provided the most accurate representation based on visual interpretation of the imagery. Pixels classified as trees in the 2010 image that lay outside the 2011 mapped area were reassigned to the next best class using the maximum likelihood classifier.

Vegetation classes that had user's accuracies greater than 65% were used to assess vegetation change within the delta. User's accuracy measures errors of commission and is defined as the number of correctly classified pixels in a particular class divided by the total number of pixels that were classified from this particular class (Stehman, 1997; Story and Congalton, 1986). An accuracy assessment of the 2011 WV-2 and Landsat 5 TM maps, made using 85 random points visited in the field in August and September 2011, indicated that the following seven classes met this criterion: trees (91%), *N. lutea* (77%), *Colocasia antiquorum* (88%), *Polygonum* species (67%), *P. nodosus* (98%), other SAV (68%), and open water (82%).

Sampling Elevation Distributions

The elevation range of the selected vegetation classes were determined based on comparison of their areal distribution as shown in the June 2010 WV-2 vegetation map and a 2-m digital elevation model interpolated from LIDAR data collected in January 2009. The LIDAR data were collected at low tide, with a point density of 4.5 points per square meter, and had an average vertical accuracy of 5.5 cm over flat surfaces (J. Buttles, unpublished data). Elevations were calculated relative to NAVD88, using the U.S. National Geodetic Survey Geoid03 model. For this analysis, it was assumed that insufficient elevation change occurred between acquisition of the 2009 LIDAR data and acquisition of the 2010 WV-2 imagery to greatly affect the distribution of plant species along the elevation gradient. While the spring floods of 2009 and 2010 were above average, they were within or just outside of one standard deviation of the average spring flood during the time of record from 1988 to 2010 (USGS, 2013). Furthermore, elevation change data from the CRMS site in the Wax Lake Delta indicate an increase in elevation of 0.59 cm from the time the site was installed in October 2009 through March 2011, just prior to the historic flood (Coastal Protection and Restoration Authority of Louisiana, 2012). While peak discharge was higher during spring 2009 than it was spring 2010, we expected that the total elevation change would not be sufficient to significantly alter species distributions.

For each vegetation class, the digital elevation model was sampled using a 400-point random sample taken from areas mapped as that class. These data were used to construct histograms representing the elevation distributions for each species. Student's t tests were performed to test for differences in the mean elevation between pairs of species, and analysis of variance (ANOVA) was used to compare the within-class and the between-class variances in elevation for groups of species growing within adjacent elevation zones. All statistical tests were performed using the Statistical Product and Service Solutions statistical software package (IBM, 2010).

Mapping Vegetation Community Change

To summarize changes in the vegetation community, the areas mapped for each vegetation class in the 2010 and 2011 imagery were compared and the area of change was calculated for each class. The WV-2 maps were used to determine areas of vegetation change within the mid- and high-elevation (channel levee) communities, including *C. antiquorum, Polygonum* species, and trees, and to determine areas of change from low-elevation communities (*N. lutea, P. nodosus,* other SAV, and water) to the mid- and high-elevation communities. The Landsat 5 TM–derived maps were used to determine areas of elevation change within the low-elevation communities. For both WV-2 and Landsat 5 TM analyses, grid cells that converted from a lower-elevation species or class to a higher-elevation species or class were assigned to the "elevation gain" class. Grid cells that converted from a higher-elevation species or class to a lower-elevation species or class were assigned to the "elevation loss" class. Grid cells where the vegetation classification did not change or changed to another species within the same elevation group (*e.g.*, *P. nodosus* to the "other SAV" class) were assigned to the "no change" class. The results of the WV-2 and Landsat 5 TM analyses were merged to create an overall map of areas that experienced elevation change following the 2011 flood.

June and August 2011 Landsat 5 TM images were compared to qualitatively account for seasonal variation in plant community distributions that may have affected the results of the vegetation change analysis. The phenology of many plant species in the delta is influenced by timing of recession of the spring flood, which was later in 2011 than in 2010. Such seasonal variation may influence the area of some species independent of elevation changes that may have occurred. Also, many of the plants are rhizomous species that spread continuously throughout the growing season after the annual flood recedes, resulting in areal coverage that is greater in the fall than in the early summer.

Validation of Vegetation and Predicted Elevation Changes

Failure of the Landsat 5 TM satellite in November 2011 prevented the acquisition of comparable imagery to monitor the vegetation changes in the delta during the second growing season following the 2011 flood. To compensate, species percent cover data were collected for 16 randomly generated plots on one island in the delta in July 2012 to determine the permanence of the vegetation changes mapped from the 2011 imagery. This field study was conducted on Pintail Island, a generally NW-SE-oriented island on the eastern side of the delta (Figure 3). Navigation to the sites in the field was accomplished using a Trimble GeoXH DGPS with submeter horizontal accuracy. At each site, percent cover values for all plant species were recorded on 5% intervals within a 1-m^2 plot centered on the point location.

Areas of predicted elevation change based on vegetation change were compared to existing pre- and postflood elevation data that has been collected in the Wax Lake Delta (C. Sasser amd G. Holm, unpublished data). The mean and variance of 2010–11 elevation change for plots mapped as elevation loss, elevation gain, and no change were compared using Student's t tests and ANOVA for the 30 plots that were located within the areas mapped for this study. Plots dominated by *Sagittaria* species were excluded because this class was not detectable in the June 2010 WV-2 image and was excluded from the elevation change study. Plots dominated by trees or open water that experienced no change from 2010 to 2011 were also excluded, because these classes could experience substantial elevation change without an associated vegetation change. For both the Pintail Island and the elevation data comparison, the number of usable plots was affected by cloud cover in the August 2011 Landsat 5 TM image. To increase the sample size, plots that fell within the clouded area were assigned 2010 and 2011 vegetation classes and a predicted elevation change class based on classification of June 2010 and June 2011 Landsat 5 TM imagery.

Finally, the impact of the 2008 Hurricanes Gustav and Ike on the distribution of *N. lutea* in the delta was assessed to determine whether expansion of this species following the 2011 flood represented a true flood effect or part of the species' longer-term recovery following these storms. Hurricane Gustav made landfall as a category 2 storm (167 km/h winds) approximately 90 km SE of the Wax Lake Delta on September 1, 2008, and it moved slowly in a W-NW direction across coastal Louisiana, passing just north of the Wax Lake Delta. The delta experienced a maximum storm surge of 1.6 m (NAVD88) as measured at the CRMS gauge in the delta (Coastal Protection and Restoration Authority of Louisiana, 2012). Hurricane Ike was another category 2 storm (176 km/h winds) that made landfall in Galveston, Texas, on September 13, 2008. It passed approximately 300 km to the south of the Wax Lake Delta in the Gulf of Mexico on September 12, 2008, and pushed a large surge of water into the delta, with a maximum depth of 2.5 m measured in the delta (Coastal Protection and Restoration Authority of Louisiana, 2012). Landsat 5 TM imagery taken after these storms on September 22, 2008, suggests that most vegetation in the delta was killed, possibly by pulses of saltwater pushed into the delta by one or both of these storms. Because there was no cloud-free imagery available between the two storms, it is impossible to separate their effects. It is also unknown how long the effect on the vegetation community persisted following the storms, but field observation suggested that *N. lutea* was particularly slow to recover. To test whether expansion of *N. lutea* following the 2011 flood was a result of continued recovery of this species to its pre-2008 distribution in the delta rather than the influence of the 2011 flood, a Landsat 5 TM image from July 28, 2008, was compared with the August 2010 and August 2011 imagery used for the flood analysis. Supervised classification of the July 2008 image was performed according to the same method used for the other dates. However, due to a lack of reference data for that date, training areas were developed based on visual interpretation of the Landsat 5 TM image, using the 2009 vegetation map as reference.

RESULTS

Change in the Vegetated Area of the Delta

The relationship between water level and land area in the Wax Lake Delta is best represented by a logarithmic function, where the increase in land area associated with a decrease in water level is larger at low water levels than at high water levels (Figure 3). The best-fit logarithmic model for 2010 was

$$\text{Area} = -9.459\ln(\text{water level}) + 32.468,$$

where water level is given in meters, relative to NAVD88, and delta area is given in square kilometers. The correlation coefficient for this model was 0.996. At a water level of 0.6 m, a 1-cm decrease in water level results in a 0.16-km^2 increase in land area. At 0.2 m, a 1-cm decrease in water level results in a 0.49-km^2 increase in land area. The best-fit logarithmic model for 2011 was

$$\text{Area} = -5.378\ln(\text{water level}) + 42.768.$$

The correlation coefficient for this model was 0.990. At a water level of 0.6 m, a 1-cm decrease in water level results in a 0.09-km^2 increase in land area. At 0.2 m, a 1-cm decrease in water level results in a 0.28-km^2 increase in land area.

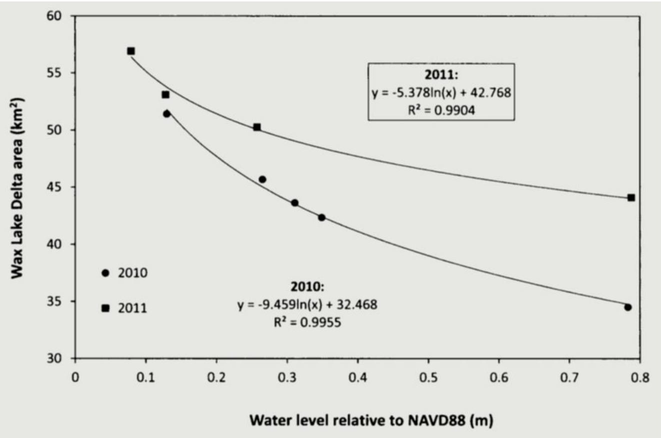

Figure 3. Relationship between water level and delta area before and after the 2011 Mississippi River flood.

The area measured by applying the NDVI threshold method to the WV-2 image was 79.86% of the area predicted at that water level using the 2010 Landsat 5 TM–based model. This percentage suggests that Landsat 5 TM–based classifications overestimate land area by about 25%. Using the two models and applying the 0.80 correction factor to account for Landsat 5 TM overestimation, we calculated that there was a 6.51-km^2 net increase in the vegetated area of the delta at mean water level (0.59 m above NAVD88, based on CRMS water level data from March 6, 2008, to August 23, 2012; Table 1). At mean sea level (0.36 m above NAVD88 at the tide gauge at Grand Isle), there was a 4.90-km^2 increase in land area. At 0.2 m above NAVD88 there was an increase of 2.98 km^2 and at 0.7 m above NAVD88 there was an increase of 7.06 km^2, representing the amount of land gain at the upper and lower ends, respectively, of the range of water levels used to construct the logarithmic models.

Figure 4 shows the spatial distribution of losses and gains based on a comparison of the August 27, 2010, and August 30, 2011, Landsat 5 TM images that were used for the vegetation change analysis. The water levels were 0.31 m above NAVD88 for the 2010 image and 0.26 m above NAVD88 for the 2011 image. Based on the 2011 equation, an increase in water level of 0.05 m would result in a 0.9-km^2 decrease in delta area due to water level variation. The spatial pattern of land gains is nonetheless apparent. Most land gain occurred within the distal island interiors. On the eastern half of the delta, deposition also occurred along the eastern side of the distributary channels. On the western half of the delta, channel deposition was less consistent, with most deposition occurring along both sides of the main island that splits flow at the river's mouth. Erosional losses were most common on the eastern half of the delta, where most channels experienced erosion along their western banks. Islands directly downstream of the river mouth and along the main distributary channel experienced erosion on both sides. Based on these two images, the delta gained 8.5 km^2 and lost 1.8 km^2 of vegetated land at a water level of 0.26 to 0.31 m above NAVD88. The net gain illustrated

Table 1. *Estimated growth of the Wax Lake Delta following the 2011 Mississippi River flood based on logarithmic models of mapped land area as a function of water level in 2010 and 2011.*

	Water Level (NAVD88, m)	2010 Area (km^2)[1]	2011 Area (km^2)[1]	Land Gain (km^2)
Low water	0.20	38.09	41.07	2.98
Mean sea level at Grand Isle, Louisiana	0.36	33.65	38.54	4.89
Mean water level in delta	0.59	29.91	36.42	6.51
High water	0.70	28.62	35.69	7.07

[1] Estimates corrected for Landsat 5 TM's overestimation of land area using a correction factor developed by comparing predicted land area to actual land area mapped using high-resolution WV-2 imagery.

in Figure 4 is 6.7 km^2 of vegetated land, of which 0.9 km^2 is attributable to water level variation between the two images.

Application of the NIR threshold method used by the USGS for coastal land loss analyses to the December 1, 2010, Landsat 5 TM image resulted in a land area estimate that was 70.6% of the predicted land area for that water level using our NDVI-based logarithmic model. Therefore, the growing-season NDVI method used in this study results in land area estimates that are approximately 40.4% greater those obtained using the NIR method. Application of the NDVI threshold method to the December 1, 2010, image resulted in a land area estimate that was only 6.6% greater than the NIR estimate, which indicates that the greatest source of variation between the two methods is the use of growing-season imagery, when floating-leaved vegetation and SAV are present throughout much of the delta.

Elevation Distributions

Histograms of the elevation distributions and mean elevations for each of the species used in the elevation change analyses are shown in Figure 5. The data show two clusters of species: a low-elevation group dominant from –0.2 to 0.4 m above NAVD88, which consisted of *P. nodosus,* other SAV, and *N. lutea,* and a high-elevation group dominant from about 0.4 to 0.9 m above NAVD88, which consisted of *Polygonum* species, *C. esculenta,* and *S. nigra*. The mean and common range, defined as plus or minus one standard deviation of elevation, for each species are listed in Table 2. This elevation-based zonation is illustrated in the conceptual vegetation change model in Figure 6. The Student's t test results indicate that mean elevations were significantly different for all pairs of neighboring species, and the ANOVA results indicate that between-group variance in elevation was significantly greater than the within-group variance for both low-elevation and high-elevation clusters (Table 3).

Patterns of Vegetation Community Change

Three of the six vegetation classes that we studied increased in distribution in 2011 compared to 2010: *P. nodosus, N. lutea,* and *C. esculenta*. Other SAV and *Polygonum* species decreased in distribution (Table 4). While the distribution of adult trees was fixed, a small area (0.03 km^2) of willow seedlings appeared following the flood in 2011. The greatest species distribution changes occurred for the species growing at the lowest elevations, with an increase in *P. nodosus* and *N. lutea* at the expense of the other SAV.

Table 5 provides additional detail on conversion between species that occurred from 2010 to 2011. The two SAV classes experienced the most change. Approximately 2.7 km^2 of *P. nodosus* and 0.5 km^2 of the other SAV converted to *N. lutea* following the flood. Some SAV beds also converted to open water following the flood: 2.6 km^2 for *P. nodosus* and 0.1 km^2 for the other SAV class. However, the area of open water that converted to SAV beds exceeded the area of SAV beds that converted to open water. These losses mostly occurred along the distributary channels that experienced erosion during the

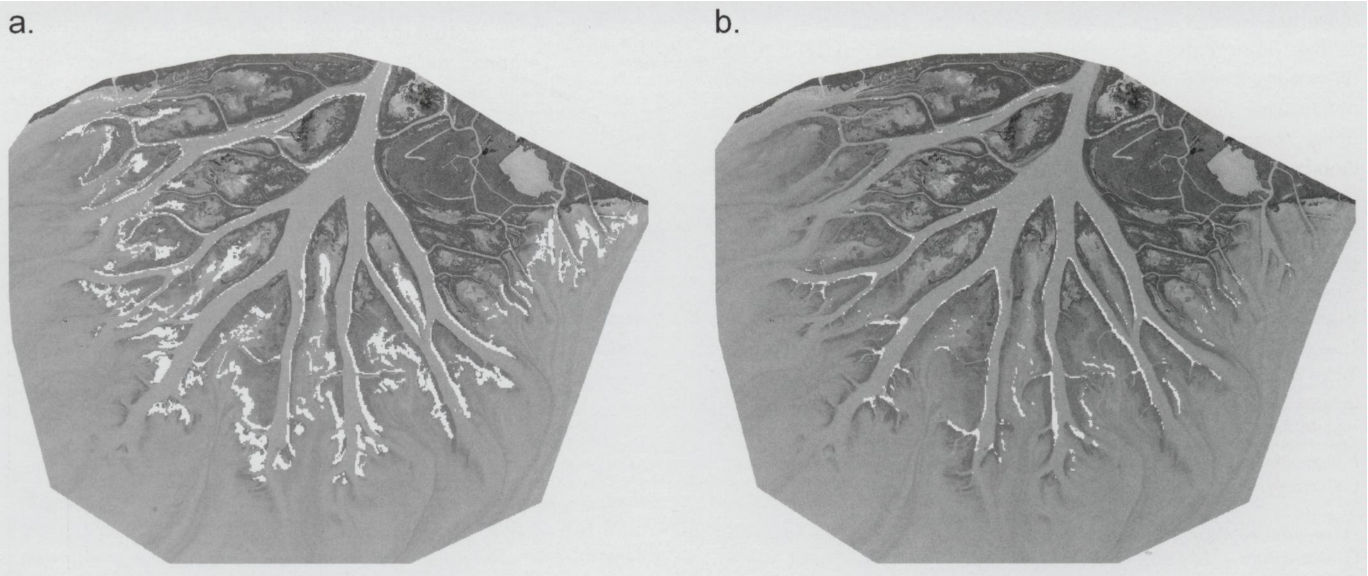

Figure 4. Spatial distribution of vegetated land gains and losses in the Wax Lake Delta following the 2011 Mississippi River flood: (a) gains and (b) losses.

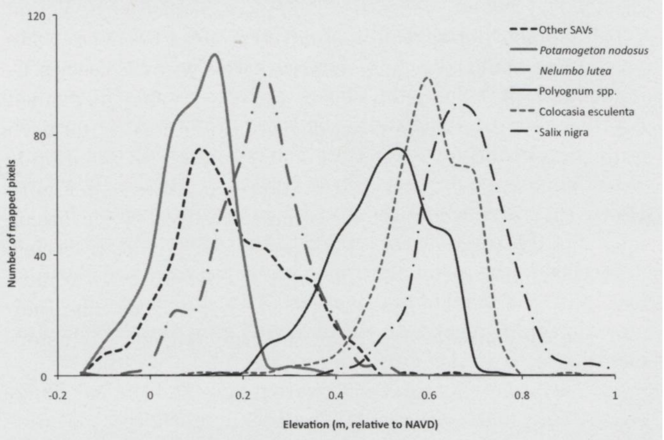

Figure 5. Elevation histograms for the six plant species used in the elevation-change analysis.

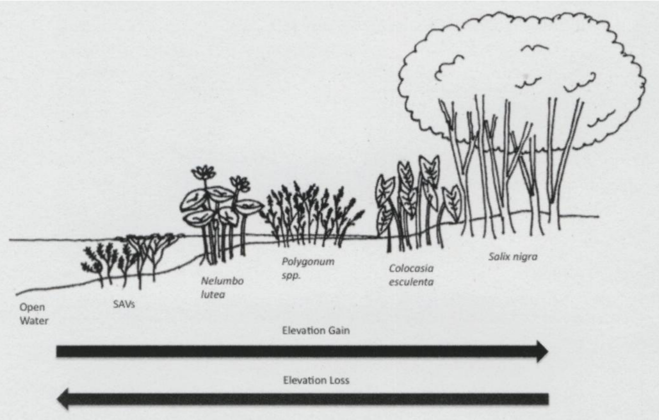

Figure 6. Conceptual model of vegetation community response to elevation change.

flood. While approximately 3.2 km^2 of lower-elevation classes converted to *N. lutea* in 2011, there was little change to areas where *N. lutea* was already dominant prior to the flood. The largest change was 0.5 km^2 that converted to *P. nodosus*. Most of this change occurred on one island, where a minor distributary channel appeared to shift location following the flood. The distribution of these vegetation changes is shown in Figure 7.

Among the high-elevation species, a substantial portion of the areas mapped as *Polygonum* species in 2010 were mapped as *C. esculenta* in 2011 (0.3 km^2 compared to 0.5 km^2 that remained as *Polygonum* spp.). While there was a small amount of conversion of *C. esculenta* to *Polygonum* species (less than 0.1 km^2), most of the change favored the expansion of *C. esculenta*. Examples of these changes are shown in Figure 8.

Overall, 8.7 km^2, or about 31.8%, of the area studied converted from a lower-elevation class to a higher-elevation class between 2010 and 2011 (Table 6 and Figure 9). About 12.8% (3.4 km^2) of the area studied converted from a higher-elevation class to a lower-elevation class and 55.5% (15.2 km^2) of the area remained unchanged. An additional 19.5 km^2 of the delta were excluded from the vegetation change study due to cloud cover or poor mapping accuracy, and the elevation change class for these areas is unknown. Areas that were classified as elevation gain were generally located within the island interiors, with more potential elevation gain mapped on the western side of the delta than on the eastern side of the delta. Figure 7b indicates that there are a few areas of potential elevation loss at the northern end of the delta. These are areas that were mapped as *N. lutea* in 2010 but mapped as *P. nodosus* in 2011. Further investigation would be required to determine whether this vegetation conversion was a result of true elevation loss versus flood stress (Hall and Penfound, 1944) or a function of the life cycle of the aging *N. lutea* stands (Whyte, Francko, and Klarer, 1997).

Table 2. *Elevation distribution characteristics of vegetation classes.*

Vegetation Class	Mean Elevation (m)[1]	±1 Standard Deviation (m)
P. nodosus	0.07	−0.01–0.15
Other SAV	0.15	0.02–0.28
N. lutea	0.21	0.11–0.31
Polygonum spp.	0.47	0.37–0.57
C. esculenta	0.57	0.47–0.67
S. nigra	0.66	0.53–0.79

[1] Relative to NAVD88.

Validation of Vegetation and Predicted Elevation Changes

Vegetation class dominance in the 16 random plots visited on Pintail Island in July 2012 displayed 50.0% consistency with the postflood vegetation maps (Table 7). However, 81.3% of the sites were classified within the same elevation class or a higher-elevation class in 2012. The degree of consistency between the 2011 mapping data and the 2012 field data varied strongly by vegetation class. Seven of the eight sites that were mapped as *N. lutea* in 2011 were still dominated by that species when they were visited in the field in 2012. Four of the sites had also been mapped as *N. lutea* in 2010. Two additional plots converted to *N. lutea* from other classes between August 2011 and July 2012. The sample sizes for the other classes were too

Table 3. *Results of Student's t tests and ANOVA tests to determine statistical significance of elevation differences among plant species used in the elevation change analysis.*

Results	t Statistic	*p* Value	*F* Statistic	*p* Value
Student's t test				
S. nigra and *C. esculenta*	11.41	0.00		
C. esculenta and *Polygonum* spp.	13.29	0.00		
Polygonum spp. and *N. lutea*	37.00	0.00		
N. lutea and *P. nodosus*	21.94	0.00		
P. nodosus and other SAV	11.00	0.00		
ANOVA				
High-elevation cluster (*S. nigra, C. esculenta,* and *Polygonum* spp.)			279.12	0.00
Low-elevation cluster (*N. lutea, P. nodosus,* and other SAV)			182.74	0.00

Table 4. *Change in species areal coverage following the 2011 Mississippi River flood.*

Vegetation Class	2010 Area (km^2)	2011 Area (km^2)	Change (km^2)
Landsat 5 TM analysis			
P. nodosus	10.89	11.29	0.40
Other SAV	4.10	1.39	−2.71
N. lutea	5.75	9.52	3.77
WV-2 analysis			
Polygonum spp.	1.70	1.13	−0.57
C. esculenta	1.32	2.12	0.80
Trees	0.37	0.37	0
Willow seedlings	0	0.03	0.03

small to allow statistical analysis, but in general, they showed poor consistency between the 2011 mapping and the 2012 field data.

Analysis of the sites by predicted elevation change class shows that six of eight, or 75%, of the Pintail Island sample plots that were mapped as elevation gain remained dominated by the same vegetation class in 2012 as in 2011 or converted to a higher-elevation class in 2012. Only two of the sites, or 25%, reverted to a lower-elevation class 1 year following the flood. One of those sites was located along the channel at the distal end of the island, an area that was observed to experience substantial erosion during summer 2012. By contrast, all three sites that were mapped as elevation loss in 2011 were determined to be a higher-elevation class in the field in 2012 than what was mapped in 2011. There was no 2011 to 2012 vegetation change among the five sites that were mapped as no change.

Table 5. *2010–11 vegetation change in the Wax Lake Delta.*

2010 Class	2011 Class	Area (km^2)
P. nodosus	*P. nodosus*	5.36
	Other SAV	0.25
	N. lutea	2.68
	Open water	2.61
Other SAV	*P. nodosus*	2.18
	Other SAV	0.48
	N. lutea	1.20
	Polygonum spp.	0.02
	C. esculenta	0.02
	Open water	0.24
N. lutea	*P. nodosus*	0.52
	Algae-covered SAV	0.01
	Other SAV	0.01
	N. lutea	5.17
	Polygonum spp.	0.06
	C. esculenta	0.02
	Open water	0.04
Open water	*P. nodosus*	3.23
	Algae-covered SAV	0.36
	Other SAV	0.28
	N. lutea	0.47
	Polygonum spp.	0.02
	C. esculenta	0.01
Polygonum spp.	*Polygonum* spp.	0.51
	C. esculenta	0.31
	Trees	0.00
C. esculenta	*Polygonum* spp.	0.08
	C. esculenta	0.85
	Trees	0.00

Table 8 shows the results of ANOVA and Student's t tests performed using the field-derived elevation data for sites mapped as elevation gain, elevation loss, and no change. The ANOVA results suggest the between-group variance is not quite significantly greater than the within-group variance in elevation change for these three classes at the $p = 0.05$ level. However, pairwise one-tailed Student's t tests comparing the means of the three classes indicate that there is a significant difference in the mean elevation change between the elevation loss and the no change classes. The difference in mean elevation change between the elevation gain and the elevation loss classes was not quite significant, and the difference in mean elevation between the elevation gain and the no change classes was not significant. The mean measured elevation changes and sample sizes for each of the classes are also provided in Table 8.

Figure 10 shows the change in distribution of *N. lutea* following the 2011 Mississippi River flood relative to areas where the species was killed by Hurricanes Gustav and Ike in 2008. These results indicate that following the 2011 flood, *N. lutea* spread into 2.1 km^2 of the delta where it had not been prior to the flood or prior to the 2008 storms. Approximately 1.7 km^2 of *N. lutea* that was killed by the 2008 storms had not recovered by August 2011.

DISCUSSION

Growth of the vegetated surface of the delta following the 2011 flood was estimated to be 6.51 km^2 at mean water level in the delta and to be 4.90 km^2 at mean sea level as measured near Grand Isle. The 4.90-km^2 estimate at mean sea level is most consistent with methods that the USGS has used to measure land gains and losses elsewhere in coastal Louisiana. It is nearly five times the average growth rate of 1 km^2 per year that Allen *et al.* (2012) found over the period 1983–2010. It is also consistent with growth rates measured for the neighboring Atchafalaya Delta following the major Mississippi River floods of the 1970s. Using a similar approach that compares multitemporal Landsat 5 TM imagery and water level data, Rouse *et al.* (1978) estimated that approximately 4 km^2 of subaerial land and 7 km^2 of subaqueous land was formed in the Atchafalaya Delta following the 1975 flood. The Atchafalaya Delta received approximately 63% higher discharge during the 1975 flood than the discharge the Wax Lake Delta received during the 2011 flood (USGS, 2013). However, the main channel in the Atchafalaya Delta is dredged, which allows more sediment to bypass that delta (Van Heerden and Roberts, 1980).

Land gains occurred mostly at the end of the distributary channels and the distal interior of the islands, which is consistent with the depositional patterns observed on a smaller scale within crevasse splays in the Mississippi River Delta (Coleman and Gagliano, 1964; Coleman, Gagliano, and Webb, 1964). Sand deposition during flood events occurs at the mouth of the distributary channels where they extend into the bay, contributing to the formation of new channel mouth bars and further bifurcation of the distributary channel network. When floodwaters overflow the channel

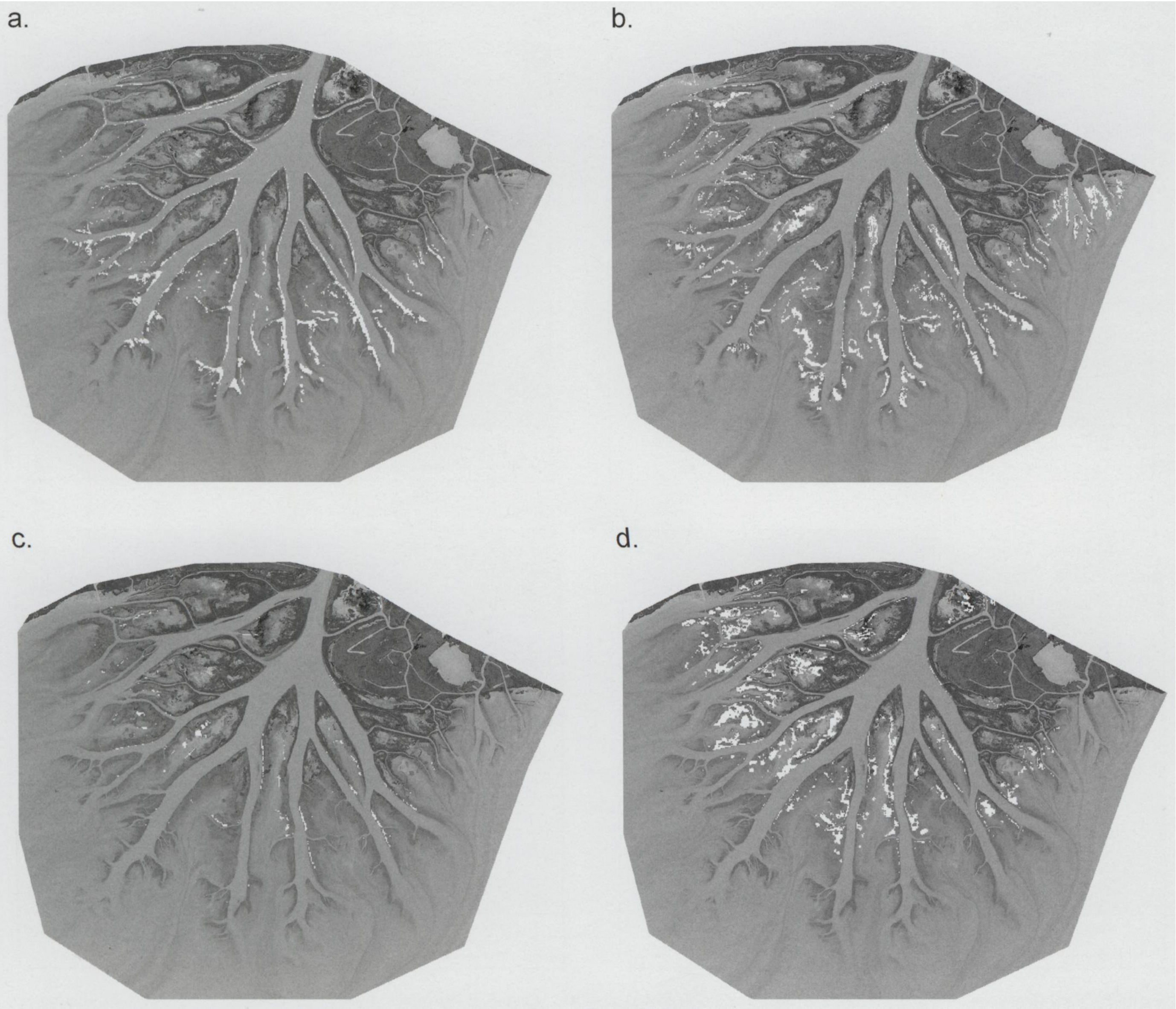

Figure 7. Vegetation change in low-elevation areas of the delta (shown in white). (a) Conversion from vegetation to open water. (b) Conversion from water to SAV (*P. nodosus* or other SAV), (c) Conversion from open water to *N. lutea*. (d) Conversion from SAV to *N. lutea*.

levees and spill into the island interiors, course sediments are deposited on or near the levees and progressively finer sediments are deposited in the interdistributary basins. The pattern of shoaling and erosion along the distributary channel banks is evidence of how flow is concentrated in the primary distributary channel during high-flow events. The channels on the western side of the delta, particularly those in the NW section, appear to be in the process of being abandoned in favor of more efficient channels in the central and eastern parts of the delta. This is the oldest part of the delta, and abandonment of these channels over time is consistent with the simplification of the distributary channel network over time that has been observed in the neighboring Atchafalaya Delta (Van Heerden and Roberts, 1988).

The total land areas presented here are much smaller than those presented by FitzGerald (1998) and further referenced by Roberts (1998) and Roberts *et al.* (2003). FitzGerald used a terrain model derived from U.S. Army Corps of Engineers bathymetry and land elevation data to estimate the areal footprint of the delta above –0.6 m NGVD29, which equates to –0.514 m NAVD88. This reference elevation is below mean low water (0.003 m NAVD88 at the Grand Isle gauge), which defines the extent of the subaerial delta (Wright, 1985), and well below the range of water levels common in the Wax Lake

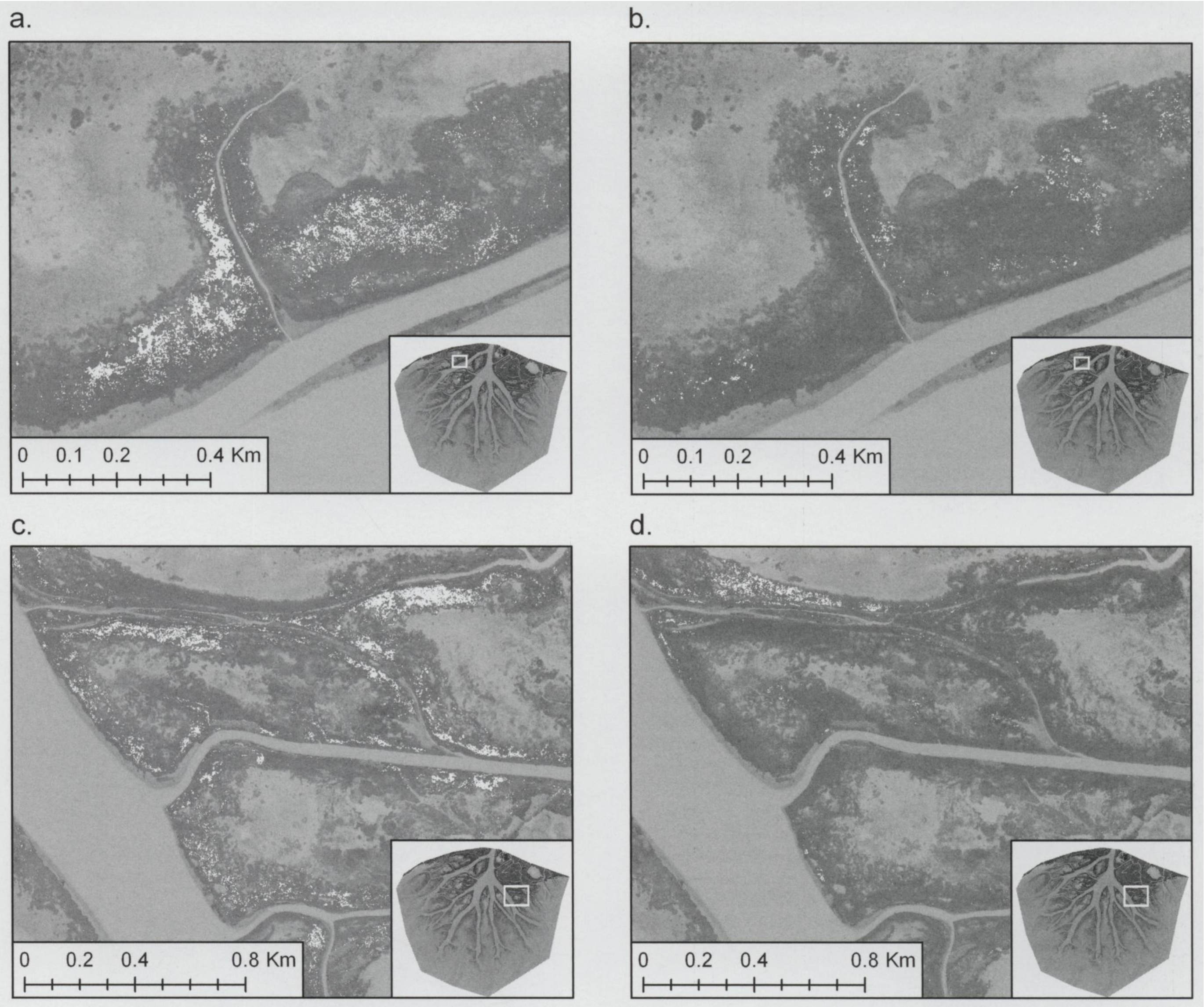

Figure 8. Vegetation change in high-elevation areas of the delta (shown in white). (a) and (c) Conversion from *Polygonum* spp. to *C. esculenta*. (b) and (d) Conversion from *C. esculenta* to *Polygonum* spp.

Delta due to the strong influence of river flow. The average water level recorded at the CRMS station at Wax Lake Delta from March 2008 through August 2012 was 0.59 m, and the minimum was –0.15 m (NAVD88; Coastal Protection and Restoration Authority of Louisiana, 2012). It is therefore unsurprising that the land area we observed was far less than that predicted by FitzGerald's model. Results from this study represent change in the vegetated area of the delta, which is less than the full subaerial delta that is exposed at mean low tide but is also easier to repeatedly measure using satellite data and of greater ecological significance.

Table 6. *Estimated area of the Wax Lake Delta experiencing elevation gains and losses following the 2011 Mississippi River flood based on vegetation community change.*

Change Class	Area (km^2)
Elevation loss	3.5
Elevation gain	8.7
No change	15.2
Unknown	19.5

Our species elevation model results demonstrate a clear separation of plant species in the delta along the elevation gradient but also show substantial overlap in the realized elevational niches of neighboring species. This finding is consistent with the continuum theory of plant community development, which suggests that plant species distributions are a function of an individual plant species' tolerance to a

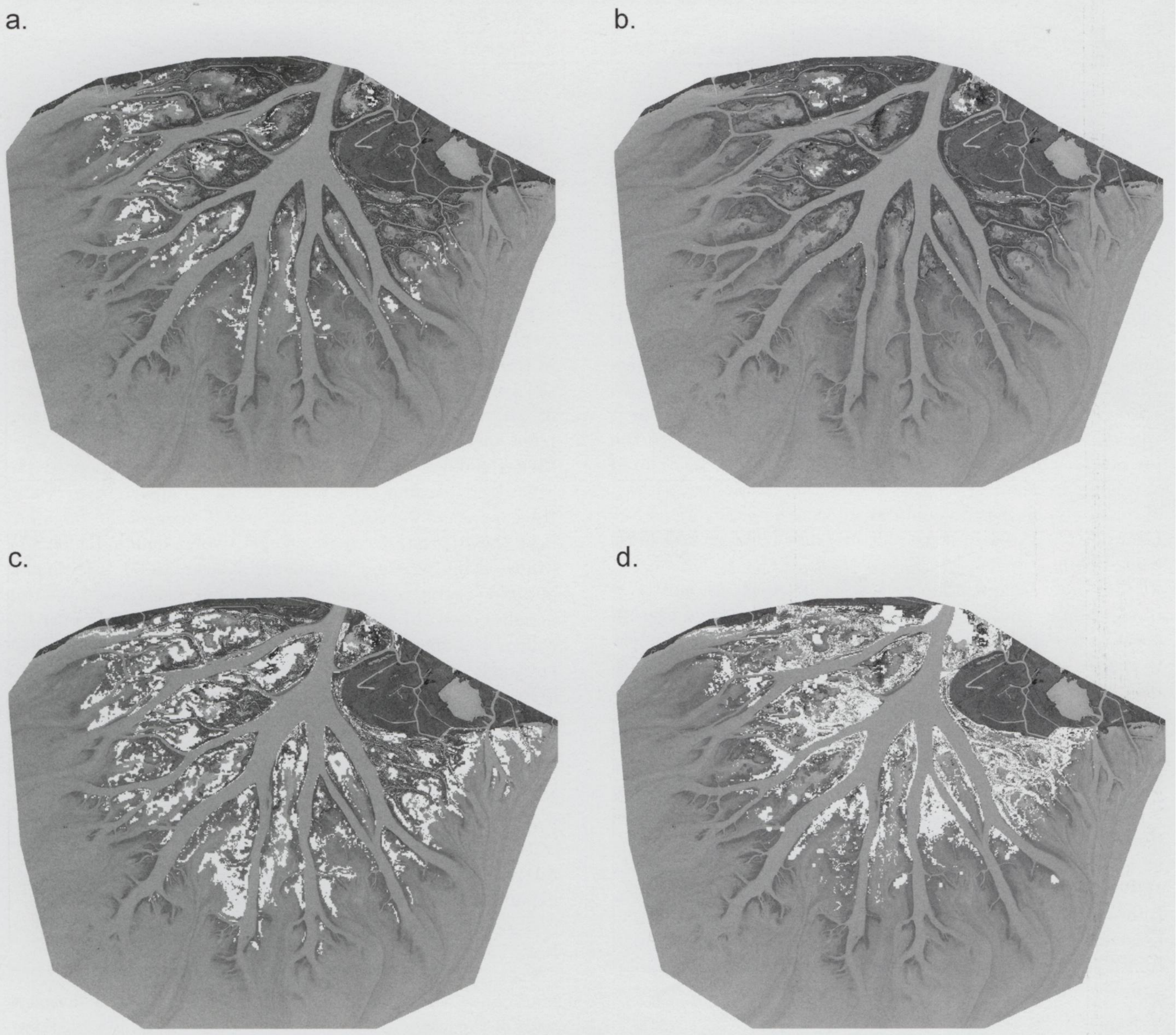

Figure 9. Vegetation change following the 2011 Mississippi River flood as related to species mean elevation (shown in white). (a) Change from lower- to higher-elevation species. (b) Change from higher- to lower-elevation species. (c) No change. (d) Unknown.

specific range of environmental conditions and competition between species in areas where their actual or "fundamental" niches overlap (Austin and Smith, 1989; Gleason, 1926; Keddy, 1990; Whittaker, 1967). Elevation is not a direct environmental gradient but rather a proxy gradient representing a combination of the frequency, depth, and duration of flooding at different elevations (Austin and Smith, 1989). While prior research has indicated that these direct hydrologic variables are better predictors of plant species distributions (Baldwin, Egnotovich, and Clarke, 2001; Casanova and Brock, 2000; Goslee, Brooks, and Cole, 1997), they are difficult to directly measure on the landscape scale. This study demonstrates that elevation can be an effective proxy variable for the landscape-scale analysis of wetland species distributions.

The two distinct clusters of species evident in Figure 5 represent those areas where the vegetation grows in nearly monotypic communities at the lower and the higher ends of the elevation gradient. The intermediate elevation communities tend to be more species rich and therefore are more difficult to map to the species level with high accuracy. Improved accuracy for these classes might be achieved through training for additional minor and subdominant species, fuzzy classification (Foody, 1996; Wang, 1990), or inclusion of one or more "mixed" classes. The greater diversity in this intermediate elevation

Table 7. *Error matrix comparing 2011 mapped vegetation classes with 2012 field data for 11 reference plots on Pintail Island.*

	2012 Field Data						
	Open water	*P. nodosus*	Other SAV	*N. lutea*	*Polygonum* spp.	*C. esculenta*	Total
2011 Mapped Data							
Open water	0	0	0	1	0	0	1
P. nodosus	1	1	1	0	0	0	3
Other SAV	1	0	0	1	0	0	2
N. lutea	1	0	0	7	0	0	8
Polygonum spp.	0	0	0	0	0	2	2
C. esculenta	0	0	0	0	0	0	0
Total	3	1	1	9	0	2	16
Overall 2010–11 agreement (%)							50.00
Same or higher-elevation group (%)							81.25

zone is consistent with the intermediate disturbance hypothesis, which states that diversity is highest in areas with intermediate disturbance or stress (Connell, 1978; Grime, 1973; Huston, 1979). Along the natural channel levees, *C. esculenta* and especially *S. nigra* outcompete less dominant species for light resources. There is less competition at the lowest elevations because fewer species are capable of surviving frequent or lengthy inundation. A similar pattern of maximum species diversity at intermediate elevations has been demonstrated in some salt marshes (Hacker and Bertness, 1999).

Many other factors influence species distributions, mostly by influencing the outcome of competition in the zone of overlap between two or more species' fundamental niche. Other factors that are known to influence plant competitive dominance include plant growth strategy (Huston and Smith, 1987), phenology relative to interannual climate fluctuations (Bazzaz, 1990; Harper, 1974), differential predation (Evers, Sasser, and Gosselink, 1998; Gough and Grace, 1998), variation in plant dispersal mechanisms and germination requirements (Grubb, 1977), differential species response to disturbance events (Bertness and Ellison, 1987; Holm and Sasser, 2001), and efficiency of plant resource use (Bazzaz, 1997; Chapin *et al.*, 1987; Levine, Brewer, and Bertness, 1998; Tilman, 1988). Interannual variability in these factors can affect the outcome of competition, resulting in species distributions that change from 1 year to the next independent of changes in elevation at a site. We must therefore take care when interpreting changes that occur from 1 year to the next and hence refer to areas that experienced change from a lower to a higher elevation class as areas of potential elevation change. Longer-term monitoring would be necessary to determine whether the changes observed in this study represent a permanent shift in species distributions or are a function of interannual variability in the outcome of interspecific competition within overlapping elevational plant species niches.

Table 8. *Results of Student's t tests and ANOVA tests for difference in mean and variance of 2010–11 elevation change for transect sites mapped as each of the elevation change classes (elevation gain, elevation loss, and no change) based on vegetation changes following the 2011 Mississippi River flood.*

Elevation Change Class	No. Plots	Mean Elevation Change (cm)
Elevation gain class	4	4.08
Elevation loss class	8	−4.57
No change class	18	4.26
Statistical Test	Test Statistic	*p* Value
ANOVA	3.29	0.053
Student's t test		
Elevation gain *vs.* elevation loss	2.28	0.053
Elevation gain *vs.* no change	0.10	0.46
Elevation loss *vs.* no change	3.40	0.002

Of the lower-elevation species, *N. lutea* experienced the greatest expansion, with much of this expansion occurring at the expense of the SAV, particularly *P. nodosus*. *N. lutea* has been shown to be effective at competitively excluding some SAV (Snow, 2000; Whyte, Francko, and Klarer, 1997). It is capable of rapid vegetative expansion by rhizome, with one study citing a radial outward expansion rate of more than 13 m over the course of a single growing season (Hall and Penfound, 1944; Heritage, 1895). While the distribution of this species in the delta was greatly reduced following Hurricanes Gustav and Ike in 2008, our analysis indicates that it had recovered to most of its pre-2008 distribution by 2010. Following the 2011 Mississippi River flood, the species expanded into many areas that had been open water or dominated by SAV species in prior years. While there are some islands, mostly on the eastern side of the delta, where *N. lutea* has never regained its pre-2008 distribution, it is clear from this analysis that the deltawide expansion of this species measured in 2011 represents a genuine change compared to its previous maximum distribution.

Potential elevation gain as indicated by shifts in plant species dominance was most common in the middle and downstream ends of the island interiors. Deposition in these interdistributary basins generally consists mostly of fine silts and clays, because most of the sand load is deposited along the subaqueous and subaerial natural channel levees (Coleman, Gagliano, and Webb, 1964; Van Heerden and Roberts, 1988). Fine sediment deposition occurs when floods recede slowly, allowing the finer sediments to become trapped in backwater areas (Asselman and Middelkoop, 1998). The hydrograph from the USGS monitoring station at the Wax Lake Outlet shows that while the river stage initially dropped quickly from 3.3 m on May 29, 2011, to 1.5 m by the end of June 2011, the Wax Lake Outlet did not reach its historic average monthly stage until mid-August of that year (USGS, 2013). Likewise, data from the CRMS site at Wax Lake Delta indicate that the water level in the marsh remained more than 0.3 m above the marsh surface from May 10 to June 24 (55 days; Coastal Protection and Restoration Authority of Louisiana, 2012). Water may

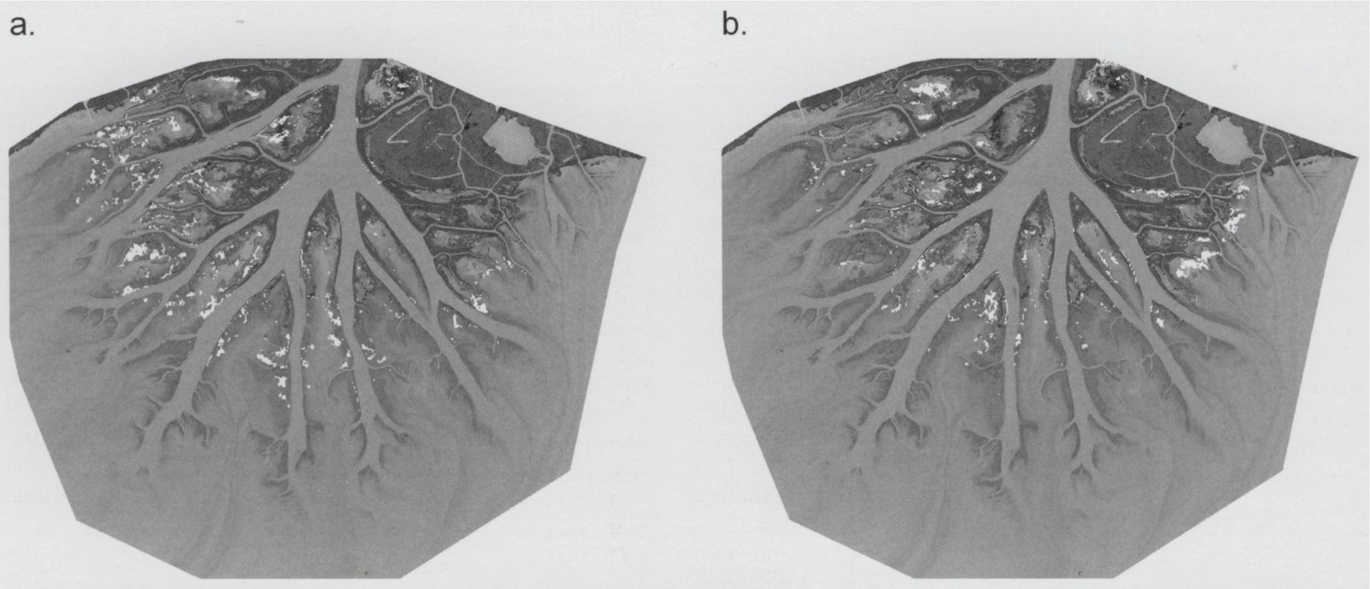

Figure 10. Change in the distribution of *N. lutea* related to disturbance by Hurricanes Gustav and Ike (2008) and the 2011 Mississippi River flood. (a) Expansion of *N. lutea* from 2010 to 2011 into areas where it was not found prior to the 2008 hurricanes. (b) Areas mapped as *N. lutea* prior to Hurricanes Gustav and Ike that had not recovered by August 2011.

have been trapped within the islands for an even longer period, facilitating deposition of finer sediments in these areas.

Most of the mapped potential elevation gain occurred on the western side of the delta, particularly in the older NW corner of the delta. This is consistent with the gradual abandonment of the older area of the delta and its less efficient distributary channels in favor of the younger channels on the eastern side of the delta. As flow diminishes in older channels, more deposition occurs, both as shoaling within the channel and as deposition in the island interiors that receive overflow from the channels. The minor distributary channels decrease in width and flow volume, and the individual deltaic islands, or lobes, eventually fuse together to form a single lobe. This is the same process that Van Heerden and Roberts (1980) observed with the abandonment of the eastern half of the Atchafalaya Delta, which was enhanced by dredging of the main channel.

It is likely that this plant species model underestimates the area of the delta that experienced elevation gains, particularly at intermediate and high elevations. First, some areas of the delta were excluded from the analysis due to poor map accuracy or cloud cover in one or more of the images. The elevation change status of these areas is unknown. Also, the field elevation data indicate that substantial sedimentation occurred along the upstream ends of the islands, particularly on the channel levees. However, these areas are dominated by trees *(S. nigra),* and an immediate shift in plant species dominance would not be expected despite substantial sediment deposition. Even within the levee zone dominated by *C. esculenta,* it is unlikely that an increase in elevation would result in *S. nigra* dominance, because *S. nigra* germinates best on newly exposed land with little competition (Ahn *et al.,* 2007; Gage and Cooper, 2004; Karrenberg, Edwards, and Kollmann, 2002). The specific germination requirements probably explain some of the overlap between its elevational niche and that of *C. esculenta,* because *C. esculenta* may prevent germination of *S. nigra* seedlings if it establishes first. Finally, most of the vegetation change observed in this study occurred at low elevations. It is possible that the response of the intermediate- and high-elevation plant communities to a change in elevation is slower than that of the low-elevation community and that more than 1 year of observation is needed to detect a change. Further monitoring of these communities for several years will provide a better indication of the degree of vegetation community change initiated by the flood event.

Comparison of the 2010 and 2011 models for land area as a function of water level supports the assertion that vegetation community changes underestimate the total area of the delta that experienced vertical accretion. More land gain was observed at higher water levels, indicating substantial accretion across the portions of the delta that were already above sea level, with less accretion occurring below sea level. This is the opposite of what Rouse *et al.* (1978) noted following the 1973 and 1975 floods and may be a function of the aging of the delta.

These observations are further supported by comparison to the pre- and postflood elevation data from the delta, which also suggest that the area mapped as elevation gain underestimates the true extent of vertical accretion across the subaerial delta. The mean elevation change for plots mapped as the no change class was positive and similar in magnitude to the mean elevation change for plots mapped as the elevation gain class. The mean was strongly influenced by two SAV sites that experienced greater than 20 cm of elevation change following the flood without a change in vegetation class. Plot-level vegetation survey data indicate partial conversion from *P. nodosus* to open mudflat, so it is likely that these outlier plots represent fine-scale variation in sedimentation pattern that cannot be detected at the 30-m mapping scale.

Comparison of the areas of mapped potential elevation change to the field measurements of elevation change from 2010 to 2011 supports the hypothesis that much of the vegetation change that occurred from 2010 to 2011 is related to elevation change. Areas mapped as elevation gain had a positive mean elevation gain, and areas mapped as elevation loss had a negative mean elevation gain, although the difference in the mean elevation of the two classes was not quite significant. This lack of significance is likely due to the small sample size of sites located within the area mapped as elevation gain. While the elevation measurements were made predominantly on the upstream ends of the islands, most of the mapped elevation gain occurred at the downstream end of the island interiors. Additional measurements at the distal ends of the islands are needed to fully capture the spatial variability in sedimentation pattern.

CONCLUSIONS

The results of this study indicate that the vegetated surface of the Wax Lake Delta grew by 4.9 km^2 from 33.6 to 38.5 km^2 at mean sea level following the historic Mississippi River flood of 2011 and that the vegetation community shifted from lower- to higher-elevation species across 8.7 km^2, or 31.8%, of the area studied. Most vegetation community change occurred among low-elevation classes, with an increase in the distribution of the floating-leaved *P. nodosus,* and the emergent *N. lutea* at the expense of other SAV. Less vegetation change was observed among higher-elevation classes, and additional monitoring is needed to determine whether less elevation change occurred at intermediate to high elevations or whether the species that grow in these areas respond more slowly to changes in elevation than do the species that grow at low elevations. The greater increase in delta area that occurred at higher water levels suggests that substantial vertical accretion occurred across these mid- to high-elevation areas, and reflects the role that the established plant community plays in trapping and stabilizing new sediments and minimizing future erosion by marine processes.

The increase in the vegetated area of the delta observed in this study is comparable to the growth of the delta observed following the large Mississippi River flood events in the 1970s. These results reinforce the importance of extreme flood events in providing large pulses of sediment to maintain the elevation of river deltas faced by rapid subsidence and sea level rise. They have particularly important implications for restoration of the Mississippi River Delta, where, throughout most of the historic deltaic plain, floodwaters are prevented from reaching deltaic marshes through an extensive levee and containment system. While approximately 11% of the historic 2011 Mississippi River flood passed through the Wax Lake Delta and contributed to the vegetated land and elevation gains observed in this study, up to 60% of the floodwaters bypassed the deltaic plain entirely and entered directly into the Gulf of Mexico. In a sediment-starved delta that is cut off from its river and undergoing rapid subsidence and land loss, this unretained sediment represents a missed opportunity for coastal restoration and highlights the need to implement large-scale diversions to reconnect the river to its delta before the next major flood event.

As a naturally evolving young river delta and one of only a few areas where the Mississippi River is actively building new land, the Wax Lake Delta provides insights into how the greatly modified Mississippi River Delta may have behaved under natural conditions. As a continuously operated large-scale river diversion, it serves as a reference system for other river diversions of a similar scale emptying into shallow coastal embayments such as Atchafalaya Bay. The actual rate of land building for new diversion will depend on the unique combination of sediment discharge, retention rate, and available accommodation space of the system in question. Nonetheless, this study indicates that such diversions function not only to build new land but also to increase the elevation of existing marshes and that monitoring the success of future projects should include both criteria.

Finally, the landscape-scale monitoring method demonstrated by this project can provide a cost-effective means to monitor the progress of large-scale coastal restoration projects. Elevation change is difficult to assess at the landscape level due to the practical limitations of large-scale *in situ* monitoring projects and the high cost of repeat acquisition of fine-resolution LIDAR. Mapping vegetation community change over time, combined with the known elevation ranges of specific species, can assist managers in scaling up *in situ* measurements of coastal sedimentation and vertical accretion and can provide more robust monitoring of elevation change over time across large coastal landscapes.

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