

2013

Spatial structure and dynamics of the plant communities in a pro-grading river delta : Wax Lake Delta, Atchafalaya Bay, Louisiana

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SPATIAL STRUCTURE AND DYNAMICS OF THE PLANT COMMUNITIES
IN A PRO-GRADING RIVER DELTA:
WAX LAKE DELTA, ATCHAFALAYA BAY, LOUISIANA

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Oceanography and Coastal Sciences

by
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December 2013

ACKNOWLEDGEMENTS

This project would not have been possible without the support of numerous individuals over the past four years. First and foremost, I would like to thank my advisor, Dr. Charles Sasser, for believing in this project and assisting me throughout the entire process of turning it into a reality. I would also like to thank Dr. Robert Twilley, who first opened the door for this research and helped me to sketch out and better define my dissertation goals. I am also grateful for the expertise and guidance provided by the other members of my committee, Dr. Harry Roberts and Dr. Lei Wang and to my Dean's Representative, Max Conrad, for bringing his unique perspective to our discussions. I am also indebted to Brian Milan for his help coordinating field work and for assistance during many long days in the field, to Elaine Hebert for assistance with image interpretation, and to Azure Bevington, for assisting with logistics and sharing her knowledge of the Wax Lake Delta.

During my time at Louisiana State University, I have been fortunate to be supported by a Board of Regents Fellowship, which was instrumental in allowing me to design and pursue this research project. I also received spatial data and support from the National Center for Earth-surface Dynamics (NCED) and from the Louisiana Coastal Protection and Restoration Authority (LCPRA). High resolution WorldView-2 imagery provided through the DigitalGlobe 8-Band Research Challenge greatly enhanced my dissertation research.

Finally, I am extremely thankful for the unending support provided by my family. I greatly appreciate the encouragement provided by my parents, Bobi and Shay Eddleman and Michael Vernon and by my in-laws, Thomas and Laureen Carle and by the entire Vernon and Carle clans. Above all, I am grateful for my husband, Timothy Carle, for agreeing to travel with me on this journey and for helping me juggle all the pieces of our busy lives over the past four years and I thank my children, Jacob, Aidan, and Sabrina, for helping me to remember to make time for laughter along the way.

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ABSTRACT

River deltas are dynamic depositional environments that are controlled to varying degrees by coastal and fluvial forces. Plant communities in deltas respond to many of the same allogenic forces that shape delta geomorphology. This study examines the factors that influence plant community development, productivity, and species distributions in the Wax Lake delta, a young, actively pro-grading river delta in coastal Louisiana, USA. A species distribution map created using high-resolution 8-band WorldView-2 imagery was found to have an overall accuracy of 75 percent. Classification tree analysis suggested that most of the observed variation in plant species distributions within the delta can be explained by variables related to flooding, riverine and tidal flushing, soil development, ecological succession, and exposure. This full model explained 65 percent of the spatial variability, compared to 54 percent explained by elevation alone, indicating that elevation is the most important driver of species distributions in this deltaic system. Analysis of a time series of NDVI data derived from 94 Landsat images from 1973 to 2011 suggests that both total and mean plant community productivity within the delta has increased over time and that seasonal fluctuations occur that are related to water temperature and discharge. While significant short-term decreases in NDVI were found following five major storm events, in each case, total and mean NDVI recovered to within the 95 percent prediction interval of the long-term trend by the following growing season. Following the historic 2011 Mississippi River flood, the area of the delta increased by nearly 5 km². Greater increases in delta area occurred at higher water levels, suggesting substantial vertical accretion across much of the subaerial delta. The plant community responded to this vertical accretion by shifting to higher elevation species across nearly 9 km² of the delta. Overall, these results indicate that the plant community in the Wax Lake delta is largely driven by allogenic factors related to delta geomorphology and is increasing in productivity as the delta continues to accrete over time. The marshes in the delta show great resilience to storm disturbance, and a strong response to allogenic succession driven by extreme flood events.

CHAPTER 1 – PLANTS IN DELTAIC ENVIRONMENTS: A SYNTHESIS

Plants are important components of river deltas that at once influence and are influenced by physical processes. On the one hand, climate, geomorphology, and the physical and chemical stresses of the deltaic environment control plant community composition and species distributions within the delta (Cahoon et al. 2011; Johnson et al. 1985; White 1993). On the other hand, plants influence the geomorphology of deltas and the rate of land-building by trapping sediments with their roots, resisting erosion, and contributing organic matter to the sediment, impacting both the rate of vertical accretion and sediment structure and cohesion (Beeson and Doyle 1995; Cahoon et al. 2011; Day et al. 2008; Edmonds and Slingerland 2009; Galloway 1975; Lorenzo-Trueba et al. 2012; Marani et al. 2013; Nyman et al. 1990; Paola et al. 2011; Rosen and Xu 2013; Turner et al. 2000; White 1993). While the factors controlling plant species distributions in other coastal environments has been reviewed elsewhere (eg. Bertness and Pennings 2000; Odum 1988), there has been little attention to plant distributions in deltaic systems. River deltas differ from other coastal settings in that they have large riverine inputs of freshwater, nutrients, and terrigenous sediment, whereas other estuarine environments are more strongly influenced by marine inputs. These riverine inputs result in rates of geomorphic change that are more rapid than those experienced by other coastal settings and have important implications for the physical factors to which plants in river deltas must adapt. As a result, plant communities in river deltas can differ substantially from plant communities in other coastal areas, both in terms of their species composition and spatial pattern and dynamics.

River deltas are ephemeral landscape features that occur throughout the world wherever a river delivers sediment eroded from its basin to the coast faster than it is eroded away by marine forces (Day and Giosan 2008; Wright 1985). Over geologic time scales, deltaic geomorphology is determined by the interplay of the riverine forces that deliver sediment and freshwater to coastlines, marine forces such as waves, tides, and coastal storm events that erode and re-work the riverine sediment deposits, and subsidence related to the dewatering and compaction of sediments and isostatic sediment loading (Blum et al. 2008; Meckel et al. 2006; Morton and Bernier 2010; Törnqvist et al. 2008; Wright and Coleman 1973; Yuill et al. 2009). However, at the ecological time scales that are relevant to the development of deltaic marshes, marsh plants have the potential to modify their physical environment by promoting vertical accretion and even maintaining elevation within their tolerance range (Corenblit et al. 2007; Gurnell et al. 2012; Marani et al. 2013). Because the degree to which plants perform these functions varies by species (Li and Yang 2009; Nyman et al. 1995; Rooth et al. 2003), the composition of deltaic plant communities and the spatial distribution of individual species has the potential to impact the physical development of the marsh surface.

While models have been developed to predict the physical processes that control river delta formation and development (Kim et al. 2009; Paola et al. 2011), there have been only limited attempts to incorporate the role of the plant community. This is in part due to limited knowledge about the factors that control plant species distributions in deltaic environments and the feedbacks that exist between the vegetation community and deltaic sedimentary processes. Here, an overview of what is currently known about the factors that control plant community pattern in river deltas is provided, drawing both from vegetation studies that have been performed in deltaic settings around the world and making inferences based on the extensive work that has been done in other coastal and riverine systems.

GENERAL FACTORS CONTROLLING PLANT SPECIES DISTRIBUTIONS

At a general level, patterns of plant species dominance are controlled by a variety of factors, including physical environment gradients and ecological interactions among species. There are two primary theories that have been proposed to explain the distribution of plant communities in the natural environment. The first is the classical theory of succession put forward by Clements (1916), where the mosaic of plant communities across landscapes is seen as representing the variety of successional stages of a fairly small set of stable climax communities. Through the process of ecological succession, plants modify their environment and create the conditions for new plant species to invade and displace them. This process continues until a stable climax community develops that resists further plant community change, except by way of a catastrophic disturbance that re-sets the process of succession. The other theory is the continuum concept, based on the work of Gleason (1926), that sees plant communities as collections of species that each respond individually to environmental gradients such as altitude (Beals 1969), water and nutrient availability (Emery et al. 2001; Parrish and Bazzaz 1982), temperature (Franklin 1998; Pielou and Routledge 1976), salinity (Crain et al. 2004; Jiang et al. 2012; Latham et al. 1994), exposure (Wilson and Keddy 1986; Wilson and Keddy 1988) and flooding. Each species has both a fundamental niche, which refers to the range of environmental conditions under which it can ideally grow, and a realized niche, which refers to the range of environmental conditions under which it actually grows in natural settings. The realized niche is generally narrower than the fundamental niche, because each species is excluded from part of its ideal range by competition with other species (Austin and Smith 1989; Whittaker 1967). Far from being antithetical, each of these processes contributes to the formation of landscape pattern. Disturbance and subsequent successional variation occurring along temporal gradients is superimposed upon spatial environmental gradients at the landscape scale (Pickett 1976; White 1979).

Ultimately, the distribution of individual species depends both on their physiological tolerances and their ability to compete with other species for space, light, water, and nutrients within the physical limitations of any particular environmental setting and their ability to adapt to changes that occur in that setting over time (Bazzaz 1997; Chapin et al. 1987; Levine et al. 1998; Tilman 1988). No species is an inherently superior competitor in all settings (Huston and Smith 1987). Because plants are limited by the resources available to them and their ability to take up and store those resources, any energy that they expend exploiting one resource will necessarily result in less energy available to exploit other resources (Bazzaz 1997; Chapin et al. 1987; Huston and Smith 1987; Tilman 1988). Hence, a plant cannot simultaneously pursue strategies of rapid aboveground growth to exploit light resources, rapid belowground growth to exploit soil water and nutrient resources, prolific reproduction, stress tolerance, and defense against competitors and herbivores. Strategies that make a plant successful in one setting and against one set of competitors will be unsuccessful in other settings. In addition, other ecological interactions such as selective herbivory and facilitation can alter the competitive hierarchy and thus influence observed plant community patterns (Bertness and Callaway 1994; Louda et al. 1990; Stachowicz 2001).

The phenology of plant species in relation to seasonal and interannual climatic variability also impacts the observed distributions of plant species and often results in patterns of species

dominance that vary over numerous timescales. Because reproduction is energy-intensive, many plant species vary their seed production from year to year based on the favorability of environmental conditions to seed survival and germination (Grubb 1977; Harper 1974). The expression of plant community composition is then, to some degree, a function of the stochastic fluctuations in environmental conditions, including temperature, rainfall, and length of the growing season and the degree to which species' maximum seed production coincides with favorable conditions for germination and growth. The specific conditions required for seed production, dispersal, germination, establishment, and growth of young plants is referred to as a species' regeneration niche, a concept first proposed by Grubb (1977). The ability of any given plant species to successfully reproduce in any given year is related to annual variation in seed production and the availability of dispersal mechanisms, the timing of germination with respect to disturbance events and species-specific germination responses to climatic patterns (Grubb 1977). Species distribution patterns are also strongly influenced by seasonal changes, particularly in herbaceous systems, where otherwise competitive species can coexist at the same site by occupying different phenological niches, where they grow and reproduce at different times of the year (Bazzaz 1990; Grubb 1977). Plant community composition at a single site can, therefore, change dramatically throughout the course of the growing season.

Seed bank contents can also influence community composition patterns, but this is mostly true only in the early years of plant community development (Parker and Leck 1985). Seed banks are frequently dominated by the long-lived seeds of ruderal species that are adapted to exploit disturbed environments (Grime 1977; Harper 1974; Leck and Graveline 1979). These plants allocate a high percentage of their resources to seed production and have seeds that are capable of remaining dormant in the soil for many years awaiting a disturbance event that creates the proper conditions for germination and rapid growth. However, as ruderal species are not shade tolerant, they are usually poorly represented in mature plant communities. They may, however, exploit temporal windows early or late in the growing season in temperate climates when perennial dominants have not yet begun to regrow their aboveground structures or after they have already begun to senesce. This seasonal pattern of plant species dominance is superimposed upon spatial patterns to form complex plant communities that vary in both space and time.

Disturbance is another important factor influencing the spatial patterns observed in plant communities at both local and landscape scales (Bertness and Ellison 1987; Brewer et al. 1998; Turner 1989; Turner et al. 2003; White 1979). The degree to which species are adapted to withstand or even benefit from a particular type of disturbance influences their competitive dominance in environments where that disturbance is common (Brockway and Lewis 1997; Garren 1943; Sousa 1984). The frequency, size, and intensity of disturbance are all important in shaping landscapes (Connell and Slatyer 1977; Pickett et al. 1989; Romme et al. 1998; van der Maarel 1993). Infrequent, but large and high intensity disturbances can re-set the process of ecological succession and provide an opportunity for disturbance species to invade an otherwise mature ecosystem (Platt and Connell 2003). Small, less intense, but frequent, disturbances create conditions under which species specifically adapted to the disturbance can dominate indefinitely as long as the disturbance regime remains unchanged. One of the more commonly cited examples of plant community adaptation to frequent, low-intensity disturbance is the historic wide-spread distribution of fire-dependent longleaf pine savannas in the southeastern United States (Brockway and Lewis 1997; Garren 1943).

SPECIES DISTRIBUTIONS IN COASTAL ECOSYSTEMS

The interplay between environmental gradients and interspecific competition has been well studied in salt marshes, where the simultaneous stresses of salinity and flooding limit the number of species involved in the interactions and simplify the study of these processes. As a result, strong elevation-based zonation is common in salt marshes (Bertness and Ellison 1987; Eleuterius and Eleuterius 1979; Kershaw 1976; Pielou and Routledge 1976; Sánchez et al. 1996; Wilcox 2004). The distribution of species is commonly limited at lower elevations by each species' tolerance to flood stress and at higher elevations by competition with less flood-tolerant species (Bertness and Ellison 1987; Pielou and Routledge 1976). The best-studied example is the distribution of *Spartina alterniflora* in salt marshes in the eastern United States. *S. alterniflora* is the only species in eastern U.S. salt marshes that is capable of tolerating the frequent inundation by salt water that occurs in the low marsh environment (Bertness 1991). However, numerous transplant and greenhouse studies indicate that *S. alterniflora* actually grows as well or better at higher elevations, as long as competitors are removed (Bertness and Ellison 1987; Pennings et al. 2005). It is, therefore, competition with other plants that excludes *S. alterniflora* from the high marsh, limiting its ecological niche to the low marsh, where it thrives in the absence of competition. The outcome of such competitive interactions can be altered, however, by changes in nutrient availability, herbivory, facilitation, and climate (Bertness and Hacker 1994; Bertness and Pennings 2000; Bertness and Sumway 1993; Brewer et al. 1998; Levine et al. 1998; McKee and Patrick 1988; Pennings et al. 2003; Wesenbeeck et al. 2007). The limitation of species distributions by physical stress tolerance at lower elevations and by interspecific competition at higher elevations has also been observed for other salt marsh species (Snow and Vince 1984).

Similar mechanisms operate to control plant distributions along salinity gradients in estuarine environments. Salt-tolerant species commonly found in salt marshes have been demonstrated to grow as well or better in freshwater environments, when freshwater marsh competitors are removed (Crain et al. 2004). This finding suggests that plant distributions are limited on the high-salinity end of their distribution by their ability to tolerate salt and on the low-salinity end by their competitive ability. In general, competition pressures are much greater in low salinity environments due to greater species richness and zonation patterns are less conspicuous (Greiner la Peyre et al. 2001; Latham et al. 1994; Odum 1988; Pasternack and Brush 1998; Sharpe and Baldwin 2009). Because of the larger species pool, differential herbivory seems to play a stronger role in influencing species dominance in freshwater marshes than in salt marshes (Bromberg Gedan et al. 2009; Evers et al. 1998; Fuller et al. 1984; Grace and Ford 1996).

Disturbance is another important factor controlling species distributions in tidal freshwater marshes. In coastal freshwater marsh environments, plants are commonly exposed to multiple stressors, including flooding, herbivory, and salt intrusion caused by storm-surge events. While freshwater plants are generally able to recover from these stresses when they occur singly, simultaneous exposure to multiple stressors often results in reduced growth or death (Baldwin and Mendelssohn 1998; Gough and Grace 1998a; Grace and Ford 1996; Slocum and Mendelssohn 2008). Because some species are more tolerant of short-term pulses of salinity than others, the frequency and duration of disturbance events can be important drivers of plant community composition (Brewer and Grace 1990; Flynn et al. 1995; Holm and Sasser 2001; Howard and Mendelssohn 2000; McKee and Mendelssohn 1989). As seeds and seedlings are

typically more sensitive to stress than adult plants, environmental conditions during and immediately after germination can have a larger influence on species distributions than average conditions (Baldwin et al. 2001; Baldwin et al. 1996; Lenssen et al. 1998).

Seasonal variability is also an important component of tidal freshwater marshes. Most tidal freshwater marshes exhibit a seasonal succession of species. Perennial species often reach their peak biomass during the mid to late summer, while annual species are more dominant during the spring and early summer and in the fall after the perennials have begun to senesce (Doumlele 1981; Simpson et al. 1983). Unlike salt marshes, which are dominated by monotypic stands of perennial species that maintain aboveground biomass throughout the year, the community composition of tidal freshwater marshes changes throughout the growing season. Thus, species distributions are, in part, a factor of the time of year at which the marsh is observed. Perennials and annuals are also separated spatially. While perennials dominate the low marsh environment, annuals are usually limited to the high marsh and intermediate elevation zones (Hopfensperger and Engelhardt 2008; Simpson et al. 1983).

SPECIES DISTRIBUTIONS IN RIVERINE ECOSYSTEMS

The factors controlling species distributions in riparian systems have also been fairly well studied and reviewed in detail elsewhere (Bendix and Hupp 2000; Hupp 1988; Hupp and Osterkamp 1996). Within riparian systems, plant species distributions are closely associated with fluvial landforms and the hydrogeomorphic processes that form them (Francis 2006; Hupp and Osterkamp 1985). The primary controls on species distributions appear to be the frequency of flooding and the degree to which plant species are adapted to tolerate destructive hydrologic forces (Bendix 1999; Bornette and Amoros 1996; Osterkamp and Hupp 2010; Toner and Keddy 1997). Within the riparian areas of high-gradient streams, the physical disturbance caused by flooding appears to be the most important driver of species distributions (Harris 1987; Hupp and Osterkamp 1996; Osterkamp and Hupp 1984). Flood events can cause direct breakage or removal of plants by water flow or floating debris, scour the substrate, and bury plants with sediment (Francis 2006). These disturbances decrease in frequency as you move away from the channel, creating a disturbance gradient along which species with different adaptations and tolerances of flood disturbance are positioned. Within low-gradient coastal streams, the most important driver of species distributions is the frequency and duration of flooding and its impact on soil redox status (Hupp and Osterkamp 1996; Wassen et al. 2002). Species distributions in these systems are most closely related to hydroperiod, with species more tolerant of long-term inundation positioned closer to the stream channel and in areas of the floodplain that are more frequently flooded (Hupp and Osterkamp 1996).

Apart from these direct impacts, fluvial hydrodynamics influence species distributions indirectly by providing new substrates for regeneration through the deposition of new fluvial features, scour, removing previously established vegetation, removing accumulated organic matter, and by delivering propagules (Bendix and Hupp 2000). Riparian systems have been described as non-equilibrium or quasi-equilibrium systems where succession is prevented from achieving a climax state by periodic disturbance (Bendix and Hupp 2000). Such disturbances, whether in the form of rare flood events or channel migrations, have the potential to re-set the successional sequence and provide the bare substrate required by early colonizing species (Francis 2006; Kalliola and Puhakka 1988; Tabacchi et al. 1998). The timing of high flows

combined with the timing of seed release then determines which species are able to successfully establish in any given year (Francis 2006).

Similar processes control plant species distributions in inland alluvial fans and lacustrine river deltas. These alluvial depositional features differ from coastal river deltas in that they are not subject to coastal forces such as tides and high wave conditions and form in areas where there are not significant density differences between the river and its receiving basin. This set of conditions results in different geomorphologies than what is seen for most coastal river deltas. The most extensive research on the factors controlling plant species distributions on inland deltas comes from the Okavango Delta, an alluvial fan in Botswana. Here, species distributions are most directly related to elevation and particularly the timing and duration of flooding (Bonyongo et al. 2000). Species distributions respond to environmental gradients that are steep perpendicular to the channel and gradual along the channel, such that the same species are commonly found far from the channel upstream but close to the channel or even on the channel levees at the downstream channel fringe (Diederichs and Ellery 2001). Other important factors include depth to groundwater, distance to a channel, sediment supply and deposition, substrate characteristics, and nutrient availability (Diederichs and Ellery 2001; Ellery et al. 1993; Ellery and Tacheba 2003). Disturbance is also important, as many ruderal species are found only on newly emergent point bars and elevated surfaces near the channels (Diederichs and Ellery 2001). Channel avulsions influence landscape-scale patterns in the delta by re-setting the sequence of succession (Ellery and Tacheba 2003).

Similar processes have been observed in other inland deltas. Dalhskog (1966) found that species distributions in the Kvikkjokk Delta in Lapland were most closely related to distance from an active channel, a relationship that he attributed to differences in sedimentation rate. Dirschl and Coupland (1972) found that vegetation in the Saskatchewan delta in Canada responded to gradients in moisture regime, nutrients, and pH, while species distributions in the Peace-Athabasca delta in Canada are related to elevation, herbivory and physical disturbance by mammals, and local landform configurations (Timoney 2008).

SPECIES DISTRIBUTIONS IN RIVER DELTAS

Species distribution patterns in coastal river deltas have not been as well-studied as those in other coastal and fluvial systems. However, the limited number of plant community studies performed in active river deltas suggests that they are subject to a combination of the factors that control species distributions in other coastal and fluvial environments. Figure 1.1 provides an overview of the factors that control species distributions in coastal and fluvial settings and how processes inherent to each setting would be expected to contribute to vegetation patterns in river deltas.

As vegetation communities in both coastal and fluvial systems are strongly influenced by flooding characteristics, hydrology should also be the primary driver of species distribution in river deltas. Species distributions should correlate strongly with elevation, but should correlate even more strongly with the frequency and duration of flooding. As deltas are depositional features, rates of sediment accumulation should strongly influence deltaic plant communities, as it influences those in other fluvial settings. Sedimentation should also be an important driver of allogenic succession in deltas. As they are coastal features, salinity should at least partially influence plant community composition and species distribution in deltas, although the

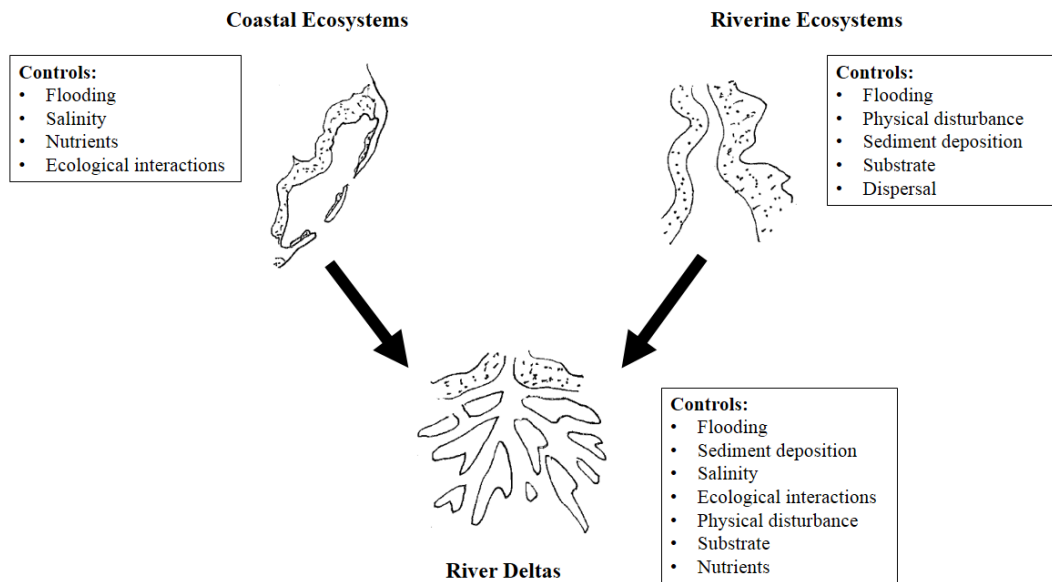


Figure 1.1 – Conceptual model of the influence of coastal and riverine process on deltaic plant communities

importance of salinity as a driver will vary depending on the specific geomorphology of the delta, the extent to which it is sheltered by other coastal features such as spits and barrier islands, and the volume of freshwater discharge. Ecological interactions such as competition, facilitation, and herbivory are expected to be at least as important as in other coastal settings and probably more important than in riparian systems, which have greater allogenic control. As in other fluvial settings, physical disturbance by floods and depositional sorting of sediments should influence species distributions, particularly for communities near high-energy distributary channels. Nutrients should be less important than in other coastal settings due to relatively constant input of nutrients from the river, but may play an increasing role in soil development at later stages of succession on the most mature deltaic islands.

The degree to which plant communities within deltas more greatly resemble coastal marshes or riparian wetlands depends on the relative strength of riverine and coastal influences. River deltas can be classified based on the relative importance that riverine, wave, and tidal forces play in shaping their geomorphology (Galloway 1975; Wright 1985). High-volume rivers that discharge into relatively low-energy coastal settings form river-dominated deltas. In these settings, there is little coastal energy in the form of waves and tides to break up the density gradient between the incoming freshwater and the salt water in the receiving basin. The freshwater forms a buoyant plume on top of the salt water and the depositional features that develop reflect rapid spreading with minimal frictional interference (Wright 1977; Wright 1985). When high-volume rivers discharge into shallow coastal settings, friction with the bed becomes important, and deltaic islands form as distributary mouth bars, with the coarsest material is deposited at the center of the bar and progressively finer material deposited outward and downstream of the bar front (Bates 1953; Wellner et al. 2005; Wright 1977). Linear subaqueous levees form along the edges of the distributary channels and further accretion of the bar and

levees eventually results in channel bifurcation (Wright 1985). Levees that form along the new channels block or reduce flow to the interdistributary basin and create low-energy environments sheltered from fluvial forces. River-dominated deltas can be formed by a combination of buoyant and frictional forces, as is the case for the Mississippi River delta (Bates 1953; Wright 1977). Bays, marshes, swamps, and lakes are the most dominant features in river-dominated deltas (Wright and Coleman 1973). Because of the tremendous volume of freshwater output and strong stratification at the mouth of the river, salinity influence is limited to temporary salt pulses provided by coastal storm events and salt-wedge intrusion at depth, particularly during periods of low river flow (Holm and Sasser 2001; Wright and Coleman 1971).

The hydrodynamic processes that build river deltas are modified in higher-energy coastal settings. In coastal settings with strong waves and currents but relatively minor tidal influence, deltas take on more of the characteristics of other wave-dominated coasts. In these deltas, wave energy quickly dissipates much of the fluvial energy entering the basin and results in rapid slowing of the effluent and sediment deposition close to the river mouth (Wright 1977; Wright 1985). This sediment is reworked laterally by the waves, forming beaches and spits along the shoreline on either side that restrict the mouth of the river and shelter the interior of the delta from marine processes (Wright 1977). When wave incidence is oblique, the delta takes on a asymmetrical geomorphology, with most sediment deposition and reworking occurring in the direction of wave incidence. Wave-formed beach ridges, dunes, spits, and barriers are dominant features in wave-dominated deltas (Wright and Coleman 1973). Salinity stratification is also quickly broken by the wave forces, creating a well-mixed saline environment with salinity that decreases upstream as tidal influence wanes (Wright 1985).

In coastal environments with relatively little wave energy but strong tides, river deltas develop as depositional features within funnel-shaped tide-dominated estuaries. Here, water and sediment transport inland by tides is as great or greater than the river discharge, resulting in bidirectional sediment transport (Wright 1977). The tides become constricted and amplified as you move upstream (Wright 1977). As in wave-dominated deltas, the strength of tidal forces counteracts the inertia of the fluvial effluent, breaking up the density stratification and concentrating sediment deposition within the estuary. The deposited sediment is reworked by the flood and ebb tidal flow to form linear subaqueous ridges and subaerial bars separated by deep channels within and seaward of the river mouth region (Wright 1977). Because of the influence of opposing river and flood tide flows, the coarsest sediment is deposited in the channels with progressive fining of sediments both upstream and offshore (Wright 1977). Strong tidal mixing creates a well-mixed saline environment with salinity gradually decreasing upstream as the tidal influence wanes.

Figure 1.2 illustrates a theoretical model of how the relative influence of the river, waves, and tides might be expected to influence the dominant factors controlling species distributions in each setting. In river-dominated deltas, plant community composition is expected to be strongly influenced by high freshwater input with less salinity influence than what is found in wave- and tide-dominated deltas. Because riverine process are more dominant in these deltas, high levels of deposition and physical disturbance by strong river currents along the distributary channels are important drivers of species distributions. However, the consistently high input of nutrients from the river makes nutrient limitation less important than it may be in other deltaic settings. Flooding in river-dominated deltas is largely driven by the river's spring flood cycle, and the seasonality of plant distributions should reflect variations in water level throughout the year. Because there is limited re-working by waves and tides, there is a strong gradient in substrate

grain size distribution related to the progressive deposition of finer sediments downstream on each deltaic island, which may influence the establishment of some plant species.

In both wave- and tide-dominated deltas, salinity is expected to strongly limit plant community composition to salt-tolerant species. In wave-dominated deltas, plant species distributions should be more strongly controlled by wave exposure gradients than by fluvial processes, particularly on the coastal side of the delta. When spits or barrier islands form in front of wave-dominated deltas, as in the wave- and current-dominated Senegal River delta (Isupova and Mikhailov 2008), they would be expected to shelter interior deltaic communities and provide a refuge for species more sensitive to wave exposure. In tide-dominated deltas, species selection will favor those adapted to wide tidal ranges and frequent flooding and drying cycles. In areas near the channel, exposure to strong tidal currents will be an important determinant of species distributions. Plant species may also respond to the non-linear gradient in sediment size within the delta.

Another factor that influences plant communities in deltas is the grain size distribution of the sediment load, which affects both the development and stability of distributary channel networks and its tendency to undergo channel avulsions. Deltas formed by coarser sediments, with a high percentage of sand, tend to form complex, unstable, braided distributary channel networks while deltas with a higher percentage of finer cohesive sediments form highly stable, branched distributary channel networks that undergo periodic avulsion (Orton and Reading 1993). At the scale of the active delta, channel avulsion can result in the abandonment of older areas of the delta and development of new channel mouth bar features and associated channel networks (Edmonds et al. 2009). However, avulsion can also occur further upstream on the river itself, resulting in a natural delta cycle where individual delta lobes are built by the river then subsequently abandoned as the river avulses and follows a more hydraulically efficient path to the coast. In the Mississippi River delta, this process occurs over a time scale of approximately

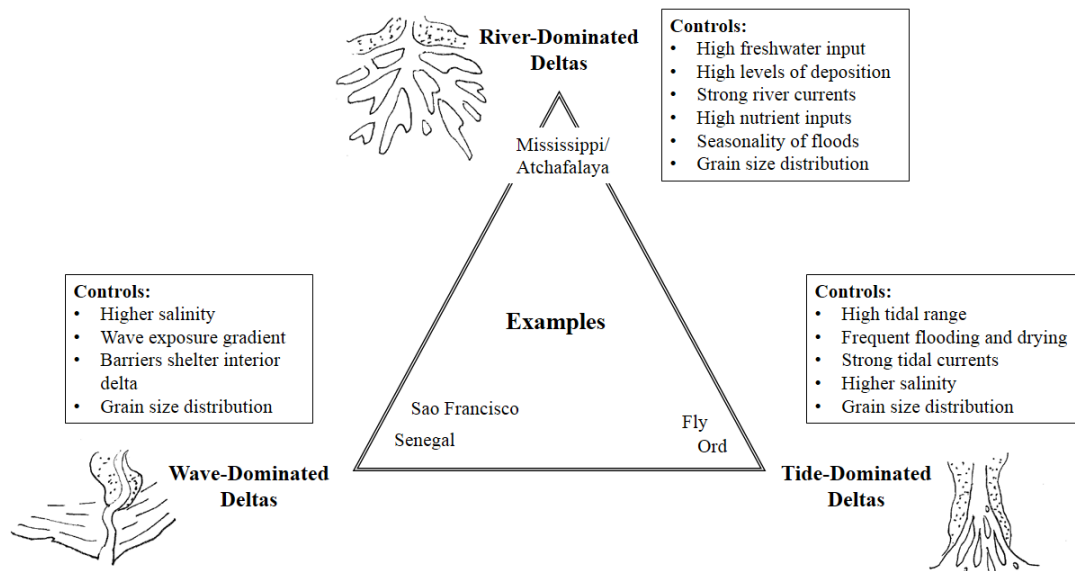


Figure 1.2 – Conceptual model of the factors controlling plant species distributions in river-, wave-, and tide-dominated river deltas (after Galloway 1975; Wright 1985)

1,000 years (Roberts 1997; Wells and Coleman 1987). After former deltaic lobes are abandoned by the river, they become increasingly exposed to coastal erosional processes and are gradually eroded over thousands of years. The delta cycle creates a gradient of riverine versus coastal influence within the greater deltaic plain that drives species distributional patterns at a larger scale. This review deals only with factors controlling plant species distributions in actively accreting river deltas. However, as an active delta is gradually abandoned through the process of channel avulsion, riverine processes would be expected to gradually decrease in importance and coastal processes to increase in importance until the plant community of the remaining marshes largely resembles those found in other coastal settings.

EXAMPLES FROM RIVER-, WAVE, AND TIDE-DOMINATED DELTAS

Most of the work that has been done on the factors controlling plant community composition and the distribution of plant species in river deltas comes from river-dominated deltas such as the Mississippi and Atchafalaya River deltas. These studies support the theory that along with elevation, riverine flooding and depositional patterns control plant species distributions in river-dominated deltas. In the active Mississippi River delta, elevation and substrate have been indicated as the most important factors controlling species distributions within the freshwater marshes that form on new deltaic splays (Cahoon et al. 2011; White 1993). Allogenic succession is an important process controlling plant community composition and there is a sequence of species turnover that occurs as the delta accretes vertically due to continued sedimentation and trapping and stabilizing of sediments by established plant communities (Cahoon et al. 2011). While ruderal annuals are important colonizing species in the early years following mudflat emergence, perennials with extensive rhizomes eventually gain a competitive advantage at lower elevations because they are better able to withstand periodic storm surges (White 1993). Similar findings have been reported for the Atchafalaya delta, a small actively pro-grading delta that has formed at the mouth of the Atchafalaya River, an important tributary of the Mississippi River. Here, plant species distributions were found to relate to variation in water level, substrate, and exposure to the river's flow (Johnson et al. 1985). As in the Mississippi delta, there is a clear allogenic successional sequence of plant communities that develop as deltaic islands accrete vertically. Herbivory and interspecific competition also appear to limit the distributions of some species (Evers et al. 1998; Fuller et al. 1984; Shaffer et al. 1992).

Substantial research has also been performed on plant community development in the Paraná River delta in Argentina. This delta has less riverine influence and more tidal influence than the Mississippi and Atchafalaya deltas (Kandus and Malvárez 2004). However, vegetation patterns in this delta are also driven by sedimentation rate, hydrologic regime, and allogenic successional processes that occur along an island age gradient (Kandus and Adamoli 1993; Kandus and Malvárez 2004). As in the Mississippi and Atchafalaya deltas, species in the Paraná River delta respond to a gradient of exposure to the river's flow, with different species dominant along the levees than in the interdistributary basins, which provide a more hydrologically-isolated and lower stress environment (Kandus and Malvárez 2004). The main difference between the Paraná River delta and more river-dominated deltas such as the Mississippi and Atchafalaya River deltas is that salinity and tidal influences become increasingly important

factors controlling species distributions as you move towards the distal regions of the Paraná River delta (Kandus and Malvárez 2004).

The Ord River delta in Australia and the Fly River delta in Papua New Guinea are some of the best studied examples of tide-dominated deltas. The Ord River delta consists of extensive tidal flats that have formed along the edges of the funnel-shaped Ord River estuary (Thom et al. 1975). The estuary itself is well-mixed, with salinities that range from 23 to 33 depending on river discharge and tidal stage (Thom et al. 1975). On the highest tidal flats that are flooded only during spring tides, desiccation between flooding events results in salt concentration and salinity levels can reach over 40 (Thom et al. 1975). These areas are generally bare of all vegetation. Other than salinity, elevation is the most important factor controlling species distributions in the Ord River delta (Thom et al. 1975). Salinity has also been indicated as the most important factor controlling species distribution in the Fly River delta, where strong tidal mixing results in a sharp, but uniform, salinity gradient from less than 5 at the upstream end of the delta to near 30 at the mouth of the estuary (Robertson et al. 1991; Wolanski et al. 1997).

Very little information has been published on vegetation patterns in wave-dominated deltas, but the dominance of sandy beaches, ridges, and dunes suggests that the controls on plant community composition in these deltas would be similar to the factors controlling plant community composition in other wave-dominated coastal environments. Two of the most commonly cited examples of wave-dominated deltas are the wave-dominated São Francisco River delta in Brazil and the wave- and current-dominated Senegal River delta in Senegal. Both of these deltas are characterized by linear shorelines and constricted river mouths compared to river- and tide-dominated deltas (Wright and Coleman 1973). They are comprised predominantly of well-sorted sands, which form high, broad beaches with extensive dune systems, some of which are stabilized by vegetation (Wright and Coleman 1973). In the Senegal River delta, extensive salt marshes and mangrove wetlands grow on mudflats sheltered behind the sand barriers and beach ridge and swale deposits (Duvail and Hamerlynck 2003; Isupova and Mikhailov 2008; Wright and Coleman 1973). In the São Francisco delta, marshes and mangroves are limited to a few low-lying areas adjacent to the river (Fuht et al. 2004; Wright and Coleman 1973). In both of these deltas, high salinity, elevation, substrate, and wind and wave stress appear to be the most important drivers of vegetation pattern.

These examples represent extreme cases of river-, wave-, and tide-dominated deltas. Most deltas will fall somewhere in the middle of these extremes, and the factors controlling plant community distributional patterns in these deltas would be expected to reflect the relative influence of the river, waves, and tides in each setting.

THE ROLE OF CLIMATE

Climate is an additional factor that is superimposed upon river, wave, and tide influences to create the vegetation community patterns found in the world's coastal river deltas. The difference in temperature variability between temperate and tropical deltas results in very different deltaic plant communities. The most conspicuous difference is that mangroves replace salt marshes at the lowest elevations in wave- and tide-dominated tropical deltas influenced by high salinity (Fuht et al. 2004; Robertson et al. 1991; Thom et al. 1975). Salt marshes are displaced to higher elevation sites that are less frequently flooded (Saintilan and Hashimoto 1999; Saintilan and Williams 1999). Tropical deltas also exhibit a different seasonality than

temperate deltas, with plant community productivity limited by variability in water availability during the wet and dry seasons as opposed to the seasonal variability in temperature experienced by temperate deltas. In the most extreme examples, such as in the Senegal River delta, low river discharges during the dry season combine with high evapotranspiration rates to create a salinity inversion in the delta, with hypersaline conditions in the upper deltaic plain (Duvail and Hamerlynck 2003; Isupova and Mikhailov 2008). Plant growth is limited in these areas until the wet season floods flush the salt from the soils and allow the regrowth of extensive salt marshes (Duvail and Hamerlynck 2003). At high latitudes, the presence of permafrost, snow and ice cover, and peat accumulation due to slow decomposition rates are additional factors influencing deltaic plant communities (Kincheloe and Stehn 1991; Thilenius 1990). Overall, the plant communities of tropical and arctic deltas have received little study compared to the plant communities of temperate river deltas.

STUDY AREA – THE WAX LAKE DELTA

This study explores the factors that control plant community composition, species distributions, and productivity within the Wax Lake delta, a small, actively pro-grading young bayhead delta that is part of the greater Mississippi River deltaic system in coastal Louisiana, USA (Figure 1.3). The Wax Lake delta is located at the mouth of the Wax Lake Outlet, an artificial diversion of the Atchafalaya River that was built in 1941 to protect the city of Morgan City, Louisiana from flooding. The Atchafalaya River is itself a distributary of the Mississippi River, and receives a fixed 30 percent of the combined flow of the Mississippi and Red Rivers at the Old River Control Station located upstream of Baton Rouge, Louisiana (Roberts 1998). While the Wax Lake Outlet was originally designed to divert approximately one third of the flow of the Atchafalaya River, the unmanaged channel has enlarged over time and recent estimates suggest that the current percentage is closer to 46 percent, with an average flow of approximately 2,677 cms measured from 1995 to 2012 (U. S. Geological Survey 2012). This represents, on average, 13 percent of the total combined flows of the lower Mississippi-Red River system.

The Wax Lake Delta first emerged from Atchafalaya Bay following record flooding on the lower Mississippi River in 1973 and 1975. Since that time, it has continued to accrete both vertically and horizontally. By 1997, the river had built 51.1 km² of new land in the Wax Lake Delta (Roberts et al. 1997a). As new shallow islands emerge in the delta, they are rapidly colonized by freshwater wetland plants, which trap additional sediments with their roots and further increase elevation (Llewellyn and Shaffer 1993; Shaffer et al. 1992). As elevation increases, additional species are able to invade, often displacing the initial colonizing species or limiting them to lower elevations (Johnson et al. 1985; Shaffer et al. 1992). A good example of primary succession, the Wax Lake Delta provides an excellent opportunity to study plant community development in a newly created sedimentary environment.

Along with the neighboring Atchafalaya River delta, the Wax Lake delta represents the latest stage of delta-building by the Mississippi River (Roberts 1998). Much of coastal Louisiana consists of the deltaic plain of the Mississippi River, which was built by the river over thousands of years since sea level began to drop following the last high stand approximately 6,000 BP. The river built the deltaic plain in coastal Louisiana by laying down sediments in its active delta and flooding surrounding wetlands with freshwater and sediment during annual floods (Kesel 1989; Roberts 1997). Every 1000-2000 years, it would change course and

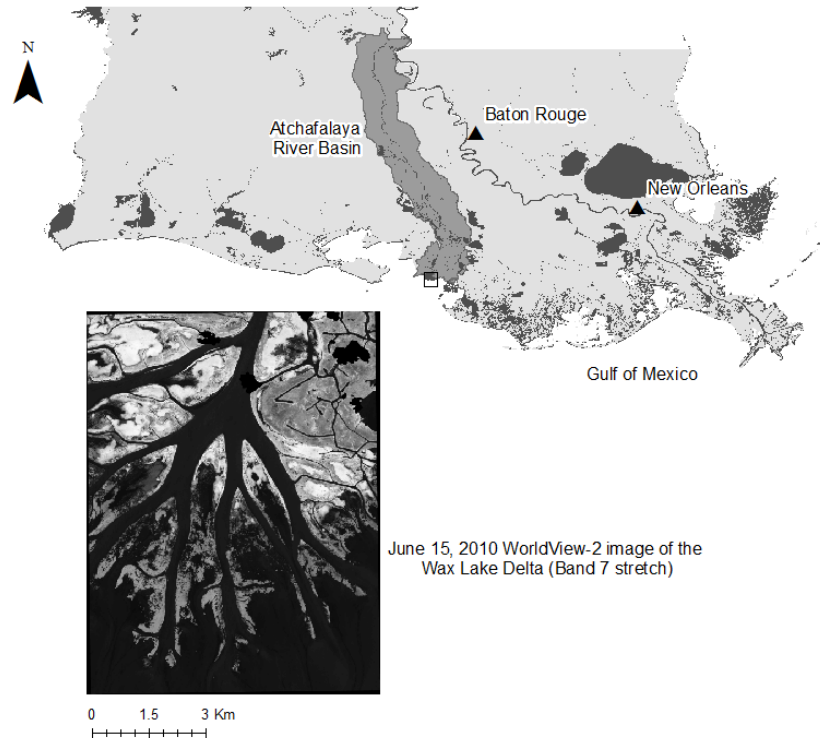


Figure 1.3 – Location of the Wax Lake delta in coastal Louisiana, USA

construct a new delta lobe, building out another area of the coast (Coleman et al. 1998; Roberts 1998).

Following the Great Flood of 1927, the federal government built extensive levees along the river to hold it in place and prevent flooding (Kesel 1989). The levees effectively halted sediment deposition within the deltaic plain by preventing seasonal flooding (Kesel 1989). It also prevented the river from switching course to develop new delta lobes. The currently active Balize birdsfoot delta, which began forming about 1000 years ago, has built out to the edge of the continental shelf and has reached the limit of its progradational stage (Roberts 1997). Most of the sediment carried through the mouth of the river now empties off the edge of the continental shelf, rather than being deposited in the coastal system where it can eventually be reworked onshore (Craig et al. 1979). While the river once had numerous small distributaries that would inundate the deltaic plain with water and sediment during large flood events, all but the Atchafalaya River have been artificially closed (Kesel 2003), further reducing sediment supply to the deltaic plain.

As a result of these policies, along with a suite of other factors including reduction of the river's sediment load (Blum and Roberts 2009; Kesel 1988), dissection of deltaic wetlands by oil and gas canals (Turner 1997), and accelerated eustatic sea level rise (Kesel 1989), the Mississippi delta is now eroding at a rate of 40 km²/year (Barras et al. 2008). Numerous large-scale river diversions have been proposed to restore marshes and build land by reconnecting between the river to its deltaic plain (Coastal Protection and Restoration Authority (CPRA) 2012). As one of few areas in coastal Louisiana where the Mississippi River is already actively building new land, the Wax Lake Delta serves as an important reference system for

understanding the impact that large diversions of river water and sediment may have on offsetting land loss and restoring coastal wetlands elsewhere in the Mississippi River deltaic plain. Understanding the processes that control plant community development and species distributions in the Wax Lake delta will provide valuable information that will assist in integrating the role of the plant community into process-based physical models of delta geomorphology and land-building. This will provide better predictions of the rate of accretion and marsh development that can be expected from river diversion projects. It will also provide an ecological reference that can be used to assess the success of large scale river delta restoration efforts.

RESEARCH OBJECTIVES

The overall objective of this dissertation is to better quantify the factors that contribute to plant community development and vegetation patterns in an actively pro-grading river-dominated delta. In particular, the degree to which plant community composition, spatial structure, and productivity are controlled by underlying gradients in elevation, substrate-type, exposure, and salinity created by sediment deposition, deltaic island morphology, physical stressors, coastal storm disturbance, and infrequent extreme flood events is considered. First, in Chapter 2, methods of mapping plant species distributions using newly available high-resolution satellite imagery are considered and the newly available imagery is compared to previously available imagery for the purposes of mapping deltaic plant communities. In Chapter 3, the mapped plant species distributions are used to build a predictive model of species distributions within the delta as a function of spatially-derived predictor variables related to flooding frequency and duration, microtopography, distance to distributary channels, substrate, exposure, dispersal, and storm disturbance. Chapter 4 considers the role that allogenic and autogenic plant community succession, seasonality, and coastal storm disturbance events play in controlling variability in plant community productivity as the delta accretes and pro-grades over time. Finally, in Chapter 5, the impact of an extreme flood event on the Mississippi River on accretion in the delta is examined and the role that such large depositional events play as drivers of plant community change is considered.

CHAPTER 2 – MAPPING FRESHWATER MARSH SPECIES DISTRIBUTIONS USING WORLDVIEW-2 MULTISPECTRAL SATELLITE IMAGERY

ABSTRACT

Freshwater wetlands are highly diverse, spatially heterogeneous, and seasonally dynamic systems that present unique challenges to remote sensing. Maximum likelihood and support vector machines supervised classification were compared to map wetland plant species distributions in a deltaic environment using high resolution WorldView-2 satellite imagery. The benefits of the sensor's new coastal blue, yellow, and red-edge bands were tested for mapping coastal vegetation and the 8-band results were compared to classifications performed using band combinations and spatial resolutions characteristic of other available high-resolution satellite sensors. Unlike previous studies, this study found that support vector machine classification did not provide significantly different results than maximum likelihood classification. The maximum likelihood classifier provided the highest overall classification accuracy, at 75 percent, with user's and producer's accuracies for individual species ranging from 0 to 100 percent. Overall, maximum likelihood classification of WorldView-2 imagery provided satisfactory results for species distribution mapping within this freshwater delta system and compared favorably to results of previous studies using hyperspectral imagery, but at much lower acquisition cost and greater ease of processing. The four new bands employed by the WorldView-2 sensor, and particularly the red-edge and coastal blue bands, appear to contribute the most to improved vegetation mapping capability over other available high-resolution satellite sensors that employ only four spectral bands.

INTRODUCTION

Coastal wetlands are valuable resources that provide essential habitat for freshwater, estuarine, and marine species, buffer shorelines, export organic carbon to estuaries, and influence biogeochemical cycles (Costanza et al. 1989; Farber 1987; Hopkinson 1985; Knutson et al. 1982; Knutson et al. 1981; Nixon 1980). Despite their important ecological role and the value they provide to society, coastal wetlands are threatened by increased populations and development in coastal regions. It has been estimated that world-wide, over one-third of people live within 100 kilometers of the coast (Cohen et al. 1997). In the United States, coastal areas are currently developing more rapidly than any other part of the country (Crossett et al. 2004). Understanding the impact of such development is essential to determine how to best protect existing coastal resources and guide the restoration of degraded ecosystems. Remote sensing provides an opportunity to monitor large-scale patterns and changes to coastal ecological systems that can be difficult to assess at the field scale, and is thus an extremely valuable tool in guiding the protection and restoration of coastal wetlands.

Mapping Coastal Wetlands

Coastal wetlands present unique challenges for remote sensing because they are composed of highly diverse mixed vegetation (Adam et al. 2010). This is particularly true of brackish and freshwater marshes, where plant community composition is not as severely limited by salinity stress as in salt marshes (Odum 1988). In addition, annual species are common in tidal freshwater marshes and many of the perennial forbs that inhabit these marshes die back to the sediment each year, creating considerable seasonal and annual variability in the distribution and abundance of individual species (Odum 1988; Pasternack et al. 2000). The phenology of freshwater marsh species commonly results in a seasonal pattern of shifting dominance where perennials are dominant early in the growing season and annuals dominate later in the growing season after the perennials have reached their peak biomass and begun to senesce (Doutrele 1981; Johnson et al. 1985; Odum 1988; Simpson et al. 1983; Whigham and Simpson 1992). In coastal river deltas, this seasonality is further complicated by the spring flood cycle, which controls spring and early summer water levels and thus the timing of species germination and re-sprouting in the early growing season (Johnson et al. 1985).

Many marsh species are spectrally similar to one another, making separation of unique signatures difficult if only a few broad spectral bands are available for classification (Ozesmi and Bauer 2002). The presence of water interspersed with the vegetation dampens the overall reflectance values and further diminishes separability of individual species (Adam et al. 2010; Silva et al. 2008). This factor is further complicated by daily and seasonal changes in water level (Ozesmi and Bauer 2002). Submerged aquatic vegetation (SAV), which is common in the understory of emergent wetlands, contributes further spectral confusion.

Most of the earliest attempts to map coastal wetlands involved visual interpretation of color infrared aerial photography (Adam et al. 2010; Ozesmi and Bauer 2002). While many of these studies achieved moderate accuracy, particularly with respect to mapping coarse wetland classes, the process is time-intensive and subject to considerable inconsistency related to variability of interpretation and human error (Ozesmi and Bauer 2002). The poor spectral resolution of aerial photography also limits its ability to distinguish the unique spectral responses of individual species (Adam et al. 2010). More recently, remote sensing researchers have explored automated classification techniques to map wetlands using medium and high-resolution satellite imagery and satellite and airborne hyperspectral imagery. While hyperspectral imagery has generally produced the most accurate maps of coastal wetland vegetation, this technology is still relatively expensive and largely inaccessible to coastal wetland managers. High resolution satellite imagery has been demonstrated to provide classifications that are nearly as accurate at significantly reduced cost (Belluco et al. 2006).

The WorldView-2 Sensor

WorldView-2 is a commercial high spatial resolution satellite that was launched by the company DigitalGlobe in 2009 and provides 2-meter imagery in 8 spectral bands: coastal blue (400-450 nm), blue (450-510 nm), green (510-580 nm), yellow (585-625 nm), red (630-690 nm), red-edge (705-745 nm), and two bands in the near-infrared portion of the light spectrum (770-895 nm and 860-1040 nm). The coastal-blue, yellow, and red-edge bands are unique to this sensor and provide information that may be particularly useful for improved vegetation mapping in coastal environments. The coastal blue band corresponds to the range of maximum

penetration of the water column and is expected to improve bathymetric mapping of shallow coastal environments and submerged vegetation (Collin and Hench 2012; Collin and Planes 2011; Marchisio et al. 2010). The yellow band corresponds to the absorption range of minor plant pigments such as the yellow carotenes, pale yellow xanthophyll, and red anthocyanin (Jensen 2007). These minor pigments are masked by chlorophyll production in the peak growing season but become important in the fall as chlorophyll production drops (Jensen 2007). Both plant stress and seasonal senescence is first observed in the 535-640 nm and 685-700 nm ranges (Carter 1993; Carter et al. 1996). Because the new WorldView-2 yellow band overlaps with the first range of sensitivity to stress and senescence, it should be particularly useful for both mapping vegetation health and discriminating between vegetation classes late in the growing season. The red-edge region of the spectrum represents the transition zone between high absorption by chlorophyll in the red region and high reflection by the spongy mesophyll cells in the near infrared region (Gates et al. 1965; Jackson 1986). During plant senescence or stress, an increase in reflectance near 700 nm results in what has been termed the “blue shift of the red-edge” (Carter and Knapp 2001; Filella and Penuelas 1994; Gates et al. 1965; Rock et al. 1988). Measuring reflectance in this region should improve classification of senescing vegetation, provide improved estimation of chlorophyll content, biomass, and leaf area index (LAI), and serve as an indicator of vegetation stress (Gitelson and Merzlyak 1994; Gitelson et al. 1996).

Multispectral Classifiers

The Maximum likelihood classifier (MLC) is a very commonly used classifier for multispectral imagery due to its ease of implementation and wide availability in popular software packages. It is a parametric classifier which relies upon the statistical distributions of the reflectance values of the target classes, as defined by the training data that is provided for each class. The maximum likelihood approach assumes that the reflectance values for each class in each band follows a Gaussian distribution and calculates the probability that each pixel in the image belongs to each of the target classes. Each pixel is assigned to the class with the highest probability and unless a probability threshold is used to generate an “unclassified” class, all pixels in the image are classified as one of the target classes.

It has been demonstrated that the assumption of normality necessary for MLC is commonly violated in remote sensing data, particularly where there are multiple subclasses or when classes contain different spectral features (Kavzoglu and Reis 2008). This problem has led to the recent proliferation of non-parametric classifiers such as classification trees, neural networks, and support vector machines (Friedl and Brodley 1997; Kavzoglu and Reis 2008; Otukey and Blaschke 2010; Zhu and Blumberg 2002). Of these, support vector machines (SVM) have most often demonstrated superior thematic classification accuracy (Dixon et al. 2008; Foody and Mathur 2004; Huang et al. 2002; Kavzoglu and Colkesen 2009; Pal and Mather 2005; Sanchez-Hernandez et al. 2007).

Support vector machines are a group of machine learning techniques based on statistical learning theory. They separate classes by identifying the optimal linear decision surface (the optimal hyperplane) that creates the largest distance, or margin, between the vectors for the two classes. The optimal hyperplane is defined by the set of vectors from each class that directly border it, known as the support vectors. Because the only training data required are those that define the support vectors, the need for large training sets is theoretically reduced (Cortes and Vapnik 1995). In situations where the training sets for the classes are not linearly separable, the

data must first be projected into a higher dimensional space where they are linearly separable (Pal and Mather 2005). This is most often accomplished using kernel functions, of which the polynomial and radial bias function (RBF) have been the most commonly adopted for remote sensing applications (Huang et al. 2002; Kavzoglu and Colkesen 2009). SVMs were originally developed for binary classification problems, but several methods have been proposed to adapt them to multiclass problems. In the “one-against-one” or “pairwise” approach, all possible combinations of two-class SVMs are compared and the class that is chosen by the most classifiers is selected (Wu et al. 2004). In an alternate approach, referred to as “one-against-many”, each class is compared to all of the others, generating a unique classifier for each class (Pal and Mather 2005).

Objectives

In this study, both MLC and SVM classifiers are used to map freshwater marsh species distributions in the Wax Lake delta using WorldView-2 multispectral imagery. The specific objectives of this study are: (1) to evaluate the value of WV-2 high spatial resolution multispectral satellite imagery for monitoring plant community composition in coastal freshwater marshes and (2) to compare the use of MLC and SVM classifiers for mapping freshwater marsh vegetation using high-resolution satellite imagery.

METHODS

Vegetation Classes

A WV-2 image of the Wax Lake delta taken on October 15, 2011 was used to map the distribution of freshwater marsh plant species within the delta (Figure 2.1). The following thirteen freshwater marsh species/land cover classes were included in the classification: trees, *Colocasia esculenta*, *Polygonum punctatum*, *Bidens laevis*, *Paspalum dissectum*, *Typha* spp., *Phragmites australis*, *Zizaniopsis miliacea*, *Nelumbo lutea*, *Sagittaria* spp., *Potamogeton nodosus*, other submerged aquatic vegetation (SAV), *Eichhornia crassipes*, water, and bare mudflats. The vegetation classes that were included in the mapping study represent some of the most dominant species in the delta and those that were identified during field reconnaissance.

At the highest elevations, along the natural river levees, the trees class is dominated by *Salix nigra* (black willow), a small to medium size tree with multiple trunks and lanceolate leaves (Chabreck and Condrey 1979). Other species of hardwood trees are found growing on dredge spoil disposal levees along the main river channel at the upper end of the delta, but no attempt was made to distinguish between the *S. nigra* and these other tree species for this study. *Colocasia esculenta* (elephant ear or taro) is an invasive perennial forb that grows at slightly lower elevations - along the lower levees on younger islands, down the backside of levees facing the interior of older islands, and in the understory of the willow community. It has large, heart-shaped leaves (up to 0.6 m) with long (1 m) petioles that emanate from a starchy underground corm and can reach a maximum height of 2.5 m with a canopy spread of 2.5 m under ideal growing conditions (Chabreck and Condrey 1979; United States Department of Agriculture). Commonly found interspersed with *C. esculenta* or in mixed communities at high to mid-elevations is *Polygonum punctatum* (dotted smartweed). *P. punctatum* is an annual/perennial

herb with branched, trailing stems, linear leaves, and long racemes of scattered white flowers that can grow to a maximum height of about 1 m under ideal growing conditions (Chabreck and Condrey 1979; United States Department of Agriculture).

Intermediate elevations within the delta are dominated by a diverse assemblage of species, many of which are clonal and form large monotypic stands. Included in this group are *Bidens laevis* (smooth beggartick or bur marigold), *Paspalum dissectum* (mudbank paspalum), *Typha spp.* (cattails), *Phragmites australis* (common reed), and *Zizaniopsis miliacea* (giant cutgrass). *B. laevis* is an annual/perennial herb with an upright, bushy growth form and a maximum height of about 1 m that often forms dense stands in freshwater marshes (Chabreck and Condrey 1979; United States Department of Agriculture). It grows numerous bright yellow flowers in the fall (Chabreck and Condrey 1979). *P. dissectum* is a low-growing perennial grass that grows to 15 to 60 cm tall and is locally abundant, forming dense mats in freshwater marshes (Chabreck and Condrey 1979). *Typha spp.* are tall grass-like, perennial herbs that grow from fleshy creeping rhizomes. The leaves are narrow and erect and grow 1.2-1.8 m tall (Chabreck and Condrey 1979). At least two *Typha spp.* are believed to grow in the Wax Lake delta: *Typha latifolia* (broadleaf cattail) and *Typha angustifolia* (narrowleaf cattail). No attempt was made to distinguish between them for this study. *P. australis* is a tall (2.5 to 3.4 m), perennial, cane-like grass with stout creeping rhizomes and a plume-like inflorescence that develops in the fall. It typically grows in dense monotypic stands, often expanding outward in a circular pattern (Chabreck and Condrey 1979). *Z. miliacea* is a tall, stout perennial grass that grows up to 2.7 m tall under ideal growing conditions and forms dense circular stands in freshwater marshes (Chabreck and Condrey 1979; United States Department of Agriculture).

Emergent, floating-leaved, and submerged vegetation dominates the lowest elevations in the Wax Lake delta. *Nelumbo lutea* (American lotus) is an aquatic, perennial herb with round, flat leaves 30 to 60 cm in diameter that can be either floating or emergent. It grows from rhizomes rooted in the bottom of shallow water areas and stands are capable of rapid radial expansion of up to 14 meters in a single growing season (Hall and Penfound 1944). Two *Sagittaria spp.*, *Sagittaria latifolia* and *Sagittaria platyphylla*, have historically been important components of the plant community in the Wax Lake delta, although their dominance appears to have waned in recent years (Holm and Sasser 2001). Both are emergent perennial herbs, but *S. latifolia* is taller, reaching mature heights of up to 1.5 m, compared to less than 1 m for *S. platyphylla* (United States Department of Agriculture). The leaves of *S. latifolia* are arrowhead-shaped while those of *S. platyphylla* are elliptical. No attempt was made to differentiate the two species for mapping purposes.

Finally, areas within the delta that are continuously flooded are dominated by floating plants and submerged aquatic vegetation (SAVs). *Eichhornia crassipes* (water hyacinth) is an invasive free-floating freshwater aquatic plant that forms dense mats over waterways, blocking light-penetration of the water column. Small, broken-off mats of *E. crassipes* are commonly found floating down the distributary channels in the Wax Lake Delta. It forms large mats in the interiors of the islands that are moved continuously by wind and tides. The most common SAV in the delta is *Potamogeton nodosus* (longleaf pondweed). It is a rhizomous perennial aquatic herb with linear leaves about 5 cm long that float at and just below the water's surface. Because its floating leaves prevent light from penetrating the water column, it often forms large homogeneous stands. This growth form gives it a very unique spectral signature compared to other SAVs, which allowed it to be mapped as a separate class for this study. All other SAVs were grouped into a single class for mapping purposes. Other SAV species present in the delta

include: *Potamogeton pusillus*, *Potamogeton crispus*, *Myriophyllum spicatum*, *Elodea canadensis*, *Najas guadalupensis*, *Zannichellia palustris*, *Herteranthera dubbia*, and *Ceratophyllum demersum*. These other species are frequently found in mixed assemblages throughout the delta (Charles Sasser, unpublished data).

Pre-processing

The image was first pre-processed by converting the original image digital number values to top-of-atmosphere spectral radiance ($L_{\lambda_{Pixel,Band}}$) is calculated according to the equation:

$$L_{\lambda_{Pixel,Band}} = \frac{K_{Band} \times q_{Pixel,Band}}{\Delta\lambda_{Band}}$$

, where K_{Band} is the absolute radiometric calibration factor ($\text{Wm}^{-2}\text{sr}^{-1}\text{count}^{-1}$) for a given band, $q_{Pixel,Band}$ is the radiometrically corrected image pixel (count), and $\Delta\lambda_{Band}$ is the effective bandwidth (μm) (Updike and Comp 2010). Radiance values were then converted to at-satellite reflectance ($\rho_{\lambda_{Pixel,Band}}$) according to the equation:

$$\rho_{\lambda_{Pixel,Band}} = \frac{L_{\lambda_{Pixel,Band}} \times d_{ES}^2 \times \pi}{Esun_{\lambda_{Band}} \times \cos(\theta_s)}$$

, where $L_{\lambda_{Pixel,Band}}$ is the top-of-atmosphere spectral radiance ($\text{Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$), d_{ES} is the earth-sun distance (AU), $Esun_{\lambda_{Band}}$ is the band-averaged solar spectral irradiance ($\text{Wm}^{-2}\mu\text{m}^{-1}$), which is specific to the sensor, and θ_s is the solar zenith angle (degrees) (Updike and Comp 2010). Because there were no clouds or haze in the image and no cross-image comparisons were going to be made for this study, further atmospheric correction was deemed unnecessary.

Reference Data

Training areas and a stratified random sample of accuracy assessment plots were collected in the field in late August and early September 2011. Training samples were collected as monotypic or nearly monotypic stands of each of the vegetation classes with polygons delineated using a Trimble GeoXH differential global positioning system (DGPS) with submeter accuracy. Accuracy assessment samples were collected by generating a stratified random sample of 400 points using a previously generated classification based on a June 2010 WorldView-2 image of the Wax Lake delta. A total of 85 of these points were visited in the field, selected based on accessibility by foot or airboat, with a goal of obtaining adequate representation of each class (Figure 2.1). For classes that were poorly represented in the 2010 vegetation map (*Z. milacea*, *P. australis*), accessible stands were haphazardly selected in the field to include in the accuracy assessment. *P. dissectum* was excluded from the accuracy assessment because it is found primarily in one isolated area of the delta and it was too difficult to access any of the reference plots, although sufficient training samples were located. *E. crassipes* was also excluded from the accuracy assessment because the floating mats of this species move continuously. At each accuracy assessment site, percent cover values were collected at 5 percent intervals within a 1-m² sample plot, which was selected such that it was representative of the

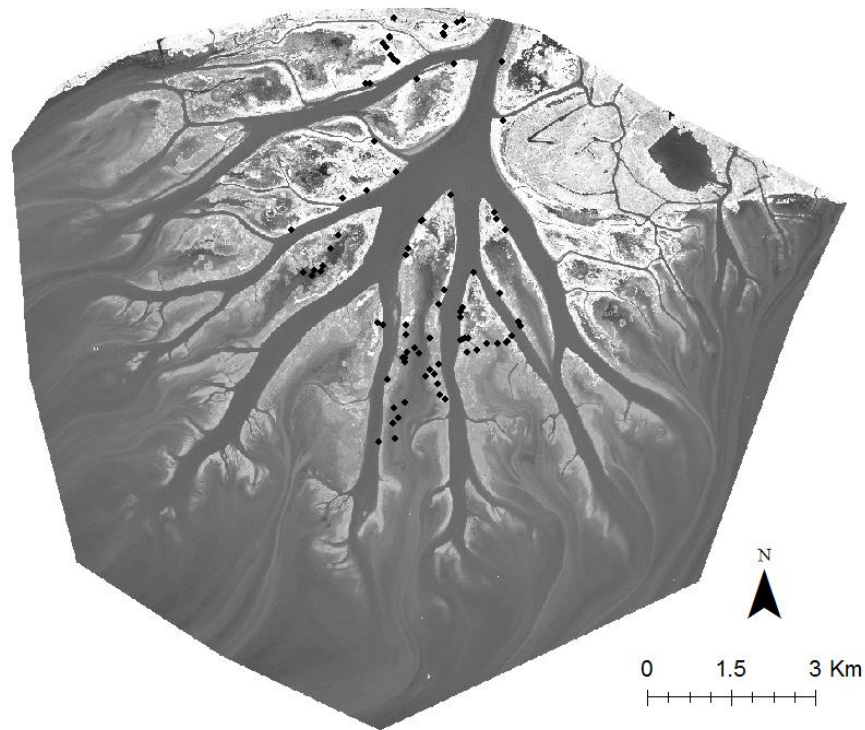


Figure 2.1 – Location of reference plots used for classification accuracy assessments

greater 5-m² area to account for the 2-m pixel size of the WorldView-2 data plus any geometric error in the GPS reading and image registration.

Use of this reference data for the October 16, 2011 WorldView-2 image was complicated by Tropical Storm Lee, which passed directly over the Wax Lake delta on September 4, 2011. This slow-moving storm brought an approximate 4-foot storm surge as measured at the Wax Lake delta Coastal Reference Monitoring System (CRMS) monitoring site maintained by the U.S. Geological Survey and the Coastal Protection and Restoration Authority of Louisiana (Coastal Protection and Restoration Authority of Louisiana 2012). This surge carried salt water into the delta that killed much of the freshwater vegetation growing at low elevations, as evidenced by wide-spread salt-burn observed in the delta in the weeks following the storm. In particular, four of the classes that normally dominate the low elevation areas of the delta – *P. nodosus*, *N. lutea*, *Sagittaria spp.*, and other SAVs – were greatly reduced in distribution as a result of the storm, while the area of bare mud or sand flats was greatly increased. Because access to the site was limited for several months following the storm, all training areas collected before the storm were screened by visual interpretation of the October 16, 2011 WV-2 image, using a June 2010 WV-2 image and a reference vegetation map created from November 2009 aerial photography as ancillary data. If an insufficient number of the original training pixels for a given class were usable due to the storm impact, additional training pixels were selected directly from the image using the ancillary data as reference. To minimize training error, new training pixels were only selected from areas that were mapped as the same class in 2009 and 2010 and where visual interpretation of the 2011 image suggested that the vegetation had not changed. The storm also resulted in a conversion of a high number of

accuracy assessment plots from the lower elevation classes to the “bare sediment” class. Conversion of these sites was verified by visual interpretation of the October 16, 2011 WorldView-2 image. As it was impossible to obtain new reference samples for these classes following the storm, they were underrepresented in the final accuracy assessment dataset.

Classification

Both the SVM and MLC classifiers were tested to determine which classifier yielded the most accurate classification of freshwater marsh vegetation using the WV-2 high resolution multispectral imagery. All classifications were performed using the ENVI 5.0 image analysis software package (Exelis Visual Information Solutions 2013). The ENVI SVM classification module employs the pairwise approach to extend binary SVM classification to multiclass problems. The Radial Bias Function (RBF) and polynomial kernels were tested to determine which provided superior classification power. The polynomial kernel function is represented by:

$$K(X_1, X_2) = (\gamma X_1^T X_2 + 1)^p$$

, and the RBF kernel is represented by:

$$K(X_1, X_2) = e^{(-\gamma \|X_1 - X_2\|^2)}$$

, where p is the degree term for the polynomial kernel and γ represents the kernel width for both kernels (Huang et al. 2002). These are user-defined parameters that must be optimized to maximize performance of the SVM classifier. Another parameter, the penalty parameter (C), must be set for both kernels and represents the trade-off between allowing some classification error for the training data and enforcing rigid margins (Kavzoglu and Colkesen 2009). While higher values of C may result in higher classification accuracy, they also increase the complexity of the model (Cortes and Vapnik 1995). To determine the optimal parameters for this study area, classification trials were performed using parameter ranges selected based on previous studies using SVM classification for land cover classification in other settings (Huang et al. 2002; Kavzoglu and Colkesen 2009; Pal and Mather 2005). For the RBF kernel, gamma was varied from 0.01 to 7 and the penalty parameter was varied from 10 to 10,000. For the polynomial kernel, polynomial order was varied from 2 to 6 and the penalty parameter was again varied from 10 to 10,000.

For MLC, ENVI uses the following equation to calculate the weighted distance (g_i) or likelihood that an unknown pixel (X) belongs to class (ω_i):

$$g_i(X) = \ln p(\omega_i) - \frac{1}{2} \ln \left| \sum i \right| - \frac{1}{2} (X - m_i)^T \sum i^{-1} (X - m_i)$$

, where $p(\omega_i)$ is the prior probability that class ω_i is in the image and is assumed to be the same for all classes, $\left| \sum i \right|$ is the determinant of the covariance matrix of the data in class ω_i , $\sum i^{-1}$ is its inverse matrix, and m_i is the mean vector (Richards 1999).

Apart from evaluating the value of the full 8-band imagery for mapping freshwater wetland vegetation, the contribution of the new coastal blue, yellow, and red-edge bands were also evaluated by performing maximum likelihood supervised classification after sequentially

removing each of these bands. Additional classifications were performed at degraded resolutions and with decreased band combinations to compare the results of the 2-m, 8-band WorldView-2 imagery to results obtainable using other high-resolution satellite sensors. To simulate IKONOS and Orbview-3 data, the W-2 image was resampled to 4-m spatial resolution and only bands 2 (red), 3 (green), 5 (red), and 7 (near infrared) were used. The same band combination was used to simulate Quickbird data, but the image was resampled to 2.4 m.

Accuracy Assessment

The accuracy assessment results were summarized in an error matrix and overall map accuracy and individual class accuracies were computed based on the dominant class in each reference plot (Congalton 1991; Richards 1996; Stehman 1997; Story and Congalton 1986). Pixels were considered correctly classified if the dominant class in the reference plot matched the mapped class. Overall map accuracy was calculated as the area of correctly classified pixels in all classes divided by the total number of pixels sampled (Congalton 1991; Story and Congalton 1986). Producer's and user's accuracies were also calculated for each class. Producer's accuracy measures errors of omission and is defined as the area of correctly classified pixels in a particular class divided by the total number of reference pixels for that class (Stehman 1997; Story and Congalton 1986). 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 from that class that were classified (Stehman 1997; Story and Congalton 1986). Kappa values were also calculated for each classification. The kappa coefficient ($\hat{\kappa}$) is a coefficient of agreement based on comparison of the predicted and actual class assignment for each accuracy assessment sample point. It is calculated according to the equation:

$$\hat{\kappa} = \frac{P_o - P_c}{1 - P_c}$$

, where P_o is the proportion of correctly classified sample points and P_c is the proportion of agreement between the map and the reference data that would be expected by chance alone (Foody 2004).

The statistical significance of differences in map accuracy was tested using the McNemar test, which is the equivalent of the chi-squared test for dependent samples. It is appropriate for this situation because the same set of reference plots was used to test the accuracy of each classification, rather than an independent sample of reference plots for each classification. The McNemar test is based on the chi-squared test statistic, χ^2 , and is calculated using the equation:

$$\chi^2 = \frac{(|f_{1,2} - f_{2,1}| - 1)^2}{f_{1,2} + f_{2,1}}$$

, where, if classification 1 and classification 2 are the two classifications that are being compared, then $f_{1,2}$ is the frequency of accuracy assessment points that are correctly classified by classification 1 but incorrectly classified by classification 2 and $f_{2,1}$ is the frequency of accuracy assessment points that are correctly classified by classification 2 but incorrectly classified by classification 1 (Foody 2004; International Business Machines (IBM) Corp. 2010).

McNemar tests were performed using the SPSS Statistics software program (International Business Machines (IBM) Corp. 2010).

RESULTS

SVM Parameter Optimization

The results of the parameter optimization trials for the RBF SVM classification are shown in Figure 2.2. Varying gamma from 0.01 to 7.0 resulted in only a slight decrease in classification accuracy for gamma values greater than 1. For gamma values below 1, overall classification accuracy was 68 percent (kappa = 0.63) and for gamma values above 1, overall accuracy dropped to 67 percent (kappa = 0.62). Accuracy among the vegetation classes remaining constant at 55 percent (kappa = 0.48) for all values of kappa tested (Figure 2.2; a). Unsurprisingly, the McNemar test results indicated that there were no significant differences in classification accuracy among the Kappa trials. The ENVI default kappa value of 0.125 was therefore selected for the remainder of the SVM classifications. Varying the penalty parameter resulted in a slight increase in classification accuracy from an overall accuracy of 67 percent (kappa = 0.62) when the penalty parameter was set to 10 to an overall accuracy of 71 percent (kappa = 0.67) when the penalty parameter was set to 10,000 (Figure 2.2; b). There was a greater increase in the accuracy of the vegetation classes from 54 percent (kappa = 0.46) to 65 percent (kappa = 0.59) over the same range. However, the McNemar test results indicated that none of these differences in classification accuracy were significant at the 0.05 probability level.

Figure 2.3 illustrates the results of the parameter optimization trials for the polynomial SVM classification. Varying the polynomial order from 2 to 6 resulted in an increase in overall classification accuracy from 67 percent (kappa = 0.62) to 71 percent (kappa = 0.67) and an increase in vegetation class accuracy from 55 percent (kappa = 0.48) to 63 percent (kappa = 0.57) (Figure 2.3; a). The results of the McNemar tests indicated that differences in classification accuracy among SVM classifications with different polynomial orders were not significant at the 0.05 probability level. A polynomial order of 6 was selected for the remaining

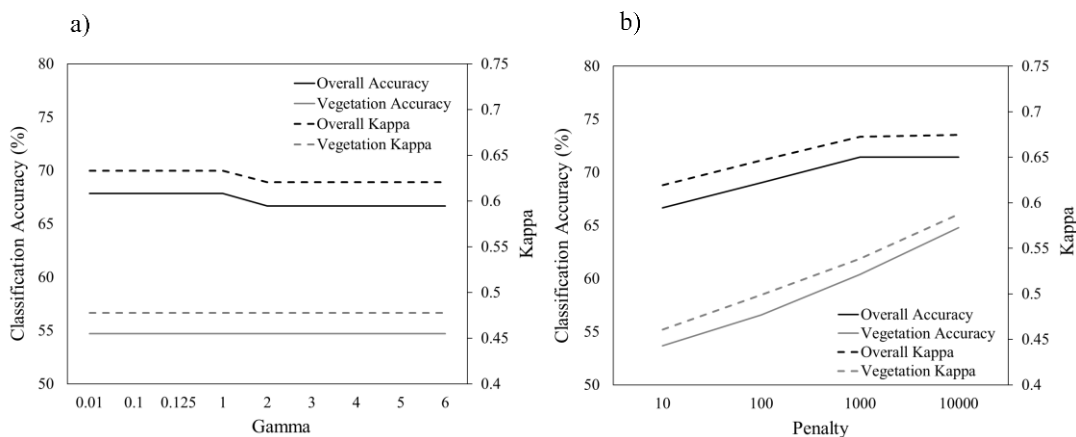


Figure 2.2 – Optimization for RBF SVM classification: a) Results of Gamma optimization trials, b) Results of penalty optimization trials

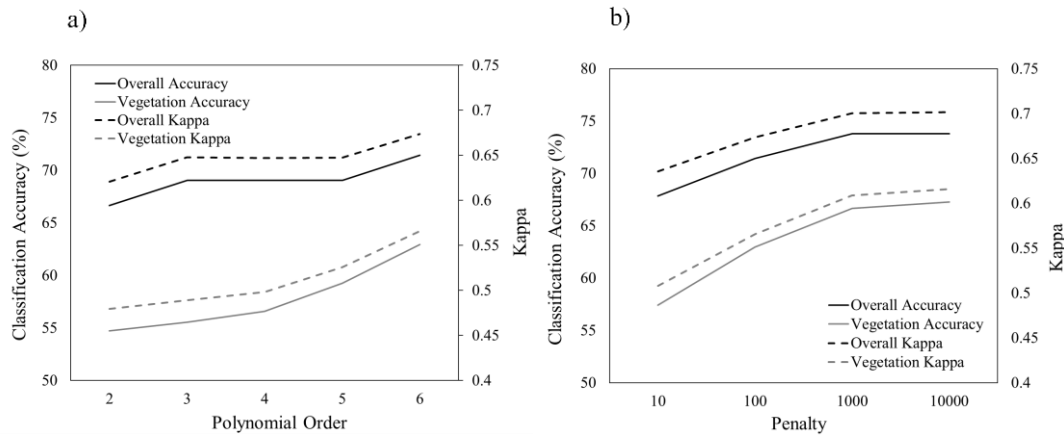


Figure 2.3 – Order optimization for polynomial SVM classification: a) Results of order optimization trials, b) Results of penalty optimization trials

polynomial parameter trials because it resulted in the highest overall accuracy, even though the differences in accuracy were not statistically significant. Varying the penalty parameter from 10 to 10,000 resulted in an increase in overall classification accuracy from 67.9 (kappa = 0.64) to 73.8 (kappa = 0.70) and an increase in vegetation class accuracy from 57.4 (kappa = 0.51) to 67.3 (kappa = 0.62) (Figure 2.3; b). Based on the McNemar test, the classification accuracy was significantly greater using penalty values of 1,000 or 10,000 as opposed to 10, but classification accuracy at a penalty value of 100 was not significantly different from the accuracies for smaller or larger penalty values.

Based on these trials, the highest overall classification accuracy of 73.8 was achieved for the SVM classification using the polynomial kernel with an order of 6 and penalty value of 10,000. This SVM classification result was compared to the MLC classification.

Comparing MLC and SVM Classifications

Overall classification accuracy for the MLC classification was 75 percent, with a kappa value of 0.71 (Table 2.1). When only the vegetation classes were considered, classification accuracy was 71.7 percent (kappa = 0.71). User's accuracy ranged from 0 percent for *B. laevis* to 100 percent for *C. esculenta*, *P. australis*, other SAV's, and water. User's accuracies greater than or equal to 70 percent were found for seven classes: *S. nigra* (89%), *C. esculenta* (100%), *Typha spp.* (75%), *P. australis* (100%), other SAVs (100%), water (100%), and bare/mudflat (93%). Producer's accuracy ranged from 0 percent for *B. laevis* to 100 percent for *P. punctatum*, *N. lutea*, and water. Producer's accuracies greater than or equal to 70 percent were found for the following six classes: *S. nigra* (89%), *P. punctatum* (100%), *N. lutea* (100%), other SAVs (75%), water (100%) and bare/mudflat (70%).

The confusion matrix for the MLC classification (Table 2.2) indicates that there is a high incidence misclassification of other vegetation classes as *P. punctatum*. The classes most commonly confused with *P. punctatum* were *C. esculenta*, *Typha spp.*, and *Z. miliacea*. Another frequent source of classification error was the misclassification of bare/mudflat areas as vegetation, particularly *Z. miliacea* and *P. punctatum*.

Table 2.1 – Comparison of SVM and MLC classification accuracy

Class	SVM		MLC	
	User's Accuracy (%)	Producer's Accuracy (%)	User's Accuracy (%)	Producer's Accuracy (%)
<i>Salix nigra</i>	81.8	100.0	88.9	88.9
<i>Colocasia esculenta</i>	88.9	66.7	100.0	66.7
<i>Polygonum punctatum</i>	56.3	81.8	50.0	100.0
<i>Bidens laevis</i>	NA	NA	0.0	0.0
<i>Typha spp.</i>	33.3	14.3	75.0	42.9
<i>Zizaniopsis miliacea</i>	16.7	33.3	25.0	33.3
<i>Phragmites australis</i>	50.0	50.0	100.0	50.0
<i>Nelumbo lutea</i>	71.4	100.0	60.0	100.0
Other SAVs	100.0	75.0	100.0	75.0
Water	100.0	100.0	100.0	100.0
Bare/mudflat	93.3	77.8	93.3	70.0
Overall Accuracy (%)	73.8		75.0	
Kappa	0.70		0.71	
Vegetation Accuracy (%)	67.3		71.7	
Vegetation Kappa	0.62		0.66	

Overall classification accuracy for the best SVM classification was 71 percent, with a kappa value of 0.67. User's accuracies ranged from 14 percent for *Z. miliacea* to 100 percent for other SAVs and water. User's accuracies greater than 70 percent were found for the following five classes: *S. nigra* (82%), *C. esculenta* (89%), other SAVs (100%), water (100%), and bare/mudflat (93%). Producer's accuracies ranged from 14 percent for *Typha spp.* to 100 percent for *S. nigra*, *N. lutea*, and water. Six classes had producer's accuracies greater than 70 percent: *S. nigra* (100%), *P. punctatum* (73%), *N. lutea* (100%), other SAVs (75%), water (100%), and bare/mudflat (74%).

Figure 2.4 shows a comparison between the maps generated by the MLC and SVM classifications. The areas mapped for each of the classes is shown in Figure 2.5. The MLC classification mapped greater areas of *Z. miliacea*, *P. nodosus*, *P. punctatum*, *P. australis*, *N. lutea*, and dead vegetation, while the SVM classification mapped greater areas of *S. nigra* seedlings, *Sagittaria spp.*, *P. dissectum*, other SAVs, *E. crassipes*, and *C. esculenta*. However, the results of the McNemar test indicate that the difference in classification accuracy between the MLC and SVM classifiers is not statistically significant.

Contribution of the new spectral bands

Table 2.3 demonstrates the change in classification accuracy associated with each of the four new spectral bands employed by the WorldView-2 sensor. The exclusion of the red-edge band (Band 6) had the greatest impact on classification accuracy, both at the level of overall accuracy and among the vegetation classes in particular. Removing this band decreased overall classification accuracy by approximately six percentage points and vegetation class accuracy by

Table 2.2 – Confusion matrix for MLC classification

Classification	Reference Data													
		<i>Salix nigra</i>	<i>Colocasia esculenta</i>	<i>Polygonum punctatum</i>	<i>Bidens laevis</i>	<i>Typha spp.</i>	<i>Zizaniopsis miliacea</i>	<i>Phragmites australis</i>	<i>Nelumbo lutea</i>	<i>Eichhornia crassipes</i>	Other SAVs	Water	Bare/Mudflat	Total
	<i>Salix nigra</i>	8	1	0	0	0	0	0	0	0	0	0	0	9
	<i>Colocasia esculenta</i>	0	8	0	0	0	0	0	0	0	0	0	0	8
	<i>Polygonum punctatum</i>	0	3	11	1	3	2	0	0	0	0	0	2	22
	<i>Bidens laevis</i>	1	0	0	0	0	0	0	0	0	0	0	0	1
	<i>Typha spp.</i>	0	0	0	0	3	0	1	0	0	0	0	0	4
	<i>Zizaniopsis miliacea</i>	0	0	0	0	0	1	0	0	0	0	0	3	4
	<i>Phragmites australis</i>	0	0	0	0	0	0	1	0	0	0	0	0	1
	<i>Nelumbo lutea</i>	0	0	0	0	0	0	0	3	0	1	0	1	5
	<i>Eichhornia crassipes</i>	0	0	0	1	0	0	0	0	0	0	0	0	1
	Other SAVs	0	0	0	0	0	0	0	0	0	3	0	0	3
	Water	0	0	0	0	0	0	0	0	0	0	11	0	11
	Bare/Mudflats	0	0	0	0	1	0	0	0	0	0	0	14	15
Total	9	12	11	2	7	3	2	3	0	4	11	20	84	

nearly ten percentage points. The coastal blue band (Band 1) had the second largest contribution to classification accuracy in this coastal deltaic system, with its removal resulting in a decrease in overall accuracy of 3.6 percentage points and a decrease in vegetation class accuracy of 5.7 percentage points. The second NIR band (Band 8) contributed minimally to classification accuracy, with its removal resulting in only a 1.2 percentage point decrease in overall accuracy and a 1.9 percentage point decrease in vegetation class accuracy. Surprisingly, removing the yellow band (Band 4) resulted in no decrease in either overall or vegetation class accuracy for this system. While these differences in classification accuracy are substantial, the McNemar test results indicated that they are not statistically significant at the 0.05 significance level, both in comparison to the full eight-band WV-2 classification and among each other.

Comparison to other high-resolution sensors

Table 2.4 shows the results of comparison between the full 8-band WorldView-2 imagery and simulated imagery from the Quickbird, IKONOS and OrbView-3 sensors. Reducing the WorldView-2 image to the 4 bands used by the Quickbird sensor and degrading the spatial resolution to 2.4 m resulted in a nearly 5 percentage point decrease in overall classification accuracy and a decrease of over 8 percentage points for the vegetation classes. Further degrading the spatial resolution to 4 m to simulate the IKONOS and OrbView-3 sensors resulted in an additional loss of 1 percentage point for overall accuracy and nearly 4 percentage points for

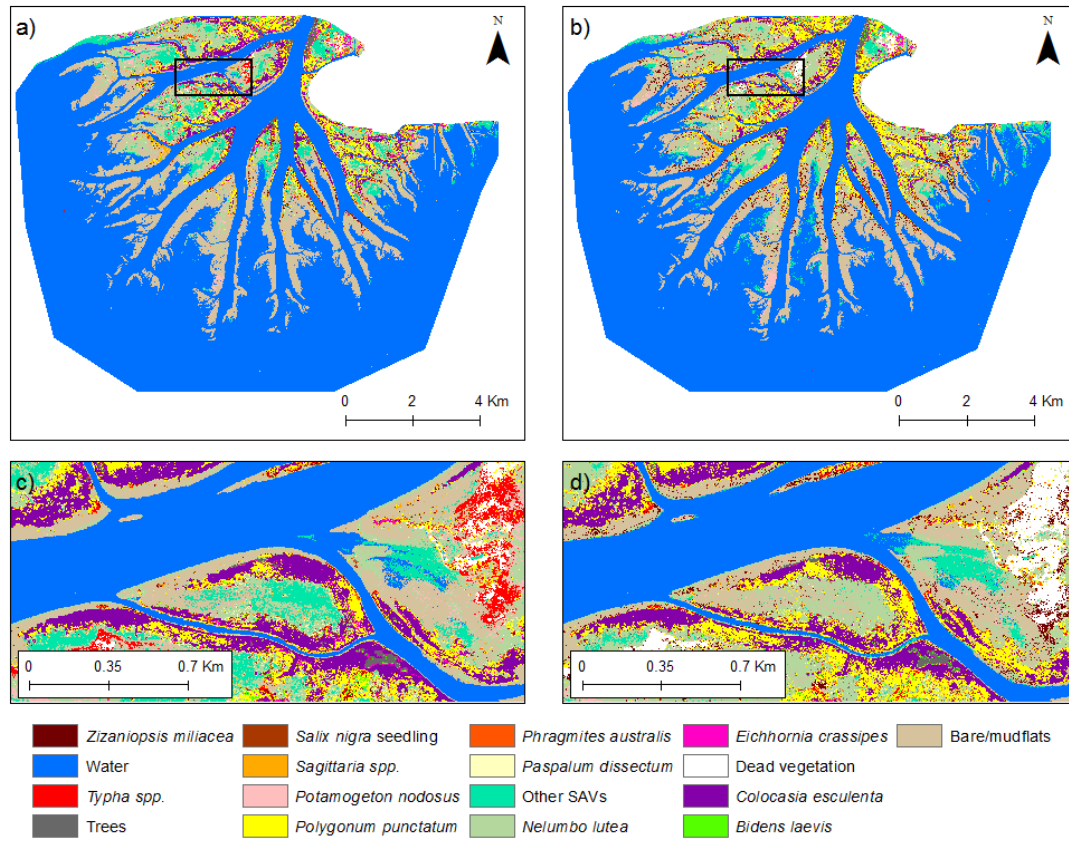


Figure 2.4 – Comparison of SVM and MLC classification maps: a) and c) SVM classification, b) and d) MLC classification

vegetation class accuracy. The results of the McNemar tests indicated that the difference in classification accuracy between the reduced-band and degraded spatial resolution classifications were not significantly different from the classification based on the full eight-band WV-2 data at the 0.05 significance level.

DISCUSSION

The results of these SVM classification kernel parameter trials differ from those of previous studies, highlighting the importance of optimizing the kernel parameters to each individual imagery source, study area, and classification task when performing SVM classification. In this study, the polynomial kernel with an order of 6 and penalty value of 10,000 gave optimal results when using WorldView-2 satellite data to map vegetation at the species-level in a deltaic, freshwater marsh setting with sharp species zonation. The different results obtained by authors of previous studies likely relates to differences in the number of available bands, spatial scale, and classification scale or degree of class heterogeneity in those studies. Huang et al. (2002) found that the accuracy of SVM classification using the polynomial

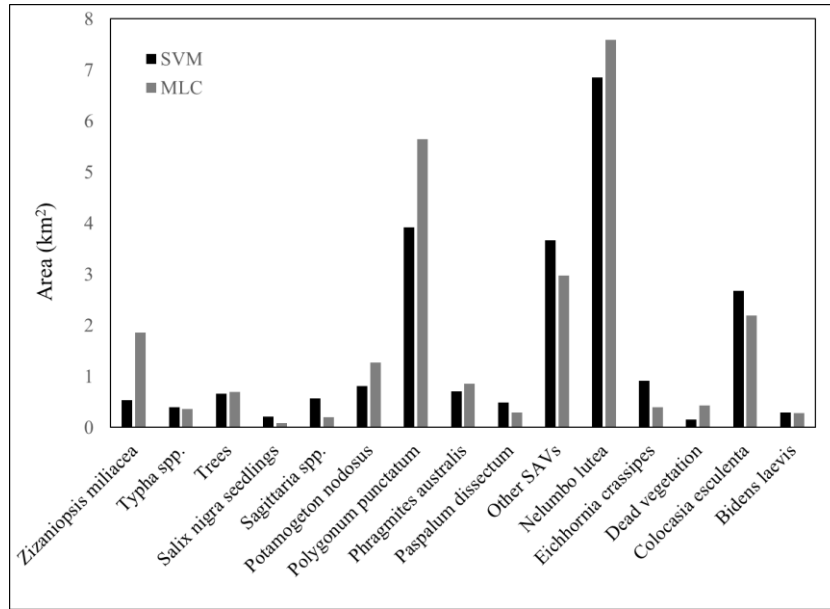


Figure 2.5 – Distribution of area among classes for SVM and MLC classifications

Table 2.3 – Change in classification accuracy associated with the new bands in the WorldView-2 sensor

Trial	All Classes		Vegetation Classes	
	Overall Accuracy	Kappa	Overall Accuracy	Kappa
All 8 Bands	75.0	0.71	71.7	0.66
Minus Band 1 (coastal blue)	71.4	0.67	66.0	0.60
Minus Band 4 (yellow)	75.0	0.71	71.7	0.66
Minus Band 6 (red-edge)	69.1	0.65	62.3	0.56
Minus Band 8 (IR)	73.8	0.70	69.8	0.64

Table 2.4 – Comparison to other high-resolution sensors

Trial	All Classes		Vegetation Classes	
	Overall Accuracy	Kappa	Overall Accuracy	Kappa
All 8 Bands, 2 m (WorldView-2)	75.0	0.71	71.7	0.66
4 Band, 2.4 m (Quickbird)	70.2	0.66	62.3	0.56
4 Band, 4 m (IKONOS, OrbView-3)	69.1	0.64	58.5	0.51

kernel increased as order increased from 1 to 8, similar to what was found in this study. They attributed this effect of polynomial order to the small number of variables (imagery bands) used in their studies. As this study also used few input bands compared to hyperspectral imagery, these results further support those conclusions. Huang et al. (2002) observed an increase in classification accuracy using the RBF kernel when gamma was increased from 1 to 7.5. In this study, no significant impact of gamma on classification accuracy was observed over the same range of values.

Many previous studies have achieved greatest classification accuracy with the SVM classifier using the RBF kernel. Pal and Mather (2005) found that the RBF kernel with a gamma value of 2 and penalty value of 5000 resulted in optimum classifier performance both for mapping agricultural crops using Landsat ETM+ data and mapping broad land cover classes (eg, vineyards, hydrophytic vegetation, pasture, urban) using hyperspectral imagery. Kavzoglu and Colkesen (2009) also found that the RBF kernel provided superior classification accuracy for mapping broad land cover classes using Landsat ETM+ and Terra Aster imagery. They found that a gamma value of 3 and penalty parameter of 250 were optimal for the RBF kernel using the Landsat ETM+ image but a gamma value of 1 and penalty parameter of 245 produced optimal results using the Aster imagery, further supporting the need to optimize each kernel to the specific imagery and classification task at hand. However, not all previous studies have favored the RBF kernel – Dixon and Candade (2008) obtained optimal results for Landsat TM 5 data using the polynomial kernel with an order of 3 and penalty value of 1,000. The polynomial kernel provided better results than the RBF classifier, suggesting that optimal kernel choice is also highly variable among remote sensing applications.

The result that the MLC classifier performed as well or better than the SVM classifier in this study differs from the findings of most other remote sensing studies, in which SVM has been shown to be superior to MLC in a wide variety of settings and using imagery ranging from moderate resolution satellite imagery (Landsat and Aster) to high-resolution hyperspectral imagery (Boyd et al. 2006; Dixon et al. 2008; Huang et al. 2002; Kavzoglu and Colkesen 2009; Pal and Mather 2005). However, the source of this discrepancy lies in the reason why SVM classification generally provides better classification results for remote sensing applications. The SVM classifier frequently outperforms the MLC classifier because it does not require that the reflectance values for the individual classes be normally distributed. Many mapped land cover classes consist of multiple materials or subclasses with different spectral properties, resulting in bimodal or multimodal distributions. Bimodal or multimodal reflectance distributions are particularly common when coarse land cover classes are used relative to the spatial resolution of the sensor. In this study, the plant species mapped grow in relatively monotypic stands, resulting in reflectance distributions that can be approximated by the Gaussian normal distribution. This makes use of the MLC classifier appropriate, particularly given its easier implementation compared to the SVM parameter, as it does not require kernel optimization. The classes that were poorly classified by the MLC classifier were those that either were potentially poorly trained due to Tropical Storm Lee (*Z. mileacea*, *Typha spp.*) or those that tend to grow in mixed stands with other species present as subdominants. The latter case is exemplified by *P. punctatum*, which was frequently over-mapped at the expense of *C. esculenta*, *Typha spp.*, and *Z. mileacea*. The *P. punctatum* class is the most heterogeneous class included in the classification, with many other species commonly growing as subdominants in the *Polygonum* mixture community. Several unclassified species that are rarely dominant over large areas of the delta (e.g. *Leersia oryzoides*, *Panicum hemitomon*, *Vigna luteola*), are present as subdominants in the

Polygonum community and can lead to classification error when they are also subdominant in other classes, particularly since they were more likely to be included in the training areas for *P. punctatum* than for the other classes. Closer examination of the misclassified accuracy assessment points indicates that most of the points misclassified as *P. punctatum* were highly mixed, with 40 percent or more combined cover values for subdominant species. *V. luteola* was also present at some of the misclassified sites. *V. luteola* is a vine that can create a dense layer on top of the herbaceous marsh vegetation, blocking reflectance from the species that would be considered dominant on the basis of cover values alone. It is therefore unsurprising that the presence of this species would result in classification error.

The results of this study compare favorably to other studies where high resolution satellite imagery has been used to map coastal vegetation. Collin and Planes (2011) achieved kappa values greater than 0.9 for both artificial neural network (ANN) and SVM classification of WorldView-2 imagery, including specific tree species as well as broader vegetation classes such as “bush” and “grass.” The lower classification accuracy in this study is most likely due to the nearly exclusive focus on individual species, without the inclusion of broader mixed classes. While overall classification accuracy and kappa values were diminished by several classes that may have been poorly trained due to Tropical Storm Lee, class-specific users and producer’s accuracies greater than 90 percent were found for several species. Immitzer et al. (2012) similarly found user’s accuracies ranging from 57 to 92 percent and producer’s accuracies ranging from 33 to 94 percent for individual tree species using WorldView-2 data. Belluco et al. (2006) achieved overall accuracies of greater than 95 percent when classifying salt marsh species using high spatial resolution Quickbird and IKONOS imagery. However, salt marsh plant zonation tends to be much stricter along tidal inundation gradients than the zonation observed among freshwater species in the Wax Lake delta, allowing for greater species-level classification accuracy. The accuracies achieved in this study also compare favorably to the accuracies achieved for species-specific classifications using hyperspectral imagery (Belluco et al. 2006; Filippi and Jensen 2006; Hirano et al. 2003), but at significantly reduced cost.

In general, bands 1 (coastal blue), 6 (red-edge) and 8 (second IR) resulted in slight increases in overall classification accuracy compared to trials where they were removed prior to classification, although the differences in classification accuracy were not statistically significant based on the McNemar test. The red-edge band contributed the most to both increased overall classification accuracy and accuracy of the vegetation classes, specifically. Unsurprisingly, its impact was greater on vegetation class accuracy than on overall accuracy. Previous studies have indicated that spectral information in the red-edge portion of the light spectrum may be particularly valuable for separating coastal marsh species (Artigas and Yang 2006), and my results support that assertion. The coastal blue band was second in terms of its contribution of increased accuracy, followed by the second IR band. Removal of the yellow band, however, resulted in no change in classification accuracy for this particular application. This is surprising considering that the yellow band corresponds to the absorption band for minor plant pigments that become more important during senescence and the image use for this analysis was taken in October. However, the growing season is quite long in coastal Louisiana with the average first fall freeze not occurring until early December (Louisiana Office of State Climatology and Southern Regional Climate Center). It is possible that the influence of the yellow band would be more apparent for imagery taken during November or December in this particular climate.

The additional four bands in the WV-2 sensor do appear to provide greater discriminating power for freshwater wetland vegetation compared to other available 4-band high resolution

satellite sensors such as Quickbird, IKONOS, and OrbView-3. The inclusion of the four additional bands resulted in a 5 percent increase in overall accuracy, compared to the spectrally-degraded dataset, and a 9.4 percent increase in accuracy among the vegetation classes. The enhanced spatial resolution of the WorldView-2 sensor is less important for mapping coastal marsh vegetation at the species-level – spatially degrading the dataset to 4-m spatial resolution to mimic IKONOS and OrbView-3 resulted in only a marginal decrease in classification accuracy compared to the spectrally-reduced 2-m dataset designed to mimic Quickbird. Overall, these results indicate that WorldView-2 imagery provides better results for mapping the distribution of freshwater marsh species than other available high-resolution satellite sensors, largely as a result of the addition of the red-edge, and to a lesser extent, the coastal blue band.

CONCLUSIONS

As this study demonstrates, the combination of eight spectral bands of information and high spatial resolution make the new WorldView-2 satellite well-suited to mapping diverse and heterogeneous coastal wetland systems such as the Wax Lake delta. An overall classification accuracy of 75 percent was achieved and individual user's and producer's accuracies greater than 70 percent were achieved for many species. These accuracies exceed species-specific mapping results found using four-band high-resolution satellite sensors such as IKONOS and Quickbird and rivals those found using satellite and airborne hyperspectral sensors, but at lower acquisition cost and reduced processing time and effort. The red-edge and coastal blue bands contributed the most to increased mapping accuracy and the combination of all eight spectral bands provided greater classification accuracy than when only the four more common bands were used. Surprisingly, the exclusion of the yellow band had no impact on classification accuracy in this instance. This is likely because most of the mapped plant species had not yet begun to senesce at the time of image acquisition. Further studies performed using imagery timed to maximize variability in the degree of senescence between species would provide a better measure of the potential benefit of this band.

Contrary to many previous studies, the parametric MLC classifier provided as high or higher map accuracy than the non-parametric SVM classifier for this particular mapping application. The favorable performance of the MLC classifier in this study is likely a result of the fairly homogenous composition of the target classes at the two-meter spatial scale and hence relatively normal distribution of the reflectance values for each class in each of the spectral bands. The SVM classifier has become increasingly popular due to its ability to handle remote sensing data that violate the assumption of normality that is implicit in parametric classifiers such as MLC. However, the SVM classifier requires substantially more effort due to the need to optimize kernel and parameter selection for each remote sensing application and computing time can be extensive depending on the parameter values selected. The results of this study suggest that the simpler MLC classifier is adequate for mapping individual plant species using high spatial resolution imagery in a river delta setting with a high degree of species zonation.

CHAPTER 3 – FACTORS CONTROLLING PLANT SPECIES DISTRIBUTIONS IN A YOUNG RIVER DELTA

ABSTRACT

Plants influence depositional patterns in river deltas but models of river delta formation generally fail to include a biological component, due to a poor understanding of the factors that control plant species distributions in deltas and the feedbacks that occur between plant community development and geomorphic processes. Classification and regression tree (CART) analysis was used to model the distribution of six freshwater wetland species at Wax Lake Delta, a small pro-grading subdelta of the Mississippi River. Thirteen candidate explanatory variables were evaluated for their significance in discriminating between species: elevation, slope, aspect, distance to any channel, distance to primary, secondary, and tertiary channels, distance to the upstream end of the island, island orientation relative to river flow, area of trees on the island, island age, distance to another patch of the same vegetation, and time since last storm disturbance event. Two single CART trees were first constructed to explore relationships between species distributions and all candidate explanatory variables and between species distributions and elevation alone. The Random Forests classification tree bagging algorithm was then used to construct a more powerful predictive model of species distributions. The optimal full CART model had a classification accuracy of 65 percent while the simple elevation-only CART model had an accuracy of 54 percent. A higher overall predictive accuracy of 71.5 percent was achieved using Random Forests. These results suggest that elevation remains the most important driver of species distributions in this deltaic setting. However, it is not as singly important as has been observed in other coastal wetlands and other factors such as inundation duration, riverine and tidal flushing, substrate-type, soil development, ecological succession, and sheltering play important secondary roles.

INTRODUCTION

Wetland plants influence the geomorphic formation of river deltas in a number of ways, including: binding sediments with their root systems, increasing surface friction, and providing organic material that contributes to sediment accretion (Day et al. 2008; Paola et al. 2011; Turner et al. 2000). While the geologic processes that control river delta development have been successfully modeled (Kim et al. 2009; Paola et al. 2011), few attempts have been made to integrate the vegetation community and its interaction with physical processes. Understanding the role of vegetation in delta formation is complicated by the fact that individual plant species vary in the degree to which they contribute to delta-building processes (Nyman et al. 1995; Nyman et al. 1993). A more thorough understanding of how the physical and ecological controls on plant species distribution impact vegetation patterns would enhance our ability to model the vegetation communities of developing and evolving river deltas and allow us to use the relative sediment-trapping and organic accretion properties of different species to better predict the influence of plants on delta geomorphology.

Plant species distributions and community formation are controlled by a variety of physical and ecological factors, including: environmental gradients such as altitude (Beals 1969),

salinity (Crain et al. 2004; Jiang et al. 2012; Latham et al. 1994), temperature (Franklin 1998; Pielou and Routledge 1976), exposure (Wilson and Keddy 1986; Wilson and Keddy 1988), and nutrient availability (Emery et al. 2001; Parrish and Bazzaz 1982); plant growth strategy (Huston and Smith 1987); phenology relative to interannual climate fluctuations (Bazzaz 1990; Harper 1974); differential predation (Evers et al. 1998; Gough and Grace 1998b); 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 et al. 1998; Tilman 1988). Natural gradients in elevation, and hence the frequency and duration of flooding, occur in all coastal wetlands and the relative tolerance of wetland plant species to flood stress exerts a strong control on the spatial patterns observed in coastal wetlands (Eleuterius and Eleuterius 1979; Kershaw 1976; Roozen and Westhoff 1985; Sanchez et al. 1998). In many systems, this physical stress controls the lower distribution limits of plant species, while interspecific competition defines the upper boundaries (Bertness and Ellison 1987; Pielou and Routledge 1976). This process has been best studied in salt marshes, where particularly strong spatial zonation is observed in the plant communities.

Less work has been done on the factors that control plant species distributions in freshwater marshes, which tend to have much higher species diversity and less clear spatial zonation compared to salt marshes (Odum 1988). The absence of salt stress allows more species to invade these environments and presumably creates higher competition pressure than is observed in salt marshes. Also, because plants that grow in freshwater marshes are not adapted to salinity, disturbance events that raise porewater salinity may have a more lasting impact on species distributions than in salt marshes. In river deltas, freshwater marshes form in a particularly dynamic environment that is subject to rapid sedimentation and both riverine and coastal influence. In addition to the factors that control plant distributions in other freshwater coastal settings, plant distributions in river deltas may be influenced by the relative tolerance of species to river flows and rapid sedimentation. River floods bring strong flows that scour channel banks and high sediment deposition that can bury adult plants and seeds (Francis 2006; Hupp and Osterkamp 1996). The relative tolerance of different species to both erosion and burial may thus be an important control on plant community spatial structure in these settings. Also, because sediment is deposited in deltas along a grain size continuum, underlying sediment texture patterns may influence the observed spatial structure of deltaic wetland communities (Wright 1977).

The objective of this study is to identify the primary drivers of plant species distributions in the Wax Lake Delta, a small, pro-grading subdelta of the Mississippi River in coastal Louisiana, USA and to compare them to the drivers of plant community composition in more thoroughly studied tidal freshwater and saltmarsh environments. Classification tree analysis, a recursive binary partitioning technique, is used to explore relationships between species distributions and a number of spatially-derived candidate explanatory variables suspected to be important in controlling species distributions in this setting. Variables believed to be related to elevation, light environment, degree of sheltering, successional stage, substrate gradients, and degree of riverine and tidal flushing are evaluated for their impact on the distribution of six common marsh species. The Random Forests classification tree bagging algorithm is then used to create a more accurate predictive model of species distributions than can be created using a single classification tree. The results are compared to a simple model using only elevation to

assess the degree to which variables other than elevation contribute to species distributions in deltaic wetlands.

METHODS

Modelled Species

A vegetation map created by maximum likelihood supervised classification of a June 15, 2010 WorldView-2 image of the Wax Lake Delta was used to determine the spatial distribution of plant species within the delta (Figure 3.2). Training areas and accuracy assessment points for the classification were derived from a reference map created by visual interpretation of 2009 color-infrared aerial photography and extensively ground-truthed in the field during the summer of 2010 (D. Elaine Hebert, unpublished data). The accuracy assessment indicated mapping accuracies of greater than 70 percent for the following six classes: *Salix nigra* (95%), *Colocasia antiquorum* (98%), *Polygonum spp.* (73%), *Nelumbo lutea* (92%), *Potamogeton nodosus* (93%), and other submerged aquatic vegetation (SAV) (89%). These classes were considered to be sufficiently accurate to use in constructing the vegetation distribution model.

Salix nigra (black willow) is a small to medium size tree with multiple trunks and lanceolate leaves that grows on the natural river levees in the delta (Chabreck and Condrey 1979). It is the only tree species found in naturally-developing areas of the delta. Other species of hardwood trees are found growing on dredge spoil disposal levees along the main channel at the upper end of the delta, but no attempt was made to distinguish between the *S. nigra* and spoil trees for this study.

Colocasia esculenta (elephant ear or taro) is a perennial forb and a member of the Arum family (Araceae). It has large, heart-shaped leaves (up to 0.6 m) with long (1 m) petioles that emanate from a starchy underground corm and can reach a maximum height of 2.5 m with a canopy spread of 2.5 under ideal growing conditions (Chabreck and Condrey 1979; United States Department of Agriculture). It is a globally important agricultural crop that has been cultivated for its edible corm for over two thousand years (Matthews 2010). However, it is considered invasive in wetlands because it forms monotypic stands that displace native plant species (Company et al. 2008; Nelson and Getsinger 2000). Within the Wax Lake Delta, *C. esculenta* grows along the lower channel levees, on the backsides of levees dominated by *S. nigra*, and in the understory of the *S. nigra* community.

Polygonum punctatum (dotted smartweed) is an annual/perennial herb with branched, trailing stems, linear leaves, and long racemes of scattered white flowers that grows to a maximum height of about 1 m (Chabreck and Condrey 1979; United States Department of Agriculture). Menges and Waller (2010) suggest that it is high-light specialist and a ruderal following the classification system of Grime (1977). They note that it reproduces both by opportunistic seed production when water levels are low and by slow vegetative growth when water levels are high. It is commonly found interspersed with *Colocasia esculenta* or in mixed communities at high to mid-elevations in the Wax Lake Delta. *Nelumbo lutea* (American lotus) is an aquatic, perennial herb with round, flat leaves 30 to 60 cm in diameter that can be either floating or emergent. It grows from rhizomes rooted in the bottom of shallow water areas and forms large, monotypic stands that are capable of rapid radial expansion of up to 14 m in a single growing season (Hall and Penfound 1944). Within the Wax Lake Delta it forms large beds

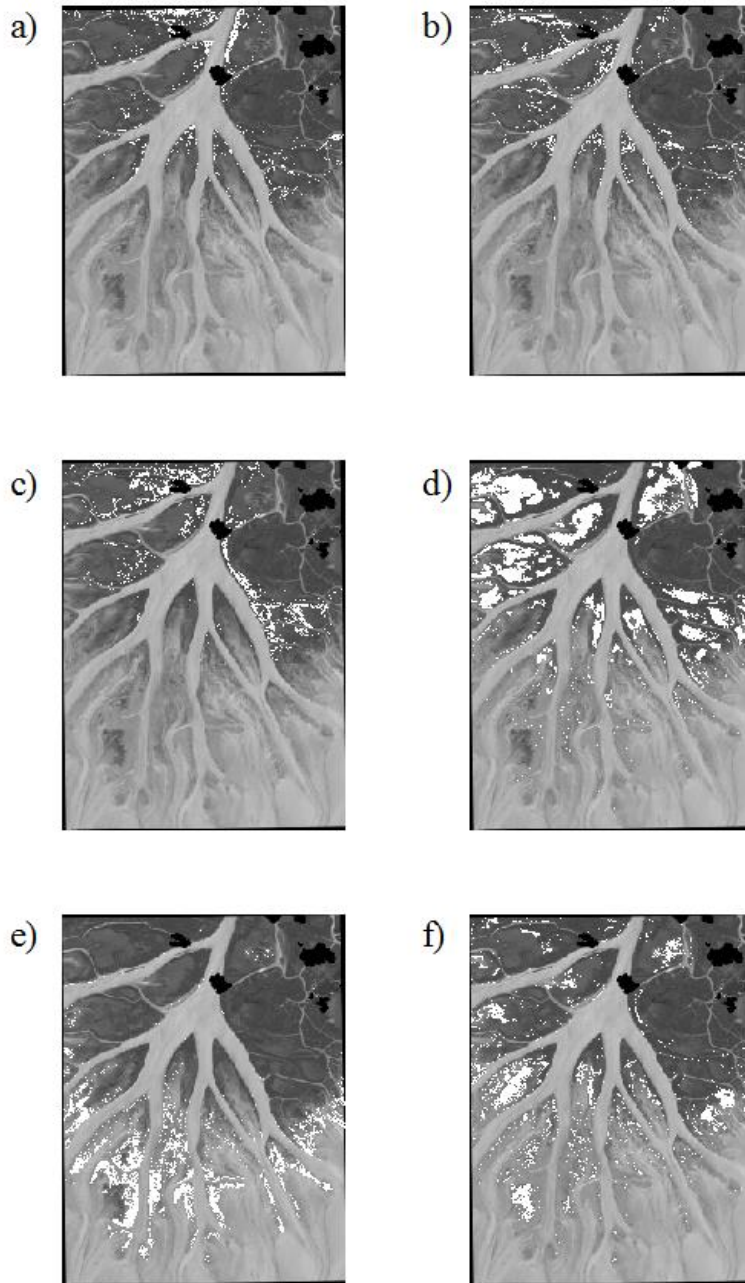


Figure 3.1 – Mapped distributions of target plant species in the Wax Lake delta: a) trees, b) *Colocasia esculenta*, c) *Polygonum punctatum*, d) *Nelumbo lutea*, e) *Potamogeton nodosus*, f) other SAVs

within the interior of the islands, with the greatest concentration at the upstream end of the islands. It is also occasionally found along shallow, gently sloping banks of the distributary channels.

Potamogeton nodosus (longleaf pondweed) is the most common SAV in the Wax Lake Delta. It is a rhizomous perennial aquatic herb with linear leaves about 5 cm long that float at

and just below the water's surface. Because its leaves block light from penetrating the water column, it often excludes other SAV species and forms large monotypic beds. The floating leaves gives it a unique spectral signature compared to the other SAVs, which allowed it to be mapped as a separate class.

The other SAV class is a mixed class consisting of all fully submerged aquatic vegetation in the delta, including: *Potamogeton pusillus*, *Potamogeton crispus*, *Myriophyllum spicatum*, *Elodea canadensis*, *Najas guadalupensis*, *Zannichellia palustris*, *Herteranthera dubbia*, and *Ceratophyllum demersum*. These other species are frequently found in mixed assemblages throughout the delta (Charles E. Sasser, unpublished data).

Candidate Explanatory Variables

Classification tree models were developed to relate the distribution of these six plant species classes to environmental variables based on their spatial distributions in the 2010 vegetation map. Fourteen candidate explanatory variables were considered for the models: elevation (*Elevation*), slope (*Slope*), aspect (*Aspect*), distance to water's edge (*WaterDist*), distance to any channel (*ChannelDist*), distance to primary (*PrimaryChannels*), secondary (*SecondaryChannels*), and tertiary (*TertiaryChannels*) channels, distance to upstream tip of the island (*TipDist*), island orientation relative to river flow (*IslandAngle*), area of trees on the island (*TreeArea*), island age (*IslandAge*), distance to another patch of the same species (nearest neighbor distance, *NND*), and years since the last coastal storm disturbance (*Storms*) (Table 3.1, Figure 3.2). The elevation variable was derived from a 2-m digital elevation model interpolated from light detection and ranging (LiDAR) data collected for the delta in January 2009. The LiDAR data were collected at low tide, with a point density of 4.5 points/m², and had an average vertical accuracy of 5.5 cm over flat surfaces (James Buttles, unpublished data). Elevations were calculated relative to the North American Vertical Datum of 1988 (NAVD88), using the U.S. National Geodetic Survey Geoid03 model. Slope and aspect were included in the model as measures of the importance of microtopography on plant species distributions. Differences in slope and aspect have been demonstrated to be important drivers of plant species distributions in other environments settings (Bennie et al. 2008; Lassueur et al. 2006). Slope and aspect grids were calculated from the digital elevation model using the Spatial Analyst extension for ESRI ArcGIS 10.0.

WaterDist is a proxy variable that is intended to measure the degree of tidal and riverine flushing and nutrient delivery to the site. In theory, areas that are further from the water should flood less frequently and be more stagnant and anoxic. Water is also more likely to be depleted of nutrients by the time it reaches these areas. To the extent that some species are more sensitive to nutrient limitation than others, this can be an important driver of plant distributions in some wetlands (Lenssen et al. 1998), but has not been directly tested at the Wax Lake delta. *WaterDist* was calculated for each grid cell using the Euclidean distance calculator in the Spatial Analyst extension for ESRI ArcGIS 10.0 and a water mask grid created from the classified 2010 WV-2 image. All primary, secondary, and tertiary channels were manually digitized from the 2010 WV-2 image and the Euclidean distance to each point on the islands was calculated according to the same matter as *WaterDist*. Distributary channels are important mechanisms by which river water, sediments, and nutrients are delivered to the delta, as opposed to the open water areas on the distal interior of the islands, which are more strongly influenced by tidal flows. The channels also have much higher energy than back water areas and plant communities growing closer to

Table 3.1 – List of Explanatory Variables

Abbreviation	Units	Description
<i>NND</i>	meters	Distance to another patch of the same vegetation class
<i>IslandAngle</i>	degrees	Angle of island relative to the river's flow
<i>TreeArea</i>	square meters	Area of trees on the island
<i>IslandAge</i>	years	Number of years since the island became subaerial
<i>Aspect</i>	degrees	Direction that the slope faces
<i>TipDist</i>	meters	Distance to the upstream tip of the island
<i>Slope</i>	degrees	Degree of inclination above a horizontal plane
<i>WaterDist</i>	meters	Distance to the nearest patch of deep water
<i>ChannelDist</i>	meters	Distance to the nearest distributary channel
<i>PrimaryChannels</i>	meters	Distance to the nearest primary distributary channel
<i>SecondaryChannels</i>	meters	Distance to the nearest secondary distributary channel
<i>TertiaryChannels</i>	meters	Distance to the nearest tertiary distributary channel
<i>Elevation</i>	meters	Meters above the North American Vertical Datum of 1988 (NAVD88)
<i>Storms</i>	years	Years since storm disturbance killed the vegetation

channels are subject to higher erosional forces. The variables *ChannelDist*, *PrimaryChannels*, *SecondaryChannels*, and *TertiaryChannels* were considered separately to test whether channel order was an important determinant of plant species distributions or whether channels of all sizes had an equal impact on the plant community.

TipDist, *IslandAngle*, and *TreeArea* are intended to measure factors that influence the degree of exposure to the river's flow at any given location within the delta. Previous work in the neighboring Atchafalaya Delta suggested that some species are limited by work in the neighboring Atchafalaya Delta suggested that some species are limited by intolerance to strong flows and do not become established on islands until the levee elevations are high enough to support trees, which effectively block flow over the lower and interior portions of the island (Johnson et al. 1985). *TipDist* was determined by digitizing the tips of the islands from the 2010 WorldView-2 image and calculating Euclidean distance in the same manner as *WaterDist* and the channel distance variables. *IslandAngle* was measured to a line digitized through the center of the Wax Lake Outlet and extending straight through the delta. For each island, a line was digitized from the channel centerline such that it would pass directly through the island tip and down the center of the island. *IslandAngle* represents the angle between the island centerline and

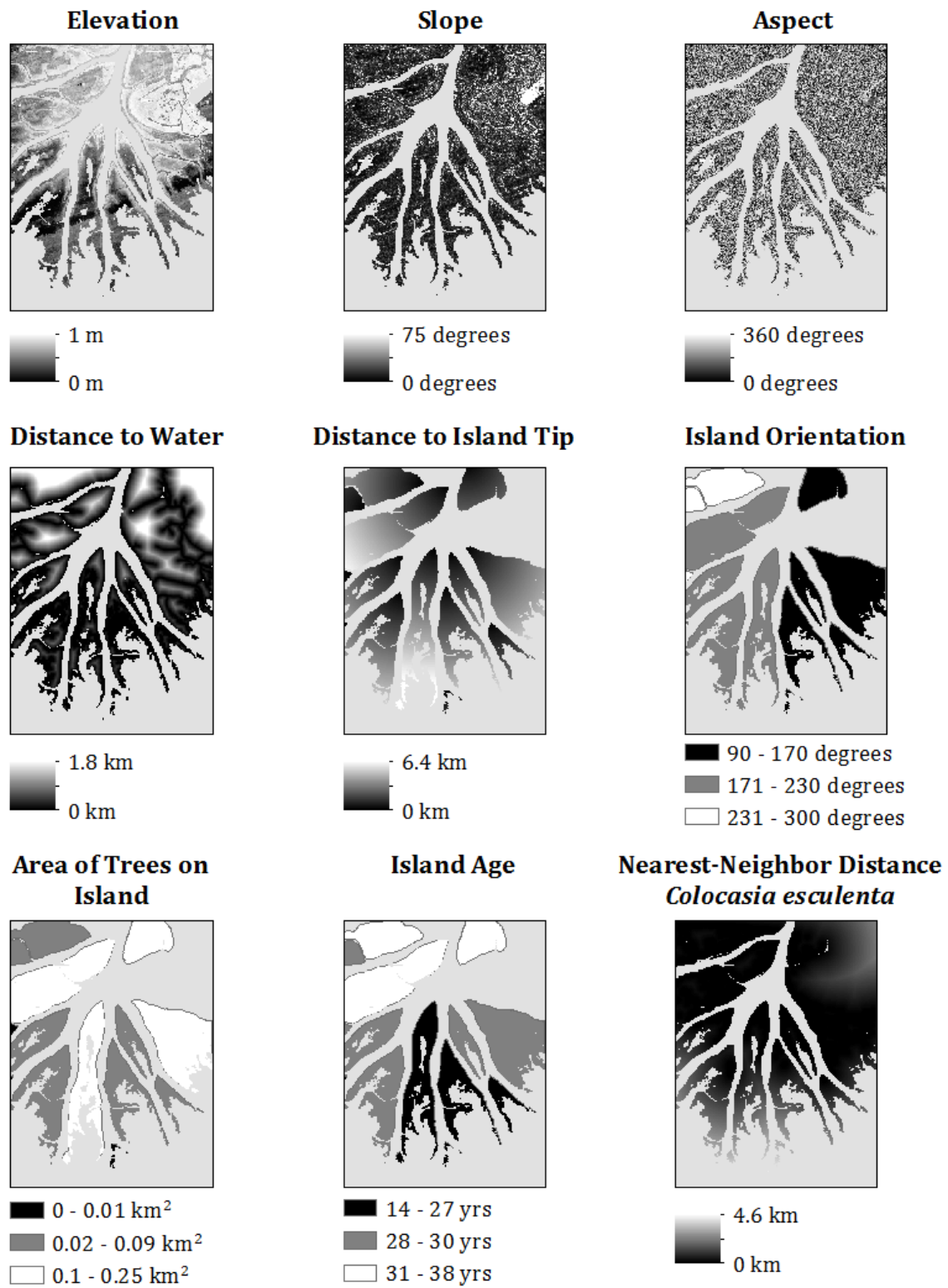
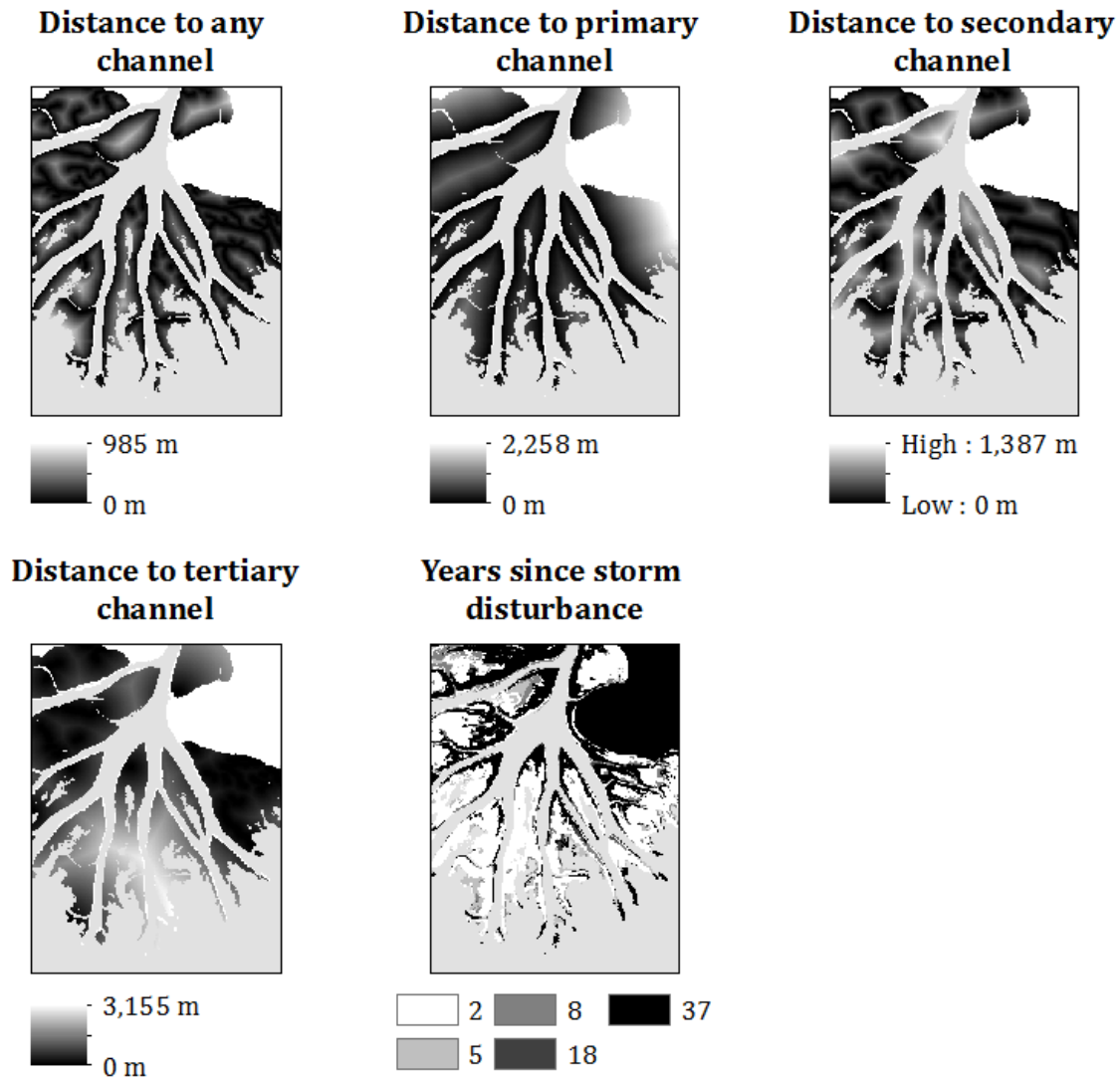


Figure 3.2 – Candidate Explanatory Variables

(Figure 3.2 continued)



the channel centerline. *TreeArea* was calculated by clipping the vegetation grid to the extent of each island and summing the area for the trees class on each island.

IslandAge was included as a candidate variable to test the degree to which ecological succession influences plant community composition and species distributions, independent of elevation. While succession in deltas is believed to be largely driven by elevation change (Johnson et al. 1985), it is also possible that the vegetation composition of individual islands changes over time independent of elevation, as soils mature and rapidly colonizing pioneer species are replaced by a more stable climax community. *IslandAge* was measured by examining winter Landsat imagery of Wax Lake Delta at 5-year intervals from the first subaerial exposure of the delta in 1973 to the present. The year that the island first appeared in the imagery was used to calculate current island age.

The *NND* variable was included as a measure of the importance of dispersal processes in the establishment of new stands of each plant species within the delta. Species with low *NND* values are those that tend to be more dispersal limited at the scale of the delta while those with

higher *NND* values are more likely to disperse readily to new habitats. However, factors other than dispersal may also influence *NND*. Species may also exhibit clumped distributions due to very specific habitat requirements that are only found in specific areas of the delta. Species with higher *NND* values may also have broader fundamental niches and an ability to colonize a wider variety of sites. The *NND* variable was calculated using the FRAGSTATS spatial analysis program (McGarigal et al. 2012). Homogeneous patches were identified for each vegetation class and nearest neighbor distance for each patch was calculated using the FRAGSTATS patch-level landscape metrics module.

Finally, to test the influence of storm disturbances on the species distributions within the delta, impact areas were identified for four hurricanes between 1973 and 2010 that had a significant impact on the vegetation community in the delta: Hurricane Andrew (1992), Hurricane Lili (2002), Hurricane Rita (2005), and Hurricane Ike (2008). The impact of these storms on the vegetation community of the delta was measured by comparing the normalized difference vegetation index (NDVI) for Landsat images of the delta taken immediately before and after each storm. The NDVI is a normalized ratio of the difference in light reflectance in the red and near infrared (NIR) portions of the light spectrum. It is calculated according to the equation:

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

Healthy green vegetation absorbs light in the red portion of the light spectrum and reflects light in the near infrared portion of the light spectrum. As a result, NDVI is strongly correlated to aboveground biomass, leaf area index, photosynthetic activity, and other indicators of vegetation health. Bare soils have NDVI values close to zero and deep water areas have negative NDVI values. To map the area of vegetation killed by each storm event, the area of the delta with positive NDVI values in the pre-storm Landsat image was identified and then areas that still had positive NDVI values in the post-storm image were removed. The impact areas from all four storms were combined to create a storm impact grid representing the number of years since each 30 m² grid cell in the delta had been impacted by a storm.

To relate plant species distributions to the explanatory variables, a stratified random sample of 400 data points was generated for each of the 6 target plant species, drawing the points from the pixels mapped as each species in the 2010 vegetation map and within the boundaries of the delta islands. Each of the explanatory variable grids was sampled at each point using the sample function in the ESRI ArcGIS 10.0 Spatial Analyst extension. Island-specific variables were sampled for each point using the Identity function in ArcGIS 10.0. To identify correlations among the set of potential explanatory variables, bivariate Pearson's product-moment correlation coefficients were calculated using the Statistical Product and Service Solutions (SPSS) statistical software package (International Business Machines (IBM) Corp. 2010).

CART Models

Classification trees were constructed for the full set of plant species and all candidate explanatory variables using the Salford Predictive Miner CART software package (Salford Systems 2013) with the Gini index as the splitting criteria (Breiman et al. 1984). Classification

and regression tree analysis (CART) is a non-parametric statistical method that repeatedly partitions the multidimensional space created by the predictor variables into zones that are as homogenous as possible in terms of the response variable (Vayssières et al. 2000). Unlike parametric statistical methods, it requires no assumption that the data fit a normal Gaussian model, an assumption that is frequently violated by ecological data in general and particularly by species responses to environmental gradients (De'ath and Fabricius 2000; Vayssières et al. 2000). In CART, a binary decision tree is constructed where successive splits are made based on values of one of the explanatory variables. At each node, all potential splits are considered for each explanatory variable, and the variable split is chosen which maximizes the homogeneity of the child nodes, with homogeneity defined by the Gini Diversity Index. The Gini Index is calculated as:

$$\phi(p) = \sum_j p_j(1 - p_j)$$

Where $p = (p_1, \dots, p_j)$ are the proportions of the j classes of the response variables for each node (Vayssières et al. 2000). The Gini Index is greatest for nodes with equal proportions of each class and least for nodes containing only a single class. The final nodes, or leaves, represent the final classification.

The Salford Systems CART software identifies the best classification tree as the tree with the minimum relative cost (classification error), regardless of the tree size (number of leaves) (Steinberg and Golovnya 2007). However, the software also indicates which other trees have a cost that is statistically indistinguishable from the “best tree.” The smallest tree that was statistically indistinguishable from the best tree for this analysis was selected for this study to improve the ease of interpretation of relationships within the data. For comparison, a simplified tree using only elevation as a predictor variable was also constructed.

Random Forests Model

While single classification trees are easy to interpret, superior classification accuracy can be achieved by bagging, a technique in which hundreds of classifications trees are constructed using randomly drawn bootstrap samples of the full dataset and the results of those trees are pooled to generate the final classification predictions. The Random Forests bagging algorithm (Salford Systems 2013) was used to create a more powerful predictive model for species distributions in the Wax Lake delta. Random Forests draws bootstrap samples of approximately 63 percent of the original dataset for use in generating each individual CART model. The unused data are referred to as the out-of-bag observations and are used for assessing the accuracy of each model. A CART tree is fit to each bootstrap sample, but at each node, only a random subset of variables is available for binary partitioning. The predicted class for any given observation is then calculated based on majority vote using all of the models, with ties split randomly (Cutler et al. 2013). Variable importance was calculated in a similar manner as in the CART models, using the Gini coefficient as a measure for how much the splits that involve each variable contribute to separating the classes. This includes variables that serve as primary splitters in the classification tree and surrogate variables. Overall importance scores are a function of both of how many nodes each variable contributes to and the location of those nodes

within the tree hierarchy. To better understand relationships between the explanatory variables and species distributions, the variable importance scores were compared from both the CART and Random Forest models. For the CART model, importance scores using all splitters (primary splitters and surrogates) were considered as well as the importance scores using only the primary splitters.

RESULTS

Variable correlations

Table 3.2 shows the Pearson's product-moment correlation coefficients for each pairwise combination of the 13 potential explanatory variables. While many of the variable combinations displayed significant correlations, most had correlation coefficients less than 0.30. The strongest bivariate correlations were between *Elevation* and *Storms* ($r^2 = 0.65$), between *TreeArea* and *IslandAngle* ($r^2 = -0.54$), between *IslandAge* and *WaterDist* ($r^2 = 0.45$), and between *ChannelDist* and *SecondaryChannels* ($r^2 = 0.44$). Both *Elevation* and *Storms* showed moderate positive correlations with *IslandAge* and moderate negative correlations with *TipDist*, *ChannelDist*, and *TertiaryChannels*. *Elevation* was also moderately correlated with *Slope*. Moderate correlations were found between *IslandAngle* and both *IslandAge* and *WaterDist*. *TertiaryChannels* had a moderate positive correlation with *ChannelDist* and a moderate negative correlation with *PrimaryChannels*.

Full CART Model

The CART analysis for the full set of explanatory variables resulted in selection of an optimal decision tree with 15 leaves and a relative cost of 0.42 (Figure 3.4). The relative importance scores for each of the primary splitters included in the CART model are provided in Table 3.3. The two most important explanatory variables in this model were *Elevation* and *WaterDist*, which had relative importance scores of 100.00 and 46.7, respectively. Two additional variables were moderately important in the model: *IslandAge* (relative importance = 26.0) and *PrimaryChannels* (relative importance = 15.7). *NND*, *Slope*, and *TreeArea* were of least importance, and each participated in only one split fairly low in the decision tree. When all splitters were considered (primary splitters and surrogates), *Elevation* and *WaterDist* remained the two most important variables, but *Storms* and *TertiaryChannels* were also fairly important, with importance scores of 47.7 and 28.6, respectively (Table 3.4). The importance of these two variables lies in their value as surrogate splitters, due to their high correlations with *Elevation* and *PrimaryChannels*. *PrimaryChannels* also remained important, with an importance score of 26.4 when all splitters were considered. Other variables that increased in importance when all splitters were considered include: *IslandAge*, *IslandAngle*, *ChannelDist*, *TreeArea*, *Slope*, and *TipDist*.

Elevation is the first splitter in the full CART tree and is used to separate the low and high marsh areas, with low marsh and submerged species (*Potamogeton nodosus*, *Nelumbo lutea*, and other SAVs) dominant at elevations less than or equal to 0.7 m NAVD88 and high marsh species (*P. punctatum*., *C. esculenta*, and *S. nigra*) dominant above 0.7 m NAVD88. For

Table 3.2 – Correlation Matrix for candidate explanatory variables. Bold represents correlations that are significant at the $p = 0.05$ level. * indicates significant correlations among variables included in the full CART model.

	NND	IslandAngle	TreeArea	IslandAge	Aspect	TipDist	Slope	WaterDist	ChannelDist	PrimaryChannels	SecondaryChannels	TertiaryChannels	Elevation	Storms
NND	1	-0.02	0.04	-0.04	-0.06	0.12	0.02	-0.02	0.11	0.05	0.01	0.03	0.00	-0.03
IslandAngle	-0.02	1	-0.54	0.34	0.01	-0.05	-0.04	0.30	0.04	-0.20	0.01	0.00	-0.01	0.02
TreeArea	0.04	-0.54	1	0.26*	-0.07	0.24	0.11*	-0.11*	0.01	0.23*	0.08	-0.28	0.21*	0.14
IslandAge	-0.04	0.34	0.26*	1	0.00	-0.06	0.07	0.45*	0.02	0.04	0.12	-0.31	0.36*	0.30
Aspect	-0.06	0.01	-0.07	0.00	1	-0.03	-0.02	0.07	0.04	-0.04	0.01	0.05	0.03	-0.04
TipDist	0.12	-0.05	0.24	-0.06	-0.03	1	-0.15	-0.14	0.08	0.24	-0.17	0.09	-0.36	-0.39
Slope	0.02	-0.04	0.11*	0.07	-0.02	-0.15	1	0.01	-0.16	0.02	0.05	-0.10	0.34*	0.18
WaterDist	-0.02	0.30	-0.11*	0.45*	0.07	-0.14	0.01	1	0.11	0.31*	-0.08	-0.25	0.14*	0.16
ChannelDist	0.11	0.04	0.01	0.02	0.04	0.08	-0.16	0.11	1	0.09	0.44	0.32	-0.38	-0.39
PrimaryChannels	0.05	-0.20	0.23*	0.04	-0.04	0.24	0.02	0.31*	0.09	1	-0.24	-0.31	-0.11*	-0.09
SecondaryChannels	0.01	0.01	0.08	0.12	0.01	-0.17	0.05	-0.08	0.44	-0.24	1	0.29	0.01	-0.02
TertiaryChannels	0.03	0.00	-0.28	-0.31	0.05	0.09	-0.10	-0.25	0.32	-0.31	0.29	1	-0.30	-0.35
Elevation	0.00	-0.01	0.21*	0.36*	0.03	-0.36	0.34*	0.14*	-0.38	-0.11*	0.01	-0.30	1	0.65
Storms	-0.03	0.02	0.14	0.30	-0.04	-0.39	0.18	0.16	-0.39	-0.09	-0.02	-0.35	0.65	1

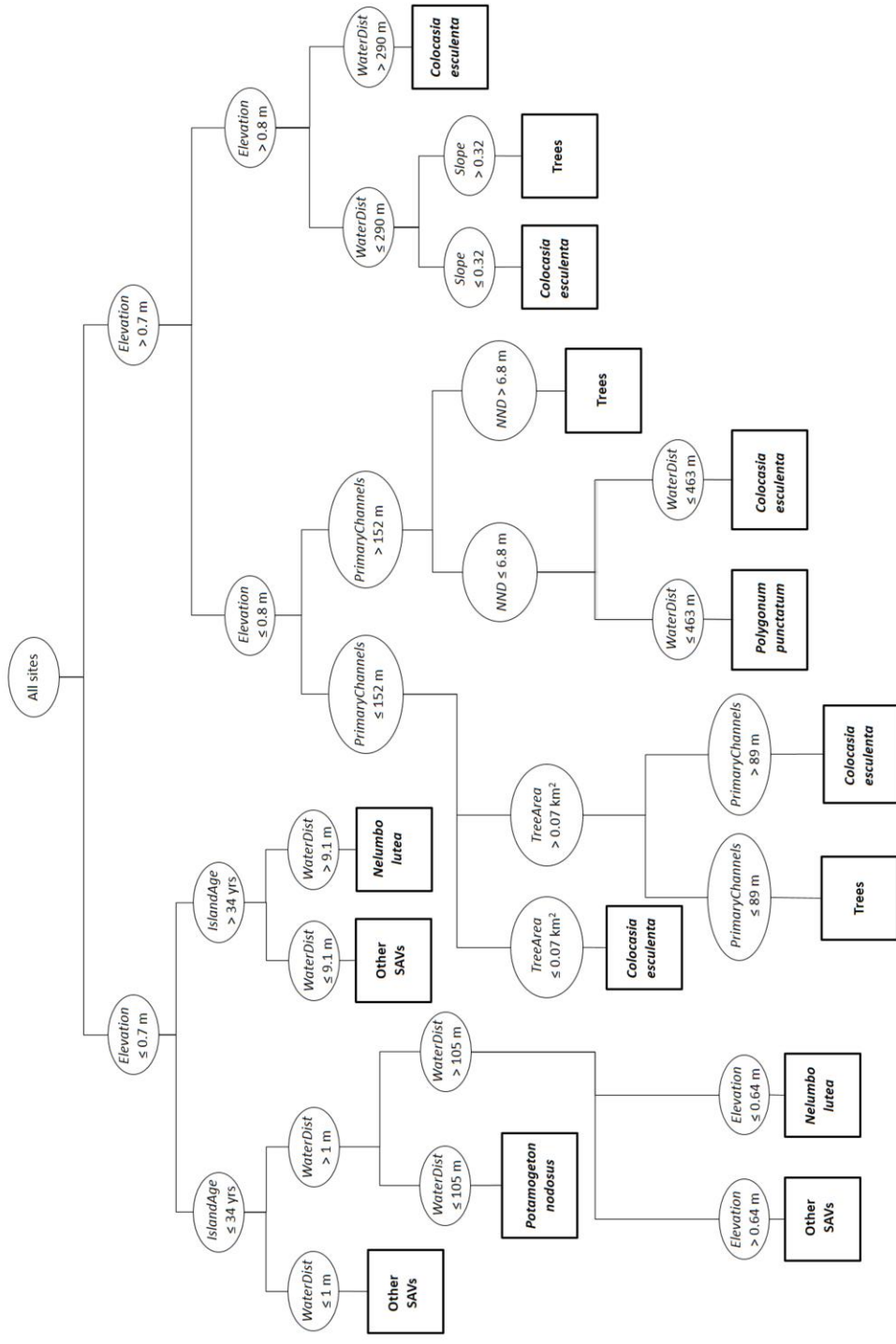


Figure 3.3 – Full CART Model

Table 3.3 – Variable importance scores for primary splitters in full CART model

Variable	Importance Score
<i>Elevation</i>	100.0
<i>WaterDist</i>	46.7
<i>IslandAge</i>	26.0
<i>PrimaryChannels</i>	15.7
<i>NND</i>	6.4
<i>Slope</i>	5.4
<i>TreeArea</i>	4.8

Table 3.4 – Relative variable importance scores for all candidate variables in the full CART and Random Forests models

Variable	Importance Score	
	CART	Random Forests
<i>Elevation</i>	100.0 (1)	100.0 (1)
<i>WaterDist</i>	63.2 (2)	35.2 (3)
<i>Storms</i>	47.7 (3)	49.0 (2)
<i>TertiaryChannels</i>	28.6 (4)	25.1 (4)
<i>PrimaryChannels</i>	26.4 (5)	14.1 (6)
<i>IslandAge</i>	23.8 (6)	9.6 (8)
<i>IslandAngle</i>	23.4 (7)	7.5 (11)
<i>ChannelDist</i>	22.6 (8)	14.3 (5)
<i>TreeArea</i>	20.0 (9)	7.9 (10)
<i>Slope</i>	16.5 (10)	8.4 (9)
<i>TipDist</i>	14.7 (11)	12.6 (7)
<i>NND</i>	5.9 (12)	2.2 (13)
<i>Aspect</i>	1.5 (13)	3.0 (12)

the low marsh areas, *IslandAge* controls whether or not *P. nodosus* is present. On islands older than 34 years, the low marsh is dominated by *N. lutea* at distances greater than 9.1 m from deep water habitats and true SAVs at distances less than or equal to 9.1 m from deep water. On younger islands, a more complex pattern is apparent. Other SAVs form a fringe less than 1 m from deep water areas, while *P. nodosus* occupies the area from 1 to 105 m from deep water. At distances greater than 105 m from deep water, *N. lutea* is present at elevations above 0.64 m NAVD88 and other SAVs occupy the lower elevations.

Among the high marsh species, a secondary split on *Elevation* occurs at 0.79 m NAVD88. Only *C. esculenta* and trees are dominant above this elevation, with the dominant class determined by a combination of *WaterDist* and *Slope*. *C. esculenta* dominates areas greater than 290 m from deep water and areas closer than or equal to 290 m from deep water that have slopes less than or equal to 0.32. The *S. nigra* class is found less than or equal to 290 m from deep water and on slopes greater than 0.32. Between the elevations of 0.7 and 0.79 m NAVD88 a much more complex picture emerges. Here, the spatial structure of the plant community is different for areas further than 152 m from a primary channel than for those areas less than or equal to 152 m from a primary channel. This effectively separates the natural channel levees communities from those closer to the interior of the islands. On the natural channel levees, *C. esculenta* is the sole dominant on islands with less than 0.07 km² of trees. On islands with more than 0.07 km² of trees, trees occupy the areas closest to the channel up to a distance of 89 m, and *C. esculenta* occupies areas further than 89 m from the channel. Beyond the natural levees, trees occur as scattered patches separated by a minimum of 6.8 m throughout an area otherwise dominated by monotypic stands of *C. esculenta* in areas less than or equal to 463 m from deep water and *P. punctatum* in areas more than 463 m from deep water.

The overall predictive accuracy of the full CART model was 65.3 percent (Table 3.5). User's accuracy, which measures errors of commission, ranged from 52.9 percent for *C. esculenta* to 82.0 percent for the other SAVs class. Producer's accuracy, which measures errors of omission, ranged from 37 percent for *C. esculenta* to 86 percent for *P. nodosus*.

Elevation-only CART Model

The elevation-only CART analysis resulted in a "best tree" with only four leaves and a relative cost of 0.59 (Figure 3.4). There were no other trees with statistically similar costs, so this was selected as the best model. As in the full model tree, the first split separated the low marsh from the high marsh at an elevation of 0.7 m NAVD88. Within the low marsh, areas higher than 0.64 m NAVD88 were dominated by *N. lutea* and areas lower than or equal to 0.64 m NAVD88 were dominated by *P. nodosus*. In the high marsh areas, elevations greater than 0.79 m NAVD88 were dominated by trees and elevation less than or equal to 0.79 m NAVD88 were dominated by *P. punctatum*.

The elevation-only CART model had a classification accuracy of 54.0 percent. User's accuracies ranged from 47.2 percent for *P. punctatum* to 94.0 percent for *S. nigra*, but could not be calculated for either the other SAVs or *C. esculenta* classes. Producer's accuracies ranged from 0 percent for the other SAVs and *C. esculenta* to 84.0 percent for the *P. punctatum* class. The producer's accuracies for the other SAVs and *C. esculenta* classes are a reflection of the exclusion of leaves for these classes in the elevation-only CART model

Table 3.5 – Predictive Accuracy of full and elevation-only CART models

	Full CART Model			Elevation-only CART Model			Random Forests Model		
Species	User's Accuracy (%)	Producer's Accuracy (%)		User's Accuracy (%)	Producer's Accuracy (%)		User's Accuracy (%)	Producer's Accuracy (%)	
Trees	62.5	75.0		93.6	73.0		75.2	79.0	
<i>Colocasia esculenta</i>	52.9	37.0		NA	0.0		54.8	46.0	
<i>Polygonum punctatum</i>	70.5	74.0		47.2	84.0		65.7	69.0	
<i>Nelumbo lutea</i>	65.2	73.0		48.6	68.0		73.0	84.0	
<i>Potamogeton nodosus</i>	63.2	86.0		47.3	78.0		80.7	88.0	
Other SAVs	82.0	47.0		NA	0.0		76.8	63.0	
Overall Accuracy	65.3			54.0			71.5		

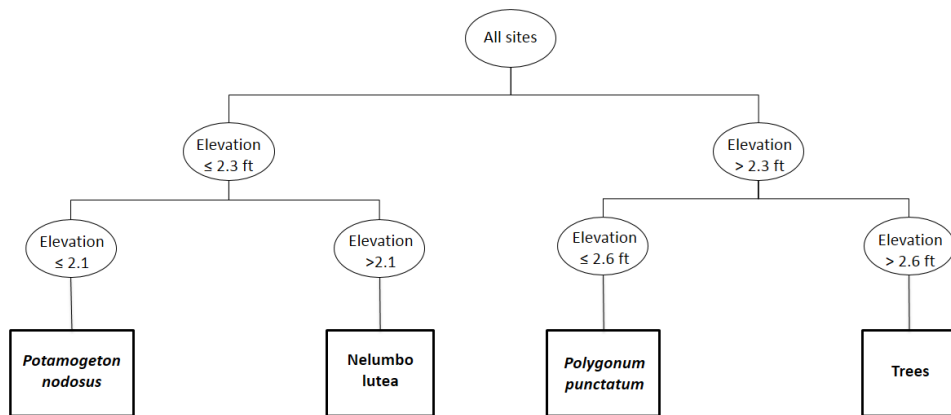


Figure 3.4 – Elevation-only CART Model

Random Forests Model

The Random Forests model had an overall accuracy of 71.5 percent (Table 3.5). User's accuracies were higher for *S. nigra*, *C. esculenta*, *N. lutea*, and *P. nodosus* than in the CART model, but lower for the *P. punctatum*, and other SAV classes. Producer's accuracies were higher for all classes except for *P. punctatum*. The top four most important variables in the Random Forest model were the same as in the CART model, although the order of importance changed. *Elevation* was the most important variable in both models. However, while *WaterDist* was the second most important variable in the CART model, *Storms* was the second most important variable in the Random Forests model (relative importance = 49.0). *WaterDist* was third most important, followed by *TertiaryChannels*. Other important variables in the Random Forests model were *ChannelDist*, *PrimaryChannels*, and *TipDist*. *IslandAge*, *Slope*, *TreeArea*, and *IslandAngle* were less important in the Random Forests model, with importance scores less than 10. As in the CART model, *Aspect* and *NND* were of low importance in predicting species distributions.

DISCUSSION

The elevation-only CART model resulted in a classification accuracy of about 54 percent, compared to about 65 percent for the full model. It is evident, therefore, that the majority of the difference in the distributions of these six species is related to their response to the elevation gradient, which influences the frequency and duration of flooding at any given site. This is not surprising, as elevation is also the primary control on species distributions both in coastal wetlands in other geomorphic settings and in other fluvial systems (Odum 1988). However, the influence of elevation is not as strong as would be expected in salt marshes, where strong zonation is observed and believed to be a consequence of the relative salt and flooding tolerance and competitive ability of salt marsh species (Bertness and Ellison 1987). Also, the relative importance of elevation compared to other factors appears to vary by species. Of the six target species considered in this study, only the *S. nigra* class was better represented by the simple

elevation-only CART model than by the full CART model. This class had both user's and producer's accuracies of greater than 70 percent in the elevation-only model. Clearly elevation is the most important driver for *S. nigra* distributions within the Wax Lake Delta and adding additional variables decreased the model's predictive ability for this species. All of the other species have lower classification accuracies in the elevation-only model, suggesting that the additional factors considered in the full CART model play important secondary roles in determining their spatial distributions.

WaterDist was the second most important variable in the full CART model and the third most important variable in the Random Forests model, suggesting that proximity to deep, unvegetated water exerts a control on plant species distributions in this setting that is independent of elevation. This variable includes proximity to both the distributary channels that carry river water into the delta and the calm areas in the distal interior of the islands which open directly to Atchafalaya Bay and are the primary inlets for tidal exchange. The *WaterDist* variable may capture variability related to the degree of tidal and riverine flushing that an area experiences, which further determines the rate of delivery of nutrients and oxygenated water and the flushing of salt and toxins such as sulfate from the sediments following storm surge events (Balling and Resh 1983; Buresh et al. 1980; DeLaune et al. 1981; Steever et al. 1976). Also, as the interiors of the islands are slow to drain once inundated, the *WaterDist* variable may better capture aspects of hydrology that are not perfectly correlated with elevation (Bockelmann et al. 2002; Snedden and Steyer 2013).

Storms was the third most important variable in the CART model when surrogate splitters were considered and the second most important variable in the Random Forests model. The importance of this variable is obscured by its relatively high correlation with *Elevation*. These were the two most strongly correlated variables considered in this study. However, previous research supports the importance of storm disturbance, and particularly storm-driven pulses of salt water, in structuring the vegetation communities of freshwater coastal marshes (Chabreck and Palmisano 1973; Holm and Sasser 2001; Howard and Mendelsohn 1999; Middleton 2009). While this variable is strongly dependent on elevation, it also relates to the magnitude and direction of storm tracks as well as the storm's areal impact, which vary greatly by storm event. It is likely that this variable is more important at larger spatial scales, where the frequency of storm disturbance is less directly controlled by elevation. It is also important to note that the high volume of freshwater input into the delta through the Wax Lake Outlet probably prevents the long-term trapping of salt in the sediments in the delta, mitigating the impact of storm events on the freshwater marsh species. White (1993) suggested that the perennials that grow at low elevations in the Mississippi Delta are better adapted to withstand storm surge than early colonizing annual species, due to their extensive belowground storage. As many of the same species are dominant at low elevations in the Wax Lake delta, periodic storm surges may be responsible for the competitive dominance of perennials over annuals in this setting, as well.

The next most important set of variables are those that relate to distance to a channel. *PrimaryChannels*, *TertiaryChannels*, and *ChannelDist* were all important variables in one or both models. The moderate inverse correlation between *PrimaryChannels* and *TertiaryChannels* and moderate positive correlation between *TertiaryChannels* and *ChannelDist* suggests that these variables represent different processes controlling species distributions. The channel variables may relate to nutrient delivery, substrate composition, or the ability of water-born propagules to colonize the islands. In many coastal systems, bioavailable nutrient concentrations are higher near tidal creeks and in riverine systems, and nutrient concentrations in floodplains typically

decrease away from the channel (Buresh et al. 1980; DeLaune et al. 1981; Spink et al. 1998; Wassen et al. 2002). However, the generally high nutrient concentrations in the Mississippi River may preclude the development of a similar gradient in the Wax Lake Delta (Turner and Rabalais 1991). There is no evidence that nutrient concentrations decrease below limiting levels as you move away from the distributary channels. Johnson et al. (1985) observed little variation in nutrient levels throughout the neighboring Atchafalaya Delta, which they attributed to the high volume of river water that flows across the surface of the delta during the spring floods. There is, however, evidence that substrate composition is correlated with distance from the distributary channels (Van Heerden and Roberts 1980; Van Heerden and Roberts 1988; Wellner et al. 2005). The coarsest sands are typically deposited along the channel levees during flood events and increasingly fine material is deposited in the interior and on the distal ends of the islands.

Whether or not a true gradient exists in the transport of waterborne seeds and propagules from the distributary channels is unknown. However, the way that *PrimaryChannels* is used to separate *S. nigra* from *C. esculenta* in the full CART model suggests that this may be an important factor. *S. nigra* has very specific germination requirements - seedlings germinate best on wet, sandy, alluvial sediments that are not permanently inundated (Gage and Cooper 2004; McLeod and McPherson 1973). These conditions are met within a narrow spatial and temporal window when new sand is deposited along streambanks during flood events (Karrenberg et al. 2002; Splunder et al. 1995; Stokes 2008). Floods may also deposit *S. nigra* seeds on the banks, where they germinate once the flood recedes (McLeod and McPherson 1973), which would explain the dominance of *S. nigra* on the distributary channels banks. The adult trees are also well adapted to withstand the physical disturbance associated with large flood events, which is most prevalent directly adjacent to the channel (Karrenberg et al. 2002). However, the distribution of these two species relative to the distributary channels may also relate to the grain size gradient. White (1993) found that mudflats in interdeltaic splays of the Mississippi River that were dominated by *C. esculenta* had finer sediments and more organic matter than those dominated by *S. nigra*, which had a significantly higher sand fraction.

IslandAge is the next most important variable in the CART model. This variable likely captures variability in species distributions related to soil development and other processes of allogenic and autogenic succession that occur over time as the newly-formed deltaic islands age. As highly dynamic systems, newly formed deltaic islands are at the allogenic end of the allogenic-autogenic spectrum of ecological succession (Shaffer et al. 1992). On the youngest islands, allogenic forces such as rapid sediment deposition and erosion, exert the greatest control on plant community development. However, as the islands gain in elevation over time, autogenic processes become more important. Newly formed soils gain organic matter and nitrogen over time, increasing the pool of plant species that are capable of invading the island (Craft 1997; DeLaune et al. 1981; Shaffer et al. 1992). This process of soil development has been observed in the Wax Lake delta, where the oldest islands have been demonstrated to have higher soil organic matter and higher soil nitrogen than the younger islands (Henry 2012). A shift in species growth strategies over time has been observed in the neighboring Atchafalaya Delta, with perennial species gradually replacing the annual species that initially colonized the newly exposed islands in that delta (Shaffer et al. 1992). A similar process appears to be occurring in the Wax Lake Delta.

IslandAngle and *TreeArea* are both moderately correlated with *IslandAge*. Despite not serving as primary splitters in the CART model they have moderate importance values due to their ability to serve as surrogates for other variables in the model. These variables relate to the

degree to which the interior island communities are protected from the river's flow. The importance of *TreeArea* is consistent with previous work in the neighboring Atchafalaya Delta, which suggested that some plant species cannot colonize the deltaic islands until a stand of willows has established on the upstream levee to protect the interior of the island from energetic flows (Johnson et al. 1985). *IslandAngle* also relates to the degree to which the interior of the island is directly exposed to Atchafalaya Bay, making it more susceptible to storm disturbance.

Slope and *TipDist* are important variables in the CART model but are less important in the Random Forests model. In the CART model, slope is a primary splitter used to differentiate between the *S. nigra* and *C. esculenta* communities on the highest elevation levees close to the distributary channels. At these sites, *S. nigra* occupies more sloped sites and *C. esculenta* occupies the flattest areas. Neither *Aspect* nor *NND* were particularly important in the CART and Random Forest models. It is not very surprising that *Aspect* does not exert the same control on the plant species in a river delta as it does in areas with greater topographic relief. Apparently the other factors in the model are more important than microtopography in determining plant dominance. However, microtopographic relief and hence light environment may still explain variation in productivity among individuals of the same species, and this is an area that warrants further research.

It also appears that dispersal does not limit species distributions at either the scale of the entire delta or within the individual deltaic islands. Many of the perennial species within the delta do not reproduce well by seed, relying instead on vegetative reproduction (Bart and Hartman 2003; Capers 2003; Kikuta et al. 1938). The energetic setting of a river delta serves these species well, as pieces of plant material broken off by flood or storm events can be transported by water and deposited in new locations (Akridge and Fonteyn 1981). Other species in the delta have seeds that float in the water and can therefore be transported throughout the delta under spring flood conditions (Hall and Penfound 1944; McLeod and McPherson 1973). The success of these dispersal strategies probably varies from year to year, depending on the degree to which flood conditions coincide with the timing of peak seed production and whether the flood recedes quickly enough to allow the transported seeds to germinate and the seedlings to become established.

The relative importance of these secondary variables also varies by species within both the CART and Random Forests models. As indicated previously, distribution of the *S. nigra* class is best predicted by *Elevation* alone. By examining the CART model, we see that *WaterDist*, *Slope*, *PrimaryChannels*, *TreeArea*, and *NND* are also important in separating the *S. nigra* class from *C. esculenta*. For *P. punctatum*, the most important variables apart from *Elevation* are *PrimaryChannels*, *NND*, and *WaterDist*. For the lower elevation species *N. lutea*, *P. nodosus*, and other SAVs, *IslandAge* and *WaterDist* are the most important primary splitters besides elevation. The importance of these variables suggests that allogenic successional processes drive species distributions in the submerged, floating, and emergent low marsh communities, with a change in species dominance on older islands. *P. nodosus*, in particular, is dominant over a much larger area of the younger islands. As the islands age and continue to increase in elevation, many areas previously dominated by *P. nodosus* convert to other classes. On the oldest islands, *P. nodosus* is found only at the distal fringe of the island.

The other SAVs and *C. esculenta* are particularly poorly represented by both the full and the elevation-only CART models. The inability of the elevation-only model to predict the distribution of these species suggests that they may have broader realized niches along the elevation gradient than the other target species. In the case of the other SAVs class, this is not

surprising because it is a mixed class containing species that were grouped primarily due to practical considerations related to the difficulty of mapping individual submersed species from satellite imagery. It is possible that the individual species in the other SAVs class occupy separate realized niches along the elevation gradient that could not be distinguished in this study. The elevation zone occupied by the group of species would then be much larger than that of any individual species. There is also potentially a fair amount of overlap between the elevation range of the other SAVs class and the elevation ranges of both *P. nodosus* and *N. lutea*.

The *C. esculenta* class also overlaps substantially with its neighboring classes along the elevation gradient. It is commonly found in the understory of the *S. nigra* community at higher elevations and as a subdominant in the *Polygonum* mixture community at lower elevations. It is possible that this species has greater tolerance of a wider range of environmental variables, and thus a broader fundamental niche than the other species examined in this study. Despite a rich literature on its cultivation and nutritional value as a food crop, very little is known about the ecology of *C. esculenta* in the wild. In the San Marcos River in Texas, it has been observed to occupy a wide range of substrates, including rock, gravel, silt, and deep mud and tolerates both high and low-light environments (Akridge and Fonteyn 1981; Staton 1992).

The failure of the CART models to predict distributions of these two classes suggests that additional factors other than those considered in this study are important in controlling their distributions. The CART model focuses on spatially variable environmental factors that influence species distributions but is unable to account for the impact of ecological interactions such as interspecific competition, facilitation, and herbivory (Bertness 1985; Bertness and Sumway 1993; Evers et al. 1998; Gough and Grace 1998b). Previous work in neighboring Atchafalaya delta has indicated that herbivory by nutria exerts a strong control on plant community composition in these deltas, particularly by reducing dominance of the emergent species *Sagittaria latifolia* (Evers et al. 1998; Shaffer et al. 1992). Reduction of this competitor may create a vacant niche that is being exploited by other species in the delta.

Variation in substrate-type, soil organic matter, and nutrient availability were not explicitly accounted for in this study. White (1993) found that both sediment grain size and organic matter content varied among plant communities growing on mudflats in the Mississippi River delta. The substrate varies spatially on each deltaic island from sands that deposited at the upstream end of the islands and along the channel levees to fine silts and muds deposited in the distal interior of the islands. Substrate concentration is expected to be strongly correlated with *TipDist* and *PrimaryChannels*, although probably not perfectly so. Both soil organic matter and soil nutrient availability have been shown to increase with island age as a function of primary soil development (Henry 2012; White 1993). Additionally, species' differential responses to increases in nutrient availability may influence the outcome of interspecific competition on older islands in the delta (Bazzaz 1997; Tilman 1987). *C. esculenta*, in particular, showed tremendous growth following the record Mississippi River flood in 2011 (M. Carle, *personal observation*). This observed growth response may reflect an ability by this species to use the elevated nutrients available during high flood years, which would in turn increase its competitive ability and its ability to invade areas dominated by other species.

It is possible that the remaining 28.5 percent of variability in species distributions unexplained by the Random Forest model relates to ecological interactions that are not inherently spatially-driven processes and are therefore not easily captured in spatial datasets. Previous studies have demonstrated the important roles that herbivory, interspecific and intraspecific competition, and mutualism play in influencing the shape of a species' realized niche as opposed

to its fundamental niche, which is defined primarily by its range of tolerances to environmental conditions. In some cases, there is a differential impact of these ecological interactions along an environmental gradient. In others cases, the outcome is more stochastic, depending on the timing of seed dispersal and germination relative to flood cycles in a given year or the random foraging patterns of herbivores. Such variability will always be difficult to incorporate into spatial models.

Finally, it is important to note that this study focused on only a subset of six species present in the freshwater marshes of the Wax Lake delta. A number of other important species were excluded from the model due to low mapping accuracy. In particular, several clonal species common in the Wax Lake delta were excluded, including *Phragmites australis*, *Typha species*, and *Zizaniopsis miliacea*. While initial stands of these species are small, they spread radially over time via vegetative reproduction and are becoming increasingly important components of the vegetation community (C. E. Sasser, *personal observation*). *P. australis* is the dominant species in the active Mississippi River delta (Hauber et al. 2011) and it is plausible that it may become an increasingly important species in the Wax Lake and Atchafalaya deltas, as well, as those deltas mature. This species is less responsive to elevation gradients than the freshwater marsh species examined in this study, as it has the ability to spread from more favorable high marsh sites to less favorable low marsh sites through clonal integration (Amsberry et al. 2000). Another important group of species that were excluded from the model are the *Sagittaria* species, particularly *Sagittaria latifolia*, which was an important dominant on the islands of the Wax Lake and Atchafalaya deltas during the first 20-30 years after emergence, but has waned in distribution in recent years. Research in the Atchafalaya delta suggests that this reduction in *Sagittaria latifolia* is most likely related to the combined stresses of herbivory by nutria and short-term pulses of salt-water delivered by coastal storm events (Holm and Sasser 2001; Shaffer et al. 1992).

CONCLUSIONS

In this study, 54 percent of the variability in plant distributions in a young, pro-grading river delta was explained by elevation alone, indicating that elevation remains the primary driver of plant species distributions in dynamic river delta systems that are subject to both riverine and coastal drivers. However, elevation was not as singularly important as it is in many salt marsh ecosystems (Adams 1963). Based on the Random Forest model, an additional 16 percent of variability in species distributions was attributed to other variables, particularly those related to distance from deep water, distance from distributary channels, and island age. Time since storm disturbance also ranked high in variable importance, but largely because it was strongly correlated with elevation. This suggests that storm disturbances do not have a long-term impact on the specific species included in this study. However, they may act to exclude other species that are less tolerant of periodic short-term salt intrusion.

Overall, the distributions of the five freshwater species considered in the study were modelled with greater than 70 percent predictive accuracy using easily-derived spatial variables related to elevation, position on the island relative to other features, years since storm disturbance, and island age. Close examination of a simple CART model revealed valuable information about the relationships between these control variables and the distributions of plant species within the delta. Comparing these results to similar studies performed in other

geomorphic setting would provide a deeper understanding of how controls of plant species distributions change under the varying influence of coastal rivers, waves, tides, and under varying disturbance intervals.

Plants modify the geomorphology of deltas by trapping sediments, increasing sediment cohesion, reducing erosion, and contributing organic matter to the sediments. As different species perform these functions to a varying degree, knowledge of species distributions and how they would be expected to change with time as a delta matures is critical to incorporating the impact of the plant community into physical deltaic models. As these results demonstrate, it is possible to predict the distributions of plant species within a river delta with a reasonable degree of accuracy. Making use of this information to refine existing models will allow for more accurate predictions of how river deltas develop over time. As a naturally developing young river delta, the Wax Lake delta provides a good reference system for ecological restoration projects attempted elsewhere in the deltaic plain. Understanding the factors that control plant community pattern in this system will provide insight into plant community development that can be expected from large-scale restoration projects such as river diversions and provide an ecological reference with which to evaluate restoration success.

CHAPTER 4 – PRODUCTIVITY AND RESILIENCE: LONG-TERM, SEASONAL, AND STORM-DRIVEN FLUCTUATIONS IN THE PLANT COMMUNITY OF THE ACCRETING WAX LAKE DELTA

ABSTRACT

River deltas are dynamic geologic features where the plant community engages in critical feedbacks with geomorphology and plant community development is impacted by both riverine and coastal drivers. A vegetation index (NDVI) calculated from a time series of 94 Landsat MSS and TM images of the Wax Lake Delta in Atchafalaya Bay, Louisiana was used to study long-term, seasonal, and storm-event driven changes in the vegetation community associated with this actively accreting area of Louisiana's coast. Analysis of peak growing season NDVI from 1975 to 2011 indicates that both total and mean (per unit area) NDVI in the delta have increased over time. Seasonal analysis of NDVI data from 2000 to 2011 demonstrates that total NDVI within the delta increases as a function of year, increasing water temperature, and decreasing river discharge. Average NDVI within the delta is a function of year and water temperature. Comparison of NDVI data from before and after major storm events shows that storms passing directly over or to the west of the delta have a significant short-term impact on the plant community, most likely as a result of pulses of salt-water intrusion associated with storm surges. However, in each case, NDVI values recovered to within the 95 percent prediction interval for the long-term trend by the following growing season. These results demonstrate that the freshwater marshes within the delta are increasing in productivity as the delta matures and are extremely resilient to coastal storm disturbance.

INTRODUCTION

River deltas are ephemeral features at geologic timescales. They occur wherever rivers deliver sediment to a coastline faster than it is removed by coastal erosional processes, and are strongly influenced by both riverine and coastal processes (Day and Giosan 2008; Wright 1985). They are also dynamic systems, constantly changing with fluctuations in sediment delivery by the river, storage within the channel and its floodplains, and reworking by waves, tides, and coastal storm events (Conner et al. 1989; McManus 2002; Tweel and Turner 2012b; Wright and Coleman 1973; Yang et al. 2003; Yang et al. 2010). The plant communities that develop on river deltas both respond to and influence this continual process of geomorphic change (Corenblit et al. 2011; Corenblit et al. 2007). On the one hand, plant distributions within river deltas are strongly controlled by physical factors such as the frequency, duration, and depth of flooding, strength of channel flow, substrate, and the frequency, extent, and duration of salt-water intrusion (Cahoon et al. 2011; Johnson et al. 1985; Kandus and Malvárez 2004). These factors are determined in large part by delta geomorphology. On the other hand, the plants that colonize river deltas themselves contribute to the geomorphological development of newly emergent islands. Plants influence vertical accretion and soil formation on the developing islands by trapping sediments with their roots, increasing sediment cohesion, reducing erosion, and

contributing organic matter that changes the composition and structure of the developing soil and increases vertical accretion (Beeson and Doyle 1995; Cahoon et al. 2011; Edmonds and Slingerland 2009; Lorenzo-Trueba et al. 2012; Marani et al. 2013; Nyman et al. 1990; Rosen and Xu 2013; White 1993).

The plant communities that develop in temperate river deltas are unique within coastal environments, because the delivery of a large volume of freshwater provides the opportunity for establishment of extensive freshwater wetlands in what would otherwise be a hostile saline environment. Primary succession initiates as soon as mudflats obtain sufficient elevation to support emergent plant species (Cahoon et al. 2011; Fuller et al. 1984; Kandus and Malvárez 2004; White 1993). A rapid increase in belowground biomass occurs following colonization, as the plants forage for nutrients in the sediment (Cahoon et al. 2011). The belowground biomass (roots and rhizomes) increases the cohesion of the sediment, while the increased surface roughness provided by the aboveground stems slows flood flows and promotes further sediment trapping (Nepf and Vivoni 2000; Temmerman et al. 2005). The first colonizing plants are frequently ruderal annuals with local seed sources (Shaffer et al. 1992; White 1993). However, once perennials reach the newly emergent mudflats, they quickly become dominant, relegating the annuals to brief seasonal windows early and late in the growing season (White 1993). As establishment of the early colonial species further increases sediment trapping compared to the bare mudflats, they create the conditions for their own replacement by superior competitors adapted to higher elevations (Kandus and Malvárez 2004; Shaffer et al. 1992). Large monotypic stands are common in deltas, particularly at the lowest and highest ends of the elevation gradient (Cahoon et al. 2011). Species richness is commonly much higher at intermediate elevations, where stress is intermediate between the high physical stress caused by frequent flooding in the low marsh and the high ecological stress caused by increased competition at higher elevations (Johnson et al. 1985; Kandus and Malvárez 2004). Overall species richness also tends to increase over time in river deltas, as elevation increases and a wider range of species is able to invade (Shaffer et al. 1992).

As in terrestrial temperate ecosystems, the plant communities in temperate river deltas exhibit a distinct seasonal pattern in aboveground biomass (Zoffoli et al. 2008). Generally, biomass is at its lowest during the winter months and begins to increase in the spring and early summer, with peak biomass occurring in late summer and early fall. However, the seasonality of biomass in deltaic wetlands is also influenced by river discharge, and may therefore differ from seasonal patterns observed in non-riverine coastal marshes (Zoffoli et al. 2008). High river discharges associated with spring floods result in high water levels in river deltas that may delay germination and re-sprouting of marsh plants in these systems until water levels drop below the flooding tolerance levels of individual plant species (Fuller et al. 1984). As species differ in their ability to germinate and grow under flooded conditions and in their water temperature tolerances, this creates a seasonality to the outcome of plant competition. It is not uncommon for SAVs to dominate large areas of the delta during late spring and early summer, when water levels remain high, but to later be displaced to the lowest elevations by emergent vegetation as the spring flood recedes and the river water warms (Fuller et al. 1984; Johnson et al. 1985). There is also a distinct seasonal pattern reflected in the contribution of annual versus perennial species to the overall biomass in many river deltas. Annuals are often dominant early in the growing season

before perennials re-sprout and then also late in the growing season after perennial species begin to senesce (Johnson et al. 1985).

While the long-term trend in accreting river deltas is naturally one of biomass accumulation, disturbance events that damage the plant community or result in physical erosion and elevation loss have the potential to reset the trajectory of marsh succession. Within coastal river deltas, hurricanes and tropical storms are among the most common disturbances to marsh communities. Impacts from coastal storms can include direct physical disturbance of vegetation by strong winds, as well as extended flooding, erosion, and salt-water intrusion associated with storm surges (Bianchette et al. 2009; Morton and Barras 2011; Ramsey et al. 2001; Rodgers et al. 2009). The degree to which any particular coastal marsh experiences one or all of these forms of stress related to a given storm depends on the size and strength of the storm, the path it takes relative to the location of the marsh, and how quickly the storm passes (Day et al. 2007; Ramsey et al. 2001; Steyer 2008). In the most extreme cases, hurricanes making direct landfall in coastal wetlands can result in direct disturbance such as uprooting of vegetation, folding of the marsh surface, or conversion of marsh to open water (Morton and Barras 2011). Indirect disturbance may also result in changes to the marsh community. Salt-water that is trapped in a marsh following a storm event can kill freshwater marsh species and promote the establishment of a more salt-tolerant community (Baldwin and Mendelssohn 1998; Flynn et al. 1995; Morton and Barras 2011). Or, marshes that are repeatedly exposed to surges of salt water from storm events may see a gradual reduction in the most salt-sensitive species and their replacement with more salt-tolerant species over time (Holm and Sasser 2001).

Holling (1973) first defined ecological resilience as the ability of an ecosystem to absorb disturbance while still maintaining the relationships between populations and state variables that define the system's equilibrium state. A related concept is that of ecological stability, which Hollings used to describe the ability of a system to return to equilibrium following a temporary disturbance. A number of authors have since modified these definitions. Two types of resilience are now generally recognized: engineering resilience and ecological resilience. The term engineering resilience refers to the amount of time it takes for a system to return to a single equilibrium state following a disturbance (Peterson et al. 1998). Ecological resilience is a more appropriate term when more than one stable equilibria exist (May 1977; Sutherland 1974). Within this context, ecological resilience refers to the amount of disturbance that is necessary to force a system to shift from its current stable state to an alternate stable state (Peterson et al. 1998). The resilience of ecosystems is not constant, but is subject to change as a result of human induced alterations and stresses (Folke et al. 2004; Gunderson 2000; Scheffer et al. 2001).

While tropical storms and hurricanes represent stochastic disturbances to which the plant communities in river deltas have adapted over time and which create diversity at both local and landscape scales, human alteration of deltas has the potential to reduce the resilience of deltaic wetlands to such disturbances (Conner et al. 1989). Many of the world's major river deltas have been heavily altered to allow them to support human activities such as urban development and agriculture. Many have been hydrologically altered in ways that cut the wetlands in the delta off from the river floods that built and sustain them (Syvitski 2008; Syvitski et al. 2009). Removing the primary source of sediment input to the delta, often leads to subsidence through the compaction and dewatering of existing sediments (Day and Giosan 2008; Meckel et al. 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). This problem has been further exasperated by the construction of dams in upstream watersheds, which reduce downstream sediment supply (Blum and Roberts 2009). When the natural processes that built and maintained deltas are disrupted, the resilience of deltaic wetlands is reduced and they become more vulnerable to localized stressors such as salt-water intrusion (Turner 1997), pollution (Silliman et al. 2012), fluid extraction, and storm disturbance (Steyer et al. 2013).

While much of our understanding of plant community productivity and the response of ecosystems to disturbance events comes from field research, remote sensing provides an opportunity to study these issues at the landscape level. Many of the vegetation community parameters that are commonly measured in the field and used to estimate primary production are correlated with plant spectral reflectance values in the visible and near-infrared portion of the light spectrum (Bartlett and Klemas 1981; Ihse and Graneli 1985; Jensen et al. 2002). The most commonly used remotely sensed indicator of plant productivity is the normalized difference vegetation index (NDVI) (Rouse et al. 1974). A weighted-ratio of spectral reflectance in the red and near-infrared regions of the light spectrum, NDVI has been shown to correlate strongly with live aboveground biomass, leaf area index (LAI), percent vegetation cover, and chlorophyll content (Gross et al. 1993; Hardisky et al. 1983; Jensen et al. 2002). These relationships have been demonstrated in a variety of settings, including forests, floodplains, grasslands, and both fresh and salt marshes (Anderson et al. 1993; Dong et al. 2003; Drake 1976; Gamon et al. 1995; Gross et al. 1993; Hardisky et al. 1983; Nagler et al. 2009; Paruelo et al. 1997; White and Lewis 2011). It has been used successfully to identify vegetation disturbance and stress, monitor restoration site establishment and the recovery of plant communities following disturbances, and scale-up in-situ estimates of net annual primary production (All and Yool 2004; Couvillion and Beck 2013; Hardisky et al. 1984; Phinn et al. 1999; Ramsey et al. 1997; Steyer et al. 2013; Wang et al. 2010a).

As a young, actively pro-grading delta, the Wax Lake delta provides an ideal opportunity to study the development of deltaic plant communities and the factors that drive long-term trends and fluctuations in vegetative productivity. It is also located in a region that experience frequent coastal storm impacts, providing the opportunity to study the impact of storm disturbance on deltaic marshes. On average, at least one hurricane or tropical storm strikes the Louisiana coast every other year. Since 1722, 35 hurricanes have had significant morphological impact on Louisiana's coast (Stone et al. 1997). Averaged over the more than 100 years of record, the return interval of hurricanes with a rating of category 3 or greater is 26 years for the central Louisiana coast (Keim et al. 2007). As an actively accreting delta at the mouth of an unmanaged river diversion, the Wax Lake Delta provides an opportunity to study the response of deltaic wetlands with a direct connection to the river to such coastal storm disturbance events.

The objectives for this study were threefold: (1) to determine the degree to which plant community production, as measured by NDVI, increases in a newly-formed river delta over time, in concert with the geomorphological development of the delta, (2) to identify and model the most important drivers of seasonal fluctuations in plant community production in river deltas, and (3) to test whether coastal storm events have a lasting impact on long-term productivity trends.

METHODS

Imagery dataset and pre-processing

Long-term, seasonal, and storm event-driven fluctuations in productivity of the vegetation community of the Wax Lake Delta were characterized using 93 cloud-free Landsat TM 4/5 and MSS images of the Wax Lake delta from the years 1975 to 2011. From this dataset, 43 images taken during the peak growing season (August-October) from 1973 to 2011 were used to analyze long-term vegetation trends over the life of the delta. Additionally, 68 year-round images taken from 2000 to 2011 were used to examine seasonal trends in the vegetation community and 8 growing season images taken before and after major storm events were used to evaluate the resilience of the deltaic marshes to coastal storm disturbance.

All images were first transformed from digital numbers to at-satellite reflectance using the radiometric calibration tool in the ENVI image analysis software package (Exelis Visual Information Solutions 2013). The original DN values were converted to top-of-atmosphere spectral radiance ($L_{\lambda_{Pixel,Band}}$) according to the equation:

$$L_{\lambda_{Pixel,Band}} = \text{Gain} \times q_{Pixel,Band} + \text{Offset}$$

, where gain is the gain value ($\text{Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$) for a given band, $q_{Pixel,Band}$ is the radiometrically corrected image pixel (count), and offset is the offset value ($\text{Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$) for a given band (Chander and Markham 2003; Chander et al. 2007). The radiance values were then converted to at-satellite reflectance ($\rho_{\lambda_{Pixel,Band}}$) according to the equation:

$$\rho_{\lambda_{Pixel,Band}} = \frac{L_{\lambda_{Pixel,Band}} \times d_{ES}^2 \times \pi}{Esun_{\lambda_{Band}} \times \sin(\theta_s)}$$

, where $L_{\lambda_{Pixel,Band}}$ is the top-of-atmosphere spectral radiance ($\text{Wm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$), d_{ES} is the earth-sun distance (AU) at the time of image acquisition, $Esun_{\lambda_{Band}}$ is the band-averaged solar spectral irradiance ($\text{Wm}^{-2}\mu\text{m}^{-1}$), which is specific to the sensor, and θ_s is the solar elevation angle (degrees) (Chander and Markham 2003). As the images were used to calculate a band-ratio vegetation index, which tends to reduce the effects of atmospheric variation between images, further atmospheric correction was deemed unnecessary.

Normalized Difference Vegetation Index (NDVI)

After radiometric calibration, the images were clipped to the Wax Lake Delta and the normalized difference vegetation index (NDVI) was calculated for each image in the time series. 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 formula (Rouse et al. 1974):

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

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 vegetation density and 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. Bare ground reflects light in both the red and NIR regions, resulting in NDVI values very close to zero. While the relationships between NDVI and measures of plant community productivity have not been tested in Louisiana coastal marshes, strong relationships between NDVI and aboveground biomass and photosynthetic activity have been demonstrated in other coastal marsh settings (Drake 1976; Gamon et al. 1995; Gross et al. 1993; Hardisky et al. 1983; Nagler et al. 2009; White and Lewis 2011).

Both total and spatially-averaged NDVI (henceforth referred to as “mean NDVI”) were calculated for the total vegetated area of the delta for each image in the time series. First, a mask was created to exclude deep water pixels from the analysis based on an NDVI threshold of less than or equal to 1. The zonal sum and zonal mean of the NDVI values were then calculated within the vegetated area of the delta for each image using the ArcGIS Spatial Analyst Tool (ESRI 2012). Mean NDVI was included as a measure of the per unit area productivity of the delta and total NDVI was included as a measure of the total productivity of the delta. Total NDVI is strongly related to the area of the delta and was expected to increase as the area of the delta increased over time, as well as respond to seasonal fluctuations in water level. Both total and mean NDVI were expected to respond to stress generated by storm disturbances.

Modelling long-term NDVI trends

To identify the long-term trend in peak growing season productivity within the delta, simple linear regression analysis was performed for both mean and total NDVI as a function of year using all growing season images from 1973 to 2011. Preliminary analysis of the long-term growing season dataset suggested that several images in the dataset represented outliers from the long-term trend. These images were each taken during the aftermath of a major storm event that affected coastal Louisiana: October 12, 1992 (Hurricane Andrew); October 16, 2002 (Hurricane Lili); October 16, 2005 (Hurricanes Katrina and Rita); September 22, 2008 and October 8, 2008 (Hurricanes Gustav and Ike); and October 1, 2011 (Tropical Storm Lee). These dates were therefore excluded from the long-term analysis and reserved for use in assessing the impact of coastal storms on the vegetation community of the delta. Excluding these dates resulted in a total of 42 dates that were used for the total NDVI regression and 43 dates that were used for the mean NDVI regression. An August 30, 2011 image was included in the mean NDVI regression but not in the total NDVI regression due to the presence of several small clouds obstructing parts of the delta. The clouds were extracted 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. Mean NDVI for this date was then calculated using only the cloud-free parts of the image.

Modelling seasonal NDVI trends

Seasonal trends in the vegetative productivity of the Wax Lake Delta were explored using NDVI from a total of 68 images from the years 2000 to 2011. Stepwise multiple regression analysis was performed for both mean and total NDVI using a set of potential predictor variables that included Wax Lake Outlet stage and discharge, tide level, and air and water temperature. The stage and discharge data came from the U.S. Geological Survey river gage at Calumet, LA (U. S. Geological Survey 2012). As stage and water level are collected hourly, a weighted-average was used to estimate the exact water level and discharge at the time of image acquisition. Tide level measurements came from the National Ocean and Atmospheric Agency (NOAA) tide gage at Grand Isle, LA. Daily maximum, minimum, and mean air temperature and monthly maximum, minimum, and mean air temperature for each Landsat acquisition date were obtained from the NOAA National Climatic Data Center weather station in Morgan City, LA (NOAA). Average monthly water temperature for the Atchafalaya River came from the Louisiana Department of Environmental Quality monitoring station in Morgan City, LA (Louisiana Department of Environmental Quality). As in the long-term trend analysis, post-storm images were excluded from the seasonal NDVI analysis to allow us to examine seasonal trends independent of disturbance events.

Measuring storm disturbance and recovery

The impact of coastal storm disturbance on the vegetation community of the Wax Lake Delta was analyzed by identifying all tropical storms and hurricanes in the Gulf of Mexico from 1973 to 2011 that passed within 400 km of the Wax Lake Delta. To do this, the NOAA Historic Hurricane Tracks tool was used to generate a list of storms passing within 400 km of the delta and then excluded those storms that approached the delta from the landward side (NOAA). A storms dataset was created based on the characteristics of each storm when it passed closest to the delta. The dataset included storm category (tropical storm or category 1-5 hurricane), wind speed, pressure, distance from the Wax Lake Delta, landfall direction relative to the Wax Lake Delta, and maximum storm surge, represented by the peak stage measurement at the USGS Wax Lake Outlet river gage in Calumet, LA. Water level measurements were only available from 1997 to the present, preventing the identification of storm surges that may have occurred from 1973 to 1997.

Based on this information and the mean and total NDVI data calculated from the LANDSAT time series, 5 storms were identified that appeared to have a significant impact on the vegetation community in the Wax Lake Delta: Hurricane Andrew (1992), Hurricane Lili (2002), Hurricane Rita (2005), Hurricane Ike (2008), and Tropical Storm Lee (2011). The mean and total NDVI values for the delta following each of these storm events were compared to the 95 percent prediction intervals for the same date based on the long-term trends that were identified using regression analysis. The mean and total NDVI values for growing season images taken the year following each storm event were also compared to the 95 percent prediction intervals for those years, to determine whether the storms had a long-term impact on the productivity of the vegetation communities in the delta. The area of impact for each storm

was also mapped based on the difference in vegetated area ($\text{NDVI} > 0$) in Landsat images taken before and after the storm.

RESULTS

Long-term NDVI trends

Figure 4.1 shows the results of simple linear regressions between total peak growing season NDVI and mean peak growing season NDVI and date in the Wax Lake Delta between 1973 and 2011. The linear relationship between total NDVI and date had a correlation coefficient of 0.86, indicating that approximately 86 percent of the variation in total NDVI is associated with the date of acquisition. This correlation demonstrates a strong trend of increasing total NDVI over time, with a long term average increase of 838 per year. However, closer examination of the plot of total peak growing season NDVI versus date (Figure 4.1; a) suggests that the relationship may not be best described by a linear model. Splitting the dataset into three time periods and developing a separate regression model for each time period illustrates the different growth rates of total NDVI from 1975 to 1983, from 1984 to 2002, and from 2003 to 2011 (Table 4.1). Total NDVI in the delta remained quite low, close to zero, from 1973 to 1983. There is a strong positive trend in increasing NDVI during this period with an average rate of increase of 26 per year. The period from 1984 to 2002 was marked by a sharp increase in total NDVI from less than 1,000 to near 25,000. There is a very strong correlation between date and total NDVI for this time period and on average, NDVI increased by over 1,300 per year. The period from 2002 to 2011 shows much more variability in total NDVI. While total NDVI increased by 173 per year, the relationship between date and total NDVI is not statistically significant for this period.

The relationship between mean NDVI and date is weaker but more consistent over the time period of analysis than the relationship between total NDVI and date (Figure 4.1; b). The correlation coefficient for this trend was 0.62, suggesting that 62 percent of the variability in mean NDVI in the delta can be explained by a gradual increase in the mean NDVI of the delta over time, at a rate of 0.007 per year.

Seasonal NDVI trends

Figure 4.2 shows the seasonal patterns in total and mean NDVI over the time period from 2000 to 2011 (Figure 4.2; a), along with trends for Wax Lake Outlet stage and water temperature over the same time period (Figure 4.2; b). From Figure 4.2, part a, it is evident that the increase in total NDVI lags behind the increase in mean NDVI each growing season, but that the peaks in mean and total NDVI occur at approximately the same time. Figure 4.2, part b illustrates the relationship between discharge and water temperature in the Wax Lake Outlet. While there are large data gaps for water temperature prior to 2006, it is nonetheless clear that water levels begin to increase during the winter months, when water temperature is at or near its lowest point, and continues to increase throughout the spring, generally reaching a peak during late spring or early summer. By contrast, the peak in water temperature does not occur until after river water levels have begun to decrease during the mid to late summer.

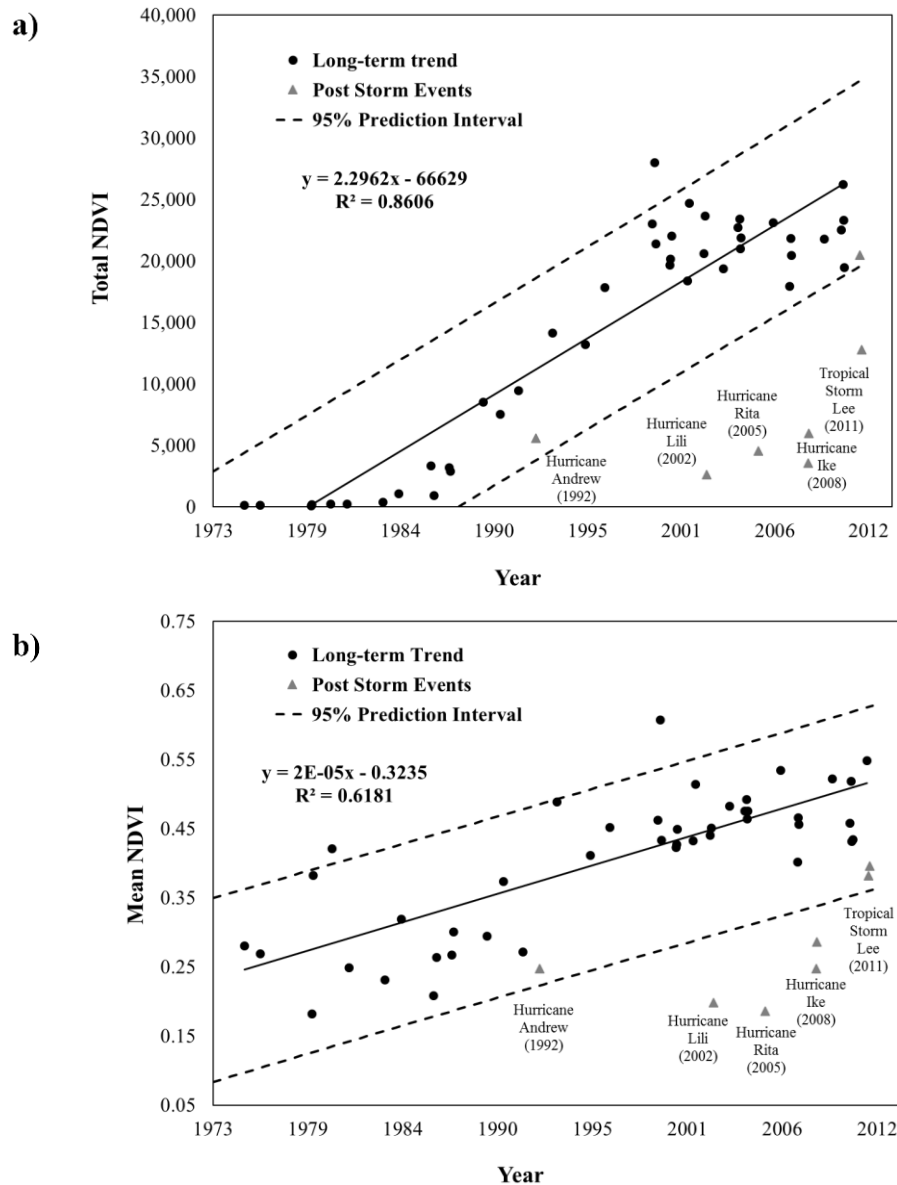


Figure 4.1 – Post-storm event total NDVI (a) and mean NDVI (b) in relation to the long-term trends of increasing total and mean peak growing season NDVI since the emergence of the Wax Lake delta in 1973

The optimum linear model for total NDVI that was selected by the step-wise multiple regression analysis included water temperature, daily mean stage, and date as predictor variables and explained approximately 82 percent of the variability in total NDVI values year-round (Table 4.2) (Figure 4.3; a). All of the variable coefficients in the model were significant at the 0.05 significance level. Figure 4.4 shows the partial regression plots for each of the explanatory variables in the model, indicating that in general, total NDVI increased with time, decreased with stage, and increased with water temperature during the 2000 to 2011 time period.

Table 4.1 – Simple linear regression model results for total NDVI in the Wax Lake delta during the sub-periods 1975-1983, 1984-2002, and 2002-2011

Time Period	Correlation Coefficient	Average Annual Increase in Total NDVI
1975-1983	0.556	26.27
1984-2002	0.915	1,343.43
2003-2011	0.050	173.13

The optimum linear model for mean NDVI included only water temperature and date as explanatory variables (Table 4.2) (Figure 4.3; b). This model explained approximately 76 percent of the variability in mean NDVI values. As with the total NDVI model, all of the model coefficients were significant at the 0.05 significance level. Figure 4.5 shows the partial regression plots for the explanatory variables in the mean NDVI model, indicating that mean NDVI increased slightly with time and increased with water temperature.

Storm disturbance and recovery

Table 4.3 lists all of the tropical storms and hurricanes that passed within 400 km of the Wax Lake Delta in the Gulf of Mexico and their characteristics. The five storm events that were identified as affecting the vegetation community of the Wax Lake Delta are highlighted and their tracks in relation to the Wax Lake Delta are shown in Figure 4.6. No water level data were available for Hurricane Andrew, which made landfall directly over the Wax Lake Delta in 1992. However, there was a large storm surge measured in the delta during each of the other four storm events that impacted the plant community in the delta.

All of the storms that impacted the plant community passed either to the west of or directly over the Wax Lake Delta. No storms passing to the east of the delta had an observable impact on NDVI. This includes several tropical storms that passed as little as 50 km east of the delta. All of the storms that impacted the plant community were Category 2 hurricanes or greater, except for Tropical Storm Lee, which passed only 50 km to the west of the delta. Several of the storms impacting the delta made landfall far to the west of the delta. Hurricane Rita, a category 3 hurricane, made landfall near the Texas-Louisiana border in 2005, over 170 km from the Wax Lake Delta. Hurricane Ike, a category 2 hurricane, made landfall in Texas, over 270 km from the delta, but still resulted in a storm surge of over 1 m in the delta and a large drop in both total and mean NDVI following the storm.

Figure 4.2 illustrates how the total and mean NDVI values in the delta following these five storm events compare to the long-term trends. Total NDVI in the delta decreased to well below the 95 percent prediction interval for the long-term trend for all storms except for Hurricane Andrew in 1992 and Tropical Storm Lee in 2011. For Tropical Storm Lee, the data point within the 95 percent prediction interval is from October 1, 2011 and the data point outside the 95 percent prediction interval is from November 2, 2011. It is likely that the lower total NDVI observed in the November 2 image from that year is related to the onset of senescence. The October 1, 2011 data point, which falls just within the 95 percent prediction interval, most

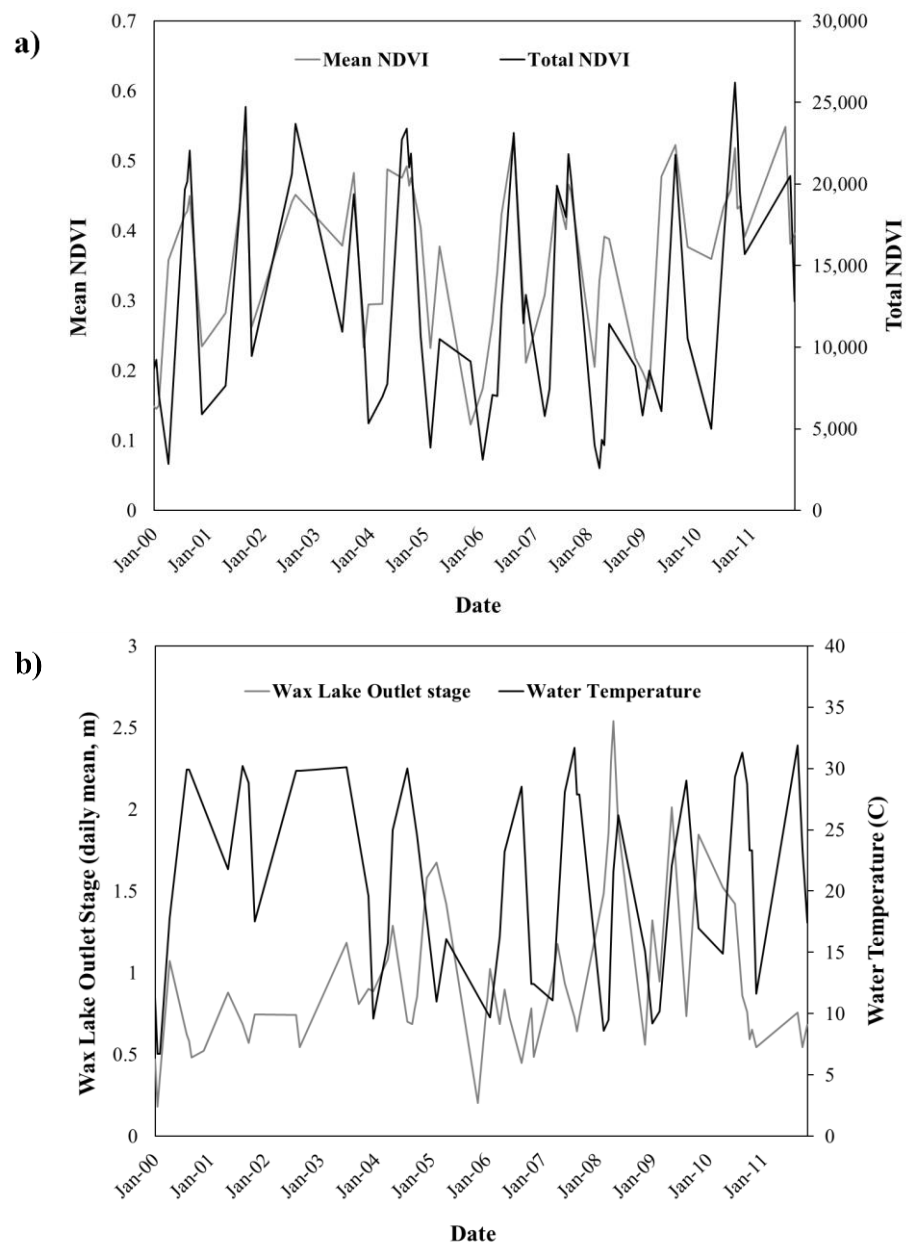


Figure 4.2 – Seasonal pattern in total and mean NDVI in relation to Wax Lake Outlet stage and Atchafalaya River water temperature

likely represents partial plant community recovery following the storm, which made landfall on September 3, 2011. Field observations made during the weeks prior to and following the storm suggest that most of the vegetation at lower elevations was killed by salt burn (Melissa Carle, personal observation).

Figure 4.7 shows the area of the delta that was impacted by each of the five storm events. Based on these maps, it is clear that Hurricane Lili and Hurricane Ike had the largest impacts on the plant community in the delta. Hurricane's Rita and Andrew had intermediate impacts and the

Table 4.2 – Parameters for multiple regression models for total and mean NDVI in the Wax Lake delta from 2000 to 2011

Model	Variable	Coefficient	Standard Error	P-value
Total NDVI	Constant	-188,947.35	56,624.50	0.00
	Water	620.71	57.51	0.00
	Temperature			
	Daily Mean	-7,213.59	920.30	0.00
	Stage			
	Date	1.47×10^{-5}	0.00	0.00
$r^2 = 0.812$				
Mean NDVI	Constant	-3.03	0.94	0.00
	Water	0.011	0.00	0.00
	Temperature			
	Date	2.36×10^{-1}	0.00	0.00
$r^2 = 0.746$				

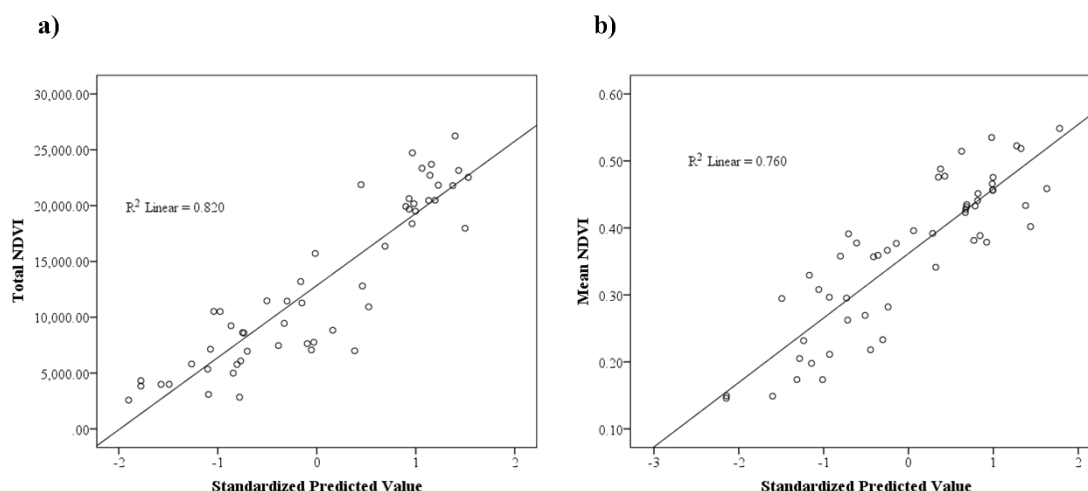


Figure 4.3 – Multiple regression models for total (a) and mean (b) NDVI in the Wax Lake delta from 2000 to 2011

impact of Tropical Storm Lee was fairly small and limited to the lowest elevation areas of the delta in the interiors of the islands and along their distal fringe. Table 4.4 compares the 1-year post-storm total and mean NDVI values for the delta to the 95 percent prediction intervals for the long-term trends for the four storms for which imagery was available for the year following the storm (Andrew, Lili, Rita, and Ike). In each case, both the total and mean NDVI values for the year following the storm fell within the 95 percent prediction intervals for the long-term trends, indicating that productivity within the delta had fully recovered from the storm disturbance.

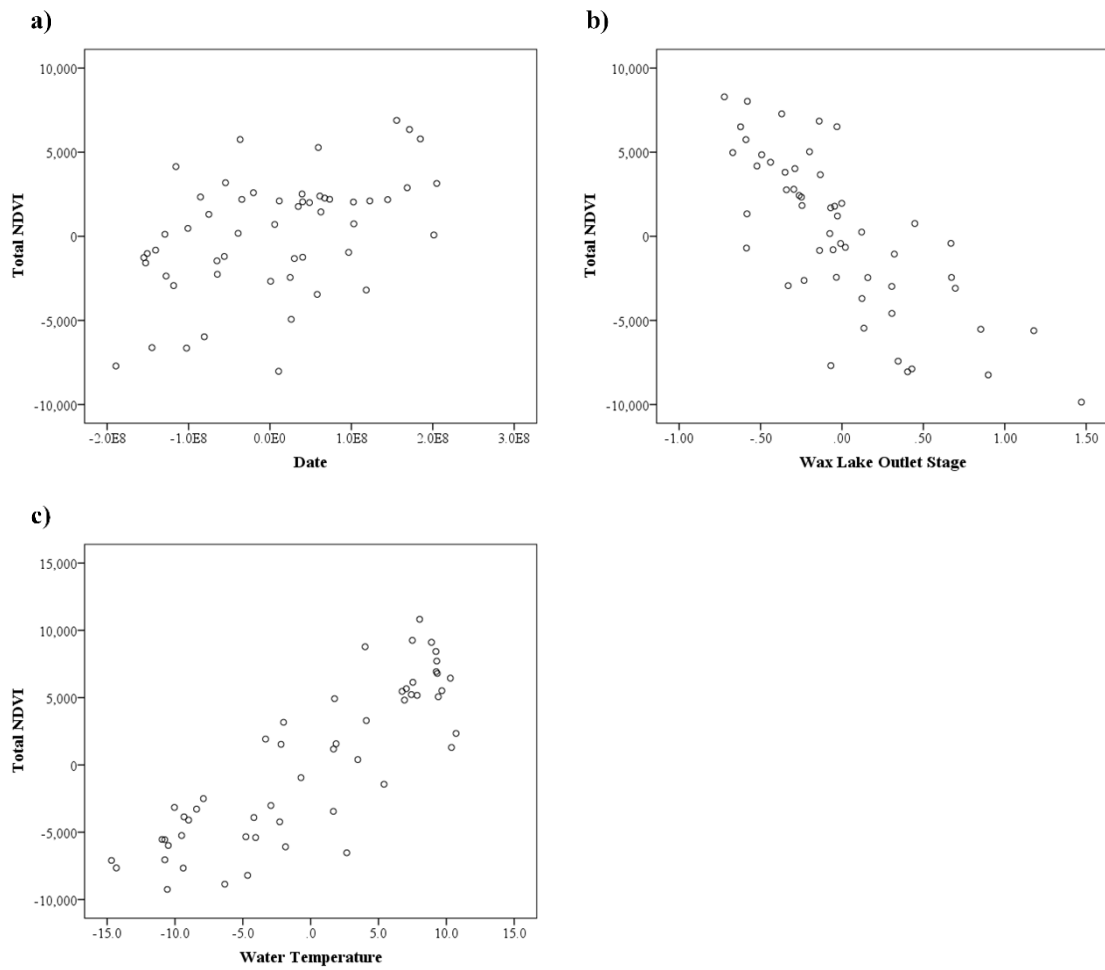


Figure 4.4 – Partial regression plots for the total NDVI model: a) date vs. total NDVI, b) stage vs. total NDVI, and c) water temperature vs. total NDVI

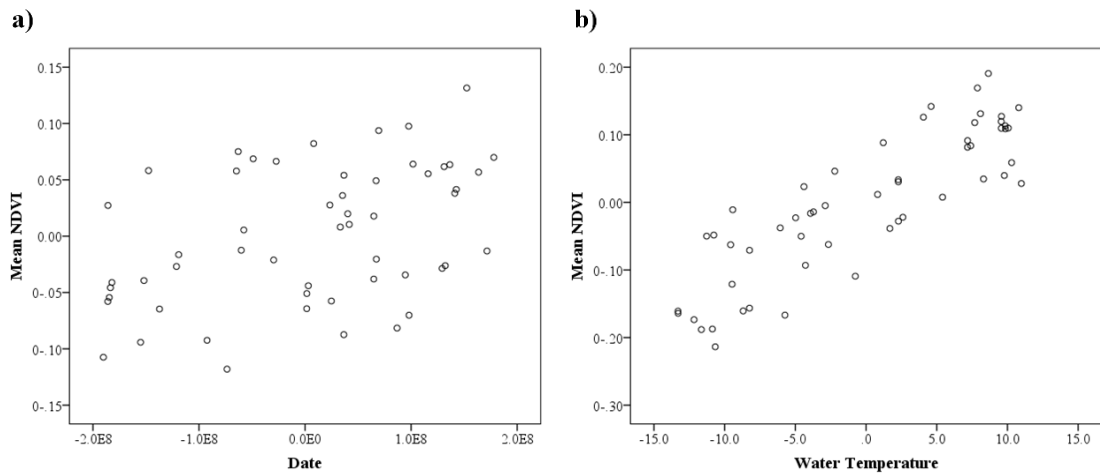


Figure 4.5 – Partial regression plots for the mean NDVI model: a) date vs. mean NDVI and b) water temperature vs. mean NDVI

Table 4.3 – Hurricanes and Tropical Storms passing within 400 km of the Wax Lake delta and their associated storm surge in the delta (for storms occurring after 1994)

Date	Storm Name	Category	Wind Speed (kts)	Pressure (mb)	Distance from WLD (km)	Landfall relative to WLD	Storm Surge (m)
9/4/1973	Delia	TS	60	993	266	west	-
9/8/1974	Carmen	3	105	937	11	at WLD	-
9/22/1975	Eloise	2	85	980	370	east	-
8/31/1977	Anita	1	75	986	321	south	-
9/5/1977	Babe	1	65	995	14	east	-
8/28/1978	Debra	TS	40	1002	199	west	-
7/11/1979	Bob	1	65	991	86	east	-
7/24/1979	Claudette	TS	35	1003	222	west	-
9/12/1979	Frederic	4	115	950	308	east	-
8/31/1979	Elena	TS	35	1004	293	west	-
9/11/1982	Chris	TS	50	1000	221	west	-
8/17/1983	Alicia	1	65	991	249	west	-
8/15/1985	Danny	1	80	988	120	west	-
9/2/1985	Elena	3	100	959	187	east	-
10/29/1985	Juan	1	65	974	9	at WLD	-
6/25/1986	Bonnie	1	65	1001	193	west	-
9/9/1988	Florence	1	65	985	144	east	-
6/26/1989	Allison	TS	35	1004	250	west	-
8/1/1989	Chantal	1	65	991	208	west	-
10/15/1989	Jerry	TS	60	991	334	west	-
8/26/1992	Andrew	4	120	955	27	at WLD	-
10/4/1995	Opal	4	130	919	359	east	-
7/17/1997	Danny	TS	50	1002	99	east	0.05
9/2/1998	Earl	TS	50	996	225	east	-0.02

(Table 4.3 continued)

Date	Storm Name	Category	Wind Speed (kts)	Pressure (mb)	Distance from WLD (km)	Landfall relative to WLD	Storm Surge (m)
9/27/1998	Georges	2	95	962	255	east	-0.07
9/20/1998	Hermine	TS	40	999	55	east	0.04
9/14/2002	Hanna	TS	50	1001	237	east	0.10
9/26/2002	Isadore	TS	55	989	112	east	-0.19
10/3/2002	Lili	3	105	957	61	west	0.68
6/30/2003	Bill	TS	50	997	53	east	0.00
7/14/2003	Claudette	TS	60	989	280	west	0.07
8/15/2003	Erika	TS	50	1001	379	west	-0.04
8/31/2003	Grace	TS	35	1008	354	west	0.18
8/11/2004	Bonnie	TS	55	1001	371	east	0.06
9/23/2004	Ivan	TS	50	998	90	west	0.26
10/10/2004	Matthew	TS	40	999	45	east	0.38
6/11/2005	Arlene	TS	60	993	377	east	-0.02
7/6/2005	Cindy	1	65	991	131	east	0.01
8/29/2005	Katrina	3	110	920	169	east	-0.13
9/24/2005	Rita	3	105	931	171	west	1.31
9/13/2007	Humberto	TS	55	997	208	west	0.23
8/5/2008	Eduoard	TS	50	999	106	west	0.23
9/1/2008	Gustav	2	90	954	26	east	0.13
9/12/2008	Ike	2	95	954	272	west	1.05
11/9/2009	Ida	1	65	990	267	east	0.11
9/3/2011	Lee	TS	50	993	50	west	0.80

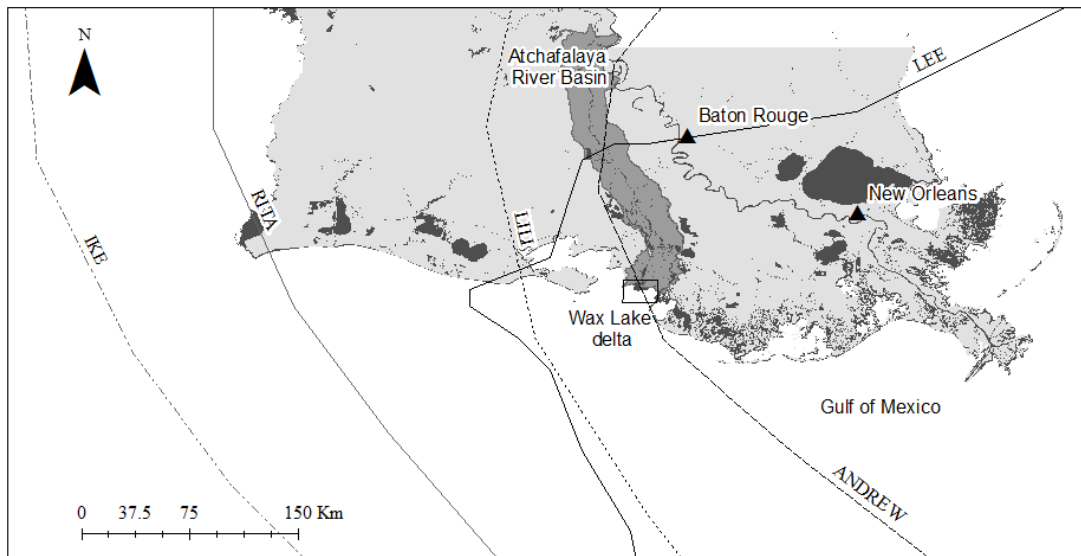


Figure 4.6 – Location of the Wax Lake delta relative to storm tracks for the five storms influencing the vegetation community between 1973 and 2011

Table 4.4 – Post-storm and post-recovery total and mean peak growing season NDVI in relation to the prediction interval for the long-term trends for 4 major hurricanes impacting the Wax Lake Delta

Storm Event	Following year total NDVI	95% Confidence Interval for total NDVI	Following year mean NDVI	95% Prediction Interval for Mean NDVI
Hurricane Andrew	14,164	3,674-18,484	0.49	0.22-0.48
Hurricane Lili	19,375	12,110-26,994	0.48	0.30-0.56
Hurricane Rita	23,153	14,581-29,515	0.55	0.32-0.58
Hurricane Ike	21,789	17,040-32,034	0.52	0.34-0.60

DISCUSSION

The results indicated a strong increase in both total and mean NDVI in the Wax Lake Delta from the time it first emerged following the 1973 and 1975 floods to 2011. However, while mean NDVI has shown a slow, but steady increase throughout the entire time period, the increase in total NDVI has been less consistent, responding strongly to changes in the emergent area of the delta. During the early years from 1975 to 1983, the total NDVI of the delta remained quite low. This trend is due, in large part, to the small area of exposed mudflats available for colonization. While the neighboring Atchafalaya Delta grew substantially following the floods in the 1970's, growth of the Wax Lake Delta lagged behind until the early

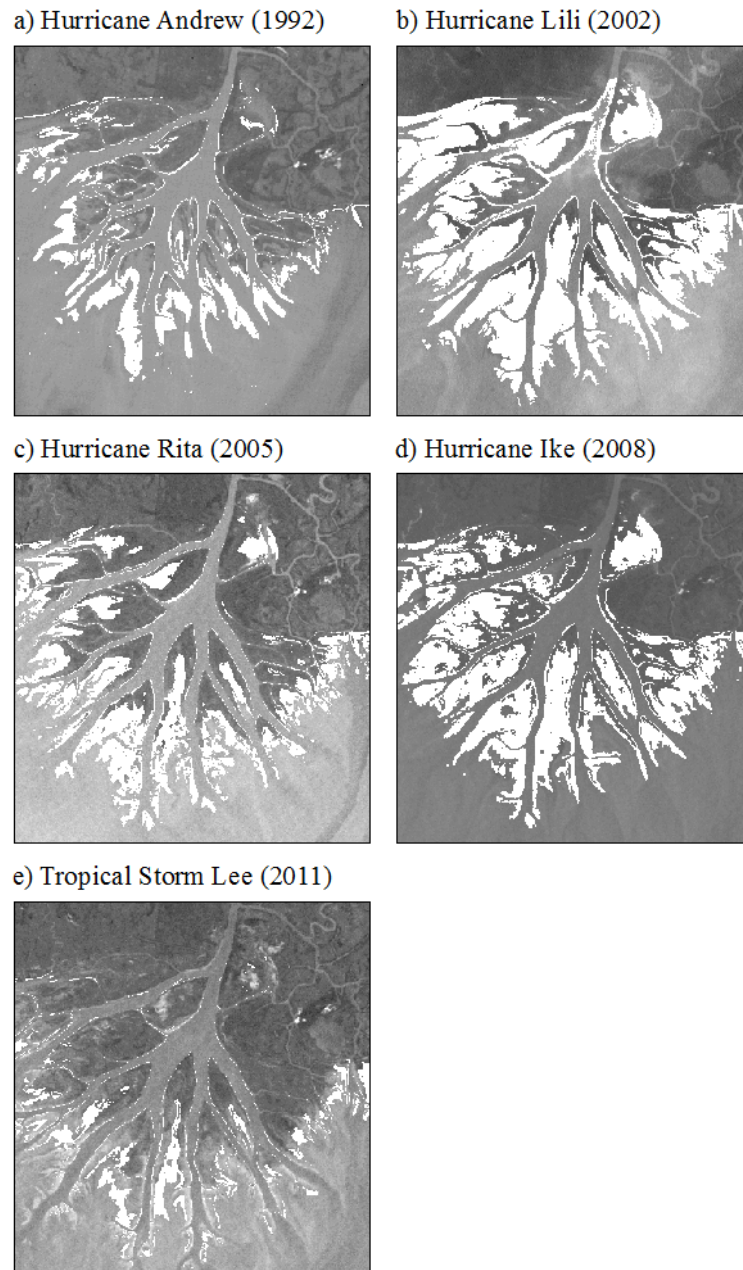


Figure 4.7 – Vegetation areas in the Wax Lake delta impacted by Hurricanes: (a) Andrew, (b) Lili, (c) Rita, (d) Ike, and (e) Tropical Storm Lee. White indicates areas that were vegetated prior to the storm event and unvegetated following the storm event.

1980's (Roberts et al. 2003; Roberts et al. 1997b). During this time sediment was filling in Wax Lake, a shallow natural basin located directly upstream of the mouth of the Wax Lake Outlet in the Atchafalaya Basin. Once Wax Lake was filled, sediment delivery to the delta increased and the rate of deltaic growth increased as well (Roberts 1998). As a result, the period from 1983 to

2002 was characterized by a rapid increase in both the area of the delta and productivity as measured by total NDVI.

The landfall of Hurricane Lili in 2002 marked the beginning of a new period in the life of the delta – a period during which the areal growth of the delta slowed considerably and there was a consequent reduction in the rate of increase of total NDVI in the delta. Morton and Barras (2011) documented the combined effects of Hurricane Lili and Tropical Storm Isadore on the central coast of Louisiana. Tropical Storm Isadore made landfall eight days before Lili and caused widespread flooding in the marshes of coastal Louisiana, which had not fully receded when Lili hit. The impact of Hurricane Lili was greatest in the right-front quadrant of the storm, where the storm formed elongated ponds in the marsh, expanded existing ponds, compressed the marsh surface, laterally displaced marsh mats up to 1 m thick, and eroded up to 70 m from the beaches of barrier islands (Morton and Barras 2011; Stone et al. 2003). Allen et al (2012) modeled land area change in the Wax Lake Delta as a function of time, river level, and tidal level from 1983 to 2010. They found a significant increase in the area of the delta from 1984 to 2002, but no significant relationship between delta area and time from 2002 to 2010. They suggest that disturbance by Hurricane Lili, combined with below average suspended sediment loads in the Atchafalaya River during most of the time period, explain the reduced growth rate of the delta during the time period. This explanation is supported by Rosen and Xu (2013) who found that net land loss in the Wax Lake and Atchafalaya Deltas during the period from 1999 to 2004 corresponded to a period without a major flood event and the highest recorded storm surge from 1989 to 2010 (Hurricane Lili).

The rapid increase in total NDVI in concert with the areal growth of the Wax Lake delta from 1983 to 2002 is consistent with rapid vegetation growth that has been observed in other emergent river deltas (Kandus and Malvárez 2004; White 1993). The steady increase in mean NDVI throughout the study period, is also consistent with the successional development of the deltaic islands, as the low-growing colonizing annuals are replaced by perennial species that increase in biomass each year. While the emergent plants in the delta die back to the sediment each winter, they contain significant underground stores and are capable of rapid regrowth in the spring. As elevations in the delta increase, the emergent plants are replaced by a much more species-rich mixed high marsh community. At these higher elevations, physical stressors are reduced and a greater range of species are able to invade and more fully exploit all of the available resources. Vegetation cover is often much higher than 100 percent in these areas, with multiple layers of marsh plants exploiting every possible niche in the canopy and understory. It is also common to find a layer of the vine *Vigna luteola* completely covering the marsh canopy. Thus, the geomorphic succession of the islands from newly emerged mudflats to higher elevation marshes is coupled with a process of ecological succession that leads to an increase in the per area productivity of the entire delta as measured by mean NDVI.

The response of total NDVI to seasonal fluctuations in water level and the response of mean NDVI to seasonal fluctuations in both water level and water temperature is consistent with the phenological patterns that have been observed in the field and supports the hypothesis that many species are unable to begin their growth until the spring floods recede and the water in the delta begins to warm (Fuller et al. 1984). A similar relationship between water level and seasonal patterns of NDVI has been demonstrated in the Parana River delta in Argentina, although river water levels were only important predictors of NDVI in parts of the delta that had a direct connection to the river (Zoffoli et al. 2008). In areas without direct riverine influence,

rainfall and tide levels showed a stronger relationship with NDVI. This same pattern has also been observed in the inland Okavango River delta in Botswana (Gumbricht et al. 2000).

The recovery of the vegetation community within the Wax Lake delta following each of the four major storm disturbances examined in this study supports the theory that the delivery of large amounts of sediment by a river to deltaic marshes instills a resilience in those marshes that is not seen when the same marshes are sediment-starved. Of the four hurricane events that impacted the delta, only Hurricane Lili had a potential long-term impact on the delta, and the larger impact of this storm event was most likely related to the lower than average sediment delivery that occurred in the years prior to the storm combined with a storm path that placed the Wax Lake delta directly in the highest-impact right front quadrant of the storm (Allen et al. 2012; Morton and Barras 2011; Rosen and Xu 2013). However, despite this combination of events, the vegetation community of the delta still recovered to within the 95 percent prediction interval for the long-term trend by the following growing season. The effect of the storm was not one of lost productivity, but a longer-term reduction in the rate of productivity increase compared to the period from 1984 to 2002.

It is worth comparing the impact of Hurricane Lili, a category 3 storm that made landfall just west of the Wax Lake delta to that of Hurricane Andrew, which made landfall directly over the Wax Lake delta in 1992. While similar impacts occurred to the marshes of the central Louisiana coast during Andrew as were observed following Lili (pond creation and elongation, marsh compression and dislocation), there was little widespread impact from this storm and much of the fresh and intermediate marshes around Atchafalaya Bay were observed to have completely recovered within six months of the storm (Guntenspergen et al. 1995; Morton and Barras 2011). This may have been related to the substantial amount of sediment that was deposited on the marsh surface as a result of the storm surge, with deposits up to 16 cm thick noted in some areas (Guntenspergen et al. 1995). Numerous studies have indicated the beneficial role that storm-event sedimentation can have on coastal marshes in Louisiana (Cahoon et al. 1995; McKee and Cherry 2009; Nyman et al. 1995; Turner et al. 2006; Tweel and Turner 2012a; Williams 2012). The annual discharge and suspended sediment yield of the Atchafalaya River were also fairly high during the years prior to Hurricane Andrew, which may have increased the resilience of the delta's marshes during this time period (Rosen and Xu 2013). High sediment delivery to Atchafalaya Bay in the years preceding the storm also likely contributed to the high sedimentation rate associated with Andrew, mitigating the overall negative impact of the storm on the marshes in this region.

In general, the influence of tropical storms and hurricanes on the plant community of the Wax Lake delta appears to be limited to those that make landfall to the west of delta, which force a strong surge of salt water into the delta that burns the vegetation and initiates a short-term die-off event. Even hurricanes that make landfall over 150 km to the west of the delta can still result in large storm surges and short-term impacts to the plant community, as exemplified by Hurricane Rita in 2005 and Hurricane Ike in 2008. When storms occur late in the growing season, plant community productivity may not fully recover until the following growing season. However for storms that occur early in the growing season, the plant community may experience at least partial recovery before seasonal senescence occurs. This appears to have been the case following Tropical Storm Lee in 2011.

My analysis of storm impacts was limited to storms for which cloud-free growing season images were available for before and after the storm event and for the growing season following the storm. Unfortunately, there were far fewer usable images for the earlier years of the Wax Lake delta's development, so it is uncertain which storms prior to 1992 impacted the vegetation community. The water level record is also incomplete, making it impossible to assess the extent of storm surge associated with storm events prior to 1997. However, based on their similarity to the more recent influential storms, Hurricane Carmen (1974), Hurricane Babe (1977), and Hurricane Juan (1985) likely had at least some short-term impact on marsh productivity in the delta. Hurricane Carmen was a category 3 storm that passed directly over the Wax Lake delta. However, as this storm occurred only a year after the first mudflats began to emerge in the Wax Lake delta, its impact was probably fairly minor. The same is likely true of Hurricane Babe, which was a category 1 storm when it made landfall just to the east of the newly-formed delta. Hurricane Juan was also a category 1 storm, but occurred in 1985, after the subareal part of the delta had begun to grow rapidly and when the plant community was more well-established. I predict that this storm had a similar effect as Tropical Storm Lee, causing minor salt burn in the lowest elevation communities, with complete recovery by the following year.

Overall, the results of this study suggest that the marshes of the Wax Lake delta demonstrate considerable resilience to storm impacts, compared to what has been documented for other wetlands in the Mississippi River deltaic plain. Steyer et al (2013) used NDVI to assess the impact and recovery of marshes throughout coastal Louisiana following Hurricanes Katrina and Rita in 2005. They found that below average values of NDVI persisted in most marsh communities one year following the storms, but that these persistent impacts were concentrated in the east and the western regions of the state, where the two storms had the most direct impact. Very little persistent impact from the storm events was observed in the central region, which includes Atchafalaya Bay (Steyer et al. 2010). The impact of Hurricane Rita was particularly strong in southwestern Louisiana, where marshes were subjected both to higher direct physical disturbance and ponding of salt water which was trapped in the marshes following the storm (Steyer et al. 2010). This resulted in greater long-term impacts to these marshes than in the central coastal region. In the case of the Wax Lake delta, the high flow of freshwater through the delta likely flushes salt from the soil quickly following such storm surge events, preventing long-term increases in pore-water salinity and consequent impacts to the vegetation. A similar rapid recovery was observed in the marshes in the Mississippi River delta following Hurricane Camille (Chabreck and Palmisano 1973).

CONCLUSIONS

This study demonstrated that the marshes in the Wax Lake delta, a small, pro-grading delta formed at the mouth of an artificial diversion of the Mississippi River, have rapidly increased in both total and mean productivity over the life of the delta. This trend of increasing productivity stands in sharp contrast to the long-term decrease in productivity occurring throughout the wetlands in the greater Mississippi River delta plain (Cardoch et al. 2002). As such, it illustrates the positive impact on deltaic marsh productivity provided by a direct connection to the river and the tremendous volume of freshwater and sediments that it provides. This connection with the river has resulted in an increase in both total and mean NDVI as the

deltaic platform has accreted vertically and laterally since the first mudflats were exposed in the early 1970's. The increase in total NDVI correlated strongly with the increasing size of the subaerial delta. The increase in mean NDVI can be attributed to plant community successional processes by which early colonizing annuals are gradually replaced by perennial species that increase in biomass each year and by the more complete utilization of available resources as elevations within the delta increase and a wider variety of plant species are able to invade.

The seasonal variation in NDVI observed in the Wax Lake delta can be attributed to the phenology of the plant community in the delta and the physical factors that limit plant growth in the delta in the spring and early summer. The river's spring flood produces high water levels in the delta that delay the onset of plant community production relative to terrestrial and other coastal marsh settings. Total NDVI in the delta is strongly correlated to river stage, which controls the area where the water level is low enough to support floating and emergent marsh vegetation. Mean NDVI, on the other hand, depends both on water level and water temperature, which is a limiting factor for plant growth in the low areas of the delta dominated by floating and submerged aquatic vegetation.

In the Wax Lake delta, the Mississippi River has built deltaic marshes that not only are increasing in productivity over time, but also demonstrate remarkable resilience to coastal storm disturbance. While long-term hurricane impacts are evident in marshes throughout coastal Louisiana, the marshes of the Wax Lake delta show no signs of long-term physical disturbance following storm events. Strong storms passing to the west of the delta are capable of producing substantial short-term impacts on the productivity of the delta, predominantly by producing large storm surges that carry salt water into the normally freshwater environment. The salt burns the vegetation in the delta and results in a temporary decrease in productivity, but productivity generally fully recovers by the following growing season. Such rapid recovery of plant community productivity occurred even following Hurricanes Andrew and Lili, two very strong storms that passed just to the west of the delta, placing the deltaic marshes directly in the most heavily-impacted front right quadrant of the storm. The high freshwater flows through the Wax Lake Outlet most likely prevent any long-term increases in pore water salinity in the delta. There was also no evidence in the Wax Lake delta of direct erosion to open water or marsh compression and dislocation, as has been observed in other coastal marshes in Louisiana following large storm events (Morton and Barras 2011).

Overall, the evidence provided by my analysis of NDVI trends in the Wax Lake delta suggests that these marshes are productive systems that are continuing to increase in productivity over time and demonstrate considerable resilience to coastal storm disturbance. As the Wax Lake Outlet is essentially an unmanaged river diversion, the results of this work have important implications for the potential success of other large-scale river diversions that have been proposed to build and restore marshes elsewhere in coastal Louisiana (Coastal Protection and Restoration Authority (CPRA) 2012). My observations at the Wax Lake delta suggest that restoring the connection between deltaic marshes and the river that built them should help to increase both the productivity and resilience of deteriorating marsh communities elsewhere in the Mississippi River deltaic plain.

CHAPTER 5 –ACCRETION AND VEGETATION COMMUNITY CHANGE IN THE WAX LAKE DELTA FOLLOWING THE HISTORIC 2011 MISSISSIPPI RIVER FLOOD

ABSTRACT

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 Landsat 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 currently building new land. Vegetation community change was mapped from 2010 to 2011 and related to elevation change using plant species elevation distributions calculated from 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 post-flood Landsat TM images. The results indicate a net growth of 6.5 km² at mean water level and 4.90 km² at mean sea level. Areal gains were greatest at high water levels, indicating substantial vertical accretion across the subaerial delta. At least 8.7 km², or 31.8 percent of the area studied converted to a higher elevation species, with most change occurring at low elevations with conversion from other submerged aquatic vegetation species to the floating-leaved *Potamogeton nodosus* and the floating-leaved and emergent *Nelumbo lutea*. Conversion to lower elevation species occurred across 3.4 km², or 12.8 percent of the study area, while 55.5 percent 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.

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 et al. 2006; Morton and Bernier 2010; Törnqvist et al. 2008; Yuill et al. 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 et al. 2008; Nittrouer et al. 2011).

The quantity and size distribution of sediments delivered during a flood event is a direct function of watershed geomorphology, land cover, land use practices, and the amount of upstream sediment capture that occurs (Chakrapani 2005). Watershed geomorphology largely

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determines the type of sediment that is available for transport and its inherent erodability while relief determines the grain sizes that a river can transport (Chakrapani 2005; Orton and Reading 1993). Watershed land cover, and 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-1900's (Syvitski et al. 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 et al. 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 for delta building (Nittrouer et al. 2008; Nittrouer et al. 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 much 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 later reworked onshore by waves, tides, and storms (Allison et al. 2000; Mossa and Roberts 1990; Reed 1989).

However, there is an inherent conflict between the critical role that floods play 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. 2010b; Weng 2000). Today, river deltas occupy less than 1 percent 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 et al. 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 currently losing land at a rate of about 40 km² per year (Barras et al. 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, due to subsidence rates that range from 1 to 2 millimeters per year at the inland boundary near Baton Rouge to as high as 6 to 8 millimeters 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 river and its deltaic plain (Coastal Protection and Restoration Authority (CPRA) 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.

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 condition (Albert and Minc 2004; Goslee et al. 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 et al. 1996; Wilcox 2004). Within river deltas, plant communities respond to a variety of riverine and coastal drivers, including 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 et al. 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 et al. 1987). As a river delta accretes vertically and matures, the plant community changes and undergoes allogenic succession over time. In temperate, river-dominated deltas such as the Wax Lake delta, submerged-aquatic vegetation may first establish on newly-formed shallow mudflats only to be replaced by floating-leaved vegetation, then emergent vegetation, diverse high-marsh meadow communities, and eventually canopies of small trees and shrubs as elevation increases over time (Johnson et al. 1985; Kandus and Malvárez 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*) along the natural channel levees, dense meadows of mixed grasses and forbs at intermediate elevations, emergent forbs such as *Sagittaria* species and American lotus (*Nelumbo lutea*) that colonize periodically exposed mudflats, and floating-leaved and submerged aquatic vegetation at the lowest elevations in the distal interior of the islands and on newly-formed shallow deposits. Most of the 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 Atchafalaya deltas since their formation. However, their dominance at the Wax Lake delta has waned in recent years, with the floating-leaved submerged aquatic vegetation (SAV) *Potamogeton nodosus* and emergent *Nelumbo lutea* spreading over much of the lower elevation areas of the delta previously dominated by *Sagittaria* spp (C. E. Sasser, *personal observation*). The expansive stands of *Nelumbo 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 coast-wide vegetation surveys conducted approximately every five to ten years suggest that its presence is gradually increasing coast-wide (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.

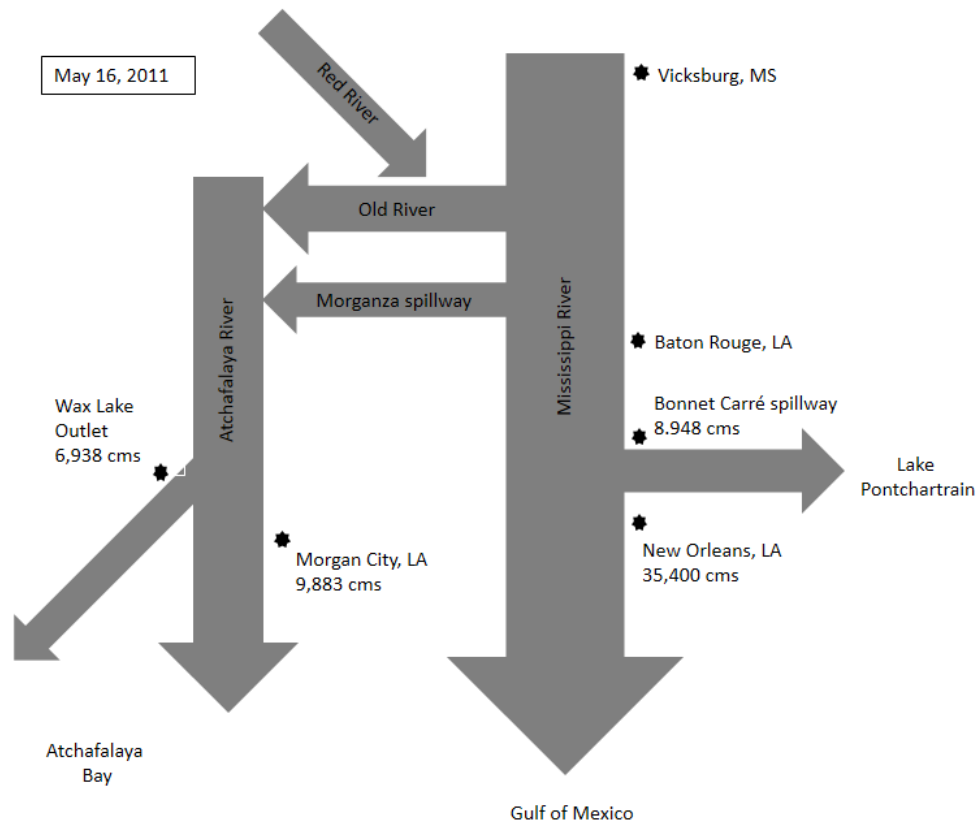


Figure 5.1 – Peak discharge on the lower Mississippi River system during the historic 2011 flood, based on discharge data from U.S. Geological Survey gauging stations

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 5.1). 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 (U. S. Geological Survey 2012). The lower river remained above flood stage for nearly two months – from early May to late June 2011. To prevent inundation of the cities of Baton Rouge and New Orleans, the United States Army Corps of Engineers (USACE) 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 4,870 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 United States 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, 8,860 cms was discharged into the Wax Lake delta (U. S. Geological Survey

2012). This represents approximately 11 percent of the total peak flood discharge on the lower Mississippi River system.

In this study, high and moderate resolution satellite remote sensing were used to measure the response of the vegetation community in the Wax Lake delta to this historic flood event. The increase in the vegetated surface of the delta was measured by comparing the relationship between water level and vegetated area before and after the flood. Light detection and ranging (LiDAR) data were used to test the relationship between elevation and the spatial distribution of 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 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, this could provide a lower cost option for assessing landscape scale geomorphic change where LiDAR data is 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 valuable 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

A threshold of the normalized difference vegetation index (NDVI) was used to separate open water from vegetated areas of the delta for a series of cloud-free or nearly cloud-free Landsat images from the summer and early fall of 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 formula (Rouse et al. 1974):

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

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 et al. 2002). For this study, a stepping method at 0.005 intervals was used to identify the optimum NDVI threshold to separate land and water for each image and the lowest value of NDVI that resulted in classification of all deep water pixels as water was selected as the threshold. 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) (Allen et al. 2012; Couvillion et al. 2011). In its coast-wide 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 Grande Isle, LA (Couvillion et al. 2011). That method was impossible to reproduce for this study due to a lack of suitable winter post-flood imagery as a result of failure of the Landsat 5 satellite in November 2011. This work represents the extent of the vegetated surface of the delta, a measure that may hold more ecological significance, but is not necessarily directly comparable to land area estimates made in previous studies. In particular, the estimate of vegetated area in this study includes shallow areas dominated by floating-leaved and submerged vegetation. These areas are very 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 et al. 1990; Serodes et al. 1984; Stumpf and 1983), 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 et al. 2012; Roberts 1998). To account for this variability, linear regression analysis was used to quantify the relationship between water level and vegetated area before and after the flood. Vegetated area gain was determined based on the difference between the pre- and post-flood 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 (LA OCPR) and U.S. Geological Survey (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 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 post-flood 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 salt water into the delta that killed most of the submerged and floating-leaved vegetation. Comparison of preliminary classifications for dates before and after the storm suggested that consistently less vegetated land was mapped using post-storm images, independent of water level, due to the loss of this vegetation. For consistency, areas that had been dominated by vegetation prior to the storm were added to the post-storm vegetated area maps, so that only changes in vegetated area related to water level fluctuations were considered.

As the water level for the post-storm images was lower than for the pre-storm images, 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 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, the Landsat results were compared to those obtained using a WorldView-2 image from October 16, 2011 (2 m spatial resolution). For this analysis, a small area of the delta was selected where the mapped area did not appear to be affected by the loss of submerged and floating vegetation following Tropical Storm Lee. Land area for this region was measured using each of the 2011 Landsat images and the exponential function describing the relationship between water level and land area was calculated. An NDVI was calculated using band 7 (NIR1) of the WorldView-2 image and the vegetated area was mapped using the same method applied to the Landsat imagery. The exponential relationship between water level and vegetated area was used to predict the amount of land that would have been mapped using Landsat imagery for the same water level and a correction factor was developed as the ratio of the area measured using the WV-2 image to the area predicted by the Landsat-based equation.

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

Vegetation mapping

Vegetation maps produced by maximum likelihood supervised classification of high resolution (2-m) WorldView-2 (WV-2) and moderate resolution (30-m) Landsat 5-TM satellite imagery obtained before and after the 2011 Mississippi River flood were used to measure the flood's impact on wetland vegetation communities in the delta. Pre-flood WV-2 imagery from June 15, 2010 and post-flood imagery from October 16, 2011 were obtained for this analysis. 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 *Nelumbo lutea*, *Sagittaria spp*, and *Potamogeton nedosus*). Landsat images of Wax Lake delta from August 27, 2010 and August 30, 2011 were used to measure the post-flood, pre-storm vegetation change in these areas of the delta. These species typically form large monotypic stands and can be mapped with reasonable accuracy using Landsat imagery.

All images were converted to at-satellite reflectance values prior to classification. Several small clouds, roads, and buildings in the northeastern 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 images using a threshold for the difference between reflectance in the visible portion of the spectrum (blue, green, 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 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 the summer of 2010 (D. Elaine Evers, unpublished data). Training areas for the 2011 WV-2 and Landsat classifications were collected in the field during late August and early September 2011 using a Trimble GeoXH differential global positioning system (DGPS) with sub-meter 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 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 with user's accuracies greater than 65 percent 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 from that class that were classified (Stehman 1997; Story and Congalton 1986). An accuracy assessment of the 2011 WV-2 and Landsat maps using 85 random points visited in the field in August and September 2011 indicated that the following seven classes met this criterion: trees (91%), *Nelumbo lutea* (77%), *Colocasia antiquorum* (88%), *Polygonum spp.* (67%), *Potamogeton nodosus* (98%), other SAVs (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 in the June 2010 WorldView-2 vegetation map and a 2-meter digital elevation model interpolated from light detection and ranging (LiDAR) data collected in January 2009. The LiDAR data were collected at low tide, with a point density of 4.5 points/m², and had an average vertical accuracy of 5.5 cm over flat surfaces (James Buttles, unpublished data). Elevations were calculated relative to the North American Vertical Datum of 1988 (NAVD88), using the U.S. National Geodetic Survey Geoid03 model. For this analysis, it is assumed that insufficient elevation change occurred between acquisition of the 2009 LiDAR data and the 2010 WV-2 imagery to greatly impact 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 (U. S. Geological Survey 2012). Further, 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 the spring of 2009 than the spring of 2010, the total elevation change should 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. 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 between class variances in elevation for groups of species growing within adjacent elevation zones. All statistical tests were performed using the SPSS statistical software package (International Business Machines (IBM) Corp. 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 *Colocasia antiquorum*, *Polygonum spp.*, and trees, and to determine areas of change from low elevation communities (*Nelumbo lutea*, *Potamogeton nodosus*, other SAVs, and water) to the mid- and high-elevation communities. The Landsat-derived maps were used to determine areas of elevation change within the low-elevation communities. For both the WV-2 and Landsat analyses, grid cells that converted from a lower elevation species/class to a higher elevation species/class were assigned to the “potential elevation gain” class. Grid cells that converted from a higher elevation species/class to a lower elevation species/class were assigned to the “potential elevation loss” class. Grid cells where the vegetation classification did not change or changed to another species within the same elevation group (e.g. *Potamogeton nodosus* to the “other SAVs” class) were assigned to the “no change” class. The results of the WV-2 and Landsat analyses were merged to create an overall map of areas that experienced elevation change following the 2011 flood.

June and August 2011 Landsat images were compared to qualitatively account for seasonal variation in plant community distributions that may have impacted the results of the vegetation change analysis. The phenology of many of the 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 any 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 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 northwest-southeast oriented island on the eastern side of the delta (Figure 5.2). Navigation to the sites in the field was accomplished using a Trimble GeoXH DGPS with sub-meter horizontal accuracy. At each site, percent cover values for all plant species were recorded on 5 percent intervals within a 1-m² plot centered on the point location.

Areas of predicted elevation change based on vegetation change were compared to existing pre- and post-flood elevation data that has been collected in the Wax Lake delta

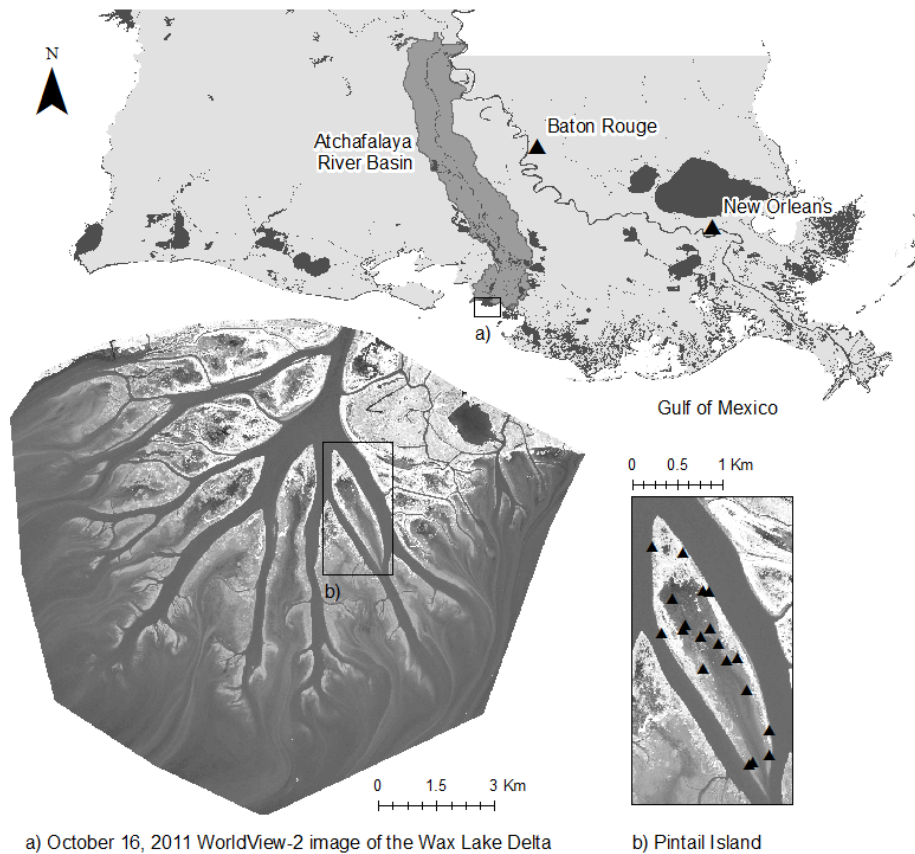


Figure 5.2 – Location of reference plots on Pintail Island

(unpublished data). The mean and variance of 2010 to 2011 elevation change for plots mapped as “predicted elevation loss,” “potential elevation gain,” and “no change” were compared using t-tests and analysis of variance, 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 vegetation-based 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 elevation data comparison, the number of usable plots was impacted by cloud cover in the August 2011 Landsat 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 imagery.

Finally, the impact of the 2008 Hurricanes Gustav and Ike on the distribution of *Nelumbo 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 southeast of the Wax Lake delta, on September 1, 2008 and moved slowly in a west-northwest direction across coastal Louisiana, passing just north of the Wax Lake delta. The delta experienced a maximum storm surge of 1.6 meters (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 meters measured in the delta (Coastal Protection and Restoration Authority of Louisiana 2012). Landsat imagery taken after these storms on September 22, 2008 suggests that most of the vegetation in the delta was killed, possibly by pulses of salt water 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 *Nelumbo lutea*, was particularly slow to recover. To test whether expansion of *Nelumbo 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 image from July 28, 2008 was compared to 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 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 5.3). 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 the NAVD88 vertical datum and delta area is 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 km² increase in land area. At 0.2 m, a 1 cm decrease in water level results in a 0.49 km² 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 km² increase in land area. At 0.2 m, a 1-cm decrease in water level results in a 0.28 km² increase in land area.

The area measured by applying the NDVI threshold method to the WV-2 image was 79.86 percent of the area predicted at that water level using the 2010 Landsat-based model. This percentage suggests that Landsat-based classifications overestimate land area by about 25 percent. Using the two models and applying the 0.80 correction factor to account for Landsat

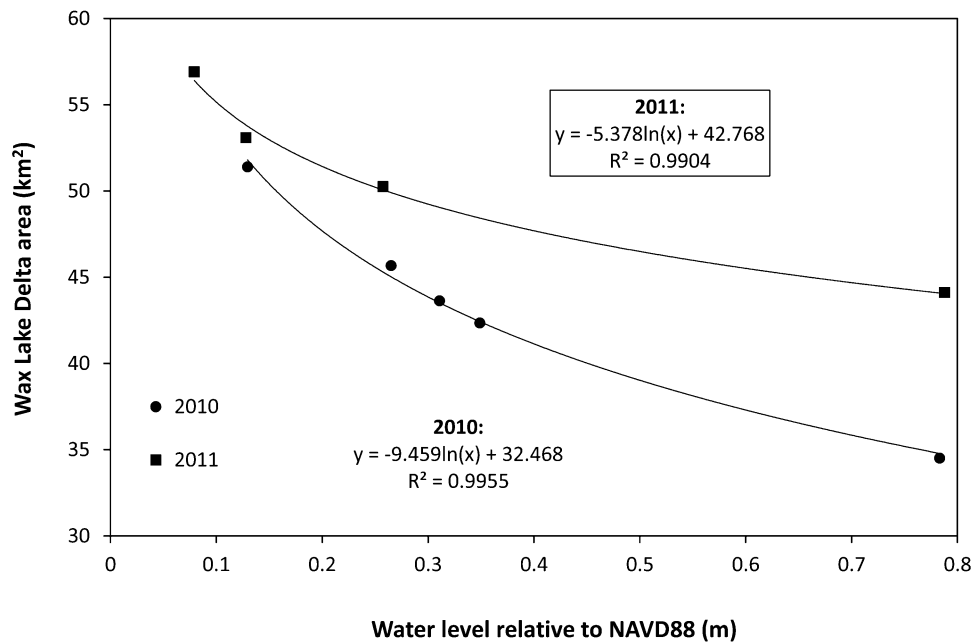


Figure 5.3 – Relationship between water level and delta area before and after the 2011 Mississippi River flood

overestimation, there was a 6.51 km² net increase in the vegetated area of the delta following the 2011 flood at mean water level (0.59 m above NAVD88, based on CRMS water level data from March 6, 2008 to August 23, 2012) (Table 5.1). At mean sea level (MSL) (0.36 m above NAVD88 at the tide gauge at Grand Isle, Louisiana), there was a 4.90 km² increase in land area following the flood. At 0.2 m above NAVD88, there was an increase of 2.98 km² and at 0.7 m above NAVD88, there was an increase of 7.06 km², representing the amount of post-flood land gain at the upper and lower ends of the range of water levels used to construct the logarithmic models.

Figure 5.4 shows the spatial distribution of vegetated land losses and gains based on a comparison of the August 27, 2010 and August 30, 2011 Landsat 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 km² underestimation of 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 km² and lost 1.8 km² of vegetated land at a water level of 0.26-0.31 m above NAVD88. The net post-flood vegetated land gain

Table 5.1 – 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. Area estimates have been corrected for Landsat’s overestimation of land area using a correction factor developed by comparing predicted land area to actual land area mapped using high-resolution WorldView-2 imagery.

	Water Level (NAVD, m)	2010 Area (km²)	2011 Area (km²)	Land gain (km²)
Low water	0.20	38.09	41.07	2.98
Mean sea level (MSL) at Grand Isle, LA	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

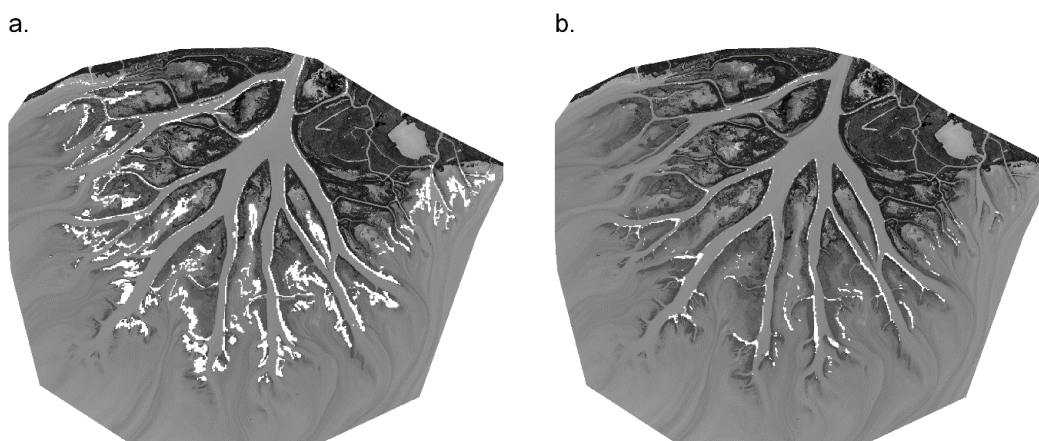


Figure 5.4 – Spatial distribution of vegetated land gains and losses in the Wax Lake delta following the 2011 Mississippi River flood: a) Gains; b) Losses

illustrated in Figure 5.4 is 6.7 km², of which 0.9 km² 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 image resulted in a land area estimate that was 70.6 percent of the predicted land area for that water level using my NDVI-based logarithmic model. Therefore, the growing season NDVI method used in this study results in land area estimates that are approximately 40.4 percent 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 percent 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 submerged and floating-leaved SAVs 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 5.5. The data show two clusters of species: a low elevation group dominant from -0.2 m to 0.4 m above NAVD88, which consisted of *Potamogeton nodosus*, other SAVs, and *Nelumbo lutea*, and a high elevation group dominant from about 0.4 m to 0.9 m above NAVD88, which consisted of *Polygonum spp.*, *Colocasia esculenta*, and *Salix nigra*. The mean and common range, defined as plus or minus one standard deviation of elevation, for each species are listed in Table 5.2. This elevation-based zonation is illustrated in the conceptual vegetation change model in Figure 5.6. The 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 the low elevation and high elevation clusters (Table 5.3).

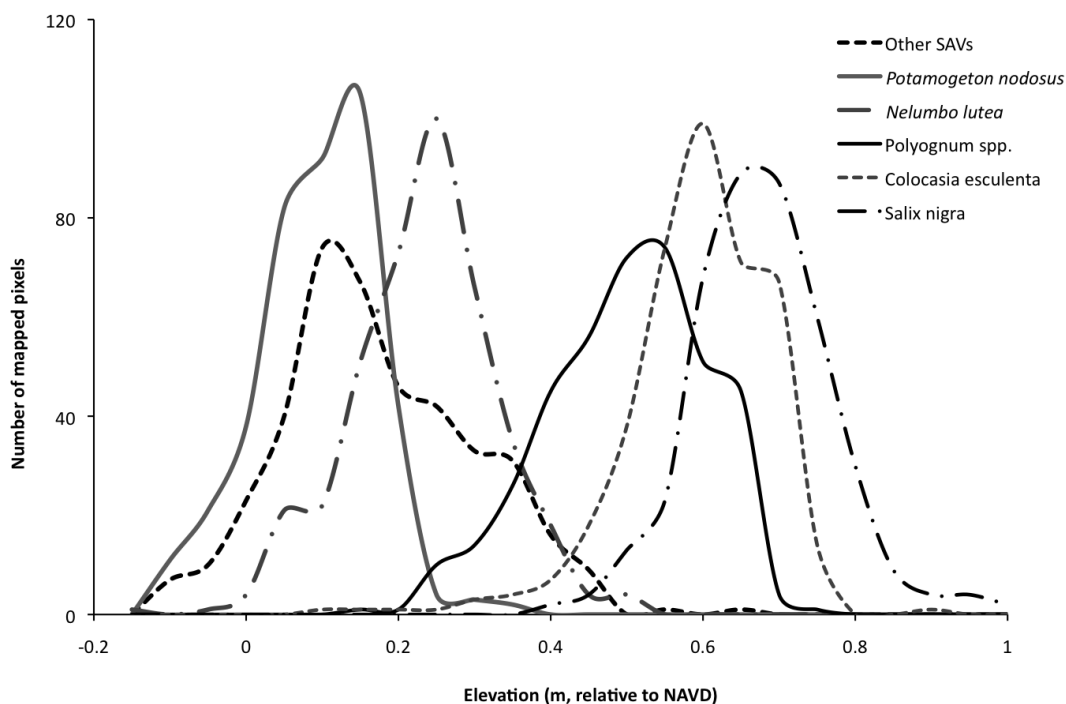


Figure 5.5 - Elevation histograms for the six plant species used in the elevation-change analysis

Table 5.2 – Elevation distribution characteristics of vegetation classes

Vegetation Class	Mean Elevation (m) ¹	± 1 Standard Deviation (m)
<i>Potamogeton nodosus</i>	0.07	-0.01 – 0.15
Other SAVs	0.15	0.02 – 0.28
<i>Nelumbo lutea</i>	0.21	0.11 – 0.31
<i>Polygonum spp.</i>	0.47	0.37 – 0.57
<i>Colocasia esculenta</i>	0.57	0.47 – 0.67
<i>Salix nigra</i>	0.66	0.53 – 0.79

¹Relative to NAVD88

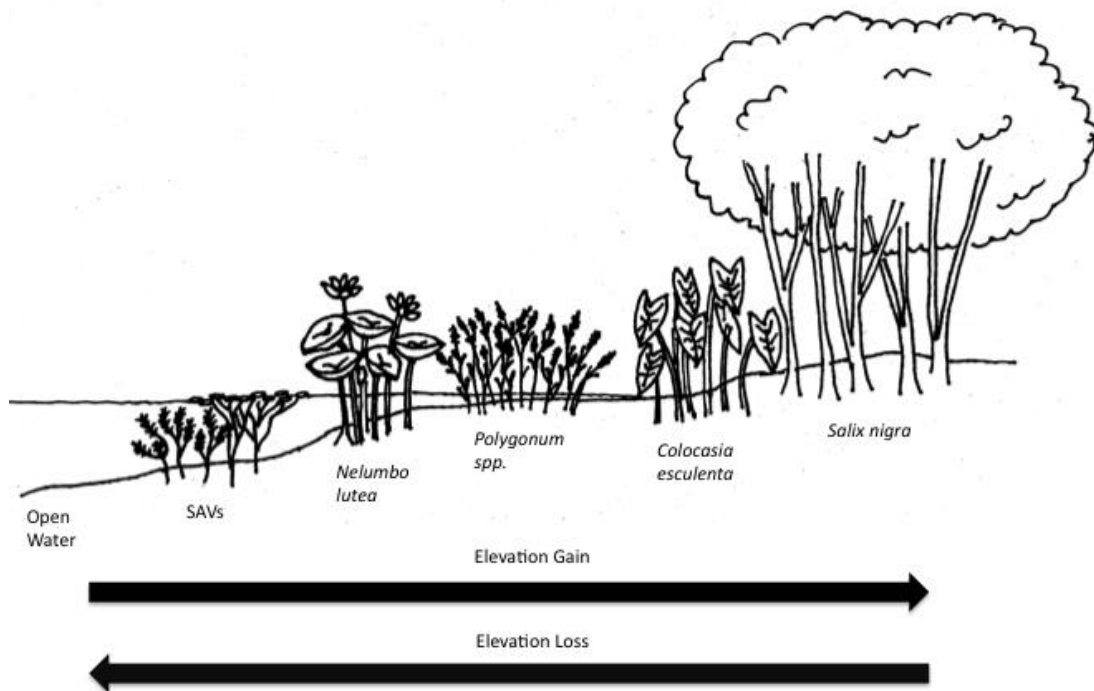


Figure 5.6 – Conceptual model of vegetation community response to elevation change

Patterns of vegetation community change

Three of the six vegetation classes studied increased in distribution in 2011 compared to 2010: *Potamogeton nodosus*, *Nelumbo lutea*, and *Colocasia esculenta*. Other SAVs and *Polygonum spp.* decreased in distribution (Table 5.4). While the distribution of adult trees was fixed, a small area (0.03 km²) of willow seedlings appeared following the flood in 2011. The

Table 5.3 – Results of t-tests and ANOVA tests to determine statistical significance of elevation differences among plant species used in the elevation change analysis

t-test results	t statistic	P-value
<i>Salix nigra</i> and <i>Colocasia esculenta</i>	11.41	0.00
<i>Colocasia esculenta</i> and <i>Polygonum sp.</i>	13.29	0.00
<i>Polygonum spp.</i> and <i>Nelumbo lutea</i>	37.00	0.00
<i>Nelumbo lutea</i> and <i>Potamogeton nodosus</i>	21.94	0.00
<i>Potamogeton nodosus</i> and other SAVs	11.00	0.00
ANOVA Results	F statistic	P-value
High elevation cluster (<i>Salix nigra</i> , <i>Colocasia esculenta</i> , <i>Polygonum spp.</i>	279.12	0.00
Low-elevation cluster (<i>Nelumbo lutea</i> , <i>Potamogeton nodosus</i> , other SAVs)	182.74	0.00

Table 5.4 – Change in species areal coverage following the 2011 Mississippi River flood

Vegetation Class	2010 Area (km²)	2011 Area (km²)	Change (km²)
Landsat Analysis			
<i>Potamogeton nodosus</i>	10.89	11.29	0.40
Other SAVs	4.10	1.39	-2.71
<i>Nelumbo lutea</i>	5.75	9.52	3.77
WorldView-2 Analysis			
<i>Polygonum spp.</i>	1.70	1.13	-0.57
<i>Colocasia esculenta</i>	1.32	2.12	0.80
Trees	0.37	0.37	0
Willow seedlings	0	0.03	0.03

greatest species distribution changes occurred for the species growing at the lowest elevations, with an increase in *Potamogeton nodosus* and *Nelumbo lutea* at the expense of the other SAVs.

Table 5.5 provides additional detail on conversion between species that occurred from 2010 to 2011. The two SAV classes experienced the most change. Approximately 2.7 km² of

Table 5.5 – 2010-2011 Vegetation change in the Wax Lake delta

2010 Class	2011 Class	Area (km ²)
<i>Potamogeton nodosus</i>	<i>Potamogeton nodosus</i>	5.36
	other SAVs	0.25
	<i>Nelumbo lutea</i>	2.68
	open water	2.61
Other SAVs	<i>Potamogeton nodosus</i>	2.18
	other SAVs	0.48
	<i>Nelumbo lutea</i>	1.20
	<i>Polygonum spp.</i>	0.02
	<i>Colocasia esculenta</i>	0.02
	open water	0.24
<i>Nelumbo lutea</i>	<i>Potamogeton nodosus</i>	0.52
	algae-covered SAV	0.01
	other SAVs	0.01
	<i>Nelumbo lutea</i>	5.17
	<i>Polygonum spp.</i>	0.06
	<i>Colocasia esculenta</i>	0.02
	open water	0.04
Open water	<i>Potamogeton nodosus</i>	3.23
	algae-covered SAV	0.36
	other SAVs	0.28
	<i>Nelumbo lutea</i>	0.47
	<i>Polygonum spp.</i>	0.02
	<i>Colocasia esculenta</i>	0.01
<i>Polygonum spp.</i>	<i>Polygonum spp.</i>	0.51
	<i>Colocasia esculenta</i>	0.31
	trees	0.00
<i>Colocasia esculenta</i>	<i>Polygonum spp.</i>	0.08
	<i>Colocasia esculenta</i>	0.85
	trees	0.00

Potamogeton nodosus and 0.5 km² of the other SAVs converted to *Nelumbo lutea* following the flood. Some SAV beds also converted to open water following the flood: 2.6 km² for *Potamogeton nodosus* and 0.1 km² for the other SAVs 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 flood. While approximately 3.2 km² of lower elevation classes converted to *Nelumbo lutea* in 2011, there was very little change to areas where *Nelumbo lutea* was already dominant prior to the flood. The largest change was 0.5 km² that converted to *Potamogeton 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 5.7.

Among the high elevation species, a substantial portion of the areas mapped as *Polygonum spp.* in 2010 were mapped as *Colocasia esculenta* in 2011: 0.3 km² compared to 0.5 km² that remained as *Polygonum spp.* While there was a small amount of conversion of

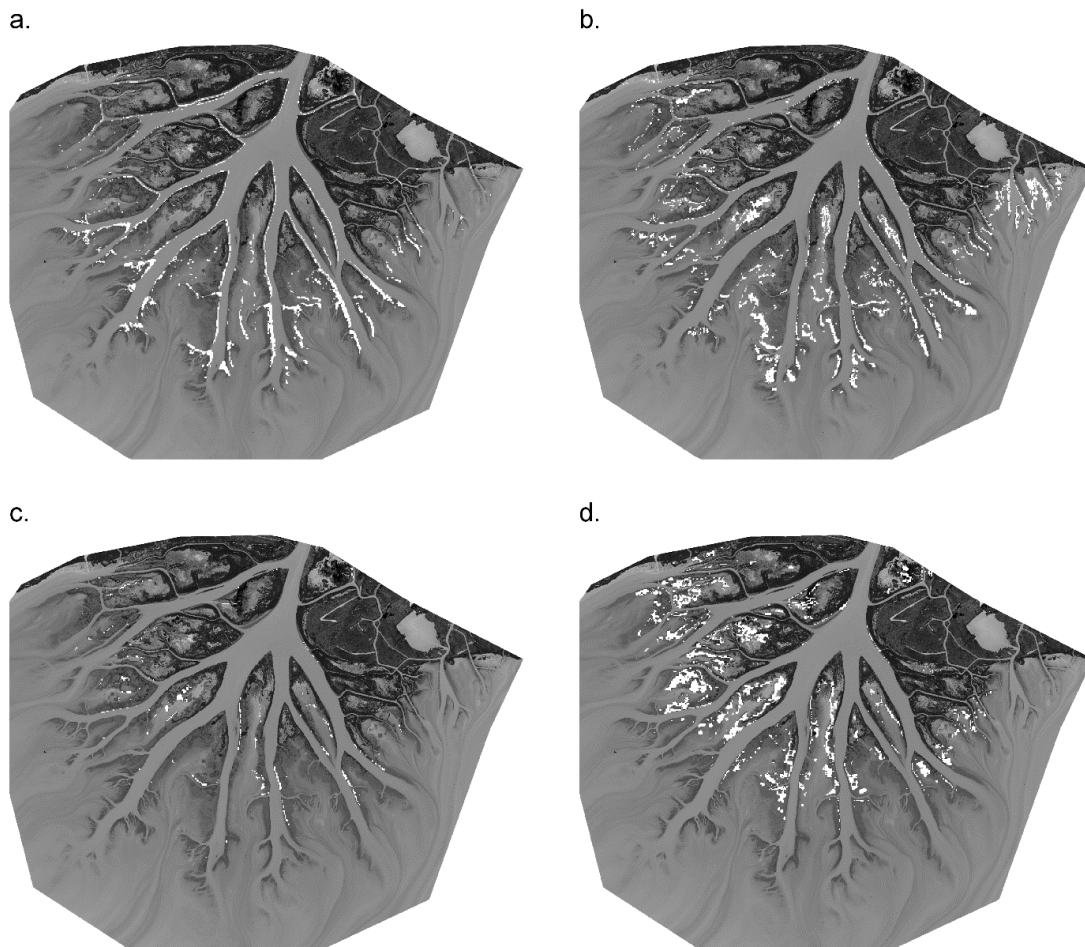


Figure 5.7 – Vegetation change in low elevation areas of the delta (shown in white): a) Conversion from vegetation to open water; b) Conversion from water to SAV (*Potamogeton nodosus* or other SAVs); c) Conversion from open water to *Nelumbo lutea*; d) Conversion from SAV to *Nelumbo lutea*

Colocasia esculenta to *Polygonum spp.* (less than 0.1 km²), the majority of the change favored the expansion of *Colocasia esculenta*. Examples of these changes are shown in Figure 5.8.

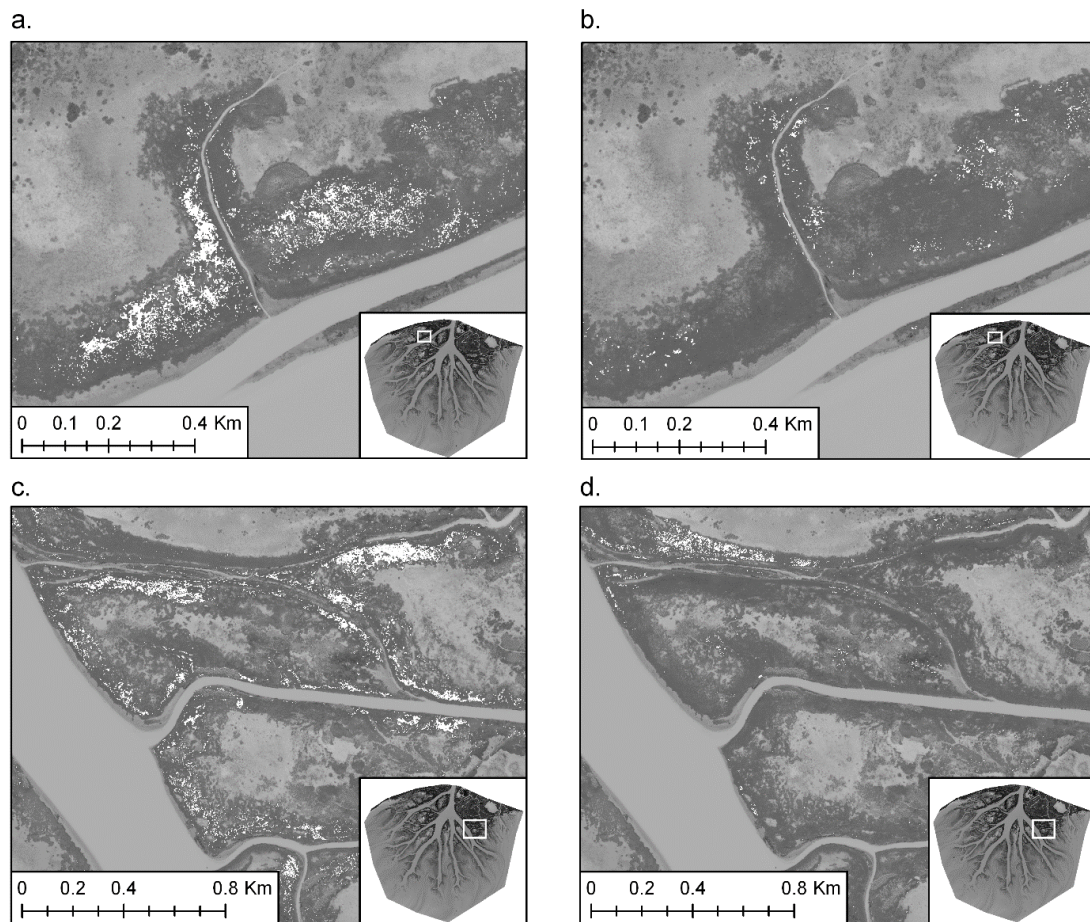


Figure 5.8 – Vegetation change in high elevation areas of the delta (shown in white):
a) and c) Conversion from *Polygonum spp.* to *Colocasia esculenta*, b) and d)
Conversion from *Colocasia esculenta* to *Polygonum spp.*

Table 5.6 – 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)
Potential Elevation Loss	3.5
Potential Elevation Gain	8.7
No Change	15.2
Unknown	19.5

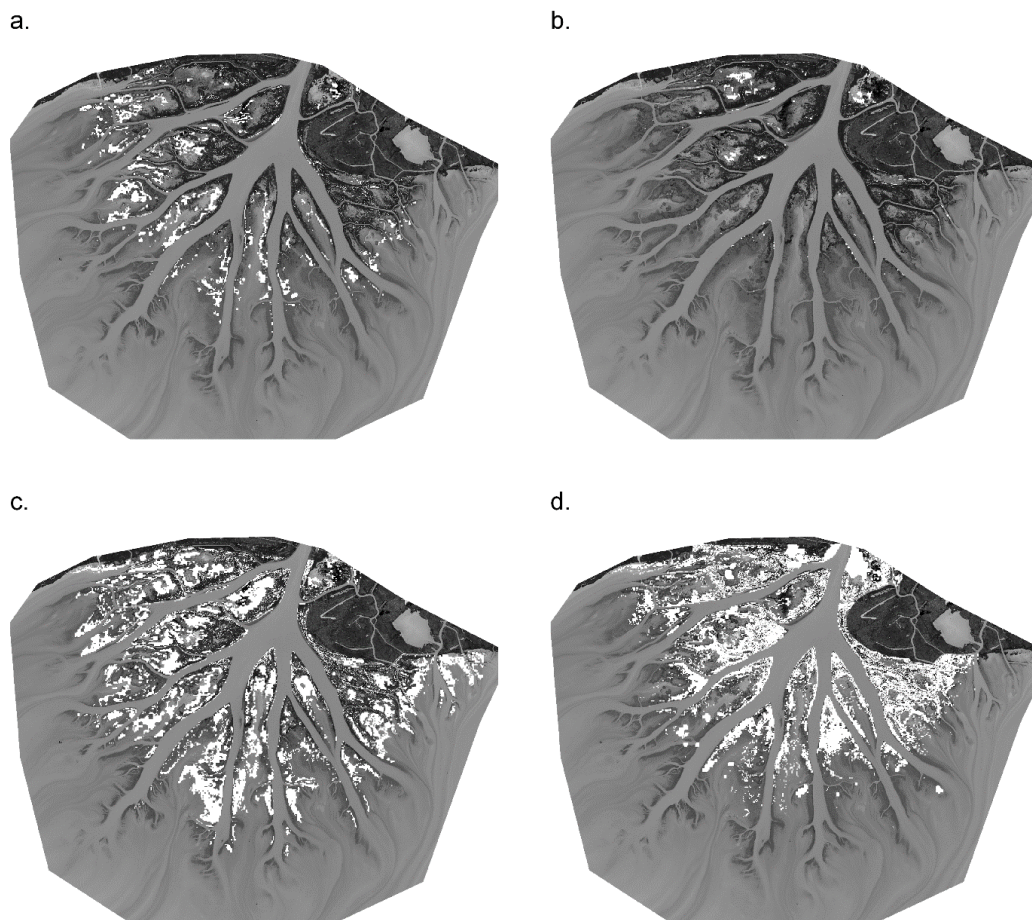


Figure 5.9 – Vegetation change following the 2011 Mississippi River flood as related to species mean elevation (shown in white): a) Change from lower to higher elevation species; b) Change from higher to lower elevation species; c) No change; d) Unknown

Overall, 8.7 km², or about 31.8 percent of the area studied converted from a lower elevation class to a higher elevation class between 2010 and 2011 (Table 5.6, Figure 5.9). About 12.8 percent (3.4 km²) of the area studied converted from a higher elevation class to a lower elevation class and 55.5 percent (15.2 km²) of the area remained unchanged. An additional 19.5 km² 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 “potential 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 5.7, part b 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 *Nelumbo lutea* in 2010 but mapped as *Potamogeton 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 *Nelumbo lutea* stands (Whyte et al. 1997).

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 percent consistency with the post-flood vegetation maps (Table 5.7). However, 81.3 percent 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 2012 field data varied strongly by vegetation class. Seven of the eight sites that were mapped as *Nelumbo 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 *Nelumbo lutea* in 2010. Two additional plots converted to *Nelumbo lutea* from other classes between August 2011 and July 2012. The sample sizes for the other classes were too small to allow for statistical analysis, but in general, they showed poor consistency between the 2011 mapping and 2012 field data.

Analysis of the sites by potential elevation change class shows that 6 out of 8, or 75 percent, of the Pintail Island sample plots that were mapped as “potential elevation gain” remained dominated by the same vegetation class in 2012 as in 2011 or converted to a higher elevation class in 2012. Only 2 of the sites, or 25 percent, reverted to a lower elevation class one 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 of the sites that were mapped as “potential elevation loss” in 2011 were

Table 5.7 – Error matrix comparing 2011 mapped vegetation classes with 2012 field data for 11 reference plots on Pintail Island

		2012 Field Data						
		Open Water	<i>Potamogeton nodosus</i>	Other SAVs	<i>Nelumbo lutea</i>	<i>Polygonum spp.</i>	<i>Colocasia esculenta</i>	Total
2011 Mapped Data	Open Water	0	0	0	1	0	0	1
	<i>Potamogeton nodosus</i>	1	1	1	0	0	0	3
	Other SAVs	1	0	0	1	0	0	2
	<i>Nelumbo lutea</i>	1	0	0	7	0	0	8
	<i>Polygonum spp.</i>	0	0	0	0	0	2	2
	<i>Colocasia esculenta</i>	0	0	0	0	0	0	0
Total		3	1	1	9	0	2	16
Overall 2010-2011 agreement:							50.00%	
Same or higher elevation group:							81.25%	

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 5.8 shows the results of ANOVA and t-tests performed using the field-derived elevation data for sites mapped as “potential elevation gain,” “potential 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 t-tests comparing the means of the three classes indicate that there is a significant difference in the mean elevation change between the “potential elevation loss” and “no change” classes. The difference in mean elevation change between the “potential elevation gain” and “potential elevation loss” classes was not quite significant and the difference in mean elevation between the “potential elevation gain” and “no change” classes was not significant. The mean measured elevation changes and sample sizes for each of the classes are also provided in Table 5.8.

Figure 5.10 shows the change in distribution of *Nelumbo 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, *Nelumbo lutea* spread into 2.1 km² of the delta where it had not been prior to the flood or prior to the 2008 storms. Approximately 1.7 km² of *Nelumbo lutea* that was killed by the 2008 storms had not recovered by August of 2011.

Table 5.8 – Results of t-tests and ANOVA tests for difference in mean and variance of 2010-2011 elevation change for transect sites mapped as each of the potential elevation change classes (potential elevation gain, potential elevation loss, no change) based on vegetation changes following the 2011 Mississippi River flood

Elevation change class	Number of plots	Mean elevation change
“potential elevation gain” class	4	4.08 cm
“potential elevation loss” class	8	-4.57 cm
“no change” class	18	4.26 cm
Statistical Test	Test Statistic	P-value
ANOVA	3.29	0.053
t-test - “potential elevation gain” vs. “potential elevation loss”	2.28	0.053
t-test - “potential elevation gain” vs. “no change”	0.10	0.46
t-test - “potential elevation loss” vs. “no change”	3.40	0.002

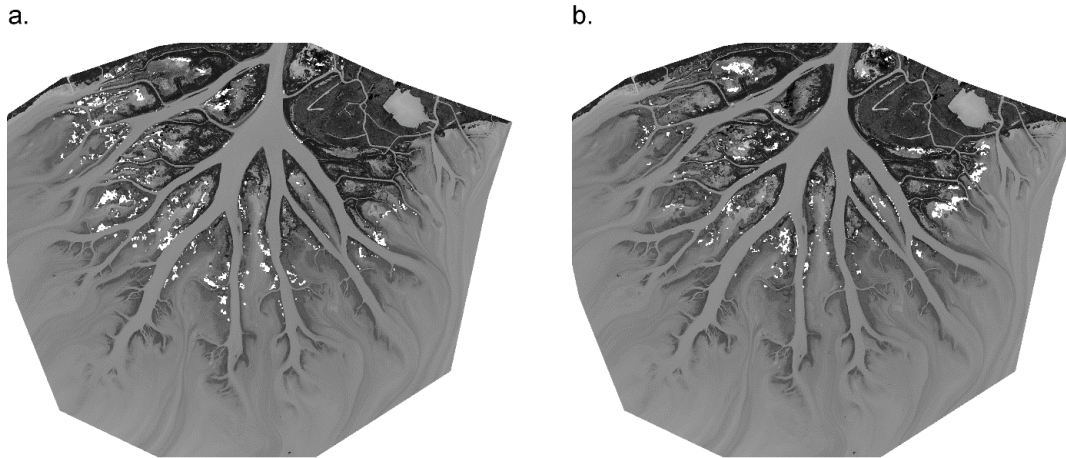


Figure 5.10 – Change in the distribution of *Nelumbo lutea* related to disturbance by Hurricanes Gustav and Ike (2008) and the 2011 Mississippi River flood: a) Expansion of *Nelumbo lutea* from 2010 to 2011 into areas where it was not found prior to the 2008 hurricanes, b) Areas mapped as *Nelumbo lutea* prior to Hurricanes Gustav and Ike that had not recovered by August 2011

DISCUSSION

Growth of the vegetated surface of the delta following the 2011 flood was estimated as 6.51 km² at mean water level in the delta or 4.90 km² at mean sea level as measured near Grand Isle, LA. The 4.90 km² 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 1 km²/yr average growth rate that Allen et al. (2012) found over the period 1983 to 2010. It is also consistent with growth rates measured for the neighboring Atchafalaya delta following the major Mississippi River floods of the 1970's. Using a similar approach comparing multi-temporal Landsat imagery and water level data, Rouse et al (1978) estimated that approximately 4 km² of subaerial land and 7 km² of subaqueous land was formed in the Atchafalaya delta following the 1975 flood. The Atchafalaya delta received approximately 63 percent higher discharge during the 1975 flood than the Wax Lake delta received during the 2011 flood (U. S. Geological Survey 2012). However, the main channel in the Atchafalaya delta is dredged, which allows more sediment to bypass that delta (Van Heerden and Roberts 1980).

That land gains occurred mostly at the end of the distributary channels and the distal interior of the islands is consistent with the depositional patterns observed at a smaller scale within crevasse splays in the Mississippi River delta (Coleman and Gagliano 1964; Coleman et al. 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 levees and spill into the island interiors, coarse 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 northwest 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 National Geodetic Vertical Datum of 1929 (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 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 I 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.

The 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 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 et al. 2001; Casanova and Brock 2000; Goslee et al. 1997), they are difficult to directly measure at 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 higher end of the elevation gradient. The intermediate elevation communities tend to be much 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 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, *Colocasia esculenta* and especially *Salix nigra* outcompete less dominant species for light resources. There is most likely less competition pressure 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).

It is important to note that 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 et al. 1998; Gough and Grace 1998b), 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 et al. 1998; Tilman 1988). Interannual variability in these factors can affect the outcome of competition, resulting in species distributions that change from one year to the next independent of any changes in elevation at a site. We must therefore take care when interpreting changes that occur from one 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.

Of the lower elevation species, *Nelumbo lutea* experienced the greatest expansion, with much of this expansion occurring at the expense of the SAVs, particularly *Potamogeton nodosus*. *Nelumbo lutea* has been shown to be effective at competitively excluding some SAVs (Snow 2000; Whyte et al. 1997). It is capable of rapid vegetative expansion by rhizome, with one study citing a radial outward expansion rate of over 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, my 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 *Nelumbo lutea* has never regained its pre-2008 distribution, it is clear from this analysis that the delta-wide 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 intertributary basins generally consists mostly of fine silts and clays, as most of the sand load is deposited along the subaqueous and subaerial natural channel levees (Coleman et al. 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 meters on May 29, 2011 to 1.5 meters by the end of June, the Wax Lake Outlet did not reach its historic average monthly stage until mid-August (U. S. Geological Survey 2012). Likewise, data from the CRMS site at Wax Lake delta indicate that the water level in the marsh remained over 0.3 meters above the marsh surface from May 10 to June 24 (55 days) (Coastal Protection and Restoration Authority of Louisiana 2012). Water may have been trapped within the islands for an even longer period of time, 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 northwest corner of the delta. This is consistent with the gradual abandonment of the older area of the delta and its less efficient tributary 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 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, it is important to note that 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 (*Salix nigra*), and an immediate shift in plant species dominance would not be expected despite substantial sediment deposition. Even within the levee zone dominated by *Colocasia esculenta*, it is unlikely that an increase in elevation would result in *Salix nigra* dominance, because *Salix nigra* germinates best on newly exposed land with little competition (Ahn et al. 2007; Gage and Cooper 2004; Karrenberg et al. 2002). The specific germination requirements probably explain some of the overlap between its elevational niche and that of *Colocasia esculenta*, as *Colocasia esculenta* may prevent germination of *Salix 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 more than one 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 post-flood elevation data from the delta, which also suggest that the area mapped as “potential 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 “potential 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 *Potamogeton 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 “potential elevation gain” had a positive mean elevation gain and areas mapped as “potential

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 “potential elevation gain.” While the elevation measurements were made predominantly on the upstream ends of the islands, most of the mapped areas of potential 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 km² from 33.6 km² to 38.5 km² at mean sea level following the historic Mississippi River flood of 2011 and the vegetation community shifted from lower to higher elevation species across 8.7 km², or 31.8 percent of the area studied. Most vegetation community change occurred among low elevation classes, with an increase in the distribution of the floating-leaved SAV, *Potamogeton nodosus*, and the emergent *Nelumbo lutea* at the expense of other SAVs. Much 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 if the species that grow in these areas respond more slowly to changes in elevation than the species that grow at low elevations. The greater increase in delta area that occurred at higher water levels suggests that substantial vertical accretion did occur across these mid- to high-elevation areas. The fact that these areas experienced greater accretion is reflective of 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 1970's. 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 percent 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 percent 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 un-retained 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 valuable 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 valuable 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 any new diversion will be dependent 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 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 provide for more robust monitoring of elevation change over time across large coastal landscapes.

OVERALL CONCLUSIONS

Coastal river deltas are dynamic environments driven by allogenic forces to which plant communities are forced to adapt. As sedimentary features that form where large rivers meet the coast, deltas are influenced by both riverine and coastal forces, and therefore maintain characteristics of both systems. As in other coastal marshes, elevation, salinity, and plant competition interact to form vegetation zonation patterns in deltas. However, these patterns are also influenced by plant responses to erosive fluvial forces along the distributary channels and rapid sedimentation during flood events. In river-dominated deltas such as the Wax Lake delta, the high volume of freshwater input largely buffers the plant community from coastal salinity other than during temporary storm surge events that push salt water into the delta. The less-stressful freshwater environment allows for development of a more diverse plant community than what is found in salt and brackish coastal marshes and makes competition of resources a more important factor driving species distributions. By contrast, salinity is one of the most important drivers of plant community composition in wave- and tide-dominated river deltas.

The objective of this study was to examine the factors that influence plant community development and spatial patterns in the young, actively pro-grading, river-dominated Wax Lake Delta. In particular, the degree to which underlying environmental gradients and extreme flood and storm events influence spatial and temporal patterns in the plant community was considered. To accomplish this, methods to map the distribution of several important freshwater marsh species using newly available high-resolution satellite imagery were tested. The resulting information about species distributions was used to develop a classification tree model to predict species distributions with the delta as a function of a set of spatially-derived variables related to environmental and exposure gradients within the delta and storm disturbance. A vegetation index time series derived from moderate-resolution Landsat imagery was also used to determine trends in productivity over the life of the delta and measure the impact of storm disturbance on the vegetation community. Finally, A combination of high and moderate resolution satellite imagery was used to measure accretion in the Wax Lake Delta following the historic 2011 Mississippi River flood and assess the flood's impact on the plant community.

Our ability to understand both the spatial and temporal dynamics of deltaic plant communities has been greatly enhanced by recent advances in the field of remote sensing. Vegetation community maps created from aerial photography and satellite imagery allow us to scale up local observations about plant community dynamics made through field or greenhouse studies to the landscape level. While earlier generations of satellite sensors provided the necessary spectral and spatial scales to perform landscape-scale analyses at the plant community level, the newest generation of high spatial-resolution multispectral satellite sensors provides the opportunity to study the distributions of individual plant species at the landscape scale. In this study, an overall mapping accuracy of 75 percent was achieved for a species-level plant community classification in the Wax Lake delta using imagery from the recently launched WorldView-2 high-resolution satellite. User's and producer's accuracies greater than 70 percent were achieved for many individual plant species. These mapping accuracies exceeded those that would have been achieved using previously available 4-band satellite sensors such as IKONOS and Quickbird and rivals species-level mapping accuracies that have been achieved using more expensive airborne hyperspectral sensors. This suggests that the advent of high spatial-

resolution multispectral satellite imagery should greatly improve our ability to monitor plant community dynamics at the landscape level.

The results of a classification tree analysis used to predict species distributions in the delta suggest that the primary drivers of species distributions in this geomorphic setting are elevation, distance to deep unvegetated water, storm disturbance history, distance to distributary channels, and island age. Over 50 percent of the variability in the distributions of six species in the Wax Lake delta could be explained by elevation alone, suggesting that elevation is still the primary driver of plant species distributions in river-dominated deltaic wetlands. However, an additional 16 percent of the variability in species distributions was associated with variables related to riverine and tidal flushing, storm disturbance, substrate, and allogenic and autogenic successional processes. These results support findings in other river-dominated deltas that vegetation patterns are primarily driven by allogenic forces such as hydrology, sediment depositional patterns, and periodic surges of high salinity water during storm events. Autogenic processes become more important in later stages of development, when increased elevation reduces the influences of riverine and coastal stressors and allows for greater soil development and invasion of the plant community by a more diverse mixture of species that compete fiercely for limited resources such as light, space, and nutrients.

This increase in species richness and more complete use of available resources is also indicated in the gradual increase in mean plant community productivity that was observed in the analysis of long-term NDVI trends. Assessment of changes in total and mean NDVI values for the Wax Lake delta from the time the first subaerial land emerged from Atchafalaya Bay in the early 1970's to 2011 indicated that both total and mean peak growing season NDVI has increased with time over the life of the delta. While the increase in total NDVI was driven largely by the increase in the area of the delta over time, the increase in mean NDVI is most likely explained by the replacement of early colonizing annual species with perennial species that increase their aboveground biomass each year and by increased efficiency of resource use by the more diverse set of species that are able to invade the deltaic islands as they accrete vertically. Seasonal fluctuations in NDVI were explained by seasonal fluctuations in water level and water temperature within the delta, which are driven by the river's spring flood cycle and strongly control plant community phenology. The results also indicate that the marshes within the Wax Lake delta are largely resilient to storm impacts. While the showed significant short-term decreases in NDVI following storm surges associated with tropical storm and hurricane impacts, the plant community recovered to within the 95 percent prediction interval for the long-term trend by the following growing season following each storm event.

Large river floods are another important allogenic factor that drives plant community development in river deltas. In my analysis of the impact of the 2011 Mississippi River flood on the Wax Lake Delta, I demonstrated that this historic flood event resulted in substantial accretion of the delta, which resulted in allogenic succession within many of the plant communities in the delta. The area of the Wax Lake delta increased by nearly 5 km² at mean sea level as a result of this single flood event. The vegetation community shifted from lower to higher elevation species across nearly 9 km² of the delta, or roughly a third of the area studied. Comparison of the relationship between water level and the vegetated area of the delta in the year before and the year following the flood event indicated that most of the difference in area between the two years occurred at higher elevations. This suggests that substantial accretion occurred across much of the subaerial delta. This reinforces the role that extreme flood events play in providing large

pulses of sediment promote accretion and maintain the elevation of river deltas faced by coastal erosional processes, subsidence, and sea level rise.

In combination, this research demonstrates the degree to which a direct connection to the river promotes growth and increased productivity in deltaic marshes and strengthens resilience to storm disturbance. While a gradual long-term increase in both total and mean productivity was observed over the life of the delta, it is also clear that large flood events are especially critical drivers of both physical growth and plant community development in river deltas. Previous studies have noted that time periods of land loss or reduced growth rates in the Wax Lake and Atchafalaya deltas have corresponded to periods where a hurricane has impacted the coast following a period in which there were no major river floods. Floods bring large volumes of sediment, and particularly coarser-grained sediment, to river delta. Sediment that is not trapped within the delta is deposited in the near-shore environment, where it can be resuspended and deposited onshore during coastal storm events. Thus, the delivery of sediment to the nearshore environment appears to play a mitigating role in these deltaic settings, offsetting the negative impacts of storm disturbance to deltaic marshes.

This has important implications for the restoration of deteriorating marshes elsewhere in the Mississippi River deltaic plain. The Wax Lake Outlet is an unmanaged river diversion of a similar scale as the other large river diversions that have been proposed to restore a connection between the Mississippi River and other parts of its historic delta. As such, the Wax Lake delta can be considered a reasonable reference system for the proposed diversion projects. Based on this research, allowing river water and sediment to flow freely to the coast through the Wax Lake Outlet has resulted in the growth of a large and robust freshwater marsh community that is both increasing in productivity with time and highly resilient to storm disturbance. While not originally intended for coastal restoration, the construction of the Wax Lake Outlet provides a model for how restoring the connection between the river and its delta can offset land loss trends in coastal Louisiana and improve the productivity and resilience of deteriorating marshes elsewhere in the Mississippi River delta region.

Future research within the greater Mississippi River deltaic plain should focus on the application of the methods described in this study to both mainland marshes influenced by the river and to marshes that are effectively cut-off from the river by the levee system. This would enhance our understanding of the factors that influence plant community productivity and species distributions in these different geomorphic settings. It would also provide a more direct means of testing the hypothesis that riverine flooding enhances marsh productivity and resilience in deltaic marshes. Applying the remote sensing approaches used in this study more broadly throughout the deltaic plain would complement existing in-situ monitoring programs and assist in scaling up local measurements of marsh function. These approaches also lend themselves readily to the monitoring of large-scale restoration projects such as the proposed river diversions, which will have landscape-scale impacts within the deltaic plain.

There is also a general need for the additional study of deltaic plant communities in a greater variety of environmental settings. Much of the vegetation research that has been performed in deltas has been in temperate, river-dominated deltas. The plant communities of wave- and tide-dominated river deltas and the plant communities of tropical and arctic river deltas have received considerably less attention. Future research should focus on the degree to which the relationships between coastal and riverine geomorphic processes and plant community pattern are modified by increases in wave and tide exposure and across latitudinal gradients. This would enrich our understanding of the processes that control plant community development

in river deltas across a range of geomorphic and climatic settings and of the feedbacks between vegetation and delta geomorphology. Combined with research on the relative contribution that individual deltaic plant species make to deltaic geomorphic processes, such studies would improve our understanding of the feedbacks between geomorphology and plant communities in deltaic systems. It would also allow for more accurate representation of the plant community contribution to river delta geomorphology in deltaic models, particularly its impact on sediment cohesion, vertical accretion, and organic matter accumulation during the later stages of river delta development.

Overall, this study demonstrated that the plant community of the young, actively prograding, river-dominated Wax Lake Delta is largely controlled by allogenic factors such as flooding, exposure to energetic river flows, sediment deposition patterns, and temporary pulses of salt intrusion. Flooding by the river drives allogenic succession within the deltaic plant communities until sufficient elevation is achieved to allow autogenic processes such as organic matter accumulation and plant competition to increase in importance. The plant community has shown a fairly steady increase in productivity over time, mirroring the growth of the subaerial delta and has remained largely immune to the long-term damage that has been caused by hurricanes and tropical storms in other parts of coastal Louisiana. These results demonstrate the important role that river flooding plays not only in building the geomorphic structure of river deltas but also in driving the development and enhancing the productivity and resilience of deltaic plant communities.

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APPENDIX

From: **Melissa Carle** <mcarle1@tigers.lsu.edu>
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Subject: Copyright for Journal of Coastal Research article
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VITA

Melissa May (Vernon) Carle is a native of Garland, Texas. She received her bachelor's of arts degree in Sociology and Environmental Studies from Tulane University in 2000 and her Master's of Environmental Management degree in Wetland Ecology and Management from Duke University in 2002. After completing her master's degree, she spent several years working first as a research associate at Duke University and later as the Wetlands Program Manager at the North Carolina Division of Coastal Management, before making the decision to return to school for her PhD in 2009. She expects to graduate with her PhD in Oceanography and Coastal Sciences in December 2013. She has been awarded a Knauss Marine Policy Fellowship for 2014 and will be moving to Washington, DC following graduation to work for the National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service, Office of Habitat Conservation as a Science-Policy Coordinator for the Deepwater Horizon Restoration Program.