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Dynamics of Land Building and Ecological Succession in a Prograding Deltaic Floodplain, Wax Lake Delta, LA, USA

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A Dissertation

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by
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# TABLE OF CONTENTS

ACKNOWLEDGMENTS........................................................................................................... ii

ABSTRACT............................................................................................................................ vi

CHAPTER 1. INTRODUCTION................................................................................................. 1
  BACKGROUND.................................................................................................................... 1
  CONCEPTUAL MODEL OF DELTAIC FLOODPLAIN DEVELOPMENT............................... 5
    Description of deltaic floodplain ecosystem development........................................ 5
  DISSERTATION OUTLINE.................................................................................................. 9
  TERMINOLOGY ................................................................................................................ 10
  LITERATURE CITED........................................................................................................ 14

CHAPTER 2. CONTRIBUTION OF RIVER FLOODS, HURRICANES, AND COLD FRONTS TO ELEVATION CHANGE IN A PROGRADING DELTAIC FLOODPLAIN IN THE NORTHERN GULF OF MEXICO, USA.................................................. 18
  INTRODUCTION............................................................................................................... 18
  METHODS ........................................................................................................................ 23
    Study area and seasonal intervals............................................................................. 23
    Sampling and analytical methods......................................................................... 27
  RESULTS .................................................................................................................................. 31
    Seasonal net elevation change.................................................................................. 31
    Discharge and sediment supply............................................................................. 36
    Sediment surface elevation change across the deltaic island elevation gradient.......................... 36
    Deltaic wetland sediment retention efficiency....................................................... 40
  DISCUSSION...................................................................................................................... 40
    River flood sediment retention efficiency............................................................ 40
    Hurricane storm surge contribution to elevation gain........................................... 42
    Long-term contribution of large river floods and hurricanes to delta growth......................... 45
    Elevation loss due to cold front passage.............................................................. 46
    Conclusions and implications for coastal restoration........................................ 47
  LITERATURE CITED........................................................................................................ 48

CHAPTER 3. DELTAIC ISLAND EDGE MORPHODYNAMICS ALONG A CHRONOSEQUENCE AND IMPLICATIONS FOR DELTAIC FLOODPLAIN WETLAND SUCCESSION AND ORGANIC MATTER SEQUESTRATION........................................... 55
  INTRODUCTION............................................................................................................... 55
  CONCEPTUAL MODEL................................................................................................. 59
  METHODS....................................................................................................................... 61
    Site description and timeline of delta development.............................................. 61
    Deltaic island age range estimation....................................................................... 63
    Field surveyed elevation transects and soil organic matter.................................. 64
LiDAR elevation transect extraction and morphometric variable
determination.................................................................65
Statistical analyses and methods test using only surveyed transects........66
RESULTS AND DISCUSSION.................................................................66
Deltaic island chronosequence map..................................................66
Comparisons of cross-sectional island profiles......................................68
Soil organic matter content relative to elevation.................................71
Conceptual model of deltaic floodplain wetland development..................75
Implications for coastal restoration...................................................77
CONCLUSIONS.................................................................................77
LITERATURE CITED............................................................................78

CHAPTER 4. DELTAIC FLOODPLAIN WETLAND VEGETATION COMMUNITY
COMPOSITION AND RESPONSE TO HURRICANE STORM SURGE AND A LARGE
RIVER FLOOD..................................................................................82
INTRODUCTION..................................................................................82
METHODS.........................................................................................87
Site description..................................................................................87
Field sampling...................................................................................89
Data processing..................................................................................91
Statistical analyses............................................................................92
RESULTS............................................................................................94
Distribution of vegetation cover and bare plots......................................94
Mean cover of dominant species over time..........................................96
Vegetation species assemblages and the response to hurricane
disturbance.......................................................................................96
DISCUSSION.....................................................................................104
Species assemblages..........................................................................104
Patterns of vegetation shift after hurricanes and large flood...............107
CONCLUSIONS................................................................................108
LITERATURE CITED..........................................................................109

CHAPTER 5. ESTABLISHMENT OF SALIX NIGRA STANDS AND THEIR ROLE IN THE
ECOGEOMORPHIC DEVELOPMENT OF DELTAIC FLOODPLAIN WETLANDS........114
INTRODUCTION................................................................................114
METHODS.........................................................................................117
Site description..................................................................................117
Salix nigra stand mapping.................................................................119
Forest structure measurements........................................................120
Statistical analysis............................................................................121
Description of experimental mesocosms.............................................121
RESULTS............................................................................................124
Salix nigra stand area..........................................................................124
Salix nigra stand structure and age classes........................................127
Island edge anchoring...................................................................130
DISCUSSION.....................................................................................130
ABSTRACT

Deltas are globally important locations of diverse ecosystems, human settlement and economic activity that are threatened by reduced sediment delivery, accelerated sea level rise, and subsidence. In this dissertation I investigated a number of aspects of the ecosystem development over time within an actively prograding river dominated delta along the northern Gulf of Mexico coast. I outlined a conceptual model of deltaic floodplain wetland establishment and succession focused on the vegetated deltaic floodplain ecosystem, which includes subtidal, intertidal and supratidal zones. This was used to guide the experimental design and statistically driven hypothesis testing in order to ascertain the validity of the processes outlined therein. I attempted to determine how sediment surface elevation of delta floodplain wetlands changed in a prograding delta as a result of flooding, hurricanes, and cold front passage, and to compare the patterns of change between years. I also investigated the patterns in island edge cross-sectional morphology over time within a chronosequence framework which encompassed the entire period of subaerial expression of the Wax Lake Delta (WLD) in Louisiana, USA. The zonation and patterns of the herbaceous vegetation community were also investigated in response the elevation as well as hurricane storm surge passage. The forest structure of Salix nigra (black willow) on deltaic floodplain islands, was investigated in response to the estimated age of the stand, (i.e. time since establishment) and the major river floods, using both the chronosequence map and aerial imagery analysis of willow stands. Based on these finding I suggest refinements and expansion of the conceptual model to allow for inclusion of the temporal aspect of the ecosystem as a whole, which at any one time consists of numerous phases of ecological development. The findings of this dissertation add to a better understanding of the deltaic floodplain ecosystem and provide a framework on which to investigate further questions of ecological development.
CHAPTER 1. INTRODUCTION

BACKGROUND

Deltas are globally important as both population centers, with over 500 million people currently occupying deltaic plains, as well as centers of commerce, supporting shipping, natural resource extraction and agriculture (Ericson et al. 2006; Syvitski et al. 2009). Deltaic landscapes also include many extensive and diverse ecological communities, including mangrove forests, as well as salt, brackish and fresh marshes (Day et al., 2008). The processes that have controlled their formation throughout the Holocene are changing, including accelerated sea level rise, sediment trapping in river basins by dams and reservoirs, human induced increases in compaction and subsidence due to fluid extraction, reduction of distributary channels and an increase in storm intensity and frequency (Day et al. 2008; Syvitski et al. 2009). All of these changes have the potential to alter the ability of deltas to persist and grow, putting at risk the safety and economic livelihood of millions of people, particularly in the face of increasing climate and land use change (Syvitski 2008; Vörösmarty et al. 2009).

The Mississippi River Delta along the northern Gulf of Mexico is an area of coastal deltaic wetlands and bays that extends over 30,000 km². The Mississippi River drains a watershed that covers 3.1 million km² and includes 40% of the continental United States and portions of Canada (Day et al., 2007). Rapid wetland loss has occurred within this delta over the past century, with an average of 43 km² of wetlands lost per year during the time period of 1985 to 2010 (Couvillion et al., 2011). The land loss has been attributed to a number of sources, including leveeing of the Mississippi River, fluid extraction and channel dredging (Day et al., 2007). With this wetland loss the proportion of progradational land has decreased relative to
degradational wetland area. There are still a few locations where coastal wetlands are building, however these are limited to the extreme terminus of the Mississippi River downstream of Head of Passes, and the deltaic floodplain wetlands along the Atchafalaya River, particularly at the mouths of the Wax Lake Outlet and the Lower Atchafalaya River (Couvillion et al., 2011). These progradational deltaic floodplain wetlands are composed of a patchwork of herbaceous floating, submerged and emergent plants, as well as shrub and tree species, particularly Salix nigra (black willow) and are affected by major hydrologic forcings both terrestrial and marine in nature. In an effort to counteract this wetland loss, major coastal restoration projects have been proposed to maintain or expand the areas of the deltaic wetlands in which riverine sediment and freshwater are able to flow (CPRA, 2012).

The Wax Lake Delta (WLD) is an area of over 50 km$^2$ of progradational deltaic floodplain wetlands located at the terminus of the Wax Lake Outlet, a constructed channel designed to limit flooding in downstream Morgan City, LA, USA (Fig. 1.1). The discharge into the Atchafalaya River distributary is maintained at 30% of the combined flows of the Mississippi and Red Rivers, and is controlled at the Old River Control Structure (ORCS), completed in 1963 (Roberts et al. 1980; Wells et al. 1982). As the Wax Lake Outlet empties into the shallow (~3-4 m) Atchafalaya Bay, the bed friction results in the formation of a shoal at the mouth and eventual divergent bifurcation of the channels separated by a triangular shaped middle ground bar with coarse grain deposition at the bar crest (upstream end) and along its lateral boundaries, and finer grain sediments in the interior portions (Wright 1977; Wellner et al. 2005). Small subaerial bars first began to appear in the WLD in 1973 on top of large (1-5 km long and 1-2 km wide) subaqueous deposits, these increased rapidly in the subsequent years, (Roberts et al 1980; Wellner et al. 2005). There has been limited channel dredging in the WLD, and as a result the
channel and bar formation of the WLD represent natural undisturbed delta morphology (Wellner et al. 2005).

![Study site map of the northern Gulf of Mexico coast and the Wax Lake and Atchafalaya Deltas.](image)

Currently, the WLD receives approximately 30-40% of the total water and sediment discharge of the Atchafalaya River (Allison et al. 2012), equivalent to 10-12% of the total Mississippi/Red River discharge. The aerial land growth rate within WLD is estimated to be between 1.0 to 3.0 km² yr⁻¹ (Roberts et al 1997; Allen et al 2011), with a delta front expansion rate of 0.3 km yr⁻¹ (Parker and Sequeiros 2006). Sediment transport in the WLD is influenced by seasonal water exchange from river flooding, tidal exchange, cold fronts, and tropical storms (Mossa and Roberts 1990; Walker and Hammack 2000; Walker 2001). During late fall, winter and early spring (October through April) the inshore to offshore exchange of water and sediments is influenced by winds associated with cold-front passage. In early spring water movement is strongly controlled by the increasing river discharge as the spring flooding occurs.
(February through June). As river discharge decreases in the summer, the microtidal regime (amplitude ~ 30 cm) becomes the dominant means of water movement. The lowest river discharge occurs during fall, when tropical storms periodically move water inshore (Walker 2001). With the exception of storm surges associated with passing hurricanes and tropical storms, the WLD is an entirely freshwater system (Holm and Sasser 2001).

The delta islands are colonized by woody, shrub/scrub and herbaceous fresh marsh species that exhibit zonation along the natural elevation gradient (Visser 1998), and these same patterns have also been documented in the Atchafalaya Delta (Johnson et al. 1985; Schaffer et al. 1992). The ecological community dynamics within this ecosystem are poorly understood, and the relative importance of environmental factors such as island age, inundation and sediment type on community composition has not been fully determined yet.

For this dissertation I will evaluate the effect of major environmental forcings on sediment elevation change and morphology as well as vegetation community zonation and elevation over time in the WLD. These analyses will include the percent cover of herbaceous submerged and emergent species from transect data as well as areal extent of S. nigra stands measured from aerial imagery. In order to better form my hypotheses regarding deltaic floodplain ecogeomorphological development, I have developed a conceptual model. This framework will be used to test hypotheses throughout this dissertation. I will also outline a proposed classification system for wetland types within progradational deltaic floodplain wetland systems, which prior to this have not been defined in a systematic way.
CONCEPTUAL MODEL OF DELTAIC FLOODPLAIN DEVELOPMENT

The following outlines a conceptual model of wetland establishment and succession in an active prograding deltaic floodplain such as WLD (Fig. 1.2). This model was developed from previous literature on the WLD and similar northern Gulf of Mexico deltaic floodplain wetlands (Cahoon et al., 2011; Holm and Sasser, 2001; Johnson et al., 1985; Kolker et al., 2012; Roberts et al., 2005; Shaffer et al., 1992; Shaw et al., 2013; Visser, 1989; White, 1993). The focus of the hypotheses in this dissertation and the conceptual model is the vegetated deltaic wetlands, which tend to occur at elevations greater than -1.0 m NAVD88 (North American Vertical Datum of 1988) in this system, and include subtidal, intertidal and supratidal zones. There are a number of aspects of ecosystem development and succession which are not included in the model, as it was designed with the objectives of this dissertation in mind. In the concluding synthesis chapter I will refine and expand the model to allow for further work to better understand the complex deltaic floodplain wetland ecosystem.

Description of deltaic floodplain ecosystem development

- Initial island growth and vegetation establishment

  (1) Friction dominated deltaic growth results in subaqueous mouth bar deposition and continued expansion of mouth bars both through building upwards in the water column and seaward. Bifurcation and distributary channel establishment occurs on either side of the subaqueous bars.

  (2) Submerged aquatic vegetation (SAV) establishment occurs once the highest elevation portion of the mouth bar reaches a critical threshold at which wetland vegetation is able to grow. This is likely at a depth of approximately 1 m below mean low water (personal
observation), however this limit has not yet been determined in the literature and is likely dependent on light availability.

(3) As the river sediment continues to be deposited on top of the submerged mouth bar, the perennial SAV persist, and are able to grow through new layers of sediment as they are deposited. As the elevation relative to the tidal range increases less flood tolerant emergent species colonize and persist as perennials.

- Three alternative successional pathways

(4a) Clonal emergents (i.e. *Colocasia esculenta*, *Alternanthera philoxeroides*, *Schoenoplectus americanus*, *Phragmites australis*, *Zizaniopsis miliacea*, *Typha* spp., and *Nelumbo lutea*) once established are able to persist from year to year and expand vegetatively from their original establishment location. They are generally able to return through layers of newly deposited mineral sediment, though there is likely a maximum depth through which they can grow, however this has not been reported in the literature. I hypothesize that the expansion of species occurrence likely follows the elevation gradient and is governed by the hydroperiod tolerances of the dominant species. However there are also likely other ecological mechanisms that control community composition, such as competitive exclusion, shading, and possibly allelopathy.

(4b) Storm surges associated with hurricanes and tropical storms can result in very high water levels, and an increase in salinity. If the salinity is high enough it can kill off the aboveground portion of many freshwater emergent species, particularly *N. lutea*, *Sagittaria platyphylla*, and *Typha* spp. If the timing of above ground die-off is early in the hurricane or growing season it can potentially adversely affect the translocation of nutrients to the roots and rhizomes and have implications for the next year’s growth. The susceptibility of species
Initial island growth and vegetation establishment

1. River mouth bar growth

2. Once critical elevation threshold is reached submerged aquatic vegetation establishment occurs

3. As elevation increases herbaceous emergent vegetation establishment occurs

Mean sea level (msl)
greater than maximum depth for vegetation establishment

Three alternative successional pathways

4a. Herbaceous emergent persistence and expansion, new species colonize as elevation increases

4b. Storm surge can result in a shift in dominant species with possible persistence or recovery in subsequent years

4c. High spring flood discharge can result in deposition of thick (>30 cm) sandy deposits along channel banks, and rapid colonization by willow (Salix nigra) seedlings

Willow erosion or persistence

5a. Rapid erosion of sandy channel bank deposits within a few years, continued expansion of dominant emergents with annual flood deposition, no new willow growth

5b. Persistence of sandy bank deposits, willow stands persist and thin out as mature, no expansion of willows into surrounding habitats, despite suitable elevations, possibly due to competition with emergent vegetation

Figure 1.2. Conceptual model of active deltaic floodplain wetland establishment and succession, steps are outlined in more detail in text.
to saltwater and possible reduction in resource allocation likely varies greatly between deltaic wetland species. It is also possible that prolonged high salinities in porewater could kill belowground portions of many species. All these processes have the potential to result in shifts in community composition within active deltaic wetlands.

(4c) Large river floods occur periodically in the deltaic floodplain wetlands, during these periods of high water and sediment discharge, large deposits of sand sized particles are often deposited along mouth bar islands. The timing of spring river flooding generally corresponds with the reemergence of the aboveground portion of perennial wetland species, however it appears that there is a threshold (possibly related to depth, grain size, and/or timing) at which the established perennial vegetation is not able to penetrate the overlying sediment deposit; this threshold is possibly different for each species and has not been determined in the literature. The resulting bare unvegetated sandy sediment is exposed as the river level falls, the timing of which (generally late May-June) corresponds with the release of wind propagated seeds from *S. nigra* in surrounding areas. The seeds are deposited and grow on the newly exposed sandy sediment and establish very dense stands of seedlings, I hypothesize that the *S. nigra* seeds are able to colonize the bare sandy sediment, and in much greater densities and abundances, than areas where emergent vegetation is already present more easily. This process results in the patchy distribution of even-aged willow stands observed along deltaic island levees.

- Willow erosion or persistence

(5a) The sandy channel bank deposits can erode partially or completely within a few years, when this is the case the *S. nigra* seedling are often eroded away and the pre-flood channel edge profile and vegetation community is maintained.
(5b) *S. nigra* stands continue to grow and thin out over time, eventually resulting in 10-15 m tall forested stands, often with a *C. esculenta* dominated understory. There is very little lateral expansion of willows into surrounding habitats (often dominated by *C. esculenta*) despite the presence of propagules in all years and the suitable elevation found in these areas. I hypothesize that this is related to competitive exclusion of *S. nigra* by established perennial herbaceous vegetation (e.g. *C. esculenta, Typha spp. Z. miliacea*).

**DISSERTATION OUTLINE**

Chapter 2 and 3 focus on sediment surface elevation change and deltaic island morphology over time due to hydrologic forcings. The hypotheses in these chapters test ideas included in a number of steps in the conceptual model related to the changes in elevation and morphology that occur over time and provide the foundation both literally and figuratively on which the rest of the dissertation rests (Fig. 1.2). In Chapter 2 I focus on the change in deltaic floodplain wetland elevation in response to river floods, storm surge, and cold fronts, to determine their relative effect on elevation change over time. I also look at the pattern of river flood sediment deposition over the natural elevation gradient and compare trends from floods of differing discharge. I estimate the retention efficiency of sediment on the deltaic islands for all spring river floods between 2008 and 2011. In Chapter 3 I construct a chronosequence map with the estimated time period of wetland emergence for all wetlands within the WLD. Using this framework of island age I utilize multivariate analysis of morphometrics measured from cross-sectional profiles of island edge elevation taken perpendicular to the channel edge, in order to estimate the pattern of change in island edge shape over time. Four years of repeated field surveyed elevation transects are also used to better understand patterns over time and in response to hydrologic forcings such as large river floods. I develop a conceptual model of deltaic island
morphological development over time, which encompasses allogenic physical factors as well as switch to autogenic organic sediment accretion over time.

Chapter 4 and 5 focus on the vegetation community dynamics, including herbaceous and woody species community zonation and patterns of establishment and recovery. These chapters test hypotheses laid out in the conceptual model steps 4a,b&c, as well as steps 5a&b (Fig. 1.2). In Chapter 4 I investigate patterns in herbaceous vegetation community composition across the deltaic floodplain wetland elevation gradient (Fig. 1.2, step 4a) as well as in response to hurricane storm surge (Fig. 1.2, step 4b). I compare pre-hurricane community composition to three years post storm and investigate trends of specific species dominance and expansion in order to understand the vegetation community recovery. In Chapter 5 I used aerial imagery to map the expansion in cover area of *S. nigra* (black willow) between 1998 and 2012. I also analyzed forest structure parameters for individual stands to determine if the patterns of stand structure and establishment in the deltaic floodplain wetlands are similar to those found in riparian floodplain wetlands and attempted to test competitive exclusion mechanism between herbaceous perennial vegetation and *S. nigra* seedlings (Fig. 1.2, steps 4c, 5a & b). In Chapter 6 I synthesize the results of the previous four chapters and refine and expand the conceptual model of deltaic ecosystem development to include simultaneous effects on multiple morphological stages, and to better represent the deltaic floodplain wetland ecosystem at WLD.

**TERMINOLOGY**

During the research and writing of this dissertation, it became clear that while numerous terms have been used in the past by ecologists and geologists to refer to deltaic floodplains and the physical surface on which they occur, that many terms were still imprecise and often
inconsistently applied. Therefore I have clearly laid out a set of terminology to describe the system and have attempted to define them based on the most common usage in the literature. I have used this terminology throughout the dissertation where appropriate to the research question and hypotheses. This is not an exhaustive list, but I think it provides a framework in which to define ecological research questions and ecosystem scales within deltaic floodplains.

Delta plain – The entire deltaic complex that is near or above sea level, including all delta lobes in all stages of progradation and degradation, i.e. the entire Mississippi River Delta Plain, analogous to coastal plain

Delta lobe – discrete progradational unit (or parasequence in the stratigraphic literature). Hence, the Lafourche Lobe all grew at roughly the same time. The lobe was abandoned when the Mississippi avulsed, and ceased transporting sediment to the Lafourche lobe.

Deltaic wetlands – refers to all wetlands in the delta plain, includes both floodplain progradational and transgressive salt, brackish, and fresh wetlands.

Deltaic floodplain – areas within the delta plain and delta, which can and do still receive overbank flow from the river, at least at very high flow. This includes all wetlands along all unveleed active distributaries including on newly formed deltaic island as well as flotant and peat marshes.

Delta apex – the upper point at which bifurcation of deltaic distributaries occurs, it needs to be defined for the system in which it is used i.e. at WLD it can be defined as above the first
bifurcation of Crewboat Channel, while for the whole Mississippi River Delta it would be located at the Old River Control Structure (Fig. 1.1).

Upstream – the direction from which the main riverine discharge flows.

Downstream – the direction in which the main riverine discharge flows.

Primary channels – major distributary channels that bifurcate below delta apex, and separate deltaic islands, may not be applicable to all deltas, but has been used in literature to describe WLD (Hiatt and Passalacqua, 2015; Shaw et al., 2016, 2013).

Secondary channels – smaller channels that usually flow into the interior of deltaic islands, such as the one on Mike Island, some also separate upper and lower portion of islands, may not be applicable to all deltas, but has been used in literature to describe WLD (Hiatt and Passalacqua, 2015; Shaw et al., 2016, 2013).

Deltaic island – all land within the delta, defined as the land area that is subaerial, above mean low water (MLW; -0.04 m NAVD88), includes deltaic island intertidal wetlands, this follows Shaw et al. (2016), and as used in Fagherazzi et al. (2015), to describe when a former mouth bar becomes vegetated and a stable component of deltaic wetland system.

Interdistributary bay – the lower elevation interior portion of a deltaic island which occurs below MLW (-0.04 m NAVD88). It is generally vegetated by subtidal emergent herbaceous
vegetation and submerged aquatic vegetation (SAV), maximum vegetated depth is not
known, however a max depth of approximately 1 m below MLW is referenced in Shaw et al.
(2016), this seems to be an appropriate cutoff for now, may be adjusted once more is learned
about the maximum vegetated depth. The downstream end of the interdistributary bays are
open to the marine system and therefore, where the transition from interdistributary bay to
delta front is located is somewhat unclear, but could be defined as the end of the vegetated
subaqueous wetland.

Interdistributary trough – the deepest interior portion of the interdistributary bay, “200-400 m
wide channel forms discernable in each interdistributary bay... oriented parallel to the
island axis, though not necessarily down its center. ... moving from upstream to downstream,
an interdistributary trough gains definition as its bed gets deeper.” From Shaw et al. (2016).
While the above definition refers to the downstream portions of the delta, these forms can be
seen in upstream interdistributary bays as well, but are often narrower and shallower further
upstream.

Deltaic floodplain wetland – this refers to all the wetlands, including forested, shrub, and
herbaceous, found within the deltaic floodplain. Because this refers to wetlands along all
distributaries including deltaic islands and interdistributary bay wetlands as well as remnant
degradational wetlands such as flotant, its usage should be qualified by the hydrogeomorphic
characteristics.
Types of deltaic floodplain wetlands

Subtidal – occurs below MLW (-0.04 m NAVD88)

Intertidal – occurs between MLW and mean high water (MHW)

Supratidal – occurs above MHW (0.30 m NAVD88)

Fringe wetlands – occur along the channel edge distributary (primary or secondary) channel, can include, subtidal, intertidal and supratidal wetlands. The most interior extent is defined as the highest point on the levee.

Interior wetlands – occur inside of the island not directly along channel edge, where these start is interior of the highest point on the levee, can include subtidal, intertidal and supratidal.

LITERATURE CITED


INTRODUCTION

Land building by both progradation and aggradation in coastal deltaic wetlands is largely controlled by sediment delivery and deposition from terrestrial sources via fluvial sediment transport and marine sources, such as offshore bay bottom deposits resuspended by waves, tides and storms. Understanding the relative contribution of these sediment delivery processes to net elevation change is important for prediction and management of deltas in the 21st century (Georgiou et al. 2005; Day et al. 2007; Paola et al. 2011). Coastal deltas are globally important as population centers, (Ericson et al. 2006; Syvitski et al. 2009) and also include extensive and diverse ecological communities, including mangrove forests, salt, brackish and fresh marshes (Day et al. 2008). The processes that have controlled delta formation throughout the Holocene are changing, including accelerated sea level rise, sediment trapping in river basins by dams and reservoirs, human induced increases in compaction and subsidence due to fluid extraction, reduction of distributary channels and an increase in storm intensity and frequency, altering the ability of deltas to persist and grow (Day et al. 2008; Syvitski 2008 Syvitski et al. 2009, Vörösmarty et al. 2009).

River discharge and sediment delivery control a large portion of the land-building in deltaic systems, for example the shift from progradation to retrogradation that was observed in the Danube Delta as a result of a decrease in sediment delivery of 30-40% due to dam construction within the past 40 yr (Panin and Jipa 1997). A loss in wetland area in the Yellow
River Delta has also been attributed to decreases in water and sediment delivery (Li et al. 2009). Marine processes can also have strong effects on delta growth; the Ebro Delta in Spain is a sediment limited system where waves, tides and storms primarily shape delta morphology (Jiménez et al. 1997, Valdemoro et al. 2007). The physical processes that shape the Mississippi River Delta (MRD), in the northern Gulf of Mexico, include river flooding, frequent winter cold front passage (20-30/yr), tropical cyclone landfall (return interval of 3-10 yr) and a predominantly east to west longshore current. Wave energy is typically very low, with wave heights between 0.5 to 1 m with a period of 5 to 6 s and a mean tidal range of 0.35 to 0.43 m (Hardy and Henderson 2003, Georgiou et al. 2005, Keim et al. 2007). Given the low energy of these coastal forcings relative to river discharge, the MRD is considered a fluvial-dominated system in the classic ternary diagram (Galloway 1975).

There has been much recent analysis looking at the variability in the amount of sediment reaching the coastal zone and its capacity to reduce land loss that is occurring there (Turner et al. 2006, Tornqvist et al. 2007, Blum and Roberts 2009, Allison et al. 2010, CPRA 2012, Rosen and Xu 2014, Nittrouer and Viparelli 2014, Roberts et al. 2015). Previous studies have generally focused on one type of forcing (e.g. floods, storms or cold fronts) and lack direct comparisons of the contribution of multiple forcings to coastal land loss and gain. Here I used observations made in the Wax Lake Delta (WLD), a young (<50 yr) prograding delta lobe of the Mississippi River, to investigate the relative contribution of three seasonally distinct hydrologic forcings on sediment surface vertical elevation change. River flooding, hurricanes and repeated cold front passage occur within this system during distinct times of the year and will be referred to throughout as seasonal forcings. I investigated the variability between seasons and among years, as well as in terms of the long-term return period of rare events such as large floods and
hurricanes, to better understand and predict how modern progradational deltas build over long timescales. This study is the first to directly compare the relative contribution of all three forcings to elevation change in coastal deltaic wetlands.

Large river floods generally result in appreciable land building along the remaining unveeved Mississippi River distributaries, and account for the majority of land building observed in deltaic wetlands (Rouse et al. 1978; Roberts and Adams 1980; Majersky et al. 1997). The loss of flood derived overbank sedimentation is a major factor in increasing rates of wetland subsidence and land loss within the MRD (Baumann et al. 1984; Day et al. 2007; Day et al. 2008; Syvitski et al. 2009; Vörösmarty et al. 2009).

The influence of tropical cyclone passage (both tropical storms and hurricanes) on deltaic sedimentary processes can be large, though they are generally too rare to result in total readjustment of the delta morphology (Syvitski 2008). The factors that determine the severity of hurricane storm surge include aspects of the storm itself, including but not limited to direction of approach, forward speed, wind speed, integrated kinetic energy of the surface wind field, and central pressure (Georgiou et al. 2005; Powell and Reinhold 2007; Irish and Resio 2010). The coastal morphology is also a strong factor in the resulting severity and pattern of hurricane surge inundation, with the broad low-lying MRD acting to enhance storm surge (Westerink et al. 2008; Dietrich et al. 2011) The return period of all tropical cyclones (wind speed ≥63 km hr⁻¹) in the vicinity of the MRD is every 3 yr and for just hurricanes (winds speed ≥119 km hr⁻¹) is every 7 to 10 yr (Keim et al. 2007).

Sediment redistribution and deposition on the surface of coastal wetlands as a result of the large hurricane storm surges has been reported across the northern Gulf of Mexico, with
deposition ranging from washover of sandy beaches and barrier islands that extends 100s of meters from the coast (Williams 2009; Morton and Barras 2011) to widespread redistribution of fine grain sediment and organic root mats that extends to interior marshes 10s of km from the coast. While a few of studies focused solely on deposition (Turner et al. 2006; Tweel and Turner 2012), many have also reported on the widespread erosion that resulted from tropical cyclone passage (Baumann et al. 1984; Rejmánek et al. 1988; Guntenspergen et al. 1995; Nyman et al. 1995; Cahoon 2006; McKee and Cherry 2009; Morton and Barras 2011). It is very difficult to determine both erosional and depositional processes associated with these storms across the entire coast because the effects of each storm are unique based on factors such as angle of approach, size, wind speed, wave height, storm surge, and tidal stage, as well as the variability in coastal wetland morphology, dominant vegetation type and density, sediment characteristics and coastal built infrastructure such as levees, canals, and impoundments, can affect sedimentary processes.

A cold front is the common term for the transition zone between two atmospheric air masses of different densities that generates a predictable set of wind, wave and current conditions as it moves through the coastal zone (Mossa and Roberts 1990). Generally the cold front passages that affect the northern Gulf of Mexico are 25 to 250 km wide and pass from a northwest to southeast direction every 4-7 days through the fall, winter and early spring (October through April, with highest occurrence in January and February), with no significant change in frequency or timing of storms among years (Hardy and Henderson 2003). The pre-frontal phase typically 24-48 hours before the front passes, is defined by strong southerly and easterly winds, producing waves and currents that push water toward the coast resulting in water level increases of 0.5 to 1 m over predicted levels and resuspension of sediment from coastal bays and low
organic matter deltaic wetlands (Rouse et al. 1978; Roberts and Adams 1980; Mossa and Roberts 1990; Feng and Li 2010; Li et al. 2011). As the front passes the coastal zone there is a sudden decrease in barometric pressure and increasing erratic winds and rain, followed by the post-frontal phase in which the temperature and humidity continue to drop and strong northwesterly and northerly winds develop. These winds move water out of coastal bays, rapidly decreasing water levels and transporting suspended sediments onto the continental shelf (Walker and Hammack 2000). The resuspension and transport of sediment from shallow bay bottoms in the vicinity of both the WLD and the nearby Atchafalaya Delta has been well established with predominant westward longshore sediment transport and deposition on the shallow continental shelf and coast of the Chenier Plain located in western Louisiana (Roberts et al. 1989; Mossa and Roberts 1990; Allison et al. 2000; Draut et al. 2005; Neill and Allison 2005; Kineke et al. 2006; Moeller et al. 2012). Water level changes due to cold front wind conditions are often referred to as meteorological tides; defined as the difference between the predicted astronomical tide and the total observed water level (Pugh 1996). In the northern Gulf of Mexico this large change in water levels of 1 m or more over 24-48 hr and their frequent reoccurrence from October to April can have a much greater effect on coastal morphodynamics and sediment transfer than astronomical tides alone (Georgiou et al. 2005).

Here I used the WLD as a long-term experimental system, which allowed us to isolate the effects of distinct seasonal forcings. Due to its relatively protected location within Atchafalaya Bay (Fig. 2.1) and the micro-tidal regime, the effects of astronomical tides and wave action are minimal (Georgiou et al. 2005), allowing for the seasonally distinct processes of river floods, cold fronts, and hurricanes to be isolated in time. In other coastal deltaic systems the confounding effects of continuous and higher magnitude marine forcings would make it more
difficult to clearly attribute observations to a single forcing. My original research objective was to compare the sediment surface elevation change during the spring flood period and the winter cold front period with the timing and location of sampling transects designed to measure a distinct seasonal interval over which each forcing was dominant and to compare seasonal and interannual patterns in elevation change across the WLD. While I did not plan this a priori I was also able to measure the effects of Hurricanes Gustav and Ike in September 2008. This long-term sampling design has allowed us to investigate a number of questions regarding the relative effect of the three dominant seasonal forcings, river floods, hurricanes, and cold fronts, on sediment surface elevation change.

METHODS

Study area and seasonal intervals

The WLD is a prograding delta forming at the terminus of the Wax Lake Outlet (WLO), a constructed distributary channel of the Atchafalaya River, which is a major distributary of the Mississippi River (Fig. 2.1). The water discharge into the Atchafalaya River is maintained at 30% of the combined flows of the Mississippi and Red Rivers, and is controlled by the Army Corps of Engineers at the Old River Control Structure (ORCS). The WLO was originally constructed in 1942 as a flood control conduit from the Lower Atchafalaya River (Shlemon 1975). As the WLO discharges into the shallow (2-3 m) Atchafalaya Bay the resulting bed friction forms distributary mouth bars with coarse grain deposition at the bar crest (upstream end) and along the lateral boundaries and finer grain sediments in the interior portions, bars are separated by bifurcating distributary channels. Over time the mouth bars increase in elevation to
greater than mean low low water (-0.14 m NAVD88) and become deltaic islands (Wright 1977; Wellner et al. 2005; Fagherazzi et al. 2015).

WLD is a relatively young deltaic system with prodelta deposits and subaqueous expansion first observed in 1952. However the majority of the fine grain sediment bypassed the bay and was deposited on the continental shelf prior to the early 1970s (Shlemon 1975). Small subaerial bars that first began to appear in the WLD in 1972 increased rapidly following high river flooding and infilling of shallow lakes upstream and adjacent to the WLO (Roberts and Adams 1980; Wellner et al. 2005). Due to its unique occurance as a constructed river outlet that has been allowed to build land under natural hydrologic conditions, this system represents an extremely valuable analogue to many MRD coastal restoration strageties, which propose diverting river water and sediment into shallow coastal basins to reduce present wetland degradation rates (Parker and Sequeiros 2006; Kim et al. 2009; Allison and Meselhe 2010; Paola et al. 2011; CPRA 2012).

The WLD currently receives approximately 30-40% of the total water and sediment discharge of the Atchafalaya River (Allison et al. 2012), equivalent to 10-12% of the total Mississippi and Red River discharge. Areal land growth rates within WLD range between 1.0 to 3.3 km² yr⁻¹ (Majersky et al. 1997; Allen et al. 2011), depending on the time period under consideration. A delta front expansion rate of 0.3 km yr⁻¹ has been estimated (Parker and Sequeiros 2006), with a vertical elevation change rate estimated at 2.7 cm yr⁻¹ from 1981 to 1994 (Majersky et al. 1997). Sediment transport in the WLD is influenced by seasonal water exchange from river flooding, tidal exchange, cold fronts, and tropical cyclones (Mossa and Roberts 1990; Walker and Hammack 2000; Walker 2001; Roberts et al. 2015). During late fall, winter and
Figure 2.1. Northern Gulf of Mexico with location of study site at Wax Lake Delta, tracks of Hurricanes Gustav and Ike are also shown (top). Sediment surface elevation map of Wax Lake Delta, LA, with 10 cm elevation ranges from 2012 LiDAR survey. Location of sampling transects indicated by black lines and letters (bottom).
early spring (October through April) the inshore to offshore exchange of water and sediments is influenced by winds associated with cold-front passage. In early spring water movement is strongly controlled by the increasing river discharge as the spring river flooding occurs (February through June). As river discharge decreases in the summer, the microtidal regime (amplitude ~ 35-43 cm) becomes the dominant means of water movement on the delta islands, however the channel discharge is maintained in a downstream direction even at rising tide. The lowest river discharge normally occurs during late summer and fall. This is also when tropical cyclones are most likely to occur (Walker 2001). With the exception of storm surges associated with passing hurricanes and tropical storms, the WLD is an entirely freshwater tidal system (Holm and Sasser 2001).

The deltaic floodplain wetlands are composed of low organic matter, highly mineral sediments, primarily fine sand and silt, and are colonized by woody, shrub/scrub and herbaceous fresh marsh species that exhibit zonation along the elevation gradient (Visser 1989). Similar vegetation patterns have also been documented in the Atchafalaya Delta (Johnson et al. 1985; Shaffer et al. 1992). Higher elevation delta islands often have a mixed canopy composed of woody Salix nigra, Baccharis halimifolia and Sesbania spp. with an herbaceous understory dominated by Colocasia esculenta. At slightly lower elevations mixed communities of C. esculenta, Phragmites australis, Polygonum punctatum, Typha spp., Schoenoplectus spp., and Zizaniopsis miliacea occur. Low elevation intertidal and subtidal emergent and submerged herbaceous communities dominated by Nelumbo lutea, Sagittaria platyphylla and Potomogeton nodosus (Johnson et al., 1985; Shaffer et al., 1992; Chapter 4).
It is likely that sedimentary processes and therefore elevation change on delta island tops are related to and controlled to some extent by the presence and morphology of vegetation (Viparelli et al. 2011; Nardin and Edmonds 2014). However these effects are extremely complex due to the high degree of heterogeneity of vegetation community composition in these freshwater tidal wetlands, as well as the drastic seasonal shifts in aboveground herbaceous biomass, ranging from 0 g/m$^2$ in the winter to 600 g/m$^2$ at peak biomass in August. (McCall unpub. data). It is likely that the lack of aboveground herbaceous cover during both the later part of the winter cold front season and the early spring flood season may play a roll in sediment surface elevation change, however it occurs at a spatial and temporal scale that was not feasible to address within the experimental design of this study.

**Sampling and analytical methods**

Between February 2008 and August 2011 elevation surveys were conducted before the spring river flood (February/March) and after water levels returned to non-flood levels (July/August) in all years. Sampling intervals were chosen to capture the period of spring river flooding and cold front passage. Additional surveys followed the passage of Hurricanes Gustav and Ike in September 2008. Due to logistical and weather constraints, field surveys often consisted of 2 to 3 sampling days completed over several days to weeks. In the case when transects were completed over more than two consecutive days the median of all sampling days was selected as the beginning or end of that seasonal interval. The number of days between pre-season and post-season sampling dates is referred to as the sampling interval duration (Table 2.1). During each survey I measured the sediment surface elevation along seven transects (Fig. 2.1, Table 2.2), for a total length of 1,950 m. Transects were established starting at the
distributary channel edge and extended into the interior of the deltaic island to capture the
geomorphic gradient that includes fringe and interior wetlands. The number of 1 m² sampling
plots per transect ranged from 9 to 14, distance between plots was 10, 20 or 40 m, and total
transect lengths ranged from 130 to 400 m (Table 2.2). The spacing and length of transects was
variable to accommodate the elevation gradient at each transect location.

Table 2.1. Seasonal sampling intervals, all transects sampled pre-season and post-season, change
over season interval is defined as the elevation difference between the two samplings.

<table>
<thead>
<tr>
<th>Seasonal interval</th>
<th>Pre-season sampling</th>
<th>Post-season sampling</th>
<th>Seasonal interval duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood 2008</td>
<td>Feb. 7 2008</td>
<td>Aug. 3 2008</td>
<td>179</td>
</tr>
<tr>
<td>Hurricanes 2008</td>
<td>Aug. 3 2008</td>
<td>Sept. 16 2008</td>
<td>44</td>
</tr>
<tr>
<td>Cold Fronts 2008-09</td>
<td>Sept. 16 2008</td>
<td>Feb. 15 2009</td>
<td>152</td>
</tr>
<tr>
<td>Flood 2009</td>
<td>Feb. 15 2009</td>
<td>July 16 2009</td>
<td>151</td>
</tr>
<tr>
<td>Cold Fronts 2009-10</td>
<td>July 16 2009</td>
<td>Mar. 9 2010</td>
<td>236</td>
</tr>
<tr>
<td>Flood 2010</td>
<td>Mar. 9 2010</td>
<td>Aug. 19 2010</td>
<td>162</td>
</tr>
<tr>
<td>Cold Fronts 2010-11</td>
<td>Aug. 19 2010</td>
<td>Mar. 1 2011</td>
<td>194</td>
</tr>
</tbody>
</table>

* Benchmark was eroded so transect F was not surveyed in summer 2011.

Sediment surface elevation was measured with a Class I laser level (Sokkia LP30A;
accuracy: 3 mm @ 100 m) and a stadia rod fit with a laser receiver (Sokkia LP100). The
maximum range surveyed along any transect was 300 m, resulting in a maximum vertical error
of ±0.45 cm. Soil elevation measurements were corrected relative to temporary benchmarks,
which consisted of 3.8 cm diameter pipes driven approximately 3-4 m into the sediment, to the
point of refusal. This was likely the consolidated pre-delta bay bottom mud (Roberts et al. 2005;
Shaw et al. 2013; Shaw and Mohrig 2013). Based on the age and consolidation of the bay bottom
sediments, it was assumed that any subsidence below the depth of the benchmarks was minimal
over the 3.5 years of sampling. Two replicate sediment surface elevation measurements were
taken randomly within each 1 m² plot, and the mean value was reported as the elevation of that plot. To compare elevation surveys taken at different times and different locations throughout the delta, all elevations were corrected first to the transect benchmark. Each benchmark was corrected to the NOAA tidal datum, in July 2008 by linear regression analysis of 30 minute water levels at each benchmark and verified water level data from Amerada Pass (NOAA 8764227), which is approximately 10 km from the transects. There was significant correlation for all benchmarks ($r^2>0.98$). Elevations were then converted from the NOAA tidal datum to NAVD88 geodetic datum, using vdatum software to determine a correction factor of -0.12 m from the NOAA tidal datum mean sea level to 0 NAVD88 (Parker et al. 2003; Shaw et al. 2013). This allowed for direct comparison to available water level and LiDAR datasets.

Table 2.2. Length of elevation survey transects, with location of first plot (located closest to channel edge) all transects extended into island interior perpendicularly to channel edge.

<table>
<thead>
<tr>
<th>Transect ID</th>
<th>Latitude (decimal degrees)</th>
<th>Longitude (decimal degrees)</th>
<th>Total length (m)</th>
<th>Number of sampling plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>29.49560</td>
<td>-91.44735</td>
<td>360</td>
<td>11</td>
</tr>
<tr>
<td>B</td>
<td>29.50113</td>
<td>-91.45125</td>
<td>400</td>
<td>13</td>
</tr>
<tr>
<td>C</td>
<td>29.51051</td>
<td>-91.44493</td>
<td>160</td>
<td>13</td>
</tr>
<tr>
<td>D</td>
<td>29.50171</td>
<td>-91.47941</td>
<td>380</td>
<td>13</td>
</tr>
<tr>
<td>E</td>
<td>29.51151</td>
<td>-91.43311</td>
<td>130</td>
<td>10</td>
</tr>
<tr>
<td>F</td>
<td>29.50315</td>
<td>-91.43520</td>
<td>230</td>
<td>15</td>
</tr>
<tr>
<td>G</td>
<td>29.49283</td>
<td>-91.44085</td>
<td>290</td>
<td>12</td>
</tr>
</tbody>
</table>

Water levels over the entire sampling period were downloaded from the U.S. Geological Survey (USGS) 07381590 gauge on the WLO at Calumet, LA (http://waterdata.usgs.gov), which will hereafter be referred to as WLO water level. Water levels from the NOAA Amerada Pass will be used for the WLD water level (Fig. 2.1). Mean daily total suspended sediment discharge in short tons per day was calculated with the rating curve equation (Eq. 1) developed for this
station (Allison et al., 2012; Allison pers. comm.). This was converted to metric tons per day and used to calculate the total suspended sediment discharge for WLO over each sampling interval.

\[ Y = Y_0 + a(1-e^{-bX}), \quad (Eq. 1) \]

where \( Y \) = total suspended sediment load (shorts tons/day), and \( X \) = mean daily sediment discharge (cfs). Coefficients in Eq. 1 are as follows: \( Y_0 = 2.057 \times 10^4 \), \( a = 3.580 \times 10^7 \), and \( b = 1.883 \times 10^{-8} \). Elevation change over each seasonal interval was calculated by subtracting the pre-season corrected elevation from the post-season corrected elevation. The individual elevation change values for each plot for each interval were used to calculate net elevation change (the mean of all positive and negative change values), mean elevation gain (mean of only positive change values) and mean elevation loss (mean of only negative change values) for each interval across the entire dataset. These values were used to compare the patterns observed during the different seasonal events and investigated relative to hydrologic factors such as water level, water discharge and duration of flooding. I also calculated mean elevation change values for 10 cm pre-event elevation ranges for each river flood interval.

I calculated the total area within each 10 cm elevation range for the delta (≥ -0.5 m NAVD88) using a 1 m horizontal resolution December 2012 airborne LiDAR digital elevation model (DEM) of the WLD derived from the USGS Atchafalaya 2 LiDAR Survey (http://coast.noaa.gov/digitalcoast/). This elevation range includes the majority of intertidal and subtidal vegetated wetland habitats. The LiDAR DEM was resampled using bilinear interpolation to fill in missing data pixels, and the histogram of elevation intervals was generated using ArcGIS 10.2 (ESRI, Redlands, CA). These area estimates for discrete elevation ranges based on the 2012 LiDAR DEM are used for the analysis of elevation change in all flood years.
While the 2012 LiDAR DEM was collected after the period of elevation sampling I consider this as a reasonable estimate of vertical elevation within the delta for the time period of 2008 through 2011, because the total elevation gain estimated over the 3.5 years of sampling was 7.4 cm, which is less than the vertical error in the LiDAR data of ±12.5 cm RMSE. Therefore any changes in elevation distribution within WLD between those years could not be resolved at the vertical resolution of the LiDAR DEM and the elevation survey from 2012 would not be significantly different from a survey obtained in 2008 through 2011.

The total mass of sediment that was deposited in the deltaic wetlands above -0.5 m NAVD88 was estimated based on the total area of each 10 cm elevation range multiplied by the mean depth of sediment deposited from each spring flood within that range. This volume was multiplied by the post-flood sediment bulk density estimated from the mean of 87 homogenized sediment cores collected in July of 2009. Bulk density cores were collected to a depth of 10 cm at a known volume, oven dried to constant mass at 60°C and weighed to determine bulk density. Statistical analyses of elevation change were conducted using SAS 9.1 (SAS Institute, Cary NC, USA), and are primarily one-way ANOVA unless otherwise noted. Tukey’s pairwise comparison with $\alpha = 0.05$ was used as post hoc test, and is indicated with letter values.

RESULTS

Seasonal net elevation change

All river floods resulted in net elevation gain, with the largest net elevation change occurring in 2008 and 2011 (Fig. 2.2). These years also exhibited similar river floods, with one main large discharge peak and only a few smaller ancillary peaks. The spring river flood of 2009
had lower total discharge and resulted in less net elevation gain than in 2008 or 2011, but was not significantly different from 2011. In 2010 while positive elevation change was observed it was close to zero and the pattern of river flood peaks was markedly different than other years, consisting of a sequence of smaller peaks beginning in October 2009 and continuing through June 2010. The overlap of the river flood with the season of winter cold front passage of 2009/10 resulted in a net elevation change of close to zero for both these seasonal intervals (Fig. 2.2). A very different pattern was observed in 2008/09 and 2010/11, when the cold front seasonal interval was distinct from the river flood and resulted in net elevation loss in both years (-2.2 cm and -2.1 cm, respectively). Hurricane Gustav made landfall on the coast of Louisiana, passing 25 km to the northeast of WLD on September 1 2008, and Hurricane Ike passed 275 km southwest of the delta on a northwesterly track on September 12 2008, making landfall in Galveston, TX on September 13 2008, 315 km from WLD (Fig. 2.1). Both hurricanes resulted in storm surges that affected the study site (Fig. 2.2). Despite the much closer proximity of the eye, Hurricane Gustav resulted in a smaller surge with WLD water level 1.1 m above predicted as the storm surge came ashore, (NOAA 8764227 Fig. 2.2). The passage of the very large Hurricane Ike 275 km to the south of WLD resulted in an increase in water level of 2.0 m above predicted despite the storm not making landfall in Louisiana (NOAA 8764227). These two hurricanes resulted in 1.2 cm net elevation gain, illustrating that hurricanes can deliver sediments, presumably resuspended from offshore, into coastal wetlands. The two storms resulted in about as much sediment elevation gain as a moderately large river flood (e.g. 2009). The passage of these two category 2 hurricanes occurred within a two-week time period, restricting my ability to sample between the
Figure 2.2. Mean ± 1 standard error (SE) net elevation change (cm) for each seasonal interval with results of one-way ANOVA (Tukey’s pairwise comparison significant differences at α = 0.05, indicated by letters). The spacing of bars is based on pre- and post-season sampling dates, which determined length of seasonal interval; see Table 2.1 for sampling dates and interval durations. Corresponding water levels reported relative to NAVD88, measured at Wax Lake Outlet gauge (USGS 07381590) shown with thin line and Amerada Pass gauge (NOAA 8764227) represented by thicker line.

storms. Therefore, the two hurricanes have been grouped into one seasonal interval. Estimating a return period for the hurricanes was therefore complicated by the probability of two storms in
such a short period of time. The actual return period for two hurricanes within two weeks is likely much greater than the estimate for one hurricane in this area of the northern Gulf of Mexico of every 7 to 10 yr (Keim et al. 2007). Due to the inability to sample the effect of each storm, I attributed half of the elevation gain to each hurricane to estimate long-term contributions. Based on the return period for one hurricane of 7 to 10 yr, I estimate that the net elevation gain that I observed from Hurricanes Gustav and Ike in 2008 of 1.2 cm would result in an annual contribution of 0.06 to 0.09 cm yr$^{-1}$.

I also investigated the differences in the depositional capacity of each seasonal forcing by comparing the mean of only elevation loss plots and only elevation gain plots separately for each season. Sampling plots with no change in elevation were not included in this analysis (Fig. 2.3). I found no significant difference in the mean of elevation loss plots from any seasonal forcing, indicating that the capacity to cause elevation loss either through sediment removal or compaction is consistent across all types of seasonal forcing and all years (Fig. 2.3). However significant differences were observed in the means of the elevation gain plots, with significantly higher elevation gain as a result of large river floods (Fig. 2.3). This indicated that as all seasonal forcings result in comparable sediment elevation loss, that the depositional capacity of the river floods and hurricanes is a result of the availability of suspended sediment brought in from outside of the system.
Figure 2.3. Mean ± 1 standard error (SE) of only elevation gain (cm) and elevation loss (cm) for each seasonal interval, including results of one-way ANOVA (Tukey’s pairwise comparison significant differences at α = 0.05, indicated by letters). There was no significant difference in elevation loss plots. The differences between seasonal events are only seen in elevation gain plots.
Discharge and sediment supply

The total water discharge and total suspended sediment discharge are based on the riverine sediment discharge rating curve (Eq. 1; Allison et al. 2012) and do not include the suspended sediment load from offshore sediments that are likely resuspended and delivered to the delta during hurricanes and possibly cold fronts, therefore underestimating the total sediment delivery from these types of events (Fig. 2.4). The total WLO water and suspended sediment discharge was higher during the 2008 river flood, with the 2011 river flood discharge just slightly lower (Fig. 2.4). This likely accounted for the greater net mean elevation change observed during the 2008 river flood compared to 2011 (Fig. 2.2). During the 2009/10 cold front seasonal interval, which had the third highest water and total sediment discharge of all seasonal forcings (Fig. 2.4), the mean net elevation change was close to zero (Fig. 2.2). This is due to the overlap of the cold front seasonal interval with the multiple low discharge river flood peaks (Fig. 2.2).

Sediment surface elevation change across the deltaic island elevation gradient

The largest net elevation change across the whole delta occurred as a result of river floods in 2008 and 2011. In both years there was a clear trend in elevation gain relative to the pre-season elevation gradient (Fig. 2.5). The direction of the trends differed from one another; in 2008 there was more net deposition at lower elevations, with the peak at -0.3 m NAVD88 and a
gradual decline to 0.1 m NAVD88 (Fig 2.5a). The opposite trend was observed in 2011, with little or no net elevation gain at elevations < 0 m NAVD88 and a gradual increase at higher elevations with a peak at 0.3 m NAVD88 (Fig. 2.5d). The difference in the location of the net elevation gain maximums between the 2008 and 2011 river floods may be due to the different patterns and duration of flooding that occurred during each seasonal interval. In 2009 and 2010, when the river flood discharge was lower, there were similar levels of net elevation gain across the whole deltaic island top elevation gradient (Fig. 2.5b&c).

Figure 2.4. Total water discharge (cubic km) on left axis and total suspended sediment discharge (million metric tons) on right axis at Wax Lake Outlet for each seasonal interval.
Figure 2.5. Mean ± 1 standard error (SE) net elevation change (cm) within 10 cm elevation ranges for all river flood seasonal intervals. Color of bars corresponds to 10 cm elevation ranges shown on map of Wax Lake Delta in Fig. 2.1.
The distribution of total area of floodplain wetlands within each 10 cm elevation range (Fig. 2.6) illustrates that a larger portion of the deltaic wetlands (≥-0.5 m NAVD88) occur at lower elevations. During the 2008 flood, the highest elevation gain was seen at lower elevations, resulting in much greater estimates of total sediment deposition than was observed from the 2011 river flood when the majority of elevation gain occurred at high elevations (Fig. 2.6). There was an estimated 2,520,000 metric tons (T) deposited on deltaic wetlands in 2008, compared to 1,344,000 T in 2011 (Table 2.3). River flood intervals in 2009 and 2010 both had similar estimates of 824,000 T and 879,600 T respectively, much lower than the two large flood years (Table 2.3).

Figure 2.6. Total area (km²) of deltaic wetlands within each 10 cm elevation range, based on USGS Atchafalaya 2 LiDAR Survey conducted December 2012. Color of bars corresponds to 10 cm elevation ranges shown on map of Wax Lake Delta in Fig. 2.1
**Deltaic wetland sediment retention efficiency**

The sediment retention efficiency of the deltaic wetlands is estimated as the proportion of total suspended sediment discharge through WLO over the flood seasonal interval that was deposited on the deltaic wetlands at elevations greater than -0.5 m NAVD88. The retention efficiency during the 2008 river flood was higher than in any other year at 16.3%, much higher than the 9.0% retention efficiency from the 2011 river flood. The river floods of 2009 and 2010 had 7.4% and 8.3%, respectively (Fig. 2.7 & Table 2.3). This analysis did not include the trapping of sediment that likely occurred in the deeper portions of the delta (<-0.5 m NAVD88), which would increase the overall retention efficiency for the delta as a whole. These results indicate that floods with lower peak discharge but longer flood duration, as was seen in 2008, maximize sediment retention efficiency and deltaic island top elevation gain. The portion of the total suspended sediment discharge that is trapped and deposited in the deltaic wetlands is critical for land building and the maintenance of the deltaic floodplain in response to sea level rise and subsidence.

**DISCUSSION**

**River flood sediment retention efficiency**

The greatest net elevation gain occurred during river flood intervals, compared to all other seasonal forcings, and is related to increased fluvial sediment delivery. The amount of sediment delivered during river floods varied between years in relation to water discharge (Fig. 2.7). A prior estimate of sediment retention efficiency for WLD was reported as 23% (Törnqvist et al. 2007), which is double what I estimated for deltaic wetlands. However, their estimate
Figure 2.7. Total suspended sediment discharge (million metric tons) at Wax Lake Outlet over each river flood seasonal interval and total mass of sediment deposited on deltaic island tops at elevation $\geq -0.5$ m NAVD88 during each seasonal interval. Retention efficiency for each river flood seasonal interval is also shown.

was based on retention for the whole delta topset, which includes both deltaic wetlands and deeper subaqueous channels, a total area of 104.6 km$^2$, approximately double the deltaic wetland area at elevations greater than -0.5 m NAVD88 used in this study of 53.2 km$^2$. Therefore if I assume the processes and deposition rates are similar in magnitude for deeper subaqueous portions of the delta (Shaw and Mohrig 2013), and scale their estimates to the smaller area I used, the resulting 11.7% retention efficacy (Törnqvist et al. 2007) is similar to my estimate of 7.4 to 16.3%.
The large difference in sediment retention efficiency observed during the 2008 compared to the 2011 river floods of 16.3% and 9.0%, respectively, was surprising as I personally observed many areas of large sandy deposits immediately after the 2011 flood. However, based on my results it is likely these were restricted to higher elevations (Fig. 2.5d) and less elevation gain occurred at lower elevations (Fig. 2.6). Analyses by Kolker et al. (2014) found evidence of a shift in the location of the primary sediment depocenter, from nearshore deltaic wetlands and the Atchafalaya Bay bottom, to the continental shelf during the 2011 flood, postulating that the higher discharge of this large flood was able to move suspended sediments further offshore. I observed a mean net elevation gain of 4.8 cm from the 2011 flood mainly in higher elevation areas (Fig. 2.5d), while the 2008 river flood had higher mean net elevation gain (5.4 cm) spread across a greater range of elevations and larger area (Fig. 2.5a). This coupled with the observed increased elevation loss at lower elevations and bank collapse in 2011 (personal observations and those of Shaw and Mohrig 2013) supports the shifting of the majority of sediment deposition to locations further offshore. This is consistent with suggestion that the extreme flooding event observed in 2011 was not an ideal model for deltaic restoration and management in open bay environments (Kolker et al. 2014). If the goal is to increase sediment delivery to nearshore deltaic wetlands, more moderate longer duration river floods such as 2008, seem to optimize water levels, sediment delivery and discharge, resulting in the greatest net elevation gain and retention on deltaic wetlands. Though I would also add that all floods deliver sediment to the coastal zone and add to the long-term cumulative deltaic land gain.

**Hurricane storm surge contribution to elevation gain**

I measured a net elevation gain of 1.2 cm following the passage of Hurricanes Gustav and Ike in September 2008. This is consistent with observations by other studies that have shown that
there is a resuspension of sediment which occurs as a result of the waves, currents and storm surge associated with hurricanes passage (Walker 2001). These sediments are re-deposited as the surge moves inland into coastal wetlands resulting in measureable elevation gain attributed to hurricanes (Rejmánek et al. 1988; Guntenspergen et al. 1995; Nyman et al. 1995; Cahoon 2006; Turner et al. 2006; McKee and Cherry 2009; Morton and Barras 2011; Tweel and Turner 2012). Recent studies have attempted to estimate mean deposition from hurricanes across the entire MRD wetland landscape; however, they over represented gross deposition as neither erosion nor elevation loss was accounted for in these estimates (Turner et al. 2006; Tweel and Turner 2012). My estimate of change in net elevation resulting from the passage of Hurricanes Gustav and Ike included both elevation gain and loss throughout the delta, which accounted for 62% and 32% of the sampling plots respectively (6% exhibited no change). Using only plots where sediment deposition was observed to estimate elevation gain, results in an overestimation of 61% compared to if they had also measured elevation loss resulting from the hurricanes (Fig. 2.3). Therefore I estimate that the reported gross deposition amounts in Turner et al. (2006) and Tweel and Turner (2012) are likely overestimated by 61%, and should be adjusted down to account for this. While this is still an appreciable sediment subsidy for coastal wetlands, especially in abandoned delta lobes that receive very little riverine sediment input (McKee and Cherry 2009; Baustian and Mendelssohn 2015), it is only a small contribution in wetlands that receive appreciable riverine sediment delivery (Törnqvist et al. 2007).
Table 2.3. Total surface area for delta island top 10 cm elevation ranges ≥ -0.5 m NAVD88, estimate of volume of sediment deposited over each river flood seasonal interval, and total suspended sediment (TSS) discharge from Wax Lake Outlet over each river flood interval. Retention efficiency is determined as the proportion of TSS discharge that is retained on delta island tops. Estimates of sediment mass based on mean post river flood bulk density of 0.86±0.02 g/cm$^3$ from 10 cm deep sediment cores collected following 2009 spring river flood.

<table>
<thead>
<tr>
<th>Elevation ranges (m NAVD88)</th>
<th>Total surface area (km$^2$)</th>
<th>Mean sediment elevation change (cm)</th>
<th>Mass of sediment deposited (metric tons)</th>
<th>Mean sediment elevation change (cm)</th>
<th>Mass of sediment deposited (metric tons)</th>
<th>Mean sediment elevation change (cm)</th>
<th>Mass of sediment deposited (metric tons)</th>
<th>Mean sediment elevation change (cm)</th>
<th>Mass of sediment deposited (metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.50 to -0.41</td>
<td>4.11</td>
<td>--</td>
<td>--</td>
<td>-1.8</td>
<td>-64,000</td>
<td>-1.1</td>
<td>-39,000</td>
<td>-0.5</td>
<td>-18,000</td>
</tr>
<tr>
<td>-0.40 to -0.31</td>
<td>5.69</td>
<td>0.5 ±2.0</td>
<td>24,000</td>
<td>3.9 ±4.2</td>
<td>190,000</td>
<td>1.7</td>
<td>83,000</td>
<td>-2.1</td>
<td>-100,000</td>
</tr>
<tr>
<td>-0.30 to -0.21</td>
<td>7.32</td>
<td>12.5 ±7.0</td>
<td>790,000</td>
<td>-0.2 ±0.3</td>
<td>-13,000</td>
<td>0.4 ±0.2</td>
<td>25,000</td>
<td>3.3 ±0.4</td>
<td>210,000</td>
</tr>
<tr>
<td>-0.20 to -0.11</td>
<td>7.27</td>
<td>10.1 ±3.6</td>
<td>630,000</td>
<td>--</td>
<td>--</td>
<td>5.3 ±2.8</td>
<td>330,000</td>
<td>-0.3</td>
<td>-19,000</td>
</tr>
<tr>
<td>-0.10 to -0.01</td>
<td>6.17</td>
<td>7.8 ±2.1</td>
<td>410,000</td>
<td>7.3 ±6.1</td>
<td>390,000</td>
<td>3.3 ±1.1</td>
<td>180,000</td>
<td>0.9 ±0.6</td>
<td>48,000</td>
</tr>
<tr>
<td>0.0 to 0.09</td>
<td>5.05</td>
<td>6.4 ±1.8</td>
<td>280,000</td>
<td>0.8 ±1.1</td>
<td>35,000</td>
<td>0.1 ±0.7</td>
<td>4,300</td>
<td>4.0 ±1.9</td>
<td>170,000</td>
</tr>
<tr>
<td>0.10 to 0.19</td>
<td>4.8</td>
<td>0.9 ±2.2</td>
<td>37,000</td>
<td>3.2 ±2.1</td>
<td>130,000</td>
<td>1.4 ±1.2</td>
<td>58,000</td>
<td>8.1 ±4</td>
<td>330,000</td>
</tr>
<tr>
<td>0.20 to 0.29</td>
<td>4.18</td>
<td>2.8 ±3.1</td>
<td>100,000</td>
<td>0.5 ±2.1</td>
<td>18,000</td>
<td>1.6 ±1.5</td>
<td>58,000</td>
<td>7.9 ±4.4</td>
<td>280,000</td>
</tr>
<tr>
<td>0.30 to 0.39</td>
<td>3.42</td>
<td>6.2 ±1.2</td>
<td>180,000</td>
<td>1.3 ±1.8</td>
<td>38,000</td>
<td>4.9 ±3.2</td>
<td>150,000</td>
<td>14.3 ±0.6</td>
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<td>0.40 to 0.49</td>
<td>3.59</td>
<td>1.6 ±0.5</td>
<td>49,000</td>
<td>1.8 ±1.3</td>
<td>56,000</td>
<td>0.8 ±1.0</td>
<td>25,000</td>
<td>-1.1 ±0.9</td>
<td>-34,000</td>
</tr>
<tr>
<td>&gt;0.50 m</td>
<td>1.55</td>
<td>1.5</td>
<td>20,000</td>
<td>3.3 ±0.4</td>
<td>44,000</td>
<td>0.4 ±0.5</td>
<td>5,300</td>
<td>4.3 ±1.8</td>
<td>57,000</td>
</tr>
<tr>
<td>Total surface area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>53.2</td>
<td></td>
</tr>
<tr>
<td>Total mass of sediment deposited on island tops (≥-0.5 m NAVD88) by flood (metric tons)</td>
<td>2,520,000</td>
<td>824,000</td>
<td>879,600</td>
<td>1,344,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage of total suspended sediment discharge over seasonal interval captured by deltaic island tops</td>
<td>16.3%</td>
<td>7.4%</td>
<td>8.3%</td>
<td>9.0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Long-term contribution of large river floods and hurricanes to delta growth

Here I use the synoptic results obtained from the passage of Hurricanes Gustav and Ike to estimate the long-term contribution of hurricanes to sediment elevation gain in the WLD, particularly relative to large river floods. While the reported return period for hurricanes (≥ category 1) along the MRD is one every 7-10 years (Keim et al. 2007), the hurricane passage that occurred during this study is unique in that it included the passage of two category 2 storms within two weeks. From an ecological and sediment transport perspective it is likely that Hurricane Ike with its larger shifts in water level had a much greater effect on the ecology and geomorphology of deltaic wetlands, however this cannot be determined from my data because no sampling occurred during the time between the two storms. I estimate that the net elevation gain that I observed from Hurricanes Gustav and Ike in 2008 of 1.21 cm would result in an annual contribution of 0.06 to 0.09 cm yr\(^{-1}\). This long-term estimate is much lower than the vertical accretion rate of 1.4 to 2 cm yr\(^{-1}\) estimated from \(^{137}\)Cs peaks in nearby wetland and bay bottoms that are also receiving riverine mineral sediment inflow (DeLaune et al. 1987; Mossa and Roberts 1990). The return period for large river floods equal or greater in water level than the 2008 flood is once every 12 yr based on the entire record of the Atchafalaya River at Simmesport LA (USGS 07381490) which extends from 1932 to 2015. Using this estimated return period and a mean net deposition of 5.4 cm and 4.9 cm in 2008 and 2011, respectively, the long-term estimate of mineral sediment contribution from large river floods is 0.42 to 0.46 cm yr\(^{-1}\). Direct comparison of the long-term sediment elevation gain contribution from large floods and hurricanes shows that long-term hurricane derived contribution to delta wetland elevation gain is less than 22% of that from large river floods.
Elevation loss due to cold front passage

The net loss of elevation resulting from annual cold front passage can effectively cancel out flood elevation gain except in large river flood years, which occur about once every 12 yr. There is little variability in number and pattern of cold front occurrence from year to year (Hardy and Henderson 2003) therefore the effects of cold fronts on elevation loss are occurring to the same degree every year. This pattern of elevation loss, due to cold front seasonal forcings in the WLD and Atchafalaya Delta has been reported in a number of other studies (Rouse et al. 1978; Kemp et al. 1980; Roberts and Adams 1980; Mossa and Roberts 1990). This has important implications for land building capacity of this type of system as the need to offset this annual elevation loss is critical for continual net elevation gain. While cold front elevation loss is significant within the wetlands within the WLD itself, it has been reported that resuspended sediments from cold front passage as well as river floods has resulted in appreciable sediment deposition along tidal creeks in nearby organic headland marshes, brackish marshes along Fourleague Bay and near shore bay bottoms (DeLaune et al. 1987; Perez et al. 2000; Roberts et al. 2015). Transport of suspended sediment via cold front water level fluctuations in areas that do not receive direct river inflow has also been shown, such as salt marshes in sediment limited Terrebone Basins (Reed 1989). Also cold front resuspension and transport of sediments westward from the Atchafalaya Bay via longshore current results in accretion of mudflats in the Louisiana Chenier Plain (Roberts et al. 1989; Mossa and Roberts 1990; Kineke et al. 2006). Therefore fluvial sediments initially deposited on the deltaic wetlands of WLD during river floods may act as a sediment source during winter cold front resuspension events and support secondary sediment transport to far field wetlands throughout the coastal zone.
While two large river floods (2008 and 2011) occurred within only four years during my sampling, the return period of river floods this size is historically one every 12 years. The large river floods resulted in net annual elevation gain, the moderate and smaller river floods, like 2009 and 2010, seem to be offset on an annual basis by cold front elevation loss, resulting in no net change in elevation across the delta for the year (Fig. 2.2). This pattern of vertical elevation gain in which there is no net growth of deltaic island elevation for a number of years (with small to moderate river floods), punctuated by net elevation gain from periodic large river floods (approximately once every 12 yr), may be important for understanding previous long term estimates of vertical delta growth and predicting future elevation gain. Previous delta land building predictions for both the WLD and Atchafalaya Deltas have been over-estimated with some researchers predicting that both deltas would merge and fill the Atchafalaya Bay within the early part of the 21st century (Shlemon 1975; Roberts and Adams 1980; van Heerden et al. 1983; DeLaune et al. 1987; Majersky et al. 1997). This may be due to the lack of inclusion of elevation loss resulting from cold fronts in predictive models. It is likely that numerical models currently used for restoration planning that do not take cold front removal into account will also overestimate land building rates (Parker and Sequeiros 2006; Hanegan 2011). Inclusion of this net degradational process in future delta models is critical for accurate prediction of delta morphodynamics and development.

Conclusions and implications for coastal restoration

Coastal Louisiana is an area where dynamic marine and riverine forces shape deltaic landforms. This study in an actively prograding delta allows us to better understand the relative contributions of three major forcings, river floods, cold fronts and hurricanes to delta growth.
River floods are the main drivers of elevation gain in the WLD with the highest discharge floods resulting in significantly more elevation gain than lower discharge floods; however without the combined elevation gain attributed to both large and small floods, net positive elevation gain would not be possible over the long-term, due to consistent annual loss in elevation due to cold fronts. I also found that while hurricanes do deliver a net elevation gain to the delta island tops, they also result in appreciable elevation loss, equal to 39% of the gross elevation gain. This is an important consideration that is often left out of other studies of hurricane sediment subsidy. The long-term annual contribution of hurricane derived sediments to deltaic wetlands based on a return period of one every 7-10 years is less than 22% of the sediment delivered by large river floods in the WLD. River diversions designed for suspended sediment delivery have been proposed as a potential means to offset wetland loss in coastal Louisiana (CPRA 2012), I conclude that in locations that experience similar hydrological forcings to the WLD, the operation of these diversions would need to be designed with these findings in mind. It is also crucial to include cold front elevation loss in numerical models of delta building to accurately predict future land building.

**LITERATURE CITED**


CHAPTER 3. DELTAIC ISLAND EDGE MORPHODYNAMICS ALONG A CHRONOSEQUENCE AND IMPLICATIONS FOR DELTAIC FLOODPLAIN WETLAND SUCCESSION AND ORGANIC MATTER SEQUESTRATION

INTRODUCTION

The morphological development of deltaic floodplain wetlands defines how these critical habitats, which are associated with depositional environments of major rivers, will respond to regional subsidence and increasing global sea level. Worldwide over 500 million people currently occupy coastal deltaic plains, a number of which are in peril due to changes in sediment and water delivery patterns (Ericson et al. 2006; Syvitski et al. 2009). Major coastal restoration projects such as those in the Mississippi River Delta are predicated on the ability of sediment delivery from river discharge to build land (CPRA, 2012). A number of studies have demonstrated the ability of the Mississippi River to build land (Cahoon et al., 2011; Kolker et al., 2012; Majersky et al., 1997; Roberts and Adams, 1980; Rouse et al., 1978). However most previous research on morphological development has focused on the planform delta dimensions (Allen et al., 2011; Edmonds and Slingerland, 2009; Kim et al., 2009; Kolker et al., 2011; John B. Shaw et al., 2013) with less emphasis on the three dimensional morphodynamics of these systems. Investigations of morphological change have found that erosion occurred within channels and in low elevation distal mouth bars even during low flow (Shaw and Mohrig, 2013). Seasonal and annual comparisons of elevation change across intertidal and supratidal vegetated mouth bars have demonstrated most elevation gain occurred as a result of large river floods with very little annual net elevation gain in mean and low discharge flood years (Chapter 2). These findings help to inform models of deltaic morphodynamics that better replicate natural delta
morphology, but they leave out the contribution of accumulated organic matter to delta morphology (Lorenzo-Trueba et al., 2012; Paola et al., 2011). This process is likely a strong driver of elevation change in the heavily vegetated islands during latter stages of deltaic wetland succession. The transition from mineral sedimentation to organic accretion that occurs as a result of the infilling of interdistributary bays has been illustrated across a number of temporal and spatial scales (Coleman and Gagliano, 1964; Frazier, 1967; Lorenzo-Trueba et al., 2012; Nyman et al., 1990). However there has been little work on coastal deltaic morphodynamics over intermediate decadal time scale, nor has it been incorporated into predictive land building models over these shorter timescales.

Here I define coastal deltaic floodplain wetlands as those that receive river and sediment inflow during natural conditions including floods. In my definition of the term this does not include deltaic wetlands which are no longer in an active floodplain such as those that have been disconnected from river inflow by avulsions and constructed flood control levees. In the Mississippi River Delta Plain the freshwater deltaic floodplain wetlands are found in locations of active sediment deposition and land building, these include the Atchafalaya Delta, Wax Lake Delta (WLD), as well as the main outlet of the Mississippi River (Couvillion et al., 2011). These wetlands are vegetated by emergent, floating leaved and submerged vegetation throughout the intertidal, and shallow subtidal portion to around 1 m below MLLW (-1.14 m NAVD 88). The vegetation zonation and composition of coastal deltaic floodplain wetland communities are controlled to a large extent by elevation gradient as well as rates of sediment deposition and erosion (Cahoon et al., 2011; Johnson et al., 1985; Shaffer et al., 1992).
Previous work has investigated the ecological development in deltaic wetlands related to soil organic matter (OM) content and biogeochemistry and have found a pattern of high OM in older portions of the delta (Henry and Twilley, 2014). However, it is not known what processes account for this pattern and if there are environmental or biological controls on when and where high OM sequestration occurs. Deltaic islands within progradational deltas of the Mississippi River system are defined by a consistent morphology where the island edges along distributary channels are higher in elevation than the island interiors (Cahoon et al., 2011; Johnson et al., 1985; Kolker et al., 2012; John B Shaw et al., 2013; Shaw et al., 2016). The cross-sectional elevation gradient resulting from this morphology likely has a strong relationship to vegetation community dynamics as flooding stress and hydroperiod exert a strong control on vegetation zonation in wetlands. The processes that control both the morphologic development of these elevation gradients include hydrodynamics and sediment transport, as well as biomass production and sediment trapping. While many of these processes are very complex and likely vary over small spatial and temporal scales, here I attempt to look at macroscale changes in the morphology with time over the entire spatial (100 km²) and temporal (40 yr) scales of the WLD. I use this prograding system to test if there is a predictable change in deltaic island edge morphology with island age and distance from upstream end of island (Fig. 2.1). I utilized a chronosequence approach, allowing for a space for time substitution often used in ecological succession studies (Walker et al., 2010). This approach has been used in the past in the WLD to look at the development of soil characteristics and biogeochemical fluxes over time (Henry and Twilley, 2014; Shields et al., 2016). Based on previous studies I know that the WLD expanded outward form the mouth of the Wax Lake Outlet since 1973 at a rate of between 1 and 3.3 km²/yr (Allen et al., 2011; Majersky et al., 1997). The known starting point of subaerial land emergence
Figure 3.1. Study site map of the Wax Lake Delta, Louisiana, USA. Location of the site within the Louisiana coast and the Gulf of Mexico can be seen in the inset maps at top. The filed surveyed transects are delineated by a series of overlapping white dots, each dot indicates a surveyed plot. LiDAR transects are delineated by black lines that represent the location and length of all 109 LiDAR extracted elevation profiles. Mike Island which is used in the conceptual model is shown in the center of the delta. The elevations reported are from the USGS Atchafalaya 2 Project LiDAR survey (2012).
at WLD makes this an ideal location for chronosequence study (Pickett, 1989; Walker et al., 2010). I assume that deltaic islands of WLD have developed along the same trajectory and under the same allogenic forcings.

CONCEPTUAL MODEL

Based on field observations and previous work in which the authors investigated seasonal controls on elevation change along deltaic islands at WLD (Chapter 2) as well as other studies of delta development (Cahoon et al., 2011; Esposito et al., 2013; Johnson et al., 1985; Kolker et al., 2012, 2011), I created a hypothesized conceptual model of island morphology over time. I hypothesize that differences in morphology and elevation range of islands edges are primarily controlled by the age of the island and primarily controlled by allogenic physical processes, particularly sedimentation (Fig 3.2). Younger more recently deposited islands at the distal portions of the delta have lower overall elevation, wider levees and more gradual interior slope. As deposition patterns change in response to elevation gain intermediate age islands begin to develop a pronounced levee ridge that increases in elevation over time. In the oldest islands with the highest overall elevation, I hypothesize that interior infilling occurs, with the interior of the islands increasing in elevation until it is equal to the levees. Processes driving this infilling may be related to the relative degree of mineral sediment delivery and the organic production, as well as protection from strong currents allowing for finer grain sediment deposition.

To test the conceptual model of deltaic island edge morphological development, I selected four morphometrics which describe the shape of the island edge cross-sectional profiles. These were used to test if island edge cross-sectional shape, as described by these parameters, changed in a consistent way with island age. The results of this analysis was used to refine the
Figure 3.2. Examples of deltaic island cross-sectional morphology from Mike Island (see Figure 3.1 for location within delta) data from 2012 USGS LiDAR DEM; similar patterns can be seen across all delta islands. These patterns were used to develop a conceptual model that describes how differences in morphology and elevation range of islands edges are related to island age and distance from the upstream end. Where younger more recently deposited islands at the distal portions of the delta have lower overall elevation, wider levees and more gradual interior slope, as deposition patterns change in response to elevation gain intermediate age islands begin to develop a pronounced levee ridge that increases in elevation over time. In the oldest islands with high overall elevation, I hypothesize that interior infilling occurs, with the interior of the islands achieving an elevation very close to the highest levee edges, possibly due to higher rates of organic accretion as well as protection from erosive processes such as floods and waves.
conceptual model of deltaic island edge morphodynamics and outline future hypotheses that will expand my understanding of deltaic floodplain wetland development over time. The trends in the morphodynamics also help to elucidate mechanisms that may explain ecosystem processes, such as wetland succession and soil development, as active deltas prograde over coastal landscapes.

METHODS

Site description and timeline of delta development

The WLD is forming at the terminus of the Wax Lake Outlet (WLO), a constructed distributary channel of the Atchafalaya River, which is in turn a main distributary of the Mississippi River (Fig. 3.1). The discharge into the Atchafalaya River is maintained at 30% of the combined flows of the Mississippi and Red Rivers, and is controlled by the Army Corps of Engineers at the Old River Control Structure (ORCS), completed in 1963. The WLO was originally constructed in 1942 as a flood control conduit on the Lower Atchafalaya River (Shlemon, 1975). As the WLO empties into the shallow (2-3 m) Atchafalaya Bay, the resulting bed friction results in the formation of distributary mouth bars and bifurcating distributary channels (Wellner et al., 2005; Wright, 1977).

Prodelta deposits and subaqueous expansion of WLD in Atchafalaya Bay were first observed in 1952, the majority of the fine grain sediment bypassed the bay and was deposited on the continental shelf (Shlemon, 1975). Small subaerial bars first began to appear in the WLD in 1972 on top of the large (1-5 km long and 1-2 km wide) subaqueous deposits, which increased rapidly following high river flooding and infilling of shallow lakes upstream and adjacent to the WLO (Roberts and Adams, 1980; Wellner et al., 2005). As the subaqueous bars increased in
elevation they are colonized by submerged and emergent vegetation, becoming delta islands, which along with channels makeup the delta top ecosystem (Fagherazzi et al., 2015). The delta islands are primarily arrowhead shaped with a subtidal (<MLLW) interdistributary bay surrounded by relatively narrow higher elevation (intertidal) levees. The interdistributary bay generally widens and deepens in the downstream direction, and often has a deeper interdistributary trough down the center (Shaw et al. 2016). These features seem to be consistent across islands and can be clearly seen on elevation contours of the delta (Fig 3.1).

There has been limited channel dredging in the WLD, mainly constrained to the northwestern most channel called Crewboat Channel (Fig. 3.1). Therefore the majority of the channel and island formation closely resembles natural undisturbed delta morphology (Wellner et al., 2005) with unique features as a constructed river outlet that has been allowed to build land under natural hydrologic conditions. Accordingly this system represents an extremely valuable analogue to many delta restoration strageties, which propose diverting river water and sediment into shallow coastal basins to counteract coastal wetland loss (Parker and Sequeiros 2006; Kim et al. 2009; Allison and Meselhe 2010; Paola et al. 2011; CPRA 2012).

Currently, the WLD receives approximately 30-40% of the total water and sediment discharge of the Atchafalaya River (Allison et al. 2012), equivalent to 10-12% of the total Mississippi and Red River discharge. The growth of WLD has occurred in alternating jet plume deposits (Wellner et al. 2005), with areal land growth rates within WLD ranging between 1.0 to 3.3 km² yr⁻¹ (Allen et al., 2011; Majersky et al., 1997). Variation in delta growth rates are mainly due to the time period under consideration and the occurrence of high discharge river floods. A delta front expansion rate of 0.3 km yr⁻¹ has been estimated (Parker and Sequeiros 2006), with a
vertical elevation change rate estimated at 2.5 to 2.7 cm yr\(^{-1}\) (Majersky et al., 1997). The delta islands are primarily composed of mineral sediments (Chapter 4), however increasing organic content has been observed in older islands (Henry and Twilley 2014).

**Deltaic island age range estimation for chronosequence**

Deltaic island age was estimated by using a number of data sources, including maps from Wellner et al. (2005), in which both subaerial and subaqueous deltaic island extent were mapped from high altitude aerial photographs for the years 1974, 1983, 1990, 1995, 1998, 2000, and 2002. I used only the subaerial extent in my analyses, which was defined in their analysis as the portion “at or near the minimum low tide of sea level”. I interpret this as near the common definition of subaerial, which is land above mean low water (Rouse et al. 1978, Roberts et al 1980). These published maps were georectified using ArcMAP 10.2 (ESRI, Redlands, CA) and manually digitized at 1:121,500 m resolution to create shapefiles of the extent of subaerial land. I also digitized the extent of subaerial land from U.S. Geological Survey High Resolution State Orthoimagery for the Coastal Wetlands collected October 2008 (viewer.nationalmap.gov). The imagery was downloaded as digital orthophoto quarter quadrangles for the desired study site and processed using ERDAS Imagine 11 (Hexagon Geospatial, Norcross, GA). The extent of land reported in 2012 was estimated by creating a layer of elevations greater than -0.5 m NAVD 88 from a December 2012 airborne LiDAR digital elevation model (DEM) of the WLD derived from the USGS Atchafalaya 2 LiDAR Survey (coast.noaa.gov/digitalcoast/). The shapefiles of deltaic island extent for each year were then overlain and clipped using the most recent channel shape from the 2012 LiDAR shapefile. This map represents the time at which deltaic wetland sediment surface elevation was first reported to be at or near MLLW (i.e. close to subaerial).
This map allows us to assign estimated age ranges to all wetland area within the delta; illustrating geographically how the planform delta built over time and resulting in a chronosequence of delta age that can be used for experimental design.

**Field surveyed elevation transects and soil organic matter**

Surveys of sediment surface elevation were measured two times per year between February 2008 and August 2011 in winter (February to early March) and summer (July/August). The original intention of the sampling intervals was to capture the effects of spring river flooding and cold front passage on change in elevation. During each survey the sediment surface elevation along seven transects was measured, over a total length of 1,950 m. Transects were established perpendicular to the channel edge to capture the geomorphic gradient that includes near-channel, levee, and interior wetlands. The detailed field survey methods and results of the initial analyses related to seasonal change are outlined in Chapter 2. As part of this campaign 2.5 cm diameter sediment cores were collected during the summer of 2010 at all field surveyed plots to a depth of 10 cm. These 87 cores were oven dried to constant mass at 60°C and weighed to determine bulk density, calculated as the total dry weight divided by the core volume. They were then homogenized and ground to 250 µm with a Wiley Mill. Total organic matter was determined by loss on ignition after combusting samples of known mass at 550°C for 2 hours (Davies, 1974).

Patterns observed in the surveyed elevation transects were used to develop the conceptual model of island morphology change with time and to do preliminary analyses of patterns of island edge morphology change with age. However, I realized that while the surveyed transects were spread throughout the deltaic islands (Fig. 3.1) and covered a 3.5 yr time period, I was limited in my ability to answer questions about delta-wide morphodynamics by both the
sampling size and spatial coverage of the field surveyed transects. Therefore, I determined to use a recently available LiDAR digital elevation model to sample transects more evenly across the delta, while still utilizing the surveyed transects to help to refine my results and lend evidence for possible mechanisms to explain deltaic island edge morphology.

**LiDAR elevation transect extraction and morphometric variable determination**

I extracted 109 elevation profiles at 500 m intervals from the upstream end along all island edges within WLD that had not been affected by dredging. The elevation profiles were extracted from a December 2012 airborne LiDAR digital elevation model (DEM) of the WLD derived from the USGS Atchafalaya 2 LiDAR Survey (http://coast.noaa.gov/digitalcoast/) using ArcGIS 10.2 (ESRI, Redlands, CA). The original 1 m horizontal resolution DEM with ±12.5 cm vertical root mean square error (RMSE) was resampled using bilinear interpolation over 15 m to fill in missing data pixels using the 3D analyst toolbar and exported as a text file to calculate morphometrics (Fig. 3.1). Each transect was extracted perpendicular to the channel edge beginning at a minimum depth of -0.3 m NAVD88 and extending into the interior of the island. The final length of each transect used in the analysis was determined by defining the levee extent and then extending 100 m from the interior terminus of the levee (Fig. 3.3). Transects ranged from 121 to 356 m in length.

The shape of each of the cross-sectional profiles extracted from the LiDAR DEM was described using four morphometric variables. A similar method has been used for stream bank profiles in riparian restoration studies (Gurnell et al. 2006). The chosen morphometric variables included: (1) levee width, defined as the highest point along the transect and all adjacent points (measured every 1 m) on either side that were within 5 cm vertical elevation; (2) interior slope to
100 m, defined as the slope of the elevation gradient starting at the interior edge of the levee extending into the interior of the island 100 m; (3) total elevation range, defined as the difference of the highest and lowest elevation values on the transect; and (4) the mean elevation, the sum of each individual 1 m elevation value divided by the length of the transect (Fig 3.3).

**Statistical analyses and methods test using only surveyed transects**

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

**RESULTS AND DISCUSSION**

**Deltaic island chronosequence map**

A chronosequence map of the WLD was created, which illustrated the age range for all deltaic wetland area (Fig. 3.4). This map allows us to geographically visualize the planform development of the delta over time. Older areas, with subaerial establishment before 1990, are found in the upstream portion of the delta near the apex. This is consistent with jet plume deposit formation over time that was clearly laid out in Wellner et al. (2005) on which much of
Figure 3.3. Illustration of morphometric variables and how they were measured on an idealized deltaic island cross-sectional profile.

This map was based as well as models of shallow bayhead delta building (Wright 1977). The intermediate aged island areas were established between 1990 and 2000, and the young islands established between 2000 and 2012. This map allows us to select transects to test the hypothesis of consistent morphology change over island age, within a chronosequence framework of deltaic ecosystem development and gives a visual estimate of land building over time. The resolution and methods used to create this map do not allow for a quantitative estimate of land building rate, as has been done in other analyses of WLD and Atchafalaya delta (Allen et al., 2011; Majersky et al., 1997; Rouse et al., 1978).
Figure 3.4. Time period of land establishment at Wax Lake Delta, Louisiana; map includes current land extent as of 2012 and colors indicate the year at which land was first reported at or near subaerial, defined as above mean low water.

**Comparisons of cross-sectional island profiles**

The two-way nested MANOVA of cross-sectional morphometric parameters equal to the age and distance within age showed that age and distance within age were both statistically significant predictors of island edge cross-sectional morphology, as described by the four morphometric variables. For age the Wilk’s Lambda F statistic was 2.86 with a p-value of
<0.0001, and for distance within age, the Wilk’s Lambda F statistic was 1.29 with a p-value of 0.0361. This indicates that age is the strongest predictor of morphology, but that distance down island is also an important factor in describing island edge morphology. This is consistent with my initial hypothesis that morphology varied in a consistent way with age, but variation in morphology that occurs along the downstream axis of delta islands could also have strong control particularly on interior elevations, due to the widening and deepening of both interdistributary bays and troughs that has been described for this system (Shaw et al. 2016). This trend would be observed as greater steepness of interior slope with distance downstream.

Results of principal components analysis (PCA) of island cross-sectional morphometrics also support and illustrate that patterns that were tested in the MANOVA. When the multivariate morphometric data are plotted on the first two principal components, which account for a total of 87.5% of the variation (Fig 3.5), there is a pattern of increasing island age from right to left along the axis of PC1. There is greater spread throughout the distribution of the transects from locations of intermediate age (1995, 1998), but a clearer distinction between the oldest land (1973, 1983, 1990) and youngest (2002, 2008, 2012). This is likely due to the variable rates of geomorphic development throughout delta. It is also possible that this difference is related to the distance from the upstream end of the islands, which was found to be significant as a nested factor in the MANOVA. The morphometric parameters are plotted as lines on the PCA, and the parameter of interior slope increases in roughly the same direction as PC2. Therefore it is likely PC2, with 21.2% of the variation, is related to distance down the island, because this is the morphometric variable which varies the most in relation to the depth of the interdistributary bay which increase in depth in a downstream direction (Shaw et al., 2016).
Figure 3.5. Results of principal components analysis (PCA) of island cross-sectional morphometrics, each transect plotted on first two principal components which account for 87.5% of the variation. Colors and symbols correspond to year land was first reported subaerial see map Fig. 3.2. General trend of increasing age along first principal component, particularly with distinction between oldest land (1973, 1983, 1990) and youngest (2002, 2008, 2012); intermediate age land (1995, 1998) spread more evenly throughout distribution.

The timing of large river floods, which result in large accumulations of sediment, may also control the morphology of island edges and initiate morphologic development by changing the flat morphology of an island to the pronounced levee edge seen in intermediate age transects. Evidence for this comes from the field surveyed transects collected from 2008 to 2011. Transect D, which was first reported subaerial in 1995 (Fig 3.1 and Fig 3.3), exhibited flat low elevation with very little apparent levee, when it was first surveyed in the winter of 2008 (Fig 3.6A). As a result of the spring flood in 2008, which had the 8th highest water levels recorded for the Atchafalaya River at Simmesport, LA (USGS 07381490) between 1932 and 2015, rapid
elevation gain occurred across the transect (Fig. 3.6B). Over the subsequent years repeated sampling in both winter and summer showed small elevation gain across the entire transect but very little change in the overall morphology (Fig. 3.6C-G). In the spring of 2011 the 3rd highest water levels were recorded at Simmesport, LA in the last 83 years, resulting in very high water and sediment discharge in the WLD. As a result of this extremely large flood the overall morphology of this transect changed dramatically, the location of the channel edge was cut into the island by 80 m from its previous location, and a distinct high elevation levee was deposited (Fig. 3.6H). This shift from the relatively flat morphology of a younger deltaic island to that of an intermediate aged island occurred very rapidly as the result of a single large river flood in the spring of 2011. This evidence supports the role of large high energy river floods as a strong driver of island edge morphological development, therefore estimates of development over relatively short timescales as in WLD are also controlled by the frequency and timing of these types of events.

**Soil organic matter content relative to elevation**

There is a significant increase in percent OM in soils at locations with increasing elevation ($R^2=0.39$, p-value $< 0.00001$; Fig. 3.7). A pattern of higher OM content in wetland soils on older islands at WLD has been shown in other studies (Henry and Twilley, 2014; Shields et al., 2016). I observed high percent OM in soils at stations along transect E, which occurs near the upstream end of an older island. Also soils associated with higher elevation levees as in transects C and F had higher percent OM, however there was a distinct decrease in percent OM
Figure 3.6. Changes in transect D cross-sectional morphology over time, from winter 2008 through summer 2011. This period included 2 large river floods, in the spring of 2008 and 2011. It is apparent from the image as well as analyses in Chapter 2, that these large river floods resulted in large amounts of deposition along the island edge and that in 2011, seem to have changed the cross-sectional morphology from that of a younger island (flat and low) to that of an intermediate aged island (distinct high elevation levee).

at lower elevations in the island interiors of these transects (Fig. 3.7). Based on results of the seven field surveyed transects measured over 3.5 yr, it appears that percent OM content increases when elevation above about 0 m NAVD 88, this is above mean low water (MLW, about -0.04 m NAVD 88; Fig. 3.7). Increased percent OM within intertidal soils, compared to subtidal sediment indicates that there is a difference in either organic production and/or decomposition rates as well
as mineral sediment input. Differing rates of OM production could be related to a shift in
dominant vegetation community with increasing elevation which has been found to occur in
deltaic floodplain wetlands (Cahoon et al., 2011; Johnson et al., 1985; Shaffer et al., 1992).
However no work has yet shown differences in production rates between these communities, and
it is possible that if production rates are similar across vegetation communities that the
differences in the soil percent OM could be related to the lower input of inorganic sediment due
to less frequent flooding at higher elevations.

Transect E, which exhibited both higher elevation and soil percent OM in interior
wetland plots represents the later stage of island interior infilling (Fig. 3.8). This same
morphology can also been seen in the upstream most transect (I-I’) from Mike Island in the
conceptual model used to develop the hypotheses (Fig. 3.2). Based on observation of all four
years of the field survey data for transect E, the interior island elevations were persistent with
only small increases in elevation along the levee edge and some seasonal fluctuations in island
interior elevation (Fig 3.8). This transect located on an older upstream portion of an island is
consistent with the hypothesis based on my conceptual model of increasing elevation, organic
content and infilling of interdistributary bays with increasing island age. Based on the location
of transect E, which was reported as subaerial in 1990 (Fig. 3.1 and 3.3), I calculate that the
infilling and successional establishment of high elevation interior wetlands occurred rapidly
within fewer than 20 yr.
Figure 3.7. Plots of field surveyed transects from summer 2010, with sediment surface elevation over distance from channel edge (m), each plot where elevation was measured is represented by a black circle, the size of the circle is determined by the organic matter (OM) percentage measured from homogenized sample from the top 10 cm. Regression analysis of percent OM over elevation, showed a significant relationship with $p$-value < 0.0001, and an $R^2$ of 0.39.
Figure 3.8. Elevation profiles of transect E from all sampling years, winter and summer. This transect which has the highest overall elevation and organic matter, also has very persistent elevation across its entire length. Variation is only seen in limited instances such as a drop of about 10 cm measured in winter of 2011 at the second most interior plot, however this drop did not persist through the following summer. Also the large river flood that occurred in the spring of 2011 increased the elevation on the remaining channel edge plot.

Conceptual model of deltaic floodplain wetland development

The development of island edge morphology over time is consistent with the hypothesized conceptual model where the initial low elevation island edge with relatively flat morphology, increases in elevation over time, first with a more pronounced levee edge and then gradual infilling of the interior and interdistributary bay wetlands (Fig. 3.2). The result of my analyses illustrate that the infilling of island interiors and interdistributary bays in upper regions of islands is occurring over time and the concurrent increase in soil OM content, indicates that it is potentially driven by the ecological succession of deltaic island wetland vegetation communities. However, there is also an effect of distance from the upstream end of the island, which results in slightly different cross-sectional morphology that is determined by processes
other than age. This pattern is evident in field surveyed transects A and G, which have lower mean elevation and a narrower range of elevation than transects within the same age range found closer to the upstream ends islands such as C and F (Fig. 3.7). This is likely related to the depositional dynamics of the jet plume delta formation where courser sediments are deposited at the upstream ends of jet deposits and finer grain further downstream (Wellner et al., 2005). As the distributaries continue downstream, the islands widen and interdistributary bays are deeper, which results in a steeper interior slope for island edge cross-sections that are located further downstream. The effect of both gravitational and metrological tidal exchange that occurs over the relatively low levees and the open distal ends of the interdistributary bays may serve to resuspend fine grain sediments and limit elevation gain (Hiatt et al., 2010). My experimental design limits any perspectives about how vegetation community change may increase accretion in island interiors, however I have seen evidence that there is an increase in percent OM in older and higher elevation islands (Fig 3.7). Deltaic vegetation zonation is strongly controlled by elevation (Cahoon et al., 2011; Johnson et al., 1985; Shaffer et al., 1992). Therefore, I can only hypothesize that infilling is at least partially controlled by increased organic accretion in interior wetlands resulting from a positive feedback of increasing elevation resulting in a successional shift toward vegetation communities that have higher below ground production rates. Deltaic floodplain wetland vegetation communities in WLD have been shown to exhibit a shift in dominant species assemblage at soil surface elevations between MLW and mean sea level (MSL), in which lower elevation sub/intertidal communities composed of *Nelumbo lutea*, *Sagittaria platyphylla*, and *Potamogeton nodusus*, transition to a dense emergent community dominated by *Colocassia esculenta* at higher intertidal and supratidal elevations (Chapter 4). It is possible that the morphological and functional differences between these dominant species could
result in differing rates of belowground production, therefore controlling the percent OM that is sequestered in wetland soils at different elevations.

**Implications for coastal restoration**

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

**CONCLUSIONS**

1) There was a clear statistically significant pattern in the cross-sectional profile shape of deltaic island edges over time. This pattern resulted from a gradual increase in overall elevation, establishment of a distinct high elevation levee edge with steep interior slope, followed by gradual infilling of the interior until similar elevation to the levee edge is achieved.
2) The distance from the upstream end of the islands also had an effect on the shape of the island cross-sectional profile, with steeper interior slopes occurring in more downstream portions of the delta where the interdistributary bay is deeper.

3) Percent organic matter content showed a significant positive trend with higher elevations, which also corresponded to older deltaic island areas, however the mechanism of this has not been determined.

4) These results are consistent with the hypotheses in my conceptual model of deltaic island edge development with age, however I do not know if these results hold for other deltas or how the island edge morphology will shift with increasing development of the delta. Will infilling be limited to the upper narrower portions of deltaic islands or will it continue downward over time filling the majority of the interdistributary bay? Is there an elevation at which organic accretion becomes the main factor controlling elevation gain? Answering these question using WLD and other systems as experimental models will help to build and refine my understanding of prograding deltaic island development.

**LITERATURE CITED**


CHAPTER 4. DELTAIC FLOODPLAIN WETLAND VEGETATION COMMUNITY COMPOSITION AND RESPONSE TO HURRICANE STORM SURGE AND A LARGE RIVER FLOOD

INTRODUCTION

Wetland loss, i.e. the conversion of land to open water, within deltas worldwide is occurring as a result of both natural processes such as subsidence and river avulsion, as well as human induced changes to sediment and water supply and delivery (Day et al., 2008, 2007; Syvitski and Milliman, 2007; Syvitski, 2008; Syvitski et al., 2009; Vörösmarty et al., 2009). The types of coastal wetlands that occur in deltas vary as a result of regional climate and oceanic influence (Twilley et al., 1998). Often there are local differences in the vegetation communities which occupy areas representing differing stages within the delta cycle (Nyman 2014, Sasser et al. 2014). As deltas prograde they are generally dominated by allochthonous freshwater and mineral sediment inputs brought in from outside of the system. Once the delta has expanded to a point that it is no longer hydrologically efficient, the river will avulse toward a shorter more direct route to the sea. When an avulsion occurs, wetlands in the previously active deltaic floodplain are essentially disconnected from most or all of the mineral sediment and freshwater provided by the river, initiating the degradation stage of delta cycle. These wetlands often continue to accrete and persist, despite continued subsidence, through the accumulation of autochthonous organic sediments. The vegetation communities found in both aggradational and degradational stages of the delta cycle often contain many of the same species, however the vegetation community composition and structure as well as its ability to withstand disturbance
are often quite different (Cahoon, 2006; Chabreck and Palmisano, 1973; Morton and Barras, 2011, Sasser et al. 2014).

Here I define deltaic floodplain wetlands as those wetlands that are forming or have formed in the active delta that is connected to and receives periodic overbank flow from an adjacent river. This definition is based on the proposed analogous function of wetlands along a continuum from riparian floodplain wetlands to deltaic floodplain wetlands. I make the important distinction between wetlands in the delta plain that have been disconnected from active riverine influence, by both natural and constructed process (i.e. the flood control levees along the lower Mississippi River) and those that still experience overbank flow, even if it is limited to only very high river stage. Historically the Mississippi River Delta (MRD) had a much greater expanse of active deltaic floodplain wetlands, as there is evidence that during high flow river water was spread across much of the delta plain (Coleman and Gagliano, 1964; Condrey et al., 2014; Roberts and Coleman, 1996). Today the main channel of the lower Mississippi River is highly controlled with overbank flow limited to the extreme lower end of the Balize Delta, and along the major distributary the Atchafalaya River, with overbank flow into both the surrounding riparian basin and the wetlands within and surrounding the Atchafalaya and Wax Lake Deltas (Allison et al. 2012).

Current restoration plans and strategies in coastal Louisiana include the use of more river diversions to be constructed with the intent to deliver high sediment loads as well as river water into more areas of deltaic wetlands. Reintroducing water and sediment into these wetlands will help to offset the subsidence and sea level rise that is contributing to land loss (CPRA, 2012; Nyman, 2014; Paola et al., 2011). Sediment delivery diversions into areas of open water also
have the capacity to build new land and increase wetland area through deposition of mouth bars and eventual establishment of deltaic islands (Kim et al., 2009; Roberts et al., 2003; Rouse et al., 1978). Previous work has helped to define and clarify the expected vegetation community that will occur on prograding deltaic islands in regard to the composition, zonation and ecological processes (Cahoon et al., 2011; DeLaune et al., 1987; Johnson et al., 1985; Rejmanek et al., 1987; Shaffer et al., 1992; Visser, 1989; White and Visser, 2016; White, 1993). Much early work focused on gaining an understanding of the community structure in the Atchafalaya, Wax Lake and Balize Deltas of the Mississippi River system in the early and mid 1980s. Recent updates to this work from the Balize delta indicate that there may have been a shift in community composition to the invasive phenotype of *Phragmites australis* in 2008 (White and Visser, 2016). Other shifts in dominance from species described in the earlier work have also occurred in the Wax Lake and Atchafalaya Deltas, where *Sagittaria latifolia* is no longer dominant and *Sagittaria platyphylla* and increasingly *Nelumbo lutea* have taken its place (Carle et al. 2014, Sasser et al. 2014). It is clear that periodic surveys of the deltaic floodplain wetland vegetation community are needed to understand shifts over time, over elevation and in response to stochastic disturbances, such as hurricanes and large river floods.

Understanding and quantifying the effects of hurricane storm surge on deltaic floodplain wetlands has been an active area of research and discussion, especially in reference to the effects of the additional delivery of freshwater, nutrients and sediment associated with diversions in the Mississippi River Delta (MRD). In particular the discussion has focused on how diversions will affect deltaic floodplain wetlands resilience to hurricane storm surge damage (Howes et al., 2010; Kearney et al., 2011). It has been reported that freshwater wetlands are more susceptible to hurricane damage compared to other wetlands types. For example, Howes et al. (2010) conclude...
that “Low salinity wetlands were preferentially eroded, while higher salinity wetlands were more resilient.” This is an inaccurate oversimplification and should have been qualified as to the type of deltaic freshwater wetland to which they refer (i.e. mineral or organic soil). This illustrates an important distinction which has been lost in much of the discussion in the literature, in regard to the differing responses of deltaic freshwater wetlands with highly mineral soils (low organic content) compared to those with highly organic soils (low mineral content). These two types of freshwater wetlands, while they often have similar species composition (Sasser et al. 2014), have very different responses to hurricane storm surge. A survey of the effects of Hurricane Camille in 1969 on freshwater deltaic wetlands in the Mississippi River Balize Delta indicated that while removal of aboveground vegetation cover occurred in the highly mineral soil wetlands, they recovered rapidly and within one growing season had regained much of their vegetation cover (Chabreck and Palmisano, 1973). Using remotely sensed imagery over the past 50 years in coastal Louisiana, Morten and Barras (2011) found that highly visual features, such as ponding, compression, plucked marsh, shoreline erosion and displaced marsh mats and balls, tend to occur more frequently in wetlands with highly organic soils, which often results in a greater focus on reporting hurricane effects in these types of wetlands, and less focus on wetlands with mineral soils (Morton and Barras, 2011). Following Hurricanes Katrina and Rita, a preliminary analysis of land loss did identify impacts within wetlands with high mineral soil; however, they acknowledge that it was likely a result of aboveground vegetation removal, not the conversion of wetlands to water. They acknowledge that to confirm permanent land loss in this type of wetland would require sampling over a number of growing seasons following hurricane passage (Barras, 2007; Morton and Barras, 2011). The preliminary land loss estimate following Katrina and Rita reported by Howes et al. (2010) as being permanent, misrepresents the resiliency of
freshwater wetlands to recover from hurricanes, given that no additional analysis of land cover change were investigated in those high mineral soil freshwater wetlands in subsequent years. In a later analysis by Carle et al. (2016) the resilience of the vegetation community in prograding deltaic floodplain wetlands with soils of high mineral content was assessed following a number of hurricanes. They found that while there was a significant reduction in vegetation cover, measured by normalized difference vegetation index (NDVI), a return to pre-disturbance cover was achieved by the end of the following growing season (Carle and Sasser, 2016). Many of these previous studies have used remotely sensed imagery to analyze overall wetland vegetation cover in response to tropical cyclones. However, in order to gain a more accurate understanding of the effects of storm surge on wetlands, field surveys of individual species cover and analysis of community composition should be completed as well to determine if the same vegetation community composition is present following the storm as was there pre-disturbance. Therefore the addition of individual vegetation species cover analysis prior to a disturbance and for a number of years following hurricane storm surge disturbance would yield insights into the effects on vegetation community dynamics.

Here I used five years (2007 to 2011) of herbaceous wetland vegetation species cover data collected at peak season biomass in the actively prograding Wax Lake Delta (WLD) to determine and define unique species assemblages relative to the tidal range as well as quantify the response and recovery of the vegetation community following the passage of Hurricanes Gustav and Ike in September 2008. This study utilized a long-term repeated sampling experimental design by which I was able to capture the effects of major hydrologic forcings, such as river floods and hurricanes. Similar long-term transect studies have been completed in the Atchafalaya and Balize Deltas, but had not been previously reported for WLD, which
represents a valuable analogue to a naturally forming delta with minimal dredging and hydrologic manipulation (Cahoon et al., 2011; Johnson et al., 1985; Shaffer et al., 1992; White and Visser, 2016; White, 1993). I recorded individual species vegetation cover one year prior, immediately following the storms and the three years following. While my dataset covers five years, I was not able to make conclusions related to questions of overall vegetation community succession over a long-term timescale due to the disturbance effect of the hurricanes in 2008. These types of studies would need to be done over longer time periods to lessen the importance of stochastic events such as hurricanes and large river floods in determining community composition (White and Visser, 2016). I also investigated the connection between elevation change and observed expansion of the large emergent species *Nelumbo lutea* between the years 2010 and 2011, as this was reported in a previous study to be a response to increasing elevation resulting from the 2011 flood (Carle et al., 2011). I hypothesized that the observed expansion of *N. lutea* was not related to elevation change, as it is unlikely that *N. lutea* was limited in its prior extent by water depth.

**METHODS**

**Site description**

The WLD is prograding into the Atchafalaya Bay at the mouth of the Wax Lake Outlet (WLO), a constructed distributary channel of the Atchafalaya River first opened in 1941 (Fig. 4.1). The water discharge into the Atchafalaya River is maintained at 30% of the combined flows of the Mississippi and Red Rivers, and is controlled by the Army Corps of Engineers at the Old River Control Structure (ORCS). The WLD is a young delta in which prodelta deposits and subaqueous expansion were first observed in 1952 and small subaerial bars first appeared in
Figure 4.1. Site map of Wax Lake Delta, LA, locations of vegetation survey transects indicated by black line and letters, elevations indicate land surface elevation relative to tidal range reported for nearby NOAA Amerada Pass Gauge 8764227. Tracks of Hurricanes Gustav and Ike are shown on map of Northern Gulf of Mexico.
1973, and increased rapidly following high river flooding and infilling of shallow lakes upstream and adjacent to the WLO (Roberts and Adams, 1980; Wellner et al., 2005). Due to its unique occurrence as a constructed river outlet that has been allowed to build land under natural hydrologic conditions, this system represents an extremely valuable analogue to many MRD coastal restoration strategies, which propose diverting river water and sediment into shallow coastal basins to reduce present wetland degradation rates (Parker and Sequeiros 2006; Kim et al. 2009; Allison and Meselhe 2010; Paola et al. 2011; CPRA 2012). The wetland soils of the WLD tend to be low in organic content, with a high proportion of mineral sediment, primarily fine sand and silt (Delaune et al. 2016). The deltaic floodplain wetland vegetation consists of woody, shrub/scrub and herbaceous fresh marsh species that tend to exhibit zonation along the elevation gradient (Visser, 1989). Similar vegetation patterns have also been documented in the Atchafalaya Delta (Johnson et al., 1985; Shaffer et al., 1992). However there is also a high degree of patchiness and heterogeneity in community zonation, and the degree to which elevation controls zonation and community composition throughout the delta is not well understood.

Field sampling

Beginning in August 2007 and continuing annually until August 2011, surveys of vegetation percent cover were conducted at peak biomass in August or early September. In 2008 the surveys occurred following the passage of Hurricanes Gustav and Ike in September 2008, and therefore provide a quantitative measure of the pattern of effects of hurricane storm surge passage on freshwater deltaic wetlands. I also measured sediment surface elevation during the 2008 through 2011 surveys at each sampling plot. Initial sampling was conducted at 871 m²
plots along seven transects, for a total length of 1,950 m. In subsequent years a few plots were lost to erosion particularly along the channel edge and in 2011 transect F was lost due to erosion of the benchmark and was not sampled. Transects were established starting at the distributary

Table 4.1. Length of elevation survey transects, with location of first plot (located closest to channel edge) all transects extended into island interior perpendicularly to channel edge.

<table>
<thead>
<tr>
<th>Transect ID</th>
<th>Latitude (decimal degrees)</th>
<th>Longitude (decimal degrees)</th>
<th>Total length (m)</th>
<th>Number of sampling plots</th>
<th>Mean soil bulk density (g cm$^{-3}$)</th>
<th>Mean soil percent organic matter</th>
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<tr>
<td>A</td>
<td>29.49560</td>
<td>-91.44735</td>
<td>360</td>
<td>11</td>
<td>0.84 ± 0.05</td>
<td>4.46 ± 0.32</td>
</tr>
<tr>
<td>B</td>
<td>29.50113</td>
<td>-91.45125</td>
<td>400</td>
<td>13</td>
<td>0.93 ± 0.02</td>
<td>3.21 ± 0.32</td>
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<tr>
<td>C</td>
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<td>-91.44493</td>
<td>160</td>
<td>13</td>
<td>0.82 ± 0.05</td>
<td>4.47 ± 0.41</td>
</tr>
<tr>
<td>D</td>
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<td>-91.47941</td>
<td>380</td>
<td>13</td>
<td>1.01 ± 0.05</td>
<td>2.81 ± 0.27</td>
</tr>
<tr>
<td>E</td>
<td>29.51151</td>
<td>-91.43311</td>
<td>130</td>
<td>10</td>
<td>0.60 ± 0.04</td>
<td>7.82 ± 1.1</td>
</tr>
<tr>
<td>F</td>
<td>29.50315</td>
<td>-91.43520</td>
<td>230</td>
<td>15</td>
<td>0.83 ± 0.04</td>
<td>4.59 ± 0.47</td>
</tr>
<tr>
<td>G</td>
<td>29.49283</td>
<td>-91.44085</td>
<td>290</td>
<td>12</td>
<td>1.11 ± 0.06</td>
<td>2.83 ± 0.42</td>
</tr>
</tbody>
</table>

channel edge and extended into the interior of the deltaic island to capture the geomorphic cross-sectional gradient. The number of 1 m$^2$ sampling plots per transect ranged from 9 to 14, distance between plots was 10, 20 or 40 m, and total transect lengths ranged from 130 to 400 m (Table 4.1). The spacing and length of transects was variable to accommodate the elevation gradient at each transect location. The distribution of sample plots along all transects throughout the WLD was consistent across years, however it was somewhat skewed to higher elevations compared to the histogram of the entire WLD elevations (Figure 4.2). There was also an unintentional gap in sampling plots at about 0.2 m NAVD in all years, which was not reflected in the delta-wide distribution of elevations.
During each survey I measured the vegetation cover by visual estimation in a 1 m² quadrat and recorded replicate sediment surface elevation measurements in the same 1 m² plot. Sediment surface elevation was measured using a Class I laser level (Sokkia LP30A) and detailed methods were previously reported in Chapter 2. The vegetation percent cover was recorded for all herbaceous emergent, floating leaved and submerged vegetation. The presence of *Salix nigra* overstory was also noted during the first and last year of sampling. Nomenclature follows U.S. Department of Agriculture National Resources Conservation Service Plants Database (USDA 2016). Soil samples were also collected to 10 cm depth during February 2009 at each sample plot and analyzed for bulk density and percent organic matter using loss on ignition, for methods details see Chapter 3.

**Data processing**

Cover values in percent for all species found over the five years of sampling (33 species) were used in multivariate analyses of community composition. Quadrats that were recorded as completely bare were removed from multivariate analyses as were floating species *Eichornia crassipes* and *Salvinia minima*. Dominant species were defined as those that accounted for greater than 20% cover in at least two quadrats over all the sampling years.

The sediment surface elevations were measured concurrently with the 2008-2011 vegetation sampling, however they were not recorded in August of 2007. In order to estimate an elevation for each plot in 2007, I used an elevation survey that was conducted six months later in February 2008, which was part of a related project to measure the seasonal elevation change (Chapter 2). Therefore using the results of that study, which concluded that the mean elevation change that occurred between late summer and late winter over four years was a loss of 2 cm, I
estimated the August 2007 elevations by subtracting 2 cm from the February 2008 elevation survey. Where these data are used it is clearly stated that they are the estimated elevations that correspond to the vegetation not the actual measured elevations as in the other years.

Statistical analyses

For analysis of the change in individual species cover over time only dominant species were used. The mean cover values for all twenty two dominant species, were calculated for each year over all elevations. The ten dominant species with the highest mean cover were reported, the mean of the twelve lower abundance species were group together and reported as ‘other’. All multivariate analyses of species community cover were completed in PRIMER 7 (PRIMER-E Ltd. Plymouth, UK). All species were included for analyses with completely bare plots removed. The Bray-Curtis Similarity Matrix was calculated between all samples using square root transformed cover values. This is a measure of the degree of similarity between each set of samples and ranges from 0, indicating no species in common, to 100 when species are identical in cover (Clarke et al., 2014, 2006). Based on this matrix, hierarchical agglomerative clustering using group-averaging was conducted and resulted in dendrograms of the similarities between samples. In order to test the significance of these sample groups, the similarity profile (SIMPROF) type 1 permutation test, at \( \alpha = 0.05 \), was used. The SIMPROF type 1 test identified statistically significant structure, defined by more positive and negative associations than would be expected by random chance in samples in which \( a \ priori \) structure does not exist (Clarke et al., 2008, 2014). In the case of my analyses, elevation values of each plot were not included in any of the multivariate analyses and were only analyzed after the species assemblages and sample groups were identified. This allowed me to avoid bias of my interpretation of
assemblages by placing arbitrary cutoffs on elevation, which can occur by binning (Clarke et al., 2014; Somerfield and Clarke, 2013). It also avoids the assumption that elevation is the only factor controlling vegetation assemblages and allows for identification of significantly different assemblages or groups which occur at the same elevation, therefore highlighting instances where other factors may be controlling community structure.

A matrix based on the Index of Association for all species was also calculated using PRIMER 7. The Index of Association, measures the degree of association for all species in the dataset across all samples, it takes the value 100 when two species have exactly the same percentage cover pattern across all samples, a full positive association, and the value zero when they are never found in the same samples, a full negative association (Clarke et al., 2014; Somerfield and Clarke, 2013). From the Index of Association matrix hierarchical agglomerative clustering using group-averaging was run to create a dendrogram of assemblages of individual species for each year. The type 2 and 3 SIMPROF permutation tests were used to look at the significance of the dendrogram species assemblages in order to test for significance at $\alpha = 0.05$ (Clarke et al., 2014; Somerfield and Clarke, 2013). The type 2 SIMPROF tests whether species are associated with one another. If the species are not associated and they vary independently of one another, this test will not be significant and therefore any further analysis of species assemblage structure is invalid. However, if the type 2 SIMPROF does report a significantly different association profile from what would be expected by the null hypothesis then it is valid to proceed to investigate further structure within the species assemblages (Clarke et al., 2014; Somerfield and Clarke, 2013). The type 3 SIMPROF allows for further analysis if the null hypothesis for the type 2 SIMPROF is rejected. In which case the type 3 SIMPROF allows for an analysis of which species are associated with one another. This analysis, is run on results of the
hierarchical agglomerative clustering, in this case the dendrogram of Index of Association (Clarke et al., 2014; Somerfield and Clarke, 2013).

The results of the dendrograms created from the Bray-Curtis Similarity matrix and the Index of Association matrix as well as all SIMPROF tests were used to create a shade plot of species cover values for all species in all sample plots for each year. The individual samples were ordered along the x-axis, in order of increasing elevation of each sample plot, while still constraining the samples within the dendrogram framework. This allowed for the visualization of community composition trends along the elevation gradient (Clarke et al., 2014). The surface elevation mean and range of each significant sample group was also plotted above the x-axis dendrogram. Analysis of variance (ANOVA) using Proc Mixed in SAS (SAS Institute, Cary NC, USA) was used to test for differences in the mean elevations for each significant sample group for each year at an $\alpha = 0.05$; single samples not in a group were excluded. The hypothesized relationship between elevation change and $N. \text{lutea}$ expansion was tested using a t-test of the mean elevation change for plots in which $N. \text{lutea}$ persisted, compared to plots in which it expanded from 2010 to 2011.

RESULTS

Distribution of vegetation cover and bare plots

Only two fully bare plots were observed along the transects in 2007, while in 2008, immediately following hurricanes Gustav and Ike, there were 65 bare plots, with the only remaining vegetated areas at high elevations (Fig. 4.2). In 2009, 2010, 2011 the number of bare plots had decreased, with 13, 2, and 6 respectively in each of those years. The mean bare area
Figure 4.2. Frequency distribution of sample plots across elevation for all years, with elevation distribution for the entire Wax Lake Delta at the top. Completely bare plots are indicated by gray and vegetated plots as black. *2007 elevations were not measured at time of vegetation survey and were estimated from an elevation survey completed six months later, with a correction of -0.02 m applied.
within vegetated plots was also greatest in 2008, compared to all other years and was greater in all years following the storm than in 2007 (Fig. 4.3). *Salix nigra* (black willow) overstory was observed at eight plots, located on the supratidal levees of transect C and E. All plots where *S. nigra* occurred were located at elevations greater than 0.25 m NAVD 88 during all sampling years, and the herbaceous understory was dominated by *C. esculenta* and *Polygonum punctatum* in all cases.

**Mean cover of dominant species over time**

A comparison of the mean percent cover for the ten major dominant species indicated that in 2007 the distribution of cover along the transects was more evenly spread amongst species (Fig. 4.3). Following the hurricanes in 2008, *C. esculenta* and *A. philoxeroides* and *S. americanus* were able to persist that year despite the storm surge and remained an important component of the vegetation composition. In contrast, *N. lutea*, *S. platyphylla*, *P. nodosus* and SAV were completely removed by the storm surge, but were able to rebound in the following years. *S. platyphylla*, *P. nodosus* and SAV recovered within one year, while *N. lutea* recovery was slower, with major recovery occurring in 2010, two years after the hurricanes. By 2011 the mean cover of *N. lutea* was much greater than *S. platyphylla*, *P. nodosus* and SAV (Fig. 4.3).

**Vegetation species assemblages and the response to hurricane disturbance**

The significant species assemblages that resulted from the Index of Association analysis and SIMPROF type 3 tests, differ in level of complexity before and in the years following the hurricanes (y axis in Fig. 4.4a, b, c, d). In 2007 there were four distinct species assemblages (Fig 4.4a. delineated by thick black line on the y-axis dendrogram). The significant species
assemblages indicate species that are found together more consistently than would occur randomly (Clarke et al., 2014). The significant sample groups, which were determined by the SIMPROF type 1 test, are constrained by groups but also plotted in order of increasing elevation (Fig. 4.4a, delineated by thick black lines x-axis dendrogram). This allows for the pattern of community composition with elevation (defined by both significant species assemblage and significant sample groups) to be represented by the shade plot. The means and range of elevations for each of the significant sample groups are plotted at the top of the x axis (Fig. 4.4a).
The sample groups (x-axis) which most closely correspond to each species assemblage (y-axis) are colored accordingly in all shade plot figures. In 2007 the lower elevation assemblage (blue) encompassed five different significant sample groups, while the higher elevation assemblage (red) is composed of only one sample group. This indicates that the complexity of the community composition was greater in the lower elevation assemblage. The result of the ANOVA of the means of elevation of each significant sample group (significant difference denoted by letters in top graph above x-axis) was that there were distinct elevations between groups ($F_{8,71}=25.96, p<0.0001$). The high elevation assemblage, which is dominated by *C. esculenta*, had a significantly higher mean elevation than all but one of the other groups, while the groups that make up the other three assemblages had elevation means that are not significantly different. This indicates that while there was variability in sample community compositions, elevation was not the main controlling factor and that there are additional factors influencing community composition, such as competition or herbivory. The bars around the mean elevations represent the entire elevation range over which the samples in that group occurred (Fig. 4.4a). Based on these ranges, the highest elevation species assemblage, dominated by *C. esculenta*, and *P. punctatum* was found to occur primarily at or above mean sea level (MSL). While the other species assemblages occurred close to or below MSL. The species assemblage characterized by *A. philoxeroides* and *H. dubia* (yellow) occurred close to MSL, while the others, one dominated by *S. americanus* and *S. latifolia* (green) and the other by *S. platypylla, N. lutea* and *P. nodosus* (blue), occurred at slightly lower elevations closer to MLW and below.

In 2008 Hurricanes Gustav and Ike, resulted in storm surges of 0.53 m and 0.91 m over predicted water levels, respectively based on NOAA Amerada Pass Gauge 8764227, located
about 10 km east southeast of the WLD. Immediately following the passage of these storms the majority of the aboveground cover below MSL was completely wiped out (Fig. 4.4b). Only two species from the lower elevation species assemblage that was observed in 2007 (Fig. 4.4a, blue) were seen in 2008, *N. lutea* and *S. platyphylla*, and each was only reported once (Fig. 4.4b). The remaining vegetation was found mainly at higher elevations, with *S. americanus* and *C. esculenta* dominating. The higher elevations received less overtopping by the storm surge, which likely contributed to the lower loss of aboveground cover. The SIMPROF type 1 and type 2 resulted in no significant species assemblages or sample groups for this year due to the extremely limited vegetation cover following the hurricane storm surge disturbance.

Recovery of much of the low elevation species assemblage was observed in 2009, one year after the hurricanes (Fig. 4.4c y-axis). There were two significant species assemblages, one at higher elevations dominated by *C. esculenta* (red) and the other at lower elevations dominated by *S. latifolia*, *P. nodosus* and SAV (blue). *N. lutea* was not included in either of the species assemblages. Overall the *N. lutea* cover was very low following the storms and the few locations it was observed were at higher elevations than it was found at in 2007. The lower elevation assemblage had only one significant sample group in 2009 (x-axis Fig. 4.4c). This was a very different pattern than was seen in this assemblage in 2007, when there were five distinct sample groups indicating distinct community composition (x-axis Fig. 4.4a). It is likely that immediately following the storm surge disturbance when the available habitat within this elevation range was wide open, species were able to colonize areas more freely resulting in a lack of complexity in the community. The results of the one-way ANOVA showed that sample group had a significant effect on the elevation means ($F_{3,64}=31.18$, and p-value $<0.0001$). However all three sample groups in the high elevation assemblage had elevation means that were not significantly different
from one another, while the lower elevation assemblage was significantly different (top x-axis, Fig. 4.4c).

In 2010, two years after the hurricanes, there were still only the two major species assemblages present (y-axis, Fig. 4.4d). The species previously found in the intermediate elevation assemblages in 2007, \textit{S. latifolia} and \textit{S. americanus}, were included in low elevation species assemblage in 2010 (blue). Much more complexity was seen in community structure of the low elevation species than in the previous year, with six significant sample groups. Only one sample group occurred in the higher elevation species assemblage (red) in 2010, a return to the same pattern as 2007. The ANOVA identified that there was a significant difference in elevations by sample group as in the previous years ($F_{7,29}=22.42$, $p<0.0001$). With the main differences in mean elevations of sample groups (denoted by letters) seen between the high elevation species assemblage group (red) and all the groups in the low elevation species assemblage (blue). The low elevation sample groups in blue exhibited very little difference in mean elevation between themselves, similar to the pattern seen in 2007 (Fig. 4.4a). While still lacking distinct intermediate elevation species assemblages, the community structure seemed to be returning to what it was in 2007.

In 2011, three years post-hurricanes, there were still only two distinct assemblages with very similar community structure to 2010, the intermediate elevation species (Fig. 4.4e). \textit{S. latifolia} and \textit{S. americanus} that were present in previous years were not observed in the sample plots in 2011. The test of the effect of sample groups on mean elevation was again significant ($F_{6,49}=19.53$, $p<0.0001$) with very similar results to previous years, in that the high elevation group was significantly different from the other groups which were not different from each other.
There was an increase in the elevations at which the low elevation assemblage occurred compared to previous years, with maximums near and above mean high water (MHW). In the spring of 2011 the 3rd highest river discharge of the last 80 years occurred on the Atchafalaya River. The occurrence of species at higher elevations may be related to the sediment deposition that was observed during this flood, where individual species did not expand into areas of higher elevation, but the sediment surface elevation of each plot increased around them due to deposition from the flood. (Chapter 2).

I investigated this process in more detail for *N. lutea*, the expansion of which has been suggested could serve as a proxy for measuring elevation gain (Carle et al., 2011). I found that there were six plots where *N. lutea* expanded between 2010 and 2011, however there was not a trend in elevation change within these plots, which ranged from -0.07 to 0.06 m, with a mean of 0.02 m in elevation change between August 2010 and August 2011 (Table 4.2). There were also four plots where *N. lutea* persisted between those years, one of which experienced 37 cm of sediment surface elevation change. While this amount of elevation change can easily occur from a large flood it is generally only over a small area and therefore this plot was removed from further analyses as an outlier. The elevation change in the remaining plots where *N. lutea* persisted ranged from -0.03 to 0.06 m and also had a mean of 0.02 m (Table 4.2). In one plot where *N. lutea* occurred in 2010 it was no longer found in 2011. A t-test did not indicate a significant difference between the means of the plots where *N. lutea* expanded or persisted.
Figure 4.4. Shade plots for each sampling year, shading in grid represents the square root transformed cover for each species listed (shown in y-axis) in each sample plot (x-axis). The dendrograms on each axis of the shade plot represent the results of the hierarchical agglomerative cluster analysis based on the Bray-Curtis Similarities for sample plots (x-axis) and based on the Index of Association for the species (y-axis).
(Figure 4.4 continued)

**D. 2010 two years post-Hurricanes Gustav and Ike**

Mean and range of elevation for each sample group

Sample groups based on Bray-Curtis similarity matrix

Species assemblages based on index of association

**E. 2011 three years post-Hurricanes Gustav and Ike, year of large spring river flood**

Mean and range of elevation for each sample group

Sample groups based on Bray-Curtis similarity matrix

Species assemblages based on index of association
DISCUSSION

Species assemblages

Based on the results of the Index of Association analysis for all four years, there were two consistent species assemblages, which persisted from 2007 through 2011. The higher elevation species assemblage (red Fig. 4.4) was dominated by *C. esculenta* and *P. punctatum*, and was generally found to be homogenous in community structure, with very little complexity in sample groups. It is likely that this is primarily due to the highly competitive *C. esculenta*, which is an introduced invasive (Moran and Yang, 2012). Early studies on the Atchafalaya indicated that the higher elevation communities with more numerous native species were common (Johnson et al., 1985; Shaffer et al., 1992). However *C. esculenta* expansion seems to have occurred starting in the mid-1980s (Rejmanek et al., 1987). I defined the range of this species assemblage by the lowest elevation at which it occurs, close to MSL and refer to it as the High Intertidal/Supratidal (HIS) community. Based on my analysis the range over which the HIS assemblage occurs at WLD is 0 to 0.55 m NAVD 88 (Fig. 4.5). The other persistent species assemblage found in the study sites occurred at lower elevations, ranging from -0.47 to 0.32 m NAVD88, therefore I will refer to this one as Lower Intertidal/Subtidal (LIS). This assemblage is dominated by the emergent species *N. lutea*, *S. platyphylla*, and the floating leaved *P. nodosus*. The LIS assemblage had a more heterogeneous community structure, and exhibited significant differences between sample groups within the assemblage that was not explained by elevation. This indicates that there were likely other factors (i.e. competition and herbivory) controlling the vegetation community composition within individual samples. The LIS community complexity was reduced in 2009 in the year following the hurricane but was reestablished in 2010 and 2011.
<table>
<thead>
<tr>
<th>Nelumbo lutea cover 2010 and 2011</th>
<th>Vegetative cover 2010</th>
<th>Vegetative cover 2011</th>
<th>Sediment surface elevation (m NAVD88)</th>
<th>Elevation change 2010 to 2011 (m)</th>
<th>Mean elevation change (± SE m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expanded</strong></td>
<td></td>
<td></td>
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<tr>
<td>A2</td>
<td>50% Sagittaria platyphylla, 20% Sagittaria latifolia,</td>
<td>50% N. lutea, 30% S. platyphylla, 5% Ludwigia sp.</td>
<td>0</td>
<td>0.06</td>
<td>0.06</td>
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<td>B7</td>
<td>25% S. platyphylla, 25% Schoenoplectus americanus</td>
<td>5% N. lutea, 25% S. platyphylla,</td>
<td>0.11</td>
<td>0.09</td>
<td>-0.02</td>
</tr>
<tr>
<td>B8</td>
<td>35% S. platyphylla, 35% S. americanus</td>
<td>65% N. lutea, 25% S. platyphylla,</td>
<td>0.03</td>
<td>0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>B9</td>
<td>50% S. platyphylla</td>
<td>40% N. lutea, 15% S. platyphylla, 10% N. lutea,</td>
<td>0.02</td>
<td>0.07</td>
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<td>70% S. platyphylla</td>
<td>10% N. lutea, 75% Heteranthera dubia,</td>
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<td>85% N. lutea, 5% S. platyphylla,</td>
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<td>0.03 ± 0.03 0.05 ± 0.04</td>
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<td></td>
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<tr>
<td>A3</td>
<td>50% Sagittaria platyphylla, 25% N. lutea, 1% SAV</td>
<td>80% N. lutea, 10% S. platyphylla, 5% Ludwigia sp.</td>
<td>0</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>A4</td>
<td>70% N. lutea, 15% S. platyphylla, 5% S. latifolia</td>
<td>80% N. lutea, 5% S. platyphylla, 5% SAV</td>
<td>-0.02</td>
<td>0.01</td>
<td>0.03</td>
</tr>
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<td>B3</td>
<td>40% S. platyphylla, 15% N. lutea</td>
<td>30% N. lutea, 5% Ludwigia sp.</td>
<td>0.1</td>
<td>0.47*</td>
<td>0.37*</td>
</tr>
<tr>
<td>B13</td>
<td>40% S. platyphylla, 5% N. lutea</td>
<td>65% Sagittaria platyphylla, 10% N. lutea,</td>
<td>-0.03</td>
<td>-0.06</td>
<td>-0.03</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.01 ±0.03 0.00 ±0.03*</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>C9</td>
<td>95% SAV, 50% N. lutea</td>
<td>5% Ludwigia sp.</td>
<td>-0.04</td>
<td>0.04</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 4.2. Nelumbo lutea persistence and expansion plots between 2010 and 2011. *Outlier removed for statistical analysis.
The LIS and HIS species assemblages occur within unique elevation ranges, however there is overlap between them at intermediate elevations, between about MLW and MHW (Fig. 4.5). In this intertidal zone, variability in flooding frequency and duration does not allow for either species assemblage to dominate in all locations. This area of overlap between the assemblages occurred at the lower end of the elevation range for *C. esculenta*, where the highest inundation occurs. It is likely that the competitive advantage that this introduced invasive exhibits is reduced as it experiences higher stress due to inundation in this intertidal elevation range. This allows for a more diverse community to exist which includes both high and low
elevation species. While this zone is described as intertidal based on the mean sea level measured at the nearby NOAA Amerada Pass tide gauge it still experiences considerable flooding related to high river discharge, that occurs primarily in the spring, at which time the intertidal zone is inundated continuously (Hiatt and Passalacqua, 2015, Chapter 2). This increased inundation likely effects the ability of species which are not adapted to long periods of inundation to dominate within this zone.

**Patterns of vegetation shift after hurricanes and large flood**

There is a decrease in mean cover for all species except *C. esculenta, P. punctatum* and *A. philoxeroides* following the hurricane. These three species are the dominants in the HIS species assemblage. The low elevation emergent and submerged community is composed of *S. platyphylla, N. lutea, P. nodosus* and SAV, and the aboveground cover was completely eliminated by the hurricanes in 2008. However *S. platyphylla* in particular returned to pre-hurricane levels within one year and then continued to increase through the following year, while *N. lutea* exhibited limited cover in the first 2 years following the storm and then increased in year three to much higher cover than was observed before the storm (Fig. 4.2).

The trend of increased cover by *N. lutea* was also observed both in my sample plots as well as using remote sensing techniques throughout the whole delta (Carle et al., 2011). However, *N. lutea* expansion was not limited to only areas that increased in elevation or occurred above an elevation threshold (Table 4.2). This is not surprising as it has been reported that *N. lutea* can grow and expand in cover at depths up to 2 m, which is 1 to 1.5 m much greater than it is found in most the WLD study site (Hall and Penfound, 1944; Sculthorpe, 1967; Whyte et al., 1997). While, I do not think that elevation gain alone controls the expansion and establishment
of *N. lutea*, it is possible that the newly deposited flood sediment resulting from the large river flood may hamper the emergence of other less robust perennial vegetation such as *P. nodusus* and *S. playtypylla*.

**CONCLUSIONS**

There were two major persistent species assemblages that occurred within the sampling plots at WLD during 2007 through 2011. They are defined by elevation within the tidal range and referred to as the High Intertidal/Supratidal (HIS) and Lower intertidal/subtidal (LIS). While these assemblages are consistent across years, there is some overlap of species especially at intertidal elevations from 0 to 0.3 m NAVD 88. Following the passage of Hurricanes Gustav and Ike the community composition returned to pre-disturbance cover and composition within two years. However not all species recovered at the same rate, with recovery of *N. lutea* occurring three years after the storms. The large increase in *N. lutea* cover observed in 2011 does not seem to be a result of increasing elevations, but could be due to other physical factors associated with the major river flood such as burial of perennial emergent vegetation, which prevented growth in the 2011 growing season. These results illustrated that vegetation community composition in mineral dominated wetlands will recover to pre-disturbance levels within two years and that loss of wetlands of this type has been overstated in previous analyses. I hope that these results will contribute to the clarification of the expected effect of hurricane storm surge on both natural progradational deltaic floodplain wetlands as those resulting from constructed diversions of freshwater and sediment.
LITERATURE CITED


CHAPTER 5. ESTABLISHMENT OF SALIX NIGRA STANDS AND THEIR ROLE IN THE ECOGEOMORPHIC DEVELOPMENT OF DELTAIC FLOODPLAIN WETLANDS

INTRODUCTION

Woody vegetation along rivers and streams contributes to habitat heterogeneity and biodiversity as well as ecogeomorphic processes such as increased sediment trapping and bank stabilization (Gurnell et al., 2012, 2006; Hupp and Osterkamp, 1996; Karrenberg et al., 2003; Osterkamp et al., 2012; Sigafoos, 1964; White, 1979). Species that occupy these habitats tend to grow rapidly, are intolerant of shading, and release large numbers of seeds that lack a dormancy period (Densmore and Zasada, 1983; Scott et al., 1996). Common trees found along riparian corridors and floodplains include early successional species in the family Salicaceae, which included cottonwoods, poplars and willows (Gage and Cooper, 2005; Scott et al., 1996). The abundant seed production and wind and water dispersal of these species allows for extensive colonization of new habitat when ideal establishment conditions exist, particularly bare mineral sediment with high moisture content and light availability (Densmore and Zasada, 1983; Karrenberg et al., 2002).

Flow regimes and geomorphological processes are critical controls on woody vegetation establishments along riparian floodplains, including, channel narrowing, meandering, and flood deposition (Hupp, 2000; Hupp and Osterkamp, 1996; Osterkamp et al., 2012; Scott et al., 1996). Woody vegetation establishment resulting from narrowing and meandering tend to be related to low or moderate river flows resulting in lower water levels or abandonment of previously inundated surfaces. For example, Populus deltoides, the eastern cottonwood, has been observed
to form linear even-aged stands along riverbanks coincident with floods (Scott et al., 1996). I contend that due to similar geomorphic process the same type of forest structure patterns will be observed in deltaic floodplain woody vegetation as well.

Progradational deltaic floodplain wetlands in the northern Mississippi River Delta Plain are currently limited to the Atchafalaya, Wax Lake and extreme lower portion of the Mississippi River Deltas, where river water is able to overtop banks and periodically deposit sediment on freshwater floodplain wetlands. These deltas exhibit similar patterns of mouth bar formation, with vegetation colonization occurring first at low elevations on subtidal mudflats and bars. While at higher elevations subtidal emergent and submerged species are replaced by intertidal emergent herbaceous vegetation. The highest elevations on deltaic islands, usually along the channel flanking levees have been reported to have stands of *Salix nigra* or black willow (Johnson et al., 1985; Shaffer et al., 1992). *Salix nigra*, the largest and longest lived of all native willow species (McKnight, 1965, Pitcher and McKnight 1996), is a common tree found throughout North America (Zasada et al. 2008). It is a relatively short lived tree (50-70 years), predominantly found in monospecific even-aged stands along bodies of water (McLeod and McPherson, 1973; Sculthorpe, 1967, Zasada et al. 2008). *Salix nigra* readily grows adventitious roots and can withstand moderate flooding during the growing season and tends to grow at or just below water level (Pitcher and McKnight 1996). It is dioecious with seed dispersal in the southern range occurring in June and July (Densmore and Zasada, 1983). The numerous very small seeds, 3-4 mm in length, which include hairs extending from the seed coat are released as the capsules dry and split open. The small seeds are dispersed by wind and also float when they land on water (Pitcher and McKnight 1996). *Salix nigra* seeds, like other North American willows do not exhibit dormancy and germinate rapidly following release when ideal substrate is
available. Favorable conditions for germination occur on moist exposed mineral soil, with no shading (Scott et al. 1996, Zasada et al. 2008). *S. nigra* is intolerant of shade throughout its life, therefore growth of young trees within established stands is limited (McLeod McPherson 1973, Pitcher and McKnight 1996). The above life history traits that have primarily been studied in populations along riparian margins and floodplains also extend to *S. nigra* in deltaic floodplains.

Similar hydrologic and geomorphic processes occur throughout river dominated deltas and along riparian corridors. For example, floods alter morphology of the riparian zone similarly to deltaic island edges, resulting in both sediment erosion and deposition (Gurnell and Petts 2002, Chapter 2). In deltaic floodplain wetlands *S. nigra* particularly occurs on the highest elevations along the natural levees that form along primary and secondary distributaries (Johnson et al., 1985; Shaffer et al., 1992; White, 1993). There has not yet to my knowledge been a thorough investigation of the stand structure in these environments and their relation to hydrologic and geomorphologic processes. In this work I hypothesize that even-aged *S. nigra* stands have established within the prograding Wax Lake Delta (WLD) on newly deposited areas of bare sediment. These areas form as a result of sediment deposition from large river floods. I hypothesize that only large river floods are able to deposit enough sediment to bury the established perennial herbaceous vegetation, in order to allow for the high light adapted *S. nigra* seedlings to establish. While under conditions of moderate or low sediment deposition the perennial established vegetation is able to emerge and quickly outcompete any *S. nigra* seedlings for space and light. The stochastic nature of *S. nigra* stand establishment should result in discrete even-aged stands which correspond to the timing of major floods that have occurred since 1973, when the WLD first became subaerial. I will test this hypothesis using aerial imagery mapping and measurements of forest structure parameters.
METHODS

Site description

The WLD is a river dominated deltaic floodplain, prograding into the Atchafalaya Bay at the mouth of the Wax Lake Outlet, a constructed distributary channel of the Atchafalaya River, which first opened in 1941 (Fig. 5.1). Subaerial land in the WLD first began to appear in 1973. The water discharge into the Atchafalaya River is maintained at 30% of the combined flows of the Mississippi and Red Rivers, and is controlled by the Army Corps of Engineers at the Old River Control Structure. Because the discharge is maintained based on this proportion, the hydroperiod of the Wax Lake Outlet closely follows that of the Mississippi River, with the natural seasonal pattern of highest discharge generally occurring in the late winter and spring and lowest discharge in the fall. Due to its unique occurrence as a constructed river outlet that has been allowed to build land under natural hydrologic conditions, this system represents an extremely valuable analogue to many Mississippi River Delta coastal restoration strategies, which propose diverting river water and sediment into shallow coastal basins to reduce present wetland degradation rates (Parker and Sequeiros 2006; Kim et al. 2009; Allison and Meselhe 2010; Paola et al. 2011; CPRA 2012). The wetland soils of the WLD tend to be low in organic content, with a high proportion of mineral sediment, primarily fine sand and silt (Delaune et al. 2016). The deltaic floodplain wetland vegetation consists of woody, shrub/scrub and herbaceous fresh marsh species that tend to exhibit zonation along the elevation gradient (Visser, 1989). Similar vegetation patterns have also been documented in the Atchafalaya Delta (Johnson et al., 1985; Shaffer et al., 1992). The zonation of the herbaceous vegetation community has been
Figure 5.1. Site map, with the location of the northern Gulf of Mexico coast, the Wax Lake Delta at the mouth of the Atchafalaya River, and the zoomed in portion of the delta, where *Salix nigra* was found. Forest structure sample plots are indicated by numbers and white squares.
shown to be controlled to a large extent by elevation, however it is likely that interspecific
competition and other mechanisms as well as elevation exert control on the vegetation
community composition as well (Chapter 4). *Salix nigra* is the only large tree that regularly
occurs on deltaic islands. It is only found at soil surface elevations greater than 0.25 m NAVD
88; this is just below mean high water (MHW) 0.3 m NAVD 88 (Chapter 4).

*Salix nigra* stand mapping

Here I use vegetation mapping from multi-temporal imagery to determine changes in *S.
*nigra* cover, similar to the approach by Lowcock (2012) to investigate *Salix* spp. along arctic
boreal ponds in Canada. Willows are an ideal vegetation type to use in these studies because they
are very fast growing and tend to rapidly colonize newly emerging habitats, such as delta islands,
forming dense easily identifiable stands. I digitized the extent of *S. nigra* cover from high
resolution imagery (≤ 1 m cell size) for the years 1998, 2004, 2008, 2009 (data sources Table
5.1). All imagery was downloaded as digital orthophoto quarter quadrangles for the desired study
site and processed using ERDAS Imagine 11 (Hexagon Geospatial, Norcross, GA). Using
ArcGIS 10.2 the extent of *S. nigra* stands were manually delineated for all years at a consistent
2,500:1 zoom in order to maintain consistency between years; the total area of *S. nigra* cover was
then calculated for each year. Work by Bevington (Chapter 4) found that *S. nigra* stands in the
WLD only occur above 0.25 m NAVD 88. The elevation of deltaic floodplain wetlands above
0.25 m NAVD was estimated from a December 2012 airborne LiDAR digital elevation model
(DEM) of the WLD derived from the USGS Atchafalaya 2 LiDAR Survey
(http://coast.noaa.gov/digitalcoast/) using ArcGIS 10.2 (ESRI, Redlands, CA). The areal extent
of *S. nigra* from 2012 was compared to the areal extent of land above 0.25 m NAVD, in order to estimate the proportion of the possible elevation range that it occupied.

Table 5.1. Aerial imagery used in *Salix nigra* stand mapping.

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Format</td>
<td>DOQQ images of Wax Lake: Color Infrared Orthophoto</td>
<td>DOQQ images of Wax Lake: Color Infrared Orthophoto</td>
<td>USGS High Resolution Orthoimagery for Atchafalaya Basin, Louisiana</td>
<td>USGS High Resolution Orthoimagery for the Louisiana Coastline</td>
</tr>
<tr>
<td>Cell size</td>
<td>1.0 m</td>
<td>1.0 m</td>
<td>0.3 m</td>
<td>1.0 m</td>
</tr>
</tbody>
</table>

**Forest structure measurements**

Based on the tree cover mapping, available maps of island age (Chapter 3) and knowledge of the site, I selected 21 sample plots spread throughout the extent of *S. nigra* cover at WLD, which included the entire age and size range found at WLD (Fig. 5.1). I grouped the 21 plots into seven hypothesized classes in which I expected similar tree age based on previous flood records and the age of the delta islands. The majority of the plots were 100 m², however smaller sizes were used where stand size or shape did not allow for a 10 x 10 m plot. I measured tree diameter at 1.4 m from the ground, also referred to diameter at breast height (dbh) for all trees and height either for 20% of the trees in the plot or 10 individuals, whichever was greater (Bonham 1989). Tree height was measured 15 m from the base of the tree using a Suunto PM-5
clinometer (Suunto, Vantaa, Finland). All forest structure measurements were completed between February and April 2015.

**Statistical analysis**

A test of the effect of hypothesized island age class on the forest structure parameters, mean diameter, mean height, and mean density for each plot were completed using PROC GLM multivariate analysis of variation (MANOVA) in SAS 9.4 (SAS Institute, Cary NC, USA). The one-way MANOVA tested a model of all forest structure parameters equal to hypothesized age class. PRIMER 7 (PRIMER-E Ltd. Plymouth, UK) was used for principal components analysis (PCA) to visualize the pattern in plots with age, as well as hierarchical agglomerative clustering using group-averaging. Clustering was based on a resemblance matrix of Euclidian distance calculated from normalized forest structure parameters for each plot. The resulting dendrograms were used to determine groupings of forest plots with similar stand structure and to test the *a priori* hypothesized age classes.

**Description of experimental mesocosms**

I attempted to test the hypothesized interspecific competition mechanism controlling *S. nigra* colonization and expansion in deltaic floodplain islands and the observed inability to expand into previously vegetated areas as well as the effect of elevation on seedling establishment. To do this I installed 54 mesocosms, constructed using five gallon buckets with the bottoms removed and holes drilled around the sides to allow for drainage and filling with the natural hydroperiod. These were established in three locations with two treatments. The treatments were: vegetated or bare sediment (two levels), and elevation (three levels, spaced at
10 cm intervals). Vegetated mesocosms contained established perennial vegetation, including *C. esculenata, Schoenoplectus americanus, Nelumbo lutea*. They were established by collecting whole cores, the diameter and depth of the mesocosms. This allowed for limited disturbance of the belowground roots and rhizomes of established perennial vegetation. Cores were collected from stands of existing vegetated areas adjacent to mesocosm locations. The bare sediment mesocosms were established using sediment from a newly forming bar just east of Mike Island, the bar was unvegetated at the time of sediment collection and represented bare sediment that would be deposited following river flooding. Vegetated and bare treatments each contained three elevation levels and three replicates at each level (Fig. 5.2). Mesocosms were established in mid-April 2015 and allowed to settle for three weeks, at that time more sediment was added to the bare mesocosms in order to bring sediment level even with the top of the buckets. Whole *S. nigra* seed heads, called catkins, were collected June 11th 2015 from mature trees that had begun to release seeds. These were identified as those that had visible open dry capsules and white fluff, which is composed of the seed hairs used for wind dispersal (Zasada et al. 2008). All catkins were allowed to dry for 48 hours in paper bags at room temperature until all the seed pods opened (Dressen 2003, Zasada et al. 2008). The seeds were then removed from the extensive fluff, by blowing compressed air through a series of sieves as in the method described by Dreesen (2003). The cleaned seeds were sorted and counted using a dissecting microscope. Only green seeds were selected, as this is indicative of viability (Dreesen, 2003). Paper envelopes with 100 seeds in each were prepared for seeding in the field. On June 19th 2015 I spread 100 seeds over each mesocosm that was above water. Due to high water this was limited to the high and mid elevation rows at each location, I intended to return later and seed the lower row when the water level fell. Unfortunately, the water level in the sites remained high
throughout the summer (Fig. 5.3). When I returned to the sites in early July all the mesocosms were inundated and no *S. nigra* establishment had occurred. I determined to wait until the water level dropped and reseed all the mesocosms, however by the time this occurred the seeds were no longer viable. I tested the viability by spreading seeds on moist soil, no seeds germinated. This is consistent with literature reports of the extremely short viability of seeds of *Salix* spp. (McLeod and McPherson 1973).

Figure 5.2. Schematic of mesocosm setup for competitive exclusion experiment. Examples of mesocosms immediately after construction, April 2015.
Figure 5.3. Daily mean water level measured at Calumet (USGS 07381590) on the Wax Lake Outlet during 2015 in blue, and the long term mean of all reported daily means from 1996-2014 in black, with one standard deviation (dashed line). The time period of activities related to the mesocosms experiment are given for reference.

**RESULTS**

*Salix nigra* stand area

Based on the tree mapping from aerial images I observed the total area of *S. nigra* coverage in WLD increased from 0.09 km\(^2\) in 1998 to 0.26 km\(^2\) in 2004 (Fig. 5.4). In these years the overall change was approximately 0.02 km\(^2\) yr\(^{-1}\), with expansion from only three islands to two additional islands further down the delta where they had previously not been observed. They also expanded their coverage with new discrete stands on the older islands over this time period.
Figure 5.4. Expansion of *Salix nigra* areal coverage on Wax Lake Delta over time.
In 2009 the total *S. nigra* area was 0.29 km$^2$, with the smallest annual increase of only 0.004 km$^2$yr$^{-1}$ between 2004 and 2009. Greater expansion in coverage occurred in the interval between 2009 and 2012 when the total *S. nigra* area increased to 0.38 km$^2$, with an annual increase of 0.03 km$^2$yr$^{-1}$ comparable to the increase seen between 1998 and 2004. In 2012 the area of *S. nigra* cover that occurred within the elevation zones that allow growth (>0.25 m NAVD88; Chapter 4) was 3.7%. This indicates that while elevation is an important factor in *S. nigra* establishment that likely other factors also play a role.

Figure 5.5. Comparison of *Salix nigra* coverage in 2012, to the areal extent of deltaic floodplain wetlands over 0.25 m NAVD 88. Which has been found to be the elevation range at which *S. nigra* can grow at Wax Lake Delta.
Salix nigra stand structure and age classes

The results of the MANOVA indicated a significant effect of hypothesized age class on stand structure parameters (Wilks’ Lambda p<0.0001). However, pairwise comparisons revealed no significant difference between some of the hypothesized age classes, which indicated that my *a priori* hypothesized age classes were not accurate. In order to define actual age classes, I used the PCA and hierarchical agglomerative clustering methods, which arranged the 21 sample plots into five distinct groups (Fig. 5.6). These groups defined by the cluster analysis were identified as C1 through C5 and were used for further analyses. They exhibited a distinct trend in decreasing diameter and height, and increasing density, which is consistent with the hypothesis that even aged stands established as a result of discrete stochastic events, like river floods (Fig. 5.7). Therefore the groups are ordered by estimated age of youngest to oldest from C1 through C5 (Fig. 5.8). Two of these five groups, C1 and C2, were consistent with the *a priori* hypothesized age classes; based on the small mean diameter and height as well as high density of these two groups (Fig. 5.7) along with the tree mapping (Fig. 5.4) I concluded that C1 and C2 were associated with the 2011 and 2008 spring river floods respectively (Table 5.2). The other three groups resulting from the cluster analysis contain trees of increasing diameter and height as well as decreasing density (Fig. 5.7). Based on this I conclude that they represent groups of older *S. nigra* stands. The oldest of these groups, C5, was composed of plots 2 and 3, which were located on an area of the WLD which was reported to have become subaerial prior to 1983 (Chapter 3), therefore I determined that these stands likely established as a result of large river flood in 1983, and that the two younger groups, C3 and C4, resulted from the major river floods in 1997 and 1991 respectively (Table 5.2). Previous studies of riparian vegetation establishment and timing have linked the stands to past flooding events based on the landscape position, i.e.
where and at what elevation they occur, however this approach requires assumptions that the water levels and timing were adequate for establishment during each river flood and that no erosion of whole stands occurred following establishment (Gurnell and Petts, 2002; Hupp, 2000; Johnson, 2000; Karrenberg et al., 2002). Therefore additional dating of tree cores may be required to confirm more precise correlations between establishment of these even-aged stands with specific major river flood.

Figure 5.6. Principal components analysis (PCA) of forest structure plots, with a priori hypothesized groups indicated by colors. The dendrogram which illustrates the groups in the PCA is also shown and the groups determined by the cluster analysis are identified as C1 (youngest) through C5 (oldest), these groups are illustrated in the above PCA by dashed circles.
Figure 5.7. The trends of forest structure parameters, mean diameter, mean height, and mean density for each age group identified in the cluster analysis. Error bars are 1 standard error for all parameters. The direction of increasing age is indicated.
Table 5.2. Estimated age groups based on hierarchical agglomerative cluster analysis and associated major river flood that likely lead to stand establishment.

<table>
<thead>
<tr>
<th>Estimated age group based on cluster analysis</th>
<th>Forest structure plots included in each group</th>
<th>Major river floods that facilitated stand establishment</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>t19, t20, t21</td>
<td>2011</td>
</tr>
<tr>
<td>C2</td>
<td>t16, t17, t18</td>
<td>2008</td>
</tr>
<tr>
<td>C3</td>
<td>t6, t8, t9, t10, t11, t12, t13, t14, t15</td>
<td>1997</td>
</tr>
<tr>
<td>C4</td>
<td>t1, t4, t5, t7</td>
<td>1991</td>
</tr>
<tr>
<td>C5</td>
<td>t2, t3</td>
<td>1983</td>
</tr>
</tbody>
</table>

Island edge anchoring

There is evidence that willow stands anchor edges of islands along distributary channels of active deltas (Shaw et al., 2013). My observations using temporal imagery analysis support this phenomena, when nearby shorelines with and without willow stands are compared. Approximately 40 m along the east side of Mike Island was eroded along the channel bank between 1998 and 2004 in a zone not colonized by willows (Fig. 5.8 white arrow). The erosion is directly downstream of a stand of willows, estimated to have established in 1991, where little shoreline erosion was observed.

DISCUSSION

Stand structure and relation to large river floods

Salix nigra stands in WLD do not exhibit mixed age forest structure, instead they have very narrow ranges of diameter, height and density within stands and large differences between stands of differing ages (Fig. 5.7). This establishment pattern is consistent with monospecific
even-aged stands that are also commonly found along rivers, where stand establishment can be linked to hydrogeomorphic conditions (Hupp, 2000). Based on the aerial imagery analysis I conclude that experimental stands in this study all established between 1983 and 2011, and that each of the estimated age groups identified in the cluster analysis likely established following the five major floods that occurred over that time period.
Stand cover and expansion

*Salix nigra* stands occupy a small area of the deltaic floodplain wetlands within WLD, covering only 0.38 km\(^2\) in 2012 or 0.7\% of the total floodplain area above -0.5 m NAVD 88. There is evidence that elevation exerts a strong control on *S. nigra* growth, which in the WLD only occurred above 0.25 m NAVD 88. This is just below the mean high tide of 0.3 m NAVD 88 and consistent with elevation limitations of willows in other ecosystems (Zasada et al. 2008). In 2012 I estimated that over 10 km\(^2\) of wetlands at WLD were within the elevation range required by *S. nigra*; however, the majority of this area is devoid of *S. nigra* and instead dominated by herbaceous perennial hydrophytes, particularly *C. esculenta* and *Polygonum punctatum* (Carle et al., 2014, Chapter 4). *Colocasia esculenta* is an introduced invasive (Moran and Yang, 2012) and has been found to dominate the community composition forming homogenous communities within this elevation range (Chapter 4). By the time that the ubiquitous *S. nigra* seeds are released in mid-June to July, *C. esculenta* aboveground cover is already well established. *Salix nigra* seedlings are unable to establish on the shaded soil, because of extensive cover by the large broadleaved *C. esculenta*. Therefore, despite favorable elevations *S. nigra* does not expand readily into these areas. However, new establishment does occur following large river flood events when bare vegetated sediment is deposited along deltaic islands. This is primarily limited to the channel edge side of levees along both primary and secondary distributary channels. In July 2011, new extremely dense stands of *S. nigra* were observed on sediment deposits along the western edge of Mike Island (Fig. 5.9a). In the image taken from the primary distributary channel, the seedlings can be clearly seen as the lighter green patch on the island edge, with darker green broad leaved *C. esculenta* and mature *S. nigra* also seen in the background of Figure 5.9b. This stand was included in the sampling design as plot number 19 (Fig. 5.1) and
was in the youngest estimated age group, C1. The mature trees in this image were also included as plot 9, and were estimated to have established in 1997 (Fig. 5.1 and Table 5.2).

Figure 5.9. Images taken by the author in July 2011, following the large river flood which peaked in late May 2011. a. Is close up of a stand of very dense Salix nigra seedlings. b. is taken from the primary distributary channel and shows newly deposited sediment near the bifurcation of a secondary distributary channel, with the S. nigra stand which can be seen as the lighter green zone. Mature S. nigra and broad leaved Colocassia esculenta can also be seen behind the seedlings, as well as on the other side of the secondary channel.

I found no natural S. nigra expansion into areas of island interiors that were not associated with secondary channels and tidal creeks. The island interiors receive limited sediment deposition and tend to have higher organic content soils (Chapter 3). Stand expansion from both suckers and vegetative fragments has been found to occur naturally for some willow species and in some cases is the dominant recruitment method (Asaeda et al., 2011). Within WLD there were extremely limited cases observed by the author in which new isolated willow stands have appeared within island interiors. However, upon further investigation it was clear these rooted seedlings were from cuttings transported by human duck hunters to build duck
blinds. Intentionally establishing cuttings has also been used in other ecosystems as a means to restore riparian vegetation and stabilize stream banks (Li et al., 2005). These techniques could potentially be a way to expand *S. nigra* cover within the WLD in the future.

**Ecogeomorphic processes**

The geomorphological processes of river flow and sedimentation control the conditions for establishment of willows on deltaic island. There is also evidence that vegetation, once established on island edge, can influence island morphology. Vegetation structure in riparian systems has been shown to reduce the erodibility of soils (Gurnell and Petts, 2002). In mineral dominated deltaic sediments, such as those in WLD, the increase in organic content at higher elevation (Chapter 3) may indicate an increased ability of belowground vegetative material to reinforce the soil and lessen erosion. For example, I observed evidence of bank erosion where *S. nigra* stands anchored the island edge, in comparison to 40 m of bank erosion over 14 years just downstream where *S. nigra* did not occur. This anchoring effect of *S. nigra* has also been found to correlate with channel margins and upstream ends of islands that migrate less over time (Johnson et al., 1985; Shaw et al., 2013). Root reinforcement of river banks by woody vegetation has been shown along riparian corridors as well (Gurnell and Petts, 2002). The role that willows play in anchoring island edges may be important for stabilizing deltaic islands and allowing for successional development of vegetation communities on higher elevations with higher organic matter soil that has been observed on older deltaic islands (Chapter 3).
Mesocosm experiment water levels

The mesocosm experiment that was conducted over the spring and summer of 2015, unfortunately did not result in any measureable *S. nigra* establishment. I attribute this to the unusually high water levels that were observed during that year (Fig. 5.3). The mean daily water levels within Wax Lake Outlet were more than one standard deviation above the long term (1996-2014) mean from mid-June through late August. I seeded the mesocosm on June 19th, under the assumption that the water levels were falling and that this would allow for the ideal conditions for establishment (McLeod and McPherson, 1973). Following the seeding of mesocosms, water levels rose and remained high through early August. When water levels began to fall, I tested the seeds that had been stored since June for viability, by dispersing 100 of them over a bucket filled with moist fine sand silt mixture that had been brought from the field sites. This sediment had been previously used successfully to germinate seeds immediately after collection. No seeds germinated during August. While the perennial herbaceous cover within the experimental mesocosms flourished during the summer growing season, no *S. nigra* seedlings established in any of the mesocosms at any of the sites, likely due to the flooded conditions which persisted for the duration of the growing season. The viability of the *Salix* spp. seeds drops of rapidly, decreasing to <10% after 6 weeks (McLeod and McPherson, 1973; Roqueiro et al., 2010, Zasada et al. 2008), therefore if the timing of the propagule release is not concurrent with flooding and subsequent drawdown then the proper conditions for recruitment establishment will not occur.
CONCLUSIONS

Deltaic floodplain wetlands experience many of the same hydrologic and geomorphic processes of riparian floodplain wetlands. Therefore I expected to find similar patterns of vegetation establishment and stand structure in WLD. I found that *S. nigra* stands in the WLD exhibit monospecific even-aged forest structure, which is consistent with reports of *Salix* spp. in riparian habitats. I used the forest structure, i.e. density, mean tree diameter and mean height, to estimate five distinct age groups. Using estimates of island age, aerial imagery and the past flood record I determined that each of these age groups likely was established during the five major floods which have occurred in the system since 1983. Evidence was also found for island edge anchoring by *S. nigra* stands, this is analogous to processes seen in riparian systems where woody vegetation stabilizes and prevents stream bank erosion. These findings add to my understanding of the similarities in ecosystem process and functions between riparian systems and deltaic floodplains.

LITERATURE CITED


CHAPTER 6. SYNTHESIS AND CONCLUSIONS

The main objective of this dissertation was to gain a better understanding of the processes related to prograding deltaic floodplain ecosystem development, starting with the factors which drive the geomorphology of the deltaic islands and the interactions between that and the biological community. I created a conceptual model of deltaic floodplain wetland ecological development based upon previous literature on the WLD and similar systems, and used this to frame my hypotheses for the dissertation (Chapter 1). In doing so I have been able to confirm aspects of the conceptual model as well as expand upon it and outline areas in which further research is needed. Here I will summarize and synthesize the findings of the previous four chapters and re-evaluate and expand upon this conceptual model of deltaic floodplain wetland development.

In Chapter 2 the effect of large river floods was determined to be the largest contributor to deltaic wetland elevation gain, as compared to hurricane storm surge and cold fronts. However it was determined that due to the consistent annual loss in elevation resulting from winter cold fronts that periodic large river floods as well as more common lower water level floods are all necessary for long-term net positive elevation gain to occur. I also found that while hurricanes do deliver a net elevation gain to the delta islands, they also result in appreciable elevation loss, equal to 39% of the gross elevation gain. This is an important consideration that is often left out of other studies of hurricane sediment subsidy in deltaic wetlands. The long-term annual contribution of hurricane derived sediments to deltaic wetlands based on a return period of one every 7-10 years is less than 22% of the sediment delivered by large river floods in the WLD. The research question and experimental design of this chapter were focused on the overall effect
of large physical forcings on deltaic floodplain elevation gradient across the entire ecosystem. It provided an understanding of the processes that drive the overall net positive elevation gain across the entire WLD and provided a foundation on which the rest of the conceptual model is built.

In order to look at the variation in deltaic island morphology and elevation change based on position within the delta and age of the deltaic islands I investigated patterns in morphology based on the seven surveyed elevation transects used in Chapter 2, however there was not enough replication over the deltaic age range or island position. So for Chapter 3 I utilized a digital elevation model (DEM) created from LiDAR elevation measurements made in Dec. 2012 to extract cross-sectional transects perpendicular to the channel along all the island edges that had not been affected by dredging. This provided a dataset that was robust enough to test hypotheses of island edge morphology change over island age and landscape position. Combined with the chronosequence map produced in this chapter, the resulting predictable pattern of island morphology change with age allows for refinement of the conceptual model, including extending the model to a later stage at which island infilling facilitated by organic matter production is likely occurring after the island has reached an elevation greater than 0.25 m NAVD88, this is very close to mean high water which is 0.3 m NAVD88. These findings may indicate that there is a shift in the relative proportion of mineral versus organic sediment input above this elevation, and that possibly a shift in vegetation community composition occurs and results in increased organic production.

In Chapter 4 the effect of elevation and hurricane storm surge on herbaceous vegetation community composition were investigated. These were questions that were based on
observations within the WLD and other deltaic floodplain ecosystems, and which were outlined in the conceptual model (Fig. 1.2). I used five years (2007 to 2011) of herbaceous wetland vegetation species cover collected at peak season biomass to define unique species assemblages within the elevation gradient as well as to quantify the response and recovery of the vegetation community following the passage of Hurricanes Gustav and Ike in September 2008. I found that there were two major persistent species assemblages that occurred during 2007 through 2011. They were defined by elevation within the tidal range and referred to as the High Intertidal/Supratidal (HIS) and Lower intertidal/subtidal (LIS). While these assemblages were consistent across years, with overlap at intertidal elevations from 0 to 0.3 m NAVD 88. The effect of vegetation assemblage shifts related to elevation likely occur due to the overlap in the two major assemblages at intertidal elevations, and the shift from LIS to HIS likely occurs heterogeneously across the ecosystem and is controlled by other factors besides just elevation. Following the hurricane storm surge passages in September 2008, the herbaceous vegetation community composition returned to pre-disturbance cover and similar major assemblage structure within two years. These results illustrate that vegetation community composition in mineral dominated wetlands is able to recover to pre-disturbance levels within two years and that loss of wetlands of this type may have been overstated in the literature. Therefore I concluded that the hypothesis from the conceptual model (Fig. 1.2) that hurricane storm surge resulted in a shift in dominant species was not supported by my results.

In Chapter 5 I investigated the pattern of woody vegetation occurrence throughout the WLD in order to test the hypothesis that *Salix nigra* (black willow) colonization was related to deposition of thick sediment deposits form large river floods. This pattern of monospecific even-aged stands has been observed for *S. nigra* and numerous other willow species in riparian
depositional environments, and I hypothesized that it would likely also occur in the river
dominated deltaic floodplain wetlands within the WLD. In order to test this hypothesis I mapped
*Salix nigra* stand occurrence from 1998 to 2012 and combined with the island age map created for
Chapter 3 I estimated the range of stand ages throughout the delta. I selected plots within stands,
across all age ranges within the delta and measured forest structure parameters. Analysis of the
forest structure of these plots showed that individual plots were composed of trees within a
narrow diameter, density and height range, indicating even-aged stands. A multivariate cluster
analysis of forest structure patterns yielded five groups, which increased in diameter and height
and decreased in density. I was able to match the plots included in the youngest two age groups
with those that occurred following the 2008 and 2011 river floods based on the aerial imagery
analysis. It was determined that the other three age groups were likely established following
three previous large floods that occurred in the WLD in 1997, 1991, and 1983. These findings
are consistent with the original conceptual model, that willow stands established following large
river floods (Fig. 1.2). I also attempted to test the hypothesis that the formation of bare sediment
area is necessary for *S. nigra* establishment, since without such newly emergent landscapes the
competitive exclusion of established herbaceous perennial vegetation will limit the establishment
of *S. nigra* stands. Unfortunately the natural water levels in the WLD were much higher than
average throughout the summer of 2015, when the experiment was setup and no results were
obtained. Therefore this hypothesis in the conceptual model remains to be tested.

The conceptual model of deltaic floodplain ecosystems provided a basis for many of the
hypotheses in this dissertation and represented the major phases of deltaic floodplain wetland
development from the initial subaqueous mouth bar through colonization by submerged and few
limitations in its original form, particularly the simplified view that it represents the delta as a whole, without inclusion of the idea that there are continual simultaneous occurrences of all

Figure 6.1. This is a view of the sediment surface elevation Mike Island in the Wax Lake Delta, with four cross-sectional transects which illustrate the large variability in the morphology and associated ecosystem which occur simultaneously throughout the delta.
stages of deltaic wetland development throughout the delta at any one time (Fig. 6.1). The representation of the established levee edge with woody vegetation used in the original conceptual model (Fig. 1.2) depicts only a very small portion of what the elevation and vegetation community of the deltaic floodplain actually looks like. I also think that the original conceptual model is limited in its lack of inclusion of tidal range as an important control on community composition. This is a river dominated delta, as well as a system where meteorological tidal fluctuations exert a strong control, and the annual hydroperiod reflects the inclusion of these forcings. However the effect of continual daily tidal fluctuations also exerts a strong control on the vegetation community zonation which has been found to follow very closely the mean high and mean low tide heights.

Therefore I suggest expanding the model to account for the various morphologies and ecological processes that are occurring throughout the delta at differing locations within the tidal frame. This could be accomplished expanding it from a generalized depiction of a supratidal levee and interior wetlands as is seen in the original conceptual model (Fig. 1.2) to include the differing morphologies and elevation ranges which can be observed throughout the delta. This also allows for inclusion of the temporal aspect of the ecosystem as a whole, which at any one time consists of numerous phases of ecological development. An example illustrating these concepts is the four elevation transects measured across Mike Island from the 2012 LiDAR DEM (Fig. 6.1). Each transect represents the elevation as well as the vegetation community assemblages that would be expected to occur at that location. However, all of the transects have different morphologies which are controlled by the age of that portion of the island as well as the position along the island and the major physical forcing which have occurred in the history of that portion of the island. All of these factors need to be taken into account when considering
how to explain processes across the entire deltaic floodplain ecosystem. The findings of the previous research chapters and the proposed refinements of the conceptual model add to a greater understanding of the deltaic floodplain ecosystem and provide a framework on which to investigate further questions of ecological development.
VITA

Born in Atlanta, GA on September 25th, 1980; Azure graduated from Logan High School, in La Crosse, WI, in May 1999. She then attended the University of Wisconsin La Crosse for three semesters, before transferring to Coastal Carolina University, where she completed a B.S. in marine science with a minor in biology in May 2005. In August 2005, she enrolled in the graduate program in the School of Marine Science at the College of William and Mary, to pursue a M.S. in marine science, focusing on wetland ecology. After completing her master’s degree in December 2007, she took a job as a Research Associate in the Systems Ecology Lab at Louisiana State University, working for Dr. Robert Twilley. There she was involved in a number of research projects both in the wetlands of Louisiana and the Florida Everglades. She worked as a researcher and project manager in the Dept. of Oceanography and Coastal Sciences for five years before pursuing a Ph.D. in Oceanography and Coastal Science full time starting in January 2013.