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Landscape analysis of vegetation change in coastal Louisiana following hurricanes Katrina and Rita

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LANDSCAPE ANALYSIS OF VEGETATION CHANGE IN COASTAL LOUISIANA FOLLOWING HURRICANES KATRINA AND RITA

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Lastly, I thank my wife Cindy, daughter Jeanne and son Zachary for all the love and support; the juggling of schedules; the acceptance of my early morning and weekend work schedules; and the encouragement that "you are almost done". I also dedicate this work to my parents, Dean and Joan Steyer, who instilled the work ethic, drive and never too old attitudes necessary to accomplish my goals.

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ABSTRACT

Investigations of hurricane disturbances on coastal vegetated communities are common, but relatively few are comprehensive across broad geographic regions. The 2005 hurricanes, Katrina and Rita, exposed Louisiana coastal landscapes to physical modifications and extensive and prolonged flooding, resulting in measurable physicochemical changes. This research used remote sensing and field investigations to regionally assess (1) porewater salinity and sulfide impacts to and recovery of coastal Louisiana vegetation communities, and (2) the importance of mineral sediment deposition on accretionary processes. Hurricane effects were most direct and prominent in eastern Louisiana from Katrina and western Louisiana from Rita, compared to central Louisiana exposed to indirect affects from Rita.

A coastwide analysis of moderate resolution imagery found over 4,714 km^2 of the prestorm coastal wetland area experienced a substantial decline in vegetation density and vigor in October 2005, with the majority of persistent damage through November 2006 in the west (1,046 km^2). In the east region, 91.8% of persistent damage was accounted for by conversion of marsh to new open water; whereas in the west region, 71% was associated with other vegetation stressors.

The physical landscape disruption in the east contributed to a high abundance of disturbance species in fresh and intermediate marsh from fall 2006 to fall 2007. Salinity and sulfide stress persisted throughout the west region, contributing to low vegetative cover, slow recovery of *Spartina patens*, and shifts towards more saline marsh classifications by fall 2007. Hydrologic barriers, including impoundments in the west, contributed to salinity and sulfide stress; however, these same structures facilitated trapping of mineral sediments delivered by Hurricane Rita, providing critical supplies of bulk sediment and nutrients. Large periodic sediment inputs partially compensate for reduced vertical accretion found in

impounded marshes. However, management actions should endeavor to optimize organic matter production to support vertical accretion.

Two full growing seasons after the 2005 hurricanes, marshes directly impacted in the east and west regions were still recovering. Although vegetation cover values were approaching pre-hurricane levels, species composition is still indicative of a disturbance environment.

CHAPTER 1

HURRICANES KATRINA AND RITA: OVERVIEW OF INITIAL ENVIRONMENTAL CONDITIONS AND POTENTIAL LONG-TERM CONSEQUENCES

INTRODUCTION

Hurricanes Katrina and Rita, two storms of exceptionally large size and strength, struck the northern Gulf of Mexico coast within a one-month period in late summer of 2005 near the state borders of Louisiana/Mississippi and Louisiana/Texas, respectively (Fig. 1.1). Catastrophic winds and waves had a direct and devastating effect on human lives, properties, and various infrastructures. Furthermore, the impacts of these two storms are expected to have major effects on coastal natural resources. Many conditions are transient, such as salinity and storm surge, in that their signals may be lost rather quickly unless rapid-response sampling takes place. While direct evidence of transient conditions may be temporary, they can be a catalyst for factors which may have long-term effects on the ecosystem.

Salinity is one of the transitory elements that are critical in understanding the long-term consequences of these storms on habitat change and coastal restoration. Coastal saltwater and freshwater marshes were flooded with storm surge for weeks in some places, which increased the time for salt to diffuse into the soil porewater. Over time porewater salinity should decline as it diffuses into overlying floodwaters, provided fresh water is available for flushing, either by precipitation or by mechanical introduction (e.g., freshwater diversions). If freshwater is not introduced, porewater salinity levels may continue to rise as a result of evapotranspiration and other processes.

Associated with salinity intrusion events are delivery of seawater-derived sulfates inland. When combined with flooded soil conditions, there is the potential for elevated concentrations of sulfide in the root zone which can be directly toxic to plants (Ingold and

Havill 1985, Koch et al. 1989). It is well documented that elevated porewater salinities and sulfides can cause decreased productivity in wetland plants (Smart and Barko 1980; Linthurst and Seneca 1981; Bradley and Dunn 1989, Koch et al. 1990, Howard and Mendelssohn 1999). Thus, the hurricanes can thereby affect primary and secondary production for an unknown time, with the duration of the effect depending on how long porewater salinity and sulfide remain elevated.

Previous research on hurricane impacts in coastal Louisiana have focused on physical disturbance of the marsh substrate (Morgan et al. 1958, Chamberlain 1959, Guntenspergen et al. 1995, Barras 2006, Barras 2007), and sediment distribution (Baumann et al. 1984, Rejmanek et al. 1988, Cahoon et al. 1995, Nyman et al. 1995, Cahoon 2003, Turner et al. 2006). Fewer studies have investigated the effects of salinity intrusion and flooding on coastal marsh vegetation (Ensminger and Nichols 1957, Chabreck and Palmisano 1973, Meeder 1987, Jackson et al. 1995). Many of the investigations were reported as general observation, and other studies were focused on small geographic areas or specific vegetation species of interest. There are relatively few studies (Cahoon et al. 1995, Guntenspergen et al. 1995, Jackson et al. 1995) that assess both physical and chemical effects of hurricanes across broad geographic regions and vegetation communities. Because the entire coast of Louisiana was influenced by Hurricanes Katrina and Rita, a coastwide assessment of impacts and recovery was designed using remote sensed and field based data acquisition.

It is the objective of this introductory chapter to provide a general overview of Hurricanes Katrina and Rita and then document the immediate extent and duration of elevated salinities in vegetative communities across coastal Louisiana and identify potential consequences of this exposure on long-term marsh community change and recovery. The research chapters that follow this introduction will investigate specific stressors and subsidies

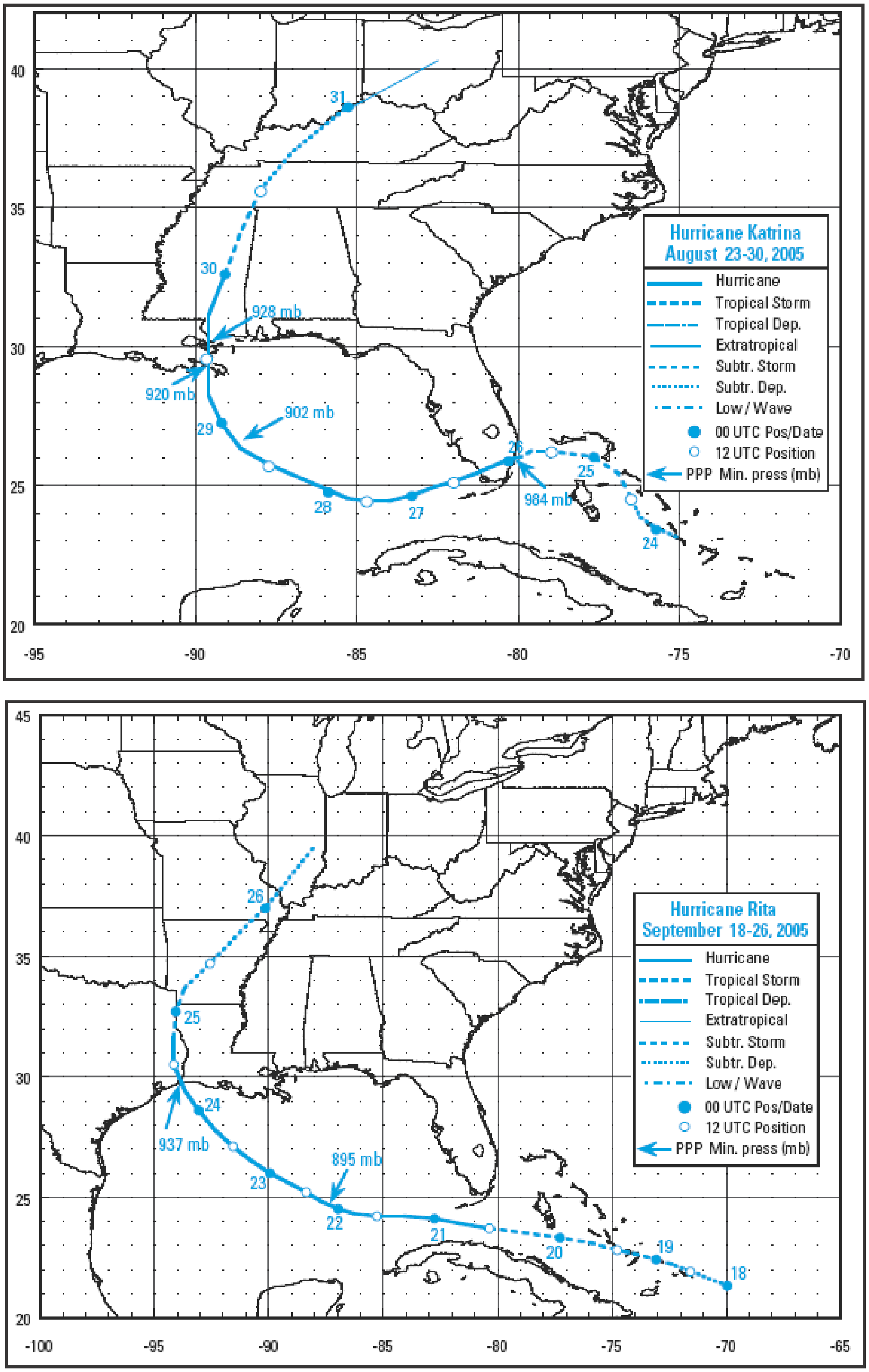


Figure 1.1. Hurricane Katrina and Rita storm tracks and landfall locations in coastal Louisiana.

associated with the storms and their influence on coastal marsh plant species, marsh communities, and entire coastal landscapes.

Hurricane Katrina

Katrina entered the Gulf of Mexico on the morning of August 26th after making landfall in Florida between Hallandale Beach and North Miami Beach as a category one hurricane. After moving west for many hours, favorable sea surface temperatures and western movement of a mid level ridge over Texas allowed Katrina to turn to the northwest and rapidly intensify to a major category 3 with winds of 51.4 m s^{-1} by the early morning of August 27th. As Katrina continued to strengthen, the first hurricane watch for Louisiana was issued at 9:00 am CDT and was upgraded to a warning at 9:00 pm CDT on the 27th as a result of her turning to the west-northwest in the evening hours of the 27th.

By 7:00 am CDT on Sunday, August 28th, Katrina's winds increased to 71.5 m s^{-1}, a very dangerous category 5 hurricane. Katrina continued to strengthen, and by the next advisory (10:00am CDT), maximum sustained winds increased to 78.2 m s^{-1} and hurricane force winds extended outward up to 169 km from the center. Katrina began to turn to the northwest by mid-day on the 28th and forward motion increased to 5.8 m s^{-1} as she advanced toward Louisiana.

Katrina made its initial landfall just south of Buras, Louisiana in Plaquemines Parish at 06:10 am CDT as a strong category 3 storm, with a windspeed of approximately 56.8 m s^{-1} and a central pressure of 920 millibars. Despite hopes of continued weakening and suggestions to such (dry air entrainment and opening of the eye wall), Katrina maintained her strength as she made her second Gulf coast landfall near the LA/MS border with maximum winds speeds estimated to be 54.1 m s^{-1}. She continued to weaken as she tracked off to the NE; however, Katrina was still a category 1 hurricane 161 km inland near Laurel, MS.

Due to the size and intensity of the storm, many reporting stations experienced instrumentation or transmission failure. As a result, total precipitation and the highest winds experienced during the passing of Katrina were not available. Rainfall estimated from local radar suggests 2-day rainfall totals for August 29th-30th ranged from under 2 cm to over 38 cm in parts of southeastern LA and southern MS. The Slidell Louisiana National Weather Service office reported 30 cm of rainfall. New Orleans Lakefront airport (NEW) recorded a peak wind of 30.6 m s^{-1}, and a gust of 38.25 m s^{-1} on the morning of the 29th. New Orleans Armstrong International (MSY) airport recorded maximum hourly winds of 13.77 m s^{-1} and gusts of 20.91 m s^{-1} before failing on the 28th. Maximum sustained wind reported in Biloxi MS was 23.95 m s^{-1} with gusts of 40.2 m s^{-1} at 8am on the 29th.

The storm surge that accompanied Katrina was devastating, especially along the western Mississippi coast. A 32 km wide swath of the MS coast experienced storm surge exceeding 8 m. Estimated LA storm surge from Katrina at initial landfall and throughout the Breton Sound Basin ranged from 3 to 6 m with average absolute errors in the prediction of 0.3 to 0.5 m (Fig. 1.2, Ebersole et al. 2007).

Hurricane Rita

Rita became the ninth hurricane of the season in the Atlantic Basin during the morning of September 20th, 2005. Once Rita reached hurricane status, she intensified rapidly. By the afternoon of September 21, Rita became the second Category 5 hurricane of the season, with top sustained winds of 78.2 m s^{-1}. By 7:00 pm CDT, Rita had become the third most intense hurricane in the Atlantic basin in terms of pressure (897 mb). She was still a strong Category 5 storm the morning of September 22nd, approximately 789 km east southeast of Galveston, TX, but she was beginning a weakening trend. Later that evening, outer rain bands of Rita began having an impact on Louisiana. By the 1:00 pm CDT

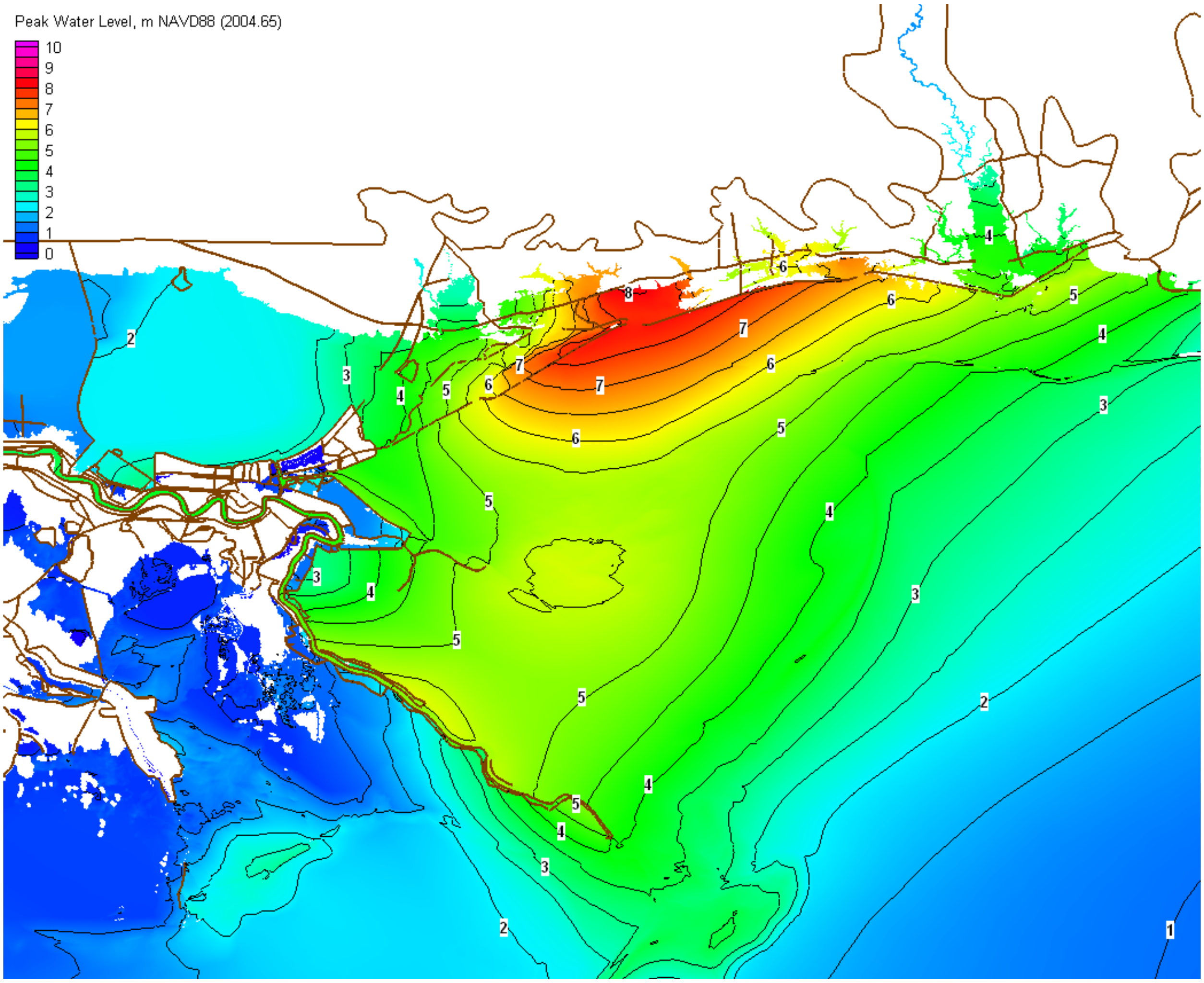


Figure 1.2. Maximum predicted water level (in meters, NAVD 88) for Hurricane Katrina in Southeast Louisiana and Mississippi (Ebersole et al. 2007, modified with permission).

advisory on September 23rd, Rita had taken a NW course and weakened to a Category 3 storm with sustained winds of 55.9 m s^{-1}. Throughout the afternoon and evening hours, Rita neared the LA/TX border and at 2:00 am CDT on September 24th, the northern eye wall had made landfall, and by 4:00 am CDT, the entire eye was over land near Johnson Bayou in western Cameron Parish, Louisiana. Rita was a Category 3 hurricane at landfall with winds of 53.6 m s^{-1} and her path inland took her near Beaumont, TX and Shreveport, LA.

Like Katrina, precipitation totals and highest wind speeds were not captured as a result of instrumentation or transmission failure during the event. The National Weather Service Forecast Center estimated storm total rainfall amounts of 25 to 38 cm in coastal southwest Louisiana. Radar estimated storm totals ranged from just over 2 cm in southeast LA and parts of MS to over 30 cm in southwestern LA and southeastern TX. As for wind speeds, Beaumont/Port Arthur (BPT) recorded sustained winds at 35.8 m s^{-1} and a peak wind of 46.5 m s^{-1} in the early morning hours on the 24^{th}. A buoy near Marsh Island monitored by Louisiana State University measured sustained winds of 31.7 m s^{-1} and a peak gust of 41.6 m s^{-1} during the night of the 23^{rd}. Another buoy station in Louisiana near Calcasieu Pass reported sustained winds of 34.4 m s^{-1} and a peak gust of 49.6 m s^{-1} near midnight on the 24^{th}. The Lake Charles airport (LCH) reported winds of 25.5 m s^{-1} and a gust of 32.6 m s^{-1} during the night of the 23^{rd} prior to station failure.

The circulation of Rita produced northeast winds across southwest Louisiana in advance of the storm causing water level set down. By the afternoon of September 23^{rd}, water began setting up along the coast and water levels in Cameron began rising rapidly. Storm surge levels from Rita recorded at landfall exceeded 4.2 m above NAVD88 at Constance Beach, Creole, and Grand Chenier, Louisiana, located approximately 32 km, 77 km, and 87 km east of the eye landfall location, respectively (Fig. 1.3, McGee et al. 2007).

MATERIALS AND METHODS

Vegetation-salinity zones previously described (Chabreck 1970) and mapped for coastal Louisiana include: swamp, fresh marsh, intermediate marsh, brackish marsh, and saline marsh (Chabreck and Linscombe 2001). In an effort to characterize the potential impacts of storm surge on Louisiana marshes, numerous federal and state agencies collected surface water salinity data at discrete locations throughout the coast and from continuous

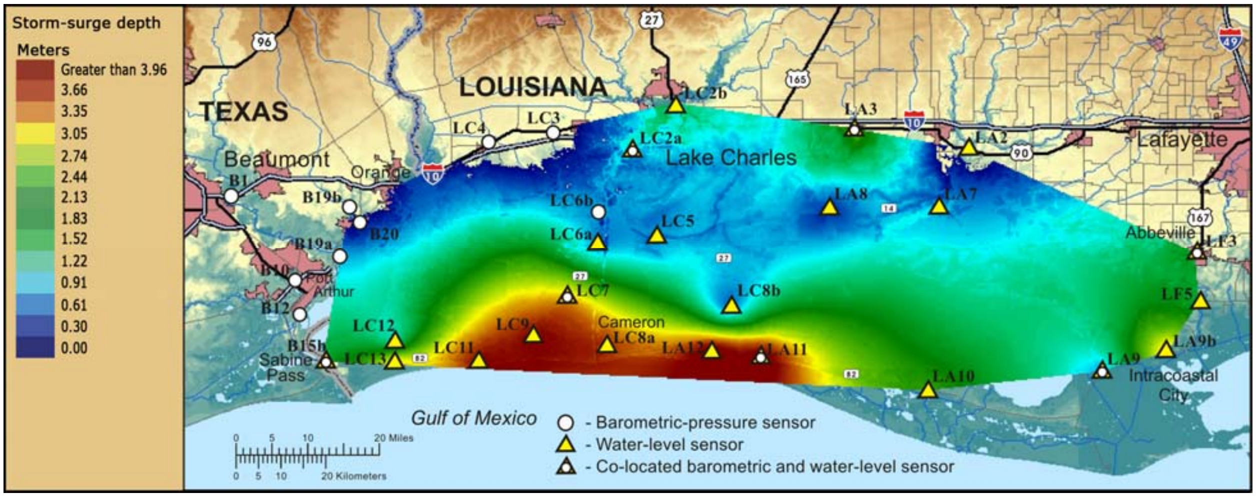


Figure 1.3. Location of USGS storm-surge sensors and computer generated storm-surge depth, in meters, on September 24, 2005 at 3 a.m. in southwestern Louisiana and southeastern Texas (McGee et al. 2007, modified with permission).

recording stations that were still operational after the storms. Storm surge elevation were also measured from high-water marks across coastal Louisiana and continuous water level recorders in the Chenier Plain by the U.S. Geological Survey's Louisiana Water Science Center to assess storm surge heights in response to Hurricanes Katrina and Rita (McGee et al. 2007). The storm surge and salinity data were overlaid on the vegetation-salinity zones to help identify whether the hurricanes caused salt water to be transported into traditionally fresher areas. These data are transitory in nature, however they can provide some supporting information to help understand the spatial extent (primarily on a north-south gradient) and the severity of the salt pulse brought in by the storm surge.

Data on porewater salinity were collected in December 2005 and March 2006 in the Chenier Plain to support investigations of initial salt stress on vegetation communities. Porewater salinity is not as variable as surface salinity, and because it is measured in the plant's root zone, it provides a good measure of salt exposure to the vegetation. These data were collected at 10 and 30 cm depth following procedures described in McKee et al. (1988).

The water quality readings were taken with a portable, hand-held instrument (YSI 30) that provides water temperature (°C), specific conductance (μS/cm), and salinity. Measurements of porewater salinity with pre and post-storm observations of vegetation cover and species composition will provide an indication of initial vegetation impacts and provide a baseline for evaluations of recovery over time.

RESULTS

Coastwide Assessment

Storm Surge

Recorded storm surge from 21 continuous water level recorders in western coastal Louisiana between the Louisiana/Texas border and Freshwater Bayou ranged from approximately 1.5 m to greater than 4.3 m. In eastern coastal Louisiana, high-water marks measured by the USGS National Wetlands Research Center and Louisiana Department of Natural Resources (DNR) in Breton Sound after Hurricane Katrina were in excess of 4.6 m. The data suggest that floodwaters inundated significant acreages of swamp and freshwater marsh communities throughout coastal Louisiana, transferring high salinity waters into these areas which typically experience no or low salt content.

Salinity

Surface salinities were measured at 821 locations across coastal Louisiana between September 26, 2005 and December 13, 2005 (Figs. 1.4 and 1.5). A total of 1,174 discrete observations were gathered on different days and at different times over this time period. Although the surface salinities are highly variable across hourly, daily, weekly and monthly scales, these measurements do clearly show that Hurricane Rita pushed saltwater well into freshwater marsh and swamp areas across coastal Louisiana. The maximum discrete salinity concentration recorded by vegetation type and the normal salinity range as described by

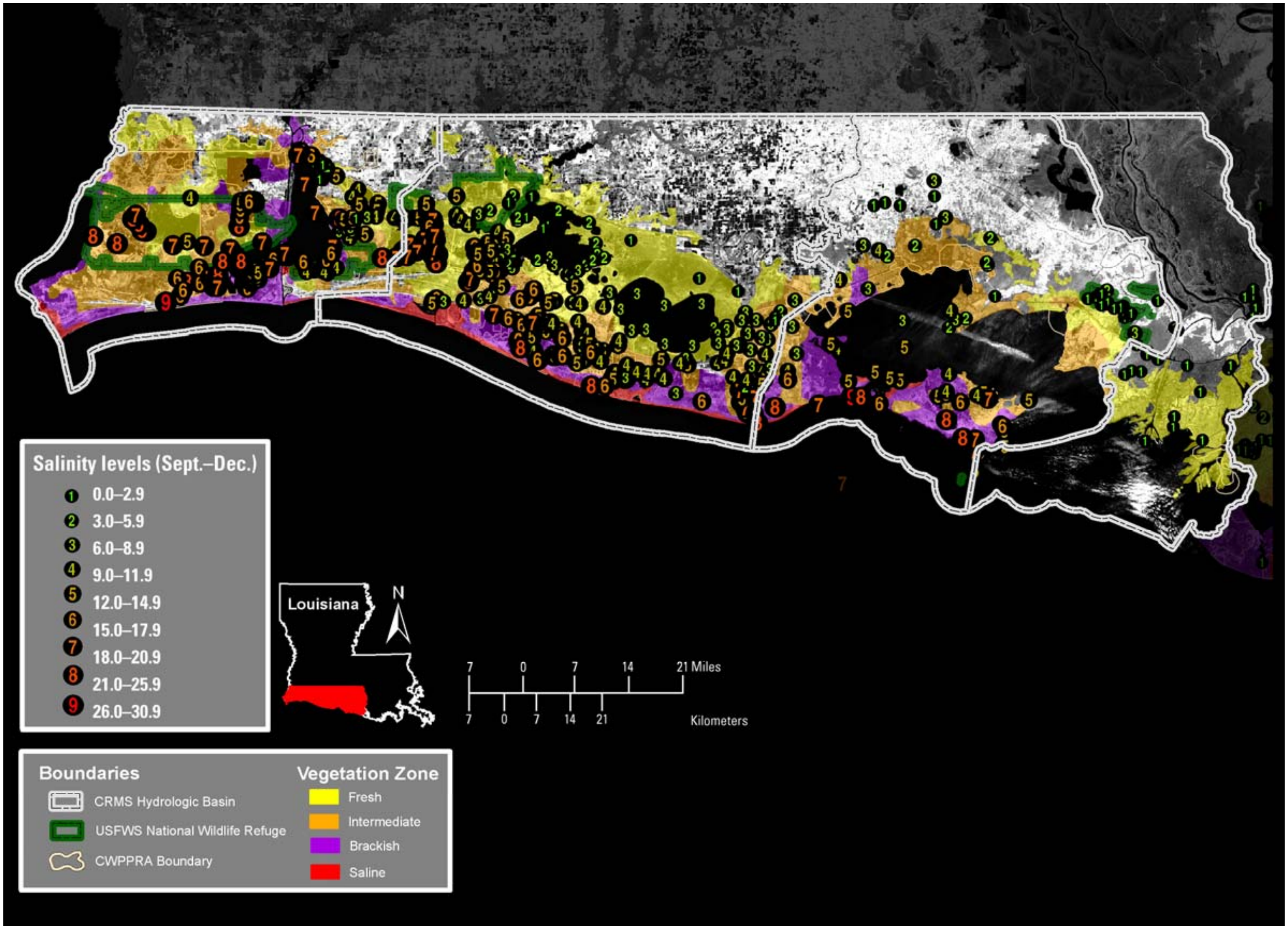


Figure 1.4. Western coastal Louisiana discrete surface salinity measurements (September – December 2005) with proximity to Chabreck and Linscombe vegetation zones (2001) and USFWS refuges.

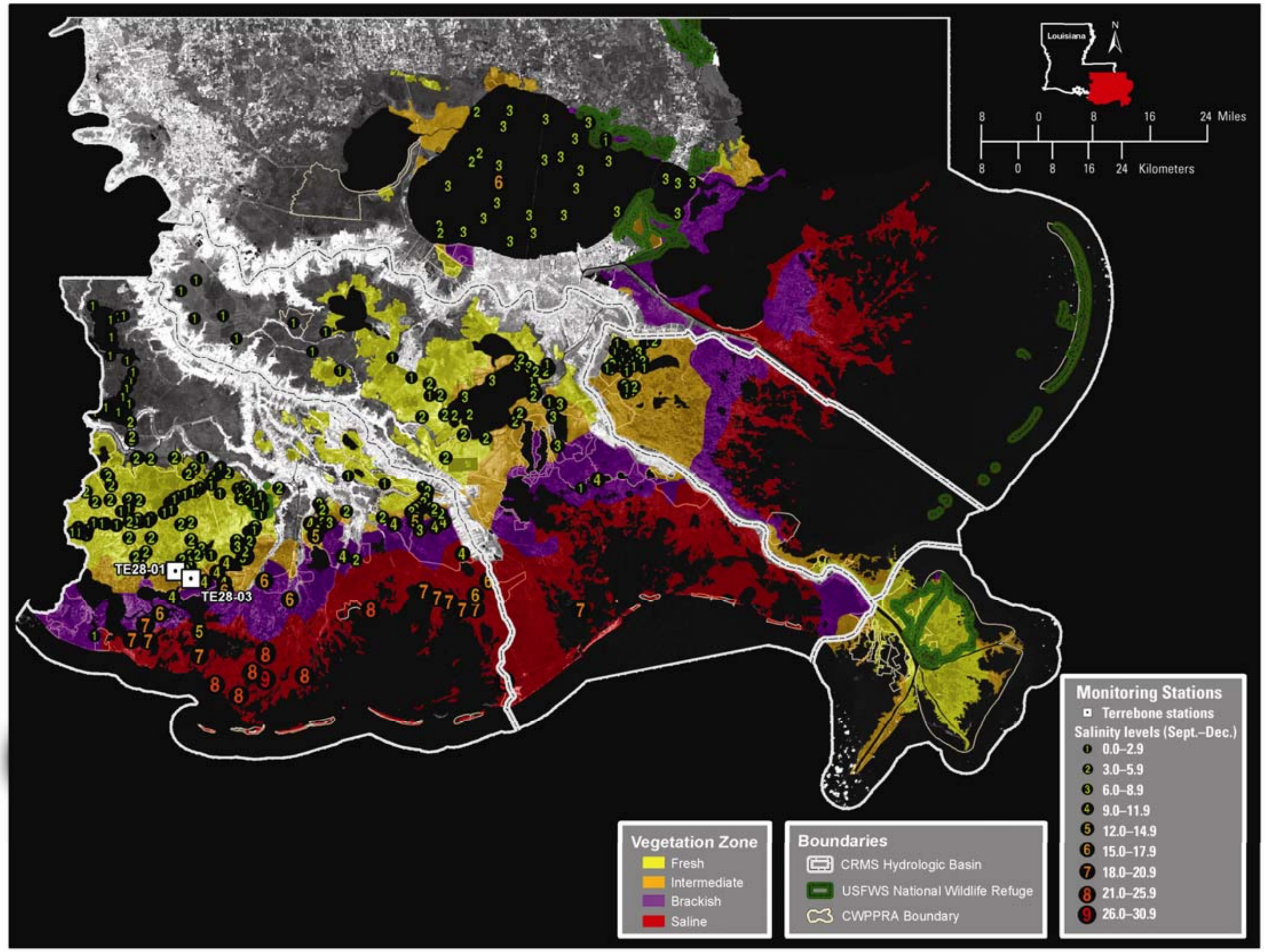


Figure 1.5. Eastern coastal Louisiana discrete surface salinity measurements (September – December 2005) with proximity to Chabreck and Linscombe vegetation zones (2001) and USFWS refuges.

Chabreck (1970) for each of these vegetation types is given in Table 1.1. The spatial distributions of salinity concentrations for western and eastern coastal Louisiana in proximity to vegetation types are shown in Figs. 1.4 and 1.5, respectively.

Limited continuous salinity and water level data within the storm track and hurricane wind fields prohibit a proper examination of spatial and temporal influences of the storms on surface water salinity. However, stations outside of the direct impact areas of the hurricanes illustrate the storm surge effects of Hurricane Rita throughout the Louisiana coast. Stations TE28-03 and TE28-01 are located in the Terrebonne Basin (central Louisiana) and represent a south-to-north transect with increasing distance from the higher salinity waters of the Gulf of Mexico (Fig. 1.5). Station TE28-03 is located in an intermediate vegetation zone (see Table 1.1 for typical salinity ranges in vegetation zones). The effects of Hurricane Katrina at this station were minimal, with only a slight reduction in salinities following the receding water levels (Fig. 1.6A). After the passage of Hurricane Rita, surface water salinity concentration peaked at almost 23, and high salinity levels continued for almost 2 months. The mean and range of observed salinities in October and November 2005 (post Rita) are greater than that would typically be expected in an intermediate vegetation zone (Table 1.1). Station TE28-01 is located within a fresh vegetation zone. The effects of Hurricane Katrina at this station were negligible (Fig. 1.6B). Surface salinity concentration peaked at nearly 17 following Hurricane Rita, and maintained levels above 6 for the duration of the data record, which ended on December 6, 2005. The mean and range of observed salinities in October and November 2005 (post Rita) are much greater than that would typically be expected in a fresh vegetation zone (Table 1.1). Summary statistics and charts from continuous gauge records for these stations are presented in Table 1.2 and Fig. 1.6, respectively.

Table 1.1. Typical salinity ranges found within various vegetation types in coastal Louisiana (Chabreck 1970) and maximum discrete salinity measurements of surface waters recorded between September and December 2005.

Vegetation type	Typical salinity range	Maximum salinity measured
Swamp	0 - 0.5	8
Fresh marsh	0 - 3	26
Intermediate marsh	2 - 8	26
Brackish marsh	4 - 10	34
Saline marsh	8 - 29	30

Note that the salinity of ocean water is approximately 35.

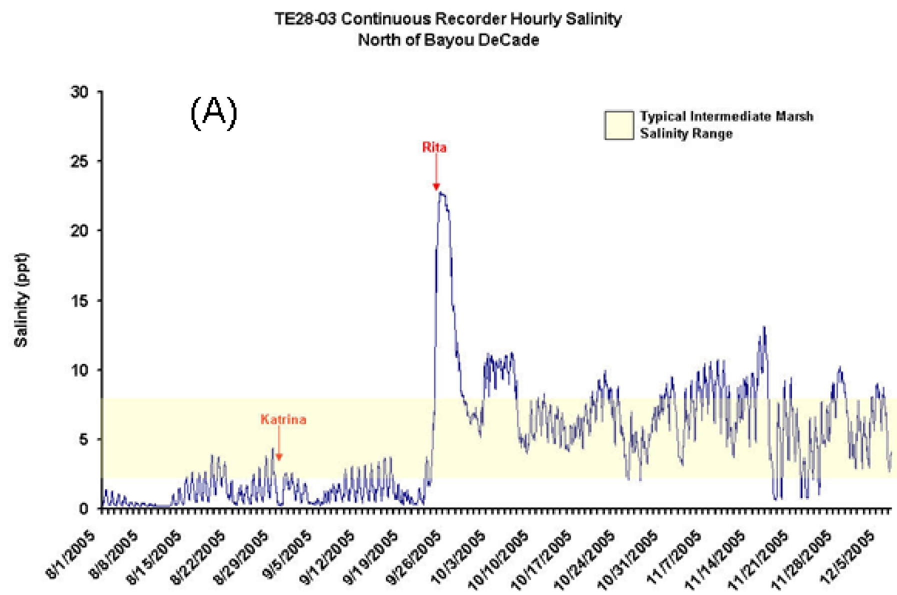
Table 1.2. Post-hurricane salinity range and mean by month from August to November 2005 and pre-hurricane mean salinity readings from 2002-2004 at stations TE28-03 and TE28-01. Standard deviations are provided in parentheses.

	2005 Salinity range	2005 Mean salinity	2002-2004 Mean salinity
Station TE28-03			
Aug	0.19 - 4.38	1.10 (0.93)	0.40 (0.54)
Sep	0.25 - 22.83	4.24 (6.03)	1.70 (1.50)
Oct	2.02 - 11.31	6.89 (2.05)	1.82 (2.24)
Nov	0.68 - 13.18	6.63 (2.65)	2.05 (1.62)
Station TE28-01			
Aug	1.14 - 2.02	1.47 (0.27)	0.42 (0.51)
Sep	0.20 - 16.92	4.48 (5.45)	1.56 (1.48)
Oct	6.57 - 13.13	9.15 (1.28)	2.35 (1.91)
Nov	6.35 - 8.75	7.43 (0.63)	3.29 (2.50)

Chenier Plain Assessment

Porewater Salinity

Porewater salinity concentrations were measured at 30 locations within the Sabine Basin on December 14 and 15, 2005 and March 27 and 29, 2006 (Fig. 1.7). There was no



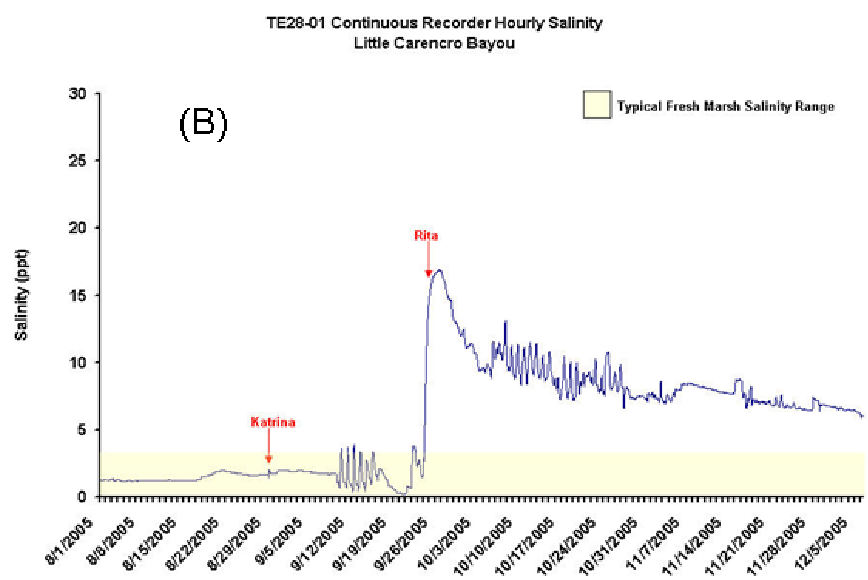


Figure 1.6. Hourly salinity from continuous recorders at the Terrebonne Basin stations (A) TE28-03 and (B) TE28-01 from August 1, 2005 to December 6, 2005.

porewater available at 10 cm depth, so all salinities reported are from 30 cm. Porewater salinities ranged from 5.0 to 17.8 with a mean of 11.1 in December and ranged from 5.1 to 17.9 with a mean of 12.2 in March. The results suggest that the saltwater was not being flushed from the system, and even more worrisome was that salinities increased by

over 1 from December 2005 to March 2006 at 38% of the sampling stations. These concentrations, measured at three and six months after Hurricane Rita, are outside the normal range described in Chabreck (1970) for the intermediate marsh plant species found within the study area except for *Spartina patens*.

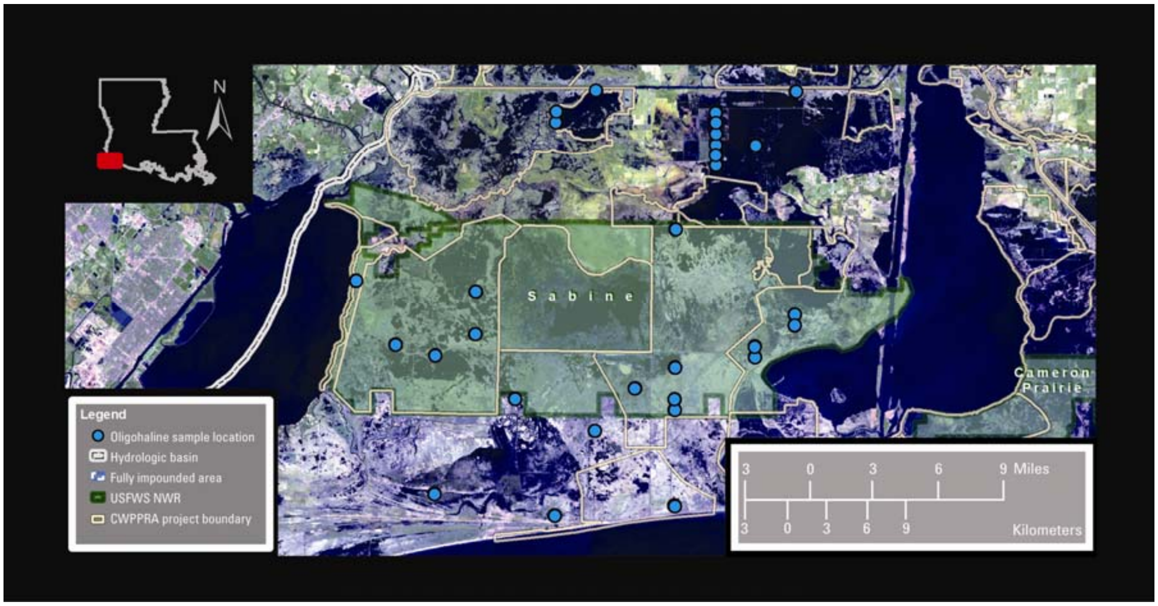


Figure 1.7. Porewater salinity concentration sampling locations within the Sabine Basin during December 2005 and March 2006.

<u>Vegetation</u>

The dominant vegetation species found at our intermediate marsh sampling locations were *Spartina patens*, *Schoenoplectus californicus*, and mixed communities of *Spartina patens*, *Typha latifolia*, and *Phragmites australis*. Site specific observations from all sampling locations generally showed the most severe physicochemical impacts in *Typha latifolia* communities, followed by *Schoenoplectus californicus*, *Phragmites australis*, and *Spartina patens*. Sampling stations that are further away from tidal influence generally appear to show greater signs of stress. Within many of these interior marsh stations porewater salinities continued to increase due to evapotranspiration; and short-term recovery of existing marsh species was limited. From December 2005 to

March 2006, it was apparent, however, that when tidal flushing occurred as shown in Fig. 1.8, plant stressors were reduced facilitating vegetation recovery. Pre-hurricane versus post-hurricane photographs of representative vegetation community types shown in Figs. 1.9, 1.10 and 1.11 illustrate the short-term effects of Hurricane Rita on marsh vegetation.

POTENTIAL IMPLICATIONS

Plant communities are defined by how individual plant species respond to salinity and other stressors and how species interact under stressed conditions (McKee and Mendelssohn 1989, and Howard and Mendelssohn 1999). Salt stress associated with elevated salinities following Hurricanes Katrina and Rita may influence the vegetation community structure throughout the study area, however, salt tolerance is species specific. Intermediate to brackish species such as *Spartina patens*, *Typha latifolia*, *Schoenoplectus californicus*, and *Phragmites australis* respond differently to salt stress depending on duration of exposure, rate of salinity increase, mineral content of the soil, and submergence (Webb and Mendelssohn 1996, Howard and Mendelssohn 1999).

Spartina patens is the dominant marsh plant within the Chenier Plain of southwestern Louisiana (Taylor and Grace 1995, Visser et al. 1999). Of the species found in our study area, *Spartina patens* can tolerate a wide range of salinity and generally recovers quickly from environmental stressors. *Phragmites australis*, another resilient species, has been shown to tolerate a wide range of salinity and inundation (Matoh et al. 1988). However, within the study area *Phragmites australis* stands browned by the saltwater surge had not recovered within 6 mo of the hurricanes. *Phragmites australis* generally grows taller than the other mixed species and is particularly susceptible to physical damage from the hurricanes. This physical disturbance may be an additional factor contributing to the recovery time for *Phragmites*

Figure 1.8. An aerial photograph from the lower Mermentau River showing the effects of tidal flushing on lowering salinity stress on adjacent marsh vegetation.

australis. *Typha latifolia* is less tolerant of saline conditions and has shown reduced growth at salinities greater than 3-5 (Hocking 1981). *Typha's* sensitivity to elevated salinities continued to be evident in the March 2006 sampling, as minimal recovery was observed in areas previously dominated by *Typha*.

This 6-mo assessment of salt water storm surge illustrates the broad extent of salt water inundation across coastal Louisiana and potential impacts to Louisiana's coastal vegetation communities. Observations from this assessment suggest post-hurricane weather will be an important factor in recovery. Coastal Louisiana was in an extended drought, beginning prior to the hurricanes of 2005, contributing to the unavailable porewater at 10 cm depth. The resulting lack of rainfall intensified porewater salinities. Hydrologic connectivity and duration and frequency of flooding also influenced the extent of salinity and other biogeochemical stressors such as sulfide on vegetation recovery. The most obvious finding from this initial assessment is that the impacts and recovery from Hurricanes Katrina and Rita will vary greatly over time and space and that research objectives must address questions at multiple scales.

Figure 1.9. *Spartina patens* and *Typha latifolia* dominated community. May 11, 2005 (left), January 12, 2006 (middle), and March 27, 2006 (right).

Figure 1.10. *Schoenoplectus californicus* dominated community with *Spartina patens*. May 12, 2005 (left), January 12, 2006 (middle), and March 27, 2006 (right).

Figure 1.11. *Schoenoplectus californicus* and *Typha latifolia* dominated community. September 16, 2005 (left), October 26, 2005 (middle) and March 27, 2006 (right).

RESEARCH OBJECTIVES

The objectives are to provide an understanding of how Hurricanes Katrina and Rita influenced vegetation changes in coastal Louisiana using research studies and

assessments designed at site specific, landscape and coastwide scales. The following research questions will be addressed in chapters 2, 3, and 4.

(1) Can the Normalized Difference Vegetation Index (NDVI) accurately detect changes in vegetation condition within different habitat types following hurricane disturbance?

(2) What was the extent of impact to herbaceous emergent vegetation communities across coastal Louisiana and to what extent have they recovered?

(3) What are the dominant spatial patterns of vegetation recovery?

(4) Were there changes in vegetation species dominance and shifts in marsh community types?

(5) How did the level of salinity and/or sulfide concentrations in soil porewater influence marsh community dynamics and recovery?

(6) How did sediment deposition from Hurricane Rita vary with distance from storm track, distance from Gulf of Mexico (GOM) or other large water bodies, and in areas under different hydrologic management?

(7) What are the relative contributions of organic and mineral accumulation to sediment accretion rates in Sabine Basin marshes dominated by *Spartina patens*?

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CHAPTER 2

MONITORING VEGETATION RESPONSE TO EPISODIC DISTURBANCE EVENTS BY USING MULTITEMPORAL VEGETATION INDICES

INTRODUCTION

Hurricanes are significant episodic disturbances that impact vegetated landscapes in coastal areas (Conner et al. 1989, Guntenspergen et al. 1995, Keim et al 2007). The impacts are from physical scouring and displacement of marsh (Morgan et al. 1958, Barras 2007a) as well as physiological impacts such as saltwater intrusion and flooding stress (Shiflet, 1963, Wright, et al. 1970, Guntenspergen et al. 1995, Steyer et al. 2007). These impacts have been well described at local, site-specific scales but not at coastwide scales, in part because of the inability to acquire comprehensive coastal datasets. Remotely sensed monitoring can resolve these limitations by providing a platform by which large spatial areas can be assessed repeatedly over time.

Remote sensing of canopy reflectance by using vegetation indices has become one of the most valuable and readily available tools for regional- and ecosystem-scale research and management applications. The Normalized Difference Vegetation Index (NDVI), which is an index to detect live, green plant canopies, has been used in many ecosystems to establish relationships with vegetation productivity, leaf area index, fraction of radiation intercepted, and canopy cover and has allowed for the detection of seasonal phenologies and possible stressors that influence these phenologies (Gamon et al. 1995, Rundquist 2002, Filella et al. 2004, Pettorelli et al. 2005). In wetland landscapes, NDVI has been used to estimate above-ground biomass and productivity (Hardisky et al. 1984, Gross et al. 1993) and wetland species distributions (Klemas et al. 1993, Zhang et al. 1997) and to detect hurricane damage (Ramsey et al. 1997). Ramsey

et al. (1997) used NDVI to investigate damage in a forested wetland following the passage of Hurricane Andrew (1992) in Louisiana and found that changes mimicked damage and recovery patterns identified from post-hurricane videography and that abnormal phenologies could be clearly detected.

Although the relationship between NDVI and characteristics of wetland vegetation canopy has been established at the site level within primarily salt marsh communities (Gross et al. 1989), there are limited data relating spectral reflectance indices to field-site measurements of cover, biomass, or productivity at landscape scales. Additionally, even fewer studies have linked NDVI to measurements of canopy structure in landscapes with multiple habitat types and in landscapes exposed to episodic stress. Penuelas et al. (1993) demonstrated that for a small lake in California, spectral reflectance characteristics could be distinguished between emergent, submerged, and floating aquatics and that the NDVI values of the emergent aquatic plants were significantly correlated with biomass. Hope et al. (1993) also found a relationship between above-ground biomass and NDVI in wet sedge tundra in Alaska and, along with Boelman (2003), suggest that this relationship can be community specific. Wetland vegetation communities (habitat types) within coastal Louisiana have been well described and mapped according to major vegetation associations in 1949, 1968, 1978, 1988, 1997, and 2001 (Penfound and Hathaway 1938, O'Neil 1949, Chabreck 1972, Visser et al. 1998, Visser et al. 2000, Chabreck and Linscombe 2001), providing the opportunity to test whether temporal trends in the NDVI vary by habitat type and whether NDVI can be used to detect changes in condition within habitat types following ecosystem disturbance.

Hurricanes Katrina and Rita

Louisiana's coastal wetlands experienced two Category 3 hurricanes within a 3-week period in late summer 2005 that directly impacted regions in east and west Louisiana and indirectly impacted the central region. Hurricane Katrina struck eastern Louisiana on August 29 with storm surge estimated between 3 and 6 m (Ebersole et al. 2007). In the west region, storm surge of Hurricane Rita exceeded 4 m at landfall on September 24 (McGee et al. 2007); however, flooding effects were identified across all regions of the coast (Doyle et al. 2007). The storm surge brought in high salinity water, exposing forested wetlands and fresh, intermediate, and brackish marshes to salinities outside their typical ranges (Doyle et al. 2007; Steyer et al. 2007). Additionally, portions of western Louisiana were subjected to persistent surge-induced flooding from October 2005 through April 2006 based on satellite image analysis (Barras 2006, 2007a, 2007b). The wave and surge also contributed to substantial physical disturbance where marsh vegetation was either partially or completely removed. These shears were detected in Landsat Thematic Mapper ™ imagery as persistent, new open water bodies (Barras 2006, 2007a, 2007b). The current study investigated the method of combining the use of field data (vegetation cover) with data from the NDVI and on land change to evaluate the impacts and recovery of several habitat types in coastal Louisiana following Hurricanes Katrina and Rita. We explored the extent to which impacts were due to physical disturbance or other physicochemical factors, how the impacts varied by habitat type and region, and whether the impacts were persistent. Additionally, we investigated the relationship between coarse resolution (250 m NDVI), moderate resolution (25 m TM), and fine resolution (4 m^2 cover plots) datasets and their utility in interpreting disturbance patterns.

MATERIALS AND METHODS

Study Area

The study area consists of the entire coastal area of Louisiana, with boundaries consistent with the Louisiana Coastal Area (LCA) trend assessment boundary (Barras et al. 2003; Fig. 2.1). This 33,458-km^2 complex of wetlands and open water extends from the Texas-Louisiana line to the Louisiana-Mississippi border and encompasses habitat types from freshwater swamps and marshes in the north to salt marshes and barrier islands adjacent to the Gulf of Mexico to the south. For the purposes of this study, fastlands (developed and agricultural areas surrounded by levees that are generally considered nonwetlands in Louisiana) and other developed and agricultural lands were excluded from analysis. These exclusions leave a 2004 wetland base of 14,312.3 km^2 for the NDVI analyses. Three regions were delineated within the study area to assess the direct effects of Hurricane Katrina (east) and Hurricane Rita (west) as well as the indirect effects (central) of both hurricanes. The Mississippi River is the boundary between the east and central regions and Freshwater Bayou is the boundary between the central and west regions (Fig. 2.1). Regional landscapes exposed to hurricane landfall and a minimum 2 m storm surge was used to delineate regions directly impacted. Indirect hurricane impacts included exposure to tropical force winds and flooding in some locations within the regional landscape.

Vegetation Index Imagery

Vegetation indices (VI) derived from the MODerate Resolution Imaging Spectroradiometer (MODIS) provide temporally consistent data (16-day composites) at a spatial frequency of 250 m. Because this combination of temporal and spatial resolution

is often considered ideal for regional-scale assessment of vegetation, MODIS 16-day composite vegetation indices (MOD13Q1 L3 V004) were chosen as the data sources for

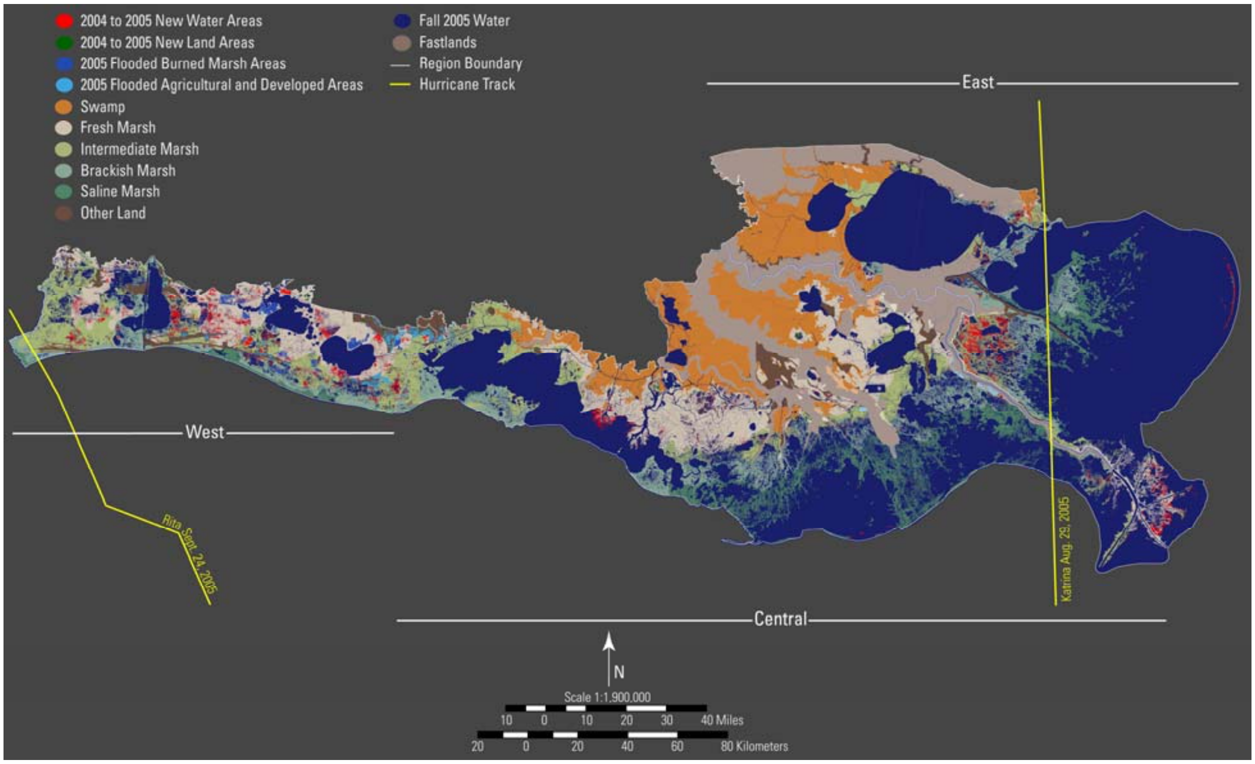

Figure 2.1. The location of the study area showing land-water area changes by marsh vegetation community types in Louisiana shortly after Hurricanes Katrina and Rita landfalls in 2005 (Barras 2007a). Red represents new open water (decreased land) areas that formed after the hurricanes based on comparison of 2004 and 2005 Landsat Thematic Mapper satellite imagery. Regional assessment areas and hurricane tracks are also delineated.

this assessment. The NDVI is a ratio that exploits varying absorption and reflection characteristics of red and near-infrared (NIR) wavelengths of light. Reflection of red wavelengths of light decreases as chlorophyll in healthy, photosynthetically active leaves absorb this energy. In contrast, reflection of NIR wavelengths increases with increasing vegetative vigor and biomass. The NDVI formula [NDVI = (Xnir – Xred)/(Xnir + Xred)] results in a theoretical range from -1 to +1. A highly negative NDVI value typically denotes water or an absence of green vegetation, an NDVI value close to zero denotes no

green vegetation, and an index value approaching +1 indicates high density of vigorous vegetation.

MODIS VI products are provided based on the Integerized Sinusoidal Grid. Tiles are identified based on horizontal and vertical grid IDs. Data utilized in this study included tiles h09v05, h09v06, h10v05, and h10v06. Further details describing the MODIS VI product preprocessing, compositing, and quality assessment can be found in Huete et al. (1999). Imagery was collected for the period of February 18, 2000, to March 5, 2005, to create baseline monthly average NDVI composites. Imagery from March 6, 2005 to December 3, 2006, was used to create monthly average NDVI composites for hurricane year evaluations. In total, 468 tiles were used to create the baseline composites, and 156 tiles were used to create the hurricane evaluation composites. Individual tiles were resampled and projected to Albers Equal-Area Conic Projection for North America, then mosaiced on a 16-day basis.

The first step in examining the effects to the vegetative community was to establish a baseline for comparison. Comparing post-hurricane imagery on a monthly basis minimizes variability caused by senescence periods and other intra-annual variations, facilitating the isolation of hurricane impacts. Before monthly composites were created, the 16-day composites were subjected to further quality assessment and quality control (QAQC) masks, cloud recognition and abnormality exclusion algorithms. Though the original MODIS algorithms for maximum value compositing (MVC) produces relatively cloud-free images, persistent cloud cover or aerosol contamination can lead to pixels that are contaminated or of unreliable quality in the final 16-day composite. Therefore, a secondary compositing methodology was employed to exclude these values from the average composites.

Those pixels with QAQC values representing "produced but with unreliable quality," "produced but contaminated with clouds," or "not produced because of bad quality" were recoded to a null value and excluded from consideration in the monthly averaging algorithm. For the baseline composites, the recoded images for that month were then inserted into an algorithm that further excluded contaminated or abnormal pixels whose values were not recognized as unreliable by the original preprocessing algorithms. For each pixel in the image, this processing step calculated the standard deviation of the included pixels for a given month, then recoded and excluded pixels whose values were 1.5 standard deviations greater than or less than the mean. The remaining included pixels were then summed and divided by the count of included pixels to form the final baseline composites.

Whereas monthly baseline averages were typically created from ten-fourteen 16-day composites, most composites for evaluating the hurricane year drew on only two 16-day composites to form the monthly average. In this case, exclusion based on standard deviations from the mean was not performed, and only the initial exclusion based on the QAQC flags was utilized. In the event that both pixels for a given month were flagged as "unreliable quality," the pixel was recoded to a null value. No further inferences can be drawn by comparing these pixels to their baseline monthly average. For pixels in which a composite to evaluate a hurricane year was calculated, pixels were then compared to the corresponding baseline composite to create a departure-from-average dataset (NDVI departure).

The NDVI departure datasets were used to classify the extent and severity of hurricane impacts. The 3 classes defined for this study are (1) anomaly, identified as below or above average NDVI departure values; (2) significant damage, identified as an

excess of one standard deviation lower than the baseline average NDVI value; and (3) persistent damage, identified as an excess of one standard deviation lower than the baseline average NDVI values during 12 out of the 14 months following a hurricane event.

Supporting Datasets

Recent identification of regional hurricane impacts was conducted by Barras (2006) by obtaining and interpreting Landsat TM imagery by using ERDAS IMAGINE® software to identify new water bodies appearing soon after hurricane landfalls. Standard methodology was used to classify land-water conditions and identify changes between 2004 and 2005 (Barras et al. 2003; Morton et al. 2005). The pre-hurricane land-water classification used images acquired between October 13 and November 7, 2004, and the post-hurricane images were acquired for 2005 between October 16 and October 25, 2005. The same methodologies were used in creating a 2006 land-water dataset from imagery acquired on October 28, 2006 (Barras 2008). New open water areas in 2005 that remain classified as open water in 2006 were classified as persistent new water areas. Classification of persistent new water included areas with physical scouring of marsh and removal of land as well as persistent flooding. The classification of persistent new water areas between 2004 and 2006 was used as a mask to identify areas of persistent damage in the NDVI values that were attributed primarily to physicochemical stressors (e.g., salinity).

Measurements of vegetation cover, species composition and relative abundance were conducted between October 12 and November 1, 2005, and remeasured between September 6 and October 3, 2006, at 130 historical monitoring stations (4 m^2) located within the impact zone of Hurricanes Katrina (east region) and Rita (west region) by

using the Braun-Blanquet method described in Steyer et al. (1995). In addition, 102 stations were established after the hurricanes to measure the same vegetation variables that were sampled across coastal Louisiana in 2006, in Spring (March 23-29), Summer (July 7-11), and Fall (October 28 – November 3) in order to assess vegetation recovery. Calculations of NDVI values from 250 m pixels corresponding to these vegetation stations were directly compared on a station-by-station basis. Changes in cover between 2 time periods were compared with changes in NDVI values from the same time periods.

Trying to correlate remotely sensed data of relatively low spatial resolution with fine-scale, ground-based vegetative sampling has inherent problems (Gould 2000, Fairbanks and McGwire 2004, Rocchini 2007), especially in heterogeneous and fragmented environments such as the coastal ecosystems of south Louisiana. However, these complications and the assumptions necessary for utilization of the plot data were considered reasonable in the present study, where the objective was not absolute accuracy but a relative evaluation of vegetation response and recovery.

Regression and correlation methods were used in this study to investigate the relationships among NDVI values, land change, and vegetation cover. We performed the statistical analyses by using SAS® software (SAS 2002).

RESULTS

NDVI Baseline Data (2000 – 2005)

The monthly baseline NDVI values for each of the predominant habitat types in coastal Louisiana by region illustrate the influence of season, growth phenology, plant morphology, and landscape fragmentation on NDVI (Fig. 2.2). The temporal profile clearly illustrates the growing season in coastal Louisiana with increasing NDVI values in March and April associated with spring green-up, highest NDVI values in summer,

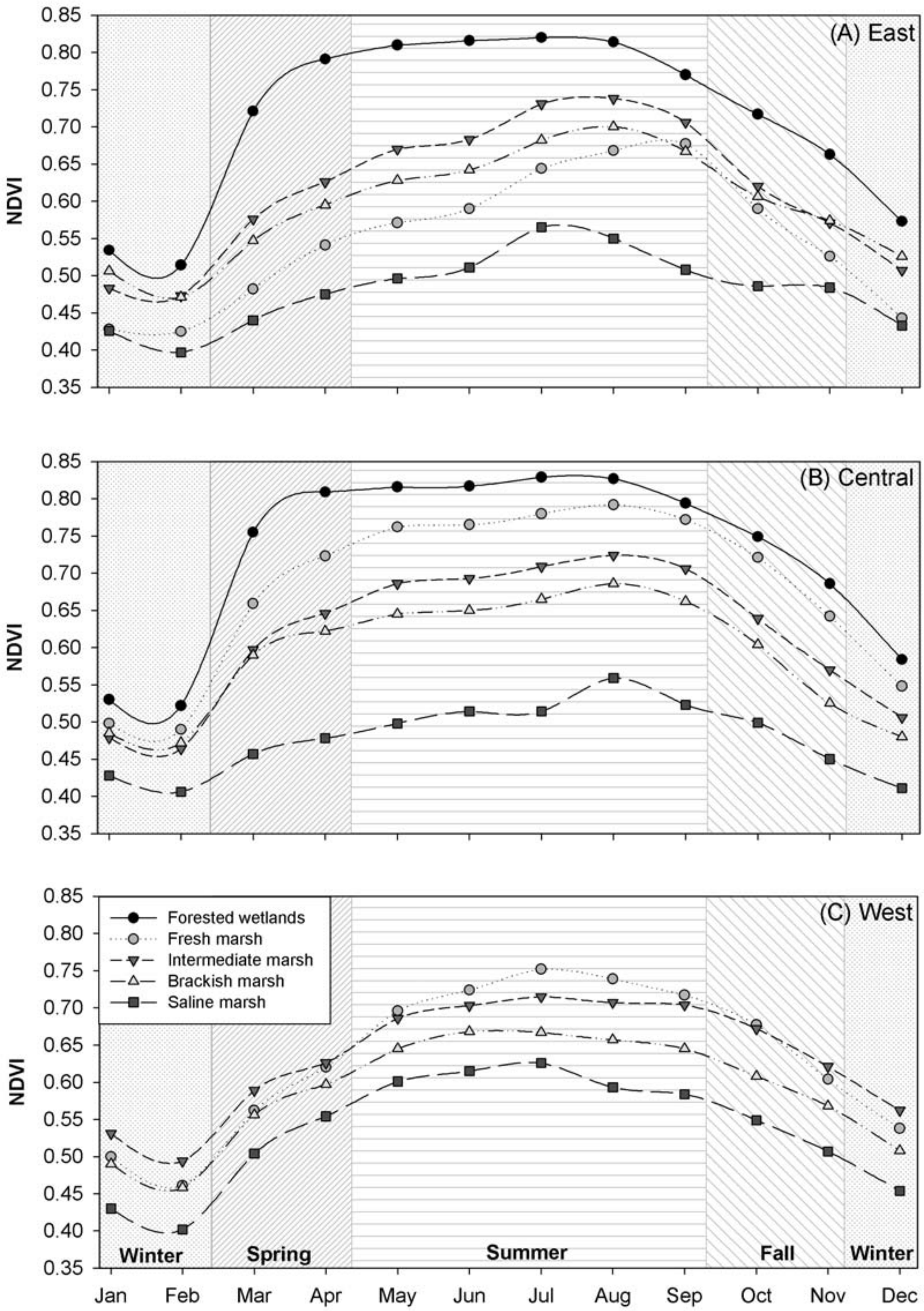

Figure 2.2. Seasonal trends of mean values in the Normalized Difference Vegetation Index (NDVI) by habitat type and regions within coastal Louisiana: (A) East, (B) Central, and (C) West. The mean NDVI value is a monthly average composite derived from imagery collected for the period of February 18, 2000, to March 5, 2005, and serves as the baseline value in the study.

and lowest values in October through February associated with senescence of emergent vegetation and forest leaf-off conditions in the winter. The NDVI summarized by habitat types showed lowest values in saline marsh followed by brackish marsh < intermediate marsh < fresh marsh < forested wetland. The fresh marsh in the east was the only deviation in this pattern and may be attributed to (1) fresh marsh comprising less than 1% of the vegetated landscape in this region and (2) high percentages of water found in this fresh marsh zone. The NDVI values by habitat type are also consistent with the extent of open-water area within each zone.

Departure Patterns and Trends in NDVI Values

Anomaly patterns in the NDVI values for coastal Louisiana are shown in Fig. 2.3. A substantial decline in vegetation density and vigor was observed across the east region from August 2005 to September 2005 following Hurricane Katrina (Figs. 2.3A and 2.3B) and was prevalent across all regions from September 2005 to October 2005 following Hurricane Rita (Figs. 2.3B and 2.3C). The yellow to red color ramp depicts increasing severity of departure from average NDVI values across the coast. The greatest anomalies are located in the direct hurricane impact areas. A conspicuous feature of these data is the large spatial extent of the Hurricane Rita impact, encompassing both direct and indirect areas. The departure patterns in the NDVI values suggest that over 4,714 km^2 or 33% of the prestorm coastal wetland area of Louisiana experienced an immediate and significant decline in the density and vigor of vegetation in October 2005, with the greatest amount of impacted vegetation in the west region at 2,400 km^2, followed by the central region at 1,268 km^2 and east region at 1,046 km^2 (Fig. 2.3C). These impacts occurred over 76% of the prestorm coastal landscape area represented in the west, while only 18% in the central region and 33% in the east region. Above average NDVI values

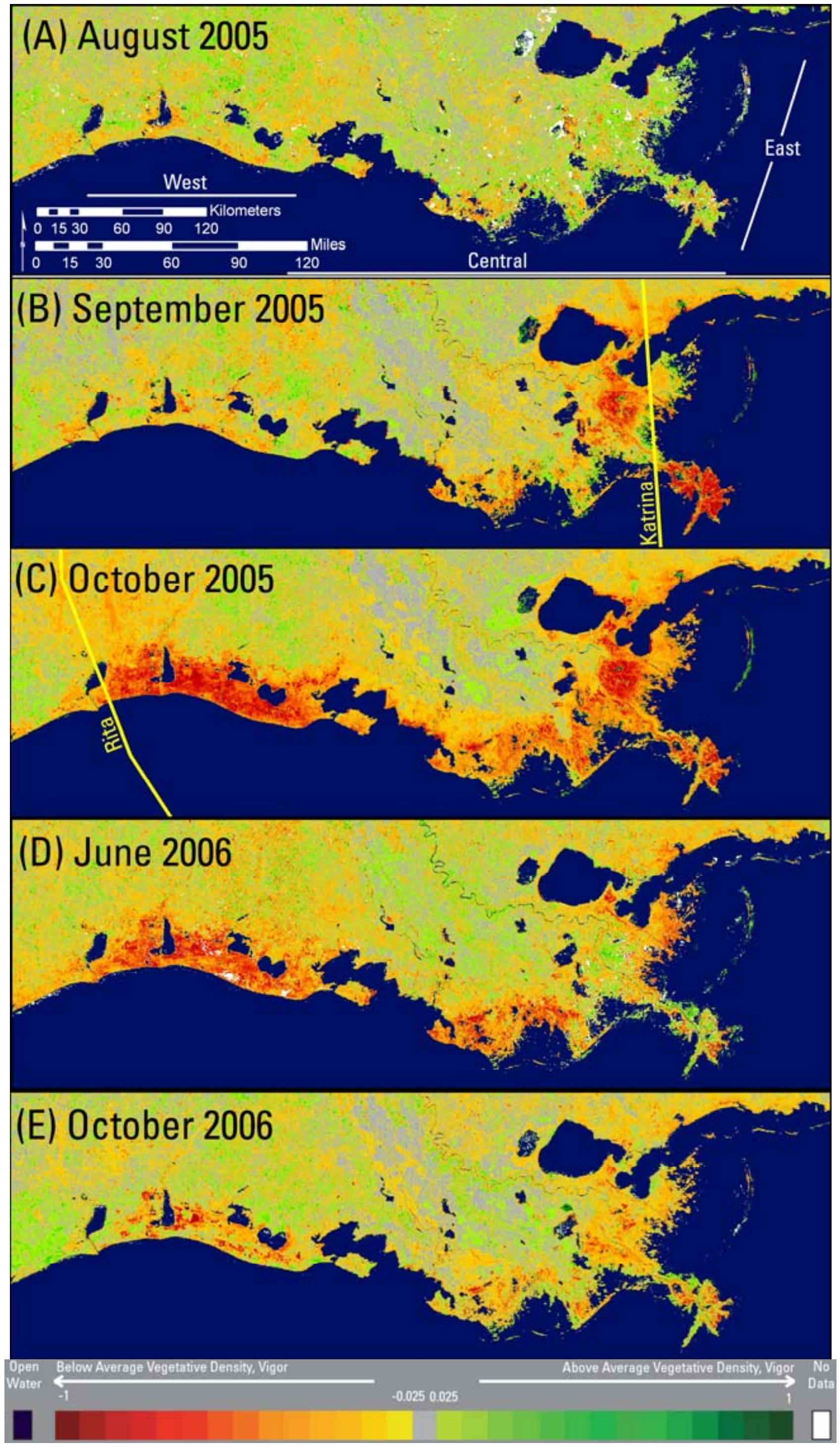

Figure 2.3. Departure from average patterns using the Normalized Difference Vegetation Index (NDVI) for the study area from August 2005 (before hurricanes Katrina and Rita), September 2005 (immediately after Hurricane Katrina), October 2005 (immediately after Hurricane Rita), June 2006, and October 2006 (one year after Hurricane Rita). Red and green color ramps represent below-average and above-average vegetation density and vigor, respectively.

(green color ramp) became conspicuous across broader landscapes in June 2006, but only in the east and central regions (Fig. 2.3D). The majority of the coast remained at below-average NDVI values in October 2006, one full growing season after the hurricanes, with significant departures from average NDVI values (Fig. 2.3E); however, all regions of the coast showed recovery in vegetation condition towards the end of the first growing season.

The monthly time series showing anomalous departures from average NDVI values illustrate effects of Hurricane Katrina in September 2005 and the combined effects of Hurricanes Katrina and Rita after September 2005 (Fig. 2.4). At a regional scale, the immediate departures from average suggest that Hurricane Katrina substantially reduced vegetation condition in the east with minimal influence in the other regions; whereas Hurricane Rita immediately influenced all regions. The departure values for emergent marshes after the hurricanes generally show positive trends through the winter, negative trends through midsummer, and positive trends from late summer to fall. The positive trend in the winter is misleading because you would expect smaller departures between baseline and post-hurricane winter months due to naturally occurring vegetation senescence. There was minimal variation in departure values in the forested wetlands throughout the study period, with a typical departure of less than -0.03 immediately following the storms. Forested wetlands were also the only habitat type where significant above-average departures occurred (in December 2005 and February 2006).

In the east region, fresh and intermediate marsh suffered the most dramatic and immediate impacts of Hurricane Katrina, with mean departure values of -0.43 and -0.30, respectively in September 2005 (Fig. 2.4A). The fresh marsh, however, rapidly improved by December 2005 with a departure value of -0.031, before a declining trend through the

early summer. A second strong recovery occurred between May and June 2006 when NDVI values reached pre-hurricane baseline values. The intermediate, brackish, and saline marshes had similar below-average departure curves throughout the hurricane time period except during June and July, the period of peak vegetation biomass, when below average salt marsh departures were much greater than in the other marsh types.

The central region experienced the smallest departure from average, with mean departure values never exceeding -0.26 across all habitat types during the post-hurricane time period (Fig. 2.4B). Brackish and salt marsh zones had the greatest below-average departures, showing gradual improvement along with intermediate marshes from May 2006 until November 2006. Fresh marsh experienced the least variability and had the smallest departures from average of all marsh types in this region.

The impacts in the west region were apparent in October 2005 following Hurricane Rita. All marsh types had mean departure values exceeding -0.28 in October 2005 and again in June 2006 (Fig. 2.4C). The departure trends and variability among marsh types in the west region were very similar, with the brackish marsh zone having the greatest departures. Positive trends in vegetation condition occurred in all marsh types beginning in July 2006, with the greatest recovery in fresh marsh between July and August 2006.

NDVI Values for Significant and Persistent Damage

The departure anomalies in the NDVI for hurricane-year evaluations account for all factors influencing the vegetated landscape over the time period. To better isolate the effects of the hurricanes, significant damage was calculated as an excess of one standard deviation lower than the baseline average NDVI values. If significant damage occurred in 12 out of the 14 months following a hurricane event, the damage was considered

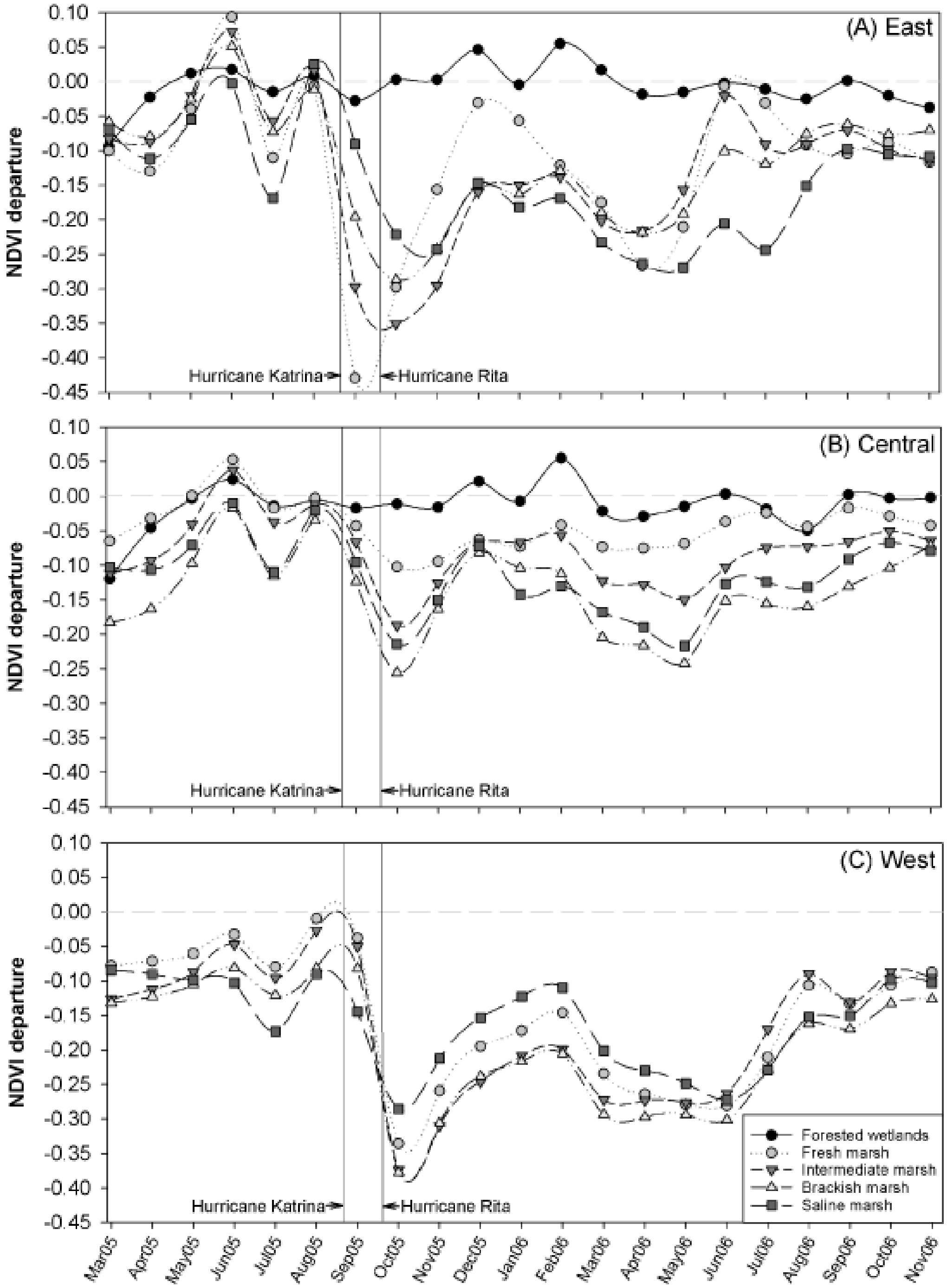

Figure 2.4. Time series of departure from average values using Normalized Difference Vegetation Index (NDVI) by habitat type beginning in March 2005 and ending in November 2006 for (A) east, (B) central, and (C) west regions. Habitat types are indicated in the key of panel (C). The vertical lines represent landfall dates of Hurricanes Katrina and Rita. A departure value is calculated from subtracting monthly average NDVI composites for the hurricane year from baseline NDVI values. The dashed horizontal line illustrates no difference in values between months investigated and baseline averages.

persistent. There was significant damage in 22% of the east region in September 2005 following Hurricane Katrina, with an increase to 31% in October 2005 following Hurricane Rita (Fig. 2.5). The percent of landscape significantly damaged following Hurricane Rita in September 2005 increased by 10.3% in the central region and 64.8% in the west region. Excluding winter senescence, significant damage remained in over 20% of the east region through May 2006 and over 45% of the west region through June 2006; whereas, significant damage never exceeded 16% of the landscape in the central region (Fig. 2.5).

Persistent damage occurred in 192.4 km^2 (5.6%) of the east, 89.4 km^2 (1.1%) of the central, and 1,045.6 km^2 (29.5%) of the west region by November 2006 (Fig. 2.6A). Though there appears to be an inconsistency among the percentage of the landscape persistently damaged in Figure 2.6A and the monthly significant damage displayed for November 2006 in Figure 2.5, the difference in definition of these two terms explains the pattern. The west region in particular displays a smaller percentage of monthly significant damage from August to November of 2006 than is defined as persistent damage. This pattern suggests that many pixels in the west region met the persistent damage criteria in 12 of the earliest months following the hurricane. This pattern may also suggest variability in how pixels pass and fail the standard deviation criteria for significant damage from month to month.

The habitats where the most persistent damage occurred were in intermediate marsh in the east, brackish marsh in the central, and fresh and intermediate marshes in the west regions (Fig. 2.6B). Fresh and intermediate marsh communities comprised 56.3% of the persistent damage in the east region, 27.5% in the central, and 77.1% in the west region.

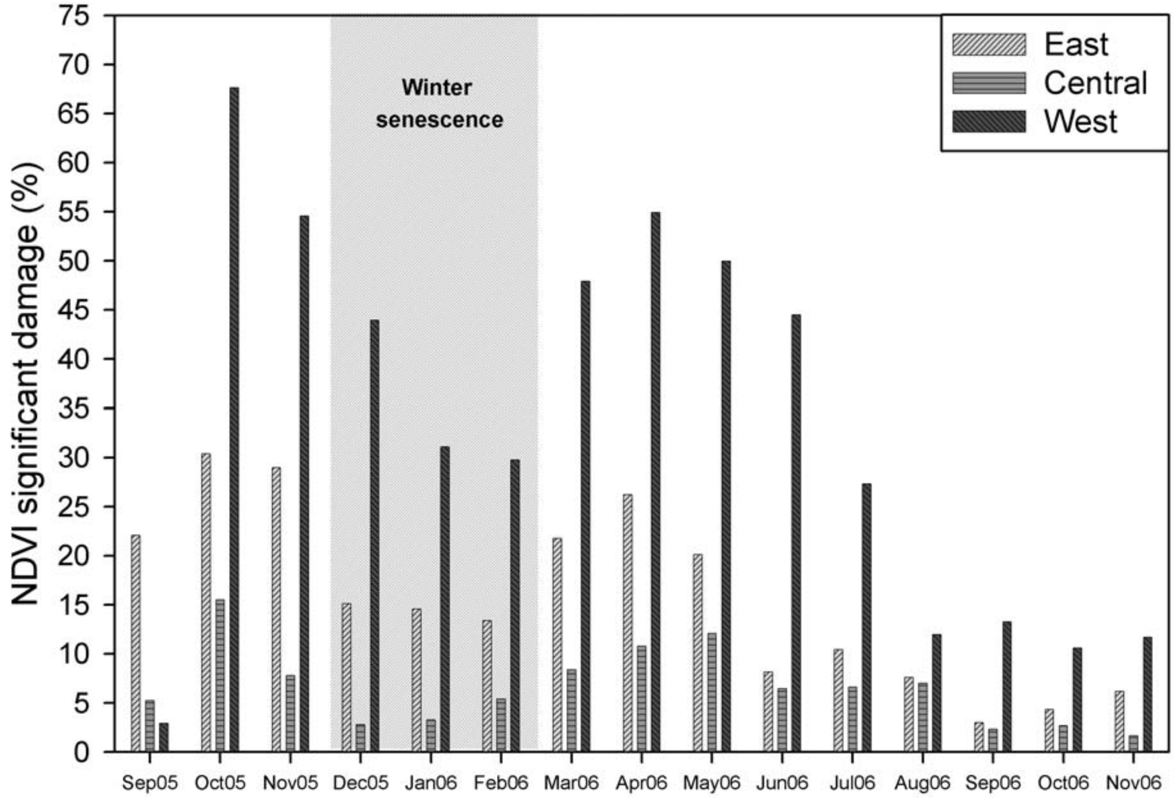

Figure 2.5. Seasonal trends of significant damage in the east, central and west regions by percentage of area following Hurricane Katrina, beginning in September 2005 and ending in November 2006. Significantly damaged is defined as an excess of one standard deviation lower than the baseline average value in the Normalized Difference Vegetation Index (NDVI). The shaded months represent the winter season when emergent marsh vegetation senescence and forested wetland leaf-off conditions occur.

Relationships among Multitemporal NDVI Values, Land Change, and Vegetation Change

The localized persistence of severe, below-average departures (Figs. 2.3 and 2.6) suggests that the creation of new water area by physical disturbance and persistent flooding may be an important causal factor. The persistence of new open water was classified by Barras (2008) as the 2004 to 2006 changes in open water that persisted for at least 1 year after the 2005 hurricanes. The persistent new water area was 527 km^2, which occurred over 5.3% of the total 2004 wetland area represented in the east region, 0.9 % in the central region, and 8.4 % in the west region (Fig. 2.6A). The percentage of area of

persistent damage accounted for by new open water in the east, central and west region is 91.8%, 81.0%, and 29.0%, respectively (Fig. 2.6A).

Persistent damage to vegetation was most prevalent in the intermediate marsh in the east, brackish marsh in the central and fresh marsh in the west regions (Fig. 2.6B). The persistent new water area was most prevalent in the intermediate marsh in the east region, and fresh marsh in the central and west regions (Fig. 2.6C). The allocations of persistent damage and persistent open water by habitat type were nearly identical in the east; however, they were quite different in the central and west regions. Persistent new water area was dominant in fresh marsh in the central region at 80% and 78% in the west region; whereas, persistent damage in the fresh marsh was only 9% in the central and 40% in the west regions. Additionally, in the central region we identified no persistent new water area in salt marsh; however, we identified nearly 21% of persistent damage in salt marsh.

Measurements of vegetation cover from field data were used to assess the spectral values in the NDVI and to ground truth vegetation recovery. The relationship between changes in NDVI values and changes in total live cover (when all potential time periods from both quarterly and annual sampling were included) produced an r^2 of 0.38 ($p < 0.0001$; $n = 287$; Fig. 2.7). Increases in NDVI change values over time generally corresponded with increases in total live cover, but the fit for this relationship was not very strong. The field data also helped corroborate spectral values from June 2006 in the east region (Fig. 2.3). The above-average density and vigor in summer appears to be associated with colonization by annual plant species (Fig. 2.8). The low cover values in the west throughout 2006 are consistent with classifications of persistent damage in the NDVI.

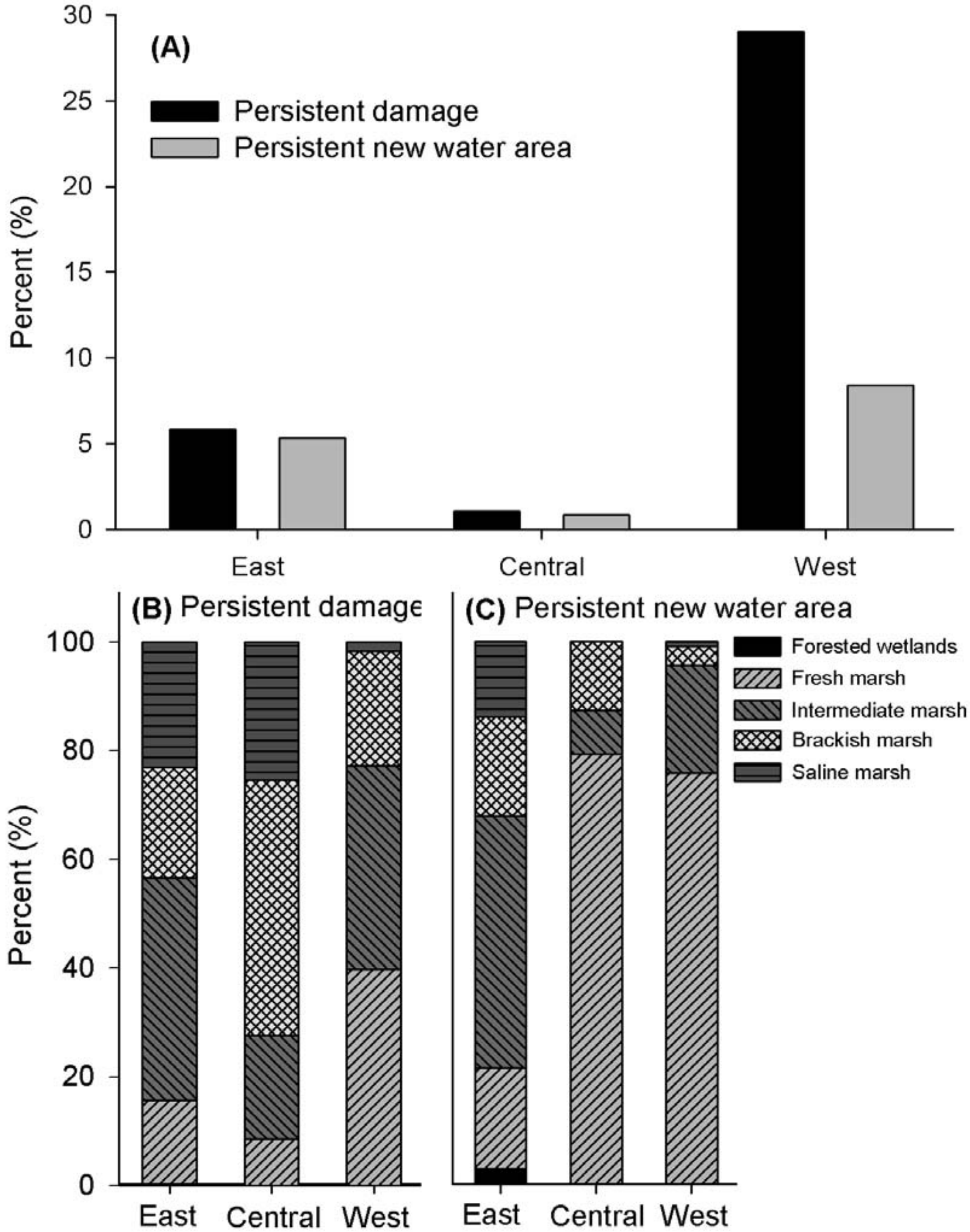

Figure 2.6. (A) The percentage of landscape area in the east, central and west regions with persistent damage through November 2006. (B) The allocation of persistent damage by habitat type in the east, central and west regions. Habitat types represented are forested wetlands, and fresh, intermediate, brackish, and saline marsh zones based on Chabreck and Linscombe (2001) classifications. Significant damage is defined as an excess of one standard deviation lower than the baseline average value in the Normalized Difference Vegetation Index (NDVI). If significant damage occurred in 12 out of the 14 months following a hurricane event, the damage was considered persistent. (C) The allocation of persistent new water area by habitat type.

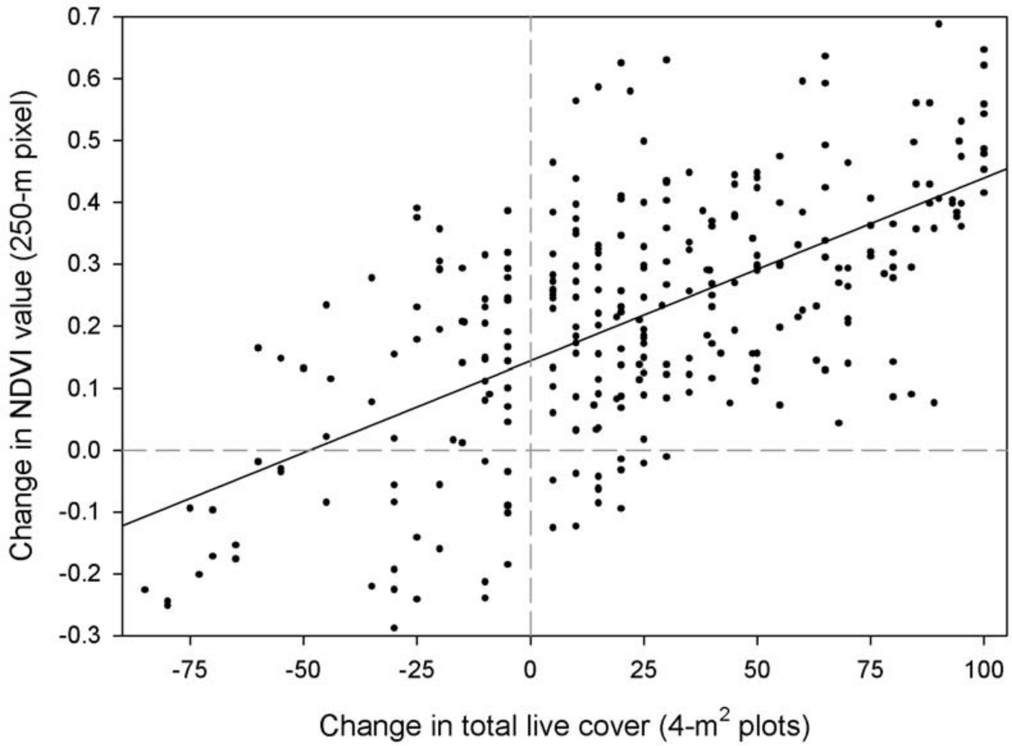

Figure 2.7. The relationship between change in NDVI value at 250-m pixels and change in total live cover at 4-m^2 plots for each time period at stations across coastal Louisiana. Time periods used to calculate change are Fall 05 – Fall 06, Spring 06 – Summer 06, and Summer 06 – Fall 06. Change in NDVI value = 0.1439 + 0.0030 (percent change in total live cover), with r^2 = 37.8%.

DISCUSSION

The mean monthly NDVI values from the 5-yr baseline time series clearly follow seasonal patterns that are consistent with growing degree day classifications for this region (U.S. Department of Agriculture 1995) and seasonal temperature reported by the National Oceanic and Atmospheric Administration, Southern Regional Climate Center (http://www.srcc.lsu.edu/southernClimate/atlas/). Seasonal trends shown in the NDVI have never been investigated across different wetland types and reported in the literature; however, the seasonal trends appear to be consistent with previous aboveground biomass studies in Louisiana that generally show increases in live, aboveground biomass from low values in the winter to peak values in summer (Conner and Day 1976, Hopkinson et al.

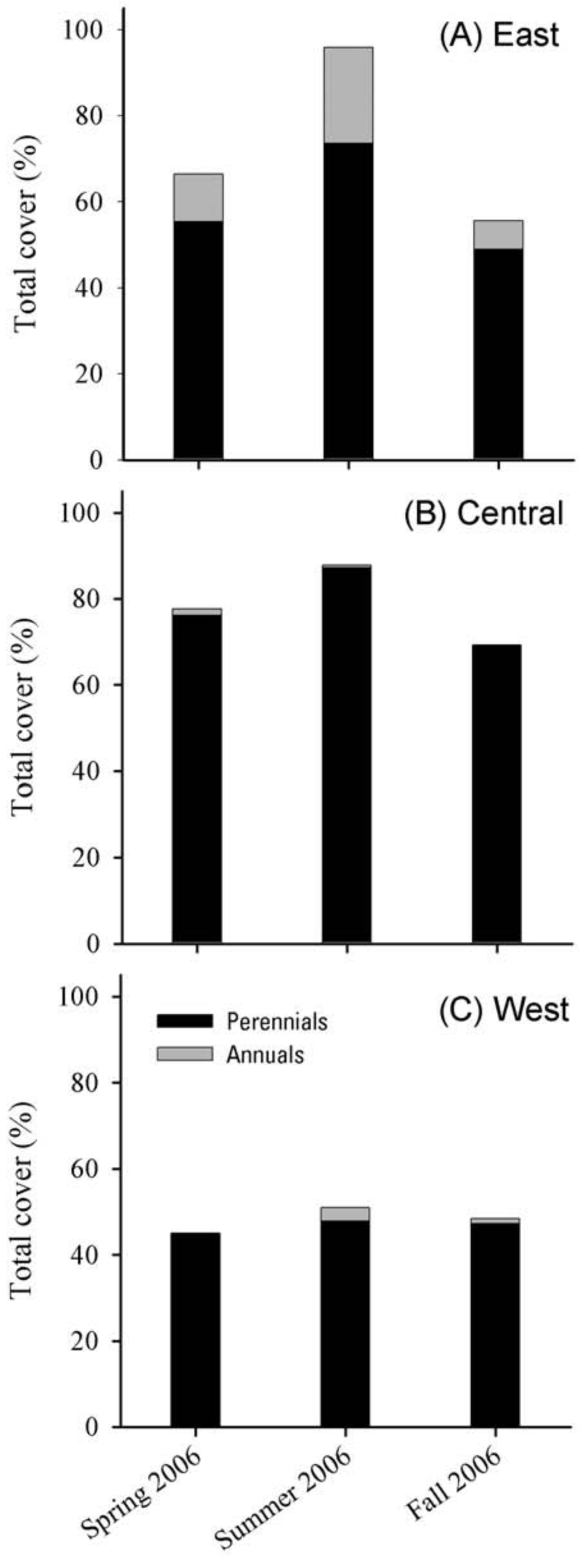

Figure 2.8. Percent cover of perennials and annuals in (A) east, (B) central, and (C) west regions across all seasons in 2006.

1978, White et al. 1978, Sasser and Gosselink 1984). Our study identified a clear differentiation among NDVI values by habitat type, suggesting that the NDVI is sensitive to phenology changes and therefore can provide a valuable tool for assessing change in coastal Louisiana habitat types. The higher NDVI values in fresh marsh may be associated with the higher reflectance from broad-leaved plants, which Hardisky and Klemas (1985) identified as having higher vegetation index scores as compared to gramineous and leafless plant canopies. Chabreck (1972) documented the greatest abundance of broad-leaved plants in fresh marsh and graminoids in brackish and salt marsh in coastal Louisiana. Landscape fragmentation patterns may also explain the higher NDVI values in fresh marsh. Barras (2006) identified the amount of land and water by 2001 marsh community type and found the greatest percentage of water in saline and brackish marsh and the highest percentage of contiguous vegetated landscapes in intermediate and fresh marsh. Within California salt marshes, Zhang et al. (1997) tested 6 spectral vegetation indices including NDVI and found that all provided reasonable estimates of biomass, regardless of species composition and specific site conditions, and that most indices provided relative trends consistent with edaphic gradients. Louisiana habitat classifications have broadly followed a gradient of salinity zones from the Gulf of Mexico (Penfound and Hathaway 1938, O'Neil 1949, Chabreck 1972), further suggesting the use of spectral signatures in evaluating habitat change.

Forested wetlands experienced a slight decline in vegetative density and vigor immediately following Hurricane Katrina; however, unlike other marsh communities, they appeared to recover readily. Aerial reconnaissance and ground surveillance confirmed the sprouting of new green leaves 5-7 weeks after the hurricanes in forested wetlands within the Pearl River basin in east Louisiana (Barras 2007b, Barrow et al.

2007). The above-average departure from NDVI values in December 2005 appears to be the result of an abnormal bloom of new leaves following defoliation and/or an increase in midstory vegetation capitalizing on new openings in forest canopy, which is consistent with findings from Ramsey et al. (1997) and Doyle et al. (1995) after Hurricane Andrew in 1992.

The monthly anomaly patterns in NDVI values in nonforested marsh communities clearly showed the effects of Hurricanes Katrina and Rita spatially and temporally. Hurricane Katrina's impacts were primarily located in the east region, where nearly 92% of persistent damage was accounted for by formations of new water area (Fig. 2.6A). The damage affected all marsh types and was formed primarily from physical scouring and the direct removal of land as described in Barras (2006). The above-average values in the NDVI in fresh and intermediate marshes within the upper east region in June 2006 (Fig. 2.3D) coincides with a significant increase in the number and relative cover of annuals and disturbance plant species identified from field sampling between late March and early July 2006 (Steyer, Chapter 3). The use of ground-truthing stations to identify changes in species composition, which are difficult to distinguish by using remotely sensed data, improve interpretations of recovery.

The impacts associated with Hurricane Rita were much greater in spatial extent and more persistent than Hurricane Katrina. The departures from average NDVI values following Hurricane Rita correspond well with the east to west increase in physical shearing and flooding observed by Barras (2007a; 2007b); however, physical removal of marsh and flooding could not solely explain the patterns observed in the west. Only 29% of the persistent damage in the west identified by using departures from average was associated with new water area. If conversion to new open water is the primary

contributing factor in departure trends at a basin scale, damage in each marsh type should be reflected in the patterns of conversion to new water area. This is not the case in the central and west regions. Though an overwhelming majority of the conversion to new water area in these regions occurred in fresh marsh, damage in all three regions was spread among all of the marsh vegetation types. While the pattern in the west region may be attributed to the large percentage of unexplained damage, one would expect the damage and new water areas in the central region to be similar. Upon further investigation, it was noted that postfrontal conditions produced strong northerly winds greater than 13 knots on the date the TM imagery was acquired for 2006 in the central region. This front pushed water out of the brackish and saline marshes, causing an underestimation of persistent change in open water area between 2004 and 2006. The NDVI is less sensitive to temporary weather phenomenon because MODIS imagery is collected on a daily basis and composited to a monthly average. This may explain some of the inconsistency in patterns we observed using the two sensors.

Utilizing the land change patterns as classified from TM imagery, in conjunction with the NDVI change detection using MODIS imagery, improved our ability to detect change and dissect causal mechanisms of that change. The 25 m spatial resolution of the TM data and the temporal consistency of 250 m MODIS imagery enhanced interpretation ability beyond that of either sensor examined alone. Based on the Landsat TM pixels indicating a conversion to new open water as classified by Barras (2006), 86% of those areas coastwide was also shown to have experienced significant damage based on the MODIS NDVI data. Though the varying resolution of the Landsat TM and MODIS sensors complicates direct comparisons, these results suggest a strong tie between the data from both.

As found in this study, the ability to integrate geographic information systems and remote sensing by using multisource and multitemporal imagery is an important method for change detection (Petit and Lambin 2001, Lu et al. 2004). We also found that field data augmented our ability to discern landscape changes at regional scales. Although the relationship we derived between vegetation data collected at 4 m^2 with 250 m NDVI was not robust, a multitude of factors including varying resolution and interspersion of land and water may explain this pattern. In this study, it was not our intent to use NDVI as a predictor of vegetation cover or to aggregate data layers to match scales.

The use of anomalous NDVI values and departures from average for greenness has been commonly used for the evaluation of drought and rainfall effects on vegetation dynamics and fire potential (Nicholson et al. 1990, Burgan et al. 1996, Burgan and Hartford 1997, Anyamba and Tucker 2005). In this study, the approach of using departures from average provided a good indication of the extent and severity of initial hurricane impacts and persistence over time across habitat types. It accurately detected that a change occurred and identified the spatial extent and pattern of change over time, which are of fundamental importance in change detection applications (MacLeod and Congalton 1998). The severe changes in the reflectance values following Hurricanes Katrina and Rita overwhelmed minor changes that could have been caused by other factors such as atmospheric conditions, sun angles, and soil moistures that may not have been captured by exclusion algorithms, thus providing confidence in our ability to detect response and recovery with this approach. However, there is still a need to examine the performance of different reflectance indices in coastal wetland community types by testing factors such as sun position, heterogeneous landscape, or atmospheric interferences. Blackburn and Steele (1999) found that the relationship between

reflectance and biophysical canopy properties can vary depending on the heterogeneous structure of different community types. Testing and verifying these relationships would provide a robust tool for evaluating ecosystem functioning at complex landscape scales (Filella et al. 2004).

The most evident value of the current research was quantifying the impacts of the 2005 hurricanes on the marshes of coastal Louisiana across regional landscapes. The power of using moderate to coarse resolution TM and MODIS imagery is that the entire spatial extent of impacts from Hurricanes Katrina and Rita could be captured and not extrapolated from regional or site-specific investigations. The departures from average NDVI values clearly illustrate how differing hurricane tracks and associated storm surges impacted the coast. Hurricane Katrina's track was northerly, isolating storm surge and associated surge-induced marsh removal primarily to the east region (Barras 2007a, Ebersole et al. 2007). Hurricane Rita's track was northwesterly and subjected the central and west regions to sustained tropical force winds and elevated water levels in advance of landfall (Lockwood et al. 2005a, 2005b) and storm surges in all regions upon landfall (Doyle et al. 2007, McGee et al. 2007). The storm surge also amplified impacts in the west region when water became impounded behind manmade levees and water control structures and became impounded naturally when existing canals and waterways were completely filled with wrack and storm debris (Michot et al. 2007). These persistently flooded landscapes made it difficult to classify whether new water area was caused by physical disturbance or other factors. It has been suggested that the persistence of high salinity conditions following widespread flooding of low salinity marshes has contributed to vegetation damage in the west (Steyer et al., 2007). Additional hurricane studies examining the influence of major stressors (e.g., salinity and sulfide) on vegetation

community dynamics are underway, and when combined with the findings of this study, should further elucidate physiological impacts and identify recommendations for restoration and management actions.

CONCLUSIONS

Integration of geographic information systems and remote sensing, using both multisource and multitemporal imagery, enhanced our ability to evaluate impacts and recovery from Hurricanes Katrina and Rita. MODIS imagery identified a clear differentiation among NDVI values by habitat type, suggesting that the NDVI is sensitive to phenology changes and therefore can provide a valuable tool for assessing and monitoring change in coastal Louisiana habitat types. The departure anomalies from NDVI suggest that over 4,714 km^2 of the prestorm, coastal wetland area experienced a substantial decline in the density and vigor of vegetation in October 2005, corresponding closely to storm surge impact areas of Hurricanes Katrina and Rita. The integration of higher resolution Landsat TM imagery to identify new open water areas, supported by field verifications, allowed direct physical impacts to be discerned from damage likely associated with other factors including saltwater intrusion, flooding, and burial by wrack. These factors were most significant in the west region where hydrologic restrictions and drought conditions contributed to 1,045.6 km^2 of persistent damage throughout the observation period. Although below average NDVI values were observed in most marsh community types through November 2006, recovery of vegetation is evident. Continued assessment of NDVI values and departure anomalies over multiple growing seasons will provide a greater understanding of the persistence of hurricane impacts to coastal Louisiana habitat types.

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CHAPTER 3

HURRICANE INFLUENCES ON VEGETATION COMMUNITY CHANGE IN COASTAL LOUISIANA

INTRODUCTION

Hurricanes are important episodic disturbances that shape coastal vegetated landscapes in Louisiana and the northern Gulf of Mexico (Conner et al. 1989, Guntenspergen et al. 1995). In addition to physical disturbance to the coastal landscape, these events provide salinity and flooding pulses to coastal marsh ecosystems that can result in significant alteration of vegetation communities (Chabreck and Palmisano 1973, Neyland 2007). Although tropical and extratropical storms have decadal scale variability in the North Atlantic Basin (Landsea et al. 1999, Keim et al. 2004), it has been suggested that hurricanes may increase in frequency and intensity in the upcoming decades (Goldenberg et al. 2001, Webster et al. 2005, Intergovernmental Panel on Climate Change 2007). An investigation by Keim et al. (2007), conducted by using records from 1901 to 2005, found that coastal Louisiana averages a 3-year return period for all tropical storms and hurricanes and a 7- to 15-year return period for all major hurricanes.

Hurricane disturbances to coastal wetland vegetation in Louisiana have been previously documented (Ensminger and Nichols 1957, Chamberlain 1959, Chabreck and Palmisano 1973, Meeder 1987, Doyle et al. 1995); however, most were reported as general observation, and other studies were focused on small geographic areas or specific vegetation species of interest. There are relatively few studies that are comprehensive across broad geographic regions and vegetation communities (Cahoon et al. 1995, Guntenspergen et al. 1995).

Hurricanes have the potential to greatly alter vegetation community development; yet, very few studies have tracked recovery beyond one growing season. The resilience of ecosystems, defined as the ability of a system to return to a predisturbance state after a disturbance (Leps et al. 1982), is also difficult to evaluate in coastal wetlands because of the variety of stressors constantly operating in the system. Vogt et al. (1997) suggest that an ecosystem is resilient if its recovery periods are shorter than the recurrence interval of disturbance events.

Plant associations are well established along estuarine salinity gradients (Odum and Hoover 1988, Latham et al. 1994, Mitsch and Gosselink 2000). Distributions of plant species in fresh marshes are primarily driven by competitive dominance, whereas the distributions in salt marshes are primarily driven by physical factors, such as salinity (Wilson and Keddy 1986, Crain et al. 2004). Disturbances that alter salinity regimes provide opportunities to directly evaluate salt tolerance and indirectly evaluate competitive ability, which have been suggested to be inversely related (Barbour 1978, LaPeyre et al. 2001, Crain et al. 2004). Additionally, disturbances commonly promote invasions by non-native or opportunistic plant species (Ewel 1986).

Sulfide also is considered an important stressor that has been shown to be detrimental to plant growth at elevated concentrations, either directly through its toxicity or indirectly by interfering with nutrient uptake (Havill et al. 1985, Mendelssohn and McKee 1988, Bradley and Dunn 1989, Koch and Mendelssohn 1989, Bradley and Morris 1990, Koch et al. 1990, Chambers et al. 1998). However, most studies that have assessed the synergistic influences of both salinity and sulfide on plant growth (McKee and Mendelssohn 1989, Naidoo and Mundree 1993, Broome et al. 1995, Flynn et al. 1995,

Chambers et al. 1998, Pahl 2002) are limited to controlled exposures of single or multiple species.

Hurricane-induced saltwater intrusion and flooding provide an ideal situation to assess how wetland plant communities and species respond to catastrophic disturbances. Our objective was to document the effect of saltwater storm surge from Hurricanes Katrina and Rita of 2005 on marsh community dynamics in coastal Louisiana. We specifically address the following questions: (1) What was the extent of impact to herbaceous emergent marsh communities across coastal Louisiana, and to what extent did they recover over two growing seasons? (2) Were there any changes in species dominance and shifts in marsh community types? (3) How did the level of salinity and/or sulfide concentrations in soil porewater influence marsh community dynamics and recovery?

MATERIALS AND METHODS

Study Area

The study area consists of 33,458-km^2 of wetlands and associated waters, with boundaries consistent with the Louisiana Coastal Area (LCA) trend assessment boundary (Barras et al. 2003, Fig. 3.1). It includes coastal wetland community types in two physiographic units, the eastern Deltaic Plain and the western Chenier Plain (Roberts 1997). Marsh types reflect gradients in salinity and elevation (Visser et al. 1998) and are roughly distributed in zones that run parallel to the Gulf of Mexico, with salt marshes furthest south, followed by brackish, intermediate, and fresh marshes further inland. These zones were initially described by Penfound and Hathaway (1938) followed by a comprehensive description and mapping of marsh communities conducted by O'Neil (1949). Subsequent coastwide surveys were conducted in 1968 (Chabreck et al. 1968,

Chabreck 1970) and in 1978, 1988, 1997, and 2001 (Chabreck and Linscombe 1978, 1988, 1997, 2001).

Within the study area, regions were assigned based on a predominance of storm surge elevations exceeding approximately 2 m at the coast (Ebersole et al. 2007, McGee et al. 2007) to assess direct versus indirect hurricane effects (Fig. 3.1). The effects of Hurricane Katrina were predominant in the east region, whereas Hurricane Rita's effects occurred mostly across the chenier plain in the west region. The central region also experienced tropical storm force winds and some degree of storm surge effects, mainly from Hurricane Rita.

The assessment of hurricane effects is confounded by drought conditions that occurred in the west and central regions prior to Hurricanes Katrina and Rita. Furthermore, all Louisiana coastal regions suffered a long period of drought conditions after these hurricanes (Fig. 3.2). The National Oceanic and Atmospheric Administration's National Climatic Data Center (NCDC) provides the Palmer Drought Severity Index (PDSI), which classifies drought conditions with values that range from equal to or less than -1 for mild drought condition to values below -4 as extreme drought. The NCDC's 3 climatic divisions in south Louisiana are classified as the southwest, south-central, and southeast, which approximately correspond to the west, central, and east regions in our study.

Vegetation and Porewater Collection

Sampling sites were randomly selected from a population of 741 existing, coastal monitoring stations established under the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) and Coastwide Reference Monitoring System (CRMS) (Steyer et al. 2003). Sample size was regionally weighted by the spatial extent of storm

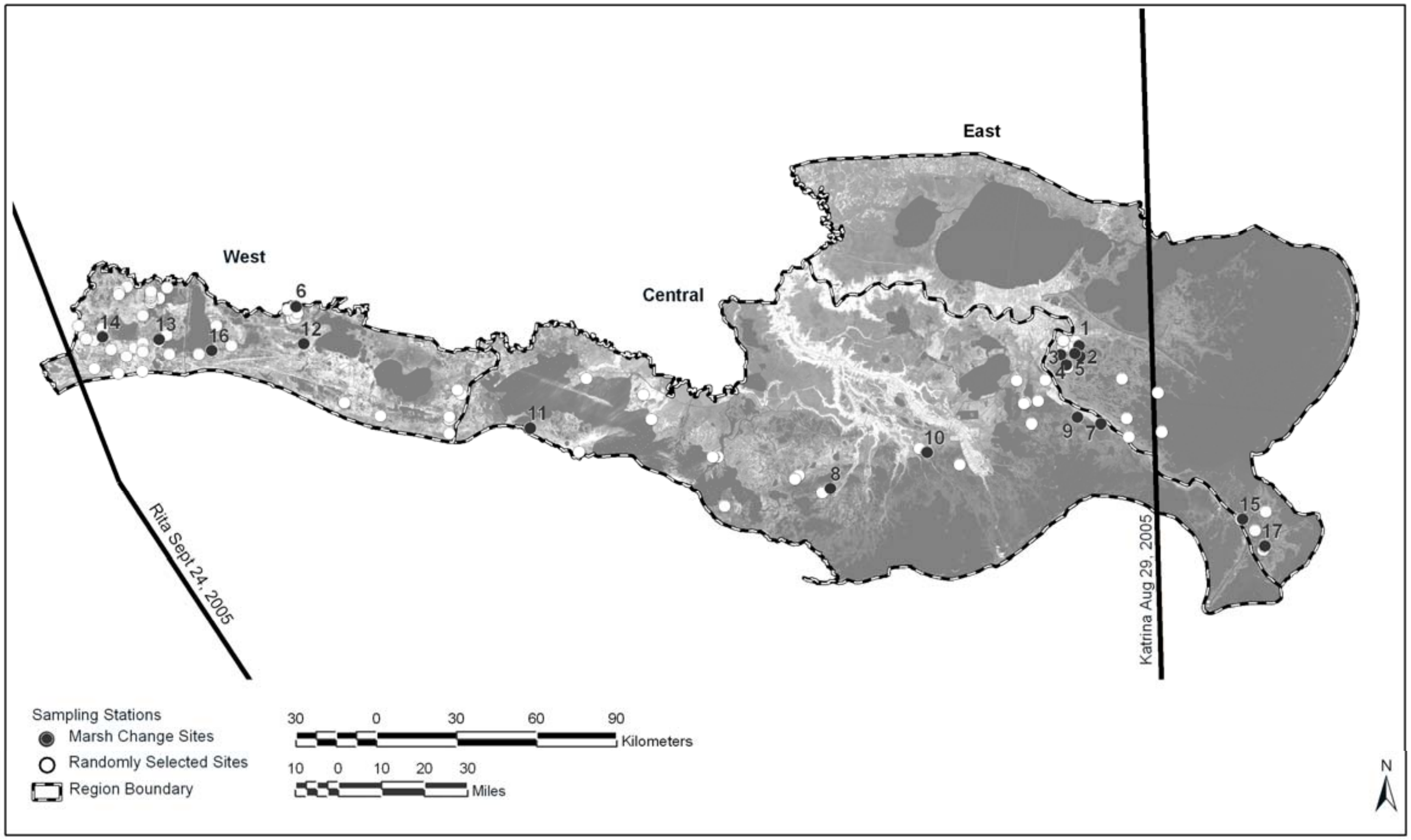


Figure 3.1. The 33,457.6-km^2 study area defined by the Louisiana Coastal Area (LCA) trend assessment boundary (Barras et al. 2003) showing one hundred (100) randomly selected sampling sites, hurricane tracks, and regional assessment areas. Numbers represent sites that changed marsh type between fall 2006 and fall 2007.

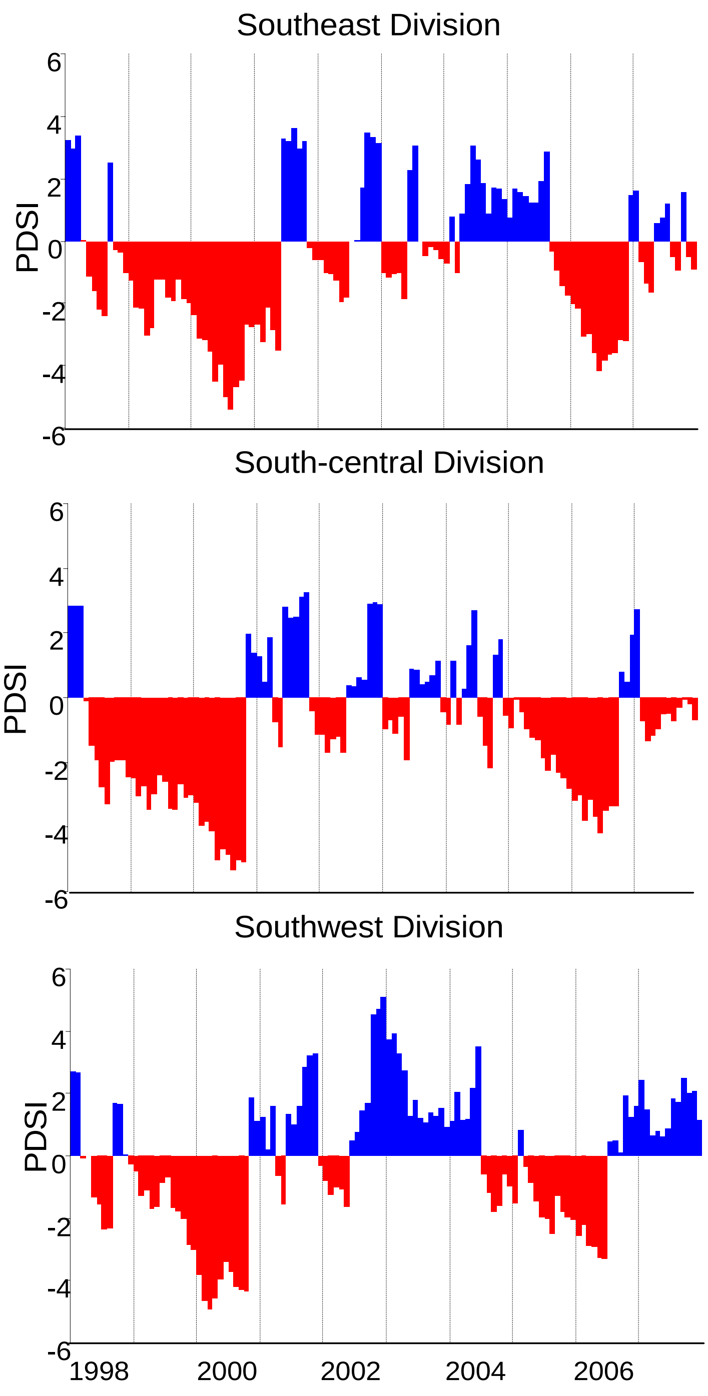


Figure 3.2. The Palmer Drought Severity Index (PDSI) reflects drought conditions (negative values) that were persistent between 1998 and 2000 and again in 2005 and 2006 in the National Climatic Data Center's Louisiana climate divisions. The south-central and southwest regions experienced drought preceding Hurricanes Katrina and Rita in fall 2005, and drought extended into summer 2006 in the southwest, fall 2006 in the south-central, and winter 2006 in the southeast region.

surge and exposure to hurricane impacts. A total of 100 sites representing fresh, intermediate, and brackish marsh community types were sampled by helicopter across coastal Louisiana. Because of the spatial extent of the impacted area, 49 stations were sampled in the west, 28 in the east, and 23 stations in the central regions (Fig. 3.1). The marsh types were initially assigned based on a coastwide survey that was conducted in summer and early fall 2001 (Chabreck and Linscombe 2001) by using methods described in Chabreck (1970).

Measurements of vegetation percent cover, species composition, and height of dominant plants and of soil porewater salinity, temperature, pH, sulfide, and nutrients (i.e., ammonium, nitrate, and nitrite) were taken in spring, summer, and fall 2006 and in fall 2007. Vegetation percent cover was estimated at each site by visual examination of a 4-m^2 quadrat assessed by following the Braun-Blanquet method described in Steyer et al. (1995). Plant nomenclature was established by using the criteria described by Godfrey and Wooten (1979). Percent cover of individual plant species and nonvegetated area (e.g., bare ground, standing water, wrack, and dead material) also were identified. Vegetation data for fall 2006 and 2007 were classified by marsh type by identifying the dominant and codominant species and assigning a salinity score based on the overall species composition and abundance, as well as the distribution of those species within fresh, intermediate, and brackish zones as described in Chabreck (1970) and Visser et al. (2002).

At each site, 3 water samples at 10 cm depth were to be collected adjacent to the vegetation plot by using a sipper probe to aid in extracting interstitial water at depth (McKee et al. 1988). There were no porewater available at 10 cm depth, so all salinities were collected from a 30 cm depth. Three 3-ml samples were buffered on-site with an

antioxidant and were analyzed within 24 hours of collection. Serial dilutions were prepared, and sulfides were measured with an Orion 9416BN Silver/Sulfide electrode (Thermo Fisher Scientific, Inc., Waltham, Massachusetts, USA) following the manufacturer's specified standard operating procedures for quality control. The remaining interstitial water was measured on-site for water temperature (°C), salinity, and pH with a YSI Model 30 hand-held instrument (YSI Inc., Yellow Springs, Ohio, USA) by following procedures described by Folse and West (2005).

Two additional 25-ml interstitial water samples were extracted and analyzed for inorganic nitrogen (NO_2-N, NO_3-N, and NH_4–N), and phosphorus (PO_4). Samples were filtered in the field by using GF/F filters and placed on ice until returned to the laboratory. Concentrations of NO_2, NO_3, NH_4, and PO_4 were measured on a Flow Solution IV automated colorimetric analyzer (O.I. Analytical, Inc., College Station, Texas, USA) using Environmental Protection Agency standard methods 349.0, 353.4, and 365.5. The fall 2006 NH_4 and PO_4 samples were contaminated and therefore were not used for further analyses.

Statistical Analyses

The PROC GLM procedure was used to perform a mixed-model nested analysis of variance (ANOVA) to statistically compare data among regions and marsh types. Tukey's HSD tests were used to evaluate differences among the mean or main effects. Vegetation cover and all other environmental data were examined for normality by using PROC UNIVARIATE. Vegetation cover data were arc-sine square root transformed and other data were log transformed; however, the assumption of normality was not met. Nonparametric rank transformations of vegetation cover and environmental data were conducted, and differences among regions and marsh types were similar to findings from

the nontransformed parametric GLM procedure. Likewise, both parametric (Pearson's) and nonparametric (Spearman's) partial correlations were evaluated for vegetation cover and the environmental variables. No considerable differences in the slopes or in the strength of the relationship were found based on these two correlation techniques. Because inferences from the parametric and nonparametric results are the same, nontransformed parametric results are presented for clarity. We performed the statistical analyses using SAS® software (SAS Institute 2002). An alpha = 0.05 was used to determine significance for all statistical analyses.

Relationships between vegetation species composition and environmental variables were estimated through ordination by using nonmetric multidimentional scaling (nMDS) based on a Bray-Curtis similarity matrix (Clarke and Warwick 1994). Bray-Curtis similarity measures were calculated by using percent species composition data (transformed by square root) for each site, taken from a combined fall 2006 and fall 2007 dataset, and assessed by marsh type. A two-dimensional solution with stress values at or below 0.13 was used for the ordinations. We developed statistical relationships between the nMDS ordinations and the environmental variables salinity, sulfide, nitrite, nitrate, ammonium, and phosphate by using vector fitting to find the direction of maximum R-square. A one-way analysis of similarity (ANOSIM) model (Clark and Warwick 1994) was used to examine how vegetation community structure by marsh type varied at a regional scale. Significant regional differences by marsh type were further investigated by using similarity percentages (SIMPER) to identify the percent contribution of each species to dissimilarities among regions. All analyses were conducted by using the Primer 6 (Plymouth Marine Laboratory) statistical software package (Primer-E Ltd., Ivybridge, UK).

RESULTS

Porewater Salinity and Sulfide

Measurements of seasonal mean porewater salinities show that high salinity conditions persisted throughout 2006 (Table 3.1). In fresh marsh, mean porewater salinities remained above 1.7 in the east, 2.5 in the central, and 7.1 in the west (Table 3.1). In intermediate marsh, mean porewater salinities generally increased throughout 2006 with fall mean salinity of 4.7 in the east and 11.3 in the central region (Table 3.1). Intermediate marsh salinities remained high throughout the first growing season in the west region, averaging over 11.1. Brackish marsh salinities were highest in summer and fall 2006 with means across regions ranging from 13.5 to 19.0. Site-specific salinity values within marsh types were wide ranging (Fig. 3.3), illustrating the extent of exposure to saltwater storm surge.

Within marsh types across the three regions, there were significant differences ($p < 0.0001$) in the 2006 porewater salinities. A multiple comparisons test showed that porewater salinities in fresh and brackish marshes were significantly higher in the west compared to the east and central regions; and furthermore, within intermediate marshes, salinities in the west and central regions were significantly higher than the east (Fig. 3.4A). Within fresh and brackish marshes, there were no statistically significant differences between central and east regions in 2006 (Fig. 3.4A). Mean porewater salinities differed between fall 2006 and fall 2007 among marsh types ($p = 0.0007$). Tukey's HSD test indicated that porewater salinities were lower in fall 2007 compared to fall 2006 in intermediate and brackish marshes, but not in fresh marsh (Table 3.1). The patterns within marsh types found among regions in fall 2007 were similar to 2006 (Fig. 3.4B).

Table 3.1. Porewater chemistry means by region, marsh type, and season. Standard error (SE) and sample size (N) are provided. Periods are missing values, and values of 0.00 ± 0.00 represent levels below analytical detection.

Marsh Type	Season	Salinity Mean ± SE (N)	Salinity Min - Max	Sulfide (mM) Mean ± SE (N)	Sulfide (mM) Min - Max	NO_2-N (µM) Mean ± SE (N)	NO_3-N (µM) Mean ± SE (N)	NH_4-N (µM) Mean ± SE (N)	PO4 (µM) Mean ± SE (N)
				East Region					
Fresh	Spring 2006	1.74 ± 0.09 (23)	0.7 – 2.7	0.13 ± 0.05 (23)	0.00 – 0.90	2.76 ± 0.40 (17)	3.65 ± 0.54 (17)	234.47 ± 92.44 (17)	15.70 ± 4.79 (17)
	Summer 2006	1.81 ± 0.18 (25)	0.5 – 3.9	0.19 ± 0.08 (25)	0.00 – 1.69	4.84 ± 0.72 (17)	13.83 ± 1.15 (17)	199.99 ± 100.56 (17)	25.52 ± 3.72 (17)
	Fall 2006	2.87 ± 0.25 (26)	0.6 – 5.6	0.27 ± 0.09 (26)	0.00 – 1.55	1.61 ± 0.26 (16)	4.38 ± 0.47 (17)	.	.
	Fall 2007	1.35 ± 0.13 (24)	0.3 – 2.4	0.18 ± 0.06 (9)	0.04 – 0.52	1.12 ± 0.22 (16)	0.22 ± 0.22 (16)	212.95 ± 71.65 (16)	29.48 ± 3.74 (16)
Intermediate	Spring 2006	2.31 ± 0.06 (40)	1.7 – 3.5	0.36 ± 0.06 (40)	0.00 – 1.43	1.04 ± 0.19 (27)	1.99 ± 0.30 (28)	430.76 ± 77.37 (28)	24.78 ± 3.80 (28)
	Summer 2006	3.11 ± 0.25 (37)	0.9 – 7.5	0.97 ± 0.11 (37)	0.01 – 2.54	1.61 ± 0.19 (25)	9.05 ± 0.32 (25)	707.94 ± 82.78 (25)	41.91 ± 3.37 (25)
	Fall 2006	4.65 ± 0.24 (48)	1.6 – 7.6	0.76 ± 0.11 (48)	0.01 – 2.44	1.90 ± 0.85 (24)	7.49 ± 1.13 (32)	.	.
	Fall 2007	1.85 ± 0.12 (46)	0.7 – 4.4	0.59 ± 0.08 (39)	0.03 – 1.83	0.14 ± 0.05 (30)	0.00 ± 0.00 (30)	772.46 ± 73.97 (30)	61.00 ± 5.91 (30)
Brackish	Spring 2006	8.47 ± 0.30 (6)	7.5 – 9.5	0.76 ± 0.14 (6)	0.18 – 1.09	1.99 ± 0.18 (4)	3.10 ± 0.56 (4)	331.62 ± 69.74 (4)	65.99 ± 31.17 (4)
	Summer 2006	15.51 ± 2.50 (9)	4.9 – 22.0	0.62 ± 0.32 (9)	0.00 – 2.36	4.69 ± 1.97 (6)	11.85 ± 1.76 (6)	150.66 ± 73.52 (6)	21.64 ± 5.00 (6)
	Fall 2006	15.20 ± 0.34 (6)	14.1 – 16.1	0.38 ± 0.33 (6)	0.00 – 2.00	1.61 ± 0.17 (4)	3.39 ± 0.98 (4)	.	.
	Fall 2007	7.94 ± 1.75 (7)	2.8 – 13.3	0.16 ± 0.07 (3)	0.01 – 0.23	0.77 ± 0.61 (5)	0.00 ± 0.00 (5)	86.00 ± 20.76 (5)	68.96 ± 31.68 (5)

Table 3.1. cont.

Marsh Type	Season	Salinity		Sulfide (mM)		NO_2-N (µM)	NO_3-N (µM)	NH_4-N (µM)	PO4 (µM)
		Mean ± SE (N)	Min - Max	Mean ± SE (N)	Min - Max	Mean ± SE (N)	Mean ± SE (N)	Mean ± SE (N)	Mean ± SE (N)
				Central Region					
Fresh	Spring 2006	2.51 ± 0.39 (16)	0.1 – 5.1	0.10 ± 0.03 (16)	0.01 – 0.44	1.99 ± 0.46 (9)	2.74 ± 0.76 (9)	75.12 ± 27.91 (9)	10.85 ± 5.20 (9)
	Summer 2006	3.03 ± 0.39 (18)	0.6 – 5.4	0.39 ± 0.11 (18)	0.00 – 1.34	2.11 ± 0.43 (12)	8.30 ± 0.44 (12)	200.35 ± 67.77 (12)	28.84 ± 5.93 (12)
	Fall 2006	2.53 ± 0.29 (18)	0.5 – 4.6	0.35 ± 0.08 (18)	0.01 – 1.00	1.46 ± 0.26 (12)	2.50 ± 0.51 (12)	.	.
	Fall 2007	1.47 ± 0.18 (14)	0.6 – 2.6	0.14 ± 0.03 (14)	0.00 – 0.33	0.12 ± 0.02 (10)	0.00 ± 0.00 (10)	81.20 ± 13.54 (10)	12.82 ± 3.98 (10)
Intermediate	Spring 2006	6.05 ± 0.81 (20)	1.7 – 12.1	0.39 ± 0.07 (20)	0.01 – 1.08	0.90 ± 0.24 (14)	2.18 ± 0.63 (13)	133.75 ± 35.10 (14)	14.99 ± 6.38 (14)
	Summer 2006	10.18 ± 1.48 (24)	1.5 – 21.7	0.64 ± 0.14 (24)	0.00 – 2.56	2.07 ± 0.21 (16)	8.05 ± 0.55 (16)	204.86 ± 68.26 (16)	15.79 ± 2.85 (16)
	Fall 2006	11.32 ± 1.40 (21)	2.2 – 20.6	0.67 ± 0.15 (21)	0.00 – 1.82	1.16 ± 0.18 (14)	2.36 ± 0.57 (14)	.	.
	Fall 2007	6.48 ± 1.01 (24)	1.1 – 14.3	0.55 ± 0.13 (24)	0.00 – 1.70	0.24 ± 0.07 (16)	1.57 ± 0.70 (16)	173.11 ± 34.34 (16)	35.89 ± 18.36 (16)
Brackish	Spring 2006	9.33 ± 0.54 (24)	6.3 – 17.1	0.74 ± 0.14 (24)	0.04 – 2.10	1.79 ± 0.41 (17)	2.36 ± 0.56 (16)	206.22 ± 56.37 (18)	16.42 ± 3.78 (18)
	Summer 2006	13.53 ± 0.92 (27)	6.7 – 23.6	1.45 ± 0.17 (27)	0.02 – 3.38	1.95 ± 0.17 (18)	8.26 ± 0.47 (18)	591.76 ± 179.01 (18)	26.83 ± 4.70 (18)
	Fall 2006	13.89 ± 0.61 (24)	9.3 – 19.0	1.87 ± 0.21 (24)	0.03 – 4.05	1.27 ± 0.17 (16)	2.79 ± 0.58 (16)	.	.
	Fall 2007	8.31 ± 0.85 (27)	2.4 – 15.9	1.73 ± 0.18 (24)	0.05 – 3.86	0.36 ± 0.06 (18)	1.30 ± 0.59 (18)	352.88 ± 68.96 (18)	33.70 ± 4.53 (18)

Table 3.1. cont.

Marsh Type	Season	Salinity		Sulfide (mM)		NO_2-N (µM)	NO_3-N (µM)	NH_4-N (µM)	PO4 (µM)
		Mean ± SE (N)	Min - Max	Mean ± SE (N)	Min - Max	Mean ± SE (N)	Mean ± SE (N)	Mean ± SE (N)	Mean ± SE (N)
				West Region					
Fresh	Spring 2006	8.11 ± 0.65 (48)	0.0 – 15.0	0.45 ± 0.07 (48)	0.00 – 1.74	1.86 ± 0.39 (32)	1.05 ± 0.18 (22)	288.37 ± 48.11 (32)	7.32 ± 2.16 (32)
	Summer 2006	10.41 ± 0.95 (45)	0.1 – 19.8	1.00 ± 0.18 (45)	0.00 – 3.88	4.29 ± 0.83 (30)	5.74 ± 1.10 (27)	393.77 ± 51.11 (30)	5.73 ± 1.13 (29)
	Fall 2006	7.19 ± 0.82 (39)	0.1 – 14.8	0.39 ± 0.09 (39)	0.00 – 2.35	1.53 ± 0.42 (24)	3.76 ± 0.51 (26)	.	.
	Fall 2007	6.12 ± 0.70 (38)	0.1 – 11.7	0.44 ± 0.12 (37)	0.00 – 2.65	0.51 ± 0.10 (26)	3.14 ± 0.68 (26)	380.16 ± 71.03 (26)	8.41 ± 2.10 (26)
Intermediate	Spring 2006	11.10 ± 0.55 (66)	1.7 – 17.9	0.67 ± 0.09 (64)	0.00 – 3.22	1.71 ± 0.34 (43)	1.04 ± 0.26 (31)	191.02 ± 29.85 (44)	9.45 ± 1.35 (44)
	Summer 2006	12.35 ± 0.56 (72)	1.9 – 23.5	0.70 ± 0.09 (73)	0.00 – 4.16	2.85 ± 0.48 (48)	5.56 ± 0.47 (45)	252.67 ± 26.74 (48)	9.03 ± 1.34 (48)
	Fall 2006	11.29 ± 0.50 (74)	2.4 – 21.4	1.04 ± 0.11 (75)	0.00 – 3.57	0.85 ± 0.13 (47)	4.18 ± 0.36 (49)	.	.
	Fall 2007	8.69 ± 0.42 (69)	0.9 – 15.6	1.23 ± 0.18 (69)	0.00 – 5.48	0.45 ± 0.05 (46)	2.35 ± 0.46 (46)	375.53 ± 41.49 (46)	21.91 ± 3.41 (46)
Brackish	Spring 2006	14.02 ± 0.65 (21)	8.9 – 19.2	0.46 ± 0.10 (21)	0.00 – 1.37	5.35 ± 2.12 (13)	3.38 ± 0.93 (11)	331.50 ± 83.05 (14)	26.71 ± 8.28 (14)
	Summer 2006	19.00 ± 1.27 (21)	9.7 – 27.0	0.70 ± 0.20 (18)	0.00 – 2.72	3.01 ± 0.67 (12)	11.59 ± 4.52 (12)	326.56 ± 103.28 (12)	14.25 ± 2.45 (12)
	Fall 2006	17.04 ± 1.78 (18)	0.9 – 24.6	0.85 ± 0.23 (18)	0.00 – 2.67	2.46 ± 0.99 (12)	8.88 ± 1.95 (12)	.	.
	Fall 2007	13.76 ± 1.20 (21)	6.6 – 21.3	1.43 ± 0.34 (21)	0.01 – 3.87	0.67 ± 0.21 (14)	4.77 ± 0.84 (14)	304.47 ± 91.05 (14)	22.23 ± 6.60 (14)

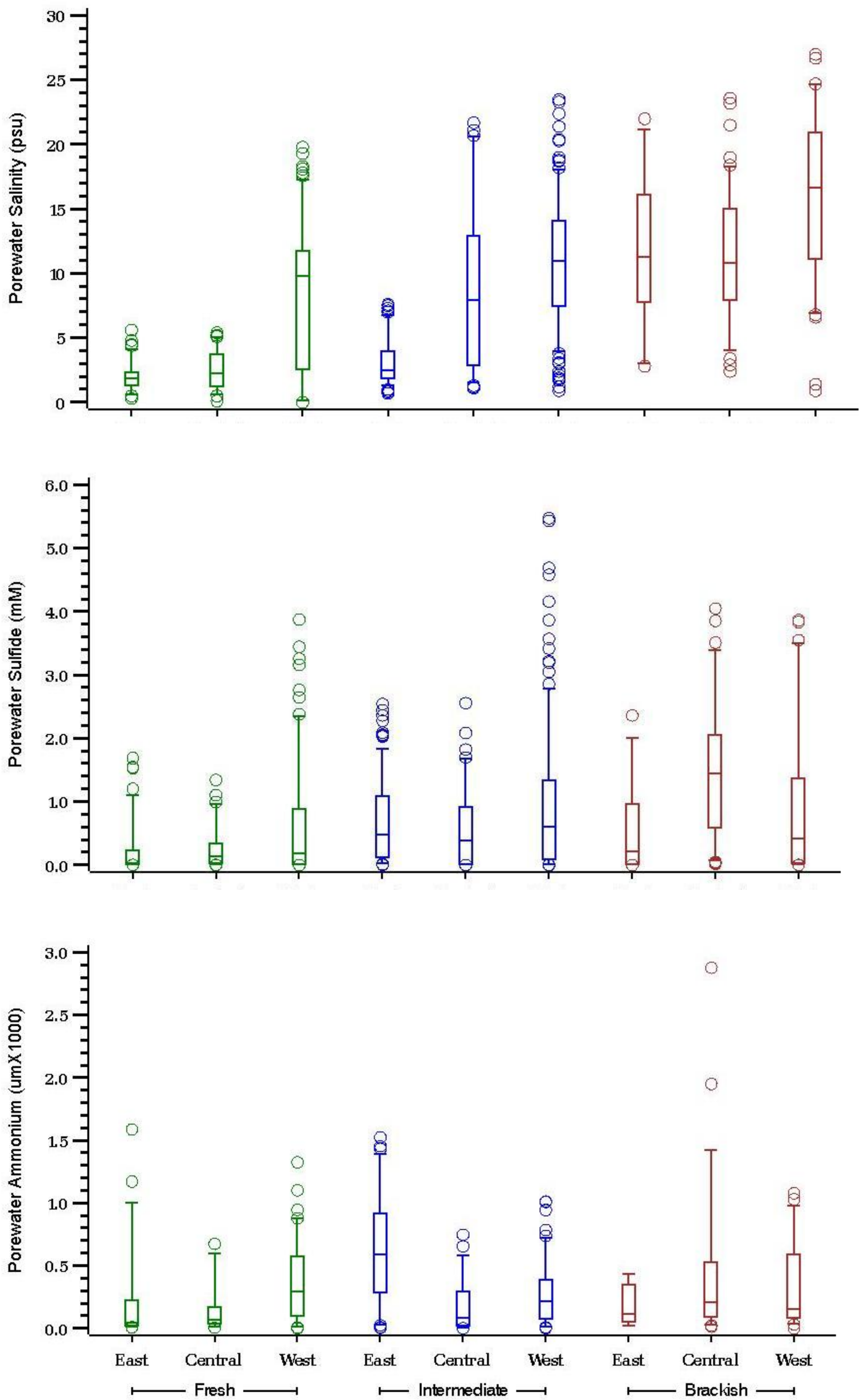
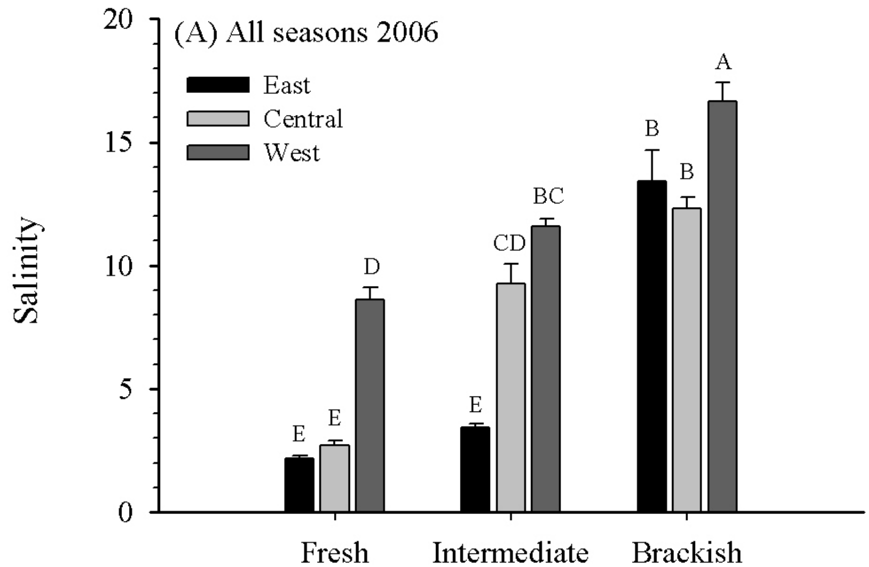


Figure 3.3. Porewater salinity, sulfide (mM), and ammonium (μM) concentrations by marsh type and region for 2006 and 2007. Horizontal lines represent 5th, 25th, 50th, 75th, and 95th percentiles. Open circles symbolize outliers.

Porewater sulfide levels were also highly variable, with values in excess of 3.0 mM found at sites in all marsh types in the west and in brackish marshes in the central region (Fig. 3.3). Sulfide levels in 2006 were greatest in brackish marsh with an average of 0.99 mM, compared to 0.74 mM in intermediate marsh and 0.43 mM in fresh marsh. In 2006 and fall 2007 there were significant differences in porewater sulfides within marsh types across the three regions ($p < 0.0001$). Brackish marshes in the central region had higher sulfides than those in the west and east regions in 2006 (Fig. 3.5A, 3.5B). No other patterns existed within marsh types among the regions. Although not significantly different, the mean sulfide concentration of 0.62 mM in fresh marsh within the west region in 2006 was over twice as high as the other regions (Table 3.1). Mean porewater sulfides did not differ between fall 2006 and fall 2007 ($p = 0.8741$). The mean sulfide values in the fresh marsh (0.44 mM) and the intermediate marsh (1.23 mM) in the west region in fall 2007 nearly doubled that of the other regional values within the same marsh type.

Inorganic Nutrients

There were no distinct differences among mean nitrate and nitrite levels in 2006 across regions and marsh types. Nitrite and nitrate levels were highest in the brackish marsh in the west and in fresh and brackish marshes in the east. The highest nitrate and nitrite levels were observed in summer 2006 and the lowest in fall 2007.Mean nitrate and nitrite levels were higher in fall 2006 than in fall 2007 ($p < 0.0001$). Averaged across all marsh types and regions, mean concentrations of nitrate at 4.64 µM and nitrite at 1.41 µM were found in fall 2006 compared to a nitrate concentration of 1.7 µM and a nitrite concentration of 0.45 µM in fall 2007.



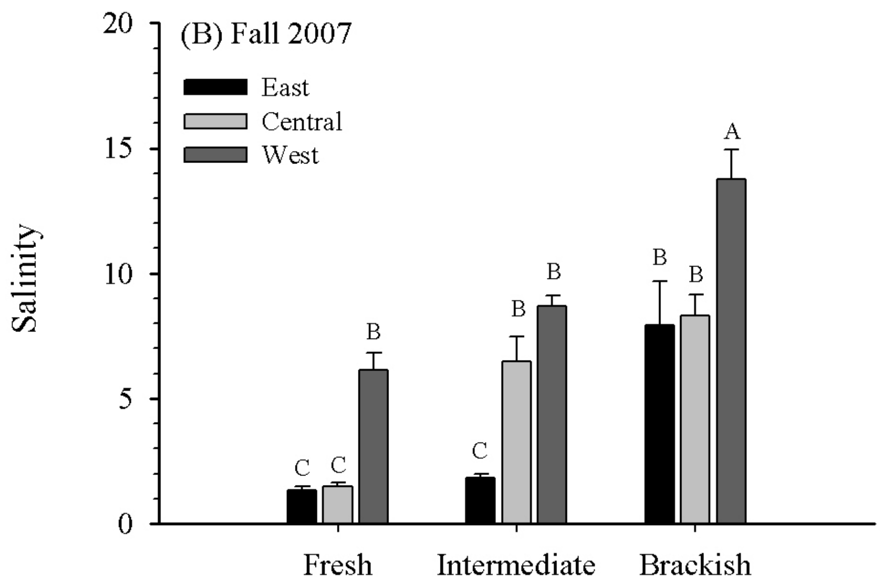


Figure 3.4. Average porewater salinity across coastal Louisiana for (A) all seasons in 2006 and (B) fall 2007. Bars with the same letter are not statistically different at $p \leq 0.05$ (Tukey's HSD test).

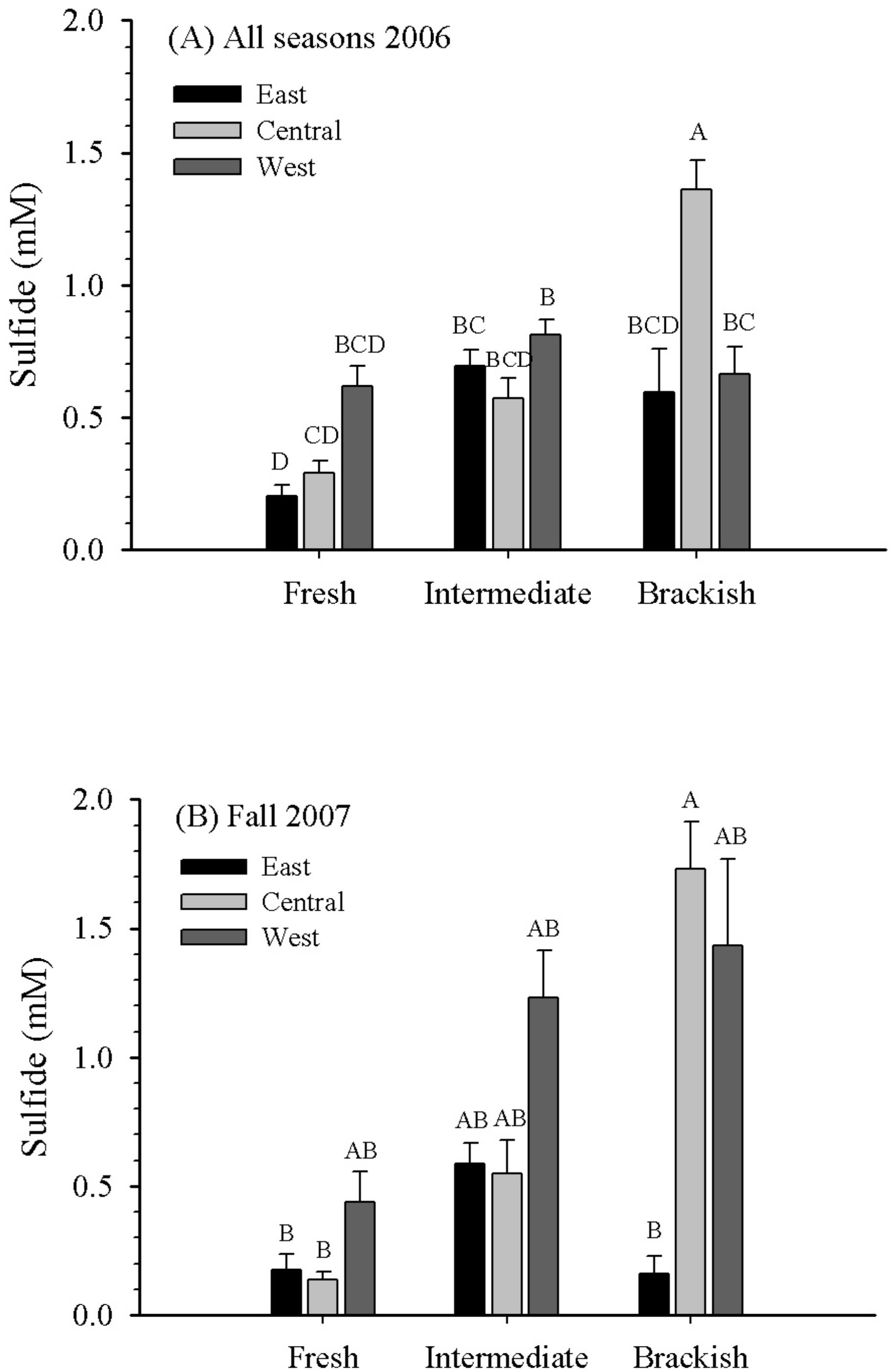


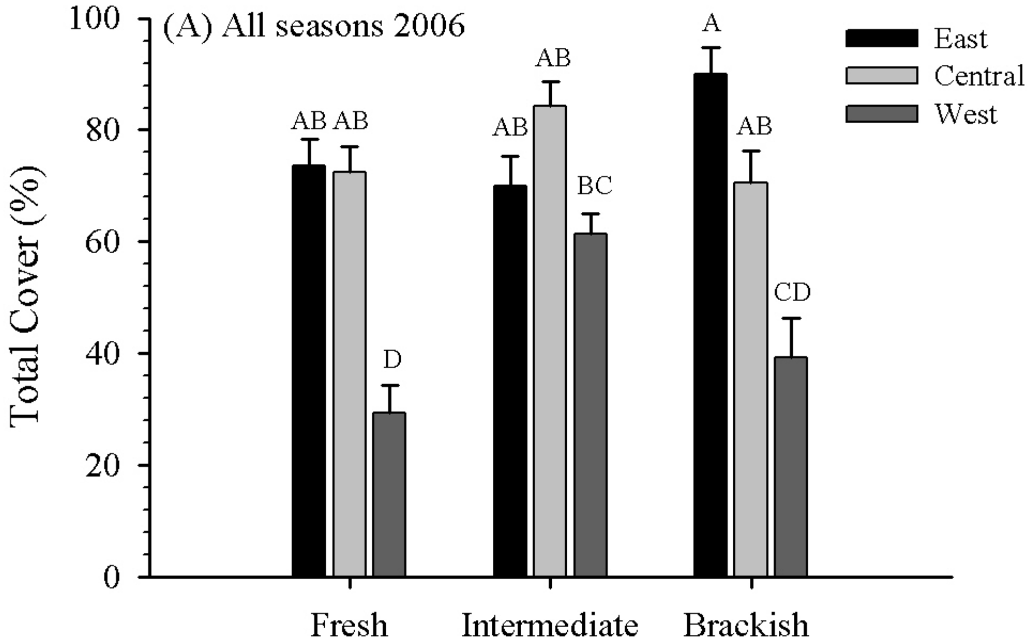
Figure 3.5. Average porewater sulfide (mM) across coastal Louisiana for (A) all seasons in 2006 and (B) fall 2007. Bars with the same letter are not statistically different at $p \leq 0.05$ (Tukey's HSD test).

Mean phosphate concentrations in 2006 and 2007 were highest in all marsh types in the east and lowest in the west region (Table 3.1). Mean phosphate concentrations were also significantly ($p < 0.0001$) highest in brackish marsh (27.34 µM) and lowest in fresh marsh (14.07 µM) across all regions. Ammonium levels were highly variable with no patterns among marsh types and regions (Fig. 3.3), other than in the east region where ammonium concentrations in intermediate marsh were over twice as high as the other regions (Table 3.1).

Vegetative Cover

Mean total percent cover differed among regions within marsh types in 2006 ($p < 0.0001$). Multiple comparisons indicated that the mean total percent cover was lower in the west among fresh and brackish marsh types in 2006 compared to the other regions (Fig. 3.6A). There were no differences in vegetation cover among regions within the intermediate marsh type in 2006 (Fig. 3.6A). In fall 2007, there were no significant differences in vegetation cover among regions within marsh types ($p = 0.0548$, Fig. 3.6B). Mean vegetation cover values were also compared between fall 2006 and fall 2007 to evaluate the first two years of post-hurricanes impact recovery. In the entire study area, irrespective of marsh types and regions, ANOVA indicated that the mean total cover of 71% in fall 2007 was significantly higher ($p = 0.0103$) than the mean total cover of 55% in fall 2006. Within marsh types, across regions there were no significant differences in total cover between fall 2006 and fall 2007 ($p = 0.8515$).

A total of 95 plant species were identified in all marsh types throughout the study, of which 22 were identified as disturbance species or taxa (Table 3.2). Disturbance species were identified in fall 2006 and 2007 as the dominant vegetation species in 38.5% of the sites in the east (n=28), 13.6% in the central (n=23), and 2.5% in the west (n=49)



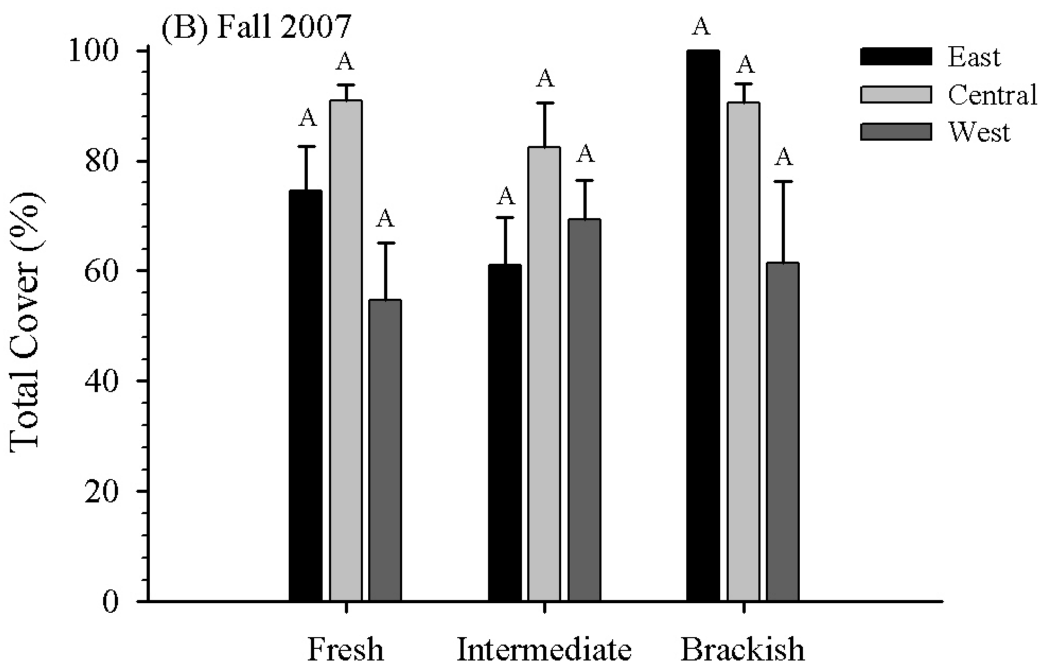


Figure 3.6. Average total percent cover across coastal Louisiana for (A) all seasons in 2006 and (B) fall 2007. Bars with the same letter are not statistically different at $p \leq 0.05$ (Tukey's HSD test).

regions. The vegetation species that composed the greatest percent cover in fresh marsh throughout the study were *Alternanthera philoxeroides* in the east and central regions and

Spartina patens in the west region (Fig. 3.7). *Alternanthera philoxeroides* and other identified disturbance species (Table 3.2) occupied over 40% of the total species cover in the east and 25% in the west regions. *Panicum hemitomon*, the dominant fresh marsh species (along with *Sagittaria lancifolia*) in the central and west regions prior to the hurricanes, contributed less than 3% cover in spring 2006. *Panicum hemitomon* then

Table 3.2. Observed taxa characterized as disturbance or opportunistic because they are commonly present in marshes that have been recently disturbed by physical or biological forces (Jenneke Visser, University of Louisiana, Lafayette and Charles Sasser, Louisiana State University, personal communication).

Disturbance Taxa
Aeschynomene indica
Alternanthera philoxeroides
Amaranthus spp.
Andropogon spp.
Cyperus spp.
Cyperus odoratus
Echinochloa spp.
Echinochloa crus-galli
Echinochloa walteri
Eupatorium capillifolium
Leptochloa fusca
Mikania scandens
Panicum dichotomiflorum
Pluchea camphorata
Ranunculus spp.
Rorippa palustris
Sesbania drummondii
Sesbania herbacea
Sesbania spp.
Symphyotrichum subulatum
Symphyotrichum tenuifolium
Vigna luteola

became codominant in the central and west regions in fresh marsh during summer and fall 2006 and dominant once again in the west region during fall 2007, then accounting for 18% of cover.

Spartina patens dominated the intermediate marsh sites in all regions, and percent cover changed very little over time (Fig. 3.8). *Spartina patens* maintained over 20% cover in the central region, 30% in the east region, and 40% in the west region throughout the study. The codominant species varied by regions: the east region consisted of disturbance species, the central of *Spartina alterniflora* and *Distichlis spicata*, and the west of *Schoenoplectus americanus*. In spring 2006, *Schoenoplectus americanus* had 15% cover in the central region and 8% cover in the west region, but declined throughout 2006 and contributed less than 5% cover in central or west regions by fall 2007.

Brackish marsh cover was also dominated by *Spartina patens*, especially in the central region where it contributed over 47% of the total species cover, but varied seasonally and annually within regions (Fig. 3.9). *Distichlis spicata* was codominant with *Spartina patens* at different times throughout the study period. In fall 2007, *Distichlis spicata* accounted for 15% of the cover in each of the 3 regions. The west region had the smallest percentage of *Spartina patens* but also the largest percentages of *Spartina alterniflora* and *Schoenoplectus robustus* (Fig. 3.9).

Nine of the 100 sample sites across all regions did not recover from initial hurricane impacts and were converted to open water by fall 2007; of these 8 were located in the west region and one in the east region. Additionally, one site in the east and one in the central region that deteriorated to 0% cover by fall 2006 had recovered to 100% cover by fall 2007. Between fall 2006 and fall 2007, changes in species dominance occurred at 53.8% of the vegetated sites in the east region, 40.9% in the central, and 22.5% in the

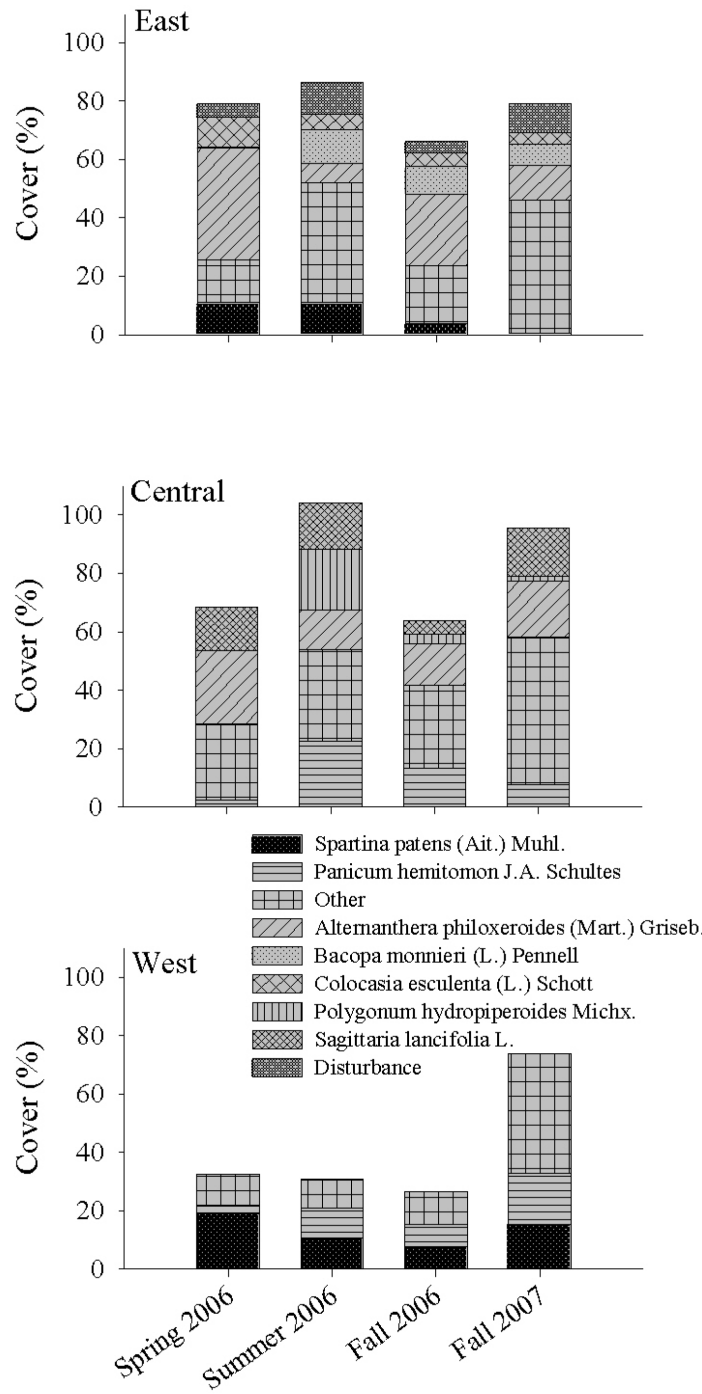


Figure 3.7. Percent cover of fresh marsh species in east, central, and west regions for all 4 seasons considered in the study. The "other" category includes 53 different species, each of which had less than 5% cover. The species that comprise the disturbance category are identified in Table 3.2. Although *Alternanthera philoxeroides* is a disturbance species, it was identified separately because it represents a high percent of cover.

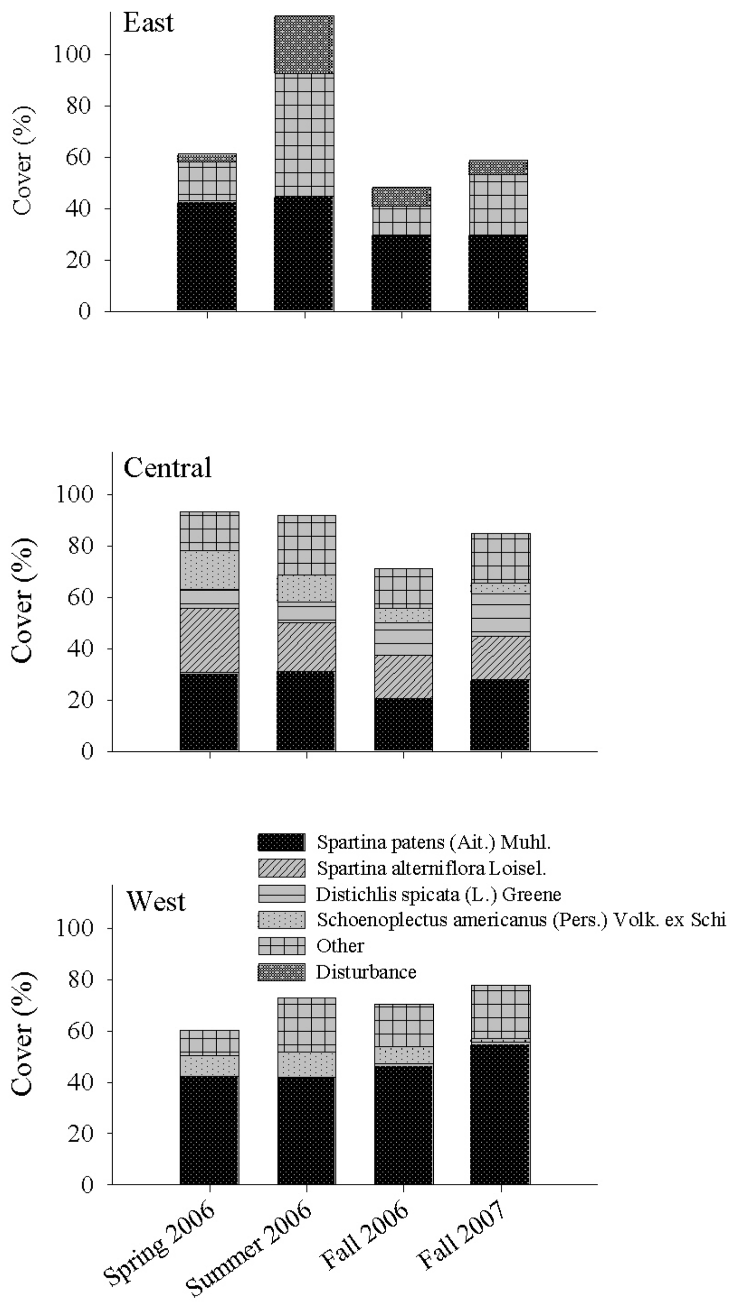


Figure 3.8. Percent cover of intermediate marsh species in east, central, and west regions for all 4 seasons considered in the study. The "other" category includes 40 different species, each of which had less than 5% cover. The species that comprise the disturbance category are identified in Table 3.2.

west regions. Species richness increased from fall 2006 to fall 2007 in 47.5% of the sites in the west region and 54.5% of the sites in the central region. Decreases in species

richness were observed at 23.1% of the sites in the east region, compared to 9.1% in the central, and 10.0% in the west regions.

Vegetation data collected in fall 2006 and 2007 were classified by marsh type by using salinity scores from Visser et al. (2002) and zones of peak occurrence from Chabreck (1970). Six sites in the east region, 5 sites in the central region, and 6 sites in the west region changed marsh classification from 2006 to 2007 (Fig. 3.1, Table 3.3). In the east region, composition changes in 5 sites were to fresher marsh classifications, and all sites had a change in species dominance. The one site that changed to a more saline marsh classification was driven by high species richness in 2007, compared to dominance by a single species, *Bacopa monnieri*, in 2006 (Table 3.3). In the central region, marsh composition at all 5 sites changed to a more saline classification, which is consistent with high fall 2006 mean salinities that exceeded mean porewater salinity levels tolerated by the dominant species, as identified by Chabreck (1970). There were minimal changes in both dominance and species richness between fall 2006 and 2007 in the central region. Five sites in the west region shifted to more saline classifications even though only 1 site had a change in species dominance. Increased species richness and more saline compositions at all sites coincided with salinity values exceeding toleration limits of dominant species identified by Chabreck (1970).

Vegetation and Environmental Correlations

Pearson correlation coefficients suggested trends between the variables measured in this study from 2006 and 2007 datasets for each marsh type (Table 3.4). Across all marsh types, total percent cover was significantly negatively correlated ($p < 0.05$) with salinity and ammonium. Additionally, in fresh marsh total percent cover was negatively correlated with sulfide ($r = -0.35$, $p < 0.0001$) and positively correlated with pH ($r = 0.18$,

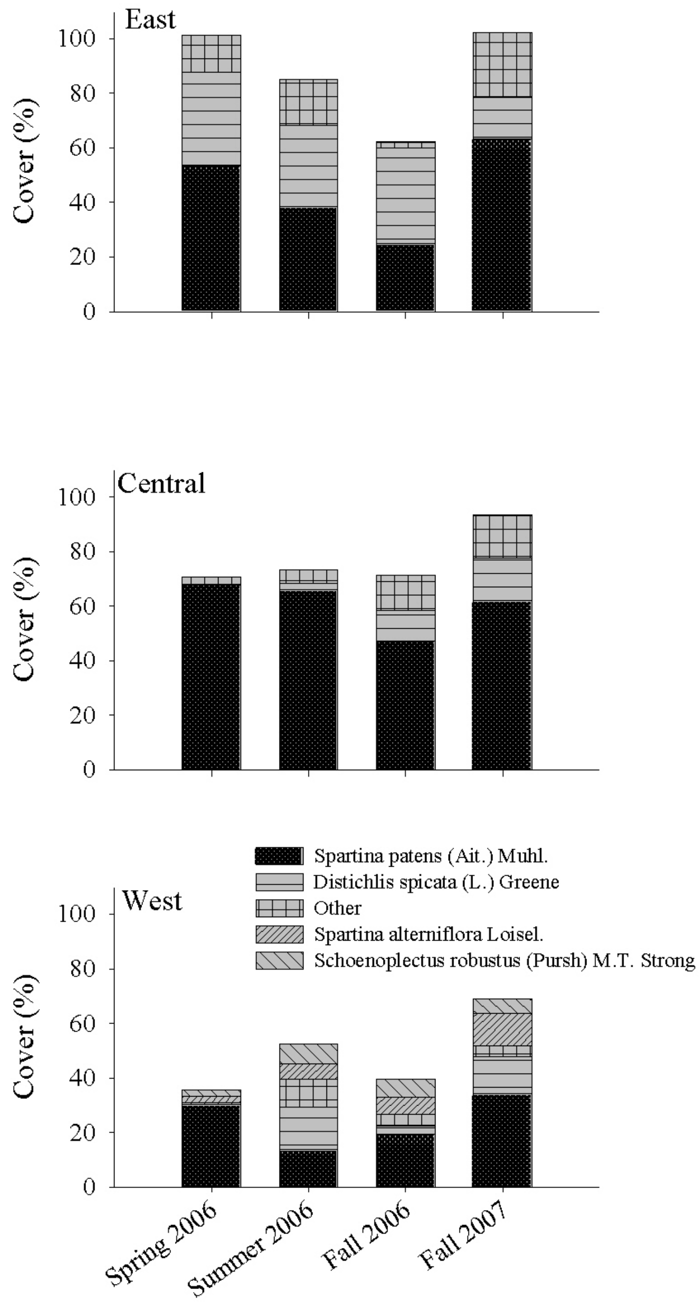


Figure 3.9. Percent cover of brackish marsh species in east, central, and west regions for all 4 seasons considered in the study. The “other” category includes 19 different species, each of which had less than 5% cover. The species that comprise the disturbance category are identified in Table 3.2.

Table 3.3. Dominant taxa, species richness, mean porewater salinity, and vegetation type (classified based on Visser et al. (2002) salinity scores) for field sampling sites where marsh species composition changed type classification between fall 2006 and 2007. Vegetation types are fresh (F), intermediate (I), brackish (B), and saline (S). Underlined salinities indicate ≥ 1 SD and bold porewater salinities indicate all of which are ≥ 2 SD higher than the mean porewater salinity of the dominant species identified from Chabreck (1970). Porewater salinity data from Chabreck (1970) was not available for taxa indicated with (*).

Region	**Site Number**	**Vegetation Type** Fall 2006	Fall 2007	**Dominant Taxa** Fall 2006	Fall 2007	**Species Richness** Fall 2006	Fall 2007	**Porewater Salinity** Fall 2006	Fall 2007
East									
	1	I	F	*Panicum dichotomiflorum**	*Polygonum* spp.	2	4	7.13	1.80
	2	I	F	*Vigna luteola*	*Panicum hemitomon*	4	3	2.37	1.17
	3	I	F	*Polygonum hydropiperoides**	*Polygonum punctatum**	2	6	2.47	1.15
	4	F	I	*Bacopa monnieri*	*Spartina patens*	1	6	5.53	1.60
	5	I	F	*Spartina patens*	*Ipomoea sagittata*	3	3	3.93	1.60
	6	S	B	*Distichlis spicata*	*Spartina patens*	3	5	15.50	11.03
Central									
	7	B	S	*Spartina patens*	*Distichlis spicata*	4	2	20.43	4.37
	8	I	B	*Juncus* spp.	*Juncus* spp.	2	2	**9.10**	4.87
	9	I	B	*Spartina patens*	*Spartina patens*	2	3	16.77	5.30
	10	F	I	*Paspalum vaginatum*	*Spartina patens*	2	2	**11.27**	10.77
	11	B	S	*Spartina patens*	*Distichlis spicata*	2	2	15.87	12.77
West									
	12	F	I	*Typha* spp.	*Typha* spp.	2	4	9.27	6.80
	13	F	I	*Paspalum vaginatum*	*Paspalum vaginatum*	2	6	**11.00**	**11.43**
	14	B	I	*Spartina patens*	*Spartina patens*	1	2	9.07	6.50
	15	F	I	*Paspalum vaginatum*	*Paspalum vaginatum*	1	3	10.00	9.30
	16	I	B	*Spartina patens*	*Spartina patens*	1	2	20.47	17.70
	17	B	S	*Spartina patens*	*Distichlis spicata*	3	4	**23.83**	21.03

$p = 0.0021$), nitrate ($r = 0.17$, $p = 0.0144$), and phosphate ($r = 0.17$, $p < 0.0283$). In brackish marsh total percent cover was negatively correlated with nitrite and nitrate ($r = -0.29$, $p = 0.0008$; $r = -0.25$, $p = 0.0035$, respectively) and was positively correlated with pH ($r = 0.28$, $p = 0.0001$) and phosphate ($r = 0.24$, $p = 0.0122$). In pairwise partial correlations among independent variables across marsh types, nitrite and salinity were found to be significantly correlated with the most of the variables. The strongest positive correlations were between ammonium and sulfide in fresh marshes ($r = 0.53$, $p < 0.0001$) and between ammonium and phosphate ($r = 0.53$, $p < 0.0001$) in intermediate marshes, followed by nitrate and nitrite for all marsh types (Table 3.4). The strongest negative correlations were between salinity and phosphate in fresh marshes ($r = -0.36$, $p < 0.0001$) and between pH and nitrate in brackish marshes ($r = -0.52$, $p < 0.0001$), followed by pH and nitrite in all marsh types (Table 3.4).

Fall 2006 data on salinity, sulfide, and vegetative cover within the west region are depicted to further illustrate relationships among the variables at the site scale (Fig. 3.10). The salinity and sulfide ranges provided are typically found within fresh, intermediate, brackish, and saline marsh types. The percent cover of vegetation is predominantly lower when out of range values for salinity and sulfide occurred; however, fresh marsh sites located furthest north within the region show low percent cover even when salinity and sulfides are within typical range.

A two-dimensional nMDS ordination (stress = 0.13) was conducted on data for percent species composition from all fresh marsh sites. The west region showed the greatest overall variation in composition and most closely corresponded to vectors of *Spartina patens* and *Panicum hemitomon* (Fig. 3.11A). Sites in the east and central regions had greater overlap in ordination space and did not tend to cluster along

Table 3.4. Pearson correlation coefficients for independent and dependent variables derived by using 2006 and 2007 datasets for (A) fresh marsh, (B) intermediate marsh, and (C) brackish marsh. Bold values represent significant correlations at $p < 0.05$.

(A) Fresh marsh

Variable	Total cover	Salinity	pH	Sulfide	NO_2-N	NO_3-N	NH_4-N	PO_4
Total cover	1.00	**-0.54**	**0.18**	**-0.35**	-0.04	**0.17**	**-0.38**	**0.17**
Salinity		1.00	**-0.23**	**0.42**	**0.19**	**-0.14**	**0.28**	**-0.36**
pH			1.00	**0.23**	**-0.27**	0.05	0.05	**0.39**
Sulfide				1.00	**-0.22**	-0.08	**0.53**	0.04
NO_2-N					1.00	**0.52**	**-0.16**	-0.11
NO_3-N						1.00	**-0.16**	0.09
NH_4-N							1.00	**0.45**
PO_4								1.00

(B) Intermediate marsh

Variable	Total cover	Salinity	pH	Sulfide	NO_2-N	NO_3-N	NH_4-N	PO_4
Total cover	1.00	**-0.15**	0.09	-0.03	-0.10	0.10	-0.16	-0.02
Salinity		1.00	**-0.11**	**0.15**	**0.23**	0.06	**-0.26**	**-0.22**
pH			1.00	**0.36**	**-0.40**	**-0.17**	**0.32**	**0.25**
Sulfide				1.00	**-0.17**	-0.01	**0.39**	0.03
NO_2-N					1.00	**0.51**	**-0.14**	**-0.16**
NO_3-N						1.00	0.01	-0.03
NH_4-N							1.00	**0.53**
PO_4								1.00

(C) Brackish marsh

Variable	Total cover	Salinity	pH	Sulfide	NO_2-N	NO_3-N	NH_4-N	PO_4
Total cover	1.00	**-0.24**	**0.28**	0.02	**-0.29**	**-0.25**	**-0.38**	**0.24**
Salinity		1.00	**-0.25**	-0.06	**0.26**	**0.44**	-0.08	-0.04
pH			1.00	**0.37**	**-0.70**	**-0.52**	-0.10	**0.22**
Sulfide				1.00	**-0.26**	-0.15	**0.25**	0.14
NO_2-N					1.00	**0.44**	0.17	-0.09
NO_3-N						1.00	**0.24**	-0.10
NH_4-N							1.00	**0.19**
PO_4								1.00

vegetation vectors. Regarding environmental variables, porewater salinity ($r^2 = 0.23$) showed a gradient across the ordination space and indicated that sites extending far into the upper left quadrant were relatively saline (Fig. 3.11B). Analysis of similarity

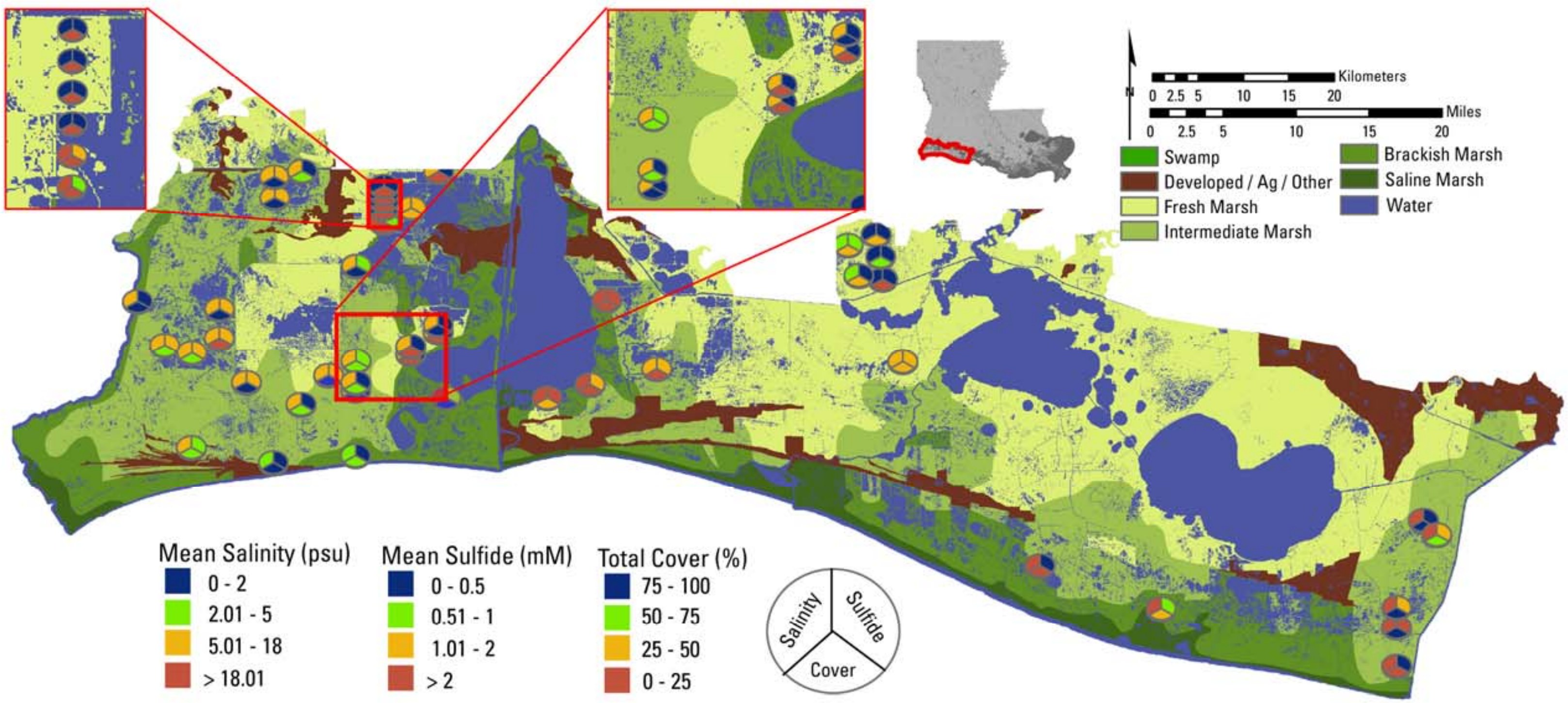


Figure 3.10. Mean salinity, sulfide, and percent vegetation cover from sampling sites within the west region from fall 2006. Pie colors for salinity and sulfide indicate typical ranges found in fresh (blue), intermediate (green), brackish (orange), and saline (red) marsh types.

(ANOSIM) revealed highly significant differences between the west and the east regions ($R = 0.217$; $p < 0.01$) and the west and the central regions ($R = 0.191$; $p < 0.01$) and significant differences between the east and central regions ($R = 0.108$; $p = 0.04$). Dissimilarities between the east and west region were contributed mostly by disturbance species in the east and *Spartina patens* in the west (Table 3.5). Dissimilarities with the central region were primarily contributed by *Sagittaria lancifolia*.

Two-dimensional nMDS ordination from intermediate (stress = 0.09) and brackish (stress = 0.12) marsh sites illustrate species composition in ordination space (Fig. 3.12). There was not a lot of separation in ordination space within intermediate marsh except for *Spartina alterniflora* and *Typha* spp. which are found primarily in the central and west regions. Within brackish marsh, the strongest gradients in ordination space are associated with *Spartina alterniflora* ($r^2 = 0.55$) and *Schoenoplectus robustus* ($r^2 = 0.57$), which were nearly orthogonal in ordination space. Separation of brackish species in ordination space tends to show higher salinity species in the lower right quadrant and lower salinity species in the upper left quadrant.

DISCUSSION

Hurricanes Katrina and Rita were important vectors for physical landscape disturbance and saltwater intrusion into Louisiana's coastal freshwater swamps and marshes. Hurricane Katrina surge (estimated between 3 and 6 m) by Ebersole et al. (2007) in the east region, flipped, compressed, scoured, and sheared the marsh landscape (Barras 2007). Persistent new water bodies formed in the east region with a broad area of disturbance in the Breton Sound estuary (Barras 2007). The coast-parallel track of Hurricane Rita pushed a storm surge across all regions of the coast with surge that exceeded 2 to 4 m in the west (McGee et al. 2007) and 1 to 2 m in the central (Doyle et

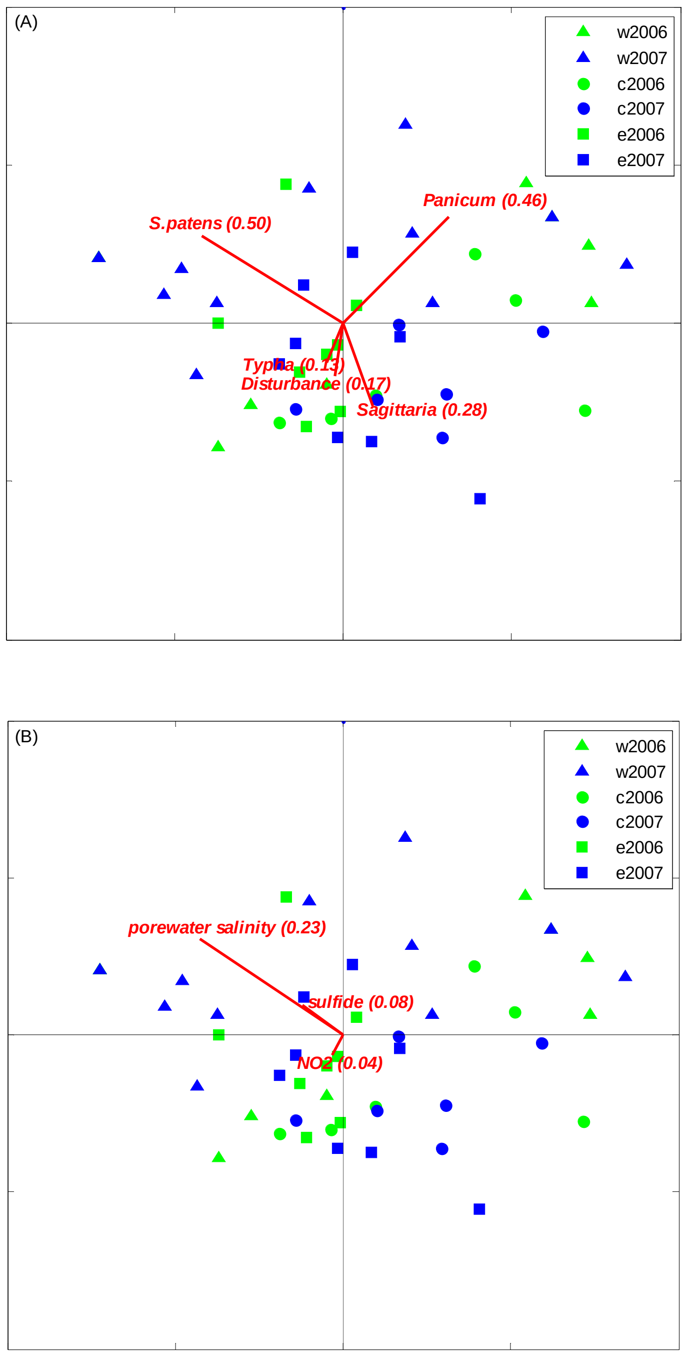


Figure 3.11. Nonmetric multidimensional scaling (nMDS) ordination within fresh marsh sites from fall 2006 and fall 2007 derived by using (A) percent species composition and (B) environmental vectors. Only common species were projected in ordination space. Symbols represent east (e), central (c), and west (w) regions by year. Plant species and environmental vectors show the magnitude and direction of significant correlations (r^2 values in parentheses).

Table 3.5. The average abundance of marsh plant species that contributes to the percent of dissimilarity between fresh marsh communities in the east and west regions.

Species	Average Abundance		% Contribution to Dissimilarity	Cumulative % Contribution
	East	West		
Disturbance spp.	5.45	1.42	17.35	17.35
Spartina patens	0.78	3.99	16.68	34.03
Panicum hemitomon	0.31	2.55	9.6	43.62
Polygonum spp.	1.9	0.19	7.18	50.81
Typha L. spp.	0.87	0.85	5.24	56.05
Eleocharis spp.	1.02	0.45	5.18	61.23
Bacopa monnieri	1.05	0.41	5.1	66.33
Sagittaria lancifolia	1.25	0	4.91	71.24
Colocasia esculenta	1.41	0	4.85	76.09
Schoenoplectus californicus	0.67	0.42	3.45	79.54
Hydrocotyle spp.	0	0.69	2.18	81.72
Bidens laevis	0.56	0	2	83.72
Paspalum vaginatum	0	0.55	1.85	85.57
Crinum americanum	0.52	0.03	1.68	87.25
Leptochloa spp.	0	0.49	1.67	88.92
Juncus spp.	0	0.41	1.64	90.56

al. 2007) regions. Surge-created shears and wrack deposits were present throughout the west region (Barras 2007, Michot et al. 2007). In fresh and intermediate marsh communities coastwide, 334 km^2 of new water area formed between fall 2004 and fall 2005 (Barras 2007). Barras (2007) also identified from biweekly satellite images areas of the west region that were persistently flooded from Hurricane Rita from September 2005 through February 2006. The saltwater storm surge into coastal marsh communities was evident from initial field sampling of surface waters immediately after the storms (Steyer et al. 2007). Discrete salinity concentrations were as high as 26 in fresh marsh, 26 in intermediate marsh, and 34 in brackish marsh (Steyer et al. 2007).

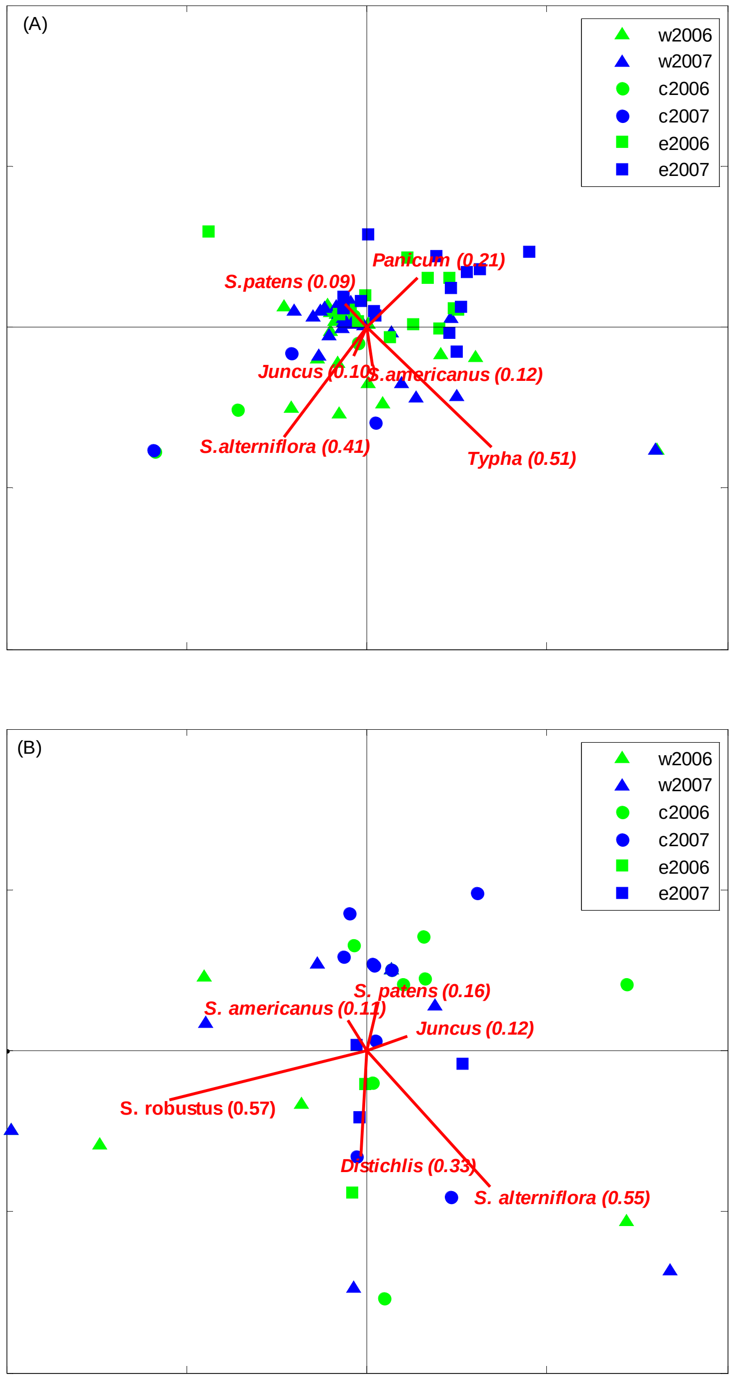


Figure 3.12. Nonmetric multidimensional scaling (nMDS) ordination of sampling sites within (A) intermediate marsh and (B) brackish marsh from fall 2006 and fall 2007 derived by using percent species composition. Only common species were projected in ordination space. Symbols represent east (e), central (c), and west (w) regions by year. Plant species show the magnitude and direction of significant correlations (r^2 values in parentheses).

Fresh Marsh

The results indicate that elevated porewater salinity and sulfide were significant stressors on vegetative cover in fresh marsh. Fresh marsh sites that converted to open water were exposed to salinities and sulfides during 2006 in excess of 10 and 1.6 mM, respectively. Mean salinities in fresh marsh greatly exceeded the typical range of 0 - 3 (Chabreck 1970) in all sampled time periods in the west region. The persistence of mean salinities above 7.1 in 2006 may have significantly affected cover values of *Panicum hemitomon*, the dominant freshwater species in the chenier plain (Visser et al. 2000) and limited the extent of its regrowth (Fig. 3.7). Salinity levels in excess of 7.6 and sulfide in excess of 0.6 mM have been reported to significantly reduce productivity and increase plant mortality in fresh marsh vegetation communities (Hester et al. 1998, Koch and Mendelssohn 1989). La Peyre et al. (2001) found that *Panicum hemitomon*, when grown in a mixture of more salt tolerant species, decreased as salinity increased, until death occurred at 8. Field observations suggest that *Panicum hemitomon* dieback at initial salinity exposure provided opportunities for *Spartina patens*, one of the dominant intermediate marsh species, to dominate cover by spring 2006. Ordination vectors illustrate that *Spartina patens* was positively associated with salinity and sulfide gradients in fresh marsh and suggest that as salinity and sulfide stress increase, *Spartina patens* outcompeted less tolerant species.

Fresh marsh in the central and east regions was exposed to salinities and sulfides on the higher end of their typical range (0 – 3 and 0 – 0.5 mM, respectively). In October 2005, leaf browning from salt burn was observed in all regions (Steyer et al. 2007); however, we observed little effect on fresh marsh cover values in the central and east regions. The fall 2006 and 2007 fresh marsh cover values measured in this study (Fig.

3.7), were similar to fresh marsh cover values measured in 2003 and 2004 (mean = 69.2%; n = 218) under the CWPPRA's monitoring program (http://www.lacoast.gov). The difference we observed was a higher percentage of disturbance species occurring, in particular *Alternanthera philoxeroides*, which is commonly found flanking marsh edges adjacent to open water. The significant area of new open water and the physical disruption of the marsh surface in fresh and intermediate marshes found by Barras (2007) after Hurricane Katrina may contribute to the predominance by *Alternanthera philoxeroides* and other disturbance species in these regions.

Intermediate Marsh

Intermediate marshes in the central and west regions were exposed to salinities well outside the 0.5-5.0 range as described in Chabreck (1970); however, they were not at levels that are lethal to the dominant marsh species. *Spartina patens*, the dominant species in all regions of the coast, generally experiences reduced growth and net photosynthesis when exposed to salinity above 10 (Pezeshki et al. 1987, Pezeshki and DeLaune 1993, Broome et al. 1995, Ewing et al. 1995); but has a high tolerance of salinity conditions, and it is commonly found to coexist with *Spartina alterniflora* in brackish communities. In the central region, *Distichlis spicata* became codominant, suggesting that parts of this region are transitioning to more brackish marsh communities (Table 3.3). The intermediate marsh in the east region appears to be transitioning to fresh marsh, with much lower salinities, high species richness, and an increase of annuals and disturbance species; however, it is not uncommon for fresh and intermediate marsh communities to transition between marsh types even in nondisturbance time periods because of similarities in species composition. The intermediate marsh in the east region had the greatest amount of new open water formation and physical disruption following

Hurricane Katrina (Barras 2007). The physical disruption covered the landscape with displaced patches of *Spartina patens*, commonly referred to as marsh balls. Marsh balls that were relocated during the storm were commonly a few meters in size. By fall 2007, most of the identified annuals and disturbance species were growing through the marsh balls in the east region, and there was limited expansion of *Spartina patens* cover.

The intermediate marsh cover values measured in the central and west regions in our study (Fig. 3.8) were comparable to the cover values from intermediate marshes measured in 2003 and 2004 (mean = 78.4%; n = 103) under the CWPPRA monitoring program. The highest cover values in the central region may be related to the transition in dominant perennials and the lowest sulfide stress among the regions.

Brackish Marsh

Salinity and sulfide concentrations were variable among sites within all 3 coastal regions of the brackish marsh communities. Although mean salinities were significantly higher in the west, concentrations were in the typical range of 5 to 18 (Chabreck 1970) in all regions. Sulfides generally increased from season to season in the central and west regions and decreased in the east region. *Spartina patens* and *Distichlis spicata* were found to be the dominant brackish marsh species in all regions of the coast during the study. The high relative cover of *Distichlis spicata* in the east region appears to be associated with physical disturbance of the marsh substrate. Observed areas of scour had some of the highest cover values. Bertness (1991) found that *Distichlis spicata* is adept at colonizing hypersaline bare space and resistant to wrack burial, which is consistent with our observations. The brackish marsh cover values in the west region in 2006 and 2007 were low compared to average conditions measured in 2003–2004 by the CWPPRA monitoring program (mean = 75.4%, n = 159). The low values we found were associated

with low cover and slow recovery by *Spartina patens*. The combined influences of high salinity and sulfide appear to favor the expansion of more tolerance *Spartina alterniflora* and *Schoenoplectus robustus*.

Landscape Response

A prolonged drought began in late 2004 in the south-central and southwest climatic regions in Louisiana and in summer 2005 in the southeast region. The drought extended into summer 2006 in the southwest, fall 2006 in the south-central, and winter 2006 in the southeast region (Fig. 3.2). Visser et al. (2002) were able to identify vegetation community changes between 1997 and 2000 across the Barataria estuarine landscape in coastal Louisiana associated with an extreme drought in 1999 and 2000. Because of the lack of immediate pre-hurricane salinity data, the vegetation change results presented in this study represent the combined affects of both hurricane and drought conditions.

Changes in marsh type from fall 2006 to fall 2007 were identified at 17 sampling sites, equally distributed among the 3 regions. The changes that occurred in the east region were primarily to fresher marsh classifications. Though the hurricanes physically disturbed the marsh landscape, stress associated with salinity and sulfide appears to have been minimal. This region received an average freshwater discharge of 85.8 m^3s^{-1} from the Caernarvon Freshwater Diversion Project located at river mile 81.5 (131.2 km) from January through May 2006. Even though the region was in an extended drought, it appears that the freshwater from the diversion structure moderated salinities, and the high nutrient loads may have contributed to rapid colonization by disturbance species in the fresh and intermediate marshes. Lane et al. (2007) showed strong inverse relationships between diversion discharge and salinity in upper Breton Sound. A box model developed

by Swenson et al. (2006) showed that river diversions have the capability to significantly reduce water residence times and salinities within upper portions of their receiving basins. The central region was only indirectly exposed to storm surge from the hurricanes, and salinity data suggest elevated exposures primarily in intermediate and brackish marshes. Changes in vegetation composition to more saline marsh classifications occurred, but ancillary salinity data (2004 and 2005) from CWPPRA suggest that some intermediate marsh sites had drought-induced salinities above typical ranges prior to the hurricanes of 2005.

The west region was most highly impacted and showed both physical and plant stress effects. The effects of salinity on plant cover appear to be amplified when sulfide stress was present. Sulfide is a phytotoxic substance that accumulates in waterlogged soils and has been shown to reduce growth in marine and freshwater species (Joshi et al. 1975, Ingold and Havill 1984, Koch et al. 1990). The excessive and prolonged flooding in the west region, identified from satellite imagery, corresponds to the many sites that had high concentrations of mean porewater sulfide in spring and summer 2006, which may have contributed to the low percent of vegetation cover in this region. Buresh and Patrick (1978) found that NH_4-N rather than NO_3-N was the primary form of nitrogen assimilated by marsh plants. Across all marsh types, total cover was inversely correlated with ammonium, suggesting uptake by the vegetation. The uptake of NH_4-N in fresh and salt marsh has been shown to be limited by high sulfide concentration (Mendelssohn and McKee 1988, Bradley and Morris 1990, Koch et al. 1990, Flynn et al. 1995). High interstitial NH_4-N was found at many of the high sulfide sites, and low cover values suggest that sulfide may have reduced plant uptake of NH_4-N. The high correlation between ammonium and phosphate in fresh and intermediate marshes might suggest that

phosphate was also not taken up at sites with high sulfide. The mobilization of phosphate and ammonium combined with phytotoxicity from sulfide was shown to favor fast-growing species that are resistant to sulfide (Lamers et al. 1998).

CONCLUSIONS

The hurricanes of 2005 contributed to vegetation community change across the Louisiana coast by stress induced from saltwater storm surge, primarily from Hurricane Rita, and physical impacts to the marsh substrate, primarily from Hurricane Katrina. Salinity and sulfide stress were persistent in the west region throughout 2006 and in fall 2007, contributing to low vegetative cover and shifts towards more saline marsh compositions with minor changes in species dominance. Although hurricane landfalls did not directly impact the central region, saltwater storm surge from Hurricane Rita did reach fresh, intermediate, and brackish marshes. Salinity intrusion in the central region combined with drought conditions may have contributed to shifts towards more saline marsh classifications, but with minimal changes in species dominance. Physical disruption of the marsh surface through shearing and removal was predominant in the east region, contributing to a high abundance of disturbance species and major changes in species dominance from fall 2006 to fall 2007. Low salinity and sulfide stress, together with abundant nutrients contributed to high vegetative cover in the east compared to the central and west regions. The variability depicted among sites within marsh types suggests the importance of species-specific tolerances to salinity and sulfide. Two full growing seasons after the hurricanes of 2005, marshes directly impacted in the east and west regions are still recovering. Although vegetation cover values are approaching pre-hurricane levels, species composition is still indicative of a disturbance environment.

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CHAPTER 4

GEOMORPHIC EFFECTS OF HURRICANE RITA IN THE CHENIER PLAIN OF COASTAL LOUISIANA

INTRODUCTION

Hurricanes have been documented in causing a wide range of impacts to coastal wetland systems. While direct destruction and/or severe modification of habitat and near-immediate mortality of vegetation due to high winds and storm surge is not uncommon (Doyle et al. 1995, Guntenspergen et al. 1995, Cahoon et al. 2003, Barras 2006, Barras 2007), there are also reports of beneficial subsidies of materials provided to coastal wetlands which may be important to the long-term viability and sustainability of these coastal systems (Cahoon et al. 1995, Nyman et al. 1995, Cahoon 2003, Turner et al. 2006). Because of the varying geology, shoreline orientation, marsh stability, and employment of active marsh management techniques, the impacts from hurricanes and tropical storms in coastal Louisiana also vary widely depending upon the storm path, magnitude, and the location along the coast where the storm makes its landfall.

The stability of wetland habitats in coastal environments depends on the ability to maintain elevation above sea level. Interactions and feedbacks between tidal flooding, sediment deposition, and plant productivity allow coastal marshes to adjust to relative water level increases from the combined effects of local subsidence and eustatic sea level rise (Morris et al. 2002). Marsh areas that are sediment poor, have low productivity, or are experiencing high subsidence rates, may over time result in conversion to open water because of accretion and elevation deficit (DeLaune et al. 1983, Baumann et al. 1984, Nyman et al. 1993, Cahoon 2003). Low frequency, high energy events such as hurricanes provide a significant pulse of mineral sediments that can contribute to

elevation gain and help offset relative sea-level rise (Rejmanek et al. 1988, Day et al. 1995, Reed 2002, Turner et al. 2006). Mineral sedimentation plays an important role in accretion by supplying nutrients that can promote plant production (Bricker-Urso et al. 1989; Nyman et al. 1990, DeLaune et al. 1992, Nyman et al. 1993); however, organic matter accumulation from above and below-ground production has been previously identified as contributing more significantly to vertical accretion (McCaffrey and Thomson 1980, Hatton et al. 1983, Nyman et al. 1993, Turner et al. 2001, Turner et al. 2004, Nyman et al. 2006). Studies that quantify whether these high energy events provide adequate mineral sedimentation to support vertical accretion in sediment poor marshes are lacking.

Spoil banks and levees have been shown to decrease the flux of water and sediment; consequently, contributing to excessive inundation, reduced sedimentation and lower vertical accretion (Swenson and Turner 1987, Reed 1992, Boumanns and Day 1994, Cahoon and Reed 1994, Bryant and Chabreck 1998). These structures may also reduce nutrient accumulation because essential nutrients such as phosphorus are associated with mineral sediments (Broome et al. 1975, DeLaune et al. 1981). In the Louisiana Chenier Plain, levees and water control structures are commonly used in marsh management to promote plant growth by regulating water levels and controlling the intrusion of saltwater. Coastal marshes in the Chenier Plain are often flooded with storm surge for extended periods of time especially when water is impounded by these hydrologic barriers. Influence of these impoundments in altering sediment deposition during major storm events is unknown. Levees may contribute to lower sedimentation by reducing the volume of water that overtops managed areas when storm surges move inland. On the contrary, levees may increase sedimentation by trapping and retaining a

large volume of water for a sufficient time for suspended sediment to deposit on the marsh surface as storm surges recede.

It is the objective of this study to characterize sediment deposition from Hurricane Rita within the Chenier Plain in coastal Louisiana and quantify the relative contribution of organic and mineral matter accumulations to sediment accretion rates in marshes dominated by *Spartina patens*. Specifically, we investigated whether sedimentation and vertical accretion varies: (1) with distance from storm track, (2) with distance from Gulf of Mexico (GOM) or other large bodies of water, and (3) in areas under different hydrologic management.

MATERIALS AND METHODS

Study Area

Two geographic areas were investigated within the Chenier Plain of southwest Louisiana: Sabine Basin and Rockefeller Wildlife Management Area (WMA). The Chenier Plain extends approximately 200 km eastward from the Louisiana-Texas border and is formed by the westward delivery of Mississippi River sediments deposited primarily by the Gulf of Mexico over the last 3,800 years (McFarlan 1961, Hoyt 1969). A series of alternating marsh and chenier ridge complexes are prominent in these areas, corresponding to the proximal shoreline location during subdelta development in the Mississippi River deltaic plain (Gould and McFarlan 1959, Frazier 1967) and as a result of local depositional and erosional processes (Wells and Roberts 1981, McBride et al. 2007). Cheniers are relict Holocene beach ridges typically 1 to 4 m high, formed by wave erosion and reworking of mudflats, and are parallel to the shore of the Gulf of Mexico within the study area.

The Sabine Basin, where Hurricane Rita made landfall, is bounded by the Sabine-Neches Waterway and Sabine Lake to the west, Calcasieu Ship Channel and Calcasieu Lake to the east, Gulf Intracoastal Waterway to the north, and the Gulf of Mexico (GOM) to the south (Fig. 4.1). The GOM shoreline is comprised of a series of cheniers and includes U.S. Highway 82, which forms a hydrologic barrier between the GOM and marshes to the north except during high energy tropical storms and hurricanes. Spoil banks and numerous access canals dredged through the marsh in north-south and east-west configurations are also prevalent in the Basin (Fig. 4.1). A large portion of the Sabine Basin is under hydrologic management that utilizes levees and water control structures to mitigate salt water channeled into the basin from the Sabine and Calcasieu deep-draft navigational waterways into the adjacent fresh, intermediate and brackish marshes. Many of these management units were constructed in the 1950's and 1960's. There are many terms in the literature used to define hydrologic or marsh management, much of which is based on the extent of impoundment and degree of water control (Cahoon and Groat 1990). In this study, 3 marsh hydrologic classes were defined as: impounded, open, and mixed. Marshes in the impounded class are completely enclosed by levees with structures that regulate the movement of water and sediments. Open marsh classes have uncontrolled water and sediment exchange. Mixed marsh classes have some barriers that partially influence water and sediment exchange. Sediment data were collected in December 2005 or August 2006 from 23 sampling sites within *Spartina patens* dominated intermediate and brackish marsh. Sites in the Sabine Basin were randomly selected in all hydrologic classes from a population of Coastwide Reference Monitoring System (CRMS-*Wetlands*; Steyer et al. 2003) monitoring stations, and along

a fixed 8 km south- north transect located 23 km east of Hurricane Rita's landfall location for paired comparison with a transect in Rockefeller Wildlife Management Area (WMA).

Rockefeller WMA is located 110 km east of the Hurricane Rita's landfall location (Fig. 4.1). A transect was established from the edge of the GOM to 8 km inland in September of 2006, approximately one year after Hurricane Rita's landfall. Unlike U.S. Highway 82 at the Sabine Basin transect, this transect has no hydrologic barrier at the GOM shoreline. The first 5.75 km of transect were in unmanaged, open marsh that transitioned from salt to brackish marshes. The remaining sites consisted of managed, impounded intermediate to brackish marshes. At all sites, *Spartina patens* was the dominant or co-dominant vegetation species.

Sabine Basin and Rockefeller WMA study areas were influenced by Hurricane Rita. On September 24th, 2005, Hurricane Rita made landfall in the Chenier Plain of southwest Louisiana near Johnson's Bayou in western Cameron Parish as a Category 3 hurricane with sustained winds in excess of 53.6 m s^{-1} (Fig. 4.1). Hurricane force winds extended 140 km from the eye early on September 23rd (Knabb et al. 2006). The coast parallel orientation of the storm track caused rapid water level set up and flooding beginning September 23rd. Storm surge levels from Rita recorded at landfall exceeded 4.2 m above NAVD88 at Constance Beach, Creole, and Grand Chenier, Louisiana, located approximately 32 km, 77 km, and 87 km east of the eye from the landfall location, respectively (McGee et al. 2007). Gosselink et al. (1979) indicated that tides within this region typically do not exceed 0.7 m.

Methodology

Sedimentation was determined from the distribution of ^{137}Cs in the sediment profile (DeLaune et al. 1978). At each site, one or two sediment cores were obtained by

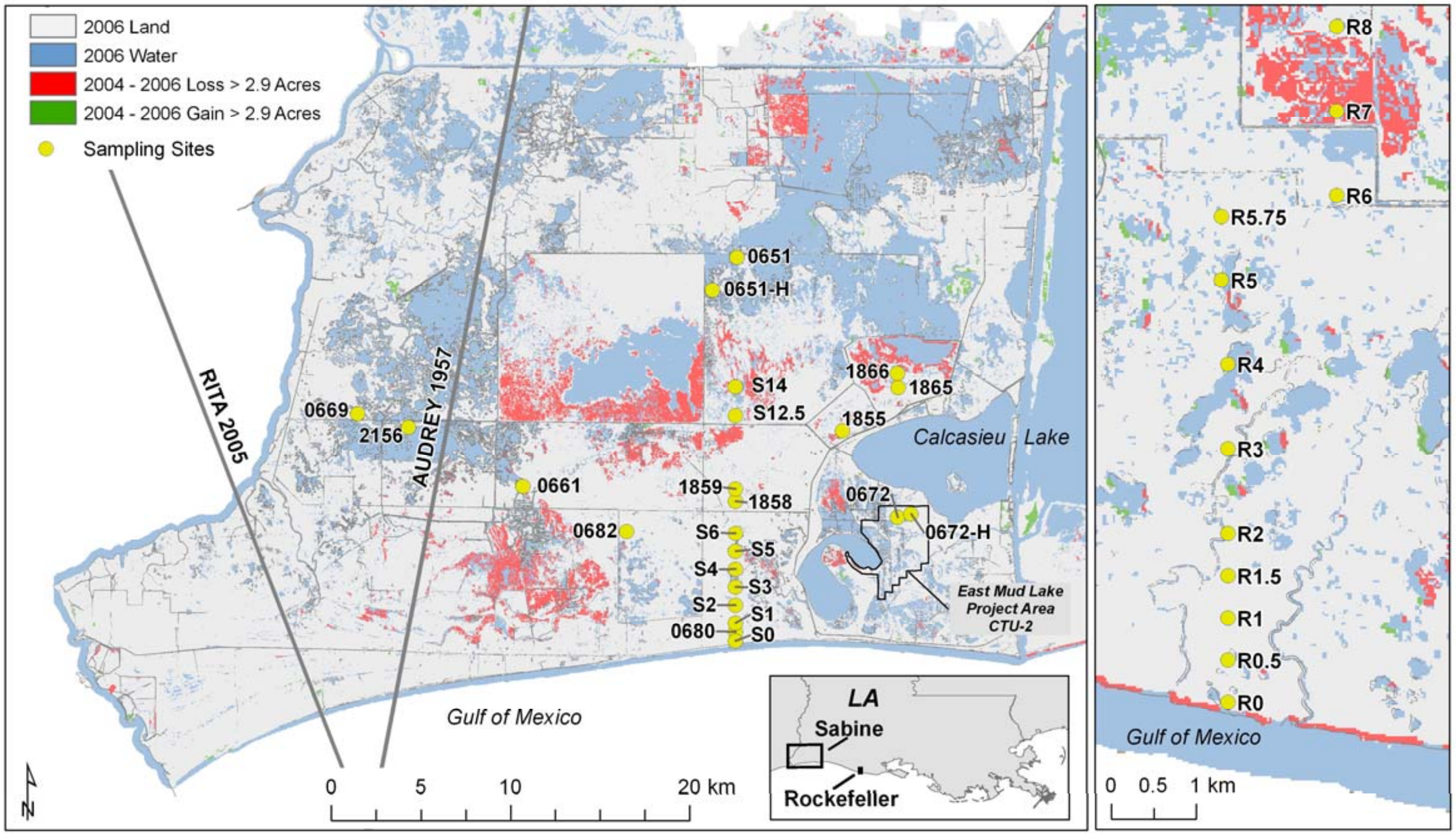

Figure 4.1. Sabine Basin (left) and Rockefeller WMA (right) sampling sites for the sedimentation investigations. Persistent new open water after Hurricane Rita (2004 – 2006 change) is identified in red (with permission from Barras et al. 2008). Tracks of Hurricane Rita from September 24, 2005 and Hurricane Audrey from June 27, 1957 are also shown.

twisting a 10-cm diameter thin-walled sharpened suction coring tube (Meriwether et al. 1996) to a maximum depth of 50 cm. Cores were sectioned into 2-cm increments in the field and upon return to the laboratory these cores were dried at 80°C. In the laboratory, the specific activity of ^{137}Cs in each section was determined by gamma ray spectroscopy using high purity germanium detectors. The 662 keV gamma emissions from ^{137}Cs were measured for a minimum of 11 h. The gamma spectrometers were calibrated for energy and efficiency using a reference mixed gamma ray source traceable to the National Institute for Standards and Technology. Sedimentation rates were calculated from the 1963 peak ^{137}Cs concentration, which corresponds to the greatest ^{137}Cs fallout (Pennington et al. 1973).

Bulk density, organic matter, and carbon and nitrogen content also were determined from all depth increments of the above described cores used for ^{137}Cs analysis. Soil bulk density was determined from its oven dried weight of a pre-measured volume of wet soil. Percentages of organic and mineral matter content by weight were determined by the loss-on-ignition method (Ball 1964). A subsample of 8 g was removed from each section and analyzed for total carbon and nitrogen contents using a Costech ECS 4010 elemental analyzer. Annual accumulation rates were calculated from all soil depth increments above and including the 1963 peak using soil bulk density and the percent of organic matter, mineral matter, carbon and nitrogen estimated for each soil increment.

Recently deposited sediments presumably from Hurricane Rita were identified from bulk density sediment profiles sampled at each site either in December 2005 or August 2006. Nyman et al. (1990) identified mean and standard deviation of bulk densities within intermediate 0.08(0.05) g cm^{-3}, brackish 0.16(0.07) g cm^{-3}, and saline

0.24(0.11) g cm^{-3} marshes in Louisiana. These values are considered representative for the respective marshes in this study. Soil samples with bulk densities 0.2 g cm^{-3} higher than means reported by Nyman et al. (1990) were considered to be deposited by Hurricane Rita for the purposes of this study.

Three 12 cm deep cores sectioned into 4-cm increments were obtained at sites along the Sabine Basin transect for particle size analysis using a 10-cm diameter thin-walled, sharpened PVC cylinder. In the laboratory, air-dried soils were pulverized to pass through a 2-mm sieve and sub-samples of each section were measured to determine percentages of sand, silt and clay using the pipette method as described by Gee and Bauder (1986).

Data Evaluation

Simple linear regressions were performed on particle size data, vertical accretion rates, and bulk density with respect to distance from the GOM shoreline. Multiple linear regressions were performed to determine the influence of mineral and organic accumulation rates on vertical accretion rates. A one-way analysis of variance (ANOVA) was used to determine significant differences in bulk density, vertical accretion, mineral matter, organic matter, carbon and nitrogen with nesting of sites within the three hydrologic classes. Because sedimentation data were unbalanced, Proc Mixed was used to perform a random effects analysis of variance. Post analysis means were compared among impounded, open and mixed hydrologic classes for vertical accretion rate and bulk density using Tukey's HSD multiple comparisons test. Shapiro-Wilk test was used to determine whether the data fulfill normality assumption. A square root transformation was used for particle size data and a logarithmic transformation of base 10 was used for bulk density data to satisfy normality of the residuals. Slopes of vertical accretion rates

against distance from the GOM shoreline in Sabine Basin and Rockefeller WMA were compared and tested for statistical significance. Statistical analyses were performed using the Statistical Analysis System (SAS Institute 2002). All statistical comparisons were evaluated at $\alpha = 0.05$.

RESULTS

Recent Deposition

Recent deposition associated with Hurricane Rita, identified from shallow bulk density peaks, was found in cores within 6 km from either the GOM or Calcasieu Lake in the Sabine Basin and 8 km inland in Rockefeller WMA. Bulk density peaks associated with Hurricane Rita were found in the top 4 to 10 cm in Sabine Basin and the top 4 to 8 cm in Rockefeller WMA (Fig. 4.2). The bulk density peak depths were similar across hydrologic class at each location (Fig. 4.2). Generally, the greatest deposition was nearest the GOM and decreased with distance inland, although this trend was not significant in Sabine Basin or Rockefeller WMA (Fig. 4.3). The slopes of the regression were not significantly different ($p = 0.5426$) between the two locations. The Sabine Basin and Rockefeller transects had similar sedimentation even though Sabine was approximately 90 km closer to the storm track. Particle size analysis along the Sabine Basin transect exhibited very high percentages of sand throughout the upper 12 cm of the soil profile within 3.2 km of the GOM shoreline and at stations located 12.7 and 14.3 km away from the GOM (Table 4.1). Regression analysis showed that there was an effect of distance on percent sand ($r^2 = 0.3421$, $p = 0.0007$) and percent clay ($r^2 = 0.5276$, $p < 0.0001$) using the 4 to 8 cm depth interval (Fig. 4.4). Sands show a decreasing trend inland whereas clays increase inland. There were no statistically significant ($p < 0.05$)

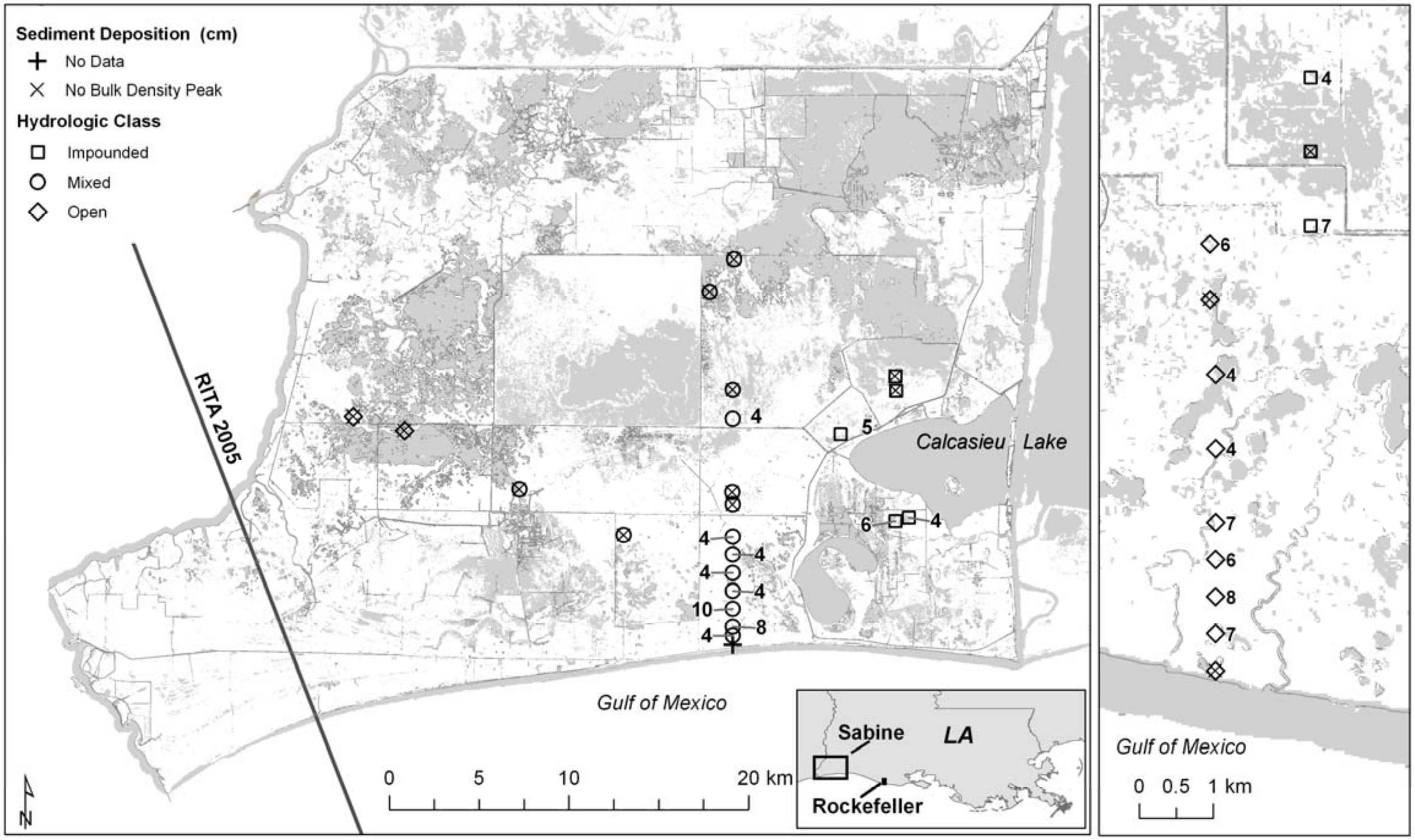

Figure 4.2. The depth (cm) of recently deposited sediments in Sabine Basin and Rockefeller WMA identified from bulk density profiles of sediment sampled at each site either in December 2005 or August 2006. Recent deposition is defined as a bulk density increase of more than 0.2 g cm^{-3} over background values. Sampling sites are classified as either impounded (i.e., completely enclosed by levees with water control structures), open (i.e., uncontrolled water and sediment exchange), and mixed (i.e., barriers that partially influence water and sediment exchange).

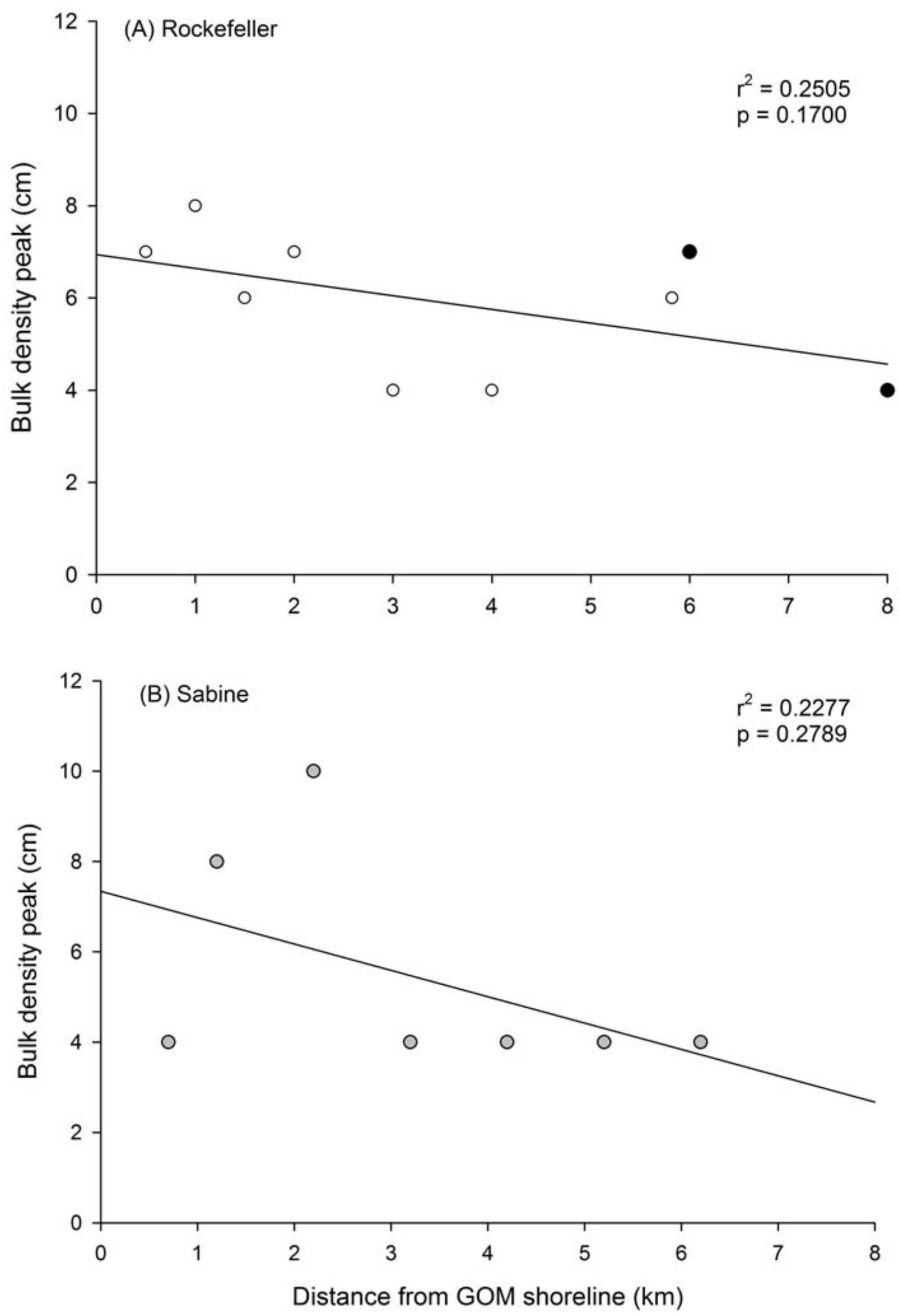

Figure 4.3. Bulk density peak (cm) at (A) Rockefeller WMA and (B) Sabine Basin transect sites regressed against distance from Gulf of Mexico (GOM) shoreline. Black, white and gray circles represent impounded, open and mixed hydrologic classes, respectively.

Table 4.1. Sediment and soil characteristics measured in August 2006 along Sabine Basin transect.

Site	Distance from GOM shore (km)	USDA Soil Map Unit	Bulk density peak (cm)	Depth intervals (cm)	Sand (%) Mean (SE)	Silt (%) Mean (SE)	Clay (%) Mean (SE)
S0	0.2	Mermentau (ME)	no data	0-4	75.5 (5.5)	11.6 (2.8)	12.7 (2.8)
				4-8	94.2 (0.6)	2.4 (0.6)	3.3 (0.1)
				8-12	95.5 (0.5)	1.2 (0.5)	3.1 (0.0)
0680	0.7	Creole (CR)	4	0-4	32.4 (11.3)	34.0 (4.7)	33.4 (6.8)
				4-8	81.7 (2.8)	9.6 (2.2)	8.6 (0.8)
				8-12	66.8 (22.6)	13.4 (8.1)	19.6 (14.4)
S1	1.2	Creole (CR)	8	0-4	14.9 (0.9)	36.1 (0.7)	48.8 (0.3)
				4-8	58.1 (1.8)	23.2 (1.5)	18.5 (1.7)
				8-12	25.9 (1.4)	29.8 (1.2)	44.1 (0.2)
S2	2.2	Bancker (BA)	10	0-4	52.7 (9.1)	12.7 (10.6)	34.5 (1.8)
				4-8	44.5 (5.7)	28.7 (8.1)	26.7 (2.5)
				8-12	40.2 (5.2)	19.4 (7.5)	40.2 (3.2)
S3	3.2	Bancker (BA)	4	0-4	16.8 (10.1)	28.3 (1.6)	54.8 (11.3)
				4-8	36.2 (4.8)	24.9 (6.3)	38.8 (1.5)
				8-12	34.4 (4.0)	16.4 (3.5)	49.0 (3.8)
S4	4.2	Bancker (BA)	4	0-4	1.1 (0.6)	30.5 (4.8)	68.2 (5.3)
				4-8	7.0 (2.3)	43.9 (3.9)	49.0 (6.0)
				8-12	41.0 (2.6)	6.2 (3.2)	52.6 (5.3)
S5	5.2	Bancker (BA)	4	0-4	4.1 (0.5)	19.4 (4.0)	76.3 (3.5)
				4-8	22.3 (2.8)	25.8 (6.9)	51.7 (4.2)
				8-12	42.6 (1.1)	13.4 (3.0)	43.9 (3.3)
S6	6.2	Creole (CR)	4	0-4	6.4 (1.3)	27.1 (1.4)	66.4 (2.5)
				4-8	31.3 (4.5)	31.0 (3.5)	37.5 (3.6)
				8-12	51.7 (3.4)	13.0 (4.1)	35.1 (1.2)
1858	8.0	Creole (CR)	no peak	0-4	no data	no data	no data
				4-8			
				8-12			
1859	8.7	Creole (CR)	no peak	0-4	no data	no data	no data
				4-8			
				8-12			
S12.5	12.7	Clovelly Muck (CO)	4	0-4	40.2 (6.3)	15.2 (2.4)	44.4 (4.0)
				4-8	30.6 (7.3)	21.0 (2.7)	48.2 (4.8)
				8-12	49.1 (2.0)	15.9 (1.6)	34.8 (0.6)
S14	14.3	Clovelly Muck (CO)	no peak	0-4	34.5 (2.4)	21.9 (0.6)	43.4 (1.9)
				4-8	24.2 (0.3)	23.5 (0.6)	52.1 (0.6)
				8-12	25.5 (3.7)	23.9 (2.9)	50.4 (0.8)

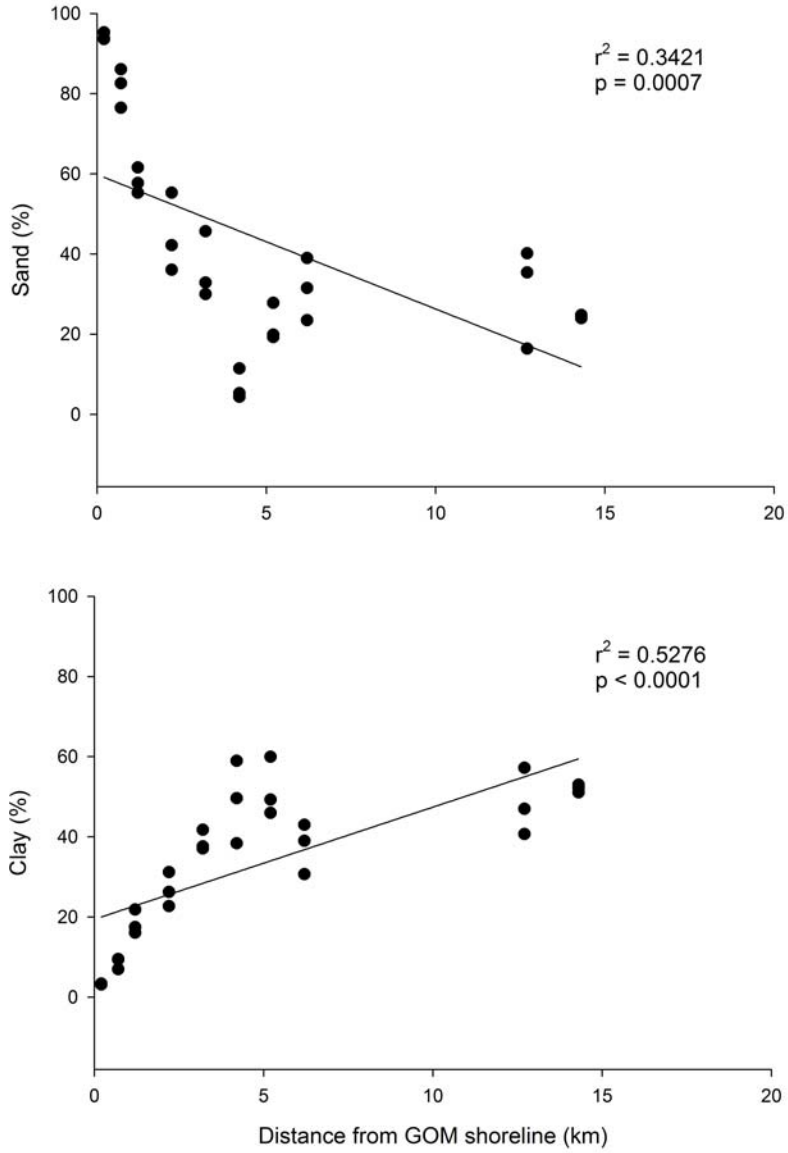

Figure 4.4. The percent composition of sand and clay from 4 cm to 8 cm soil depth along Sabine Basin transect sites regressed against distance from Gulf of Mexico (GOM) shoreline.

relationships found between percent silt and any of the other sand and clay depth intervals with distance from GOM shoreline.

Accretion

Vertical marsh accretion rates at the Rockefeller WMA sites indicate a reduction in accretion rates with distance from the GOM shoreline ($r^2 = 0.5397$, $p < 0.0001$; Fig. 4.5A). The highest rate of 0.85 cm yr^{-1} was found at site R0, located 200 m from the GOM and the lowest rate of 0.27 cm yr^{-1} was found at R5, 5 km inland. The 3 sites located in impounded marshes furthest inland averaged 0.43 cm yr^{-1}. The Sabine Basin transect accretion rates were very similar among sites with distance inland and no significant trend was found ($r^2 = 0.0088$, $p = 0.8414$, Fig. 4.5B). The slopes of the regression were significantly different ($p = 0.0174$) between the two locations.

Sites within the Sabine Basin had mean vertical accretion rates that ranged from 0.26 to 0.60 cm yr^{-1} (Fig. 4.6). Mean vertical accretion differed among the hydrologic classes in Sabine Basin ($p = 0.0332$). Accretion rates were higher in the open (0.51 ± 0.05 cm yr^{-1}) and mixed (0.44 ± 0.02 cm yr^{-1}) marsh classes compared to impounded marsh (0.36 ± 0.02 cm yr^{-1}, Fig. 4.7). There were no significant differences among replicate cores within sites.

Bulk Density and Soil Nutrient Content

Mean soil bulk density in the top 15 cm differed among the hydrologic classes ($p = 0.0392$). Bulk density was lower in the open marsh class (0.12 ± 0.01 g cm^{-3}) than in the mixed (0.18 ± 0.01 g cm^{-3}) and impounded marsh classes (0.24 ± 0.01 g cm^{-3}, Fig. 4.7). The differences in bulk densities found among hydrologic classes were also reflected in soil depth profiles. Open marsh sites (i.e., 0669 and 2156) had lowest bulk densities at the surface that increased with depth; unlike representative impounded sites (i.e., 0672 and 0672-H) that demonstrated shallow bulk density peaks (Fig. 4.8). The

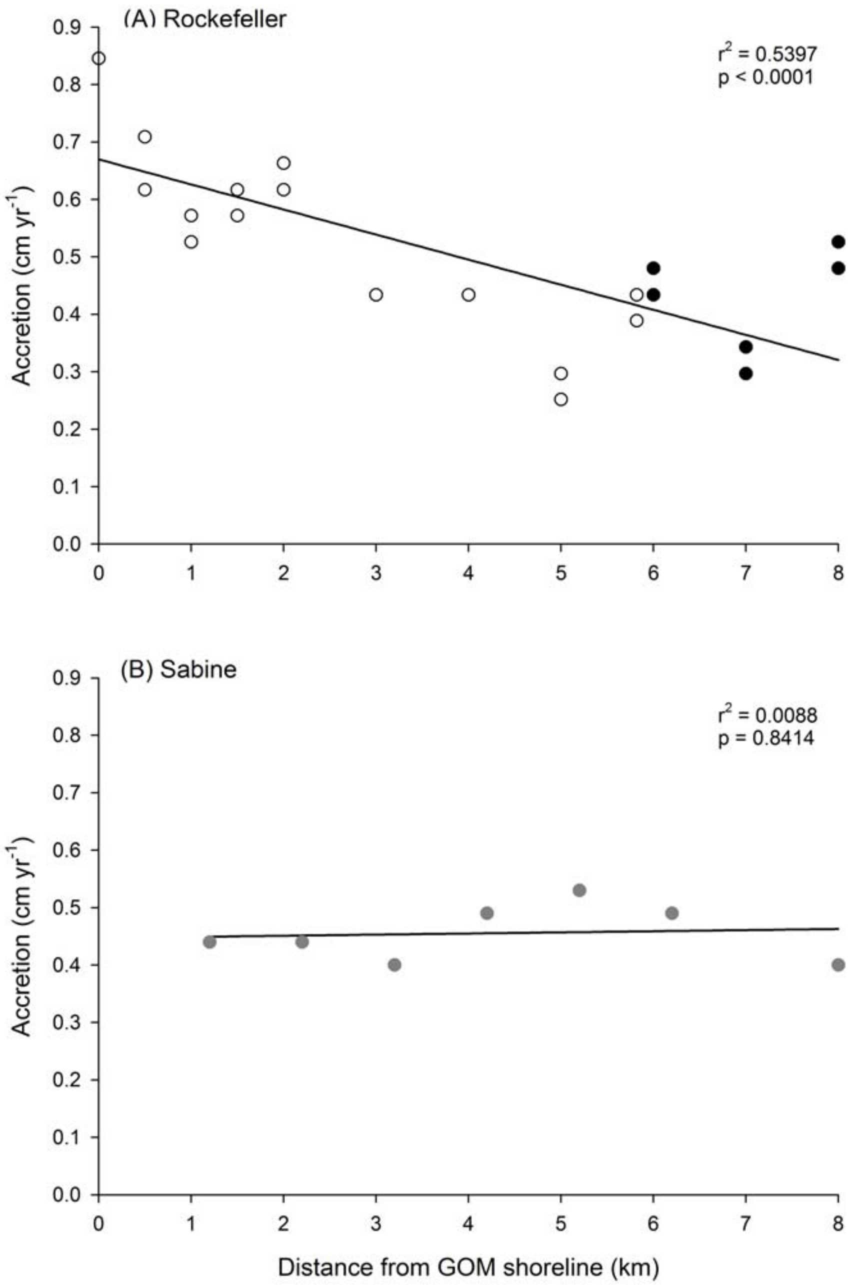

Figure 4.5. Vertical marsh accretion rate averaged from 1963 to 2006 at (A) Rockefeller WMA and (B) Sabine Basin transect sites regressed against distance from Gulf of Mexico (GOM) shoreline. Black, white and gray circles represent impounded, open and mixed hydrologic classes, respectively.

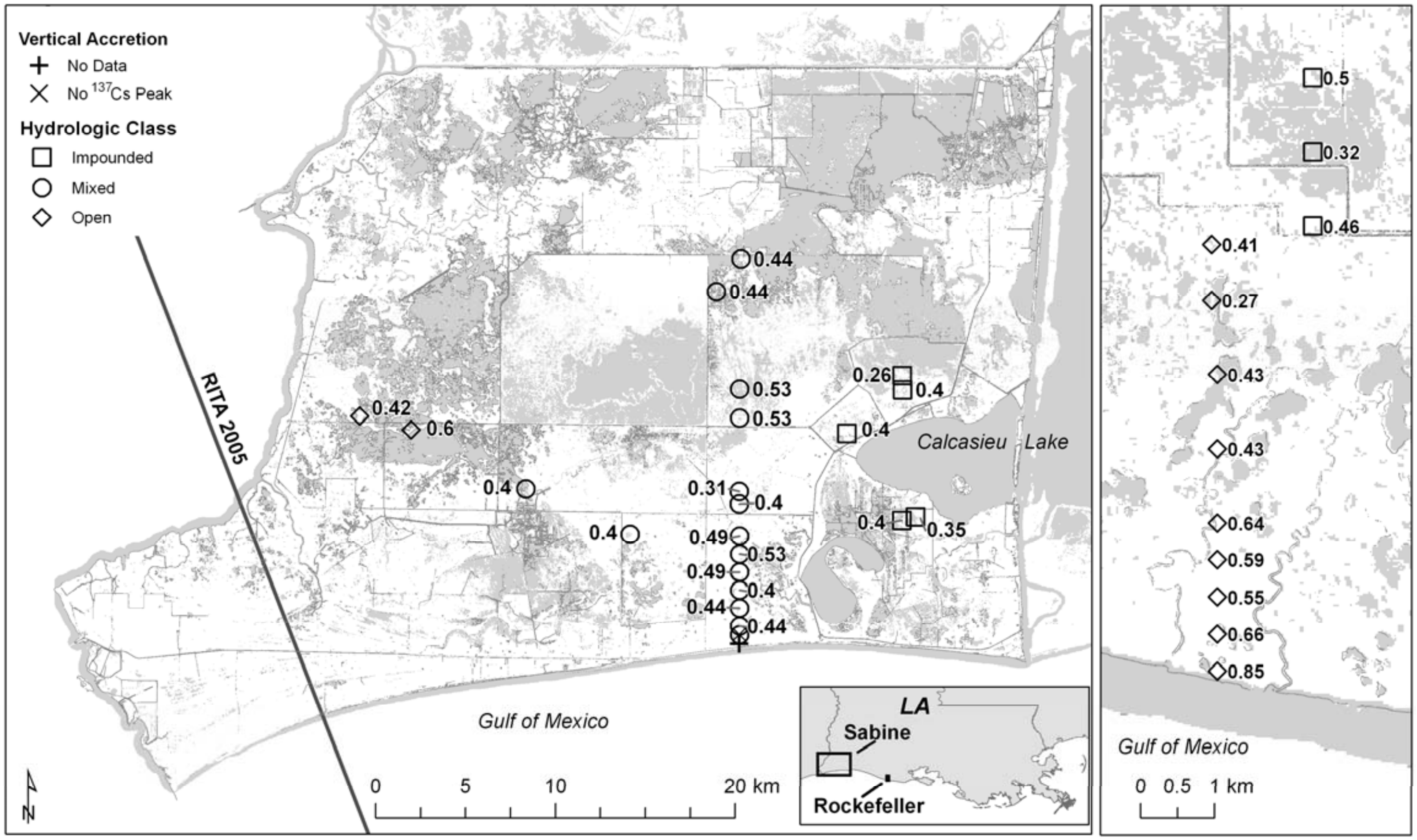

Figure 4.6. Vertical accretion rates (cm yr^{-1}) determined from ^{137}Cs in Sabine Basin and Rockefeller WMA. Rates determined from more than one core are represented by their average.

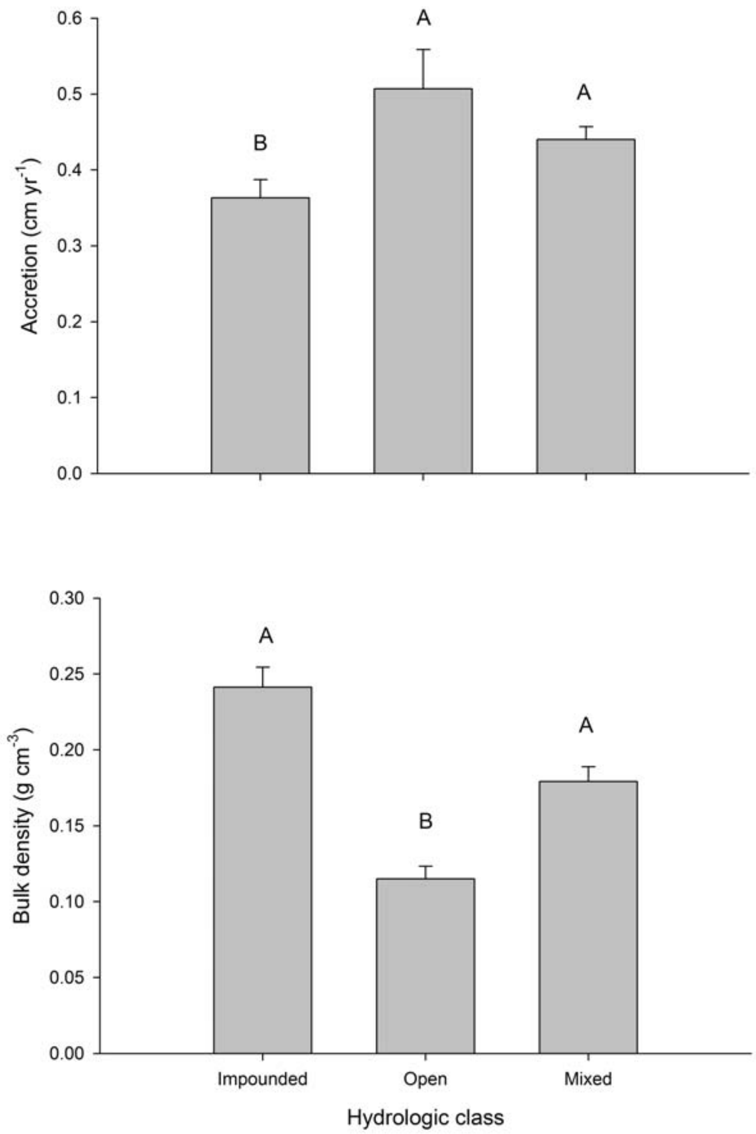

Figure 4.7. Mean vertical accretion rates (top) and mean bulk density of the top 15 cm of marsh soil (bottom) in impounded, open and mixed hydrologic classes within Sabine Basin. Bars with the same letter above them are not significantly different ($p > 0.05$) as determined by Tukey's HSD multiple comparison test.

open marsh sites also had higher nitrogen and carbon content than the impounded marsh sites on a percent and unit volume basis; however, it varied with depth (Fig. 4.8). Soil nitrogen and carbon content (mg cm^{-3}) in open marsh sites were higher than impounded marsh sites in the top 8 cm and deeper than 24 cm. Across all sites (n=21), percent

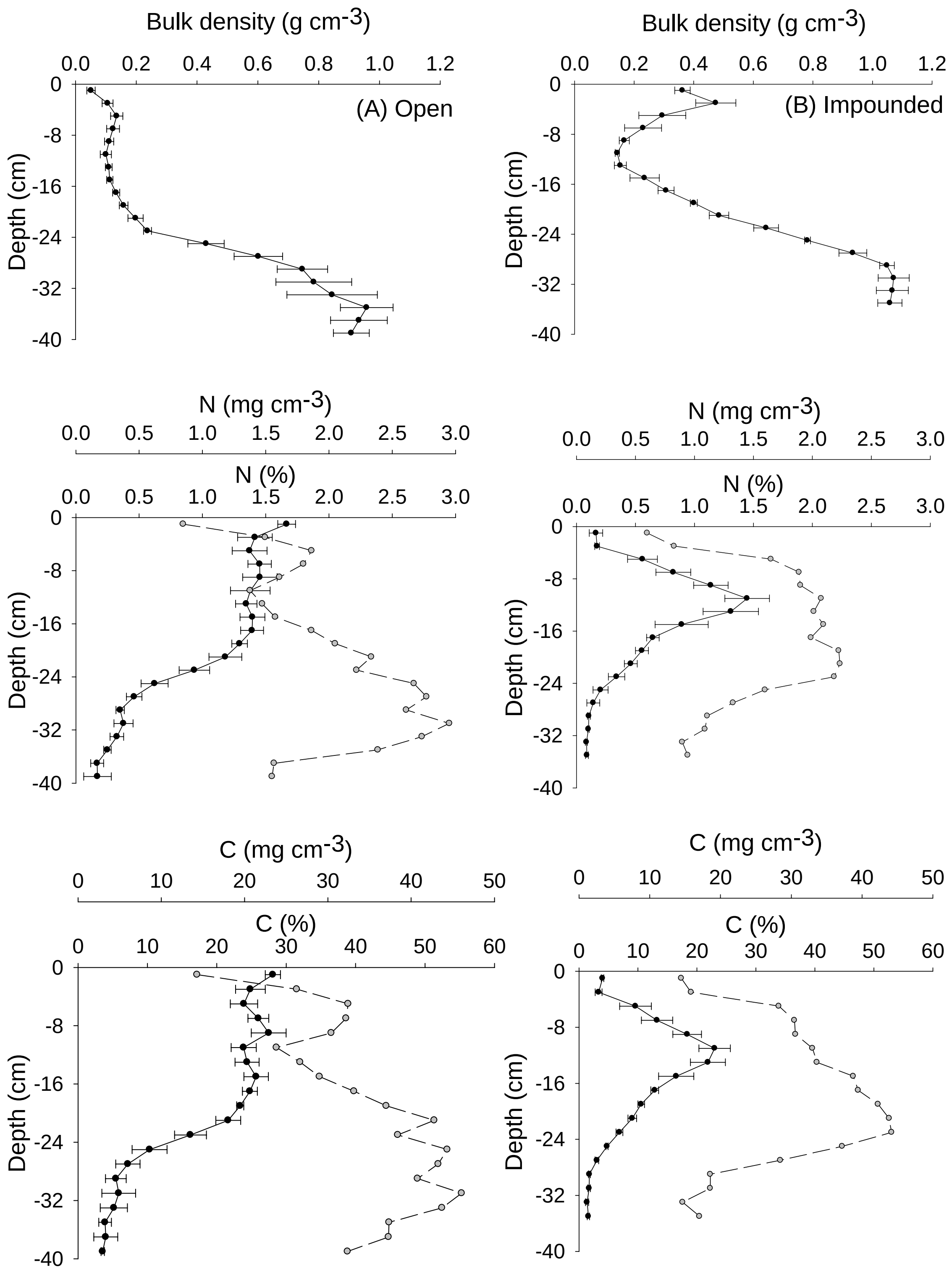

Figure 4.8. Mean bulk density, total nitrogen (gray dots (mg cm^{-3}) and black dots (%)) and organic carbon (gray dots (mg cm^{-3}) and black dots (%)) with depth in representative (A) open and (B) impounded hydrologic classes. Means (±1SE) were calculated from 4 cores from impounded (sites 0672 and 0672-H) and open (sites 0669 and 2156) sites.

nitrogen and carbon content showed significant inverse relationships with bulk density. The slope between the average bulk densities from the top 15 cm depth and percent carbon content was found to be -0.0193 ($p = 0.0002$, $r^2 = 0.4385$) and the slope with percent nitrogen was -0.3647 ($p = 0.0003$, $r^2 = 0.4731$).

Table 4.2. Vertical accretion, bulk density and accumulation rates of organic matter, mineral matter, carbon and total nitrogen from all cores within sites in the Sabine Basin.

Site	Vertical accretion ($cm\ yr^{-1}$)	Bulk density[a] ($g\ cm^{-3}$)	Mineral matter accumulation ($g\ m^{-2}\ yr^{-1}$)	Organic matter accumulation ($g\ m^{-2}\ yr^{-1}$)	Carbon accumulation ($g\ m^{-2}\ yr^{-1}$)	Total nitrogen accumulation ($g\ m^{-2}\ yr^{-1}$)
			Impounded			
CRMS0672	0.40	0.30	975.26	282.88	73.13	7.07
CRMS0672	0.40	0.26	776.66	327.06	65.57	7.66
CRMS0672-H	0.30	0.26	550.31	243.64	44.74	4.26
CRMS0672-H	0.40	0.21	597.12	302.88	63.99	5.57
CRMS1855	0.40	0.17	429.76	302.15	38.14	5.66
CRMS1855	0.40	0.21	580.54	320.89	64.16	7.81
CRMS1865	0.50	0.19	762.48	395.14	101.71	11.13
CRMS1865	0.31	0.24	362.85	262.86	61.89	7.14
CRMS1866	0.26	0.28	496.37	229.35	68.50	6.10
CRMS1866	0.26	0.30	555.99	194.01	55.03	5.25
Mean ± SE	0.36 ± 0.02	0.24 ± 0.01	608.74 ± 57.58	286.08 ± 18.06	63.69 ± 5.43	6.76 ± 0.60
			Open			
CRMS0669	0.40	0.09	136.32	256.71	36.05	6.38
CRMS0669	0.44	0.09	182.22	285.69	45.16	5.97
CRMS2156	0.60	0.15	418.06	521.94	102.22	13.85
CRMS2156	0.60	0.14	536.17	530.50	116.11	13.77
Mean ± SE	0.51 ± 0.05	0.12 ± 0.01	318.19 ± 95.33	398.71 ± 73.88	74.89 ± 20.08	9.99 ± 2.20
			Mixed			
CRMS0651	0.40	0.33	1025.31	477.07	121.50	12.32
CRMS0651	0.50	0.27	1018.81	560.24	148.57	15.96
CRMS0651-H	0.44	0.12	501.02	327.82	82.56	9.32
CRMS0651-H	0.44	0.17	629.71	386.10	97.17	11.05
CRMS0661	0.40	0.14	302.26	183.93	48.61	5.70
CRMS0682	0.40	0.25	866.86	311.71	91.48	7.81
CRMS1858	0.40	0.20	564.10	270.66	110.00	6.08
CRMS1859	0.31	0.14	227.49	217.75	47.65	5.54
CRMS1859	0.31	0.13	175.80	218.01	59.75	3.81
S1	0.44	0.36	1438.59	311.18	80.18	6.91
S2	0.44	0.13	456.01	249.57	48.71	4.48
S3	0.40	0.13	391.31	196.13	40.74	4.37
S4	0.49	0.16	474.64	303.04	45.79	7.15
S5	0.53	0.12	325.68	289.21	50.24	6.92
S6	0.49	0.13	396.91	302.62	48.97	6.24
S12.5	0.53	0.12	272.64	370.61	56.61	9.59
S14.0	0.53	0.17	522.26	482.39	111.35	13.63
Mean ± SE	0.44 ± 0.02	0.18 ± 0.01	564.08 ± 82.20	321.06 ± 25.69	75.88 ± 7.90	8.05 ± 0.84

[a]Bulk density is estimated from 0 - 15 cm of soil; accumulations estimated from all soil overlying the 1963 marsh surface

Accumulation Rates

ANOVA revealed no significant differences in the accumulation rates of organic matter ($F_{2,18} = 1.03$, $p = 0.3773$), mineral matter ($F_{2,18} = 0.74$, $p = 0.4928$), carbon ($F_{2,18} = 0.21$, $p = 0.8112$), or nitrogen ($F_{2,18} = 0.82$, $p = 0.4546$), among impounded, open and mixed marsh classes. The impounded marshes accumulated an average of 63.69 ± 5.43 g $m^{-2}yr^{-1}$ carbon compared to 74.89 ± 20.08 in open marsh and 75.88 ± 7.90 in mixed marsh classes (Table 4.2). The open (9.99 ± 2.20 g $m^{-2}yr^{-1}$) and mixed (8.05 ± 0.84 g $m^{-2}yr^{-1}$) marshes also accumulated more nitrogen which was associated with higher organic matter accumulations in these marsh classes (Table 4.2). Average mineral accumulation rates were much higher in the impounded marshes as compared to the open marshes (608.74 ± 57.58 g $m^{-2}yr^{-1}$ compared to 318.19 ± 95.33 g $m^{-2}yr^{-1}$).

Vertical accretion rates were determined through multiple regression (Proc Mixed; SAS Institute Inc.) to be strongly related to the amount of organic matter accumulation ($F_{1,27} = 22.89$, $p < 0.0001$) but not mineral accumulation ($F_{1,27} = 2.62$, $p = 0.1175$). This is illustrated in Fig. 4.9 which plots field observations against modeled probabilities along organic and mineral accumulation gradients. The modeled surface is described by,

$$\text{Accretion} = 0.2386 + 0.000699(\text{organic}) - 0.000069599(\text{mineral}).$$

The coefficient of multiple determination (r^2) for the equation is 0.57 ($p < 0.0001$). The model used did not include an interaction term even though a significant interaction between mineral accumulation rate and organic accumulation rate was found ($p = 0.0335$). A multiple regression analysis including the interaction only improved the r^2 by 0.06, and plots of the interaction did not show any ecologically meaningful patterns. The

analysis indicates that mineral accumulation is important through interaction with organic accumulation but contributes little in describing the variance in accretion rate.

DISCUSSION

Hurricane Rita Deposition

Sediments were not uniformly deposited over the coastal marshes of Sabine Basin and Rockefeller WMA as identified from shallow bulk density peaks and site specific evidence of soil vertical profiles taken at all study sites using a Macaulay auger. Hurricane Rita deposition was clearly evident in eight of the Rockefeller sites as a light brown viscous mud that was free of roots and coarse debris. This deposition layer was typically 0 to 2 cm greater than estimated deposits from shallow bulk density peaks. There was a general trend in higher deposition near the GOM, reducing inland before increasing adjacent to a levee located at 6 km inland on Rockefeller WMA. The deposition layer is consistent with previous descriptions of distal mud and inner-shelf sediments that can be resuspended during the passage of winter cold fronts and large storms in the Chenier Plain (Roberts et al. 1987, 1989, Draut et al. 2005, Turner et al. 2006). In Sabine Basin, there was no clear layer of sediment on top of the marsh surface at most sites, and no shallow bulk density peaks were found within 20 km of the hurricane track. This may be attributed to surface wind shear and churning of surface waters during the storm or due to the long duration of flooding after the storm causing the redistribution of sediments. Turner et al. (2006) sampled 16 locations within the Sabine Basin after Hurricane Rita and found an obvious sediment layer that ranged in depth from 0 to 10 cm, which was consistent with our findings from shallow bulk density peaks.

The high percentage of sand in the upper 12 cm of the soil profile suggests that storm surge overwash deposits were transported onshore by Hurricane Rita that

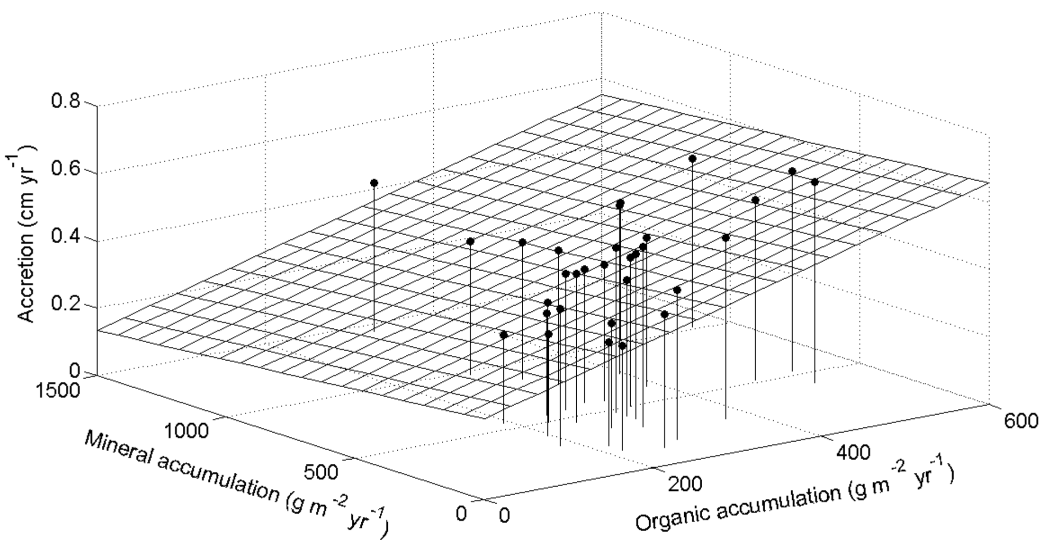

Figure 4.9. Modeled (gridded surface) versus observed (dots) accretion rate as a function of organic and mineral accumulation. Accretion rates are from 21 sampling sites in Sabine Basin (N = 31).

originated from coarse beach sands on the Gulf shoreline or even coarser inner continental shelf sands. Stockdon et al. (2007) used light detection and ranging (LIDAR) and measured cross-shore elevation profiles on the GOM shoreline at Holly Beach, Louisiana and found that large volumes of sand were removed from the beach. They hypothesized that a large quantity of sand was moved offshore because of minimal evidence of overwash deposits in the adjacent marsh. Our results suggest that the intensity of the storm surge carried sands much further inland than the area investigated by Stockdon et al. (2007).

The percent sand values found at sites S0, 0680, S1, S2, S3, S12.5 and S14 in this study were well above representative values identified in the National Soil Information System database (http://ssldata.nrcs.usda.gov/querypage.asp) for soil map units in the Sabine Basin (Table 4.1), suggesting sand deposits from Hurricane Rita. Although the source of sands for stations S0, 0680, S1, S2, and S3 is assumed to be from the GOM, the

sands found at stations S12.5 and S14 might also suggest a possible source being the west bank of Calcasieu Lake. Demcheck et al. (1989) conducted particle size distribution of bottom material from one site in north Calcasieu Lake and identified 46% sand and 54% silt and clay in the top 10 cm. Additionally, sands are found when maintenance dredging is conducted in the Calcasieu Ship Channel. With southeast prevailing winds and storm surge associated with Hurricane Rita, mineral sediments from Calcasieu Lake could have been transported the 2.5 km distance to sites S12.5 and S14.

Within Rockefeller WMA, the higher accretion rates at the GOM shoreline with reductions with distance inland may be contributed to by the high frequency of overwash events associated with winter cold fronts. Roberts et al. (1989) describes the frequency of these events as 20 to 30 times each winter, with pre-frontal winds from the south setting up waters in excess of 1 m in height. The cross-shore transport of the suspended fluid mud is then deposited along the shoreface and adjacent marsh. The natural berm on the GOM shoreline at Rockefeller WMA averages between 1 and 1.5 m NAVD 88, providing many more opportunities of introducing suspended sediment during winter cold fronts than on the Sabine Basin transect, fronted by U.S. Highway 82 which averages between 2 and 3 m NAVD 88. The lack of relationship between accretion rates and distance inland in Sabine Basin transect may be related to the infrequency of these overwash events coupled with extensive hydrologic alterations to wetland building and maintenance processes. Rita has been the only hurricane since Hurricane Audrey in 1957 and Hurricane Carla in 1961 with sufficient storm surge to flood the entire study area and potentially provide a large input of suspended sediments.

Sediment Accretion and Accumulation

The accretion rates we found for *Spartina patens* marshes in all hydrologic classes are comparable to those previously reported in Rockefeller WMA by Foret (2001), who described average ^{137}Cs accretion rates of 0.50 ± 0.04 cm yr^{-1} in open reference sites compared to 0.36 ± 0.04 cm yr^{-1} in manipulated sites (i.e., mixed and impounded). Phillips (2002) also reported lower ^{137}Cs accretion rates in impounded marsh (0.19 ± 0.06 cm yr^{-1}) compared to semi-impounded (i.e., mixed) and open reference sites (0.31 ± 0.09 cm yr^{-1}) in Rockefeller WMA. The accretion rates found in Sabine Basin and Rockefeller WMA are generally lower than rates found in the Deltaic Plain of coastal Louisiana and higher than those reported for the U.S. Atlantic coast (Table 4.3). Within the Sabine Basin, the only historical accretion rates for *Spartina patens* dominated marshes are from feldspar plots in the East Mud Lake project area, a marsh management project where impounded sites 0672 and 0672H are located (Fig. 4.1). The East Mud Lake project averaged 0.40 cm yr^{-1} accretion from 1997 to 2003 and over 3.0 cm yr^{-1} from 2003 to 2006, accounting for Hurricane Rita deposition (Castellanos et al. 2007). The 3.0 cm yr^{-1} of accretion was reported to result in 2.1 cm yr^{-1} of elevation gain, suggesting sediment compaction of underlying soils from the combined weight of storm surge and mineral deposition. The pre-hurricane short term accretion rate obtained by Castellanos et al. (2007) is equivalent to what was found in this study (using data from 1963 to 2006) for sites 0672 and 0672H (0.40 cm yr^{-1}), which incorporates the 4 to 6 cm of Hurricane Rita mineral deposition. Assuming a relative sea-level rise rate of 0.34 to 0.57 cm yr^{-1} in the Sabine Basin from two long-term tide gauge stations (Penland and Ramsey 1990), it appears that impounded sites that do not receive large sediment pulses are in jeopardy of not vertically accreting sufficient to keep pace with relative sea-level

rise. Alternatively, if the frequency of hurricane sediment deposition increases in the future, elevation gains may contribute to a change in vegetation community type. Vertical accretion alone may overestimate a sites potential for surviving increases in relative sea-level rise because elevation change is not necessarily equivalent to vertical accretion (Cahoon 2003). Castellanos et al. (2007) observed compaction of existing sediments by Hurricane Rita storm surge and sedimentation, which would reduce the positive effects of the deposition in regards to relative sea-level rise.

The mineral input associated with Hurricane Rita contributed to differences in bulk densities from the top 15 cm of marsh soil among sites. The impounded sites had bulk densities significantly higher than the open marsh sites, suggesting that levees and other hydrologic barriers serve as sediment traps when overtopped by storm surge. Previous research has shown impounded soils to have lower bulk densities than open marsh soils, primarily due to limited delivery of mineral sediments to the marsh surface (Cahoon 1994). Sediment trapping during infrequent high energy events, as shown in this study, is important because impoundment levees typically reduce tidal flux of water and sediment and obstruct the delivery of mineral sediment during cold front passage (Reed 1992, Boumanns and Day 1994, Cahoon and Reed 1994, Reed et al. 1997, Bryant and Chabreck 1998). The bulk density profiles from all cores reflect a second large mineral peak below the ^{137}Cs peak at depths below 24 cm (see representative cores, Fig. 4.8). These lower deposits of mineral sediment may have been attributed to other historical high energy events, such as Hurricane Audrey in 1957 (Fig. 4.1) and Hurricane Carla in 1961, that affected the area. Morgan et al. (1958) described a thick layer of mineral sediment associated with the 3.5 m storm surge from Hurricane Audrey that affected our study area. Unfortunately, most of our cores were too shallow to determine

Table 4.3. Long-term vertical accretion rates (cm yr-1) reported in natural and impounded Spartina patens marshes from the U.S. Atlantic coast and Gulf of Mexico. Rates with an asterick are from impounded marsh sites and italics denote Louisiana Deltaic Plain locations.

Accretion rate (cm yr^{-1})	Location	Method	Source
0.17-0.36	Maryland	^{210}Pb	Stevenson et al. 1985
0.11-0.41	New York	^{210}Pb	Cochran et al. 1998
0.18-0.20	Connecticut	^{210}Pb	Orson et al. 1998
0.17	Connecticut	^{137}Cs	Orson et al. 1998
0.38-0.81	*Louisiana*	^{137}Cs	Hatton et al. 1983
0.67-0.72	*Louisiana*	^{137}Cs	Nyman et al. 1990
0.47-0.75	*Louisiana*	^{137}Cs	Chmura and Kosters 1994
0.5-0.67	*Louisiana*	^{137}Cs	Nyman et al. 1994
0.27-0.58	Louisiana	^{137}Cs	Foret 1997
0.33-0.64*	Louisiana	^{137}Cs	Foret 1997
0.46-0.54	Louisiana	^{137}Cs	Foret 2001
0.31-0.38*	Louisiana	^{137}Cs	Foret 2001
0.28-0.35	Louisiana	^{137}Cs	Phillips 2002
0.16-0.38*	Louisiana	^{137}Cs	Phillips 2002
0.51-1.11	*Louisiana*	^{137}Cs	DeLaune et al. 2003
0.31-0.60	Louisiana	^{137}Cs	This study
0.26-0.50*	Louisiana	^{137}Cs	This study

whether bulk densities declined or not after the peak, preventing the opportunity to isolate those events. Foret (2001) and Phillips (2002) found similar large pools of mineral sediments below the 1963 ^{137}Cs peak and attributed them to Hurricane Audrey. Bulk density values declined from the second mineral peak to the marsh surface, suggesting that organic production becomes the main contributor to vertical accretion

following these large mineral deposition events. In the Sabine Basin, hurricanes appear to be the primary mechanism for the delivery of mineral inputs of sediment to marsh surfaces.

Soil bulk density varied inversely with total percent nitrogen and carbon content across all marsh classes, indicating that nitrogen and carbon are positively related to the amount of organic matter. The positive relationship for organic matter content with total percent nitrogen is consistent with findings from Craft et al. (1991) for marsh soils. Mineral sedimentation also plays an important role in accretion by supplying nutrients that can promote plant production (Bricker-Urso et al. 1989; Nyman et al. 1990, DeLaune et al. 1992, Nyman et al. 1993). The nutrient budgets of phosphorus and iron in brackish and salt marsh are primarily from mineral sediments (DeLaune et al. 1981, DeLaune and Pezeshki 1988, DeLaune et al. 2003). Foret (1997) concluded that brackish and intermediate tidal marshes of the Chenier Plain that are far from fluvial inputs are phosphorus limited, whereas marshes with adequate sediment input tend to be nitrogen limited. Large mineral inputs into impounded and mixed marshes found in this study should provide essential nutrients to support plant production and organic matter accumulation over time. The peaks in nitrogen and carbon content (mg cm^{-3}) near 30 cm in the open marsh class and near 24 cm in the impounded marsh class (Fig. 4.8) coincide with elevated bulk density found below the 1963 peak ^{137}Cs layer. This further suggests that Hurricanes Audrey and Carla influenced mineral and nutrient inputs in the Sabine Basin. Nyman et al. (1995) stated that nutrients that are buried are available to plants until they are below their rooting zone. With low accretion rates (0.26 – 0.60 cm yr^{-1}), such as those found in this study, and an estimated live rooting depth of 20 cm, nutrients from hurricane deposition could be available for approximately 33 to 80 years.

The importance of the mineral sedimentation in accretion and nutrient accumulation in Sabine Basin is complicated by the extent of hydrologic management, which can greatly affect factors controlling wetland structure and function (Mitsch and Gosselink 2007). There was a high degree of variability among sites that prohibited the findings of any significant differences in mineral, organic, carbon or nitrogen accumulations over the past 43 years between the three marsh classes studied. There was however significantly higher vertical accretion in the open marshes compared to the impounded marshes. The highest vertical accretion in the open marshes was associated with the greatest amount of organic matter, carbon and nitrogen accumulation. Our findings that vertical accretion was strongly related to the amount of organic matter accumulation and not mineral accumulation matches the conclusions by Hatton et al. 1983, Bricker-Urso et al. 1989, Nyman et al. 1993, Turner et al. 2001, Turner et al. 2004, Nyman et al. 2006). Some of these investigators found strong positive correlations between organic and mineral accumulations and concluded an importance of mineral sediments on plant growth. We found a significant interaction between organic and mineral accumulation rates, which have not previously been reported, that strengthens that assertion.

The lower accretion rates found in impounded marshes appear to be associated with the lack of organic matter accumulation. This might suggest that extremes between excessive flooding and soil drainage during hydrologic management have contributed to increased decomposition, oxidation of soil organic matter, and/or inadequate belowground production (Nyman and DeLaune 1991, Nyman et al. 1993). Castellanos et al. (2007) suggests that all three have occurred within the East Mud Lake project area. Nyman et al. (1990) estimated the proportions of mineral and organic matter

accumulations necessary to counter submergence from relative sea-level rise for coastal Louisiana marsh communities. If we apply the higher relative sea-level rise estimate of 0.57 cm yr^{-1} from Penland and Ramsey (1990), based on anticipated increases in relative sea-level rise since their analysis period of record (1942-1988), to Nyman et al. (1990) soil formation requirements for brackish marsh, our impounded marshes would require 332 g $m^{-2}yr^{-1}$ of organic matter accumulation and 600 g $m^{-2}yr^{-1}$ of mineral accumulation. Only one of our 10 impounded sites would meet these requirements. The mixed and open marsh sites are slightly less saline and are currently classified as intermediate marsh (Sasser et al. 2008). The soil requirements of 258 g $m^{-2}yr^{-1}$ of organic matter accumulation and 198 g $m^{-2}yr^{-1}$ of mineral accumulation would be met by 66% of the sites. It is apparent that sedimentation from hurricanes can provide a large percentage of mineral accumulation requirements; however, understanding the hydrologic management strategies that are being deployed at each of the sites is necessary to provide guidance on how to optimize organic production and accumulation. It is also necessary to step back and look at landscape scale influences of hurricanes to understand how landforms and management practices influence both sediment deposition and erosion in order to provide information useful for improved restoration planning and decision-making.

Landscape Influences on Sedimentation

Barras et al. (2008) estimated from a 2004 to 2006 landscape change analysis that 287.5 km^2 of land was lost from Hurricane Rita in the Chenier Plain. This amount was ten times greater than the loss rate estimated between 1978 and 2004 (28.4 km^2). From Barras (2008), we determined that 58 km^2 of the Hurricane Rita loss was within our Sabine Basin study area (Fig. 4.1). This loss represents both physical removal of marsh and conversion to open water caused by saltwater and flooding stress to plants (Steyer,

Chapter 3). Barras (2007) identified wrack and large organic matter deposits along most impoundment and canal levees south of the Sabine Pool and between southeast directional shears in the marsh landscape. It was therefore not surprising to find a high amount of variability in sediment deposition at the micro-scale among sites, considering the disruption of the marsh landscape within the Sabine Basin; organic soils were scoured, large wrack fields formed, and new mineral matter was introduced. Chmura and Kosters (1994) found that shallow storm deposits were due to the coincidental timing of erosion and deposition, which was clearly evident within this landscape study. Irregularities in the radionuclide vertical profiles in the surficial sediments (<14 cm) of a few cores suggest disruption of these sediments, and one core had the 1963 ^{137}Cs peak at the surface, suggesting deposition of scoured marsh on top of existing marsh. Ground truth of one new open water area (shear) near S14 found the entire organic substrate down to 20 cm was removed. This shows that surface deposition of within-system eroded soils was occurring. Future efforts at quantifying sedimentation associated with hurricanes should include calculations of sediment erosion in order to determine the net hurricane-induced sedimentation signature.

CONCLUSIONS

The deposition of sediments from Hurricane Rita was highly variable across the landscape and did not appear as a uniform blanket of sediments. The greatest deposition was generally found closest to the GOM within Sabine Basin and Rockefeller WMA. Although the Sabine Basin transect was 90 km closer to the storm track, sediment deposition patterns were similar to Rockefeller WMA. Particle size analysis confirmed the introduction of new mineral sediments from the GOM into Sabine Basin but also suggests that other large inland water bodies such as Calcasieu Lake could be sources of

sedimentation on the marsh. Mineral sediments that were introduced were trapped within impounded sites when levees were overtopped and contributed to the highest bulk densities among marsh classes.

Infrequent, high energy events such as Hurricane Rita provide critical supplies of bulk sediment and nutrients, and these events are important mechanisms indirectly controlling vertical accretion in impounded marshes with low organic matter accumulations. This study has shown that vertical accretion is directly related to the amount of organic matter accumulation and not mineral accumulations. Inadequate vertical accretion in impounded marsh can be partially compensated with large periodic sediment inputs; however, management actions should focus on creating hydrologic conditions that can optimize organic matter availability, if submergence is to be counteracted.

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CHAPTER 5

OVERALL CONCLUSIONS

This dissertation investigated impacts of Hurricanes Katrina and Rita to Louisiana's coastal marsh vegetation and discerned factors influencing marsh recovery. Available literature indicate that hurricanes generally provide net benefits by introducing sediments and nutrients and typically do not produce long-term detrimental impacts associated with saltwater intrusion and flooding. Limitations of past studies were that they typically examined immediate impacts or benefits and/or only focused on small geographic areas. The objectives of this research were to provide a broader spatial assessment of how the hurricanes of 2005 influenced vegetation changes in coastal Louisiana using remote sensing techniques, and to further determine causal mechanisms of that change through field investigations.

A Normalized Difference Vegetation Index (NDVI) calculated from MODerate-resolution Imaging Spectroradiometer (MODIS) Terra imagery was used to quantify the coastwide extent and severity of damage to vegetative communities and their subsequent recovery by November 2006. The pre-hurricane monthly average NDVI values (considered as baseline) exhibited a clear differentiation among NDVI values by habitat type. The sensitivity of NDVI values to phenology changes suggested that a departure from average statistic would provide a valuable tool for assessing and monitoring change in coastal Louisiana habitat types. The departure anomalies from NDVI quantified declines in the density and vigor of vegetation by habitat type, which corresponded closely to storm surge impact areas of Hurricanes Katrina and Rita. When NDVI anomaly results were combined with moderate resolution TM imagery assessments of new open water areas, the area of persistent vegetation damage due to the formation of

new open water could be differentiated from damage associated with other physicochemical factors.

A field study was initiated to examine the influence of two primary physicochemical stressors, porewater salinity and sulfide, on vegetation community dynamics following the hurricanes. Sampling sites were established at 100 locations across the coast in fresh, intermediate and brackish habitat types. Data revealed that salinity and sulfide values highly exceeded their typical range in fresh marsh within the west region throughout 2006 and in fall 2007. The persistent stress contributed to low vegetation cover, conversion to open water, or conversion to more saline habitat types. The persistence of these stressors appears to be associated with limited freshwater inputs associated with drought conditions and the lack of hydrologic flushing to remove accumulated phytotoxins. Percent cover of vegetation within each marsh type in the east region were not severely impacted by salinity and sulfide stress even though the marshes were exposed to substantial storm surge. The open basin hydrology combined with additional freshwater inflow into the basin from the Caernarvon Freshwater Diversion Project may have moderated salinities in the east region. However, this region had the highest abundance and cover of disturbance species in fresh and intermediate habitat types and major changes in species dominance, which correspond to areas with greatest new open water formation and other physical disruption following Hurricane Katrina. These results indicate that vegetation changes in the east region were primarily driven by physical impacts; whereas, changes in the west region were primarily due to physicochemical stressors. Even after two full growing seasons, vegetation cover and species composition were still indicative of a disturbed environment. The site specific data corroborated the spectral values from the NDVI, confirming that vegetation impacts

and recovery patterns can be accurately determined using the NDVI, especially when integrated with assessments of physical landscape changes and field verifications.

The assessment of landscape changes over time must also account for beneficial subsidies of sediments that are delivered to coastal marshes during hurricanes. Two geographic areas were investigated within the west region to determine whether sedimentation and vertical accretion rates vary with distance from storm track, distance from shoreline of Gulf of Mexico (GOM), and areas under different hydrologic management. Sediments were also examined to identify the relative importance of mineral accumulations to sediment accretion rates. Sediment depositions from Hurricane Rita were highly variable and widely distributed across the coastal landscape. Similar deposition patterns were observed in sites located 23 km and 110 km from the storm track with greatest deposition generally found closest to the GOM. New sediments were delivered to the marshes from the GOM, but findings suggest that other large inland water bodies provide within-system sources of sediments and scoured surficial marsh sediments were also redistributed. The orientation of landscape features such as canals, levees, and natural ridges to storm surge direction and hydrologic pathways influenced depositional patterns. Mineral sediments that were introduced were trapped within impounded sites and contributed to the highest mineral matter accumulations compared to open and mixed hydrologic classes; however, accretion rates in impounded sites were the lowest. This study has shown that vertical accretion is directly related to the amount of organic matter accumulation and indirectly associated with mineral accumulations. Inadequate vertical accretion in impounded marsh may be partially compensated with large periodic sediment inputs, but management actions should focus on creating

hydrologic conditions that can optimize vegetation productivity in order to maximize organic matter availability.

This research quantified the large spatial extent of vegetation impacts in coastal Louisiana associated with Hurricanes Katrina and Rita and provided a better understanding of the susceptibility of specific habitat types to hurricane-induced effects. There is a need for longer-term studies that can determine the resiliency of vegetation communities to such disturbance events. This study also calls for further research to better quantify hurricane driven sediment deposition and erosion. Incorporation of erosion losses may provide an opportunity to determine the net hurricane-induced sediment balance. This study illustrates that hurricanes can dramatically change the configuration and composition of the vegetated landscape, which may influence long-term mineral and organic matter accumulations and potentially marsh sustainability.

APPENDIX

SITE COORDINATES

Appendix Table A. Chapter 3 sampling site coordinates.

	UTM coordinates			UTM coordinates	
Site name	Easting	Northing	Site name	Easting	Northing
CRMS0154	870403.96	3226490.13	CRMS0494	616778.15	3290944.33
MR09-150202	870799.22	3228074.14	CRMS0530	595825.77	3272352.23
MR09-150203	870863.92	3228363.83	CRMS0633	565586.09	3270516.23
MR09-200102	867373.51	3233947.33	CRMS0580	565531.21	3275441.37
MR09-510104	871355.31	3240968.60	ME04-137	565553.64	3276575.08
MR06-0202	862011.01	3238105.04	ME04-116	570009.97	3285010.34
CRMS0148	820058.99	3269267.49	CRMS0571	568581.82	3286764.51
BA04-111	809568.69	3274057.97	ME16-03	539751.18	3276868.45
BA04-101	800853.53	3276449.02	CRMS0581	526310.51	3281834.98
DCPBS04	819210.99	3275954.65	CRMS0591	511053.98	3304170.98
DCPBS05	817396.72	3290878.37	LAC08	506489.11	3313673.48
BS03A-306	801761.20	3299549.11	CRMS1425	508039.65	3313796.38
BS03A-33	800892.95	3299764.20	LAC07	508661.44	3315773.66
BS03A-62	799903.23	3300502.08	LAC04	508038.48	3318063.59
BS03A-206	801203.10	3301001.02	CRMS1407	505150.18	3316992.57
BS03A-22	799617.50	3302199.96	CS17-32	478339.73	3310909.27
BS03A-15R	801437.02	3303262.26	CRMS2417	483905.52	3303343.87
BS03A-55R	801499.21	3303252.85	CS17-46	476498.90	3301668.37
BS03A-205	800400.64	3302942.37	CRMS0644	471777.25	3300171.27
BS03A-502R	800132.12	3305111.22	CRMS2246	444765.78	3325263.05
BS03A-606R	797240.98	3295597.06	CRMS2228	441741.59	3323583.14
BS03A-605R	797074.30	3295235.32	CRMS2227	441701.11	3322673.57
BS03A-604R	796602.23	3296238.07	CRMS2189	426633.89	3310852.77
BS03A-402	794440.63	3300073.32	CRMS0660	435588.19	3309946.07
BS03A-54	794640.12	3300032.00	CRMS0683	435597.58	3306740.16
BS03A-204	798937.99	3302386.97	CRMS2156	432423.18	3305240.87
BS03A-202	797666.45	3303003.14	CRMS0669	429590.81	3305879.03
BS03A-31	795357.14	3302663.07	CRMS1838	432541.14	3294745.01
BS03A-21	795326.60	3305124.54	CRMS0661	438811.69	3301935.98
BS03A-106	795514.15	3305238.27	CRMS2219	441622.99	3292937.42
BA20-137	778051.93	3290221.80	CRMS0682	444607.75	3299411.25
BA03C-25	788674.59	3290345.82	CRMS0677	447622.93	3302610.15
BA03C-49	786025.83	3282563.31	CRMS0638	450644.94	3304260.69
BA23-101	781325.04	3281912.89	CRMS1859	450672.64	3301797.26
BA23-102	780803.63	3281524.82	CRMS1858	450679.27	3301113.53
CRMS0220	783559.10	3273969.92	CRMS0680	450622.57	3293768.24
CRMS0400	741597.27	3264935.92	CS20-41	460648.41	3300140.79
CRMS0416	744388.61	3263377.93	CRMS1855	456669.64	3305038.93
CRMS0386	756717.29	3258835.65	CRMS1856	456717.33	3305876.46
CRMS0394	708306.91	3249613.99	CRMS1866	459738.70	3308244.17
CRMS0396	705275.22	3248180.55	CRMS1865	459770.58	3307449.55
TE28-98	696412.93	3254764.38	CRMS2353	459828.92	3325098.15
TE28-104	694991.05	3253394.98	CRMS2328	456877.62	3321238.63
TE26-30R	668659.52	3243016.87	CRMS0651	450766.81	3314738.45
AT03-09	666105.65	3261723.58	CRMS2305	453783.73	3319525.80
AT03-54	664320.59	3261747.33	CRMS0636	454126.29	3320499.52
AT03-56	664115.33	3261722.18	CRMS2306	453683.03	3321503.11
CRMS0544	638125.61	3284915.69	CRMS2307	453800.65	3321956.95
CRMS0489	641263.68	3275582.38	CRMS2308	453771.20	3322752.71
CRMS0522	614116.92	3263672.64	CRMS2309	453808.31	3323558.16

Appendix Table B. Chapter 4 sampling site coordinates.

Site number	Site name	UTM coordinates Easting	Northing
0669	CRMS0669	429573.82	3305990.69
2156	CRMS2156	432423.18	3305240.87
0661	CRMS0661	438811.69	3301935.98
0682	CRMS0682	444607.75	3299411.25
0651-H	CS23-115	449408.00	3312912.00
0651	CRMS0651	450766.81	3314738.45
S14	S14	450691.27	3307485.25
S12.5	S12.5	450691.27	3305876.75
1859	CRMS1859	450672.64	3301797.26
S6	S6	450691.27	3299313.25
S5	S5	450691.27	3298313.25
S4	S4	450691.27	3297313.25
S3	S3	450691.27	3296313.25
S2	S2	450691.27	3295313.25
S1	S1	450691.27	3294313.25
0680	CRMS0680	450691.27	3293813.25
S0	S0	450691.27	3293313.25
R8	R8	540871.80	3280758.00
R7	R7	540871.80	3279758.00
R6	R6	540871.80	3278758.00
R5.75	CRMS0609	538302.69	3278508.00
R5	R5	538302.69	3277758.00
R4	R4	538302.69	3276758.00
R3	R3	538302.69	3275758.00
R2	R2	538302.69	3274758.00
R1.5	R1.5	538302.69	3274258.00
R1	R1	538302.69	3273758.00
R0.5	R0.5	538302.69	3273258.00
R0	R0	538302.69	3272758.00

VITA

Greg was born in New Carrollton, Maryland, on August 2, 1963. He graduated from Parkdale High School in Riverdale, Maryland, in 1981. He attended the University of Maryland in College Park where he received his bachelor's of science degree in biology in 1985. He traveled to Louisiana, where he entered graduate school at the University of Southwestern Louisiana and received a master of science degree in 1988. After working for the Louisiana Department of Natural Resources for 12 years, Greg was hired by the U.S. Geological Survey, National Wetlands Research Center, in 2001. He entered the doctoral program within the Department of Oceanography and Coastal Sciences that same year as a part-time student. He is married to his lovely wife Cindy, and has two children, Jeanne age 12 and Zachary age 7.