Coastal Ecosystem Resiliency after Major Disturbances

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AFTER MAJOR DISTURBANCES

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Laissez les bon temps roulez!
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ABSTRACT

Disturbances are a common occurrence in coastal ecosystems and can provide opportunity for adaptation and renewal in healthy systems; hurricanes bring mineral accretion to a marsh, floods provide a pulse of freshwater and nutrients to estuaries, and fires increase species diversity and abundance in forests. Humans, however, have depleted the resiliency of many coastal systems via top down and bottom up mechanisms, leaving these ecosystems more vulnerable to both natural and anthropogenic disturbances. Louisiana’s wetlands have been modified for centuries via canals, levees, agricultural impoundments, etc., leading to a decreased resiliency to land loss. The Deepwater Horizon (DWH) oil spill had the potential to further reduce marsh resiliency, potentially precipitating a “regime shift” where natural disturbances that were once a subsidy to the system are now a stress.

The DWH oil spill released 4.9 million barrels of oil into the northern Gulf of Mexico, covering 2,000 km of shoreline from Florida to Texas in the world’s largest accidental marine oil spill. I examined the direct and indirect impacts of the oil spill on salt marsh erosion rates in southeastern Louisiana on varying spatial (from cm to km) and temporal scales (from hours to years). I chronicled the effects using multiple techniques of documentation including field data collection of the marsh edge for 5 years, GIS analysis spanning 15 years, and time-lapse photography for one year.

The DWH oil spill directly increased erosion rates for 2 years and also left a continuing land loss legacy of cascading erosional effects lasting for 3+ years. The salt marsh shoreline eroded unevenly, leaving behind micro-headlands that eroded at an accelerated rate, leading to cascading heightened land loss along the study area. The shoreline erosion rates immediately
after the DWH oil spill that included Hurricane Isaac were higher than any time period in the last 15 years, including after the hurricane seasons of 2004 and 2005. The oil depleted the resiliency of the marsh, making it more susceptible to erosion precipitated by natural disturbances, and leaving a land loss legacy much greater than the initial impacts.
CHAPTER 1. INTRODUCTION

1.1 General Introduction

The concepts of resiliency, vulnerability, regime shifts, and adaptability for ecological systems evolved over the last 40 years from an equilibrium-centered view of the natural community that is often separate from the human world to one with multiple alternative stable states that are integrated social-ecological systems. Coastal ecosystems, for example, are impacted heavily by humans because almost 25% of the world’s population lives within 100 km of the coast (Small & Nicholls 2003). This also means that a large portion of the coastal population is reliant on the coastal ecosystems for, for example, fisheries, tourism, and storm protection. Yet, humans have eroded the resiliency of coastal ecosystems from fishing down the food web, eutrophication and climate change, and modifying hydraulic regimes. This leaves the ecosystem and, subsequently, the dependent social system, more vulnerable to regime shifts from disturbances that previously were absorbed (Adger et al. 2005). The coastal wetlands of Louisiana help supply one of the largest commercial fishing industries in the nation and with that nearly 30,000 jobs (National Marine Fisheries Service 2010). Many livelihoods are dependent on the resiliency of Louisiana’s marshes and the health of the coastal ecosystem is dependent on the adaptive management capacity of humans. Louisiana’s ecosystem and culture are, therefore, intrinsically inter-connected. Other systems have external economic drivers that are also independent of the ecological system (Davis et al. 2010).; Louisiana’s are intrinsically connected. Knowing where a social-ecological system is on the resiliency continuum is important in determining the optimal management actions.
1.2 Disturbances and resiliency

1.2.1 Ecological resilience

Estuaries are subject to a range of disturbances (e.g., hypoxic events, salinity fluctuations, and natural disasters). These disturbances, whether natural or anthropogenic, can be either a stress or a subsidy to the affected ecosystem or organisms (Odum 1985). Small disturbances in estuaries may have positive impacts on the ecosystem (e.g., periodic flood events bringing sediment and food resources), however large disturbances may negatively affect the ecosystem, possibly leading to an alternative stable state (e.g., prolonged flooding may move an estuarine ecosystem to a freshwater ecosystem). The difference between a perturbation being deemed a stress or subsidy depends not only on the magnitude of the disturbance, but also on the scale being studied. For instance, a competing organism may capitalize on the reduction of interspecies competition or flooding (and subsequent salinity reductions) could be a stress to oysters, but a subsidy to blue crabs.

Engineering resilience (stability) is defined as the time it takes to return to one global equilibrium state after stress. This equilibrium-centered view does not account for the transitional nature of ecosystems that may not be near the documented equilibrium (Holling 1973). There have been a number of definitions of resiliency since C.S. Holling (1973) interpreted the word in an ecological context. Holling (1973) offered a differing definition of resiliency: “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.” This general definition has persisted in the ecological literature for the last four decades. Simply said, ecological resilience is the capacity of the system to absorb a disturbance while maintaining
the same structure and function and without changing stable states (Gunderson 2000, Folke et al. 2004).

Resiliency can be thought of as the size of the basin of attraction (Figure 1.1, Scheffer et al. 2001). The ball in this diagram represents the system and the valleys are the stable states or basins of attraction. Engineering resilience is the slope of the basin; the steeper the slope, the more resilient the system as it would take a larger perturbation to move the system out of the basin. Ecological resilience is described as the width of the basin; the larger the basin, then the more resilient the system is. Resistance is the ease or difficulty in changing the system and can be seen as the depth of the basin (Folke et al. 2004). Resiliency may be slowly eroded by human behavior via top down (e.g., overharvesting of top predators) and bottom up (e.g., excess nutrient additions) mechanisms, and by alterations of natural disturbance regimes (e.g., climate change, controlling fires in grasslands). These external factors may shrink the basin of attraction and reduce the basin rim height, resulting in a reduction of the system resiliency without affecting the equilibrium state. The system may appear unaltered but it has become fragile and one small perturbation could move the ball into an alternate stable state (Scheffer & Carpenter 2003).

Estuaries may be adapted to disturbances; but does this mean that they will be able to absorb anthropogenic stressors and still maintain the same functional properties? Other coastal ecosystems (e.g., coral reefs, kelp forests) have undergone regime shifts as a result of human activity (Jackson et al. 2001), leading to a decline in the ‘ecosystem services’ (McClenachan 2009; zu Ermgassen et al. 2013). Regime shifts are generally not precipitated by one disturbance, but occur as forms of resiliency in the system are allowed to decline or deliberately removed over a long period of time (Holling 1973; Adger et al. 2005; Biggs et al. 2009). Overfishing, climate change, and chronic pollution are the most common factors cited in causing the
The appearance of these alternative stable states (Folke et al. 2004). The ability of an ecosystem to regenerate after a disturbance is linked to the magnitude of stressors it has already been exposed to. Wetlands, for instance, have been altered by humans for centuries through levees, impoundments, canals, and diversions (Salinas et al. 1986). As natural hydrologic regimes are modified, the coast becomes more vulnerable to land loss (Deegan et al. 1984), potentially pushing a marsh’s erosional resilience past a threshold where one perturbation causes cascading effects (van de Koppel et al. 2005).

Figure 1.1. The basin represents a stable state for the ecosystem. As resiliency is eroded, the basin becomes smaller and its basin edges become less defined, making it easier for one disturbance or perturbation to move the system into an alternative stable state. The figure is from Scheffer et al. (2001).

1.2.2 Social-ecological resilience

The ideas of resilience, vulnerability and perturbation for ecosystems that are discussed above have been extended to include the dependent social systems. Social resilience has been defined as the ability of a community to withstand disturbances to their social infrastructure (Adger
Resilience, however, is not only about how much of a disturbance can be absorbed. Folke (2006) defines social-ecological resilience in three parts: (1) the amount of disturbance a system can absorb and still remain within the same state or domain of attraction, (2) the degree to which the system is capable of self-organization (versus lack of organization, or organization forced by external factors), and (3) the degree to which the system can build and increase the capacity for learning and adaptation. In resilient systems, disturbances have the ability to create opportunity for innovation and development (Folke 2006); resilience can provide adaptive capacity. In systems with eroded resilience, however, even small disturbances may cause catastrophic social consequences (Adger 2006).

Coastal human communities are generally thought to be more resilient than communities reliant on other ecosystems because they are dependent on not just one resource, but on an integrated ecosystem with a variability of resources (e.g., numerous types of commercial fisheries, tourism, etc) (Adger 2000). However, the resiliency is still tied to one ecosystem; any disturbances affecting the resiliency of the coastal ecosystem will also affect the resiliency of the human communities dependent on the resource. Social resilience cannot only be eroded by disturbances in the ecological system, but also in the market system; resilience is dependent on the functional diversity of the ecosystem, as well as on the laws that govern the social systems (Adger 2000). Overfishing, pollution, and “command and control” management techniques (managing for just one target variable) have all led to an erosion of resilience in social-ecological systems (Gunderson 2000; Jackson et al. 2001).
1.3 Louisiana coast

The Mississippi river is the 8th largest river system in the world by discharge and drains over 40% of the contiguous U.S. (Turner & Rabalais 1991). The formation of the Mississippi river delta began approximately 7500 years ago, when sea level rise slowed enough to allow for sediments to accumulate at a faster rate than sea level rise (Stanley & Warne 1994). All major current deltas were formed during this era of Holocene sea level rise deceleration, but not all delta formation and maintenance is driven by the same forces. Deltas can be river-, wave-, or tide-dominated (Galloway 1975). Due to the high river discharge and small tidal range, the Mississippi delta is a river-dominated delta, producing the elongated shape resembling fingers of levees extending seaward. The relatively large drainage area and high discharge supplies the northern Gulf of Mexico with the 7th highest sediment load in the world (Milliman & Meade 1983). The hydrologic gradient is gradually reduced as the river fills with sediment and its position extends seaward. The Mississippi switches course roughly every 600 to 1000 years, finding a more efficient route to the Gulf (Coleman et al. 1998). Over the course of its history, the Mississippi has had 6 Holocene delta complexes, including the most recent Atchafalaya. Each delta complex is in various stages of compaction, subsidence, and building. The delta switching, combined with the high sediment load, has resulted in the current wetland rich Louisiana coast, with 30,000 km² of delta plain and 41% of the coastal wetland area of the United States (Coleman et al. 1998).

The Louisiana coast is an incredibly productive ecosystem largely because of these extensive wetlands. Numerous species of fish, birds, and invertebrates use the coastal waters for a portion of their life history and some reside there for their entire life (Chesney et al. 2000). The wetlands act as fishery nursery grounds, potentially increasing recruitment success (Beck et al.).
2001), and provide food and refuge to many species and their prey (Boesch & Turner 1984; Baltz et al. 1993). The productivity of important commercial fisheries, including shrimp and blue crab, are closely linked to access to the marsh (Turner 1977; Zimmerman et al. 2000). The marsh edge is utilized by more species and at a higher rate than any other area of the marsh (Baltz et al. 1993; Peterson & Turner 1994). The slumped, submerged edge of a coastal marsh may actually act as additional habitat area for some species (Rozas & Reed 1993).

The Louisiana commercial fishing industry is one of the most productive in the country (2nd only to Alaska in lbs/year (National Marine Fisheries Service 2010)). The Gulf of Mexico accounted for 18% of total US landings (by weight) and 16% of the total US landings revenue in 2009 (National Marine Fisheries Service 2010). Of that, Louisiana supplied 70% of the GoM landings and 45% of GoM revenue (National Marine Fisheries Service 2010). Louisiana’s total annual landings from 1969 to 2000 have exceeded 1 billion pounds (Chesney et al. 2000). Louisiana’s coastal wetlands provide many other benefits than solely fishery production, including recreational uses and storm protection (Costanza et al. 1989). Recreational fishing in Louisiana accounted for 4 million trips in 2009 (National Marine Fisheries Service 2010). Hurricane protection supplied by coastal wetlands alone has been estimated at over $23 billion dollars for the US (Costanza et al. 2008).

Rapid land loss (42.9 km² y⁻¹ from 1985 to 2010; Couvillion et al. 2011) has lead to Louisiana accounting for 80% of total coastal wetland loss in the U.S. (Boesch et al. 1994). Humans have altered the coastal ecosystem for centuries through levees, impoundments, canals, and river diversions. Beginning in the 18th century, natural levees were reinforced in attempts to control the annual flooding of the Mississippi River. By 1926, the levees extended from Illinois to New Orleans. Recent land loss (both direct and indirect) from oil and gas canals (Bass &
Coastal land loss can be broken into two general categories: interior loss and edge loss. From 1990 to 2001, approximately twenty-percent of land loss in Louisiana can be attributed to edge erosion (Tweel 2013). Edge erosion is generally controlled by the health of the salt marsh grass. The below- and above-ground biomass of *Spartina alterniflora*, the dominant salt marsh grass in coastal Louisiana salt marshes, helps to increase the marshes’ resistance to erosion. The belowground plant biomass provides erosion protection to the shoreline edge via root strength and mass (Gabet 1998; Micheli & Kirchner 2002). The aboveground stems of *S. alterniflora* trap sediment by slowing the tidal and wave energy, which can help maintain a sustainable marsh elevation as sea level continues to rise (Redfield 1972; Stumpf 1983; Li & Yang 2009). However, there is some recent debate as to how much the erosion of the marsh edge is dependent on vegetation (Feagin et al. 2009).

### 1.4 Disturbances in Louisiana

While highly productive, the Louisiana coastal zone absorbs a multitude of stressors, both natural (hurricanes, floods, droughts) and anthropogenic (hypoxia, oil spills). Large-scale disturbances can be a stress or subsidy to the coastal ecosystem. Hurricanes and tropical storms rework the coastal environment, scouring barrier islands and marsh edges, but also depositing sediment in the marsh (Stone et al. 1997; Tweel & Turner 2012a). Despite initially decreasing populations of certain fish species, hurricanes may actually increase the productivity of the coastal marsh in the long term (Conner et al. 1989). There is some evidence that hurricanes can...
increase landings of certain fisheries via freshwater “flushing” from rainfall, which aggregated blue crabs in North Carolina after hurricanes Dennis and Floyd (Burgess et al. 2007), leading to record catches in 1999. In 2000 and 2001, record lows of spawning stock were estimated. The commercial fishing industry may also experience an initial decrease in productivity due to the forced time not fishing and from the damages incurred to fishing equipment. Natural, semi-regular floods of a river delta have long been considered vital to both freshwater and saltwater fisheries’ productivity (Viosca Jr. 1927; Junk et al. 1989). The pulse of food rich freshwater and increased spawning grounds and refuge areas are thought to increase the recruitment success of many species (Junk et al. 1989; Bayley 1991).

Oil spills are a somewhat regular occurrence in the Gulf of Mexico with the extensive drilling activity. The Deepwater Horizon (DWH) oil spill, however, was the largest spill event in US history and the fifth largest in the world. The DWH oil spill at Mississippi Canyon Block 252 killed 11 people, injured 17, and released approximately 5 million barrels of oil into the Gulf of Mexico 66 km from the Louisiana coastline from 20 April to 15 July. Of all five of the Gulf of Mexico states, the oil released disproportionately affected Louisiana. Roughly 1000 km of Louisiana’s shoreline was oiled, equaling about 60% of the total oiled shoreline in the Gulf of Mexico (Michel et al. 2013). Seven times larger than the Exxon Valdez oil spill, the DWH spill had the potential to cause significant damage to Louisiana’s coastal habitats as well as the social system that relied on this ecosystem.

1.5 Research goals and questions

The research presented here attempts to provide a perspective of the Louisiana coastal wetlands’ resiliency to disturbances. I study the initial impacts of the 2010 Deepwater Horizon oil spill on
coastal edge wetland (marsh) erosion, as well as document the cascading erosional processes that occur post disturbance. This research leads to a greater understanding of the impacts of disturbances in the coastal system and the potential for synergistic effects of multiple disturbances occurring in a short period of time.

The primary research questions are:

1. What were the initial effects of the DWH oil spill to marsh edge erosion? This question is addressed in Chapter 2 and was published in 2013 (McClenachan et al. 2013).

2. Does a disturbance indirectly increase marsh edge erosion after the disturbance’s initial impacts? This question is addressed in Chapter 3 and uses time lapse photography to document the effect micro-bay formation from a disturbance can have on continued erosion, leading to a cascading land loss legacy. This has been submitted to Ecological Applications.

3. How long have erosional impacts of the DWH persisted and has the DWH oil spill weakened the resiliency of the marsh to absorb natural disturbances? This question is addressed in Chapter 4 and uses a GIS analysis and is coupled with almost 5 years worth of field data to document impacts of the DWH and Hurricane Isaac on varying spatial scales.

Chapter 5 is a summary of the findings and puts them in a larger context of disturbance and resiliency of the coastal ecosystem.

1.6 References


CHAPTER 2. EFFECTS OF OIL ON THE RATE AND TRAJECTORY OF LOUISIANA MARSH SHORELINE EROSION

2.1 Introduction

Salt marshes have long been considered to be resilient to natural and anthropogenic disturbances (Gedan et al 2011). However, other coastal ecosystems have shifted to alternative stable states induced by human activity (Jackson et al 2001), leading to a decline in the services they supply (McClenachan 2009; zu Ermgassen et al 2013). Originally thought to provide no benefit in their natural state, wetlands have been altered by humans for centuries through levees, impoundments, canals, and diversions (Salinas et al 1986). As natural hydrologic regimes are modified, the coast becomes more vulnerable to land loss (Deegan et al 1984), potentially pushing a marsh’s erosional resilience past a threshold where one perturbation could result in cascading effects (van de Koppel et al 2005).

The April 20th, 2010 Deepwater Horizon (DWH) oil spill at Mississippi Canyon Block 252 killed 11 people, injured 17, and released approximately 5 million barrels of oil into the Gulf of Mexico 66 km from the Louisiana coastline from April 20th to July 15th. It was the largest ‘spill’ event in US history and the fifth largest in the world. Of all five of the Gulf of Mexico states, the oil released disproportionately affected Louisiana. Roughly 1,000 km of Louisiana’s shoreline was oiled, equaling about 60% of the total oiled shoreline in the Gulf of Mexico (Owens et al 2011). Seven times larger than the Exxon Valdez oil spill, the DWH spill had the potential to cause significant damage to Louisiana’s coastal habitats.

The rate of land loss in Louisiana was significant before 2010 (42.92 km² y⁻¹ from 1985 to 2010; Couvillon 2011), and so the threat of increased erosion rates from the oiling in 2010 are an additional concern. There are many contributing factors to the disappearance of Louisiana’s coastal marshes, both anthropogenic (e.g., oil and gas canals (Bass and Turner 1997), sediment supply (Tweel and Turner 2012; Blum and Roberts 2009)) and natural (e.g., subsidence; Blum and Roberts 2009). Major episodic disturbances, such as the DWH spill, can contribute to the short- and long-term yearly estimates of land loss, but, depending on the time series analyzed, may not be recognized as the source of elevated erosion. Chronic exposure to oil can cause increased shoreline erosion (Hershner and Lake 1980), and results from a small sample size of heavily oiled marsh sites (n = 3) after the DWH disaster indicate that exposure to oil elevated marsh shoreline erosion rates (Silliman et al. 2012). Although thought to be tied to salt marsh plant health, the mechanisms controlling this increased erosion are poorly understood.

The below- and above-ground biomass of *Spartina alterniflora*, the dominant salt marsh grass in coastal Louisiana salt marshes, helps to increase marsh resistance to erosion. The belowground plant biomass provides erosion protection for the shoreline edge via root strength and mass (Gabet 1998; Micheli and Kirchner 2002). The aboveground stems of *S. alterniflora* trap sediment by slowing tidal and wave energy, which can help maintain a sustainable marsh elevation as sea level continues to rise (Redfield 1972; Stumpf 1983; H. Li and Yang 2009). Marsh loss potentially will be enhanced if the marsh plants’ health is compromised.

The results of laboratory and field studies on the effects of oil on *S. alterniflora* growth have shown that high amounts of oil can have significant negative impacts on both above- and belowground production (Li *et al* 1990; Lin and Mendelssohn 1996). The most severe impacts tend to occur when the oil is applied during the growing season of the plants (spring and early
summer) (Alexander and Webb 1985; Webb 1994) and when the oil persists in highly organic soils (Pezeshki et al. 2000). NOAA reported DWH oil entering Louisiana’s coastal marshes in June 2010 (NOAA 2010). This timing coincides with the most intense growth of *S. alterniflora*, giving the oil the potential to impart substantial damage to the vegetation and, in turn, cause a significant increase in shoreline erosion. Lin and Mendelssohn (2012) reported significant initial aboveground dieback of heavily oiled *S. alterniflora*, while Silliman *et al* (2012) documented significantly greater erosion at three heavily oiled sites following the DWH spill event, which is attributed to a decrease in aboveground plant cover.

Here, I provide a trajectory of the rate of erosion and recovery over two years in low and high oiled coastal marshes in southeast Louisiana. I also investigated some of the physical and biological mechanisms driving the variation in the erosion rates among sites and over time.

### 2.2 Materials and Methods

#### 2.2.1 Site selection

I established 30 closely-located *Spartina alterniflora* dominated salt marsh sites on 12-13 November 2010 along the northern edge of Bay Batiste in the southeast Louisiana estuary of Barataria Bay (Figure 2.1). November 2010 was approximately 6 months after the DWH oil first reached the barrier islands at the entrance to the bay (Port Fourchon 11 May 2010, and on Raccoon Island on 13 May 2010). There are a total of 10 groups of 3 sites each. The three sites within each group of 3 were 10 m apart. NOAA SCAT shoreline survey maps (NOAA 2010a) were used to incorporate a range of oiling, with the non-oiled sites acting as the control or reference group. The sites were subsequently separated into high and low oiled categories (see below).
Figure 2.1 Locations of 30 sampling sites along Bay Batiste’s northern edge. There is a cluster of three sites, 10 m apart, at each of the 10 red dots.

2.2.2 Field measurements

I collected a surface oil sample within the top 5 cm of soil, one meter from the marsh edge, from each site in February 2011, August 2012, and September 2012. The samples were analyzed by gas chromatography/mass spectrometry for petroleum hydrocarbons including the normal and branched saturated hydrocarbons (from C10 to C35), the one- to five-ringed aromatic hydrocarbons and their C1 to C4 alkyl homologs, and the hopane and sterane biomarkers. All GC/MS analyses use an Agilent 7890A GC system configured with a 5% diphenyl/95% dimethyl polysiloxane high-resolution capillary column (30 m, 0.25 mm ID, 0.25 micron film) directly
interfaced to an Agilent 5975 inert XL MS detector system. The data are reported in Turner et al. 2013 (in revision). The samples containing oil were identified as MC252 oil by comparing key markers of petroleum hydrocarbons in the sample to MC252 source oil (Overton et al. 1981, Iqbal 2008).

The polycyclic aromatic hydrocarbon (PAH) concentrations were used as the proxy for oil exposure in the analyses discussed here. The average PAH concentrations in these samples and others demonstrate no statistically significant decline from September 2010 to October 2012 (Turner et al. 2013 in revision).

The sites were divided into high and low oiled sites. The 13 sites where the PAH concentration was < 1000 ug kg⁻¹ were considered ‘low’ or ‘background’ oil sites and used as the control or reference sites. The 17 sites where the PAH concentration was >1000 ug kg⁻¹ were placed in the high oiled category.

The horizontal shoreline erosion, soil strength, percent cover of *S. alterniflora*, and marsh edge overhang were sampled at each site. I placed permanent PVC poles 1.5 m and 4.5 m in a straight line into the marsh from the shoreline edge. Edge erosion and gain were measured five times using these poles as reference points. Soil strength measurements were taken in November 2010 and August 2012. Soil strength and percent cover of *S. alterniflora* were measured at the 1.5 m pole until the edge eroded past this location; after this occurred, the readings were taken 1.5 m into the marsh from the marsh edge. A shear vane was used to measure soil strength in a 1 m profile, at 10 cm intervals using a Dunham E-290 Hand Vane Tester. The percent cover of live *S. alterniflora* was estimated for a 0.5 x 0.5 m plot. The portion of the intact marsh overhanging a missing layer beneath was measured as an indicator for future erosion potential. I measured marsh overhang roughly 15 cm below the top of the marsh surface.
2.2.3 Energy calculation

I calculated the wave energy at each site to test the hypothesis that the erosion rates I measured were due to normal physical stress (i.e., wave and wind force) at these specific locations and that they were not due to the exposure to oil. Because of their close proximity, I calculated wave energy for each of the 10 groupings of three sites rather than the individual sites, with the middle site in each grouping serving as the location for the estimation of fetch. The PAH concentrations and total erosion were also averaged for the three sites in each grouping of 10. Wind speed and direction data were downloaded from the Louisiana State University (LSU) AgCenter website for a weather station located in Port Sulphur, LA at 10 m-height and 13 km from the study sites (LSU 2012). The data interval is for April 2007 to June 2011. I used SAS (SAS 9.3, SAS Institute, Inc. 2012) to calculate the percent frequency the wind blew from each direction and the associated average wind speed with this direction. I used fetch lengths calculated using ArcInfo10.0 (Environmental Systems Research Institute), together with the wind speed and direction data and an online software program (USGS 2012), to estimate wave height and period for each of the eight major directions (N, NE, E, SE, S, SW, W, NW) at each of the 10 locations for the prevailing wind patterns. A water depth of 2 m was used for all sites since Bay Batiste has a relatively shallow homogeneous depth. These parameters were then used to calculate a weighted average “wave energy” at each site based on the percent frequency of time the wind blew from each direction.

2.2.4 Bay Batiste Shoreline Change

I used vectorized aerial imagery to investigate historical changes to the morphology of the Bay Batiste shoreline. Imagery was compiled at four time intervals between 1956 and 2012 from the
USGS Earth Explorer (1956, 1972, and 1998) and TerraServer (2012). Pixel sizes were 2.2 m (1956), 3 m (1972), and 1 m for all other years, and data were projected in North American Datum 1983 UTM Zone 16 North. Images were classified into a bi-color raster to distinguish between vegetation and water, and then converted to vector data using ArcScan, which is an extension of ArcInfo.

2.2.5 Statistical Methods

I used an ANCOVA to determine if oil concentrations or exposure time had significant effects on erosion, percent cover, and overhang. I used a two-way ANOVA for the same independent variables once the oil concentrations were split into categories (high and low) and tested for interactions between the categories and time. Separate covariances were used to meet the assumptions. Student’s t-tests were used to detect differences in the soil strength because it was not measured at every site visit. Student’s t-tests and multiple regression analysis were also used to determine if there were differences in the energy calculations for the oil categories and the range of oiling at the 10 groupings. A Tukey’s HSD post-hoc test was used to test for significant differences, which were at alpha < 0.05, unless otherwise indicated. SAS 9.3 (SAS Institute, Inc. 2012) was used for all statistical analyses.

The data are archived in the Coastal Waters Consortium webpage at the Louisiana Universities Marine Consortium (www.lumcon.edu) and also with the Gulf of Mexico Research Initiative Information and Data Cooperative (http://griidc.gomri.org).
2.3 Results

2.3.1 Oil concentration

The PAH concentrations varied from 82 to 133,000 ug kg\(^{-1}\) across all samples at the 30 sites, with approximately 150× higher concentrations when DWH oil was present. Every site contained some oil, but all of the sites with high oil concentrations were contaminated with oil from DWH (MC252) (Figure 2.2). Only two of the sites in the low category had MC252 oil. The sites contaminated with MC252 oil, and those in the high oil category, had average PAH concentrations more than 150 times higher than those without MC252 oil and those in the low oil category (Table 2.1).

![Figure 2.2 Oil concentration (log aromatics) at each of the 30 sites. The black circles indicate the presence of DWH oil; grey squares designate the presence of oil from other sources.](image)

Table 2.1. Concentration of PAH (µ ± 1 SE) in sites contaminated with Macondo oil (MC252) and those without (No MC252), and low (<1000 ug kg\(^{-1}\)) and high (>1000 ug kg\(^{-1}\)) oiled categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Sample size</th>
<th>PAH concentration (ug kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC252</td>
<td>19</td>
<td>23,648 ± 7405</td>
</tr>
<tr>
<td>No MC252</td>
<td>11</td>
<td>143 ± 15</td>
</tr>
<tr>
<td>High</td>
<td>17</td>
<td>26,390 ± 8030</td>
</tr>
<tr>
<td>Low</td>
<td>13</td>
<td>172 ± 30</td>
</tr>
</tbody>
</table>
2.3.2 Erosion Rates

The erosion rate for the entire sampling time period (November 2010 to August 2012) was lower for the low oil sites (100 cm yr$^{-1}$) than for the high oil sites (133 cm yr$^{-1}$), but did not differ significantly ($F_{(1,65)} = 0.85; p = 0.36$). Despite no significant differences in the total erosion rate between the two oil categories, an interesting pattern emerged when the erosion rates of high and low oil sites were analyzed with sampling time added as an additional variable. Both time ($F_{(4,35)} = 5.68; p < 0.01$) and category $\times$ time ($F_{(4,35)} = 3.62; p = 0.01$) were significant variables in the ANCOVA. The low oil sites had a greater rate of erosion for the first four time periods (November 2010 to May 2012). However, the erosion rate was significantly greater at the high oil sites in the last time period (May 2012 to August 2012; Figure 2.3).

![Figure 2.3 Annualized erosion rate for high and low oil sites in each time period. Positive erosion values indicate erosion, whereas negative values indicate accretion. The error bars are ± 1 SE. A ‘*’ indicates significant difference ($p < 0.01$).](image)

The erosion rate accelerated at the low oil sites for the first three time periods. There was also greater overall erosion at the low oil sites than at the high oil sites during this time period, culminating in a significant difference in the erosion rate in the third time period. After October...
2011, however, the low oil sites’ erosion rate decreased and lateral accretion began in May 2012, as the high oil sites experienced increased erosion rates.

2.3.3 Soil Strength

The November 2010 soil strength measurements in the top layer (0-50 cm) of soil were not significantly different in the two categories ($p = 0.19$). The soil strength in the bottom layer of soil (60-100 cm), however, was significantly weaker in the high oil sites than in the low oil sites ($p = 0.008$; Figure 2.4). There were no significant differences between the high and low oil sites in the August 2012 readings.

Figure 2.4 Soil strength in the top layer (0-50 cm) and bottom layer (60-100 cm) of high and low oil sites in November 2010. The error bars are ± 1 SE. A ‘*’ indicates significant difference ($p < 0.01$).
2.3.4 Overhang

The amount of marsh overhang showed a consistent relationship between low and high oil sites throughout the sampling period. The high oil sites had a significantly greater overhang than the low oil sites ($p < 0.03$ for all) for all time periods except July 2011 (Figure 2.5).

![Figure 2.5 Overhang of the marsh (cm) for each time period in high and low oil sites. The error bars are ± 1 SE. A ‘*’ indicates significant difference ($p < 0.05$).](image)

2.3.5 Aboveground plant cover

There was no significant difference in percent cover of *S. alterniflora* between the high and low oil sites, for any of the time periods except for October 2011. The percent cover of *S. alterniflora* was marginally significantly higher ($p = 0.09$) at high oil sites (39% cover) compared to low oil sites (26% cover). There was a significant time effect for both oiling levels due to the seasonality of aboveground cover.
2.3.6 Energy

The wave energy at the low oil sites (n = 3) was not significantly different (p = 0.103) than at the high oil sites (n = 7). The erosion rate at the low oil sites was lower (59 cm yr\(^{-1}\)) than at the high oil sites (116 cm yr\(^{-1}\)), although not significantly different (p = 0.62). There was no significant relationship between erosion rate and wave energy (R\(^2\) = 0.063; p = 0.48).

2.4 Discussion and conclusion

2.4.1 Vegetation

This data supports the idea that, while the impact to *S. alterniflora* marshes from the DWH oil may not be evident from the presence or absence of aboveground cover or even in the top layer of soil, heavy oiling significantly weakened the bottom layer of soil. The weaker bottom layer of soil, coupled with the same, or slightly stronger, soil in the top layer, has produced the dramatic overhang pattern observed at the high oil sites (Figure 2.6). Coastal marshes attenuate wave energy from storms and reduce shoreline erosion (Gedan et al. 2010; Shepard et al. 2011) and soil strength can be directly linked to plant belowground biomass (Turner 2010; Micheli and Kirchner 2002). The compromised integrity of the marsh should, therefore, eventually lead to greater erosion at the high oil sites, which is what I observed in 2012. Since there was no difference in the wave energy at low and high oil sites, the increased erosion documented at the high oil sites is most likely due to oiling and not background conditions.
The weakening of the soil at the high oil sites can lead to direct erosion via increased susceptibility to daily wave and tidal action. Concomitantly, reducing the belowground biomass may lower the marsh’s ability to sustain an elevation that matches the high relative sea level rise (~1 cm) of the Gulf of Mexico (Penland and Ramsey 1990). There is a direct relationship between the accumulation of organic matter and the vertical accretion of the marsh, which allows for the marsh surface to keep up with sea level rise (Turner et al 2001). The slow land loss caused by sea level rising at a greater rate than the marsh can accrete, a possible consequence of
heavy oiling, demonstrates the difficulty in accurately and completely quantifying the damages associated with exposure to oil.

The mechanisms behind the oil’s impact on vegetation are varied and complex. The effects can be physically or chemically induced and the severity may vary depending on where the oil lands (plant stems, plant leaves, or soil) (Pezeshki et al. 2000). Previous studies looking at the effect of oil on marsh vegetation have mainly focused on the aboveground growth as an indicator of stress (DeLaune et al. 1979; Lin and Mendelssohn 1996), although a few of these studies have documented increased aboveground growth with small oil additions (Hershner and Moore 1977; Li et al. 1990). Nutrient additions to salt marshes have also elevated aboveground cover, but have simultaneously decreased belowground growth and soil strength at deeper depths (Turner 2010). A similar effect of growth stimulation, leading to decreased soil strength, may be in play at the high oil sites. Increased oil may also accelerate microbial activity in fresh marsh soil (Nyman 1999). This could potentially increase the rate of decomposition, perhaps fueling the weakening of the soil and large undercuts in the high oil areas. I saw no significant difference in aboveground cover for the low and high oiled sites, yet I documented differing erosion rates and soil parameters. Although I am unsure of the exact processes involved in a cause-and-effect manner, this data provides evidence that quantifying belowground health up to one meter deep may be needed to accurately evaluate the impact that heavy oiling may have on coastal marshes.

2.4.2 Erosion over time

Although I did not observe a significant difference in total erosion rates between the high and low oil sites, focusing on the changing erosion rate of the individual time intervals reveals an interesting pattern. The NOAA SCAT oiling surveys observed heavy-to-moderate oil reaching
the majority of the northern shore of Bay Batiste by the end of June 2010 (NOAA 2010). However, I did not conduct the first site visit until 5 months after the initial oiling. There is a high likelihood the heavy oil may have impacted the vegetation before I arrived, leading to a possible missed erosion event at the highly oiled sites. A large erosion event in certain areas of the shoreline would have left those that did not erode as micro headlands. As headlands, these areas would now be receiving more energy than those that had eroded, causing an accelerated rate of erosion (Figure 2.7).

The erosion rate increased for each of the first three time periods at the low oil sites, suggesting that they were headlands when I first sampled in November 2010. Roughly 1.5 years after the initial heavy oiling of Bay Batiste, the erosion began decreasing at the low oil sites and increasing at the high oil sites, suggesting that the low oil sites are no longer headlands. If I truly did miss an erosion event at the heavily oiled sites, then not only has the oil caused increased erosion at the locations it came ashore, but also at the adjacent marsh as the shoreline was eroded to a new equilibrium.

The erosion feedback mechanism has been seen over short periods of time in Delaware marshes as well, where erosion rates varied for clefts and necks (Schwimmer 2001). This data may be an indicator of the mechanism by which the marsh shoreline is eroding in Louisiana. As a section of marsh is weakened and subsequently erodes, the erosion of the adjacent marsh accelerates, causing a cascading effect of increased erosion along the Louisiana shoreline. Historical shoreline imagery for Bay Batiste shows that the gentle arc of the northern shoreline has remained constant despite significant retreat since at least 1956 (Figure 2.8). After the 1998 hurricane season, small inlets and micro headlands formed (Figure 2.8, 1998). The shape of the original coastline returned as the headlands retreated in response to increased wave energy.
Rather than eroding at a steady rate each year, the shoreline may be lost in segments of rapid erosion after major disturbances.

Figure 2.7 Schematic of oil landing on portions of marsh edge. A. Marsh before oil lands (picture 1). B. Oil lands on certain portions of marsh and erodes those sections (dashed line). C. This erosion causes headlands to form (picture 2), which, in turn, are exposed to wave energy from more directions. D. Erosion rate accelerates at non-oiled section (dotted line). E. Equilibrium is reached and erosion rates slow to background rates until next event. I began sampling the sites between C and D.
Figure 2.8 Historical shorelines of Bay Batiste since 1956. The study sites span the entire range of the coastline pictured (see Fig 1 for site locations).

The sequential erosion demonstrated within this dataset may suggest that coastal marshes are not as resilient to large disturbances as previously thought. The timescale of monitoring has a large effect on whether a system is considered resilient or not. This concept has been extensively studied in fisheries as the idea of shifting baselines (Jackson et al. 2001). Shifting baselines along an erosional coast may imply a shoreline that looks the same pre- and post-disturbance, suggesting that no erosion occurred as a direct result of the disturbance. If the shoreline were observed before the oil spill and again two years after, then the equilibrium of form demonstrated in Bay Batiste could have been seen as resiliency. In actuality, erosion accelerated at both high and low oiled sites and the current marsh edge may now be more vulnerable to increased erosion via weakened soil strength. Previous models suggest that after an initial disturbance occurs at the marsh edge, the increased erosion may cause a cascading effect that can be visible years after (van de Koppel et al. 2005). The evidence from the first two years post oil spill suggest this may be the case at these sampling sites.
These results demonstrate that it could take at least two years to document the detrimental effects heavy oiling has had on the marsh shoreline. The results from other studies indicate that heavily oiled marshes are eroding faster than non-oiled marshes over the first 18 months post spill (Silliman et al. 2012). This observation is consistent with Alexander and Webb’s (1987) findings of shoreline erosion occurring after 16 months, and continuing through 32 months, at heavily oiled locations after an oil spill on the Texas coast. Despite these sites appearing recovered as measured by changes in plant cover, I have documented increased erosion at the high oil sites 22 months post spill and elevated erosion at the low oil sites roughly 12-18 months post spill. Silliman et al (2012) found erosion rates at heavily oiled locations leveled off to reference rates by 1.5 years. However, I have not seen the same recovery at these sites. The larger sample size and wider range of oil levels may be driving the differences documented in recovery and resilience of the salt marshes post disturbance. The full extent of the DWH oil’s impact to marsh erosion rates may not be evident for many years; the weakening of the soil and possible decrease in organic matter accumulation could lead to submergence of the marsh edge as relative sea level increases faster than the marsh can vertically accrete soil.

2.5 References


CHAPTER 3. DOCUMENTING MARSH SHORELINE EROSION OVER DAYS, MONTHS AND A YEAR: THE LEGACY EFFECTS OF DISTURBANCES

3.1 Introduction

Disturbances may provide the opportunity for renewal in a healthy ecosystem. Hurricanes, for example, deposit sediment to a marsh (Tweel & Turner 2012; Bianchette et al. 2016), floods regulate the biota of river-floodplain systems (Junk et al. 1989), and fires allow for biogenic succession in forests (Oliver 1981). Humans have altered coastal ecosystems for centuries through levees, impoundments, and canals. However, as an ecosystem’s resiliency is eroded via anthropogenic influences, what was once a stimulant of ecosystem health could now be viewed as a stress, potentially precipitating a regime shift in the ecosystem (Paine et al. 1998; Folke et al. 2004; Davis et al. 2010). These alterations could make the coast more susceptible to sustained damages from large-scale disturbances.

The Louisiana coastal zone absorbs a multitude of stressors from both natural (hurricanes, floods, droughts) and anthropogenic (hypoxia, oil spills) factors. Major episodic disturbances, such as the Macondo Deepwater Horizon (DWH) disaster and hurricanes, can contribute significantly to wetland loss over the short- and long-term (McClenachan et al. 2013). The yearly land loss estimates for Louisiana, for example, increased by 12.4 km² yr⁻¹ when years 1985-2010 were used for the analysis, compared to using data from 1985-2004 (Couvillion et al. 2011), suggesting that hurricanes Katrina and Rita (in 2005) accelerated land loss significantly. Disturbances can have such a large impact on coastal land loss years after the initial event potentially because the marsh edge keeps the same ‘equilibrium of form’. That is, although the disturbance (e.g., oil landing on marsh, or hurricane hitting in particular section of marsh) may
be localized, the effects can cascade forward at a slower rate to create the same morphology existing before the disturbance. For example, as the unaffected areas are left as micro-headlands, the effect may be to accelerate their erosion rates as the shoreline attempts to reach an equilibrium of form (McClenachan et al. 2013).

Micro-headland formation has been observed in other marshes (Schwimmer 2001), but there is no real-time documentation of the accelerated land loss associated with these formations that we know of. This can be done using time-lapse photography. Time-lapse photography has been used to study glacier movement and snow cover (Raymond et al. 1995; Ahn & Box 2010; Parajka et al. 2012), as well as erosion and sediment movement in the short term (Rowe et al. 1974; Wobus et al. 2011), but the technology has not been often utilized for a longer term study in the field. One of the best uses of environmental time-lapse photography may be the documentation of glacier retreat and cleaving done by the Extreme Ice Survey (Balog 2008), which brings the science to a broad audience of scientists, managers, and general public.

I used time-lapse photography to address whether disturbance-driven micro-bay formation accelerates the erosion of the adjacent areas, leading to a “land loss legacy” persisting long after the event. How quickly did erosion occur on a daily basis, and was it episodic, constant, or seasonal? I supplemented these visual/digital techniques with traditional field methods to measure marsh edge erosion over one year at two sites in a south Louisiana salt marsh.
3.2 Methods

3.2.1 Field methods

Waterproof cameras, set on a two-hour time lapse interval, took pictures of shoreline erosion for a coastal Louisiana marsh to document edge erosional processes over one year. The custom-designed camera outfits were placed in two locations, with one camera at each location, 1 km apart along the northern shoreline edge of Bay Batiste in southeastern Louisiana where shoreline erosion measurements were made by McClenachan et al. (2013). Go-Pro (©) cameras were fitted with intervalometers to control the time intervals between photographs. I put the cameras in waterproof housing, which included a battery pack and flash capabilities. One camera was facing an even shoreline edge with no indentations, while the other was facing an uneven edge that included two micro-headlands surrounding one micro-bay. Both cameras faced the marsh edge in permanent housing 1.5 m from the edge of the grass on the shoreline. A 2 m metal pole, pushed 1.5 m into the ground, stabilized the housing to minimize camera movement during high water events. Three poles were placed laterally along the marsh edge and in view of the camera to create a reference for measurement in each picture. Each pole was 1.5 m apart from the next closest pole. This placement allowed for the calibration in each set of photographs, even if the camera were not replaced in the housing at exactly the same angle each time the camera was changed.

The cameras were replaced roughly every six weeks when the batteries were nearly drained. I measured the width of the micro-headlands and micro-bay in the field at this time, as well as the distance from each of the three poles to the marsh edge to calculate an erosion rate.
Water height data was downloaded from the USGS water data website for site CRMS0282, located 7 km from the camera locations (http://waterdata.usgs.gov/la/nwis/uv?site_no=292952089453800).

3.2.2 Image analysis

I used ImageJ (Ver. 1.48V, National Institute of Health) to measure the width of the micro-headlands and micro-bay in the photographs. The distance between the poles calibrated the measurements for each sequence of photographs. This approach allowed for comparisons between picture sets, even if the camera was placed in the housing at a slightly different angle each time. An ‘event’ was determined to be any change accurately measurable from the pictures. An event was qualitatively established from measurements of multiple photographs to be a change greater than ~2 cm.

3.2.3 Statistical analysis

A one-way ANOVA was used to determine statistical differences between the yearly erosion rates for the uneven shoreline, the even shoreline, and the bay average, which was collected over 5 years for 30 sites and included a mix of even and uneven sites that changed as erosion continually occurred.

3.3 Results

A one-minute video of the land loss documented at the uneven site over the course of the entire year is available to watch on YouTube (https://www.youtube.com/watch?v=bEumDAFWnqw). An analysis of the video data extracted from the two sites showed the uneven site lost nearly
50% (5.2 m²) of the initial 10.5-m² study area within one year, whereas the even (or smooth shoreline) site lost 21% (2.25 m²). Figure 3.1 depicts what this land loss looks like at both sites over the entire study period. There is a stark difference between the uneven and even site when viewed pictorially. The right micro-headland of the uneven site is completely lost by the end of the year, with roughly 13% of the left micro-headland width remaining from the original micro-headland (Figure 3.2). The daily distribution of erosion events ranged from 2 cm to 23 cm, had an accuracy of ~1-2 cm, and is not normally distributed; there were many small events and fewer, but larger events (Figure 3.3). Eight width erosion events greater than 5 cm at the right headland constituted 74% of the total width erosion of the headland. For the left headland, five width erosion events greater than 5 cm made up 70% of the total width erosion.

Figure 3.1. Photographs of land loss at the two study sites. A. The uneven site at the beginning of the study (August 2014). B. The uneven site at the end of the study (September 2015). C. The even site at the beginning of the study (August 2014). D. The even site at the end of the study (September 2015).
Figure 3.2. Width of the micro-bay and micro-headlands at the uneven site from August 5, 2014 to August 5, 2015 as measured from the photographs. RH= Right micro-headland, LH= Left micro-headland, Bay= micro-bay.

Figure 3.3. Frequency of the size (cm) of erosion events for the right headland at the uneven site, measured from the photographs.
The average erosion at the three poles of each site, which spanned a 3 m section of the shoreline, was significantly higher at the uneven site (2.65 ± 0.51 m y\(^{-1}\)) compared to the even site (0.72 ± 0.02 m y\(^{-1}\)), and the bay average (1.63 ± 0.17 m y\(^{-1}\); Figure 3.4, \(p < 0.05\)). Not only was the overall rate of erosion higher at the uneven site, but also the variability between the three poles was much greater (Figure 3.5). Erosion at all three poles of the even site was similar. The uneven site land loss, however, had a pattern of escalating erosion rates from left to right at the poles (which is west to east at the site). These variable erosion rates could be a good indicator of the shoreline “evening out” the micro-headlands.
3.4 Discussion

Disturbances can put in motion episodic erosion events persisting longer than the initial perturbation. Over the course of just one year, the presence of a micro-bay more than doubled marsh land loss compared to the area with no indentations. Micro-bays form because a disturbance causes a significant fast erosion event, leaving micro-headlands adjacent to this eroded coast. These micro-headlands eroded at an increased rate after the initial disturbance erosion event. The indirect cascading erosion is what forms the land loss legacy.

3.4.1 Episodic erosion

The micro-headlands erode after the initial disturbance event in a non-continuous time-step manner. The micro-headlands tended to erode via larger sections collapsing into the water after an initial crack or fissure, eating away at the width first, before moving inward. While the
magnitude of erosion is different for the left and right micro-headlands of the uneven site, the episodic erosion appears to occur at roughly the same time (Figure 2.4). This process could be a response to several factors, including hydrologic conditions or to variations in soil strength over time.

**Hydrologic conditions:** the seasonal variation in erosion may be driven by one or many high water events, whether it is one event, a certain continuous duration of high water, or multiple high water events in a short time period. I was not able to determine which high water events triggered each erosion event. There were bimodal peaks in micro-headland erosion when the data were averaged by month. The first peak was at the rise in water level, and the second peak was as water level declined (Figure 3.6A). There appears to be about a month lag between high water months and high erosion; there may be a threshold of wave energy/continuous days of high water that is needed before larger erosion events occur. The water levels were the highest from May-October and the highest amounts of erosion occurred in November and February, suggesting that there could be a “ramping up” effect. Over 4 years, the uneven site had a significantly lower average marsh elevation change than the even site (58 cm vs. 69 cm; data from McClenachan et al. 2013). Being lower in elevation could potentially explain why different areas are more susceptible to disturbances than others.

**Soil Strength:** The variation in micro-headland width erosion could also be due to seasonal changes in soil strength caused by the seasonal variations in belowground biomass. The soil strength in the 0-30 cm soil profile is directly related to root biomass, and can be reduced by various stressors, including oil and nutrients (Turner 2011; McClenachan et al. 2013). Darby and Turner (2008) measured the seasonal amounts of live root and rhizome biomass 12 times over 329 days in a south Louisiana salt marsh. The seasonal variations in live biomass are indirectly
mirrored by the seasonal variations in erosion (Figure 3.6B). The R² value of the two, by month, is equal to 0.38. Belowground biomass (and, by proxy, soil strength) seems to be a driving factor in the seasonal erosion patterns seen in the micro-headland width erosion.

Figure 3.6. Monthly width erosion (cm) of the right headland of the unven site (solid line) (error bars are ±1 SE for width erosion events in each month) with (A) the average monthly water level from USGS gage (dashed line) (error bars are ±1 SE for water height in each month); and (B) belowground biomass (inverted; the more negative the biomass, the higher biomass there is) from a salt marsh in southeastern Louisiana averaged by month (dashed line) (error bars are ±1 SE for root biomass in each month). Data for the belowground biomass are from Darby & Turner 2008.
3.4.2 Marsh resiliency

Increased variance has been suggested as a way to test for weakened resiliency and the potential for a regime shift (Biggs et al. 2009; Brock & Carpenter 2012). This particular study is composed of a limited sample size, but could be considered to be a proof-of-concept of this theory. The uneven edged site not only had higher erosion rates than the even edged site, but also had a higher variance among the three poles. The uneven site had an order of magnitude higher concentration of aromatics and alkanes when measured in February 2011 (data from McClenachan et al. 2013), but the erosion between the two sites was not significantly different after the initial disturbance event (oil spill). Three years later, the sites were vastly different in their erosion rates, suggesting that the oil may have weakened the resiliency of the marsh at this site, perhaps by loss of soil strength, leaving it susceptible to increased erosion.

3.4.3 Communicating the significance of these marshes

Louisiana contains over 40% of the United States coastal wetlands (30,000 km²) (Coleman et al. 1998). Rapid land loss there (42.92 km² y⁻¹ from 1985 to 2010; Couvillion et al. 2011), however, accounted for 80% of the total coastal wetland loss in the U.S. (Boesch et al. 1994). Numerous fish, bird, and invertebrate species use these coastal waters and wetlands for part of their life (Chesney et al. 2000). The wetlands act as nursery grounds, increasing recruitment success (Rothschild 1986) by providing food and refuge for prey and predator (Boesch & Turner 1984; Baltz et al. 1993). The productivity of important commercial fisheries, including shrimp and blue crab, are closely linked to access to the marsh (Turner 1977; Zimmerman et al. 2000). Knowing more about marsh erosion rates and pattern is advantageous to understanding the significance of
various factors that may, or may not, affect wetland conservation, if not restoration. Communication of research results to others is of significance.

How we study and present science can determine the interpretation of the size and length of its impact. The time-lapse video of the marsh eroding has been shown to laypersons and scientists in the office, on social media, and in bars. Scientists who have studied coastal Louisiana for 30 years were taken by surprise that the coast was eroding as fast as the pictures depicted; they were certain the cameras must have moved, for example. Educated laypersons literally stared, mouths agape at the loss, asking to see the video again. Technology has the ability to bring to life the science we are studying in a way that words cannot and give the general public a way to visualize something like land loss. The use of time-lapse photography has brought more attention to the issue of glacial retreat and climate change; harnessing this technology for other means can help depict the urgency and importance of these issues.

Climate change and sea level rise will continue to increase and there will be higher average water level, more over marsh events, and higher intensity storm events, such as hurricanes (Knutson et al. 2010). Higher continuous water levels will begin to erode the resiliency of the marsh, leading to potentially larger land loss legacies after disturbances. The time scale of measurement needs to match the disturbance size to capture the potential increased erosion that results so that we understand their consequences. The land loss legacy of a disturbance could potentially last for years as the coastline continues to have accelerated erosion rates while the edge reaches an equilibrium of form. Understanding the mechanisms behind edge erosion will help to direct future efforts in restoration and wetland conservation.
3.5 References


CHAPTER 4. SALT MARSH RESILIENCY SHIFTS AFTER THE DEEPWATER HORIZON OIL SPILL

4.1 Introduction

Coastal ecosystems are impacted greatly by the 25% of the world’s population living within 100 km of the coast (Small & Nicholls 2003). This also means that a large portion of the population is reliant on the coast for many of the services they provide (e.g., fisheries, tourism, and storm protection). Yet, humans have eroded the resiliency of coastal ecosystems via overfishing, pollution, by modifying hydraulic regimes, and even well-meaning but sometimes compromising management efforts. These dependencies and interrelationships may leave the ecosystem and, subsequently, the dependent social system, more vulnerable to regime shifts from disturbances that previously were absorbed (Adger et al. 2005). The coastal wetlands (marshes) of Louisiana, for example, are fishery nursery grounds for one of the largest commercial fishing industries in the nation and, with that, support nearly 30,000 jobs (National Marine Fisheries Service 2010). Many livelihoods are dependent on the resiliency of Louisiana’s marshes, therefore the health of the coastal ecosystem is dependent on the adaptive management capacity of humans. From this perspective, wetland resiliency and management is fisheries management.

Resiliency can be thought of as the size of the basin of attraction (Figure 4.1). Ecological resilience is described as the width of the basin; the larger the basin, the more resilient the system is. Resistance is the ease or difficulty in changing the system and can be seen as the depth of the basin (Folke et al. 2004). The ball in this diagram represents the system and the valleys the stable states or basins of attraction. Resiliency may be slowly eroded by human behavior via top-down (e.g., overharvesting of top predators) and bottom-up (e.g., excess nutrient additions) mechanisms, and alterations of the natural disturbance regimes (e.g., climate change, controlling
fires in grasslands). These external factors may shrink the basin of attraction, reducing the resiliency of the system without affecting the equilibrium state. The system may appear unaltered, however, it has become fragile where one small perturbation could move the system into an alternate stable state (Scheffer & Carpenter 2003).

![Figure 4.1](image)

Figure 4.1. The basin represents a stable state for the ecosystem. As resiliency is eroded, the basin becomes smaller, making it easier for one disturbance or perturbation to move the system into an alternative stable state. The figure is from Scheffer et al. 2001.

Estuaries may be adapted to disturbances, but does this mean that they will be able to absorb anthropogenic stressors and still maintain the same functional properties? Other coastal ecosystems (e.g., coral reefs, or kelp forests) have undergone regime shifts as a result of human activity (Jackson et al. 2001), leading to a decline in the ‘ecosystem services’ (McClenachan 2009; zu Ernmgassen et al. 2013). Regime shifts are generally not precipitated by one disturbance, but occur as forms of resiliency in the system are allowed to decline or deliberately removed over a long period of time (Holling 1973; Adger et al. 2005; Biggs et al. 2009). Overfishing, eutrophication, and climate change are the most common factors cited in causing the appearance
of these alternative stable states. The ability of an ecosystem to regenerate after a disturbance is linked to the magnitude of stressors it has already been exposed to.

An iconic example of this ecosystem behavior is the tension between wetland transitions to open water, e.g., wetland loss. Wetlands have been altered by humans for centuries through levees, impoundments, canals, and river diversions (Salinas et al. 1986). As natural hydrologic regimes are modified, then these wetlands may become more vulnerable to land loss (Deegan et al. 1984), potentially pushing a wetland’s erosional resilience past a threshold where one perturbation could result in cascading effects that were not previously occurring (van de Koppel et al. 2005).

Edge erosion is generally controlled by the health of the salt marsh grass both above- and below-ground, which affects the wetland’s (or marsh’s) resistance to erosion. The aboveground stems of *S. alterniflora* trap sediment by slowing the tidal and wave energy, which can help maintain a sustainable marsh elevation as sea level rises (Redfield 1972; Stumpf 1983; Li & Yang 2009). The belowground plant biomass provides resistance at the shoreline edge via root strength and mass (Gabet 1998; Micheli & Kirchner 2002), is the principle component of soil dry matter accumulation in organic soils, and contributes significantly to vertical accretion in Louisiana salt marshes (Turner et al. 2001).

About five million barrels of oil leaked into the Gulf of Mexico (McNutt et al. 2012) over 3 months in 2010 (20 April – 15 July), making the Deepwater Horizon oil spill the largest marine spill in history (Camilli et al. 2010). There were unmistakable initial effects, with nearly 2,000 km of shoreline oiled from Florida to Louisiana, 45% of that was marshes (Michel et al. 2013). Salt marsh periwinkle densities decreased (Zengel et al. 2016) and areas with reduced plant biomass increased (Mishra et al. 2012), potentially leading to initial increased erosion
(McClenachan et al. 2013). Such a large disturbance may seem like a discreet event, but there is the potential for lingering indirect effects.

The Deepwater Horizon oil spill had the capability to directly increase erosion in coastal Louisiana in the short term and also accelerate land loss after future disturbances via weakened resiliency. I examined some indices of wetland or marsh resiliency to address how it responded to this stressor in time and space in two basic ways: 1) measured edge erosion at 30 sites along the northern edge of Bay Batiste for 4.5 years after the oil spill, and 2) used aerial images to document the erosion pattern and amount after disturbances on a larger spatial and temporal scale.

4.2 Methods

I used two different techniques to study the effects of disturbances on edge erosion of Louisiana salt marshes. I measured edge erosion for almost 5 years at a 1 cm scale every few months for 30 sites located along the northern edge of Bay Batiste, LA. To encompass a longer temporal scale, I analyzed aerial images of Bay Batiste (approximately a 4 km long stretch of the northern edge) from 1998-2013 using geographical information system at a m scale for area of edge eroded and length of shoreline. This allowed for comparisons of the erosion of the shoreline after the hurricane season of 2005 (without an added oil stressor) and 2012 (with an added oil stressor).

4.2.1 Field measurements

Thirty sites were established along the northern edge of Bay Batiste in southeastern Louisiana (same sites as McClenachan et al 2013) and were monitored for roughly 4.5 years from November 2010 to February 2015. The 30 sites were placed in 10 groups of 3 parallel to the
shoreline. Each center pole in the group of 3 was 10 m apart from the pole on either side. The erosion, percent vegetative cover, soil strength, marsh edge overhang at three places, shoreline slope and elevation, and oil concentration were measured throughout the study. Eleven visits were made to the sites during the study period, but only erosion, percent cover, and undercut were recorded at every visit. The 30 sites were broken into high and low oil categories from oil concentrations that were collected in February 2011 (McClenachan et al. 2013). I measured erosion by placing poles 3 m apart back into the marsh. Additional poles were added as the marsh edge eroded. I measured the percent vegetative cover by estimating the percent total cover within a 0.5 m² quadrat, placed near the marsh edge. Soil strength was measured at 10 cm depth intervals with five replicate measurements with a Dunham E-290 Hand Vane Tester in the same quadrat. The amount of the top layer of marsh protruding overhead and past the bottom layer was measured as marsh edge overhang. I took these overhang measurements roughly 15 cm from the top of the marsh surface. Elevation change was determined by placing a leveled 3 m long pole half on the marsh and half off the marsh and taking depth readings every 10 cm to create a shoreline relief profile. The difference between the highest and lowest values on the marsh was used to determine a marsh elevation change.

4.2.2 Geographical Information Systems analysis-shoreline length

I used ArcGIS (Ver. 10.3, ESRI) to measure the length of the marsh edge in order to study the idea of micro-headland and micro-bay formation after disturbances. The length of the shoreline was used as an indicator of disturbance erosion - the longer the shoreline, then the greater number of micro-headlands and micro-bays that formed after the disturbance event eroded the shoreline. I hypothesized that the increased micro-headland formation should then erode at a rate
faster than average, as the shoreline “evens out” (McClenachan 2016). Wetland aerial images were downloaded from the USGS EarthExplorer website (http://earthexplorer.usgs.gov/). Maps were available for Bay Batiste that had no aerial obstructions for 1998, 2004, 2005, 2007, 2010, 2012, and 2013. All images have a 1 m resolution. The northern edge of the Bay Batiste shoreline was hand digitized in all images at 1:1000 zoom scale to ensure consistency among pictures. The ‘calculate geometry’ tool in ArcGIS was then used to measure the length of the hand digitized shorelines.

4.2.3 Geographical Information Systems analysis-land loss calculations

The same aerial images that were used to study the shoreline length changes were also used to calculate the rate of land loss along the edge of the marsh for 6 time periods (1998-2004, 2004-2005, 2005-2007, 2007-2010, 2010-2012, 2012-2013). I created polygon shapefiles from the hand-digitized shoreline by selecting an arbitrary point back in the marsh as a landward end point, and drawing lines from each edge of the shoreline polyline to meet this end. I first did this for 1998, because this would be largest polygon, and then used the trace tool to ensure the area behind the marsh edge was exactly the same for all years. I calculated the area for each year using the “calculate geometry” function. By subtracting each polygon area from the previous year’s area, I was able to calculate the total area lost from one image to the next, creating an area lost in each time period. I divided this by the number of days from one image to the next to ensure the yearly rate was accurate as possible for each time period. The mid point of each interval was used to be able to graph on an accurate time scale.
4.3 Results

4.3.1 Shoreline erosion at 30 sites

The erosion rate is increasing over time at the 30 field sites in Bay Batiste (Figure 4.2; $R^2=0.66$, p-value=0.0045). There appears to be a pattern of switching higher and lower erosion rates when broken into the original high and low oil categories until roughly 3.5 years after the oil spill (Figure 4.3). After 3.5 years, the high and low oil sites appear to have similar trends in erosion rates, which is increasing.

Figure 4.2. Yearly average erosion rate (cm y$^{-1}$) in each time period for 30 sites along the northern edge of Bay Batiste, LA. Error bars are ±1 SE for the 30 sites at each measurement interval.
Figure 4.3. Yearly erosion rate (cm² y⁻¹) for the mid point of each of the 10 time periods for low (dashed line) and high (solid line) oil sites along the northern edge of Bay Batiste, LA. Error bars are ±1 SE for the sites in the high and low oil categories at each measurement interval.

4.3.2 Overhang at 30 sites

The overhang is fairly consistent in the low oil sites for the entire 4.5 years after the oil spill. However, the high oil sites show a pattern of increase and decrease overhang as, presumably, the overhang becomes too large and a portion of it breaks off. Overhang in the high oil sites does seem to be decreasing over time (Figure 4.4, $R^2=0.4$, p-value=0.051) and should eventually reach the same levels as the low oil sites.
Figure 4.4. Average overhang (cm) at the low (dashed line) and high (solid line) oil sites along the northern edge of Bay Batiste, LA. Error bars are ±1 SE for the sites in the high and low oil categories at each measurement interval.

4.3.3 Percent vegetative cover

No significant trend was seen in the percent vegetative cover over time for the 30 sites as a whole, nor were there significant differences between the high and low oil sites.

4.3.4 Soil Strength

In November 2010, the bottom layer (60-100 cm) of soil of the high oil sites was significantly weaker (p=0.02) than for the low oil sites (Figure 4.5). This is the only time there is a significant difference in soil strength between the high and low oil sites. The high and low oil sites appear to follow the same pattern of increasing and decreasing soil strength in both the top (0-50 cm) and
bottom layer of soil. Beginning in June 2013, the low oil sites are consistently (but not significantly stronger in the top layer of soil than the high oil sites (Figure 4.6).

Figure 4.5. Soil strength (kPa) in the bottom layer of marsh (60-100 cm) of the high (solid line) and low (dashed line) oil sites from November 2010- August 2014. Error bars are ±1 SE for the sites in the high and low oil categories at each measurement interval.

Figure 4.6. Soil strength (kPa) in the top layer of marsh (0-50 cm) of the high (solid line) and low (dashed line) oil sites from November 2010 to August 2014. Error bars are ±1 SE for the sites in the high and low oil categories at each measurement interval.

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4.3.5 Elevation change

The elevation change at the high oil sites was consistently higher than at the low oil sites (Figure 4.7). There was no change in trend over time for either high or low oil separately or combined.

Figure 4.7. Elevation change (cm) at the low (dashed line) and high (solid line) oil sites along the northern edge of Bay Batiste, LA. Error bars are ±1 SE for the sites in the high and low oil categories at each measurement interval.

4.3.6 GIS - Shoreline length

The length of the shoreline from 2007 to 2013 increased from 3,578 m to 4,574 m (Table 4.1, Figure 4.8). This is the longest length of the northern edge of Bay Batiste in the 15-year extent of pictures measured, and is even longer than the shoreline after the 1997, 2004, and 2005 hurricane seasons. The shoreline length did not increase immediately; from 2010 to 2012 there is a minimal length increase (34 m). From 2012 to 2013, however, there is an over 900 m increase in shoreline length, meaning more micro-bays and micro-headlands formed during this time period.
Table 4.1. Length of shoreline along the entire northern edge of Bay Batiste, LA.

<table>
<thead>
<tr>
<th>Date of image</th>
<th>Shoreline Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 January 1998</td>
<td>4093</td>
</tr>
<tr>
<td>21 January 2004</td>
<td>3716</td>
</tr>
<tr>
<td>27 October 2005</td>
<td>3617</td>
</tr>
<tr>
<td>20 September 2007</td>
<td>3578</td>
</tr>
<tr>
<td>31 July 2010</td>
<td>3625</td>
</tr>
<tr>
<td>20 October 2012</td>
<td>3659</td>
</tr>
<tr>
<td>7 October 2013</td>
<td>4574</td>
</tr>
</tbody>
</table>

Figure 4.8. Length of shoreline measured (m) from aerial imagery for the entire northern edge of Bay Batiste, LA. See Table 4.1 for exact dates.

4.3.7 GIS – Shoreline land loss

The highest yearly edge land loss rate occurred from 2010-2012 (Figure 4.9, 5267 m² y⁻¹) and was 50% more than the average land loss rate of this area from 1998-2013 (3,524 m² y⁻¹). This was again a higher loss rate than during the period after Hurricane Katrina (2005-2007, 4687 m² y⁻¹).
y\(^{-1}\)), which was 33% higher than the average land loss rate. No other time period measured had a land loss rate that exceeded the yearly average for the northern edge of Bay Batiste.

**Figure 4.9. Land lost per year (m\(^2\) y\(^{-1}\)) at the end point of each of the 6 time periods measured.**

### 4.4 Discussion

Erosion accelerated after the oil spill for at least 1.5 years on all spatial scales examined: the shoreline at 30 individual sites spread over 3 km for 4.5 years, and the aerial imagery of ~4 km over 15 years. These results corroborate what others who studied shoreline retreat after the oil spill found (Silliman et al. 2012). However, unlike these studies, recovery was not seen in the areas for which there is data collected for after 2012. The oil spill appears to have weakened the
resiliency and ability of the system to recover from natural perturbations, and to intensify the impact of Hurricane Isaac. The only other time period during the 15 years studied that had an erosion rate higher than the average was after Hurricane Katrina in 2005, which was a Category 3 hurricane at landfall. This erosion rate in 2005-2007 was still lower than the rate seen in the time period that included the oil spill as well as the initial effects of Hurricane Isaac (2010-2012).

There is a trend of increased edge erosion rate through time, from both the aerial imagery (1998-2013, $R^2=0.13$, $p=0.48$) and the field data (2010-2015, $R^2=0.66$, $p=0.005$). This trend is only significant in the field data, which is solely from after the 2010 oil spill. It is telling that the stronger relationship of increasing erosion rate over time is after the oil spill and, especially, after Hurricane Isaac. The erosion rate in one bay (Bay Batiste) is increasing as the coastwide and Barataria basin (where Bay Batiste is located) land loss rate is decreasing (Figure 4.10). The oil spill may have changed the trajectory of erosion in areas that were heavily oiled. I conclude that the resiliency of the coastal marsh ecosystem is being depleted, causing more land loss with each subsequent large disturbance event. Oil has been found to persist in other marshes for up to 30 years after an oil spill (Peacock et al. 2007). The increasing erosion rate caused by weakening the belowground soil strength (McClenachan et al. 2013) could continue with persistent oil in the environment and the cascading erosional patterns that follow a disturbance (McClenachan 2016, in prep).
Micro-bays and micro-headlands can form after a disturbance, which leads to increased land loss via cascading erosion along the shoreline (McClenachan 2016, in prep). The length of shoreline along the northern edge of Bay Batiste increased from 2007 to 2013 by nearly 30%, suggesting that the oil spill has a wetland loss legacy that has lasted at least 3 years. The micro-bay and micro-headland formation can be seen when zooming in to the aerial images (Figure 4.11). Interestingly, the length of shoreline did not increase significantly until 2013; there was no real difference in shoreline length in 2012 compared to shoreline length in 2010. However, the highest rate of land loss occurred before this longest shoreline length. Hurricane Isaac came through as a slow moving Category 1 hurricane in southeastern Louisiana in the fall of 2012, roughly a month before the aerial image was taken that I measured shoreline length from.
Because the storm was so slow moving, flooding may have caused the majority of damage. The wetland loss from 2010 to 2012 was 50% higher than the average wetland loss for that area during the 15 years studied, and was even higher than after Hurricane Katrina. This is because the marsh had to navigate two disturbances: the oil spill, and Hurricane Isaac. The wetland loss rate from 2010-2012 includes the effect from the initial oil spill effects, the cascading oil spill effects, and the initial hurricane effects. There was a re-oiling of the marsh from Hurricane Isaac, as the higher water brought oil that had settled on the bottom of the bay on top of the marsh (Turner et al. 2014). This re-oiling and continuous flooding of the marsh platform, coupled with weakened soil strength from the initial oiling two years prior (McClenachan et al. 2013), caused more embayments along the shoreline in 2013 than at any other date I was able to measure. The length of shoreline in 2013 was 112% of the shoreline in 1998 (the next longest shoreline), a few months after the Hurricane Danny storm track moved close to Bay Batiste. The oil not only weakened the marsh initially, but also depleted the resiliency of the system and its ability to recover from the next disturbance. As newer aerial images become available, it will be interesting to see whether the erosion rate and micro-bay formation continue at the increased rate or if it moves back to the rate prior to the spill (i.e., was it a persistent increase or a peak).
Figure 4.11. Aerial images depicting increased micro-bay and micro-headland formation after the 2010 Macondo DWH oil spill. Images from top to bottom are from 2007, 2010, and 2013. The 2007 shoreline is depicted in green, 2010 in yellow, and 2013 in red. The black triangle is the location of the uneven site from McClenachan 2016 (in prep).
The perception of impact of a disturbance can change depending on the spatial or temporal scale that is being studied. There are localized effects that may not be seen on a regional scale and vice versa. Because the 30 field sites are closely located along the same arc of a bay, the cascading erosion effect makes them all essentially “oil impacted” when studied on a long enough time scale; what is happening in one area will affect the surrounding areas. Studying sites on this small m scale allowed us to describe the cascading erosion effect, but the larger km spatial scale of the aerial imagery was needed to document the marsh land loss legacy this effect put in motion. The short time scale of other studies prematurely proclaimed the marshes recovered; however, cascading erosional processes worked concomitantly with weakened resiliency to indirectly impact the marsh land loss for at least 4 years after the spill, which could only be discerned from a longer time scale. Short term studies are necessary to assess initial impacts, but long term studies should continue to document direct and indirect effects.

It may take years to document how much damage should be attributed to the disturbance of a large event such as an oil spill or hurricane. Many other studies have found that the effects of an oil spill are chronic and can be seen in the system 30+ years after the event (Culbertson et al. 2008; Soto et al. 2014). There is evidence in other systems that multiple disturbances or stressors to an ecosystem can lead to a regime shift (Paine et al. 1998). Coral reef dominated systems have shifted to algal dominated systems as overfishing by humans decreased the resiliency of the ecosystem and, subsequently, its ability to rebound from natural disturbances and fluctuations (Nyström et al. 2000). Poor crop management practices of the early 20th century amplified drought conditions into an environmental disaster during the “dust bowl” in the 1930s (Cook et al. 2009). In both cases, a disturbance that the ecosystem would have recovered from manifested into a regime shift due to human induced degraded resiliency.
The Louisiana coastal marsh system was dealt two disturbances within a two-year time frame, one anthropogenic and one natural. There appears to be a synergistic effect of the oil spill combined with a hurricane soon after; the highest rates of wetland loss occurred in the time period which included the oil spill plus Hurricane Isaac, and the indentations along this coastal marsh edge were the highest three years after the DWH oil spill of the 15 years of the aerial imagery studied. The oil diminished the resiliency of the marsh to absorb subsequent natural disturbances and potentially amplified their effects. The impacts of the DWH oil spill have lasted 4+ years. The cascading erosion of the shoreline coupled with reoiling events after large storms and reduced resiliency, provides the potential for the land loss legacy to last for many more years.

4.5 References


CHAPTER 5. CONCLUSIONS

5.1 Introduction

The research described here set forth to more fully understand the impacts the Deepwater Horizon oil spill imparted on the Louisiana coastal wetlands and the potential shift in the resiliency of the marsh. I studied the issue at various temporal and spatial scales to determine the immediate impacts and how these may differ from longer term (5 years post spill) results, which include greater erosion from natural disturbances due to weakened resiliency after the DWH oil spill. Here I summarize the major findings from each question and how the combined results lead to a conclusion of sustained impacts to the marsh from the DWH oil spill.

5.1.2 Second chapter summary

Question one: What were the initial effects of the Deepwater Horizon oil spill to marsh edge erosion?

Oil can have long-term detrimental effects on marsh plant health above- and below-ground. There are few data available, however, that quantify the accelerated shoreline erosion rate that oil causes and the trajectory of change over time and place. I collected data between November 2010 and August 2012 on shoreline erosion, soil strength, the percent vegetative cover of *Spartina alterniflora*, and the marsh edge overhang at 30 closely-spaced low oil and high oiled sites in Bay Batiste, Louisiana. I located the sites along the same bay shoreline to minimize the effects physical characteristics might influence erosion rates over time and place. Surface oil samples were taken one meter into the marsh in February 2011. All high oiled sites in Bay Batiste were contaminated with Macondo 252 oil (oil from the Deepwater Horizon oil spill,
20 April – 15 July 2010). There is a threshold where various soil parameters changed dramatically with a relatively small increase in oil concentration in the soil. Heavy oiling weakens the soil, creating a deeper undercut of the upper 50 cm of the marsh edge, and causing an accelerated erosion rate that cascades along the shoreline. There are a couple different processes that may explain a decreased soil strength at the high oiled sites in the bottom layer of the marsh, but not the top layer: 1) Increased oil may accelerate microbial activity in fresh marsh soil (Nyman 1999). This could potentially increase the rate of decomposition, perhaps fueling the weakening of the soil and large undercuts in the high oil areas. 2) Due to a stress in the environment, the plants may be putting fewer resources into growing their root structure and more resources into ensuring the stress does not kill the plant. There is evidence from nutrient addition studies that the soil parameters on the surface can affect the belowground root structure (Turner 2011). Although I am uncertain of the exact mechanism behind this pattern, the presence or absence of aboveground vegetation by itself may not be an appropriate indicator of recovery after the initial direct toxic effect occurs. The erosion rates began increasing at the low oil sites ~9 months after the spill before beginning to decrease ~17 months after the oil spill due to a believed cascading erosion of the marsh edge. The results demonstrate that it could take more than two years to document the effects heavy oiling has had on the marsh shoreline.

5.1.3 Third chapter summary

Question two: Does a disturbance indirectly increase marsh edge erosion after the disturbance’s initial impacts?

Disturbances to marshes from hurricanes and oil spills can accelerate land-to-water conversions in the short term and leave a land loss legacy of cascading erosion persisting 1.5
years afterwards. The effects of the cascading erosion may be expressed in an apparent ‘equilibrium of form’, whereby a shoreline will keep the same general shape although continuing to erode for many more years. This semi-constant shape is accomplished by inconsistent erosion rates across an uneven shoreline as the coastline “evens out” to resemble the original shape. This equilibrium of form was posed as a theory for why edge erosion increased at the low oil sites of Chapter 2. I tested whether this could be true by documenting the daily marsh loss over a year in a southeastern Louisiana salt marsh using time-lapse photography for both an uneven edged site and an even edged site. The land loss seems almost inconceivable when viewed in real time: https://www.youtube.com/watch?v=bEumDAFWnqw. The uneven edged shoreline, which had a micro-bay surrounded by two micro-headlands, had more than twice the land loss of a shoreline with an even edge (50% vs. 21% of the initial study area, respectively). The rate of shoreline erosion was 162% of the bay average (1.63 m y⁻¹) at the uneven site (2.65 m y⁻¹), and 44% of the bay average at the even site (0.72 m y⁻¹). The monthly distribution of the erosion width was inversely related to the seasonal belowground plant biomass. The erosion rate for individual daily events over a year allows for a more accurate understanding of the impacts of disturbances by discrete sudden as well as baseline events. The documentation of increased land loss at the site with a micro-bay, used as an example for the indentations caused by a physical disturbance to the marsh edge, lends support to the idea of a cascading legacy effect of erosion from disturbances.
5.1.4 Fourth chapter summary

Question 3: How long have the erosional impacts from the DWH oil spill persisted, and, did the DWH oil spill weaken marsh resilience to natural disturbances?

The ability of an ecosystem to absorb the effects of a disturbance is directly and indirectly linked to its resiliency. Humans have eroded the resiliency of the Louisiana coastal marshes for centuries through pollution, canals, levees, and impoundments, resulting in extraordinarily high loss rates. The potential for a large disturbance to cause significant additional loss to Louisiana’s coastal marshes is, therefore, even more likely than in a system with uncompromised resiliency. The DWH oil spill was the largest marine oil spill in history and oiled nearly 2,000 km of shoreline along the northern edge of the Gulf of Mexico. The spill not only immediately resulted in land loss in the form of marsh grass die-off, but decreased the capacity of the ecosystem to absorb the effects of a natural disturbance (e.g., hurricane). The data this is based on is from studies on marsh erosion after the oil spill collected at varying spatial and temporal scales. Marsh loss accelerated after the oil spill for at least 1.5 years at all spatial scales. The edge loss was greater in the two years following the oil spill than it was in the two years after the 2005 hurricane season. The edge damage caused by the synergistic effects of the DWH oil spill and Hurricane Isaac was greater than any hurricane since at least 1998. The spilled oil on the marsh had the effect of depleting marsh resiliency, to make it more susceptible to erosion precipitated by natural disturbances, and leaving a land loss legacy much greater than the initial direct impacts.
5.2 Synthesis

Disturbances and perturbations in ecosystems offer an opportunity for renewal and increased resiliency (Holling 1973); hurricanes, for example, bring mineral accretion to a marsh (Tweel & Turner 2012; Bianchette et al. 2016), floods provide a pulse of freshwater and nutrients to estuaries (Viosca Jr. 1927; Junk et al. 1989), and fires increase the diversity and abundance of species in forests (Webster & Halpern 2010). Estuaries, in particular, are regarded as well adapted to natural stressors because, for example, of the frequent regular and irregular salinity and water height changes (Elliott & Quintino 2007). Although salt marshes are resilient and dynamic ecosystems in many ways, there is also evidence that anthropogenic stressors may increase the salt marsh’s vulnerability to future disturbances (Gedan et al. 2011).

Human behavior has driven changes in natural disturbance regimes and weakened the ecosystems’ resiliency to natural stressors (Gunderson 2000; Folke et al. 2004). Regime shifts are not usually brought on by one disturbance, but by multiple disturbances that weaken the resiliency of a system (Paine et al. 1998; Biggs et al. 2009). The Dust Bowl of the early twentieth century, for example, was largely a human-induced catastrophe stemming from poor soil management practices that exacerbated drought conditions, and led to a regime shift in the US midwest (Cook et al. 2009). Kelp forests and coral reefs have undergone regime shifts precipitated by anthropogenic stressors that result in the ecosystem’s decreasing ability to renew and adapt after natural disturbances (Jackson et al. 2001). Anthropogenic changes (e.g., canals, levees, agricultural impoundments) have acted to deplete the resiliency of Louisiana’s coastal wetlands for centuries. The DWH oil spill had the potential to further reduce the resiliency of the wetlands, perhaps precipitating a “regime shift” where natural disturbances that used to be subsidy to the system are now a stress, causing a salt marsh to convert to open water.
I studied the impacts the DWH oil spill could have on salt marsh erosion both directly and indirectly on multiple spatial and temporal scales (Figure 5.1). Initially, soil strength was weaker in the 60-100 cm layer of soil in the high oil sites, overhang was greater in the high oil sites, and there was an acceleration of erosion rates at the low oil sites until about 1.5 years after the oil spill. This acceleration could potentially be caused by cascading erosion along the shoreline edge as the shoreline attempted to reach an “equilibrium of form.” When micro-bays are formed after a section of the marsh edge erodes, the micro-headlands left behind will erode at an accelerated rate, increasing erosion rates not only in the initial disturbances area, but in those areas surrounding it.

![Figure 5.1. Varying scales used to measure the direct and indirect effects of the DWH oil spill on salt marsh erosion rates in Bay Batiste, LA.](image)

I used time-lapse cameras to document this accelerated erosion in real time at one site (uneven site) and compared the measured daily erosion to a marsh edge with no micro-bays or micro-headlands (even site). The uneven site eroded over 100% faster than the even site over one
year. The micro-headlands eroded in episodic erosion events, potentially driven by seasonal changes in soil strength and wave energy. The photographs provide qualitative documentation of cascading erosion and the indirect effects a disturbance may cause, although they compared only two sites and therefore cannot be used to quantitatively infer the dynamics at other similar sites.

The formation of a micro-bay led an increased land loss compared to a location without a micro-bay, and also to an increased variance in erosion rates within a small (3 m) localized area of the shoreline. The increased variance has been suggested as a means to test for an impending regime shift (Biggs et al. 2009; Brock & Carpenter 2012). Potentially, the increased variance of erosion along the same shoreline is an indicator of a past disturbance that caused a “regime shift.” A decreased resiliency to natural disturbances, creating a cascading erosional effect, converted a salt marsh ecosystem to an open water system. Documentation of erosion on such a short time step (hourly) helped inform how the DWH oil spill produced a land loss legacy along one shoreline, indirectly affecting areas that were not directly impacted by the oil. Studying smaller time and spatial scales may be a way to detect whether the resiliency of a system is eroding and if it is vulnerable to a regime shift.

The land loss rate derived from the GIS analysis over 15 years produced two interesting results supporting the idea of weakened resiliency of the salt marsh after DWH: 1) The marsh loss rate of the 15 years studied along the northern edge of Bay Batiste was the highest (50% more than the 15 year average, and 12% more than the time period after Hurricane Katrina) in the time period that encompassed the DWH oil spill and Hurricane Isaac (2010-2012), and, 2) The extent of micro-bay formations was the greatest in 2013 compared to any year since 1998, suggesting that the DWH oil spill increased the impact of Hurricane Isaac by re-oiling the marsh, setting in motion a second cascading erosion scenario. The erosion rate from the 30 field sites
over a smaller temporal (5 years vs. 15 years) and spatial (m vs. km) scale, after the DWH oil spill has been consistently increasing in Bay Batiste as the overall basin, and the coastwide wetland loss rates have been decreasing or stabilizing in recent years (Couvillion et al. 2011). The DWH oil spill, therefore, may have set in motion an increase in the erosion rates that is persisting for at least 5 years.

The DWH oil spill directly increased edge erosion along a Louisiana salt marsh shoreline for at least 2 years. The indirect erosion effects persisted for at least 3 years from a cascading erosional effect caused by micro-bay formation and the weakened soil strength after the initial oiling and subsequent re-oilings. The legacy effects of the DWH spill decreased the resiliency of the marsh and its ability to withstand natural disturbances, because the land loss rates after the DWH spill and Hurricane Isaac were the highest over the prior 15 years, including being higher than after the hurricane seasons of 2004 and 2005. In this coastal system, a regime shift could potentially refer to two different concepts: 1) The salt marsh ecosystem converted to open water after a disturbance (the oil spill and hurricane). There is almost no chance for the open water ecosystem to convert back to the salt marsh and 2) The erosion rate increased after the oil spill and continues to increase at the field sites. If this rate does not return to the pre-oil spill rate, a regime shift in erosion rates may have occurred. If, however, the rate declines back to the pre-spill rate, the erosion along the shoreline could be seen as recovered.

The Louisiana coast has relative sea level rise rates more than three times the current global sea level rise rate (10 mm vs. 3 mm). The relatively faster sea level rise rates, coupled with the anthropogenic modifications that have already decreased the resiliency of the Louisiana marsh, makes the Louisiana salt marsh system a sentinel ecosystem representing the future of other coastal wetlands. While other areas of marsh may not currently have the multitude of
stressors of Louisiana, the quickening rates of sea level rise could place many more salt marshes in danger of increased impact from disturbances that were absorbed in another time. By studying how the Louisiana marsh responds to multiple disturbances, we may be able to predict, manage, or even avoid similar synergistic effects in other estuarine ecosystems.

5.3 Project Implications

This study has led to a deeper understanding of disturbances, resiliency, and vulnerability in coastal ecosystems after multiple disturbances. Chronicling salt marsh land loss trends after the DWH oil spill on differing temporal and spatial scales has shown that human actions can erode the resiliency of an ecosystem, leaving it more susceptible to detrimental effects of a natural disturbance. The legacy effects of a disturbance can last for longer than anticipated in ecosystems with eroded resiliency. Disturbances must be studied on the proper temporal and spatial scale to ensure that the indirect effects are attributed to the disturbance. Successful coastal management depends on knowledge of the resiliency (and factors which can erode this resiliency) and the adaptability of these systems.

5.4 References


APPENDIX A. OPEN ACCESS EVIDENCE

CHAPTER 2
Environmental Research Letters

LETTER • OPEN ACCESS

Effects of oil on the rate and trajectory of Louisiana marsh shoreline erosion

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