THE RECOVERY OF THE COASTAL ECOSYSTEM OF SOUTHERN JEFFERSON COUNTY, TEXAS FROM THE STORM SURGE OF HURRICANE IKE

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Hurricane Ike made landfall on the upper Texas Gulf coast on 13 September 2008 as a category 2 hurricane on the Saffir-Simpson scale and was the fourth most destructive storm to effect the United States (Berg, 2009). The storm tide surge in southern Jefferson County in the neighborhood of Sabine Pass was 4.3 m. Water depths of at least 3.3 m occurred all the way to the intercoastal ship channel and in some areas beyond (Berg, 2009). The surge severely damaged coastal communities and caused high human and livestock mortality. The vegetation and much wildlife did not survive due to the flooding and the salinization of the soil in the surge area (Hurricane Ike Impact Report, 2008). The rate of recovery of the animal and plant communities in the surge zone is an important component of the management of coastal ecosystems and the recovery of local communities (Day et al., 2007).

The recovery rate of coastal marshes depends in part on the change in salinity and how long the marshes were inundated by the storm surge. The mashes in southern Jefferson County are concave, “bowl”, in shape and do not normally drain as fast as tidal fringe marshes (Hurricane Ike Impact Report, 2008). Recovery rates of marshes are relatively rapid when the salinity change resulting from the surge is low and the inundation is short term. Recovery rates are much slower when the salinity change is high and inundation is prolonged (Chabreck & Palmisano, 1973). Therefore southern Jefferson County may suffer from long term impacts from Hurricane Ike (Hurricane Ike Impact Report, 2008).

The objective of this study was a post-storm analysis of the impact of the tidal storm surge on the marsh communities in southern Jefferson County. We examined the recovery of microbial, plant, amphibian, reptilian, mammalian, and avian communities, on a longitudinal gradients from J.D. Murphree Wildlife Management Area (WMA) and McFaddin and Texas Point National Wildlife Refuges (NWR) along the coast. Our specific objectives were to: 1. to examine which species of microbe, plant, amphibian, reptile, bird, and mammal survived the storm surge and their population sizes, 2. determine if new or invasive species have become established, 3. determine if any invasive species previously present have been eradicated by the storm surge, 4. examine the rate at which the aforementioned groups of species re-invade and their recovery rates in the inundated habitats, 5. examine soil chemistry and salinity effects on the microbial community , and soil-micro-plant interactions, 6. examine changes in species diversity, richness, and composition on the plots along the longitudinal gradients.

The McFaddin, Texas Point NWRs, J.D Murfee WMA are located on the upper Gulf Coast in southern Jefferson county, Texas . Both McFaddin andTexas Point NWRs, are adjacent to the Gulf of Mexico. While the southern edge of J.D Murfee WMA is about 9 km inland and lies on either side of the ship channel.

McFaddin NWR was established in 1980 and is 58,861 acres. The refuge contains a variety of habitats but the majority is intermediate coastal marsh (37,468 acres, 67%). It also contains the largest remaining fresh marsh in Texas (5,356 acres, 9.6%) and significant acreage of Brackish marsh (3,294 acres, 5.9%). The terrestrial habitat is primarily salty prairie (3,817 acres, 6.8). McFaddin also contains several areas of open water; inland open water (646 acres, 1.2%), intermediate natural lakes (712 acres, 1.3%), and brackish natural lakes (1,479 acres, 2.6%).

The Texas Point NWR was established in 1979 and is 8,968 acres. The majority of the refuge is saline marsh (4,865 acres, 54.2%) but there are areas of intermediate marsh (1,362 acres, 15.2%) and brackish marsh (2,300, 25.6%). The terrestrial habitats include non-saline prairie (232 acres, 2.6%) and salty prairie (209 acres, 2.3,%).

The J. D. Murphree WMA is 24,250 acres. It consists of fresh, intermediate, and brackish marsh. There are three distinct units: the Big Hill Unit (8,312 acres), the Hillebrandt Unit (591 acres), and the Lost Lake Unit (4,074 acres). J. D. Murphree WMA is north of the Gulf of Mexico and a portion of the Big Hill unit was above the maximal storm surge for Hurricane Ike.

Task 1: Survey of the survival and recovery of the amphibian and reptile populations.

Introduction

The growing concerns over the loss of amphibian and reptile species world wide has initiated studies on the factors that are effecting their decline (Arau´jo et al., 2006; Gibbon et al., 2000). There are many factors that are effecting heterological communities such as human population growth, habitat loss, introductions of evasive non-native species, and natural disturbances (Arau´jo et al. 2006 ; Dodd et al., 2007; Gibbon et al., 2000). In recent years there has been increasing interest in how stochastic disturbances such as hurricanes effect the ecology of heterological species (Dodd and Dreslik, 2008).

Habitat disturbances resulting from hurricanes may cause significant effects on surviving heterological communities but no clear pattern has emerged (Reagan, 1991; Woolbright, 1996; Greenberg, 2001; Vilella and Fogarty, 2005). The kind and magnitude of the effects of hurricanes can depend upon the timing of the event (Schoener et al., 2004), the locality (Schoener et al., 2004), the kind and degree of the damage (Vilella and Fogarty, 2005; Reagan, 1991), the particular species and its life history (Dodd and Dreslik, 2008; Reagan 1991; Schoener et al., 2004; Woolbright 1991). In some cases hurricanes drastically effect species and communities and in others there are no apparent effects. The habitat disturbance caused by hurricanes is known to effect movement patterns (Dodd et al., 2006; Wunderle et al., 2004), survivorship (Woolbright, 1991; Reagan, 1991; Vilella and Fogarty, 2005), habitat usage (Reagan 1991; Wunderle et al., 2004), growth rates (Dodd and Dreslik, 2008), and species abundance (Vilella and Fogarty, 2005; Greenberg, 2001; Reagan, 1991; Schriever et al., 2009; Woolbright, 1991), diversity, and evenness (Vilella and Fogarty, 2005; Schriever et al., 2009).

Study Site Description

Three study sites were established to sample amphibian and reptile populations on each of two longitudinal gradients (Figure 1.1, Table 1.1). The first gradient was from the Big Hill spoil pile on J.D. Murphree Wildlife Management Area (WMA) to Texas Point National Wildlife Refuge (NWR). The second gradient was from the boundary of McFaddin NWR and the La Belle Ranch to McFaddin beach on McFaddin NWR. There was at least 6.5 km between study sites on each of the gradients. Three trapping arrays were established within each study site. The trapping arrays within a study site were at least 200 m apart. All of these study sites except Big Hill spoil pile were under at least 3 m of water during the Hurricane Ike storm surge.

Study site A1 was located on the “spoil pile” in the Big Hill Unit of the J.D. Murphree WMA. This study site was located about 21.76 km from the Gulf of Mexico. The “spoil pile” is a levee that is between 4.88 and 5.49 m above sea level, which was above the level of the storm surge in that area. However the majority of surrounding mash is 0.61 to 0.91 m above sea level and was inundated. Two of the trap sites at this location were at the base of the levee and the third was on top of the levee. The habitat surrounding the study site was fresh marsh.

Study site A2 was on a levee adjacent to Lost Lake in the Lost Lake Unit of the J.D. Murphree WMA. This study site was located about 11.74 km from the Gulf of Mexico. The area surrounding Lost Lake is approximately 1.83 m above sea level and was inundated by the Hurricane Ike storm surge. Two of the trapping sites were located on the levee adjacent to Lost Lake. The third trapping site was located on a low levee that entered the marsh adjacent to Lost Lake. This trapping site had to be abandoned when a mud slurry was dumped into the marsh as part of the Texas Parks and Wildlife Department's marsh restoration project. The area surrounding the study site was brackish marsh.

Study site A3 was located in Texas Point NWR. The area surrounding the traps was 0.91 to 1.22 m above sea level and was inundated by the Hurricane Ike storm surge. This study site was located about 1.70 km from the Gulf of Mexico. One trapping site was located in the salty prairie habitat, the second on a levee extending into the salty marsh habitat, and the third on a levee between the brackish and saline marsh habitats.

Study site B1 was located on the levee that forms the boundary between Mc Faddin NWR and the La Belle Ranch. This study site was located about 12.30 km from the Gulf of Mexico. The marsh surrounding the levee is between 0.91 to 1.52 m above sea level and was inundated by the Hurricane Ike storm surge. All three trapping sites were located on the levee and the surrounding habitat to the north of the levee was fresh marsh and the habitat to the south of the levee was brackish marsh.

Study site B2 was located near the ship channel on Mc Faddin NWR. This study site was located about 6.25 km from the Gulf of Mexico. The area surrounding the traps was about 1.52 m feet above sea level and was inundated by the Hurricane Ike storm surge. All tree trapping sites were located on levees and the surrounding habitat was Intermediate Marsh.

Study site B3 was located within sight of the beach (about 300 m) on Mc Faddin NWR. The area surrounding the traps was about 1.52 m above sea level and was inundated by the Hurricane Ike storm surge. All three trapping sites were in salty prairie habitat.

Weather

Weather conditions during the trapping period were obtained from the Beaumont Port Arthur weather station. The relationship between amphibian and reptile activity and weather conditions were evaluated with Spearman rank correlations.

Reptile and Amphibian Sampling Procedures

The terrestrial amphibians and reptiles were sampled with three funnel-box trap arrays at each of the six study sites (Lewis et al., 2000). A trap consisted of a central funnel trap (122 cm X 122 cm x 61 cm) and two peripheral traps (61 cm X 122 cm x 61 cm). The traps were constructed of exterior plywood and 0.634 cm hardware cloth. Hardware cloth funnels (20 cm diameter) were placed at ground level in the center of each side of the central trap and one end of the peripheral traps. Two 15 meter black erosion cloth drift fences 91 cm high were placed $180^{O}$from the central trap. Peripheral trap were placed at the end of each drift fence. The drift fences abutted the central and peripheral traps in the center of the funnels. Plywood shelters (25 cm x 25 cm) were placed in the traps to provide a place for animals to hide. The presence of turtles and other reptiles (such as alligators), that did not readily enter the box terrestrial box traps, were noted in the field book. We set the box traps and drift fences up along levees and were able to capture the semi aquatic turtles. The problem with the aquatic traps was that the crabs got in and ate whatever was trapped. So we stopped setting those traps after the first month.

Amphibians and reptiles were sampled one week each month from February through November. Traps were checked every other day. Upon capture, all specimens were counted, identified, and released. We did not sample reptiles and amphibians during January or December. Reptiles and amphibians are ectotherms and are not active during the colder months. Snakes were individually tagged using PIT tags. We toe clipped the lizards that were caught in the traps. When we realized how few lizards we were capturing in the traps we recorded every lizard seen near the traps. The majority of these lizards were ground skinks that are able to move through the trap mesh. No we did not toe clip the frogs because they were so rarely captured in the traps.

The major weakness of the research in this study is that we do not have accurate quantitative data on what species were present and their densities prior to the storm surge from Hurricane Ike. Therefore, we can not make any quantitative before or after comparisons. However, we can estimate the potential species pool from museum records of amphibians and reptiles previously collected in Jefferson County. We examined the country record maps for all species of amphibians and reptiles recorded in Texas published on the Texas Memorial Museum's web site Herps of Texas, www.zo.utexas.edu/research/txherps. Using the web site and the county maps we compiled a potential species list of amphibians and reptiles for Jefferson county Texas. We then examined the species habitat descriptions and classified them into categorizes based on our consensus of their probability of occurrence. Those categories are;

Very Low - The species is, in all probability, not present because southern Jefferson county lacks the appropriate habitat or because the species is either very rare or extirpated from Jefferson county.

Low - The species might conceivably be present if the appropriate habitat exits. For many of these species the Big Hill is the only area that might have the appropriate habitat.

Moderate -There is appropriate habitat for the species in localized areas like Big Hill or the wooded areas near Lost Lake and on the La Belle Ranch.

High - These species are often encountered elsewhere in marsh habitats and probably occurred in southern Jefferson country prior to Hurricane Ike.

Known -These species had been observed by the authors, TPW or UFWL personal in southern Jefferson county prior to Hurricane Ike.

Found - These species were encountered in southern Jefferson county after Hurricane Ike.

The analysis presented in the results uses species that are categorized as: moderate, high, known, and found.

Deliverables

1. Knowledge of which species survived the storm surge.

Six species of terrestrial amphibians and 15 species of reptiles are currently to be found in southern Jefferson county, Table 1.2, Figure 1.2. There were six species of anurans, the American alligator, three species of turtles, two species of lizard, and nine species of snakes. When data from the two transects are combined, there was a significant positive relationship between the number of species and number of individuals and distance the study site was from the coast, $R_S = 0.94$, $P = 0.017$, Figure 1.3. The number of taxa also tended to decline towards the coast, with anurans and lizards being the most rare, $R_S = 0.83$, $P = 0.058$.

The majority of these species (N = 18) were either collected or observed at study site A1 at the Big Hill spoil pile on the Big Hill Unit of J.D. Murphree WMA, Table 1.3. All six species of anurans were known from this site. There were two species of turtle, the American alligator, two species of lizard, and seven species of snake. The three species encountered at other study sites but not observed at Big Hill were extremely rare. These rare species were captured a single time at a single study site during the entire year of sampling. The elevation of the spoil pile was above the storm surge from Hurricane Ike and probably acted as a refuge for these species. In the future, it may act as the origin for the re-invasion of the areas closer to the coast for species that did not survive the storm surge.

The study site with the second highest species diversity was study site B1 on the border of Mc Faddin NWR and the La Belle Ranch, Table 1.3. This study site also the furthest north on the B transect and therefore closer to the northern limit of the storm surge. Eleven species were found at study site B1. There were three species of anuran, two species of turtle, the American alligator, zero species of lizard, and five species of snake.

Study sites A2 and A3 had a similar number of species, seven and six respectively, Table 1.3. Study site A2 had no anurans, the American alligator, one species of turtle, one species of lizard, and four species of snakes. Study site A3 had one species of anuran, the American alligator, one species of turtle, one species of lizard, and two species of snakes. However, 21 individuals were captured in the box traps at A3 while only five individuals were captured at A2. This difference in the number of individuals captured was due to the high capture rated for speckled king snakes, gulf coast toads, and cotton mouths at A3.

Study sites B2 and B3 had very little to no species diversity, respectively, Table 1.3. Only four species were observed at B2. Only four individuals of two species were captured in the box traps and then only in the fall. The study site yielded only one species of anuran, the American alligator, one species of turtle, and one snake. No species of amphibian or reptile was encountered at study site B3. Study site B3 was within 300 m of McFaddin beach.

Alligators had previously been reported from all of the wetland habitats on the three refuges. After Hurricane Ike we observed alligators on or near all of our study sites except B3. Study site B3 is located next to the beach and adjacent to Wiseman Lake. Presumably alligators frequented this lake prior to Hurricane Ike. But, the storm surge from Hurricane Ike deposited so much sediment into the lake that is now dry for much of the year. We found water in the lake from January through April. Other than Wiseman Lake there is currently not any standing water or wetlands in the immediate vicinity. Therefore alligators are absent as well any of the semi-aquatic or aquatic snakes like cotton mouths and other water snakes.

The monthly activity patterns of amphibians and reptiles in southern Jefferson county exhibited the typical yearly patterns, Table 1.4 and Figure 1.4. The number of species and individuals trapped increased in the spring as the weather warmed and then declined to their lowest level in August, increased in September and then declined thereafter. The largest number of species were captured in April, June, and September, with the most captured in September, Table 1.4. The highest number of individuals was captured in September and was slightly over twice that in the next highest month of March, Table 1.4. The significant increase in both the number of species and individuals captured in September occurred as the weather cooled and the summer's crop of juveniles were added to the community. Activity then declined in October and November until the cold weather drove them to inactivity.

Twenty four species of amphibians and 48 species of reptiles are historically known from Jefferson county, Texas, Table 1.5, www.zo.utexas.edu/research/txherps/. Of these species, 31 species probably were not found in Southern Jefferson county prior to Hurricane Ike. These species normally inhabit forests or upland habitats and would not be found in marshes or along the coast or have been locally extirpated. The remaining 41 species are likely to have been found prior to Hurricane Ike. Of these species 12 are amphibians and 29 are reptiles. These reptile and amphibian species are probably the effective species pool for the marshes and coastline of southern Jefferson county. The percent saturation of herptiles for southern Jefferson county ranges from a high of 60% for anurans to a low of 33 % for lizards, with turtles and snakes being intermediate, Table 1.6. The data indicate that the herpetological community of southern Jefferson county is far from saturated.

The percent saturation for individual groups provides more detailed information about the distributional patterns of the various taxa of herptiles in southern Jefferson county, Figure 1.5. Anurans and snakes show clear patterns whereas, turtles and lizards do not. The percent saturation of anurans declines towards the coast. Study sites A1 and B1 have the highest saturation and saturation drops thereafter, with the two other sites with anurans only having the gulf coast toad. Sites A1 and B1 are in fresh marsh. Anurans would be able to reinvade that habitat quickly once the salt was flushed form the marsh. The sites in the brackish marsh only have the gulf coast toad, a species with higher salt tolerances.

The percent saturation of snakes also shows a clear decline towards the coast with the highest saturation at A1 on Big Hill and the lowest at B3, Figure 1.5. If assumes (see below) that all of the species occurring on Big Hill at present also occurred at the other sites prior to Hurricane Ike one might conclude that given time, these snakes will move towards the coast.

The apparent pattern of the turtles declining towards the coast must be interpreted with caution, Figure 1.5. These turtles are semi aquatic to aquatic and our sampling methods were not designed to capture turtles. Therefore these species may be present at more sites toward the coast, as well as other species that were not captured or observed.

There is no distance pattern for the percent saturation of lizard species, Figure 1.5. The pattern that exists is one that can be attributed to the study site transect. Study sites on transect A had lizards. Study sites on transect B lacked lizards. Only two of the six possible lizard species are present. Lizards are primarily terrestrial, and while they can swim, they probably do not readily cross large areas of marsh as in transect B. Transect A has many interconnected areas of levees, forests and grasslands that might serve as reinvasion routes. These areas also have numerous buildings, trees, and other structures that lizards may have been able to retreat to during the surge and survive the inundation.

An assumption being made in the foregoing analysis of percent saturation of the various taxa is that all of the species in the species pool could and did occur at all of study sites in southern Jefferson county. This is probably not the case. For example there are very few place on the B transect that would be suitable habitat for lizards. There are a few islands on the La Belle

Ranch and a forested area at the end of the levee at B1 that may have lizards but, the two lizard species that were recorded probably did not occur across the ship channel at B2 or B3. These two study sites did have lizards before the storm but they were the glass lizard and the six-lined race runner. Both of these species did occur at B3, personal observation. Therefore the numbers for percent saturation are probably smaller that they would be if we had accurate "before" data on the herptile community in southern Jefferson county.

2. Knowledge of the recovery of the populations of each species.

It is difficult to evaluate the recovery of animal populations based upon one year's worth of data. Many species that have been encountered are rare and there are probably others equally as rare that are present but simply have not been encountered. These species would be discovered in the course of a longer term study. A year is also too short a time for many of the species present to move towards the coast and re-invade those habitats. Additionally, re-invasion of habitats by species with long generation times like the reptiles involved or the salt intolerant amphibians is a slow process.

One method of evaluating the recovery of the populations is examining cumulative gain curves. A cumulative gain curve plots the cumulative number of species captured over time. When sampling begins in a new study, the rate of encounter with new species is high and the slope of the curve is steep. As the study progresses fewer new species are encountered and the slope declines and the gain curve begins to level off. The curve reaches an asymptote and levels off when all the species in the region have been encountered.

A cumulative gain curve can be constructed for the species pool in southern Jefferson county by combining all of the data for all of the sites and plotting the cumulative number of species captured in the traps over the nine months of the study, Figure 1.6. As can be seen, the cumulative number of species rises through out the study . The curve begins to level off after September but the lack in gain of new species is probably do to the deceased activity exhibited by reptiles and amphibians with the cooler months of October and November. The line labeled "All sites" then represents a minimal estimate of the known species pool of amphibians and reptiles currently available for re-colonization in southern Jefferson county. The gain curve of study site A1 is slightly below the gain curve for all sites indicating that almost all of the species encountered during the study occurred a this study sites. It also suggests that A1 was a refuge from the storm surge and that most species present in southern Jefferson county are present at study site A1 on Big Hill.

The cumulative gain curves for the other five low diversity study sites are well below those of "All sites" and A1. The gain curve for site B1 is similar to those of the other low diversity sites in that it has a relatively shallow slope for most of the year until the fall, where it rapidly increases. This may indicate the beginning of re- colonization of this area. Study sites A2, A3, and B2 all exhibit very shallow slopes with diversity well below that of sites A1 and B1. These sites also exhibit a slight increase in slope in the fall, again suggesting the beginning of re-colonization by particular species. However, the shallow slopes and low diversity both indicate that these sites are a long way from recovering their herpetological species diversity.

Effect of weather

There was no relationship between amphibian and reptile diversity or numbers and any temperature or precipitation variable analyzed, Table 1.7.

Conclusions from Task 1

The storm surge from Hurricane Ike had a devastating effect on the herpetological community of southern Jefferson county. Only 21 species of the potentially 41 species that might have once occurred have been captured or observed two years after the storm. A similar number of species were encountered after Hurricanes Katrina and Rita in coastal habitats in southeastern Louisiana (Schriever et al., 2009). The majority of the species that survived or have reinvaded (N = 18) occur at Big Hill in the Big Hill unit of J.D. Murphree Wildlife Management Area . Three of these species were first encountered at Big Hill in the fall. Drastically fewer species are found at other sites and the number of species declines precipitously towards the coast. The recovery of the populations near the coast has only just begun and is occurring very slowly. Of the sites nearer the coast, only B1 off of the La Belle Ranch is exhibiting an increased rate of recovery, with five new species added in the fall sampling. Three sites, A2, A3, and B2 have added between one and three species, while site B3 is still totally lacking a herptile fauna.

While the timing and the duration of a storm tide surge is of the first importance in determining if animals are able to survive and persist (Schoener, et al 2004), The greatest stress on animal populations may occur after the passage of the hurricane (Ackerman et al., 1991). Therefore, a storm surge of short duration, hours or a few days, has less of an impact than a surge whose waters persist for a period of a week or more. Aside from the initial damage and habitat destruction of the surge itself, a surge that can deposit saline water into low lying areas. The damage by the saline water left behind increases drastically with time. Therefore, the devastation to the herptile fauna is unusual and can probably be attributed to the geography of southern Jefferson county and the unprecedented length of the inundation. The marshes of southern Jefferson county are bowl shaped and retained the storm surge water for several weeks to a month.

One pattern that has emerged from this study is that the sites that were either on the edge of the “bowl”(Hurricane Ike Impact Report, 2008), above the storm surge, or had structure that could serve as refuges are being reinvaded faster than those that lacked these features. Study site A3 was on the edge of the “bowl” and had either buildings or other human structures or trees nearby which may have served as temporary refuges. Study site B1was near Gum and Hog islands on the La Belle Ranch and the trees on these islands may have served as temporary refuges. The open marsh habitats of A2, B2 and B3 did not have any structures that withstood the surge and were inundated for a longer period of time. This edge of the “bowl” effect is probably why more individuals survived at study sites A3 and B1 than at the sites within the “bowl”, sites A2, B2, B3.

An examination of aerial photographs taken by USGS on September 15, 2008, two days after the landfall (http://coastal.er.usgs.gov/hurricanes/ike/photo-comparisons/highisland.html) clearly show that large areas of Mcfaddin NWR near our sites B2 and B3 remained inundated, Figure 1.7. While, photographs taken on the same day of Texas Point NWR show that the storm surge had drained from large areas around our study site A3, Figure 1.8. Therefore individuals of some species that were able to survive the inundation by escaping to some structure above the surge or remained underground were probably able to persist. While those in at the sites that remained inundated probably perished.

One interesting case is the speckled king snakes encountered at site A3 on Texas Point NWR. This site is within 1.70 km of the Gulf of Mexico. But as discussed above, photographs of the area taken three days after the surge show large areas of Texas Point that were relatively free of water, Figure 1.8. The king snakes that we captured at Texas Point were adults and were undoubtably survivors of the surge. King snakes are fossorial and like all reptiles are ectothermic and have low metabolic rates. These snakes may have been able to survive the storm surge underground and due to the short inundation and their low metabolic rates were able to survive long enough for the habitat to recover.

If this is the case, then there are probably two sources for the current species pool in southern Jefferson county. The first source are those species that were able to survive the storm surge and subsequent inundation. These species may have been on the edges of the "bowl" that were not inundated for a long period or survived in isolated refuges or "lifeboats" (Sexton et al. 2007) like human structures or trees (Schoener et al. 2001; Sexton et al. 2007). The second source are species from areas that were not inundated by the storm surge (Waide, 1991). These species are reinvading by diffusion from those areas.

There is very little information on how storm tide surges effect animal communities (Schoener, et al 2004). This is due to several interacting factors. First the storm tide surges are stochastic events, making before and after comparisons difficult. Second, they are short term events, making their effects drastic over the short term but having very few long lasting effects on species diversity. In this case animals are able to retreat into local refugia and then quickly recolonize. Third, the focus of funding agencies is on the human recovery from the hurricane and less so on that of animal communities. Fortunately there is increasing national awareness of the importance of marsh ecosystems in the stability of shorelines and tidal marshes. Tidal marshes in particular are of the upmost importance in buffering human habitations from the effects of storm surges. So, there is more interest in the entire community of organisms that inhabit these marshes. For these reasons, there are no long term studies of the effects of storm tide surges on how these effect marsh animal communities (Michener et al., 1997).

The situation created by Hurricane Ike in the Northern Texas Gulf coast and in particular Southern Jefferson county, Texas, has presented the unique opportunity to study the long term effects of storm tide surges on animal communities. Hurricane Ike generated a storm tide surge that inundated all of southern Jefferson county Texas. The saline water from the surge persisted in some of those areas for over a month. The persistence was due to the bowl like nature of the marshes in this region. The length of the inundation probably had a drastic effect on the animal community. Our data indicate that at least a portion of the coast is still without a herpetile fauna two years after the event and the inland areas are recovering but slowly.

References Introduction and Task 1

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Table 1.1. Amphibian, reptile, and mammal trapping sites in southern Jefferson County.

Site	Location	North	West
A1-1	JD Murphree WMA, Spoil pile	29º 52' 25.2"	94º 03' 02.5"
A1-2	JD Murphree WMA, Spoil pile	29º 52' 09.87"	94º 02" 42.35"
A1-3	JD Murphree WMA, Spoil pile	29º 52' 14.49	94º 02' 42.48"
A2-1	JD Murphree WMA, Lost Lake	29º 47' 10.6"	93º 58' 27.9"
A2-2	JD Murphree WMA, Lost Lake	29º 47' 0.393"	93º 58' 26.12"
A2-3	JD Murphree WMA, Lost Lake	29º 46' 36.2"	93º 58' 29.1"
A3-1	Texas Point NWR	29º 41' 55.0"	93º 55' 03.4"
A3-2	Texas Point NWR	29º 42' 25.5"	93º 55' 13.9"
A3-3	Texas Point NWR	29º 43' 32.9"	93º 53' 09.5"
B1-1	McFaddin NWR, La Belle’s	29º 46' 24.1"	94º 05' 44.4"
B1-2	McFaddin NWR, La Belle’s	29º 46' 16.1"	94º 05' 46.5"
B1-3	McFaddin NWR, La Belle’s	29º 46' 08.0"	94º 05' 48.8"
B2-1	McFaddin NWR, Ship Channel	29^0 43' 2.7"	94º 07' 1.5"
B2-2	McFaddin NWR, Weather station	29º 42' 28.7"	94º 07' 10.7"
B2-3	McFaddin NWR, Hog Run	29º 42' 20.3"	94º 07' 213.5"
B3-1	McFaddin NWR, Maintenance barn	29º 40' 15.8"	94º 04' 25.8"
B3-2	McFaddin NWR, Maintenance barn	29º 40' 33.4"	94º 04' 33.4"
B3-3	McFaddin NWR, Wiseman Lake	29º 40' 0.15"	94º 04' 43.2"

Table 1.2. Species list of reptiles and amphibians captured or observed two years after the Hurricane Ike storm surge.

Species	Common name
Bufo valiceps	Gulf Coast toad
Bufo woodhousei	Woodhouse toad
Hyla cinerea	Green tree frog
Rana utricularia	Southern leopard frog
Rana catesbeiana	Bullfrog
Gastrophryne carolinensis	Eastern narrowmouth toad
Alligator mississippiensis	American alligator *
Kinosternon subrubrum	Mississippi mud turtle *
Sternotherus odoratus	Common musk turtle
Trachemy scripta	Red-eared slider *
Anolis carolinensis	Green anole
Scincella lateralis	Ground skink
Agkistrodon piscivorus	Cottonmouth
Farancia abacura	Mud snake *
Lampropeltis getula	Speckled kingsnake
Masticophis flagellum	Coachwhip
Nerodia cyclopion	Green water snake
Nerodia erythrogaster	Yellow belly water snake
Nerodia fasciata	Banded water snake
Regina rigida	Glossy crayfish snake
Thamnophis proximus	Western ribbon snake

* Species observed at the study sites but not captured in the box traps.

Table 1.3. The number of individuals of each species of amphibian and reptiles captured at the six study sites in Southern Jefferson county.

	Study site					
Species	A1	A2	A3	B1	B2	B3
Bufo valiceps	2		6	2	1	
Bufo woodhousei	3			2		
Hyla cinerea	5			1		
Rana catesbeiana	2					
Rana utricularia	1					
Gastrophryne carolinensis	obs					
Alligator mississippiensis	obs	obs	obs	obs	obs	
Kinosternon subrubrum				obs		
Sternotherus odoratus	1					
Trachemy scripta	obs	obs	obs	obs	obs	
Anolis carolinensis	4					
Scincella lateralis	14	2	1			
Agkistrodon piscivorus	15	1	5	13	3	
Farancia abacura		obs				
Lampropeltis getula	1		8	1		
Masticophis flagellum	1	1				
Nerodia cyclopion	1					
Nerodia erythrogaster				1		
Nerodia fasciata	4			2		
Regina rigida	2	1				
Thamnophis proximus	3			1		
Number of species	18	7	6	11	4	0
Number of individuals	58	5	21	23	4	0

Table 1.4. The monthly number of individuals of each species of amphibian and reptiles captured at the six study sites in Southern Jefferson county.

	Month								
Species	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Bufo valiceps	1						2	4	4
Bufo woodhousei							3	2	
Hyla cinerea		1		1	1				2
Rana catesbeiana				1	1				
Rana utricularia							1		
Gastrophryne carolinensis		Obs							
Alligator mississippiensis	0bs	0bs	0bs	0bs	0bs	0bs	0bs	0bs	0bs
Kinosternon subrubrum				1					
Sternotherus odoratus	1								
Trachemy scripta	0bs	0bs	0bs	0bs	0bs	0bs	0bs	0bs	0bs
Anolis carolinensis		2							2
Scincella lateralis	11	2					4		
Agkistrodon piscivorus		4	5	2	4		16	4	
Farancia abacura									
Lampropeltis getula		2	2	2	1	2			
Masticophis flagellum				1	1				
Nerodia cyclopion							1		
Nerodia erythrogaster								1	
Nerodia fasciata	3	1	1				1		
Regina rigida			1				2		
Thamnophis proximus				2			1	1	
Number of species	6	9	6	9	7	3	11	7	5
Number of individuals	16	12	9	10	8	2	31	12	8

Table 1. 5. The amphibians and reptiles historically known from Jefferson county Texas and their probably occurrence in southern Jefferson county.

Species	Common name	Probability
Amphiuma tridactylum	Three-toed Amphiuma	Known
Desmognathus auriculatus	Southern Dusky Salamander	Very Low
Eurycea quadridigitata	Dwarf Salamander	Very Low
Notophthalmus viridescens	Eastern Newt	Very Low
Siren intermedia nettingi	Eastern Lesser Siren	High
Ambystoma opacum	Marbled Salamander	Very Low
Ambystoma texanum	Smallmouth Salamander	Very Low
Bufo valliceps	Gulf Coast Toad	Found
Bufo woodhousii	Woodhouse's Toad	Found
Acris crepitans	Northern Cricket Frog	Moderate
Hyla versicolor	Gray tree frog	Very Low
Hyla cinerea	Green Treefrog	Found
Hyla squirella	Squirrel Treefrog	High
Pseudacris crucifer	Spring peeper	Low
Pseudacris streckeri	Strecker's Chorus frog	Low
Pseudacris triseriata	Western Chorus Frog	Low
Gastrophryne carolinensis	Eastern Narrowmouth Toad	Found
Scaphiopus hurterii	Hurter's Spadefoot	Low
Rana areolata	Crawfish Frog	Low
Rana catesbeiana	Bullfrog	Found
Rana clamitans	Bronze Frog	Low
Rana grylio	Pig Frog	Known
Rana palustris	Pickerel Frog	Moderate
Rana sphenocephala	Leopard Frog	Found
Alligator mississippiensis	American Alligator	Found
Ophisaurus attenuatus	Slender Glass Lizard	Known

Species	Common name	Probability
Hemidactylus turcicus	Mediterranean Gecko	Known
Sceloporus undulatus	Fence/Prairie Lizard	Low
Anolis carolinensis	Green Anole	Found
Eumeces fasciatus	Five-lined Skink	High
Eumeces laticeps	Broadhead Skink	Very Low
Scincella lateralis	Ground Skink	Found
Cnemidophorus sexlineatus	Six-lined Racerunner	Known
Chelydra serpentina	Common Snapping Turtle	Known
Macroclemys temminckii	Alligator Snapping Turtle	Low
Deirochelys reticularia	Chicken Turtle	Very Low
Malaclemys terrapin	Diamondback Terrapin	High
Pseudemys concinna	Eastern River Cooter	Known
Terrapene carolina	Eastern Box Turtle	Very Low
Terrapene ornata	Ornate Box Turtle	Very Low
Trachemys scripta	Slider	Found
Kinosternon subrubrum	Eastern Mud Turtle	Found
Sternotherus odoratus	Common Musk Turtle	Found
Apalone spinifera	Spiny Softshell	Very Low
Cemophora coccinea	Scarlet Snake	Very Low
Coluber constrictor	Eastern Racer	Low
Diadophis punctatus	Ringneck Snake	Very Low
Elaphe obsoleta	Texas Rat Snake	Moderate
Farancia abacura	Mud Snake	Found
Heterodon platyrhinos	Eastern Hognose Snake	Low
Lampropeltis calligaster	Prairie Kingsnake	High
Lampropeltis getula	Speckled Kingsnake	Found

Species	Common name	Probability
Lampropeltis triangulum	Louisiana Milk Snake	Low
Masticophis flagellum	Coachwhip Snake	Found
Nerodia clarkii	Gulf Salt Marsh Snake	High
Nerodia cyclopion	Mississippi Green Water Snake	Found
Nerodia erythrogaster	YelLow belly Water Snake	Found
Nerodia fasciata	Southern Water Snake	Found
Nerodia rhombifer	Diamondback Water Snake	High
Opheodrys aestivus	Rough Green Snake	Moderate
Regina grahamii	Graham's Crayfish Snake	Moderate
Regina rigida	Gulf Crayfish Snake	Found
Storeria dekayi	Brown Snake	High
Storeria occipitomaculata	Redbelly Snake	Very Low
Thamnophis proximus	Western Ribbon Snake	Found
Thamnophis sirtalis	Common Garter Snake	Very Low
Virginia striatula	Rough Earth Snake	Low
Micrurus tener	Texas Coral Snake	Very Low
Agkistrodon contortrix	Copperhead	Very Low
Agkistrodon piscivorus	Cottonmouth	Found
Crotalus horridus	Timber Rattlesnake	Very Low
Sistrurus miliarius	Pigmy Rattlesnake	Very Low

Table 1.6. The number of species of amphibians and reptiles that probably occurred prior to Hurricane Ike and the number found after Ike. The percent saturation is the number of species found divided by the number of species thought to be present prior to the storm.

Taxon *	Pre-Ike	Post-Ike	Percent saturation
Anurans	10	6	60
Turtles	6	3	50
Lizards	6	2	33
Snakes	16	9	56

* We did not set traps designed to collect the aquatic salamanders or turtles. We have no information about the recovery of these species. Nor did we include the single crocodilian species, the American alligator in the table.

Figure 1.1. Locations of the study sites for amphibians, reptiles and mammals in southern Jefferson county after the storm surge from Hurricane Ike.

Figure 1.2. The number of species and individuals encountered or caught at six study sites in southern Jefferson county, Texas in 2010.

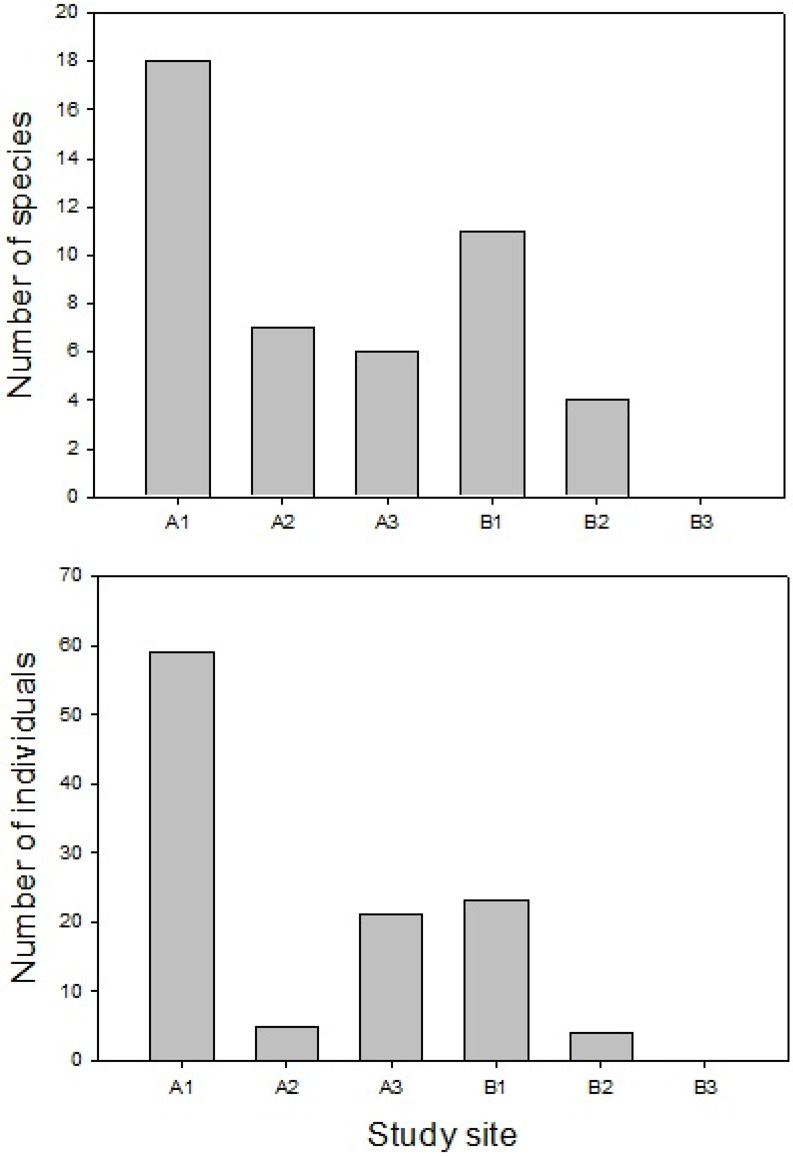

Figure 1.3. The relationship between the distance from the coast of the Gulf of Mexico and the number of species and individuals of amphibians and reptiles caught in southern Jefferson county Texas, in 2010.

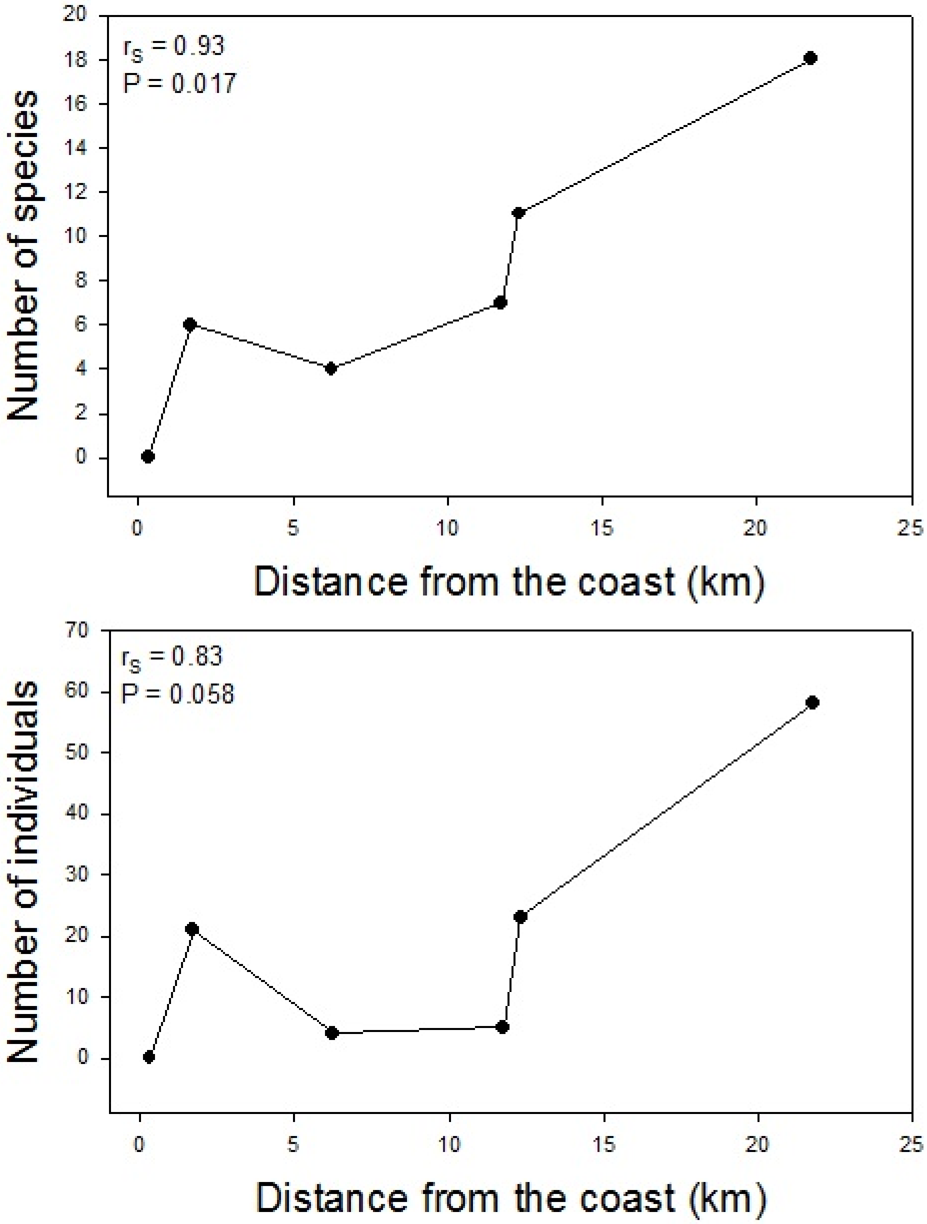

Figure 1.4. The number of species and individuals caught monthly in souther Jefferson county Texas in 2010.

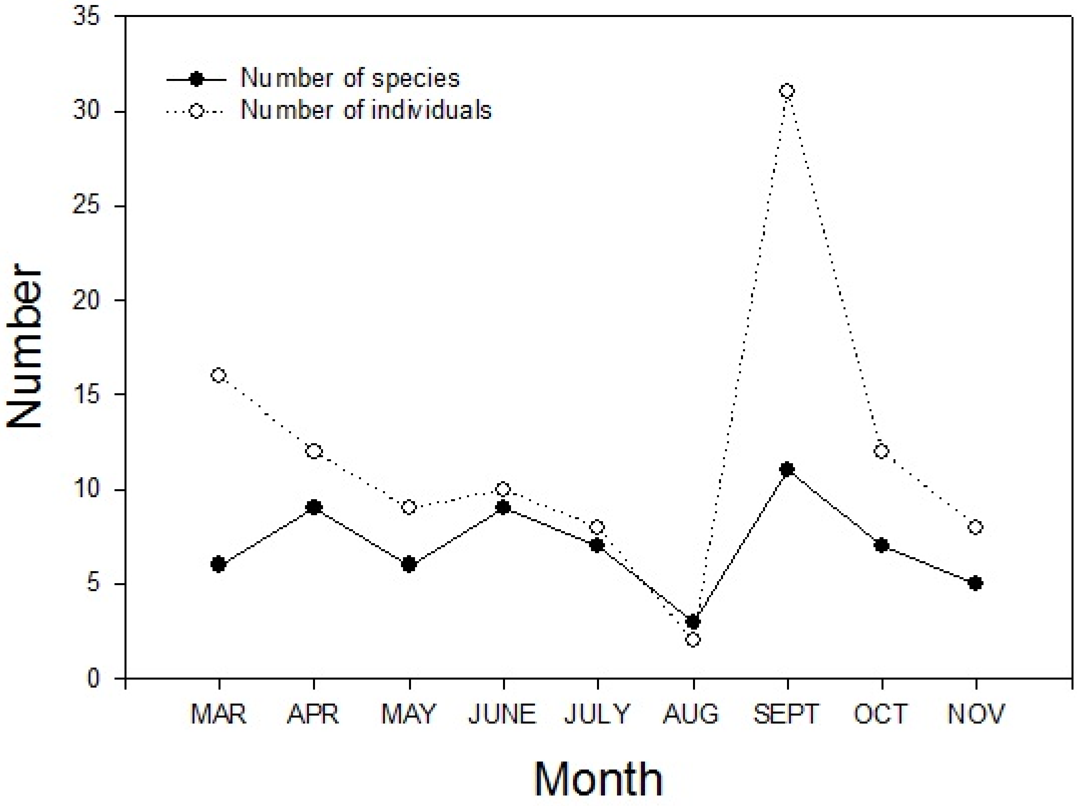

Figure 1.5 The percent saturation of the reptile and amphibian community in southern Jefferson county Texas in 2010.

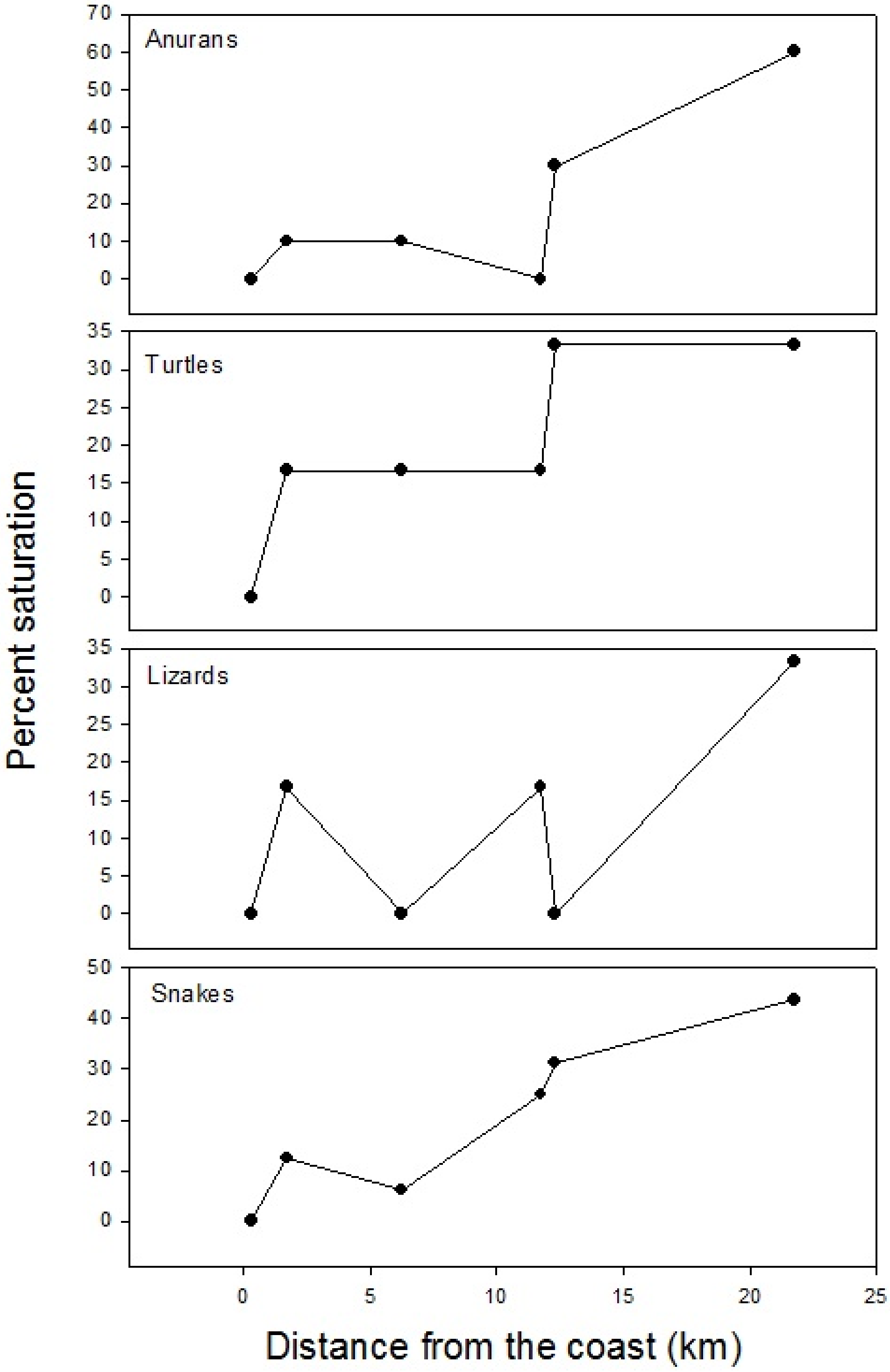

Figure 1.6 The cumulative frequency distributions of the number of reptiles and amphibians captured and observed in southern Jefferson county Texas in 2010.

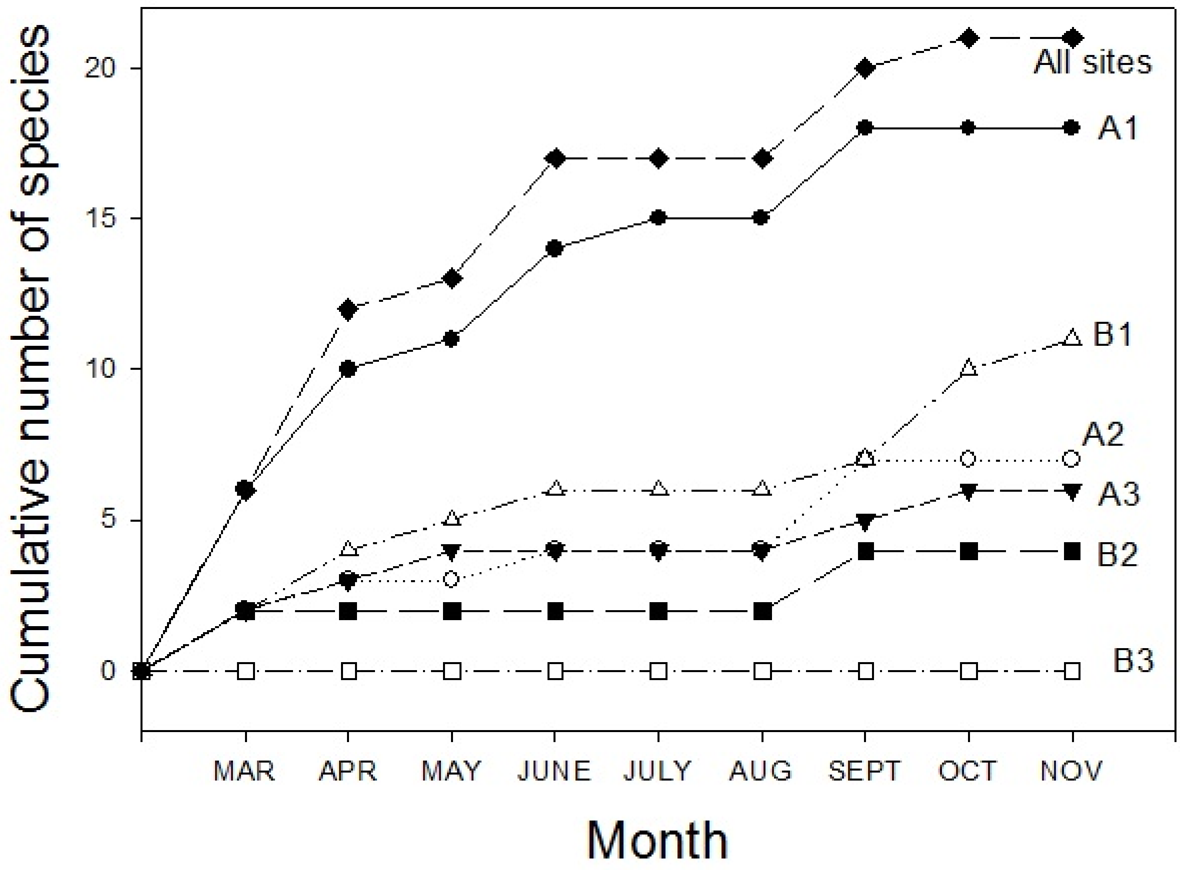

Figure 1.6. “Oblique aerial photography near McFaddin Wildlife Refuge, TX, on September 9, 2008 (top) and September 15, 2008, two days after landfall of Hurricane Ike (bottom). Yellow arrows mark features that appear in each image. Again, widespread inundation and persistent flooding are obvious. The white foam at the bottom of the post-storm photo is due to the return flow cascading over the berm as the area drains into the Gulf of Mexico.” http://coastal.er.usgs.gov/hurricanes/ike/photo-comparisons/highisland.html

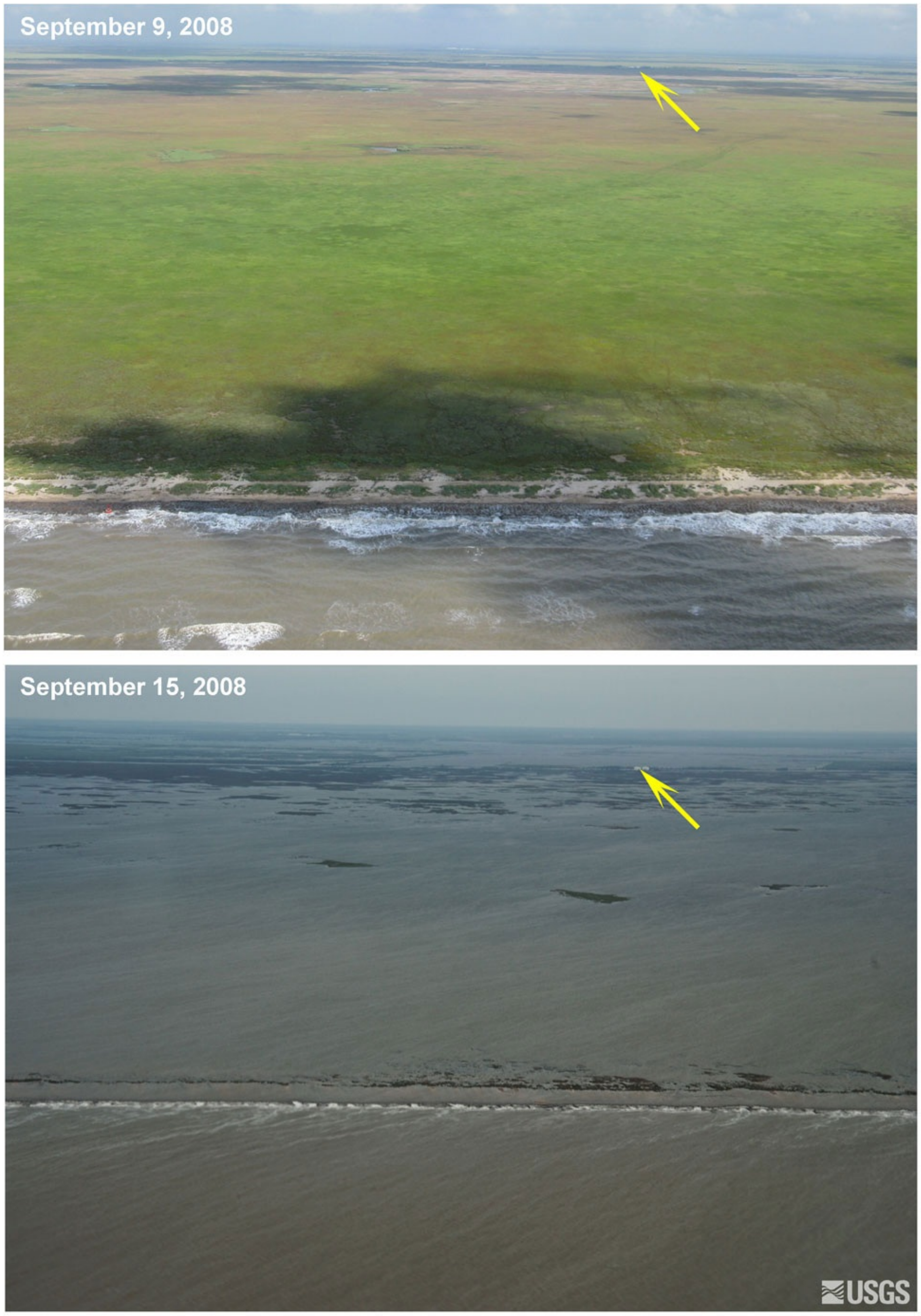

Figure 1.7. “Oblique aerial photography near the Texas Point National Wildlife Refuge, TX, on September 9, 2008 (top) and September 15, 2008, two days after landfall of Hurricane Ike (bottom). Yellow arrows mark features that appear in each image. Severe inundation and erosion of channels through the beach from a seaward-directed flow are evident here. http://coastal.er.usgs.gov/hurricanes/ike/photo-comparisons/highisland.html

Task 2: Survey of the survival and recovery of the mammal populations

Introduction

The impact of hurricanes on local mammalian populations has not been well studied, but many of the same ecological and life history parameters such as survivorship, reproductive rates, habitat utilization and vagility that affect amphibian and reptilian populations are also important for mammals. Disturbances caused by hurricanes can directly impact population densities, resource availability and species diversity, but the magnitude of the impact depends on the biology of the species involved as well as the nature of the storm itself (intensity, duration, and timing).

Several pre- and post- hurricane studies of mammalian populations indicate that the immediate impacts vary for different species, but that post-storm recovery can be rapid. One study of white tailed deer (*Odocoileus virginianus*) following hurricane Andrew (August, 1992) revealed that there was no significant impact on population density due to the storm (Labisky et al., 1999). However, it was also demonstrated that there was a significant (13 fold) decrease in fawn production for 1993. Reproductive rates returned to normal levels by 1994, suggesting that the main consequence of Hurricane Andrew was a temporary degradation of resources critical to successful reproduction (Labisky et al., 1999).

Another study of deer in the Florida Keys involved monitored herds and the consequences of Hurricanes Georges (1998) and Irene (1999). The herds were not impacted severely by the storms directly with only one mortality due to drowning (Lopez et al., 2003). Additional negative impacts to the environment included salinization of some of the water sources used by the deer, but the deer populations were not adversely affected. In fact, The fawn:doe ratio increased from 0.31 pre-hurricanes to 0.64 post-hurricanes (Lopez et al., 2003).

Studies of the beach mouse (*Peromyscus polionotus*) before and after Hurricane Opal (1995) revealed a more pronounced but transitory impact on these rodents. Prior to the storm this species was abundant in both the primary dunes and the secondary scrub dunes. Following the hurricane, the population was reduced by 30%, the species was absent from many primary dune habitats, and 47% of the individuals collected in the scrub were originally collected and marked in the primary dunes prior to the storm (Swilling et al., 1998). A later study of this area indicated that the primary dunes were being recolonized and trapping results yielded 47-60% occupancy of dunes that were 100% occupied prior to the storm (Pries et al., 2009). The same study confirmed a stable population in the scrub relative to pre-storm densities suggesting that the scrub habitat was a refugium from which the primary dunes were recolonized (Pries et al., 2009).

Mammalian Sampling Procedures

Mammals were sampled by trapping. Standard, folding Sherman small mammal traps were used for small mammals. Three trap lines were set at each study site (described above) and each line consisted of 40 Sherman traps. The individual traps in each line were set about 10 m apart and baited with commercial wild bird seed. Six standard Havahart traps were set at each study site to sample mid-sized mammals like racoons and opossums. The Havahart traps were baited with canned sardines. Traps were set once each month at each study site. Traps were set in the evening and checked and retrieved the next morning. Captured animals were identified, sexed, measured (body length and tail length), weighed, ear tagged, and released. Tagging was done with consecutively numbered small mammal ear tags (National Band & Tag Company) placed in the right ear.

The mammal sampling procedures stated in the original grant proposal were way too ambitious given the time constraints placed on ourselves and our students. Therefore, we reduced the sampling at a single site to one night a month and that allowed us to sample for two weeks each month and get all of the sampling done and still teach our classes. The logistics and the animal mortality that were involved with the other method would have been too much. The presence of mammals too large or too wary to enter the traps was determined by various signs like foot prints, dig marks, scats, or road kills.

Deliverables

1. Knowledge of which species survived the storm surge.

The list of species of mammals that have been trapped, observed, or detected in southern Jefferson county since Hurricane Ike are listed in Table 2.1. We encountered or trapped a total of 14 mammal species during the study. There were seven species of rodents, four species of carnivores, one species of marsupial, one species of lagomorph, and one species of suid.

The majority and the minority of species were captured on the A transect. Both sites A1 and A3 had the highest number of species caught in the study, but A2 had the lowest, Table 2.2. The species diversity of the B transect was lower overall, and virtually the same for all three sites, Table 2.2. The number of individuals also varied among sites. Site A1, that was not inundated, and sites A3 and B3 on the edge of the "bowl" (Hurricane Ike Impact Report, 2008) had the highest number of individuals and those in the "bowl" (A2, B1, and B2) had fewer numbers of individuals. There was no relationship between the number of species ($r_s = 0.08$, df = 5, P > 0.80) or individuals (rs = -0.029, df = 5, P > = 0.90) and distance from the coast. There was however, a significant positive relationship between the number of species and the number of individuals captured (rs = 0.84, df = 5, P = 0.033).

At site A1, Big Hill, 11 species of mammals and 154 individuals were trapped. This site had the second highest number of species and the highest numbers of individuals. The dominant species were the cotton rat, rice rat, and harvest mouse, respectively Table 2.2. Two species, the swamp rabbit and the opossum, were only encountered at Big Hill. The Big Hill study site is 2.2 km from the Jefferson county land fill. Therefore it was surprising to have only captured one roof rat and no house mice. These invasives were encountered at other sites nearer the coast.

At site A2, Lost Lake, seven species of mammals and 59 individuals were trapped. These are the fewest number of species and individuals encountered at any site during the study. The dominant species was the cotton rat followed by the rice rat, Table 2.2. The roof rat was the third most common species but no house mice were captured.

Site A3, Texas Point NWR, had 11 species of mammals and 124 individuals trapped. This site has one more species than site A1 and the second highest number of individuals. The dominant species was the cotton rat followed by the rice rat, Table 2.2. The house mouse was the third most common species. There was also a single roof rat captured. The pygmy mouse was only encountered at Texas Point and then only in early spring. It is interesting to note that when we were capturing the pygmy mouse, we were not capturing the house mouse.

Site B1, La Belle Ranch, had eight species of mammals and 80 individuals trapped. The dominant species was the rice rat followed by the cotton rat. The harvest mouse and the house mouse were a distant third in abundance. No roof rats were captured. Anecdotally, we observed the highest number of feral hogs and the highest level of habitat destruction by hogs at this site.

Site B2, the Ship channel, had nine species of mammals and 83 individuals trapped. The dominant species was the rice rat, Table 2.2. The two invasive species, the roof rat and house mouse were the distant second and third most abundant species, respectively. The cotton rat was not abundant at this site, probably due to the inappropriate habitat.

Site B3, Maintenance Yard, had eight species of mammals and 113 individuals trapped. The dominant species was the rice rat followed by the house mouse, Table 2.2. Three other species of rodents were captured at site B3 but these species were rare, Table 2.2. The monthly capture pattern for the rice rat and house mouse suggest that these species are competing, Figure 2.1. However, there was an insignificant negative correlation between the number of individuals of these two species monthly ($r_s = -0.53$, df = 10, P =0.088). The lack of statistical significance may simply be due to the small sample size, 11 months. More intensive monthly sampling potentially could resolve this issue.

Our trapping success for the larger mammals was low and several species like mink, skunks, and nutria were not encountered. The larger mammals are generally more trap shy. We commonly observed the animal or tracks and other signs of racoons, bobcats, otters, coyotes, and feral hogs. We observed rabbits at site A1 but not on any other. Several road killed otters and racoons were seen during the study. But, skunks and minks are also commonly killed by vehicles on roads, yet we observed no road kills of these species. Based upon our observations it appears that skunks and mink were more drastically effected by the storm surge than other intermediately sized mammal species.

2. Knowledge of the recovery of the populations of each species.

The small mammal populations seem to be recovering relatively quickly. The mammal community at site A1 appears to be relatively stable. This is further indicated by the observation that invasive species have not invaded this community in spite of their close proximity. Site A1 is only 2.2 km from the Jefferson county landfill. The site is also approximately 2 km from the southern edge of the city of Port Arthur. The land fill and the city are areas where the house mouse and roof rat are probably found abundantly. Study site A1 was not inundated and therefore the current small mammal community probably more closely reflects the original community assemblage.

All other study sites were inundated by the storm surge from Hurricane Ike. But, the disruption at A3 and B3 was not a long as at the inland sites of A2, B1, and B2. This was because of the “bowl” effect of the geography of southern Jefferson county (Hurricane Ike Impact Report, 2008). While the small mammal species assemblages at sites within the “bowl” were similar, the numbers of individuals captured within the “bowl” was much less than the two sites on the edge of the “bowl”. This is probably due to the longer period of the inundation. In addition, at least one of the invasive species was found at all of these study sites and both invasive species were found at three of the sites. The two study sites nearest the coast, A3 and B3, had the highest numbers of individuals of invasive species, Table 2.1. In spite of the presence of invasives two of the native species, the rice rat and cotton rat, have recovered dramatically. It also appears that the rice rat is out competing the house mouse in the two habitats in which they co-occur Figure 2.1.

Our knowledge of the recovery of the larger mammals is uncertain, Table 2.2. Our trapping success for these species was very low. But based upon other signs such as tracks, scats, and road kills, raccoons, coyotes, and pigs seem to be abundant. In contrast, the absence of any sign of skunks, mink, or nutria is remarkable. Additionally, the relative scarcity of opossums was also surprising. Prior to the storm it was not uncommon to see skunks, mink, nutria or opossums “dead on the road”. Given the abundance of the rodents it is a mystery as to why these species appear to be absent or very rare.

The recovery of the mammalian fauna in southern Jefferson county from the storm surge of Hurricane Ike appears to be progressing rapidly, at least for the small mammals. The stability of the community at study site A1 is probably due to the fact that it was a refugium during the storm. Site A3 and B3 were on the edge of the “bowl” and in close proximity to potential refugia, as well as being inundated for a short time period. At both of these sites the density of the rice rats is high, with site B3 being the second highest of all studies. Cotton rats have recovered at all sites with the appropriate habitat, with site A3 having the highest density. Cotton rats at site B3 are at low density, but because of the habitat they probably always were rare. Rice rats were abundant at all the study sites within the “bowl”. Rice rats are more aquatic and will disperse in marsh habitat readily. Cotton rats were abundant at sites A2 and B1, where there was appropriate habitat, but rare at site B2, where there is not appropriate habitat.

The status of the pygmy mouse is in question. We captured them in February and not thereafter. We did not catch any house mice during February but captured them every other subsequent month except June. There are two possible explanations for the pygmy mouse results. First, the habitat in which they were captured was Spartina grass with standing water. By March much of this standing water was gone. Additionally there could have been direct competition with the house mouse.

The fulvous harvest mouse was common at site A1, where there is appropriate habitat. The mouse was very rare or absent at the other study sites and was likely so before the storm. The fulvous harvest mouse more commonly occurs in upland habitants and is rare in marshes.

There are two processes that would enable the recovery of animal communities from a major ecological disturbance like the storm surge from Hurricane Ike. First, the survival of small founder populations in local refugia and the subsequent recolonization of the area at large from these source areas. This phenomenon was documented for beach mice in Florida and Alabama (Swilling et al., 1998 and Pries et al., 2009). Second, recolonization from populations outside of the area of disturbance could occur. In the study areas, it is more probable that mammals recolonized from local refugia than from outside sources. The reasons that local refugia are more probable have to do with time, distance, and barriers. The cotton rat, in particular is unlikely to have migrated from outside areas because individuals are somewhat sedentary with average daily movements of 13m (Cameron et al., 1979). Also, physical barriers and even paved roadways serve as effective barriers against migrations (Joule and Cameron, 1974; Wilkins and Schmidly,1977). Establishing a stable local population from refugia could occur rapidly because dispersal of cotton rats is positively correlated with population density and the migrating group would reflect the age class structure and sex ratios of the source population (Joule and Cameron, 1975).

Our study started 15 months after Hurricane Ike. We captured all of the species of small mammals encountered in this study within the first two months at all of the sites indicating that they were already established by this time. The closest refuge for small mammals in southern Jefferson county was study site A1 on Big Hill on the J.D. Murfee WMA. Study site A3 on

Texas Point NWR is approximately 22 km from Big Hill. Texas Point had the most species of any study site in our study, one more than Big Hill, and the second highest number of individuals. We think that it is very improbable that these species could have moved from Big Hill or any other outside source in 15 months. It is more probable that they were able to survive in some local refugia like the trees in Sabine Woods or nearby human structures and then dispersed and recolonized the surrounding areas. The reproductive output of the rodent species is such that a small surviving group could expand rapidly into suitable habitat. For example, cotton rats have a gestation period of 27 days, litter sizes of 2-7 young, and remain reproductively active through much of the year (Schmidly, 1983; Wilkins and Schmidly, 1977). The pygmy mouse has a gestation of 20 days, liter size averages 2.6 young and in captivity nine litters were produced in 202 days (Blair, 1941). Rice rats typically have gestation periods of 25 days and litters of 5-6 young (Schmidly, 1983). Rice rats and harvest mice also shift their diets from granivore/herbivore to omnivorous when resource availability changes (Kincaid and Cameron, 1982; Schmidly, 1983).

In addition there are significant habitat barriers for many of the species found near the coast. These barriers include, the Innercoastal Canal, the Keith Lake system, and the extensive marshes. While some species such as rice rats could readily disperse over these barriers other species like the cotton rat, the fulvous harvest mouse and the diminutive pygmy mouse would not. The pygmy mouse was only found at Texas Point, which suggest that it survived nearby and did not migrate from an outside source. The invasive species could have survived in the same refugia as the native species, but could have also been reintroduced by human activities. All of this circumstantial evidence taken together suggests that local refugia were the source of the recolonizing mammals, not an outside source.

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Table 2.1. Species list of mammals captured or observed in southern Jefferson county Texas two years after the Hurricane Ike storm surge.

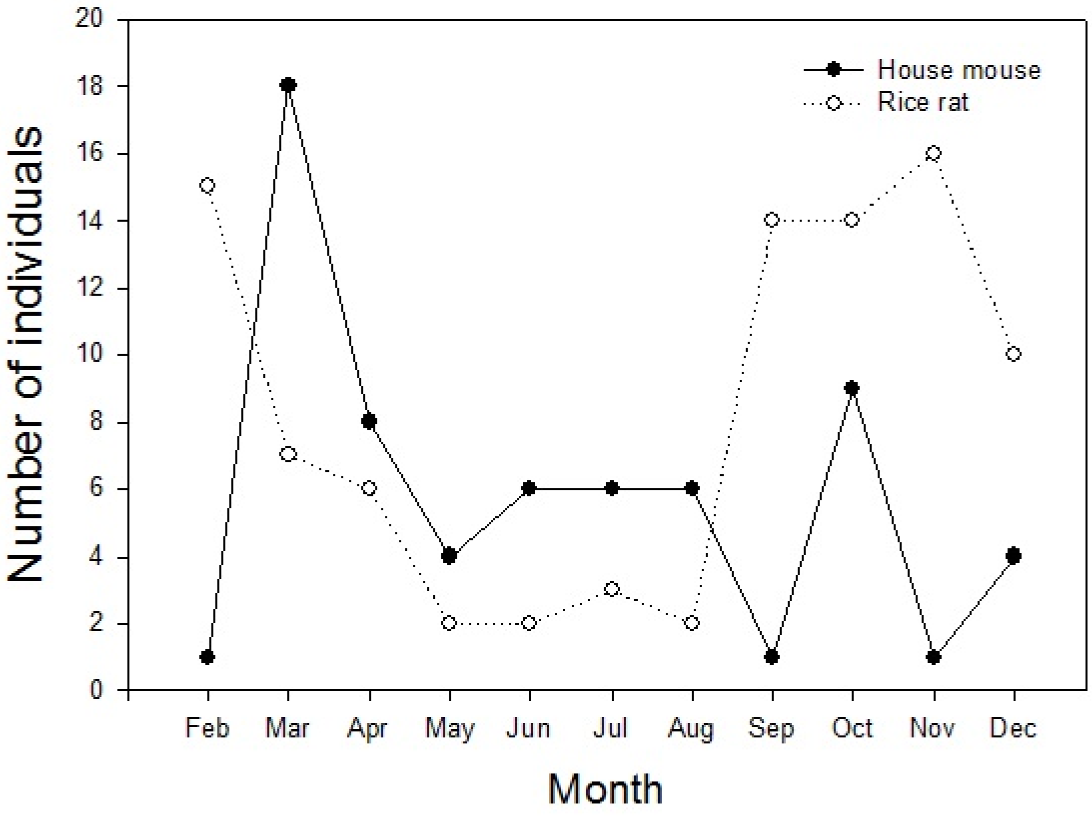
Species	Common Name
Oryzomys palustris	Rice Rat
Sigmodon hispidus	Cotton rat
Reithrodontomys fulvescens	Fulvous harvest mouse
Baiomys taylori	Pygmy mouse
Ondatra zibethicus *	Muskrat
Mus musculus	House mouse
Rattus rattus	Roof rat
Procyon lotor	Racoon
Sylvilagus aquaticus *	Swamp rabbit
Didelphis virginiana	Opossum
Lutra canadensis *	River otter
Canis latrans *	Coyote
Sus scrofa *	Wild pig
Felis rufus *	Bob cat

* Species observed or indirectly observed at the study sites but not captured in the traps.

Table 2.2. The species and number of individuals of each species captured at site sites in southern Jefferson county, Texas two years after the storm surge from Hurricane Ike.

	Study site					
Species	A1	A2	A3	B1	B2	B3
Oryzomys palustris	47	23	31	38	69	60
Sigmodon hispidus	61	30	62	34	3	4
Reithrodontomys fulvescens	37	0	2	3	0	2
Mus musculus	0	0	18	3	4	46
Baiomys taylori	0	0	9	0	0	0
Rattus rattus	0	4	1	0	7	1
Procyon lotor	0	2	1	2	obs	obs
Sylvilagus aquaticus *	4	0	0	0	0	0
Didelphis virginiana	4	0	0	0	0	0
Lutra canadensis	obs	obs	obs	obs	obs	
Canis latrans	obs	obs	obs	obs	obs	obs
Sus scrofa	obs	obs	obs	obs	obs	obs
Felis rufus	obs		obs			
Number of species	10	7	11	8	8	8
Number of individuals captured	154	59	124	80	83	113

Figure 2.1. The numbers of house mice and rice rats trapped over an 11 month period in southern Jefferson county Texas in 2010.



Task 3. Survey of the survival and recovery of migratory and resident bird populations.

Introduction

Hurricanes directly affect bird populations through mortality caused by the storm (Capobianco and Davis 2008; Haney et al. 1991; Michener et al. 1997; Wiley and Wunderle 1993) and through geographic displacement as a result of the strong winds (Dinsmore and Farnsworth 2006; Haney et al. 1991; Lehman and Brinkley 2009; Michener et al. 1997; Wiley and Wunderle 1993). Water birds are more often directly affected by the wind, rain, and storm surge associated with hurricanes than land birds (Wiley and Wunderle 1993). In addition, hurricanes indirectly affect bird populations by altering food availability (Michener et al. 1997; Varty 1991; Wiley and Wunderle 1993), removing nesting substrates and sites (Engstrom and Evans 1990; Loope et al. 1994; Michener et al. 1997; Pimm et al. 1994; Torres and Leberg 1996; Wiley and Wunderle 1993), or altering habitat structure (Canepuccia et al. 2007; Dunning and Watts 1991; Michener et al. 1997; Torres and Leberg 1996; Wauer and Wunderle 1992; Wiley and Wunderle 1993; Wunderle 1995).

Hurricane Ike made landfall in Southeast Texas on 13 September 2008 (Berg 2009). It caused extensive damage to vegetation due to flooding and salinization of the soil. We studied the recovery of the coastal marshes of Jefferson Co., TX following Hurricane Ike at sites inundated by at least 3 m saltwater for more than a week. Our objectives were to characterize the survival and recovery of the migratory and resident bird populations following the hurricane.

Methods

Research was conducted at six study sites (three each along two parallel transects). Each transect represented a gradient from freshwater marsh in the north to saltwater marsh in the south (Fig. 4.1). The northernmost sites, north of the Gulf Intracoastal Waterway (GIW), were La Belle Ranch (BR) and J. D. Murphree north (JN). La Belle Ranch is on private property and encompasses freshwater marsh. J. D. Murphree north is on the J. D. Murphree Wildlife Management Area (WMA) and encompasses freshwater marsh and reed grass marsh (the latter dominated by *Phragmites*). The middle sites, south of the GIW, were McFaddin north (MN) and J. D. Murphree south (JS). McFaddin north is on the McFaddin National Wildlife Refuge (NWR) and encompasses brackish marsh and reed grass marsh. J. D. Murphree south is on the J. D. Murphree WMA and encompasses brackish marsh and salt meadows (the latter dominated by *Spartina patens* or *Distichlis*). The southernmost sites, also south of the GIW and closest to the beach, were McFaddin south (MS) and Texas Point (TP). McFaddin South is on the McFaddin NRW and encompasses brackish marsh, reed grass marsh, and salt meadows. Texas Point is on the Texas Point NRW and encompasses salt meadows.

Standardized point counts were used to estimate species richness of the avian communities and population densities of the resident and migrant bird species found at the study sites (Ralph and Scott 1981). Six 3-km roadside transects, each with seven 250-m radius points separated by 500 m, were established at each study site. Data were collected during ten-minute point counts conducted during the first four hours after dawn. Point counts were not conducted during heavy rains or high winds. All birds detected were recorded, along with the distance to each bird. Point counts were conducted at each study site every two to three weeks. Due to constraints on time and manpower, it was not feasible to conduct mist-netting in conjunction with the point counts, but the point counts provide much more extensive coverage and generate much more data than an equivalent amount of effort spent mist-netting.

A Kruskal-Wallis test in SigmaPlot 11 was used to compare the mean abundance of birds per survey among the four seasons. A second Kruskal-Wallis test was used to compare the mean species richness of birds per survey among the four seasons. Data were summed across sites. Using data for each season, a linear regression analysis was conducted in SigmaPlot 11 to determine if mean abundance of birds at a site was dependent upon the distance of that site from the coast. Similarly, a linear regression analysis was conducted to determine if mean species richness of birds at a site was dependent upon the distance of that site from the coast. A final linear regression was conducted to determine if mean abundance of birds at a given site was dependent upon mean species richness of birds at that site, using data from the entire year. Using data for each season, densities were estimated for the most common species using Distance 6.0 (Buckland et al. 2004). Data were summed across sites in order to obtain sufficient sample sizes for analysis.

Results

The mean abundance of birds per survey differed significantly among seasons (H = 15.351, df = 3, n = 581, p = 0.002, Kruskal-Wallis test). Mean abundance was highest in the fall (45.1 ± 5.9), intermediate in the winter (33.8 ± 6.6), and lowest in the summer (26.1 ± 5.3) and spring (26.0 ± 5.0). Similarly, the mean species richness of birds per survey differed significantly among seasons (H = 38.617, df = 3, n = 581, p < 0.001, Kruskal-Wallis test). Mean species richness was highest in the spring (6.7 ± 0.2), lowest in the summer (4.7 ± 0.2), and intermediate in the fall (5.7 ± 0.2) and winter (5.5 ± 0.3). Because of the seasonal differences in mean abundance and species richness, seasons were treated separately in subsequent statistical analyses.

Sites ranged from 1.6 to 20.9 km from the coast, as measured from the middle of the point count transect at each site (Figs. 3.1 and 3.2). There was no significant relationship between mean abundance of birds at a site and the distance of that site from the coast for the entire year or for any season, except for spring, during which individual abundance of birds increased with increasing distance from the coast (Fig. 3.1, Table 3.1). Similarly, there was no significant relationship between mean species richness of birds at a site and the distance of that site from the coast for the entire year or for any season (Fig. 3.2, Table 3.2). There was a trend for sites with higher mean species richness to have higher mean individual abundance (Fig. 3.3), but the trend was not significant (R = 0.643, F = 2.821, df = 1, n = 6, p = 0.168, linear regression analysis).

During the winter, the most common species were permanent resident or winter resident passerines, including the Red-winged Blackbird (*Agelaius phoeniceus*), Marsh Wren (*Cistothorus palustris*), and Boat-tailed Grackle (*Quiscalus major*). The Yellow-rumped Warbler (*Dendroica coronata*) and Savannah Sparrow (*Passerculus sandwichensis*) were also common in winter (Table 3.3). During the spring, the most common species were permanent resident or winter resident passerines, including the Tree Swallow (*Tachycineta bicolor*), Red-winged Blackbird, Boat-tailed Grackle, Marsh Wren, and Savannah Sparrow. Passage migrants, such as the Eastern Kingbird (*Tyrannus tyrannus*), Baltimore Oriole (*Icterus galbula*), and Orchard Oriole (*Icterus spurious*), were also present (Table 3.3). During the summer, the most common species was the Red-winged Blackbird, and during the fall, the most common species were the Red-winged Blackbird and the American Coot (*Fulica americana*) (Table 3).

Discussion

There was not a steady increase in the mean abundance of birds throughout the duration of the study, suggesting that abundances had already rebounded in the year between Hurricane Ike and the beginning of the study. There were seasonal differences in the mean abundance of birds, as expected in a community composed of both resident and migrant species. Mean abundance of birds was highest in the fall and lowest in the winter. A high abundance of birds is expected in the fall when many migrants are passing through the region, but the low abundance of birds in the winter was unexpected, given that many species, especially waterfowl, overwinter in the region (Texas Parks and Wildlife Department 2008). Only two of the six study sites (La Belle Ranch and McFaddin south) had extensive open water (Table 4.2) that would attract wintering waterfowl, which may help to explain the low abundance of birds recorded in winter. Similarly, there was not a steady increase in the mean species richness of birds throughout the duration of the study, suggesting that species richness had also rebounded between the hurricane and the beginning of the study. There were seasonal differences in the mean species richness of birds, with the highest species richness being recorded in spring and fall, when migrants are passing through the region.

There was no relationship between distance of a site from the coast and mean abundance of birds in any season, except for the spring, when mean abundance was increased with increasing distance from the coast. This is due primarily to the high abundance of birds at the J. D. Murphree south site (Fig. 3.1), where the presence of very shallow water and extensive mudflats promoted a high abundance of birds throughout the year. Water level is one of the most significant habitat factors influencing the abundance and species richness of wetland birds, with shallow water and associated mudflats promoting high abundance and richness (Bancroft et al. 2002; Darnell and Smith 2004). There was no relationship between distance of a site from the coast and mean species richness of birds in any season, but the J. D. Murphree south site, which had extensive mudflats, and the J. D. Murphree north site, which was centered on an artificial impoundment that was more or less protected from the storm surge and remained mostly freshwater, had higher species richness than the other four sites (Fig. 3.2).

Densities were estimated for 44 species of birds at the study sites. In general, small-bodied passerines had higher densities than large-bodies waders and waterfowl. Although there are no estimates of bird densities at the study sites for the years prior to Hurricane Ike, two species appear to have experienced drastic reductions in population size since the hurricane. The Least Bittern (*Ixobrychus exilis*) and the Purple Gallinule (*Porphyrio martinica*) were previously common birds in the region during the breeding season (pers. obs.), but the Least Bittern had a very low density during the 2010 breeding season, and the Purple Gallinule was recorded so infrequently that its density could not be estimated. Both species may have been adversely affected by the lingering effects of salinization associated with Hurricane Ike's storm surge. The Purple Gallinule is a freshwater species (West and Hess 2002), and the Least Bittern is a species of freshwater to brackish marshes (Poole eta al. 2009). Salinity tolerances of young birds may be more limited than those of adults, and some species of waterbirds that nest in saltwater marshes may feed freshwater prey to their young (Bildstein et al. 1990).

Endemic and endangered species of birds are most vulnerable to the effects of hurricanes (Engstrom and Evans 1990; Haney et al. 1991; Pimm et al. 1994; Varty 1991). Marsh birds are probably less affected by hurricanes than forest birds, as vegetation, which provides foraging and nesting substrates for birds, is less likely to be damaged in marshes than in forests (Michener et al. 1997). Even among marsh birds, the effect of hurricanes on breeding birds is more pronounced among shrub-nesters than among grass-nesters (Shepherd et al. 1991). Most birds at the coastal marshes of Southeast Texas probably retreated before Hurricane Ike and returned as soon as suitable habitat and food resources were available, often within the first year after the storm. Many species of waterbirds travel long distances to foraging sites and change foraging sites in response to changing food availability (Kushlan 1976). Given the potential mobility of birds, it is not unexpected that there was no gradual increase in abundance or species richness of birds over the course of the study or that there was no strong relationship between a study site's distance from the coast and abundance or species richness, as might be expected for amphibians, reptiles, and small mammals gradually re-colonizing the coastal marshes from inland sites.

Unfortunately, there is no comparable data on the abundance and species richness of birds prior to Hurricane Ike at the six study sites, and data collection for this study did not begin until 16 months after the hurricane. Nonetheless, no expected species are obviously missing, and only two species, the Least Bittern and Purple Gallinule, have noticeably diminished populations, which may suggest that they are particularly susceptible to the effects of elevated salinities. Hurricanes are known to affect the size and location of waterbird nesting colonies (Leberg et al. 2007), but no such effect was noted at the six study sites, because there were no significant waterbird colonies at the study sites either before or after the hurricane, although the study sites are important foraging areas for waterbirds.

Continued monitoring is recommended in order to characterize possible long-term responses of the avian community to the effects of Hurricane Ike and the subsequent changes in habitat structure and quality, such as an increase in the amount of open water, due to erosion in some areas during the storm surge, and an increase in productivity, due to sedimentation in other areas during the storm surge. The results reported here provide a baseline against which to assess future changes in the resident and migrant bird populations as the marshes of Southeast Texas continue to recovery from the effects of Hurricane Ike.

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Table 1. Results of regression analyses to determine if distance from coast determined mean individual abundance of birds at a given site.

season	R	F	p
spring	0.087	7.456	0.052 *
summer	0.134	0.729	0.800
fall	0.360	0.596	0.483
winter	0.165	0.111	0.755
entire year	0.442	0.972	0.380

Table 2. Results of regression analysis to determine if distance from coast determined mean species richness of birds at a given site.

season	R	F	p
spring	0.658	3.054	0.155
summer	0.186	0.143	0.724
fall	0.553	1.755	0.255
winter	0.551	1.745	0.257
entire year	0.703	3.900	0.120

Table 3. Density estimates (mean ± SE birds/ha) for different species in different seasons. Results were averaged across study sites in order to achieve sufficient sample sizes for estimation.

common name	scientific name	winter	spring	summer	fall
Neotropic Cormorant	*Phalacrocorax brasilianus*	0.10 ± 0.04	0.06 ± 0.02	0.35 ± 0.18	0.11 ± 0.06
Blue-winged Teal	*Anas discors*		0.13 ± 0.04		
Green-winged Teal	*Anas crecca*	0.06 ± 0.04			
Mottled Duck	*Anas fulvigula*		0.02 ± 0.01		
Great Blue Heron	*Ardea herodias*	0.02 ± 0.01			0.02 ± 0.01
Great Egret	*Ardea alba*	0.14 ± 0.13	0.02 ± 0.01	0.15 ± 0.07	0.09 ± 0.03
Snowy Egret	*Egretta thula*	0.11 ± 0.05	0.02 ± 0.01	0.14 ± 0.11	0.02 ± 0.01
Tricolored Heron	*Egretta tricolor*			0.02 ± 0.01	
Green Heron	*Butorides virescens*			0.02 ± 0.01	
Black-crowned Night-Heron	*Nycticorax nycticorax*			0.04 ± 0.01	
Least Bittern	*Ixobrychus exilis*		0.05 ± 0.02	0.08 ± 0.05	
White Ibis	*Eudocimus albus*		0.06 ± 0.04		0.06 ± 0.03
Northern Harrier	*Circus cyaneus*	0.02 ± 0.01			
Black-necked Stilt	*Himantopus mexicanus*	0.58 ± 0.52	0.20 ± 0.08	0.03 ± 0.01	
Killdeer	*Charadrius vociferus*	0.12 ± 0.04	0.25 ± 0.08	0.12 ± 0.07	0.04 ± 0.02
Greater Yellowlegs	*Tringa melanoleuca*		0.02 ± 0.01		
Lesser Yellowlegs	*Tringa flaviceps*		0.16 ± 0.11		
Willet	*Catoptrophorus semipalmatus*		0.13 ± 0.04	0.02 ± 0.01	
Least Sandpiper	*Calidris minutilla*				0.10 ± 0.07
Laughing Gull	*Larus atricilla*			0.45 ± 0.41	
Sora	*Porzana carolina*		0.05 ± 0.02		
Clapper Rail	*Rallus longirostris*		0.02 ± 0.01	0.33 ± 0.09	0.02 ± 0.01
Common Moorhen	*Gallinula chloropus*	0.58 ± 0.14	0.29 ± 0.04	0.09 ± 0.02	0.07 ± 0.03
American Coot	*Fulica americana*	0.23 ± 0.15	0.19 ± 0.09		0.95 ± 0.52
Mourning Dove	*Zenaida macroura*		0.05 ± 0.01	0.11 ± 0.06	
Belted Kingfisher	*Ceryle alcyon*				0.03 ± 0.01

Eastern Phoebe	*Sayornis phoebe*				0.03 ± 0.01
Eastern Kingbird	*Tyrannus tyrannus*		0.49 ± 0.09	0.22 ± 0.07	
Tree Swallow	*Tachycineta bicolor*		4.15 ± 4.02		
Barn Swallow	*Hirundo rustica*			0.28 ± 0.16	
Marsh Wren	*Cistothorus palustris*	1.69 ± 0.24	0.91 ± 0.29		0.10 ± 0.03
Sedge Wren	*Cistothorus platensis*				0.65 ± 0.09
Northern Mockingbird	*Mimus polyglottos*			0.08 ± 0.03	
Yellow-rumped Warbler	*Dendroica coronata*	5.88 ± 0.87	0.40 ± 0.07		
Common Yellowthroat	*Geothlypis trichas*	0.67 ± 0.16	0.21 ± 0.03	0.08 ± 0.03	0.16 ± 0.04
Dickcissel	*Spiza americana*			0.43 ± 0.32	
Savannah Sparrow	*Passerculus sandwichensis*	2.49 ± 0.32	0.85 ± 0.16		0.46 ± 0.09
Seaside Sparrow	*Ammodramus maritimus*	0.14 ± 0.04	0.31 ± 0.05	0.49 ± 0.15	0.06 ± 0.01
Brown-headed Cowbird	*Molothrus ater*		0.41 ± 0.10	0.12 ± 0.07	
Red-winged Blackbird	*Agelaius phoeniceus*	4.13 ± 0.77	2.14 ± 0.25	1.04 ± 0.15	1.23 ± 0.41
Great-tailed Grackle	*Quiscalus mexicanus*				0.13 ± 0.06
Boat-tailed Grackle	*Quiscalus major*	1.19 ± 0.65	1.84 ± 0.58	0.50 ± 0.09	
Baltimore Oriole	*Icterus galbula*		0.08 ± 0.03		
Orchard Oriole	*Icterus spurius*		0.14 ± 0.04	0.23 ± 0.05	

Figure 1. Mean individual abundance of birds per site as a function of distance from the coast. Data is for entire year. Error bars represent SEs.

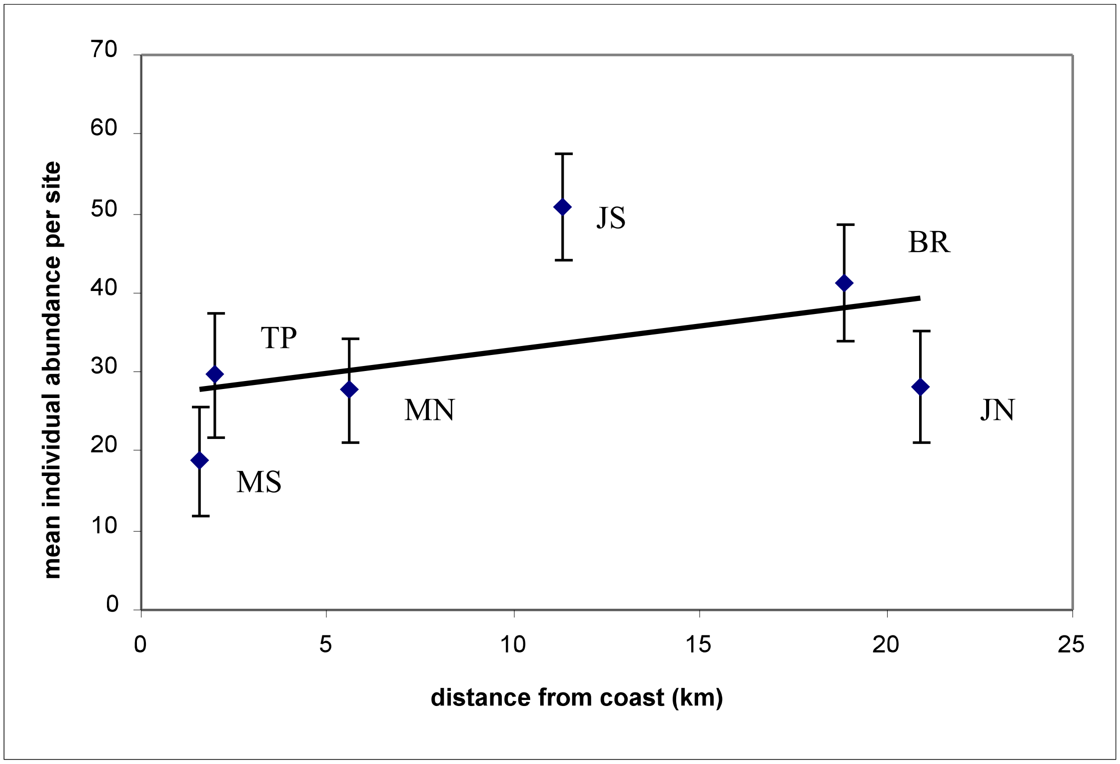


Figure 2. Mean species richness of birds per site as a function of distance from the coast. Data is for entire year. Error bars represent SEs.

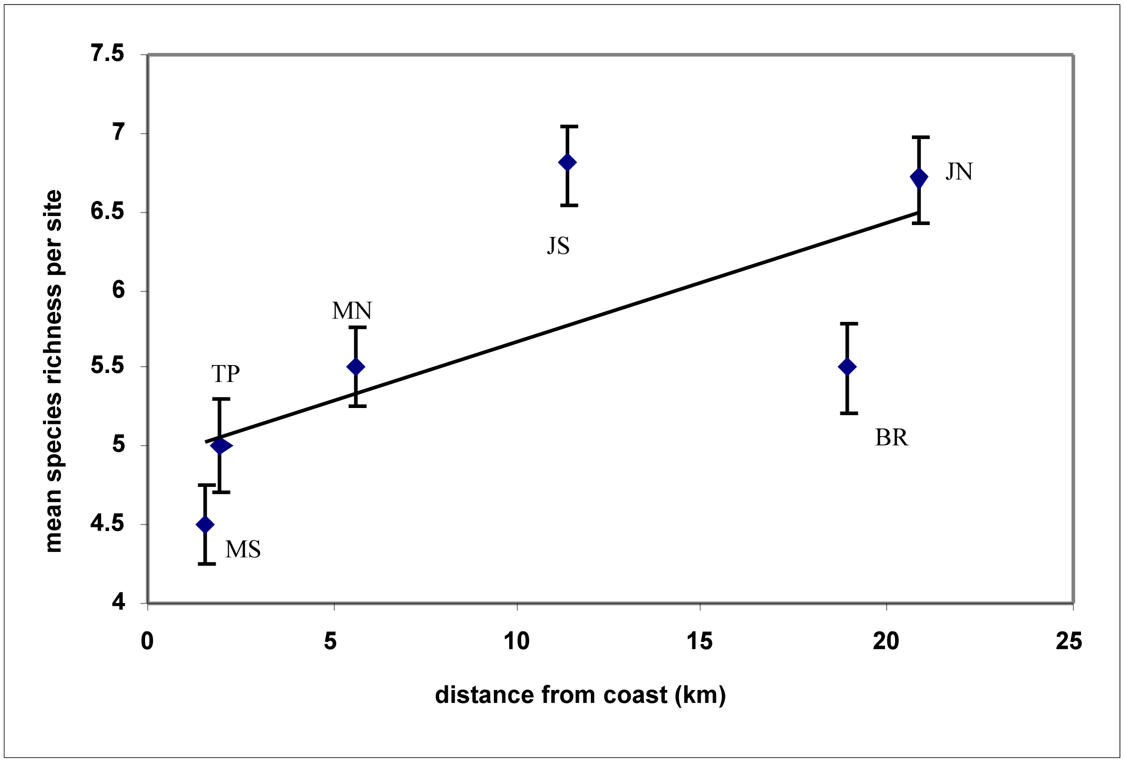
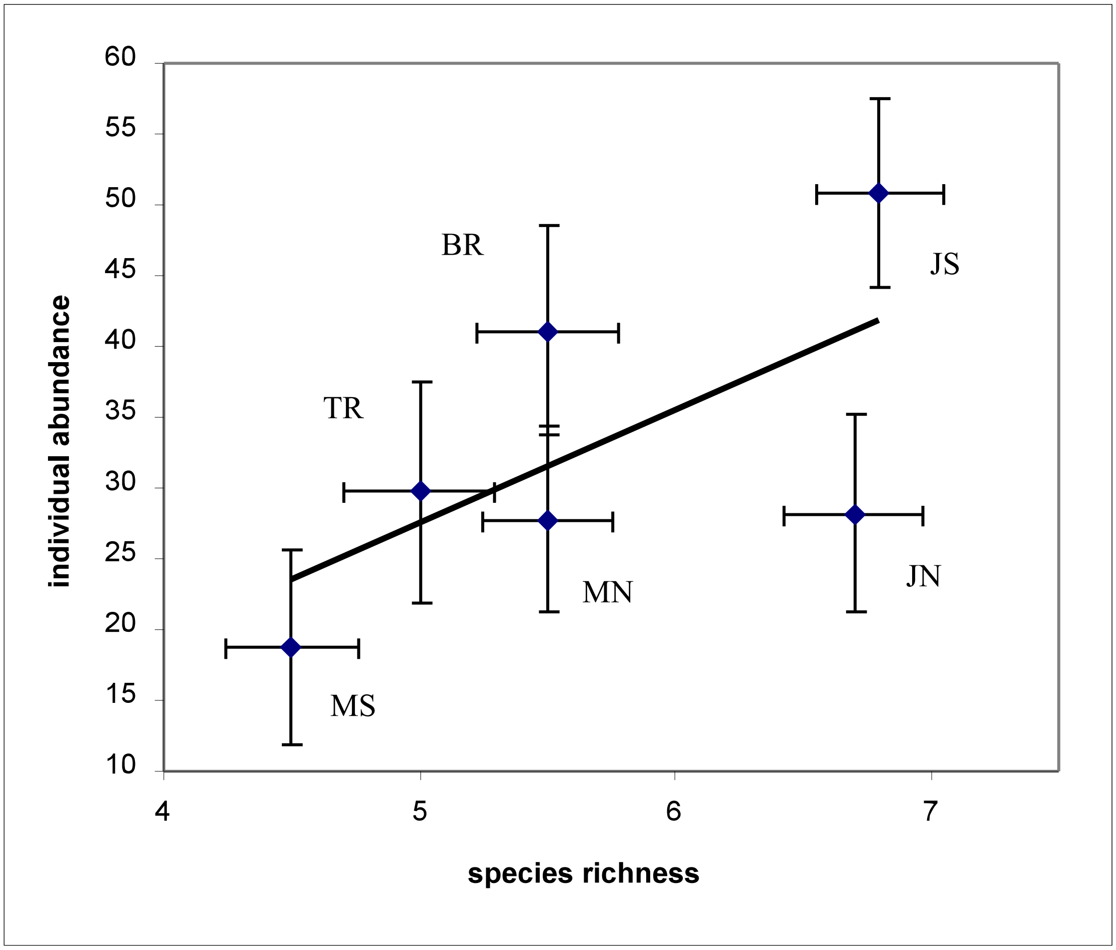


Figure 3. Relationship between mean individual abundance and mean species richness of birds per site (abbreviations as in Methods). Data is for entire year. Error bars represent SEs.



Task 4. Characterization of vegetative structure and floristics.

Introduction

Marsh ecosystems are adapted to hurricane disturbances and are less susceptible to hurricane damage than other ecosystem types, such as forests (Michener et al. 1997). Marsh vegetation is relatively resistant to wind damage, but can be affected by storm surges and saltwater inundation (Pimm et al. 1994). Not unexpectedly, saltwater inundation causes greater disturbance to freshwater and brackish marshes than to saltwater marshes (Michener et al. 1997). Hurricane damage to marshes is often short-term, with rapid regrowth of vegetation (Chabreck and Palmisano 1973), and the detrimental short-term effects of erosion and inundation are often offset by the beneficial long-term effects of the surge of sediment deposition (McKee and Cherry 2009, Conner 1989).

Hurricane Ike made landfall in Southeast Texas on 13 September 2008. It caused extensive damage to vegetation due to flooding and salinization of the soil. We studied the recovery of the coastal marshes of Jefferson Co., TX following Hurricane Ike at sites inundated by at least 3 m saltwater for more than a week. Our objectives were to characterize the survival and recovery of native marsh plants and to document changes in the status of invasive marsh plants.

Methods

We conducted research at six study sites (three each along two parallel transects). Each transect represented a gradient from freshwater marsh in the north to saltwater marsh in the south (Fig. 4.1). The northernmost sites, north of the Gulf Intracoastal Waterway (GIW), were La Belle Ranch and J. D. Murphree north. La Belle Ranch is on private property and encompasses freshwater marsh. J. D. Murphree north is on the J. D. Murphree Wildlife Management Area (WMA) and encompasses freshwater marsh and reed grass marsh (the latter dominated by *Phragmites*). The middle sites, south of the GIW, were McFaddin north and J. D. Murphree south. McFaddin north is on the McFaddin National Wildlife Refuge (NWR) and encompasses brackish marsh and reed grass marsh. J. D. Murphree south is on the J. D. Murphree WMA and encompasses brackish marsh and salt meadows (the latter dominated by *Spartina patens* or *Distichlis*). The southernmost sites, also south of the GIW and closest to the beach, were McFaddin south and Texas Point. McFaddin South is on the McFaddin NRW and encompasses brackish marsh, reed grass marsh, and salt meadows. Texas Point is on the Texas Point NRW and encompasses salt meadows.

We established 42 sampling plots (seven at each of the six study sites). Each sampling plot was a 250-m radius circle centered on a road through the study site. Locations (latitude and longitude) of the centers of the sampling plots are given in Table 4.1. At each sampling plot, we visually estimated the percent cover of open water, mud, and standing vegetation. For the areas covered by standing vegetation, we visually estimated the percent cover of live versus dead vegetation. Also for the areas covered by standing vegetation, we visually estimated the percent cover of 13 dominant plant species, plus trees (not broken down by species) and “other” plants that were less common that the 13 dominant species. We conducted vegetation sampling during the late summer of 2010. These methods differ from those in our research proposal, but this less intense but more extensive (in areal coverage) approach provides a better characterization of the vegetation at a landscape level and complements small-scale vegetation sampling being conducted by Texas Parks and Wildlife personnel. We conducted principle components analysis (using the program PCORD 4) to ordinate the sampling plots according to vegetative structure and floristics.

Results

We characterized the vegetative cover at 42 sampling plots (seven at each of the six study sites). Overall, 64% of the area sampled was covered in vegetation, 33% was open water, and 3% was mud during the late summer of 2010 (Table 4.2). Ninety percent of the standing vegetation was live and only 10% was dead (Table 4.2), so the vegetation that did survive the hurricane had largely recovered by summer 2010. The plant species with the most extensive areal coverage was *Phragmites* (27% cover), followed by *Spartina patens* (17%) and *Typha* (10%) (Table 4.2). Invasive species were present, but there were not extensive areas dominated by invasive species. These data provide a baseline for comparison with future results from long-term monitoring following the hurricane.

We used principle components analysis to ordinate the sampling plots according to vegetative structure and floristics. In an initial ordination of all 42 sampling plots, two plots at J. D. Murphree south stood out as conspicuous outliers, because they were the only sampling plots with significant coverage in mud in late summer 2010 (Table 4.2), so we removed these two points from the data set and conducted a second principle components analysis on the remaining 40 sampling plots. The first principle component (eigenvalue = 4.115) explained 21% of the variance among plots, and the second principle component (eigenvalue = 2.855) explained an additional 14% of the variance. The first principle component was highly correlated with live (versus dead) vegetation cover, and the second principle component was highly correlated with vegetation cover (versus open water) (Table 4.3). There was extensive overlap among sampling plots from different study sites (Fig. 4.2), as expected for vegetative communities that grade into one another, but there was some segregation of sampling plots from the north (inland), middle, and south (coastal) regions (Fig. 4.3), representing a rough salinity gradient.

Discussion

We sampled marsh vegetation in the summer of 2010, the second growing season after Hurricane Ike, which made landfall in the fall of 2008. Ninety percent of the vegetation was growing, and all expected species were present. Although hurricane damage was extensive immediately following the storm surge, much regrowth had already occurred during the summer of 2009. Extensive damage followed by rapid regrowth, with vegetation approaching a pre-hurricane state in a single growing season, was also observed in the marshes of the Mississippi River Delta following Hurricane Camille in 1968 (Chabreck and Palmisano 1973).

Invasive species were present, but did not constitute dominant vegetative types in most areas sampled. Chinese tallow tree (*Triadica sebifera*) was common in some higher areas prior to Hurricane Ike, and many were killed by saltwater inundation. In general woody vegetation is less resistant to hurricane damage than herbaceous vegetation (Michener et al. 1997).

Open water constituted 33% of the area sampled, as a result of erosion during Hurricane Ike. The loss of vegetation to open water may eventually be offset by increased vegetative growth and decreased rates of subsidence caused by the large influx of sediment during the hurricane (Conner 1989). We recommend continued monitoring of the recovery of marsh vegetation in Southeast Texas, and our results will provide a valuable baseline dataset.

Literature cited Task 4

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Table 4.1. Locations of the 42 vegetation sampling plots.

Site	point	north	west	site	point	north	west
La Belle Ranch	1	29.82749	94.09294	JD Murphree south	1	29.79247	93.96313
	2	29.83225	94.09447		2	29.78987	93.96751
	3	29.83602	94.69608		3	29.78766	93.97221
	4	29.83608	94.10151		4	29.78380	93.97387
	5	29.83416	94.10654		5	29.77917	93.97430
	6	29.83332	94.11145		6	29.77490	93.97618
	7	29.83345	94.11607		7	29.77142	93.97815
JD Murphree north	1	29.87553	94.05385	McFaddin south	1	29.69151	94.08077
	2	29.87281	94.04943		2	29.68762	94.08262
	3	29.87087	94.04636		3	29.68482	94.07914
	4	29.87047	94.04121		4	29.68523	94.07925
	5	29.86992	94.03624		5	29.67626	94.08035
	6	29.86642	94.03643		6	29.67269	94.07790
	7	29.86694	94.04104		7	29.66911	94.07481
McFaddin north	1	29.71538	94.11988	Texas Point	1	29.70799	93.92104
	2	29.71176	94.11584		2	29.70375	93.92026
	3	29.70862	94.11241		3	29.69951	93.91808
	4	29.70535	94.10885		4	29.69533	93.91585
	5	29.70219	94.10547		5	29.69192	93.91209
	6	29.69853	94.10149		6	29.68906	93.90792
	7	29.69655	94.09786		7	29.68767	93.90332

Table 4.2. Vegetative and habitat characteristics of the 42 sample plots. All values are percent coverages within the 250-m radius plots.

Relative position [1]	north (inland) [2]													
Site	La Belle Ranch							JD Murphree north						
Plot	1	2	3	4	5	6	7	1	2	3	4	5	6	7
open water	75	75	40	70	60	25	10	30	50	25	15	30	30	20
Mud	5	10	5	0	0	0	0	0	0	0	0	0	0	0
vegetation [3]	20	15	55	30	40	75	90	70	50	75	85	70	70	80
live veg.	95	95	95	100	100	100	95	95	95	90	95	95	95	95
dead veg. [4]	5	5	5	0	0	0	5	5	5	10	5	5	5	5
Phragmites	30	0	10	0	10	0	0	45	30	45	60	70	20	10
Paspalum	10	0	0	0	0	0	0	50	50	10	15	10	40	30
Spartina patens	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S. alterniflora	20	0	40	0	20	10	20	0	0	5	10	0	0	0
Typha	30	50	40	60	20	20	30	0	0	0	0	0	20	40
Juncus	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scheonoplectus	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Setaria	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Salicornia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Baccharis	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Iva	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distichlis	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atriplex	0	0	0	30	40	40	30	0	0	0	0	0	0	0
Trees	0	0	0	0	0	0	0	0	10	25	0	0	0	0
other veg. [5]	10	50	10	10	10	30	20	5	10	15	15	20	20	20

1. Position along latitudinal gradient from north (inland) to south (coastal)
2. north sites (La Belle Ranch and JD Murphree north were north (inland of the Gulf Intracoastal Canal)
3. Open water, mud and vegetation are mutually exclusive and should sum to 100 for a plot
4. Live vegetation and dead vegetation are mutually exclusive and should sum to 100 for a plot
5. Vegetation types (Phragmites through other) are mutually exclusive and should sum to 100 for a plot

Table 4.2 (cont.). Vegetative and habitat characteristics of the 42 sample plots. All values are percent coverages within the 250-m radius plots.

Relative position [1]	middle (intermediate)													
Site	McFaddin north							JD Murphree south						
Plot	1	2	3	4	5	6	7	1	2	3	4	5	6	7
open water	55	10	10	10	25	40	55	15	15	40	30	40	35	40
Mud	0	0	0	0	0	0	0	0	0	0	0	0	50	50
vegetation [3]	45	90	90	90	75	60	45	85	85	60	70	60	50	10
live veg.	99	90	70	70	90	100	80	95	90	85	90	90	15	60
dead veg. [4]	1	10	30	30	10	0	20	5	10	15	10	10	90	40
Phragmites	50	30	20	20	75	100	50	45	45	30	20	60	10	0
Paspalum	50	0	0	0	0	0	0	0	0	0	0	0	0	0
Spartina patens	0	40	0	0	10	0	0	25	50	60	60	25	50	40
S. alterniflora	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Typha	0	25	0	0	0	0	0	0	0	0	0	0	0	0
Juncus	0	0	40	40	0	0	0	0	0	0	0	0	0	0
Scheonoplectus	0	0	40	40	0	0	50	0	0	0	0	0	0	0
Setaria	0	0	0	0	10	0	0	0	0	0	0	0	0	0
Salicorni	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Baccharis	0	0	0	0	0	0	0	0	0	0	20	5	25	30
Iva	0	0	0	0	0	0	0	0	0	0	0	10	25	30
Distichlis	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Atriplex	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trees	0	0	0	0	0	0	0	10	0	0	0	0	0	0
other veg. [5]	0	5	0	0	5	0	0	10	5	10	0	0	0	0

1. Position along latitudinal gradient from north (inland) to south (coastal)
2. north sites (La Belle Ranch and JD Murphree north were north (inland of the Gulf Intracoastal Canal)
3. Open water, mud and vegetation are mutually exclusive and should sum to 100 for a plot
4. Live vegetation and dead vegetation are mutually exclusive and should sum to 100 for plot
5. Vegetation types (Phragmites through other) are mutually exclusive and should sum to 100 for a plot

Table 4.2 (cont.). Vegetative and habitat characteristics of the 42 sample plots. All values are percent coverages within the 250-m radius plots.

Relative position [1]	south (coastal)													
Site	McFaddin south							Texas Point						
Plot	1	2	3	4	5	6	7	1	2	3	4	5	6	7
open water	25	50	70	60	40	10	5	0	15	10	40	40	30	20
Mud	0	0	0	0	0	0	0	0	0	0	0	0	0	0
vegetation [3]	75	50	30	40	60	90	95	100	85	90	60	60	70	80
live veg.	95	95	95	95	95	95	95	95	100	100	95	90	95	90
dead veg. [4]	5	5	5	5	5	5	5	5	0	0	5	10	5	10
Phragmites	45	40	80	85	0	0	0	0	0	0	0	0	0	0
Paspalum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spartina patens	0	0	0	0	65	40	0	60	50	50	0	0	0	80
S. alterniflora	0	0	0	0	0	60	35	0	0	0	0	0	0	0
Typha	0	5	20	15	0	0	0	0	50	0	0	0	0	0
Juncus	0	5	0	0	30	0	0	0	0	0	0	0	0	0
Scheonoplectus	0	50	0	0	0	0	0	0	0	0	0	0	0	0
Setaria	45	0	0	0	0	0	0	0	0	0	0	0	0	0
Salicornia	0	0	0	0	0	0	60	0	0	0	0	0	0	20
Baccharis	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Iva	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distichlis	0	0	0	0	0	0	0	0	0	50	100	100	95	0
Atriplex	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trees	0	0	0	0	0	0	0	40	0	0	0	0	0	0
other veg. [5]	10	0	0	0	5	0	5	0	0	0	0	0	0	0

1. Position along latitudinal gradient from north (inland) to south (coastal)
2. north sites (La Belle Ranch and JD Murphree north were north (inland of the Gulf Intracoastal Canal)
3. Open water, mud and vegetation are mutually exclusive and should sum to 100 for a plot
4. Live vegetation and dead vegetation are mutually exclusive and should sum to 100 for a plot
5. Vegetation types (Phragmites through other) are mutually exclusive and should sum to 100 for a plot

Table 4.3. Eigenvectors showing correlation of variables to first two principle components.

Variable	pc 1	pc 2
open water	0.2568	-0.4108
Mud	0.2368	-0.2509
vegetation	-0.267	0.4158
live veg.	0.4051	0.2334
dead veg.	-0.4054	-0.2413
Phragmites	-0.0516	-0.1789
Paspalum	0.0907	-0.0375
Spartina patens	-0.1306	0.3118
S. alterniflora	0.1016	0.1437
Typha	0.3192	-0.1443
Juncus	-0.3353	-0.3081
Scheonoplectus	-0.3054	-0.3346
Sertaria	-0.0088	0.0277
Salicornia	-0.0358	0.2016
Baccharis	-0.0634	0.0616
Iva	-0.0392	-0.0164
Distichlis	-0.0118	0.0845
Atriplex	0.2061	0.0022
Trees	-0.0529	0.191
other veg.	0.2829	-0.1212

Figure 4.1. Location of the six study sites in Jefferson Co., TX.

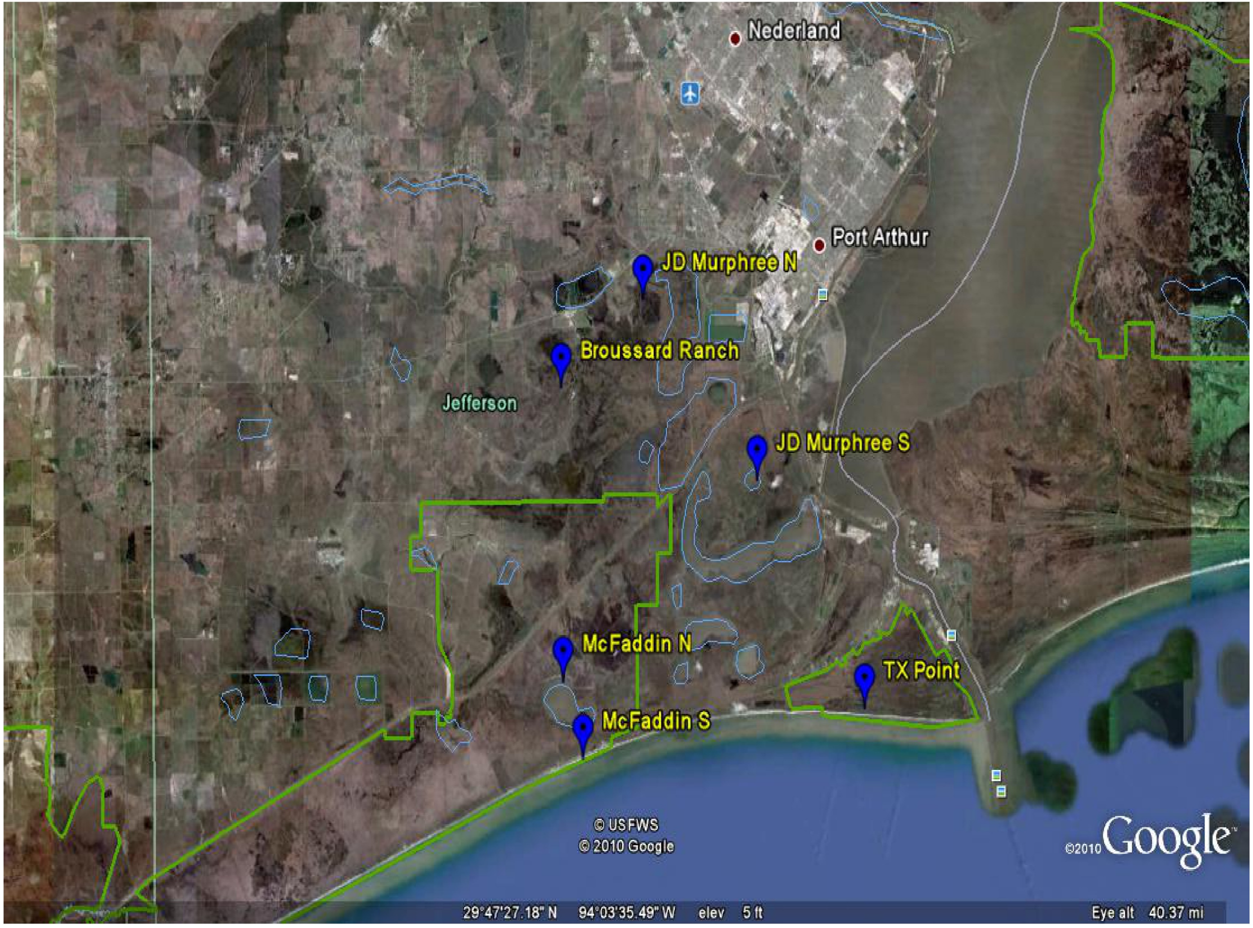


Figure 4.2. Principle components ordination of 40 sample plots. Principle component 1 represents a gradient from more dead vegetation to more live vegetation, and principle component two represents a gradient form more open water to more dense vegetation. Note that there is extensive overlap between sites.

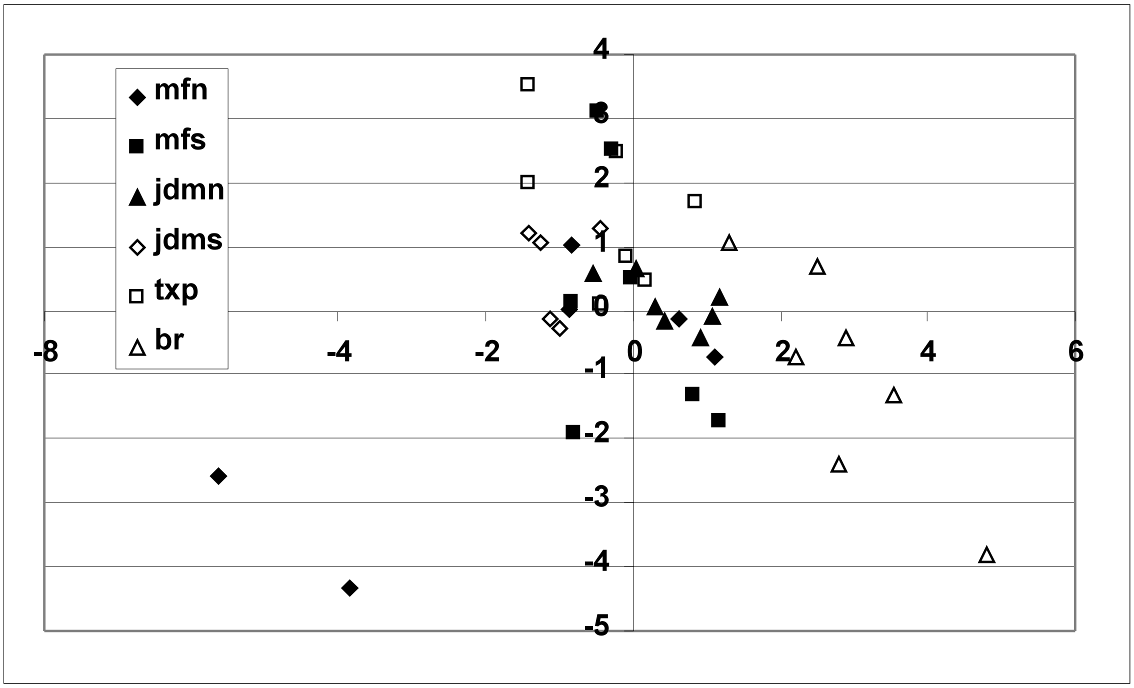
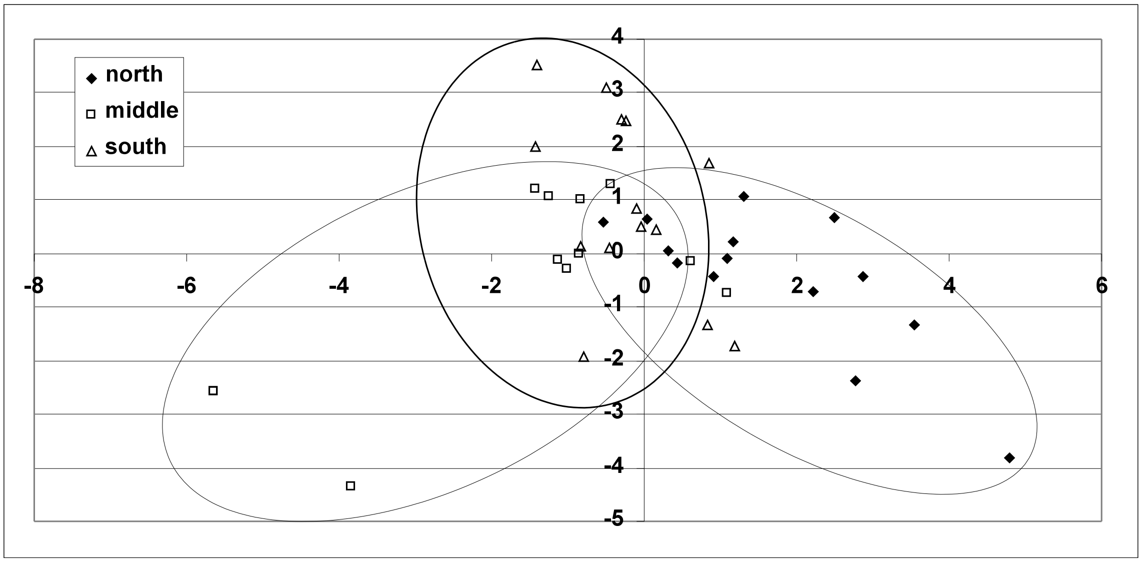


Figure 4.3. Principle components ordination of 40 sample plots. Note that there is a rough segregation of north (inland), middle, and south (coastal) sites, such that, with the exception of two outliers within the middle group, the second principle component generally represents a gradient from freshwater to saltwater.



Task 5 Sediment Biogeochemistry and Microbiology of Sulfate Reducing Bacteria.

Introduction

Sulfate reducing prokaryotes (SRP) are the primary anaerobic decomposers of organic matter produced by the marsh grass *Spartina* in coastal salt marshes (Howarth and Teal, 1979). Senescent biomass and root exudates of marsh grasses drive SRP community activity in anaerobic marsh sediments, especially when supplied with the their terminal electron acceptor sulfate which is abundant in seawater. Physiologically, the SRP community is versatile in the organic substrates utilized (Klepac-Ceraj et al., 2004), and some can grow independently of sulfate respiration via fermentation (Plugge et al., 2011). The SRP community in marsh sediment is very diverse (Klepac-Ceraj et al., 2004). Its composition varies with ecological differences in habitat (Devereux et al., 1996), including sediment characteristics (Purdy et al., 2002), seasonal differences in plant growth (Rooney-Varga at al., 1997), plant species-specific differences within rhizospheres (Nie et al., 2009), and exposure to pollutants such as petroleum hydrocarbons (Suárez- Suárez et al., 2011). Salinity tolerances vary among SRP taxa (Muyzer and Stams, 2008), and the SRP community structure in agricultural soils and brackish marsh sediments has been demonstrated to rapidly change (days-weeks) in response to seawater exposure due to sea-level rise (Melitto et al., 2010) or hurricane storm surge inundation (Rainey et al., 2010).

The byproduct of sulfate respiration by the SRP community is sulfide, a toxin. Much of the sulfide produced under anaerobic conditions reacts readily with metals, mostly ferrous iron. Sulfide reaching aerobic zones in the sediment or overlying waters may be oxidized by sulfide oxidizing bacteria, or escape from the marsh to the atmosphere as H_2S gas. At high sediment porewater concentrations (mM S^{2-}) sulfide becomes phytotoxic to root tissues of *Spartina* species and can limit marsh primary productivity (Mendelssohn and Morris, 2000). Conditions that favor increased rates of sulfate reduction to allow phytotoxic levels of sulfide to occur include abundant organic matter as substrate, water saturated sediments that limit O_2 diffusion and promote anaerobic condition, and ample supply of sulfate.

Coastal marshes of the Northern Gulf of Mexico experience multiple stresses, both nature and manmade, that impact SRP communities and their role as agents of sulfide phytotoxicity, marsh grass die-back, and subsequent sediment erosion of land area. Eustatic sea-level rise and subsidence due to petroleum extraction in the Cheneir Plain and Delta Plain of LA have caused a relative sea level rise of 6-12 mm/yr (White and Morton, 1997; Williams et al., 1994). Additional contributing factors to loss of marsh elevation include reduced sedimentation and sediment autocompaction due to organic matter decay (Day et al., 2011). Hurricane storm surge, such as Ike in September 2008, can inundate coastal marshes with seawater for kilometers inland, which should favor sulfate reduction in sediments by enhanced organic matter via vegetation die-back, anaerobic conditions, and sulfate supply.

This project task addresses the change in marsh sediment physicochemical characteristics and its relationship to the community structure of SRP at six study site in

Jefferson County, Texas, of varying distance from the Gulf of Mexico coast during the period of February 2010 to January 2011. In addition to molecular analysis of sediment SRB communities and sediment physicochemical parameters, vegetation cover and biomass was determined at each sediment coring site by Angela Shrift of the Texas Parks and Wildlife Department, Austin, TX (Schrift, 2011; appended to this document).

Methods

Sediment study sites:

Sites for marsh sediment physicochemical parameter, sediment molecular microbial analysis, and vegetation analysis were selected based on proximity to animal survey sites and within an area of locally representative vegetation (Fig. 5.1). The western N-S transect include the La Belle Property (BP) to the north, marsh adjacent to Clam Lake (CL) in the McFadden National Wildlife Refuge, and another site in the refuge just inland (ca 400 m) from the former dune system of McFadden Beach (MB), also in the refuge. The distances from the Gulf of Mexico coast were 10.7, 2.9, and 0.37 km for BP, CL, and MB sites, respectively. The CL site also had evidence of fire in the past couple years, and surface sediment at MB was mostly sand. The eastern N-S transect included sites in compartment 1 (Hillbank; HB) of the Hill Bank Unit and compartment 15 (Lost Lake; LL) of the Salt Bayou Unit of the J.D. Murphrey Wildlife Management Area, and a site in the Sabine Pass delta of the Texas Point (TP) National Wildlife Refuge. The distances from the Gulf of Mexico coast were 21.6, 11.0, and 0.83 km for HB, LL, and TP sites, respectively. The LL site in Pintail Flats has been characterized as ‘flotant’ marsh, as the vegetation is not well anchored in consolidated sediments. Eleven samplings were performed at each site from February 2010 to January 2011, except at the LL site where the last sampling was in late July 2010 due to the site being covered with dredge material in August 2010 during sediment subsidy restoration to counteract subsidence.

Before the first sampling, three 1.00 meter deep wells of PVC pipe were install at the ends and middle of 60 m transect at each site. Each well was fabricated from a 1.25 m long, 5.1 cm inside diameter, PVC pipe, drilled with 5 mm holes spaced at 1 cm increments for 98 cm from one end to allow porewater to enter. The porous end was capped before hammering into the marsh sediment to a depth of 1.0 meters, which left 25 cm above the sediment surface to prevent surface water from entering (Roman et al., 2001). Another cap was placed on the surface end to prevent rainwater accumulation in the wells. Depth of the water table was measured at each sampling.

Vegetation Biomass:

Both aboveground (live and dead) and belowground biomass was sampled in winter. A cube of sediment was excised from three randomly placed 0.1 m^2 quadrates, aboveground biomass was clipped to the sediment surface, and the root mass was removed by washing away sediment placed on 2 mm mesh screening. Obviously dead debris was removed and samples were allowed to air day for three days, after which they were dried for three more days at 85 ˚C in a forced-air drying oven before being weighedon a Metler digital pan balance at ± 0.1 g precision. Live and dead aboveground biomass was sorted and then dried and weighed as for belowground biomass.

A thorough student of vegetation cover, aboveground biomass, photo-documentation, and annual aboveground primary production at the sediment study sites was performed by Angela Schrift, TPWD, Austin, Texas, and her report (Shrift, 2011) is amended to this document.

Sediment cores and porewater collection:

At each site sampling, five sediment cores and five porewater samples were collected along the well transect, one adjacent to each well and the others at the midpoint between the three wells. Porewater was drawn from a 15 cm depth using a sipper-tube and vacuum generated by a 60 ml syringe equipped with a three-way valve (Roman et al., 2001; Portnoy and Giblin, 1997). Sippers were fabricated from 2 mm diameter stainless steel tubing with one end sealed by crimping and three holes cut within 1 cm of the crimp. Tygon tubing (4 cm) connected the outflow end to the syringe. About 3-5 ml of porewater was collected for sulfide, salinity and pH determination.

Sediment cores were collected by rotating and hammering 5.1 cm outside diameter polycarbonate tubing to a sediment depth of about 30 cm. Polycarbonate tubes were beveled at one end to facilitating cutting through grass roots. When sites were dry (e.g., MB and BP), polycarbonate tubes were first inserted within a 5.1 cm inside diameter PVC pipe, also beveled, to allow more force pounding into the sediment. Polycarbonate tubes with their core were capped at both ends with silicon stoppers until processed at the lab. In the lab cores were removed from tubing and cut into three sections (surface, middle , bottom) at about 6 cm increments depending on visibly distinct horizons of color change (deep brown at the surface to jet black in the middle) and mineral characteristic (dark grey-black clay), which varied with site and season (Fig. 5.2). Replicate horizons were pooled and homogenized before subsamples of each horizon were collected and stored for further chemical and molecular analysis. Sediment sample for water content and nucleic acid extraction were freshly frozen immediately at -70 ˚C until analyzed. Remaining sediment was spread-out on plastic sheeting, air dried for a week, pulverized to pass a 1 mm sieve, and then analyzed for ash free dry mass (AFDM) and sulfate.

Physicochemical analyses of porewater and sediment:

Porewater sulfide, redox potential, salinity, and pH were all measured in the field at the time of sample collection. Sulfide and salinity (ppt) was measured on porewater filtered through a 0.45µm Millipore™ Millex-LH filter unit. Salinity was measured on filtered sample by a refractometer. Sulfide analysis will use the methylene blue method (Cline, 1969; Simpson, 2001). Filtrate for sulfide analysis was drawn directly from a 4 cm length of tygon tubing connected to the syringe filter tip into a gas-tight syringe, diluted, and immediately reacted with methylene blue reagent (MBR). Sulfide reactions were read at 670nm in the lab with the Thermo Scientific™ Nano Drop 2000c spectrophotometer. Sulfide standard dilutions were made under a N_2 atmosphere in a glove bag and reacted with MBR as the samples. The pH of unfiltered porewater was measured with a Beckman™ ϕ10 pH Meter, calibrated in the field.

Redox potential and temperature were measured from a sediment depth of 15 cm at five random locations within a 2 m radius adjacent to each core, i.e. 25 readings total per site. Temperature was measured with alcohol thermometers (± 0.5 ˚C) after about five minutes of stabilizing. Redox potential was measured with six replicate platinum electrodes and a calomel reference electrode, which was inserted at the sediment surface. Platinum electrodes were constructed according to the design of I.A. Mendelssohn, Louisiana State University (Schrift, 2008; McKee, 1988). The exposed copper end of the Pt electrode was clipped to the cathode connector of a voltmeter and the calomel reference electrode was connected to the anode connector of the voltmeter. Readings were recorded as units of millivolts (mV) once stable. Field measurements using the calomel reference electrode were corrected to a standard hydrogen reference electrode by adding +244 mV.

Homogenized sediment horizons were used to determine water content, ash free dry weight (AFDW), and sulfate content. Water content was determined by difference in mass between 5 g of wet sample in tarred 5 cm diameter Al-foil boats and after drying for 24 hours at 85 ˚C in a forced-air drying oven. AFDW was determined on about 5 g of air dried sediment in tarred Al-foil boats by first drying for 24 hours at 65 ˚C in a forced-air drying oven and recording the mass. Oven dried sample was then combusted at 550 ˚C for 12 hours and the ash mass recordered. All mass measurements used a digital Metler analytical balance at ± 0.1 mg precision.

Sulfate content will be determined on 40 ml deionized water extracts of 5.00 g of air dry sediment using the barium sulfate method. Sediment and water in 50 ml conical centrifuge tubes will be shaken for 1 hour, followed by addition of 0.5 g activated charcoal dust (Hach Co.) and further shaking for 10 min to adsorb colored organic matter. The suspension was centrifuged for 10 min at 5,000 rcf in a 45˚ fixed angle rotor. The supernatant was transferred to a new tube for storage at 4 ˚C until analyzed. Sulfate in extracts was determined by the barium sulfate method according to USEPA protocol 375.4 for wastewater. Extract was diluted as necessary and reacted with a SulfaVer4 powder pillow (Hach Co.) according to manufactures instructions. Turbidity was measured as absorbance at 450 nm using a DR 2000 spectrophotometer (Hach Co.) standardized with sulfate solutions. Sulfate content is reported as μmol SO_4^{2-} g^{-1} dry sediment.

Molecular analysis of SRB communities:

The MoBio™ Powermax Soil DNA Extraction Kit was used to extract DNA from 10 g of the freshly homogenated sediment horizons. A 1 ml aliquot from each extract was stored in a sterile 2 ml cryotube with O-ring screw-cap at -20 ˚C until used as PCR template. The remaining 4 ml of DNA extract was arshived in the original 50 ml tube at -70 ˚C in case needed later. A nested PCR approach will be used to amplify a 350 bp fragment of the *dsr*B gene for DGGE analysis (Miletto *et al.* 2007). The first PCR performed is to amplify the *dsr*AB genes of SRP, which generates an amplicon of about

1900 bp (Loy et al., 2002). The 25µl reaction volume contained, 1µl of soil extract DNA (about 50ng/µl DNA concentration), 12.5µl of 2x AccuPrime Super Mix II (Invitrogen, Carlsbad, CA), 0.5 µl of each primer, and 10.5µl sterile DNase-free PCR-grade water. Product of the *dsr*AB1900bp PCR were then used as template for the *dsr*B-DGGE PCR (Miletto *et al.*, 2007). The *dsr*B-DGGE PCR reaction included 2µl of *dsr*AB1900bp PCR products as template, 25µl of 2x AmpliTAQ Gold TAQ polymerase with 5µl GC Enhancer, 1 µl of each primer, and 16 µl of sterile DNase-free PCR-grade water to a 50 µl reaction volume.

The *dsr*B-DGGE PCR products were run on a a 1.5mm thick 8% [w/v] polyacrylamide gel with a gradient of 30-70% [w/v] denaturant (100% denaturant contained 7M urea and 40% [v/v] formamide). Cap gel (8% [w/v] polyacrylamide with 0% denaturant) was cast on top of the gradient gel to prevent any anomalies due to differential interactions of DNAs as they enter the gradient. A 25 well comb with 1.5mm well width was used. Lanes were loaded with 3 µl of PCR reaction. Four replicates of "marker" sample derived from SRP enrichment cultures were run on both outer and two inner lanes of each gel for standardization of relative migration distances among lanes between gels. Gels were run at 150 V for 6h, at 60.0°C (Dar *et al.* 2007). After the run, the gel was stained with SybrGreen I for 15 min, and then digital imaged using the Fotodyne Imaging System. Bands with relatively high DNA content, i.e. dominant, and other uniquely uncommon bands were excised from the gel with a razor blade, rinsed briefly in sterile DNase-free PCR-grade water and archived in microcentrifuge tubes at -80 ˚C for future reamplification, sequencing, and BLAST analysis for identification.

Data analyses:

Descriptive statistics of physicochemical parameters were determined in Microsoft Excel. For all physicochemical parameters of porewaters and sediment horizons, the mean and standard deviation were calculate for replicate measurements at each site and sampling period. Annual means and 95% confidence intervals were determined for comparisons between sites and with horizon depth. To explore important relationships among parameters, principle component analysis will be performed on all parameters and site means for all sampling periods using SYSTAT v13 software with pairwise deletion.

All DGGE gel images were analysed with Phoretics Software v1.0 to determine band intensity and migration distances relative to marker bands. These data were used to construct dendrograms using the unweighted pair-group method using arithmetic averages (UPGMA). By defining each band as an operational taxonomic unit (OTU) of SRP, the number of bands and their relative intensities can be used to calculate a Shannon diversity index (H'), along with evenness (E) and richness (S), for the SRP community of each sample.

Results:

Vegetation biomass:

There was no significant different ($p > 0.05$) in total aboveground biomass between any sites, but this appears to be attributed to variation in dead biomass rather than live biomass (Fig. 5.3). Live aboveground biomass was lowest at LL ($p < 0.05$) relative to all other sites. The high live aboveground biomass at MB was attributed to woody shoots of *Iva* sp. Dead above ground biomass was about equal to below ground biomass at most site. The LL site had extreme variation attributed to one quadrate falling on sediment nearly devoid of biomass. Belowground biomass in the eastern transect sites was greatest at TP ($p < 0.05$).

Sediment physicochemical properties:

Sediment temperature varied throughout the year as expected for the temperate climate (Fig. 5.4). Maximum sediment temperature at time of sampling was greater in summer months at the western N-S transect sites than eastern N-S transect sites. The most erratic profile was at the BP site (Fig. 5.4A). Daily weather differences and time of day during sample collection needs to be considered in drawing conclusions, and that greater water content and the high heat capacity of water may determine the sensitivity of sediment to daily changes in solar radiation and air temperature.

Annual mean percent water content (Fig. 5.5A) was greater at all depth for eastern N-S transect site. For most sites there was a trend of decreasing water content with depth, with the consolidated clay bottom horizon with 30-40% water content. Lost Lake sediment was about 80% saturated at both surface and middle horizons ($p > 0.05$) and the bottom horizon had 60 % water content which was greater ($p < 0.05$) than any other sites' bottom horizon. On the western N-S transect, the mean annual water content was greatest at CL for all three depths ($p < 0.05$). The driest site was MB, which experiences sand deposition during the storm surge in September 2008. Here the moistest sediment was in the bottom horizon. During the year, water content of surface sediment was variable at western N-S transect sites, with driest months in May to July 2010 and again in October and November (Fig. 5.6A), which coincides with precipitation patterns in 2010 (not shown). Porewater could not be drawn for three months in spring at BP and CL, and for three months in fall at BP. Porewater could be drawn only in February and March 2010 at MB (Table 5.1), where PVC wells were mostly dry the remainder of the study year. In contrast, there was relatively little seasonal variation in water content of surface sediments at eastern N-S transect sites (Fig. 5.6B), where PVC wells were typically full, surface sediment remained saturated at 70-85% water content, and porewater was easily drawn throughout the year.

Annual mean sulfate content (Fig. 5.5B) was lowest (< 15 μmol SO_4^{2-} g^{-1} dry wt) in the drier sediments of BP and MB, and in middle and bottom horizons of HB. Clam Lake had the highest surface sulfate concentrations of any site; the concentration was around 150 μmol SO_4^{2-} g^{-1} dry wt from May until August when concentrations decreased to < 50 μmol SO_4^{2-} g^{-1} dry wt (Fig. 5.7A) coincident with increased rainfall. The greatest annual mean sulfate content was in surface sediments of LL (Fig. 5.5B); however, LL annual means only include the months from February to July. Hillbank surface sediment lost sulfate during most of the year, but with the most dramatic loss from July to September (Fig. 5.7B). Surface sulfate increased at TP from February to June, but then declined until October 2010.

The LL site also had the highest annual mean % AFDM ($p < 0.05$), which is a proxy for organic matter content (Fig. 5.5C). Percent AFDM was generally lower ($p < 0.05$) in the bottom clay horizon, except for the MB where recently deposited sand covered a more organic rich dark sandy horizon. As with water and sulfate contents, there was no difference ($p > 0.05$) in the annual mean %AFDM between surface and middle horizons at LL. Surface sediment % AFDM did not vary much throughout the year at BP, CL, MB, and TP, but there was a slight rise from fall to winter (Fig. 5.8). The BP surface %AFDM was erratic with decreasing content in winter.

Annual mean porewater salinity (Fig. 5.9A) increased from the north at HB (7 ppt) to south at TP (25 ppt). A similar increase occurred from BP (5 ppt) to CL (25 ppt); however, surface sediment at MB to the south of CL was 10 ppt, on average for the February and March 2010, which were the only two months when porewater could be drawn at MB (Table 5.1). The 8 ppt lower porewater salinity at MB than CL sediments may have facilitated rain water leaching of sea salts deeper into the sandy sediments at MB. Although there were too few porewater samples to discern a seasonal pattern at BP and MB, porewater salinity increase at CL from about 18 ppt in late winter to about 25-29 ppt from June 2010 to January 2011 (Table 5.1). During the drier months from May through July 2010, the porewater salinities at both LL and TP increased by about 10 ppt, after which values remained relatively constant at TP (Fig. 5.10A). In contract, during these same drier months the salinity at HB decreased by about 5 ppt, which may be related to the control of freshwater flow into this managed wetland compartment.

Annual mean pH values did not vary more than a one unit of pH (Fig. 5.9B). Annual mean pH was about 6.5 at the moist, organic rich sites of the eastern transect, and lower ($p < 0.05$) at the drier sites to the west, BP and CL. The MB site was an exception to the latter; this sandy site had the highest annual mean pH of 6.9, but again this was an average for just February and March 2010 (Table 5.1). The pH values at HB and TP increased from late summer 2010 to winter 2011, but by about 0.6 units (Fig. 5.10B).

The porewater samples that could be drawn at the drier western N-S transect sites had either undetectable sulfide concentrations or just a few micromolar (Table 5.1). This is a curious result for the CL site where sediment was more saturated with seawater, based on water content, sulfate content, and porewater salinity. In contract, annual mean sulfide concentration (Fig. 5.8C) was 1.2 mM at LL, and 200 µM and 400 µM at HB and TP, respectively. There were distinctly different seasonal variations in porewater sulfide concentrations (Fig. 5.10C). At HB, the mean concentration increased from undetectable levels in March to 550 µM in June 2010 when concentrations ranged from 200 µM to 1.4 mM along the sampling transect. By July the concentration had decreased to < 80 µM and remained low to undetectable throughout the remaining study period. Porewater sulfide at LL was never below 200 µM in any replicate sample, and lowest mean value was 360 ± 180 µM in spring, after which the mean concentrations increased to 3.0 ± 0.64 mM in late July. Unlike the seasonal trends at HB or LL, porewater sulfide concentration remained undetectable to < 50 µM from February until July when mean concentration reached 0.9 mM. Sulfate content in the TP sediment was also initially low at the beginning of the study, in contrast to ≥ 100 µmol SO_4^{2-} g^{-1} dry wt at BH and LL. The sulfide concentration at TP continued to increase from mid-summer into fall, reaching a maximum of 1.6 mM by October 2010 and then declining to about 80 µM in January 2011.

Annual mean redox potentials were positive for all sites but at LL, which was -90 ± 40 mV and significantly different from annual means of the other sites (Fig. 5.8D). The only other significant difference ($p < 0.05$) was between TP and MB, the site with the second highest porewater sulfide concentrations and the driest site, respectively. Mean redox potential at the western N-S transect sites did not vary greatly after spring 2010, and CL values were less than BP and MB for most months (Fig. 5.11A). LL mean redox potentials did not vary, but those at HB went from negative in spring when sulfide concentration increased in porewater to a dramatic shift to positive values in August 2010 (Fig. 5.11.B). The TP values gradually increased from 20-50 mV in spring to > 120 mV by late fall 2010 and January 2011; the increase in redox potential during late summer and early fall is counter intuitive given the accumulation in porewater sulfide concentration during this same period.

A principle component (PC) analysis of the sediment physicochemical data for all sites and samples dates was performed to help identify parameters driving variation among sites. Four components explained 78 % of the variance in the data set (Table 5.2). Parameters with loading values > 0.6 or < -0.6 were considered important to driving variance in the data. PC1 explained 44% of data variance largely due to redox, water and sulfate content, %AFDM, and sulfide concentration. Salinity and distance from the coast drove PC2, which explained 17% of variance. PC3 and PC 4 explained less than 10% of variance and were driven mostly by pH and temperature, respectively. A plot of principle component values of each site for PC1 and PC2 reveals distinct clusters for each site (Fig. 5.12), with LL being most unique due having conditions favoring sulfate reduction, i.e. high water content, sulfate, sulfide, and organic matter and negative redox. Sites with low or no sulfide in their porewaters generally had opposing conditions. For MB there was at least one missing parameter for all sampling dates, which excluded it from the PC plot.

SRB communities:

Denaturing gradient gel electrophoresis (DGGE) of amplified *dsr*B genes was performed for each depth horizon at five annual intervals (Feb-Apr, May-June, July-Sept, Oct-Nov, and Dec-Jan) for BP, CL, MB, HB, and TP. All month sampled at LL were analyzed. Each gel band was considered an operational taxonomic unit (OTU), and dendrograms were constructed to compare the similarity in SRP community structure at each site.

Along the western N-S transect surface SRP communities were generally more similar throughout the year for surface sediments at BP (Fig. 5.13) and CL (Fig. 5.14) than at MB (Fig. 5.15). At BP surface communities were > 55% similar for all season but Oct-Nov. Middle horizon communities were > 60% similar for three of five seasons, with July-Sept and Dec-Jan being very anomalous < 40% similar to all other communities identified (Fig 5.13). There were similarities between middle and bottom depth communities from Feb to June. After which the bottom community underwent a transition to less similar community structure. The CL surface community was > 70 % similar throughout the year (Fig. 5.14), with Feb-June being 83% similar. Middle and bottom horizon communities were > 70% similar during this same period. After which the middle and bottom horizon communities each changed to communities that were 45% and 55 % different, respectively, from those prior to July. For the MB surface community there was greater stability in middle horizons (4 of 5 seasons with > 70% similarity) and bottom horizons (3 of 5 seasons with > 63% similarity) than at the surface where similarity was just 45-60% (Fig. 5.15), and there was less stability at these depths than those for BP and CL. The number of OTUs (bands) that were ubiquitous within a site over time and depth were 4, 8, and 0 for BP, CL, and MB, respectively.

Along the eastern N-S transect surface and middle community had greater similarity the with bottom communities at BP and TP, but the reverse was seen for LL where middle and bottom communities were more similar than at the surface. At HB bottom communities varied more throughout the year than for most seasons at the surface (Fig. 5.16). At LL the surface horizon community was > 77% similar from May-July when sulfide was accumulating rapidly in porewaters (Fig. 5.17). The middle and bottom communities at LL were more similar to each other than to the surface communities, and bottom communities were > 70 similar from Feb – June. At TP the surface and middle communities were more similar (> 75%) to each other than to the bottom community, which differed by > 60% (Fig. 5.18). The number of OTUs that were ubiquitous within a site over time and depth were 4, 10, and 5 for HB, LL, and TP, respectively.

Discussion:

Most marsh sites for sediment analysis were dominated by *Spartia patens*, except for the *Distichlis spicata* dominated site near Clam Lake (CL) in the McFadden National Wildlife Refuge (Schrift, 2011). McFadden Beach (MB) also had about 50% cover of *Borrichia frutescens* and *Spartina spartinae*. Texas Point (TP) had about 40% cover as dead *Schoenoplectus americanus*, no growth was observed during the study period suggesting this species has not recovered since Hurricane Ike. Lost lake was essentially a mono-culture of *S. patens* (species richness of 1.3). There was about 55% cover of dead S. patens than live at the Lost Lake (LL) site, which was at least three times more dead vegetation relative to live than at any other site (Schrift, 2011; Fig. 5.3). Annual areal primary production for above ground vegetation was 900-1400 g dry wt m^{-2} for CL and HB. Primary production at TP and LL were about a third and tenth, respectively, of CL and HB. Aboveground live biomass at LL was about a fifth of other sites, and that for total belowground biomass was also less than other sites (Fig. 5.3). Longer term studies are necessary to further understand the vegetation recover to hurricane storm surge, especially when compared to other manmade impacts such as subsidence, hydrodynamic alterations within, the watershed and eustatic sea level rise.

The most northern site along the western transect of this study, BP, was below a water management spill-way, which may have contributed to its drier conditions. BP sediment was susceptible to variations in water content. The most stable SRP communities were below the surface horizon, and when the sediment had highest water content, and porewaters could be sampled. With its positive redox, low water content and low sulfate the site never experienced sulfide accumulation; although the organic matter content in the surface sediment was comparable to eastern transect sites.

Clam Lake was a site that had undergone burning prior to Hurricane Ike, and charred shoots were still evident. For all but three month from May-July the sediment was saturated enough to draw porewaters. During the dry conditions in late spring, sediment sulfate content increased. After July when porewater could be collected the salinity has increased about 8 ppt compared to early spring. By October and through January 2011 sulfate content returned to levels seen in February 2010. There was no sulfate accumulation at Clam Lake despite saturated sediments and sulfate availability, the redox potential was never negative. Two differences at this site aside from SRB communities was the dominance of *D. spicata* and about half the organic content, i.e. %AFDM) in the sediment. The SRP communities changed community structure following the May-July dry period, although there were 8 OTUs that were ubiquitous in time and depth suggesting a larger resilient sub-community than seen at other sites where the environment was variable.

The MB site closest to the coast had a sand layer of about 10 cm deposited by Hurricane Ike, which kept sediments particularly dry and low in organic content and sulfate. Sandy sediment of an elevated marsh like at MB will allow leaching of ions from the surface sediment during rain events. Lack of ample sulfate and organic matter under largely aerobic conditions (positive redox) does not favor high sulfate reduction rates. The SRP community was the most variable at this site, and there were no obvious OTUs that were ubiquitous in time and depth. We contend that this is a harsh environment for SRP, which appears to have greater OTU richness at MB than other sites.

The most northern site along the eastern transect of this study, HB, was within a management compartment that could have surface water flow regulated. Efforts had been made during our study period to increase the flow and turnover of the compartment to facilitate “freshening” of the wetlands within. It was interesting to see that while most other sites experienced increased salinity sulfate from spring to summer 2010 during drier weather conditions, the salinity and sulfate at HB decreased. Although sulfide began to accumulate at the site during this period, it then decreased by August 2010. Although salinity continued to fluctuate around 7 ppt for the remainder of the year the sulfate concentrations continued to decline, suggesting that sulfide production by sulfate reducing bacteria was balanced by metal precipitation and oxidation reaction to prevent its accumulation in porewaters. Lack of sulfide favors root health and uptake of nitrogen; hence overall great primary production. SRP communities at HB were more dynamic than at other high water content sites, CL, LL, and TP, and there were fewer ubiquitous SRP OTUs throughout the year and with depth compared to other sites.

Lost Lake site was not only distinct in its vegetation but it also had unique sediment biogeochemistry suggestive of high sulfate reduction rates. The sediment was water saturated, rich in organic matter relative to other sites, and high in sulfate and salinity, especially upon as weather condition became drier in spring and early summer in

2010. This is a site that is presumed to have experienced subsidence, and was scheduled for sediment subsidy restoration in August 2010. Although an annual profile at this site was not possible due to dredge fill covering the site as part of the restoration, the six months studied does suggest that salinity and sulfate are not a result from Hurricane Ike. Instead, we suggest that saltwater intrusion from canals or groundwater is more likely contributing to chemical conditions favoring sulfate reduction and sulfide accumulation to phytotoxic level. The SRP community at LL was fairly stable compared to other sites, especially at the middle and bottom core horizons where redox potential was negative.

Texas Point was sediment was not in a flotant marsh state like at the LL site, and was at a lower water content in surface sediments than at HB or LL. Like CL and LL, during the dry period of May-June 2010, the sulfate content and salinity increased. Salinity continued to increase during summer, but sulfate declined to low (< 40 µmols g^{-1} dry wt) by September and remained there into January 2011. With the decline sulfide began to accumulate in porewaters, to 0.8 to 1.4 mM during fall. The SRP community remained fairly stable and comparable for surface and middle sediment horizons collected, and it was the bottom community that varied more during the year. A perplexing result for TP was that we never measured negative redox values despite active sulfate reduction, based on porewater sulfide accumulation. One simple explanation for this was that sulfate reduction was happening at a greater depth than our 15 cm deep redox measurements, which would suggest that what was measured in the porewater collected at 15 cm was the result of a diffusive sulfide flux. Alternatively, based on the high belowground plant biomass and the pronounced bands on DGGE gels suggestive of SRP dominant populations, one can speculate that our redox probes were responding to both anaerobic and aerobic conditions, with the latter due to oxygen release by plant roots. Either hypothesis for sulfide accumulation in the presence of positive redox potentials would help explain the large variation in sulfide concentration among replicate porewater samples.

As with the vegetation analysis, a longer term study could more definitively determine the effect of sea salts from Hurricane Ike storm surge on sediment biogeochemistry versus other. During the February 2010 to January 2011 study period the seasonal weather patterns, especially periods of drought, appear to be a greater controlling factor for explain some of the physicochemical and SRB community changes over time. The increase in salinity and sulfate under drier conditions may be evidence of saltwater intrusion due to limited freshwater flow and lowering of the water table. Between site variation appears to be influenced by factors effecting sediment water content and composition, such as subsidence and proximity to a seawater supply via canals which facilitate tidal exchange further into the marsh. Clearly there are differences in related to water content, anaerobic conditions, sulfate supply, sulfide production, and the SRP community response between the western and eastern transect sites of this study.

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Table 5.1. Mean values (± SD; n = 5) for porewater salinity, pH, and sulfide concentration for the western N-S transect sites.

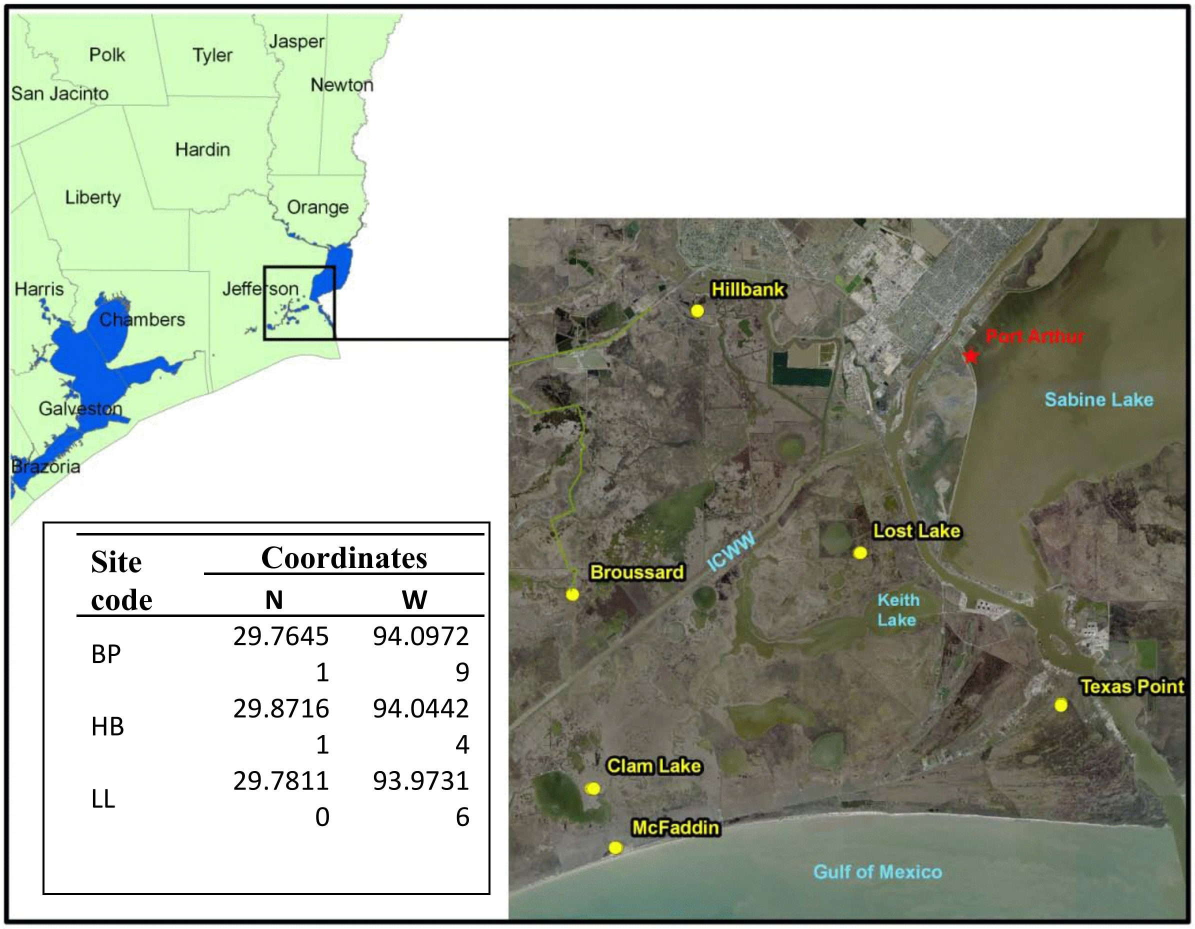
Site	Date	Salinity (ppt)	pH	Sulfide (mM)
BP	2/24/2010	5.6 ± 2.3	6.1 ± 0.15	nd
BP	4/6/2010	7.7 ± 1.2	6.0 ± 0.14	0.003 ± 0.005
BP	4/26/2010	td	td	td
BP	5/26/2010	td	td	td
BP	6/22/2010	td	td	td
BP	7/30/2010	3.4 ±1.9	5.9 ± 0.14	0.003 ± 0.004
BP	9/1/2010	td	td	td
BP	10/1/2010	td	td	td
BP	10/27/2010	td	td	td
BP	12/4/2010	2.0 ± 0.0	6.4 ± 0.00	0.000 ± 0.000
BP	1/14/2011	9.0 ± 1.7	5.8 ± 0.22	0.001 ± 0.001
CL	3/12/2010	20.8 ± 0.91	6.3 ± 0.03	nd
CL	4/5/2010	15.6 ± 2.97	6.3 ± 0.08	0.004 ± 0.007
CL	4/27/2010	td	td	td
CL	5/25/2010	td	td	td
CL	6/23/2010	td	td	td
CL	7/29/2010	27.2 ± 4.60	5.7 ± 0.13	0.004 ± 0.007
CL	9/3/2010	25.4 ± 4.28	5.9 ± 0.12	0.001 ± 0.000
CL	10/2/2010	28.4 ± 2.19	6.0 ± 0.12	nd
CL	10/30/2010	29.2 ± 1.04	6.2 ± 0.14	0.001 ± 0.000
CL	12/3/2010	28.6 ± 1.98	6.2 ± 0.14	0.001 ± 0.000
CL	1/13/2011	27.2 ± 2.59	6.2 ± 0.17	0.001 ± 0.001
MB	3/12/2010	9.7 ± 4.49	7.0 ± 0.20	nd
MB	4/5/2010	12.5 ± 4.95	6.8 ± 0.14	nd
MB	4/27/2010	td	td	td
MB	5/25/2010	td	td	td
MB	6/23/2010	td	td	td
MB	7/29/2010	td	td	td
MB	9/3/2010	td	td	td
MB	10/2/2010	td	td	td
MB	10/29/2010	td	td	td
MB	12/3/2010	td	td	td
MB	1/13/2011	td	td	td

nd = not detectable.

td = too dry; no porewater collected.

Table 5.2. Component loadings from principle component analysis of sediment physicochemical parameters. The percent of total variance explained by each PC is given in parentheses.

Sediment Parameter	PC1 (44 %)	PC2 (17 %)	PC3 (9 %)	PC4 (8 %)
Distance from coast	0.294	0.845	0.351	-0.051
Sediment temperature	0.100	-0.268	0.429	-0.799
Redox potential	-0.655	0.020	0.305	0.230
Surface water content	0.799	0.221	0.146	0.294
Middle water content	0.932	0.017	0.071	0.197
Bottom water content	0.885	0.020	-0.076	0.165
Surface AFDM	0.749	0.497	0.186	-0.052
Middle AFDM	0.828	0.124	-0.135	-0.088
Bottom AFDM	0.699	0.052	-0.336	-0.039
Surface sulfate	0.748	-0.230	0.294	0.023
Middle sulfate	0.753	-0.452	0.206	0.073
Bottom sulfate	0.685	-0.584	0.180	0.125
Porewater salinity	0.036	-0.835	-0.234	0.142
Porewater pH	0.247	0.322	-0.733	-0.110
Porewater sulfide	0.609	-0.110	-0.267	-0.518



Site code	Coordinates	
	N	W
BP	29.76451	94.09729
HB	29.87161	94.04424
LL	29.78110	93.97316

Figure 5.1. Map of Southern Jefferson County, Texas, indicating the six Lamar sediment and TXPWD vegetation sites: La Belle Property (BP), Hillbank (HB), Lost Lake (LL), Clam Lake (CL), McFadden Beach (MB), and Texas Point (TP) (modified from Schrift, 2011).

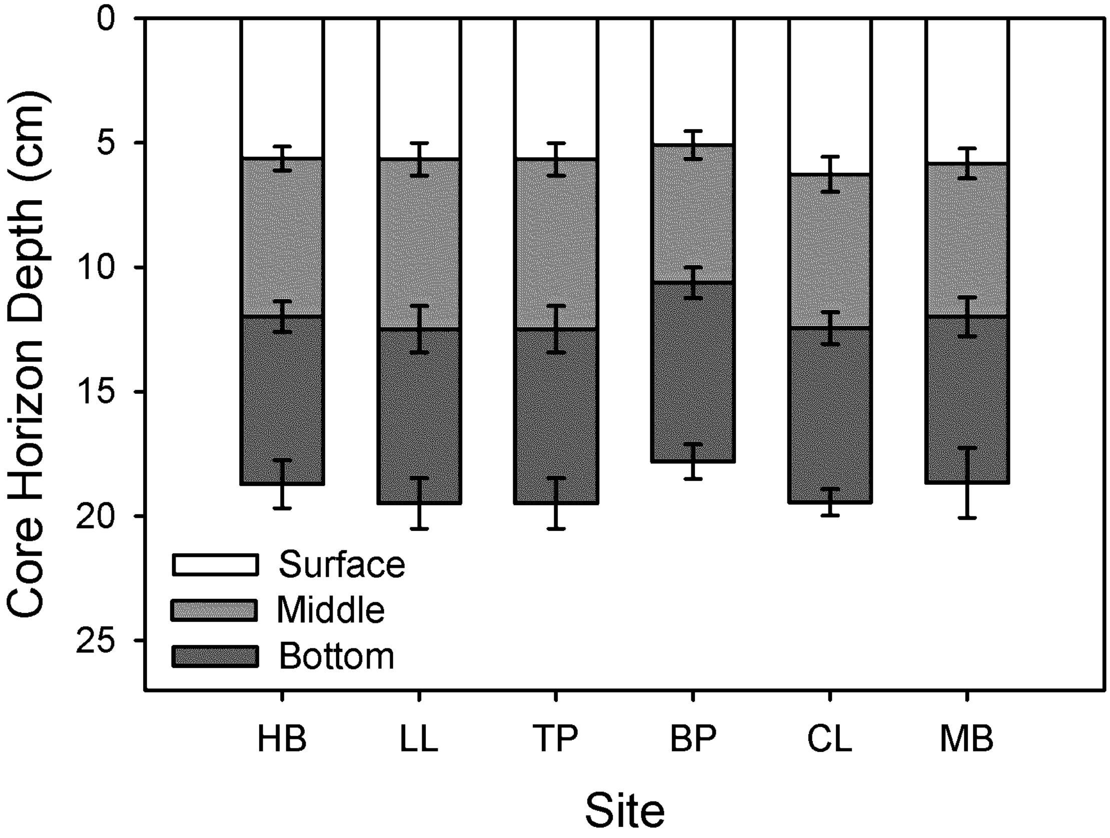


Figure 5.2. Average depths of sediment core horizons sub-sampled for chemical and microbial analyses. Error bars are ± 95% confidence intervals ($\alpha = 0.05$; $n = 11$, except LL where $n = 6$).

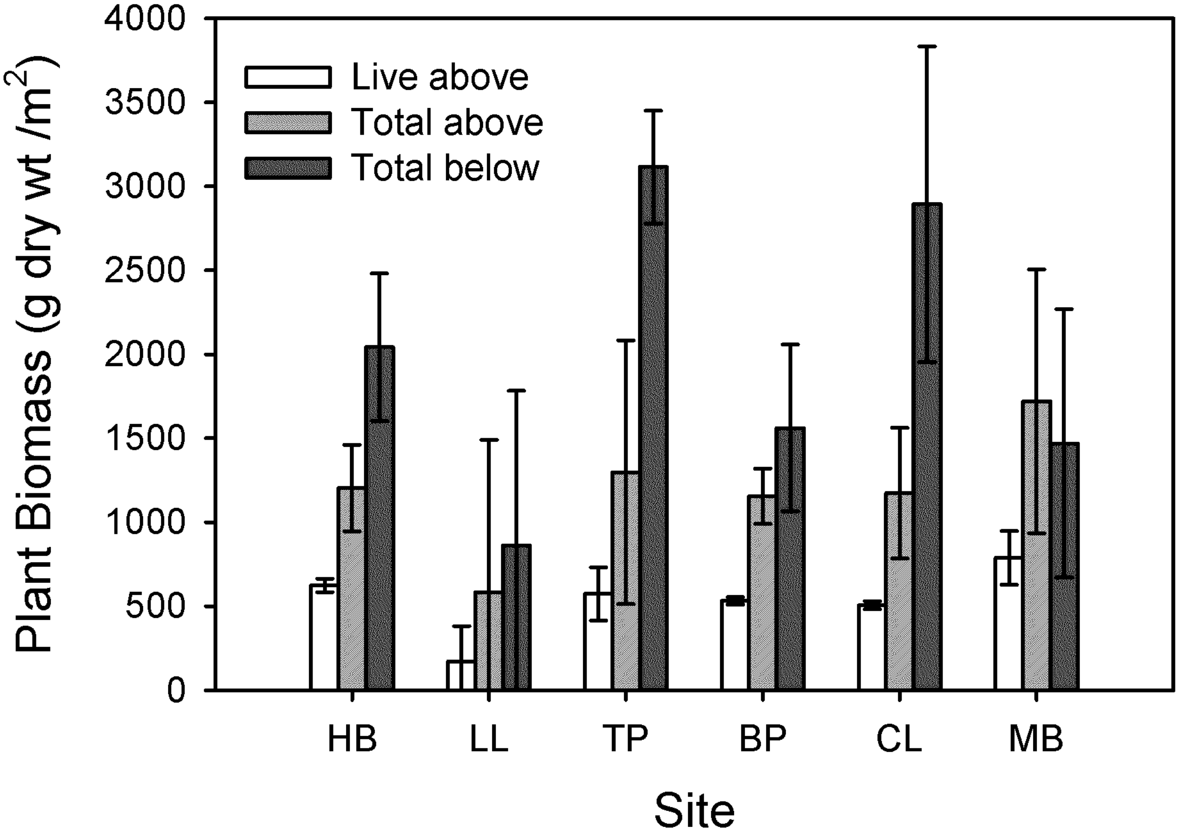


Figure 5.3. Average winter aboveground (live and total) and total belowground biomass. Error bars are ± SD (n=3)

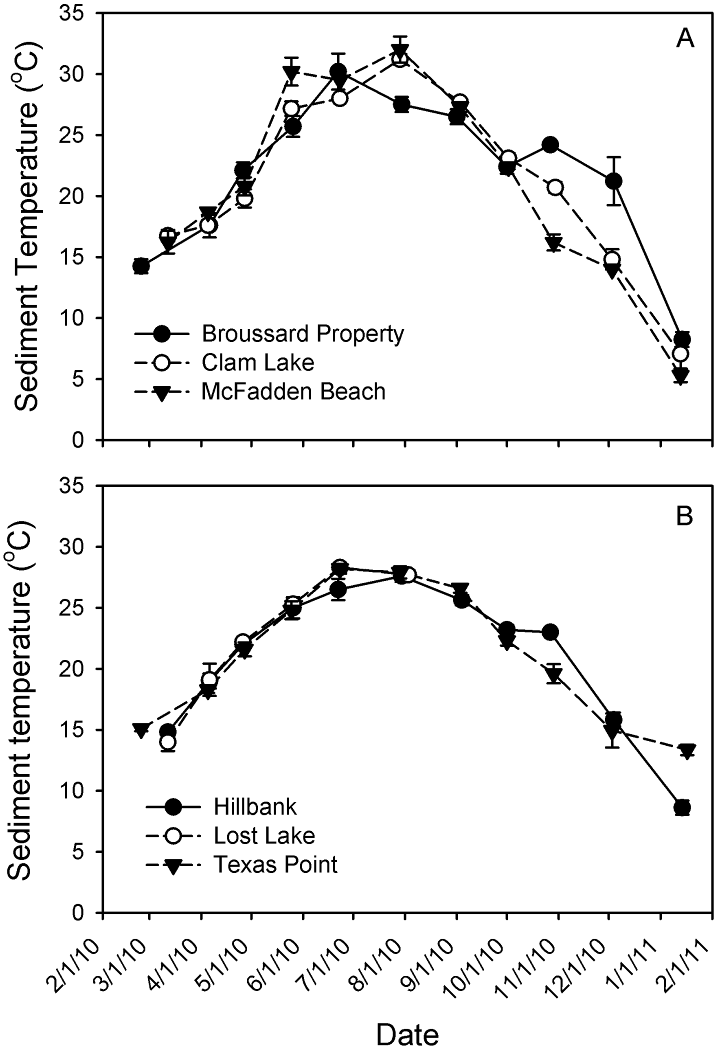


Figure 5.4. Sediment temperature at 15 cm depth for the western N-S transect (A) and eastern N-S transects (B) from February 2010 to January 2011 for all sites but Lost Lake when the last sampling was in late July 2010. Error bars are ± SD (n = 5).

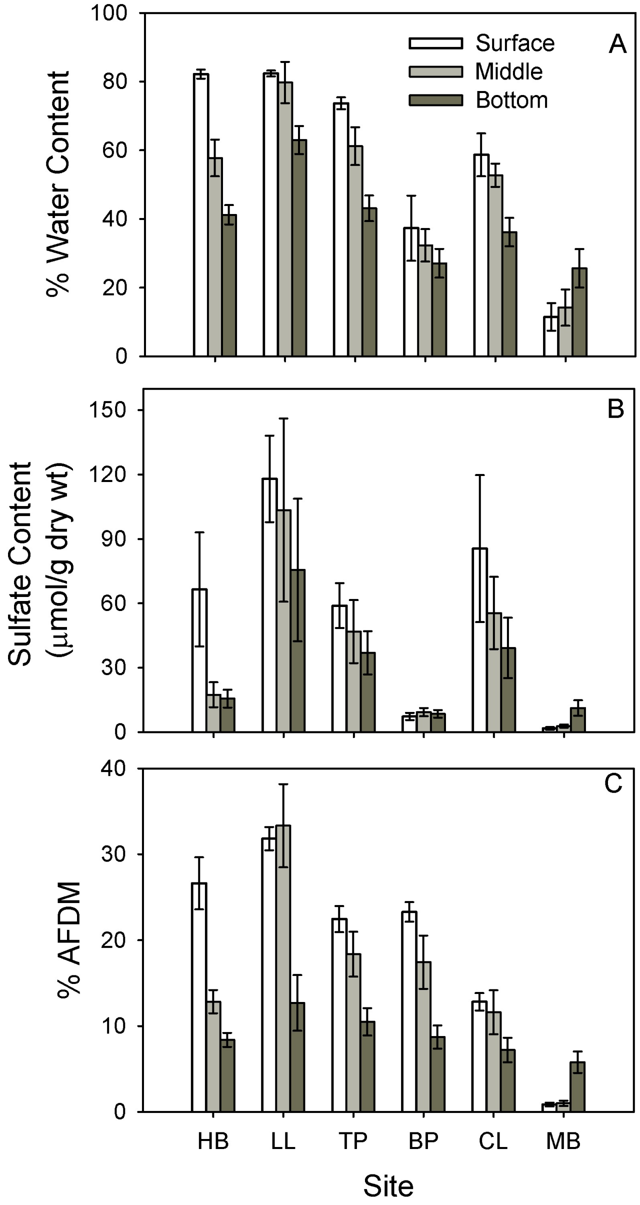


Figure 5.5. Annual mean of percent water content (A), content of extractable sulfate (B), and percent ash free dry mass (% AFDM; C) in sediments collected from February 2010 to January 2011. Error bars are ± 95% confidence intervals (α = 0.05; n varied with site; see Table 5.1).

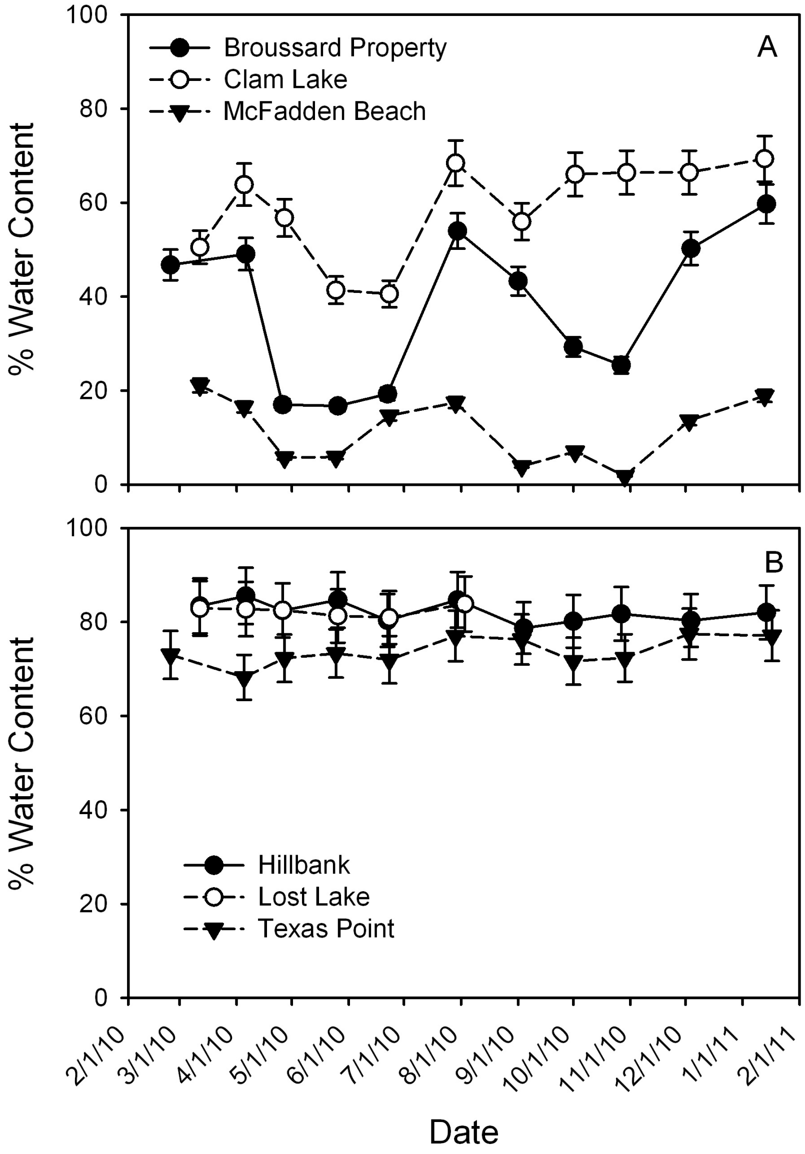


Figure 5.6. Percent water content in the surface sediment horizon for the western N-S transect (A) and eastern N-S transects (B) from February 2010 to January 2011 for all sites but Lost Lake when the last sampling was in late July 2010. Error bars are ± SD (n = 3).

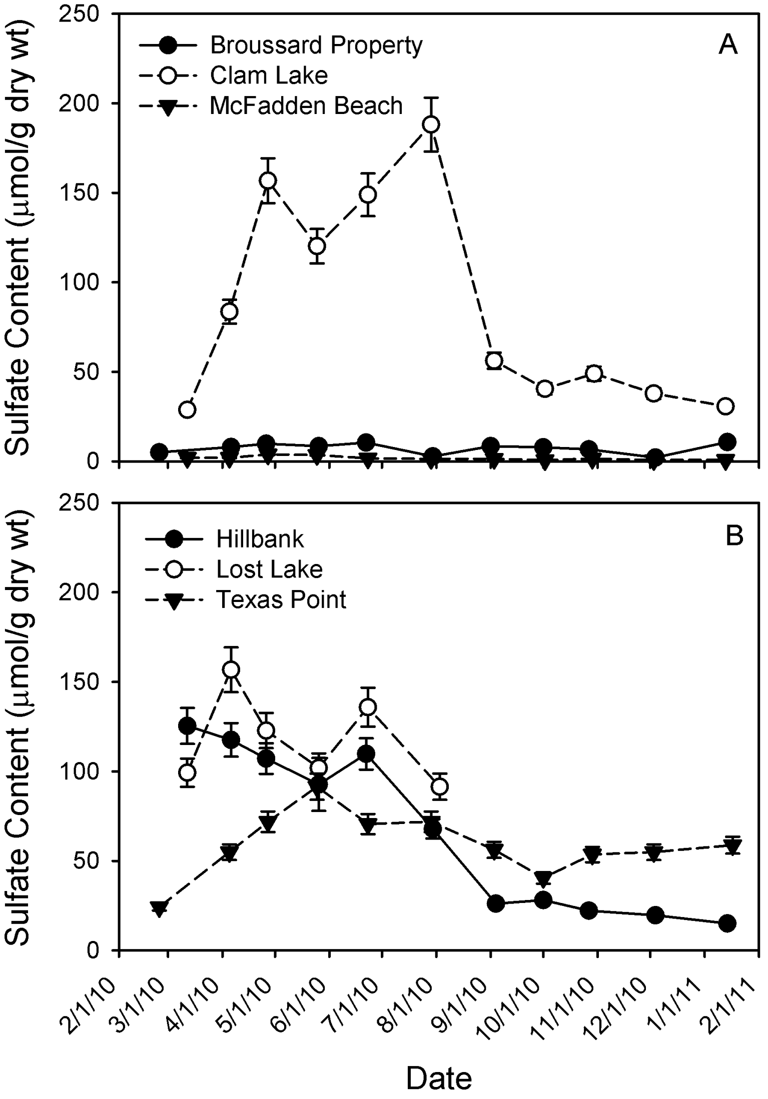


Figure 5.7. Extractable sulfate content of sediment from surface horizons for the western N-S transect (A) and eastern N-S transects (B) from February 2010 to January 2011, for all sites but Lost Lake where the last sampling was in late July 2010. Error bars are ± SD (n = 3).

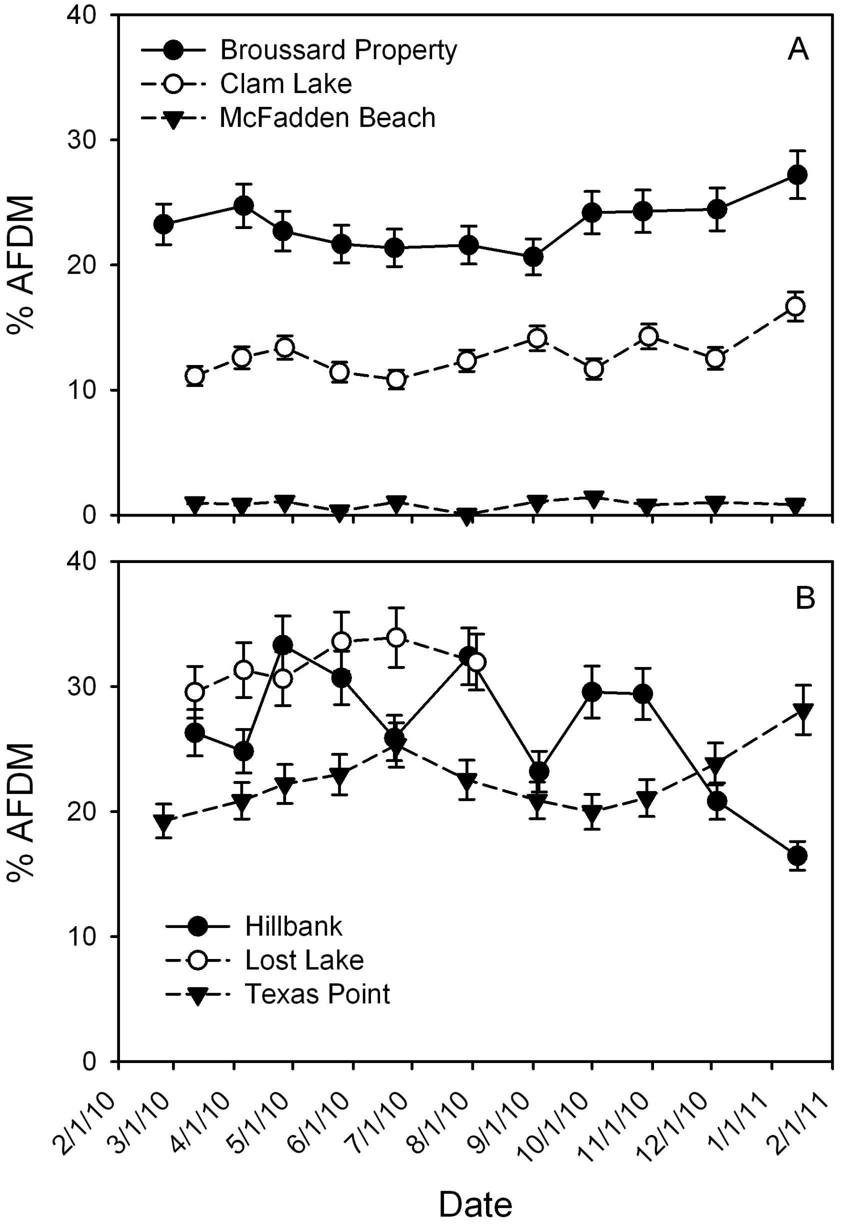


Figure 5.8. Percent AFDM content of dry sediment from surface horizons for the western N-S transect (A) and eastern N-S transects (B) from February 2010 to January 2011, for all sites but Lost Lake where the last sampling was in late July 2010. Error bars are ± SD (n = 3).

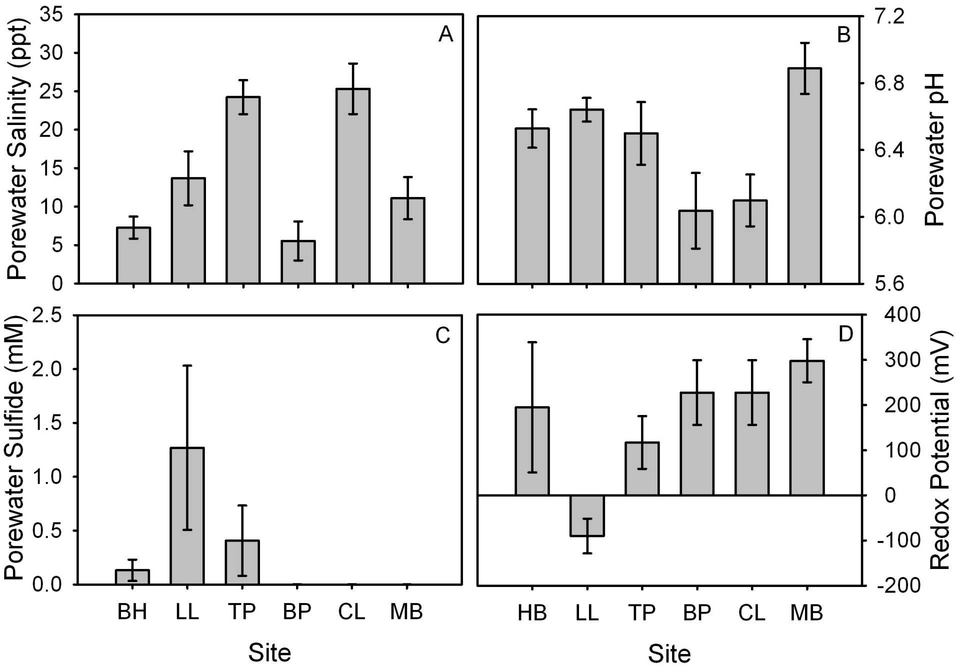


Figure 5.9. Annual mean of porewater salinity (A), pH (B), and sulfide concentration (C) and sediment redox (D) for February 2010 to January 2011. Error bars are ± 95% confidence intervals ($\alpha = 0.05$; n varied with site; see Table 5.1).

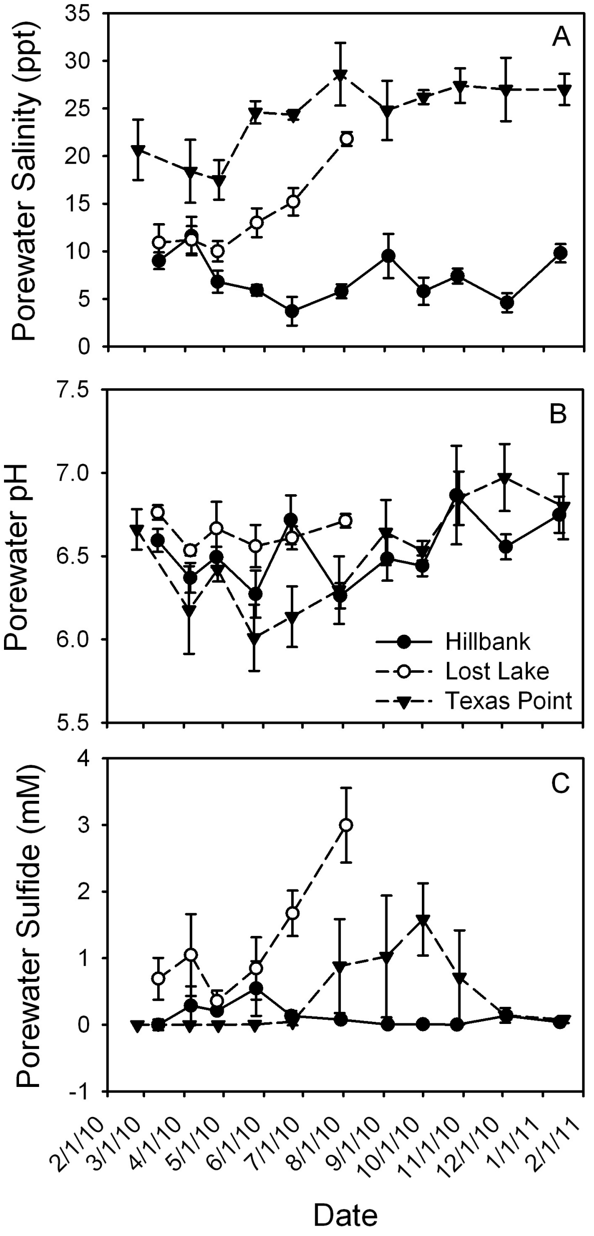


Figure 5.10. Sediment porewater salinity (A), pH (B), and sulfide (C) at 15 cm depth for the eastern N-S transect sites sampled from February 2010 to January 2011 for all sites but Lost Lake when the last sampling was in late July 2010. Error bars are ± SD (n = 5).

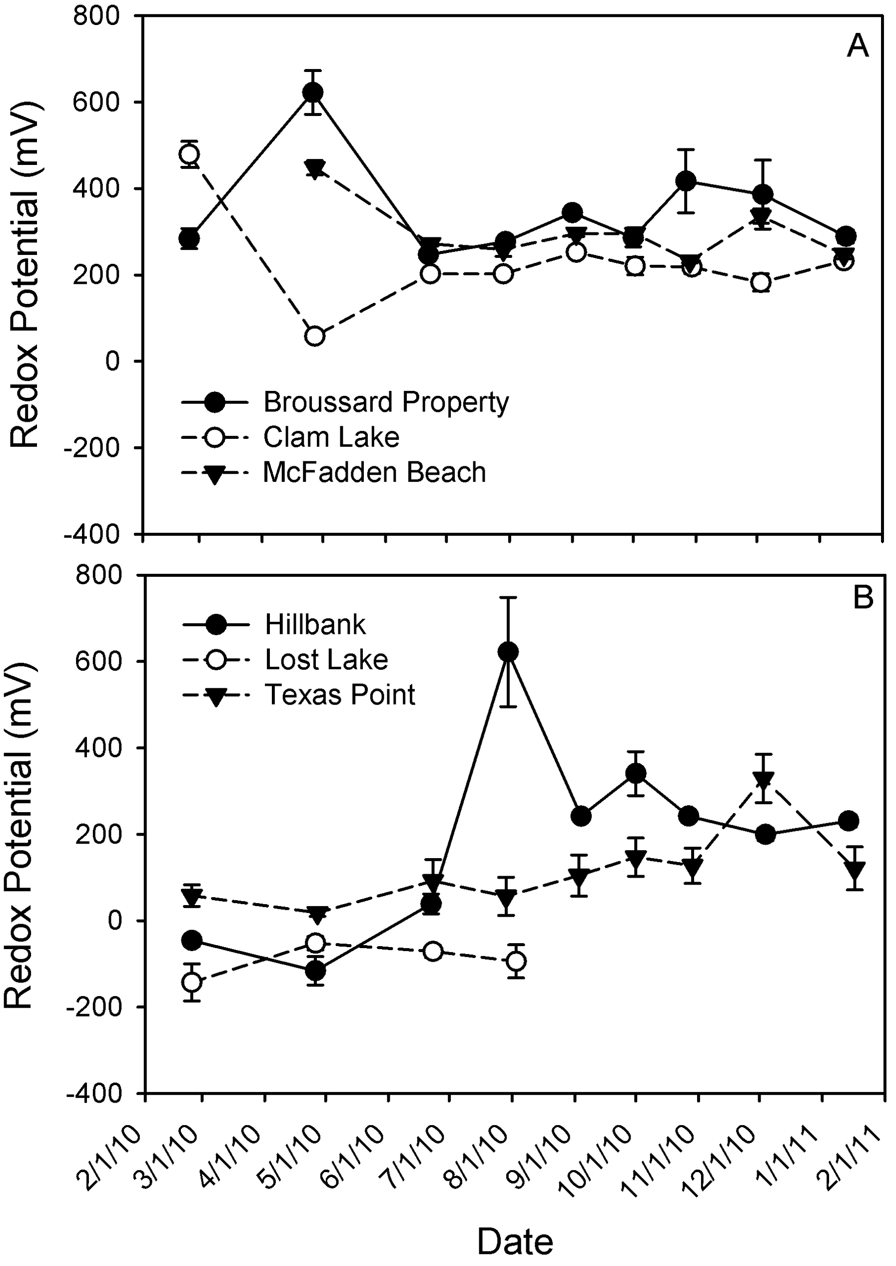


Figure 5.11. Sediment redox potential measured at 15 cm depth for the western N-S transect (A) and eastern N-S transects (B) from February 2010 to January 2011, for all sites but Lost Lake where the last sampling was in late July 2010. Error bars are ± SD (n = 5).

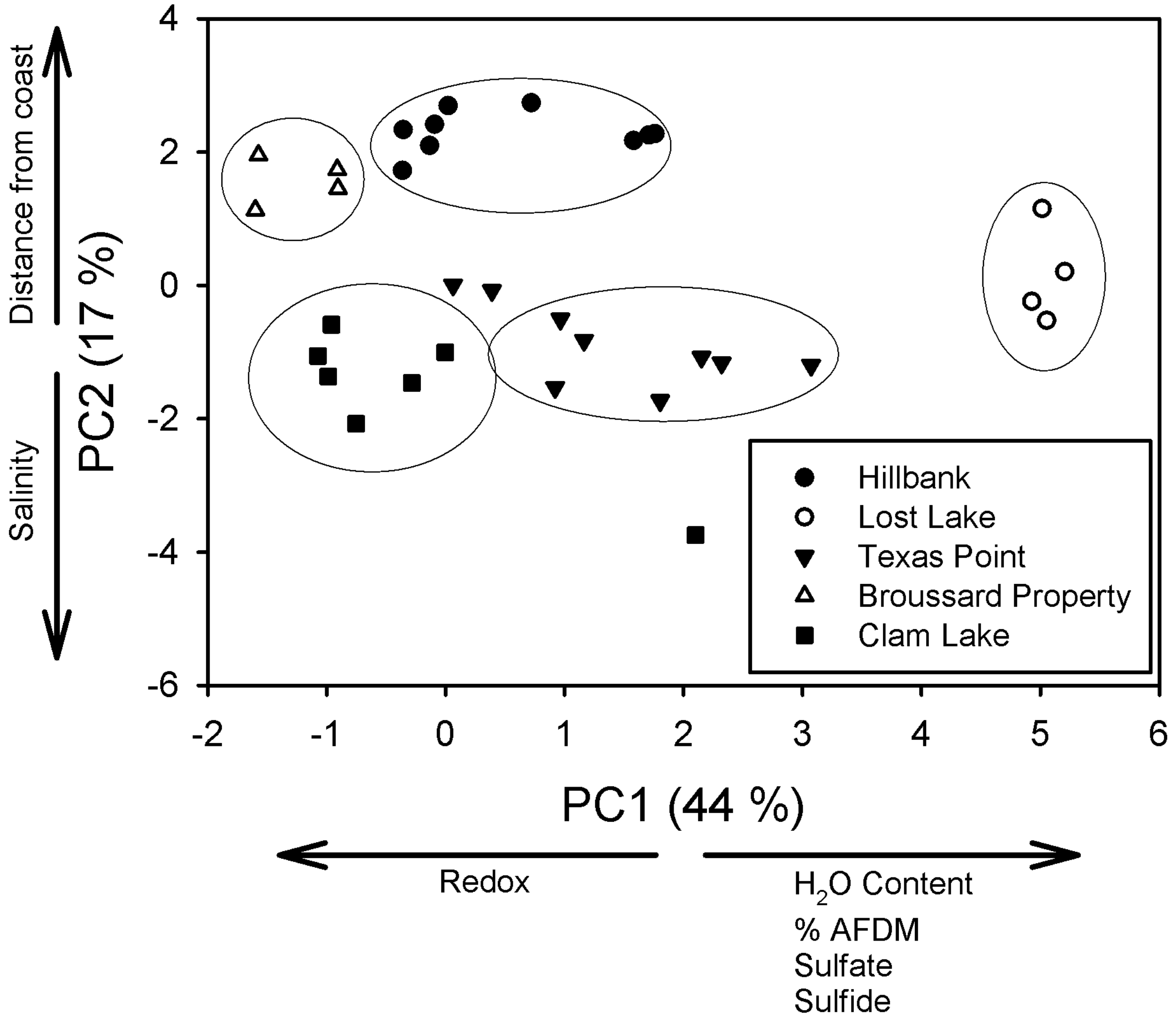


Figure 5.12. Plot of principle component 1 (PC1) vs PC2 for sediment physicochemical parameters. The percent of total variance explained is given in parentheses. Arrows along axes indicate the direction of influence of parameters driving variance.

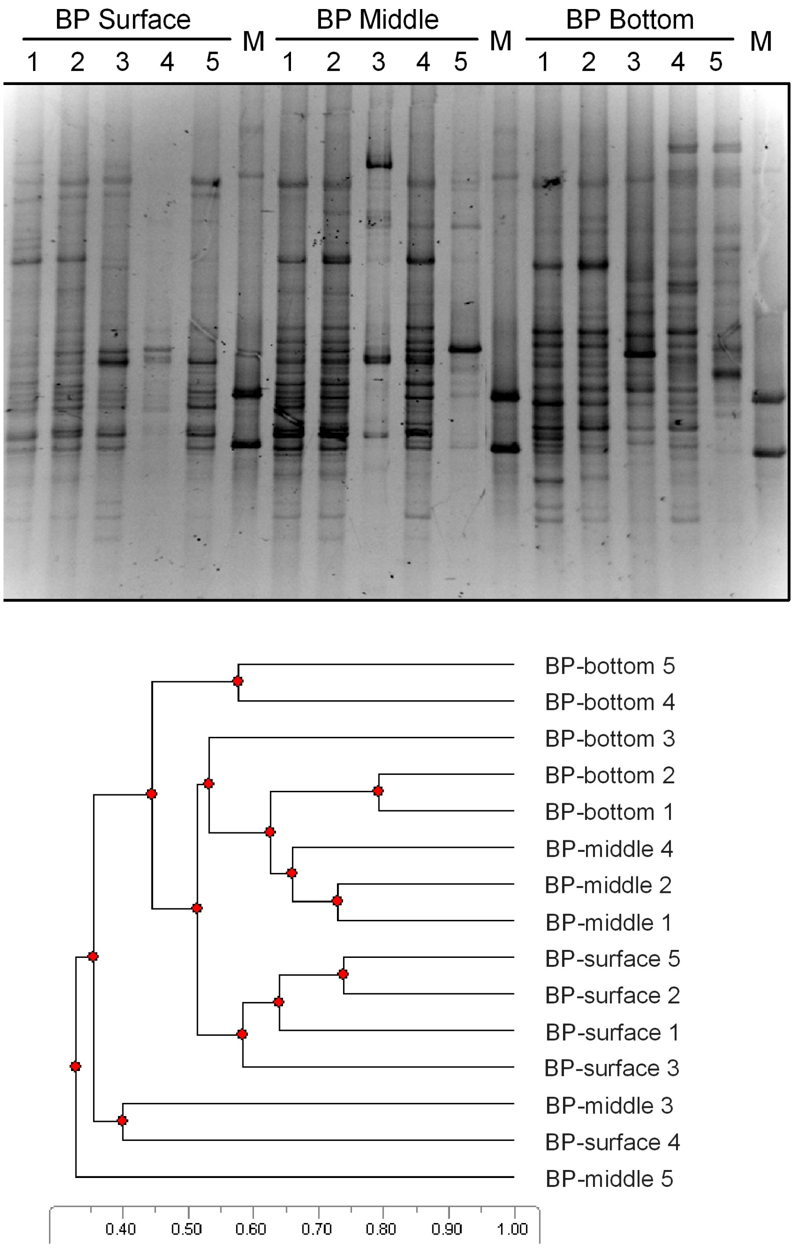


Figure. 5.13. La Belle Property (BP) DGGE profiles for the *drs*B genes of SRP in three sediment horizons (surface, middle, and bottom) samples from February 2010 to January 2011 pooled into five seasonal increments (1= Feb-Apr; 2 = May-June; 3 = July-Sept; 4 = Oct-Nov; and 5 = Dec-Jan), and the corresponding UPGMA dendrogram with the scale indicating the proportion of similarity per node.

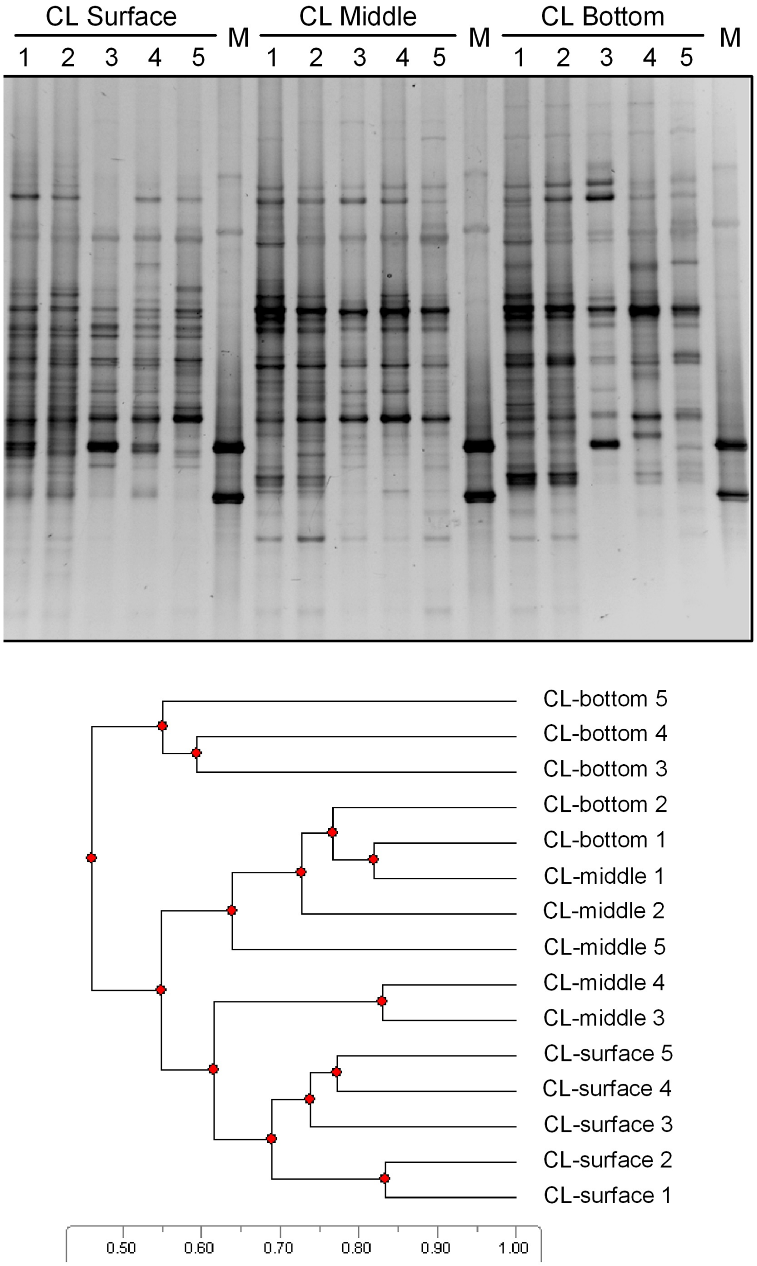


Figure. 5.14. Clam Lake (CL) DGGE profiles for the *drs*B genes of SRP in three sediment horizons (surface, middle, and bottom) samples from February 2010 to January 2011, pooled into five seasonal increments (1= Feb-Apr; 2 = May-June; 3 = July-Sept; 4 = Oct-Nov; and 5 = Dec-Jan), and the corresponding UPGMA dendrogram with the scale indicating the proportion of similarity per node.

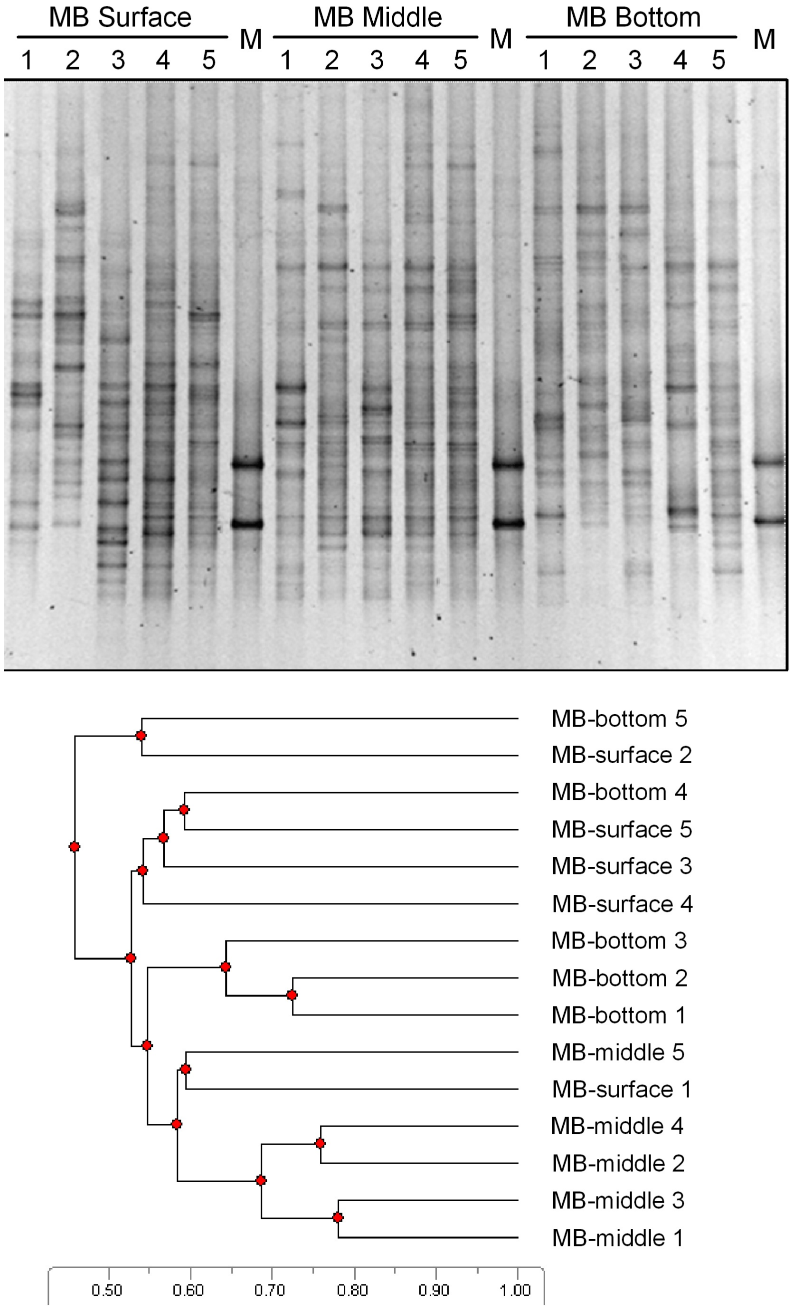


Figure. 5.15. McFadden Beach (MB) DGGE profiles for the *drs*B genes of SRP in three sediment horizons (surface, middle, and bottom) samples from February 2010 to January 2011, pooled into five seasonal increments (1= Feb-Apr; 2 = May-June; 3 = July-Sept; 4 = Oct-Nov; and 5 = Dec-Jan), and the corresponding UPGMA dendrogram with the scale indicating the proportion of similarity per node.

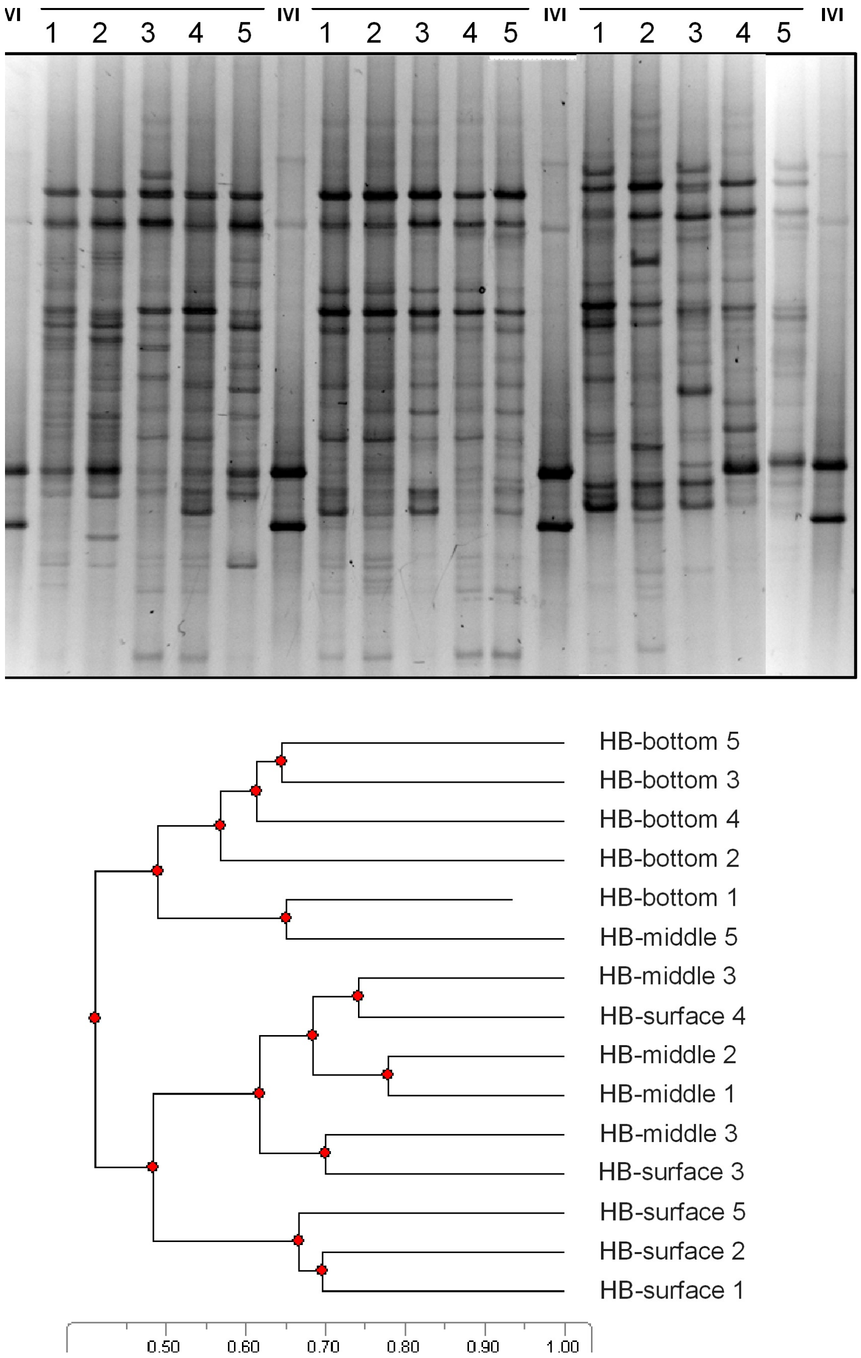


Figure. 5.16. Hillbank (HB) DGGE profiles for the *drs*B genes of SRP in three sediment horizons (surface, middle, and bottom) samples from February 2010 to January 2011, pooled into five seasonal increments (1= Feb-Apr; 2 = May-June; 3 = July-Sept; 4 = Oct-Nov; and 5 = Dec-Jan), and the corresponding UPGMA dendrogram with the scale indicating the proportion of similarity per node.

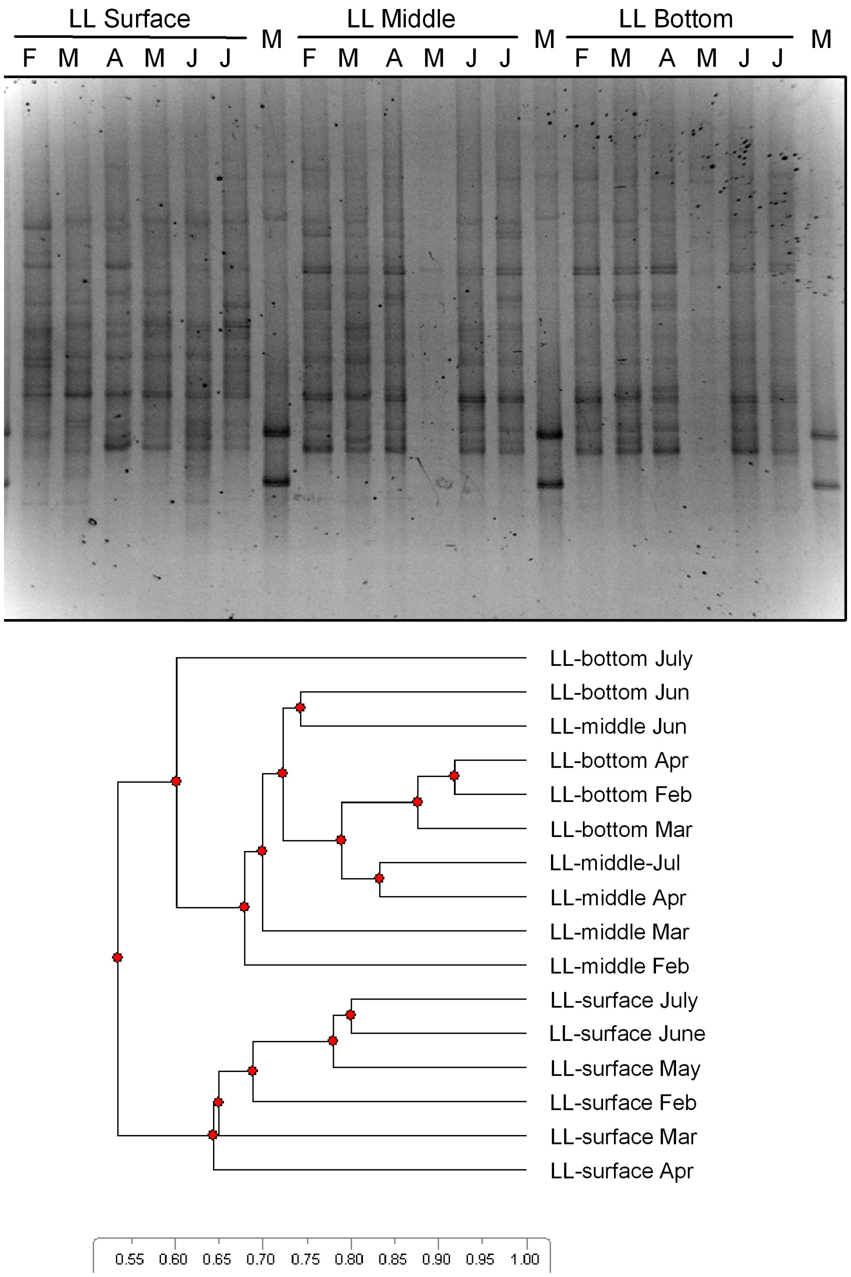


Figure. 5.17. Lost Lake (LL) DGGE profiles for the *drs*B genes of SRP in three sediment horizons (surface, middle, and bottom) samples from February 2010 to late July 2010, and the corresponding dendrogram from hierarchical cluster analysis of profiles. Scale is the proportion of similarity per node.

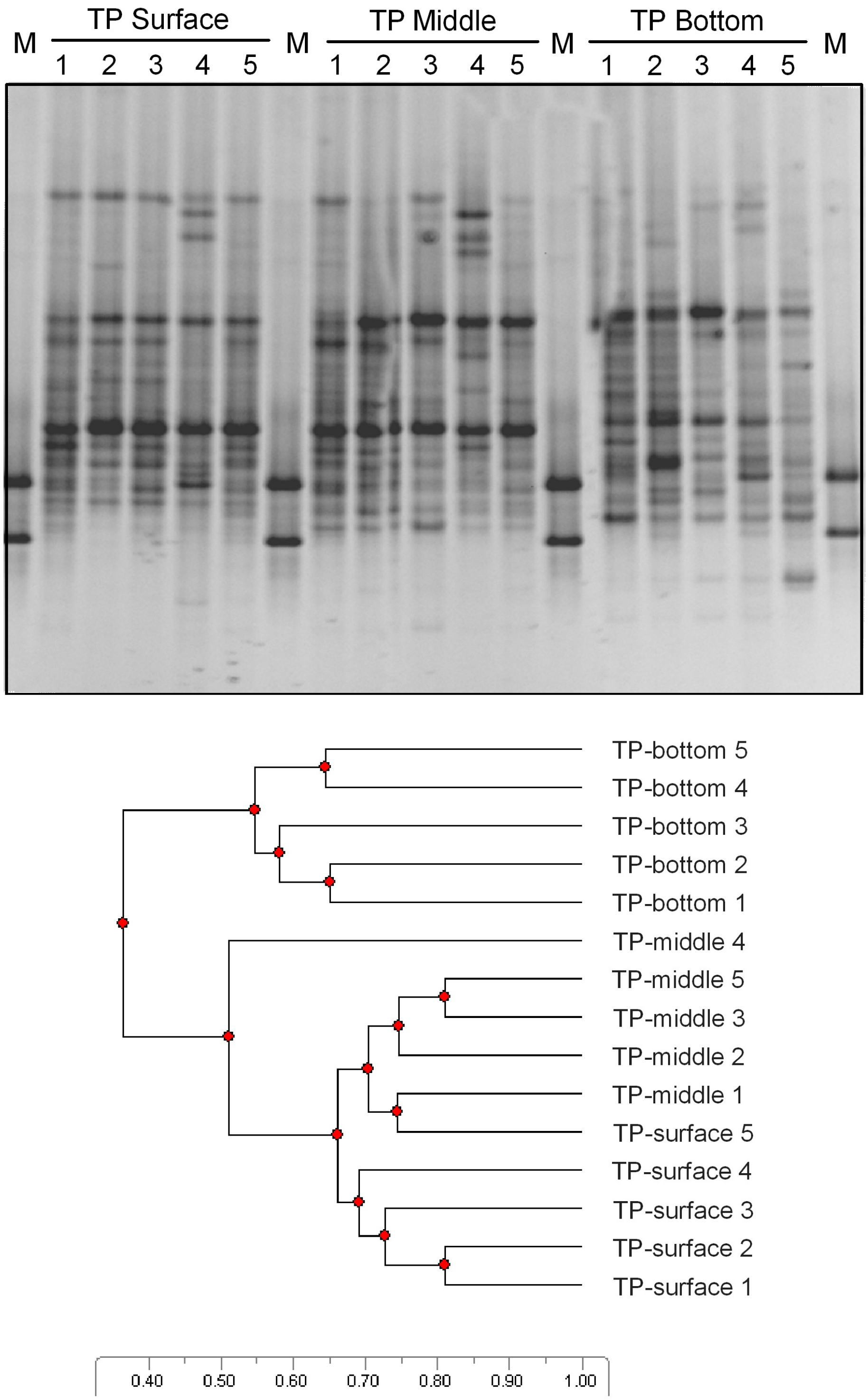


Figure. 5.18. Texas Point (TP) DGGE profiles for the *drs*B genes of SRP in three sediment horizons (surface, middle, and bottom) samples from February 2010 to January 2011, pooled into five seasonal increments (1= Feb-Apr; 2 = May-June; 3 = July-Sept; 4 = Oct-Nov; and 5 = Dec-Jan), and the corresponding UPGMA dendrogram with the scale indicating the proportion of similarity per node.