COASTAL MARSH VEGETATION DYNAMICS OF THE EAST BAY OF GALVESTON BAY, TEXAS

A Thesis

by

JEREMY SCOTT JOHNSON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2011

Major Subject: Geography

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Approved by:

Chair of Committee,	David M. Cairns
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ABSTRACT

Coastal Marsh Vegetation Dynamics of the East Bay of Galveston Bay, Texas.

(August 2011)

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Chair of Advisory Committee: Dr. David M. Cairns

The structure and function of coastal marshes results from a complex interaction of biotic and abiotic processes that continually influence the characteristics of marsh vegetation. A great deal of research has focused on how tidal processes influence vegetation dynamics along the Atlantic coast, but few studies have investigated the influence of similar processes in the marshes along the Gulf of Mexico. This study aims to identify the characteristic vegetation assemblages of the coastal marshes bordering the East Bay of Galveston Bay, Texas, and identify if elevation, inundation frequency and burning frequency are important to their structure.

To identify characteristic vegetation assemblages, hierarchical cluster analysis was used. The cluster analysis resulted in seven statistically different vegetation assemblages that were used in diversity analysis and classification and regression analysis (CART) as dependent variables.

Diversity measures were calculated at both the plot and assemblage scale using Shannon's diversity index and species richness. The resulting diversity measures were used as predictor variables in the CART analysis as well as regression analysis.

Hydrologic modeling was accomplished using Mike 21, a flow and wave simulation model, along with a geographic information system (GIS), to model hourly inundation frequency at each of the sampled plots. The inundation frequency was then used as a predictor variable in the CART analysis and regression analysis.

This study found that the main factor contributing to species richness was elevation. Vegetation assemblages at high elevations generally had high diversity, and assemblages at low elevations had lower diversity. Elevation and inundation frequency are inversely related, and the strong correlation between species richness and elevation also assumes that inundation frequency is important in structuring the marsh. Burn frequencies had no influence on diversity in general, but more frequent burning did result in monospecific stands of *Spartina patens* at Anahuac NWR.

DEDICATION

To My Wife, Lesley

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I would like to thank my advisor, Dr. David Cairns, for his guidance and insight over the past two years of my research. I would also like to thank my committee members, Dr. Charles Lafon, Dr. Chris Houser, and Dr. Robert Coulson for their contributions and suggestions to my research.

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CHAPTER I

INTRODUCTION

Coastal marshes are complex ecosystems that are subject to dynamic environmental process and human driven landscape modification. The marshes along the Gulf of Mexico are composed of stress tolerant vegetation, termed halophytes, that can withstand extend periods of inundation by saline waters. The dominant vegetation found in the Gulf Coast marshes consists of marshhay cord grass (*Spartina patens*), Gulf cordgrass (*Spartina spartinae*), Saltgrass (*Distichlis spicata*), Jointgrass (*Paspalum vaginatum*), and Olney three-square (*Schoenoplectus americanus*). Marshhay cord grass is the dominant species in the coastal marshes due to its ability to withstand variable salinity levels.

Coastal marshes are sensitive to climatic and anthropogenic changes (Adam 2002, Cahoon 2006, FitzGerald et al. 2008, Kennish 2001, Kim, Cairns and Bartholdy 2011, Morris et al. 2002), and much research has been conducted on how coastal marshes will respond to sea-level rise and climate change (Cahoon 2006, FitzGerald et al. 2008, Morris et al. 2002). The classic salt marsh structure is composed of discrete zones of shore parallel bands of vegetation that are the result of a predictable semidiurnal tidal regime (Adam 1990). However, this may not be the case along the Gulf Coast where diurnal and mixed tidal regimes and strong southerly winds lead to irregular flooding which may influence the distribution and composition of marsh vegetation

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This thesis follows the style of *Annals of the Association of American Geographers.*

(Costa, Marangoni and Azevedo 2003, Kunza and Pennings 2008). Along with unpredictable marsh flooding, management practices are very influential in structuring the coastal marshes. Grazing, burning, use of water control structures and levees are all common along the Gulf Coast.

Most research on the vegetation dynamics of coastal marshes has been conducted along the Atlantic coast of North America where predictable, mesotidal process create a stress gradient that influences plant distribution. Few studies along the Gulf Coast have investigated if the same processes are important in structuring the marsh. In this study, I investigate species composition and distribution of marsh vegetation along the East Bay of Galveston Bay in Chambers County, Texas. I collected floristic data at the study sites, classified vegetation assemblages, modeled inundation frequency, and used classification and regression tree analysis to identify threshold values of processes important to the marsh structure in order to identify which variables explain the dominant patterns on the landscape. Few studies have investigated marsh vegetation through hierarchical classification and CART modeling along the Gulf Coast to identify processes associated with marsh structure, and most vegetation classification along the Gulf Coast has occurred at much larger scales (e.g. (Visser et al. 2000). This study provides a landscape level analysis of the influence of elevation, inundation frequency, and management practices on coastal marsh vegetation along the East Bay of Galveston Bay, Texas.

SPECIFIC AIMS

Global climate change is increasingly becoming an important consideration in management of the world's resources. Indicators of climate change can help inform management decisions relating to attempted mitigation of negative impacts. The utility of salt marsh vegetation to fill the role of early indicator of global climate change may be an important one. By establishing an initial vegetation survey of the coastal salt marsh vegetation along the East Bay of Galveston Bay and identifying the processes important to their structure, future studies can be conducted and vegetation composition and distribution can be compared to identify change trajectories.

It is the purpose of this research to study the vegetation dynamics of the Galveston Bay salt marshes and how the composition and distribution of vegetation are influenced by biotic, climatic, and anthropogenic factors.

The objectives of this study are to first establish a baseline vegetation survey of marsh vegetation, secondly identify dominant landscape level vegetation assemblages and thirdly determine which physical processes are influential in structuring the identified vegetation assemblages.

CHAPTER II

LITERATURE REVIEW

COASTAL MARSHES

Definition

Climate change impacts can alter landscapes in many ways but may be more dramatic at the boundary between two ecosystems. It is because of the sensitive nature of ecotones that coastal marshes are excellent locations to study the effects of climate change. As with many ecotones, the difficulty in accurately defining the system leads to difficulty in studying their changes. Coastal marshes are complex systems that inhabit the transitional zone between intertidal marine and terrestrial uplands, generally within a relatively short distance. It is this continuous variation from sea to uplands that blurs the boundaries on the edges and contributes to the difficulties in defining the system (Mitsch and Gosselink 1986). Many researchers have defined the coastal marsh system but few are in complete agreement about what characteristics best describe it. Odum (1988) grouped marshes into five different classes related to salinity level and the vegetation present: nontidal freshwater (having no tidal influence and generally the product of freshwater processes), tidal freshwater < 0.5 parts per thousand (ppt), Oligohaline 0.5 – 5.0 ppt, Mesohaline 5.0 – 18.0 ppt, and Polyhaline > 18.0 ppt (Odum 1988). Stutzenbaker (1999), using four marsh classes but still followed a similar method as Odum of classifying marsh vegetation based on salinity level used; fresh marsh < 0.5 ppt, intermediate marsh 0.5 – 3.5 ppt, brackish marsh 3.5 – 10.0 ppt, and salt marsh > 10.0 ppt. Adam (1990) defines salt marshes as areas bordering saline water bodies that are vegetated by salt tolerant species, termed halophytes, which experience variable periods of inundation by saline water. Many of the common marsh classifications are based on salinity level and the corresponding vegetation that inhabits a marsh zone, but Adam (1990) notes that there is a great deal of variability in salinity tolerance of halophytic species within a marsh. Salinity levels in marshes are highly variable and tend to fluctuate based on precipitation, freshwater flushing from rivers or overland runoff, percolation rate of the soil, tides, biological interactions, and also low frequency high magnitude events such as hurricanes or tropical storms (Adam 1990, Day et al. 2008, Mitsch and Gosselink 1986). Mitsch and Gosselink (1986) note that characteristics of coastal marshes include: tidal inundation, extreme variation in salinity, and vegetation adapted to inundation and saturated soil. The stressful biotic and abiotic factors influencing the marshes result in strong environmental gradients that have significant influence on marsh structure (Bertness, Gough and Shumway 1992, Emery, Ewanchuk and Bertness 2001, Pennings and Callaway 1992, Pielou and Routledge 1976, Redfield 1972). The salinity gradient is predominantly a result of changes in elevation away from the shore and tidal creek systems, and marsh vegetation tends to align itself in zonal bands parallel to the shore as elevation increases (Costa et al. 2003, Adam 1990). The seaward limit of coastal marshes is defined as the furthest position of vascular plant inhabitance that does not experience permanent submergence (Adam 1990). The upper limits are much more difficult to define as tidal freshwater marshes have a greater distribution into terrestrial environments. It is also important to distinguish between the different tidal classifications: micro, meso, and macro tidal systems. Macro tidal systems experience on shore tides greater than four meters, meso tidal systems experience tides two to four meters high, and micro tidal systems experience tides of less than two meters (Short 1991).

Types of Marshes

As mentioned briefly above, there are primarily four types of coastal marshes found throughout the world: Saline, Brackish, Intermediate, and Fresh (Stutzenbaker 1999). It is the hydrological and salinity gradients that primarily influence the distribution and function of marsh assemblages (Brewer and Grace 1990) and marsh types are classified based on these factors. As distance from the coast inland increases marsh types will usually progress successively from one type to the next along an environmental salinity gradient. It should be noted that the salinity levels found in all four marsh types are highly variable and may shift by season, climate, or due to disturbance events (Odum 1988).

Saline marshes (Polyhaline), or salt marshes, are found along coasts in locations that are protected form the direct energy of waves. The salinity levels typically range from 18.0 – 35.0 ppt. In many cases, they are found in protected bays or estuaries, but may also be found behind dune systems or along low energy coasts (Mitsch and Gosselink 1986). Saline marshes are composed of salt tolerant vegetation known as halophytes that experience inundation by seawater for a substantial portion of their life (Adam 1990). Adam (1990) defines halophytes as any species that completes the majority of its life in a saline environment. In comparison to the other three marsh types, saline marshes have relatively low diversity and tend to be dominated by only a few species (Odum 1988). The primary driver of inundation in saline marshes is the lunar tide and as a result will vary by location throughout the world. Life history traits are important for vegetation inhabiting all marsh types, and the strategies employed differ from one type to the next. In salt marshes, the dominant vegetation strategy is stress tolerance. Most halophytes that inhabit saline marshes reproduce vegetatively, usually through tillers, rhizomes and stolons.

Brackish marshes (Mesohaline) transition from true saline marshes into intermediate marshes. Salinity levels can range from 5.0 – 18.0 ppt. Vegetation composition in brackish marshes is based on a species ability to tolerate fluctuating salinity levels. Tidal inundation is less frequent and is associated with spring high tides.

Intermediate marshes (Oligohaline) are found further inland from both brackish and saline marshes. Intermediate marshes do experience tides but generally do not experience salt stress as a result of them (Brewer and Grace 1990). The salinity levels can range from 0.5 – 5.0 ppt. Vegetation types change with the lowered salt stress and as a result the intermediate marshes are ideal locations for studies investigating the influence of salinity level on competition and distribution of the marsh vegetation (Odum 1988). Intermediate marshes are highly productive and have high biodiversity associated with them (Mitsch and Gosselink 1986).

Tidal Freshwater marshes are also influenced by tidal inundation but they do not experience salt induced stress that is typically found in the other three marsh types and salinity levels are less than 0.5 ppt. Fresh marshes have high biodiversity and the vegetation life history strategies are competitive in comparison to the stress tolerator traits of halophytes in the saline influenced marshes. Vegetation propagation occurs through seed dispersal as well as vegetatively. The distribution of tidal freshwater marshes tend to occur in estuary and fluvial locations where freshwater inputs often offset the influence of seawater (Odum 1988). Soils are typically saturated and flooding occurs via fluvial and climatic processes.

Marsh Vegetation Dynamics

Vegetation dynamics is the term used to describe how vegetation interacts within its biological and abiotic environment. Grime (1977) argued that there are three strategies that dictate where species will best be suited. The first is stress tolerant, the second is competitor, and the third is ruderal. This model has been termed CSR (Grime 1977). The ability of a plant to cope with different levels of stress and disturbance are related to the plant's ability to evolve competitive strategies. Grime (1977) stresses the importance of understanding what factors are limiting vegetation biomass and views these limiting factors as drivers of plant succession. Grime classifies the limiting factors affecting most vegetation as some combination of stress and disturbance. Stress is defined as any condition that restricts production of vegetation biomass, while disturbance is defined as the partial or total destruction of the vegetation biomass (Grime 1977). The two limiting factors, stress and disturbance, are grouped into levels of intensity, e.g. low-stress/low-disturbance, low-stress/high-disturbance, high-stress/low-disturbance, and high-stress/high-disturbance. Grime postulated that vegetation can only survive in three of the four combinations, and precludes high-stress/high-disturbance as a location where disturbance removes the vegetation and stress inhibits it from reestablishment. Grime’s CSR theory states that all species fit best into one of these life history strategies. For example, stress tolerant species, such as those found in salt-marshes, have reduced vegetative growth but are adapted to withstand frequent prolonged stress from salt water inundation. On the other hand, marsh vegetation that experiences less frequent inundation may have a more competitive strategy allowing its adaptations to competitively exclude species with other life history strategies. In contrast to Grime’s (1977) CSR theory, Tilman (1985) developed the resource ratio hypothesis to explain two primary adaptations that are responsible for vegetative patterns; inter-specific competition and the supply of a limiting resource. This theory implies trade-offs between a plants ability to utilize two different limiting resources, (e.g. light and soil nutrients in Tilman’s model). Vegetation thus adopts traits to compete for the limiting resource at a given time and location. The “superior competitors” for a limiting resource will be the dominant vegetation (Tilman 1985).

The concepts of CSR and Resource Ratio fit into the vegetation dynamics of coastal marshes by suggesting that the spatial distribution and composition of marsh vegetation are related to their biotic and abiotic environment, and that individual species have adopted different strategies for dealing with the varying levels of stress and competition for resources. Emery et al. (2001) suggested that the influence of resource availability and non-resource stress has not been considered together and that both CSR and the Resource Ratio Hypothesis do not distinguish between resource and non-resource stress. In their study, Emery et al. (2001) find that when nutrient availability improves stress tolerant marsh species become better competitors, but when nutrient availability is low the same marsh species are restricted to non-resource stressful environments such as salt pans or low-lying frequently inundated areas.

Similarly, Crain et al. (2004) found that in a New England marsh all species grew optimally in fresh water when they were competitively isolated, but when competitive species were introduced stress tolerant species were out competed thus restricting them to more stressful locations. The competitive vegetation, however, was not able to survive in stressful, saline environments (Crain et al. 2004).

Marsh literature contains many studies investigating vegetation dynamics as influenced by stress: herbivory (Andresen et al. 1990, Bakker 1985, Bos et al. 2002) and tidal inundation (Armstrong et al. 1985, Baldwin and Mendelssohn 1998, Bertness et al. 1992, Broome, Mendelssohn and Mckee 1995, Casanova and Brock 2000, Costa et al. 2003, Silvestri, Defina and Marani 2005) as well as competition (Bertness 1991a, Bertness and Shumway 1993, Emery et al. 2001, Phillips 1992, Levine, Brewer and Bertness 1998). Past research in North America focusing on vegetation dynamics of coastal marshes have predominantly occurred along the Atlantic coast, specifically in New England, and to what extent these process can be applied to the Gulf Coast is unknown (Kunza and Pennings 2008).

Studies have shown that patterns in marsh structure are a result of strong interspecific competition (Bertness 1991a) where successive species are restricted to more stressful environments by competitively superior species. Interspecific competition is not always the driving force in structuring the marsh, and facilitation also plays a role, especially in secondary succession of bare patches after disturbances (Bertness et al.

1992). It is not always clear where the most stressful environment in coastal marshes will occur. For example, tidal flooding and water-logging may produce a stressful environment at the seaward boarder of the marsh but salinities may be greater at higher elevations where less frequent flushing of the soil and exacerbation of salinity through evaporation leads to salt pans that are highly stressful environments (Bertness et al. 1992, Pennings and Callaway 1992).

Most marsh vegetation dynamics studies have occurred in mesotidal, semi-diurnal environments where predictable tidal regimes lead to predictable salinity gradients and distinct zonation patterns are the result. There are few studies that examine diurnal and mixed diurnal microtidal systems and their influence on marsh patterns. Microtidal systems tend to be less predictable in regards to stress induced by inundation and salinity level (Costa et al. 2003). Because of the unpredictable environmental gradients these microtidal marshes frequently have less distinct patterns of zonation. In many cases, wind-forced tides are much more important in creating stress gradients than are tidal processes (Costa et al. 2003, Kim et al. 2011) . Costa et al. (2003) note that as a result of the unpredictable stress gradients interspecific competition is much more important than tide in structuring the landscape.

Coastal marshes form partly as a function of relatively little elevation variability, where a gently sloped tidal mudflat is inhabited by marsh vegetation (Mitsch and Gosselink 1986). Because of the small elevation gradient and the disproportionately high effects of elevation on inundation frequency and depth, studies have found that patterns of establishment may be related to microtopography (Emery, Stanton and Rice 2009, Kim, Cairns and Bartholdy 2010).

The inclusion of facilitation into marsh literature has lead to a great deal of research on strategies of marsh vegetation and their ability to inhabit highly stressful portions of the marsh platform and reduce the stress of the marsh for less stress tolerant species. First introduced by Connell and Slatyer (1977), facilitation is the theory of positive interactions between two or more species. The basic premise of facilitation in coastal marshes is the trapping of sediment on bare tidal mudflats by pioneer species that leads to the accretion of the platform facilitating the environment for later successional species. Not only do pioneer species help to stabilize the marsh platform, but also shade the surface and reduce evaporation thereby allowing stress intolerant species to establish (e.g. Emeroy et al. 2001). Facilitation also occurs when one species buffers another from competitive effects and leads to other forms of indirect or direct interactions (Bertness 1991a, Bertness and Shumway 1993, Bruno, Stachowicz and Bertness 2003, Callaway and Pennings 2000)

Zonation and Succession

There is a debate in the literature about the processes that influence the dominant structure in coastal marshes. Specifically, there has been confusion between the two concepts of vegetation zonation and succession (Adam 1990, Bertness and Shumway 1993, Davy 2000, Kim et al. 2011, Pennings and Callaway 1992, Ranwell 1972, Van der valk 1981). It is important to try and understand the difference between the two concepts in order to better understand the processes influencing vegetation composition and distribution.

The classic concept of succession in salt marshes argues for the conversion of marine or estuarine environments into terrestrial uplands through a linear autogenic process of sediment accumulation and vegetation replacement directed towards a climax (Mitsch and Gosselink 1986). There is little evidence to suggest that such a terrestrial climax exists in the marsh literature, and in many cases an individualistic approach to succession is accepted (Van der valk 1981). Van der Valk (1981) developed a model to investigate freshwater succession by analyzing life history traits of wetland species and predicting vegetation patterns resulting from autogenic succession and the plants ability to adapt to environmental gradients. Any time a disturbance creates a bare patch, such as salt pans after a hurricane or the deposition of floating wrack on a marsh, true secondary succession can occur. Colonization of the bare patch will occur and vegetation will successively replace earlier inhabitants, usually through a form of facilitation (Davy 2000).

Zonation, on the other hand, is associated with the variability in vegetation composition related to a dominant environmental gradient to which individual species are adapted (Adam 2002, Mitsch and Gosselink 1986). Zonation does not result in a linear replacement of vegetation over time, but well organized patterns along environmental gradients, usually related to flood frequency, salinity level, and competition. Because elevation ranges are so small on the marsh platform small variations in elevation, possibly as a result of changes in sediment deposition rates and patterns, can result in significant variation in vegetation assemblages, micro-topography thus has a disproportionately large influence on spatial variability of marsh composition (Kim et al. 2010, Mitsch and Gosselink 1986). Although abiotic autogenic factors were originally thought to be the primary control of zonation, competitive processes are also important in structuring zones (Bertness 1991b, Crain et al. 2004, Cui, He and An 2011, Kim et al. 2010, Pennings and Callaway 1992).

Salinity gradients are predominantly the result of changes in elevation away from the shore, or tidal creeks, and marsh vegetation tends to align itself in zonal bands parallel to the shore as elevation increases (Costa et al. 2003, Adam 1990). Increases in elevation influence the inundation frequency and duration so that vegetation occupies a location based on its ability to tolerate heightened periods of inundation and thus heightened salinity levels. Zonation of marsh vegetation should be predictable based on the known relationship between inundation frequency and elevation. Because of the relationship between elevation and zonation, it is common to see higher biodiversity at higher elevations due to less frequent stress from flooding and lower diversity at the seaward limit of the marsh where a few dominant species are able to tolerate the stress of salt and frequent and prolonged inundation (Adam 1990). Commonly, marsh environments at low elevations will experience daily tidal flooding and mid and high elevation marshes will only experience inundation during high spring tide cycles or storm events thus creating a spatial salinity gradient across the marsh influencing vegetation zonation (Emery et al. 2001). However, in a microtidal environment the relationship between tidal regime and elevation may be less important than variations in rainfall and wind forced marsh inundation which leads to a less predictable inundation regime (Costa et al. 2003, Kim et al. 2011) and less pronounced vegetative zones. It should also be noted that tidal inundation is not the only process that influences patterns of zonation. Competition for resources may also interact with salinity stressors to influence vegetation distribution (Brewer and Grace 1990, Emery et al. 2001, Pennings and Callaway 1992, Pielou and Routledge 1976). In many marshes, limits of vegetation zones are structured relative to competition between species at the upper marsh limits but facilitation and stress tolerance at lower limits (Pennings and Callaway 1992, Bertness and Shumway 1993). While vegetation zonation tends to be stable over long temporal scales, succession of marshes can and does occur as a result of disturbance, or anthropogenic influences. Adams (1990) mentions changes in management as an instance when succession may occur; e.g. cessation of cattle grazing.

Geomorphology

The geomorphology of a salt marsh is characterized by processes of erosion, accretion, and progradation (Adam 1990), that contribute to changes in marsh elevation, hydrology and as a result, the salinity level experienced throughout the marsh. Salt marshes are unique environments, and most processes controlling vegetation structure result from strong environmental gradients. The composition of the marsh vegetation occurs as a function of tidal regime, edaphic characteristics, sea-level change, elevation, climate, addition of ground or surface water, and disturbance events; such as hurricanes and tropical storms (Adam 1990, Baldwin and Mendelssohn 1998, Bertness et al. 1992, Davy 2000, Stutzenbaker 1999, White et al. 1985, Bertness 1991a). The characteristic vegetation of a salt marsh can be classified by their varying ability to tolerate the heightened stress imposed on them by varying salinity levels and competition between species (Bertness 1991a, Bertness and Shumway 1993).

The basic premise behind salt marsh formation and persistence involves two processes, the input of sediment and coastal submergence (Mitsch and Gosselink 1986). Initially a gently sloped, protected mudflat or platform is inhabited by halophytic vegetation that can withstand extended periods of inundation by sea water. The establishment of vegetation results in a positive feedback where increased trapping of sediment leads to increased vegetative growth via facilitation (Bertness et al. 1992, Bruno et al. 2003). This facilitory process also contributes to changes in elevation where halophytic vegetation begins to contribute to accretion by trapping sediment that is being imported into the marsh by rivers, tides and waves and in turn leads to a heightened marsh platform that is flooded less frequently by tides. As the elevation of the marsh increases salt tolerant vegetation is replaced by more competitive less salt tolerant species and succession occurs (Kim 2009, Bertness et al. 1992). As marsh vegetation dies, above and below ground biomass contributes to vertical marsh accretion, this process along with sediment importation allows the marsh platform to prograde seaward and extends laterally along the shore. As long as a sufficient supply of sediment is delivered to the marsh the platform can accrete vertically and withstand processes of subsidence and erosion and marsh stability will be ensured (Adam 1990, Davidson-Arnott 2009, Kim 2009). There is some precedence along the Gulf Coast to indicate that winter storms and cold fronts are important contributors to the net importation of sediment. Studies along the Gulf Coast of Louisiana and the Mississippi deltaic plain have shown that maximum sedimentation is found to be associated with winter storms and strong southerly winds, which cause increased marsh inundation and sediment distribution (Reed 1989).

Many processes are important in the formation and stabilization of both terrestrial and coastal marshes. Coastal processes influencing specific marsh locations include, importantly, tidal processes, but also climatic processes such as storm and wind waves. Along with coastal processes fluvial systems are important contributors to marsh structure via their importation of continental sediments and their ability to flush the system lowering salinity levels and thereby reducing stress.

Coastal marshes occur in the upper intertidal portion of the coastal profile in bays and estuaries that are usually protected by barriers (Adam 2002, Davidson-Arnott 2009, Redfield 1972, Mitsch and Gosselink 1986). A fundamental aspect of coastal marsh formation is that their location is in an area protected from the energy of the open ocean. Most processes necessary for the formation of a coastal marsh cannot occur if they are constantly experiencing wave action and as a result coastal marshes rely heavily on barrier systems and estuaries to protect them and contribute to their continued persistence (Mitsch and Gosselink 1986).

Management

Coastal communities are some of the fastest urbanizing environments in the world. This phenomenon has resulted in many challenges to coastal marsh management. Because of the close proximity to most of the world's coastal marshes a disproportionately high amount of resource extraction and land use has occurred. Values that have been assigned to these environments are varied, but most of them are the result of ecosystem services that they provided to society (Mitsch and Gosselink 2000). In the future, ecosystems such as coastal marshes will be of greater importance due to the services that they provide (Day et al. 2009). Coastal marshes are managed for many reasons, including agriculture, resource extraction, ecosystem services (e.g. flood control, pollution retention), and recreation to name but a few (Adam 1990), and the management practices employed vary as widely as the service provided.

Grazing is one of the oldest uses of coastal marshes, first being practiced on European marshes and continued in the U.S. The effects of grazing on marsh vegetation have been studied with regards to their influence on the composition and distribution of marsh vegetation (Andresen et al. 1990, Bakker 1985, Esselink, Fresco and Dijkema 2002). Grazing as a form of herbivory is not only an activity carried out in a managed agricultural sense, but also occurring via undomesticated wildlife such as migratory waterfowl and mammals (Bhattacharjee, Haukos and Neaville 2007). Grazing has a major influence on the diversity of vegetation found in coastal marshes primarily as a function of preferential selection of vegetation by grazers (Adam 1990). Grazing can be seen as a form of stress, both herbivory and trampling (Adam 1990), and vegetation more adapted to this form of stress will dominate grazed marshes (Grime 1977).

One of the methods used for managing marshes for wildlife, both agricultural and wild, is burning. Burning is commonly employed along the Gulf of Mexico in the winter as a method to reduce dead biomass and dominant marsh vegetation (Gabrey and Afton

2001). Use of this method to manage coastal marshes varies based on management objectives, which usually is related to removing dominant vegetation in favor of opening up patches for vegetation with greater wildlife value (Gabrey and Afton 2001).

Along with burning, the use of structural marsh management (SMM) is employed to regulate salinity levels and enhance tidal freshwater marsh species that are preferred by migratory waterfowl and game (Gabrey and Afton 2001). SMM is a method of regulating water levels and salinity through the use of levees, dams, and water control structures (Reed, Luca and Foote 1997). Studies along the Chenier plain of the Gulf Coast have investigated SMM finding that SMM decrease spatial variability of water depth but also lead to an increase in seasonal variability as a result of storm events (Bolduc and Afton 2004).

CLIMATE CHANGE

Climate and Marshes

Climate is defined as the long term trend in weather patterns that influence a particular location. It has been shown in the literature that the 20th century experienced a rapid increase in global temperatures (Mann and Bradley 1999, Crowley 2000). The causes of this rapid increase have primarily been linked to anthropogenic activities, specifically the combustion of fossil fuels leading to an increase in green house gases in the atmosphere. This increase in global temperatures may have implications for the stability of coastal marshes (Nicholls et al. 2007, Simas, Nunes and Ferreira 2001).

Coastal environments, specifically coastal marshes, are particularly susceptible to climate change. The potential affects of climate change include increasing tropical storm and hurricane frequency and intensity (Cahoon 2006, Emanuel 2005, Hoyos et al. 2006, Webster et al. 2005), increasing sea-level rise, and shifts in weather patterns, such as an increase in localized precipitation, decrease in mean precipitation, and increased temperatures (Nicholls et al. 2007). How marshes respond to these changes depends on the ability of the marsh to adapt through accretion of marshes (Morris et al. 2002), and migration of vegetation (Donnelly and Bertness 2001). Locations where coastal marshes have been cut off from their sediment sources through alteration of hydrology are more susceptible to the adverse effects of climate change (Nicholls et al. 2007).

Sea-Level Rise

The effects of climate change on marshes have been studied primarily in regard to long-term sea-level rise, and the influence of increasing storm events on the sustainability of coastal marshes. Current research indicates that, along with altered hydrology reducing sediment inputs, sea-level rise will significantly alter vegetation dynamics of coastal marshes (Adam 2002, Day et al. 2008, FitzGerald et al. 2008, Morris et al. 2002, Reed 1990, Reed 1995, Warren and Niering 1993).

Studies in New England have shown that with rising sea-level low marsh species have migrated landward displacing higher marsh salt-intolerant species (Donnelly and Bertness 2001). As long as marshes are able to migrate with sea-level rise they may persist, but in many cases fragmentation of the landscape and barriers do not allow for shoreward migration and marsh drowning occurs as a result (Donnelly and Bertness 2001, Reed 1995).

Mean sea-level rise has been occurring at a steady rate since the end of the last glacial cycle (Redfield 1972). It is in this period of the Late Holocene that coastal marshes along with coastal barriers began to form under the steadily rising sea (Michener et al. 1997, Redfield 1965). A simple positive feedback is responsible for marsh stability in a rising sea; coastal marshes must accrete at a rate equal to that of sea-level rise. If, due to a lack of sediment input, accretion occurs slower than sea-level rise the marsh will flood and conversion to open water will occur, if accretion is greater than sea-level rise then the marsh will increase in elevation and experience fewer periods of inundation while converting to a terrestrial upland landscape (Adam 2002). It is this dynamic equilibrium that stabilizes coastal marshes due to increased biomass creation with increased sea-level rise and a resulting increase in sediment trapping capabilities of the marsh (Morris et al. 2002).

Along with mean sea-level rise, subsidence can cause a decrease in marsh platform elevation and thus result in more frequent inundation by coastal waters. Subsidence can occur as compaction, when marshes decrease in elevation under their own weight, or through natural tectonic processes or human induced faulting as a result of fluid extraction (Adam 2002, White and Tremblay 1995). Relative sea-level rise is thus, the combined land subsidence and eustatic sea-level rise (Morris et al. 2002).

Hurricanes and Tropical Storms

High magnitude low frequency storm events such as hurricanes and tropical storms are important factors in determining the structure of coastal marshes. The redistribution of sediment that influences marsh elevation and nutrient allocation and also the inundation of vegetation by saline sea water has the potential to alter the dynamics of marsh vegetation (Cahoon 2006, Michener et al. 1997, Middleton 2009). Typically, marshes have evolved over a dynamic climate regime and, as a result, have been able to adapt along with the changing climate. Recently, however, a rapidly changing climate has led to more frequent storm events, including hurricanes and tropical storms, and marshes may not be able to adapt at the same rate as the recent increase in storm frequency and intensity (Hoyos et al. 2006, Emanuel 2005) leading to shifts in marsh zonation (Michener et al. 1997). Alteration of marsh elevation can occur as a result of net importation of sediment from storms (Reed 1995) contributing a large portion of sediment that would otherwise never contribute to accretion due to recent trends in altered hydrology. Cahoon (2006) investigated the nature of elevation change and marsh stability as a product of low frequency high magnitude storm events, including the ability for hurricanes to alter marshes on a landscape level through the redistribution of sediments via erosion and accretion of the marsh. This alteration and modification of coastal marshes is expected to increase with increased frequency of storms as predicted by the Intergovernmental Panel on Climate Change's (IPCC) 2007 report (Nicholls et al. 2007). An increase in tropical storm and hurricane occurrence was noted for the Atlantic basin from 1995 – 2005 (Webster et al. 2005). Increasing intensity and destructiveness of hurricanes and tropical storms was investigated by Emanuel (2005) showing an increase in intensity for the Atlantic basin as a result of increased sea surface temperatures (SST) and other factors. The occurrence of all tropical storms, subtropical storms, and hurricanes has increased since records began in 1851 (Figure 1). An increase in inundation frequency has the potential to lead to retrogressive succession in the marsh or erosion and loss of the marsh as a whole (Kim et al. 2011, Ravens et al. 2009). Storms may damage marsh vegetation and alter landscape pattern through many processes, including high winds, heavy rainfall, storm surge, and salt spray (Michener et al. 1997). Coastal marshes are resilient systems and have the ability to adapt to a dynamic climate and human environment. If factors result in increased frequency and intensity of storms at a rate that is faster then vegetation reestablishment the marsh systems may fail (Day et al. 2008).

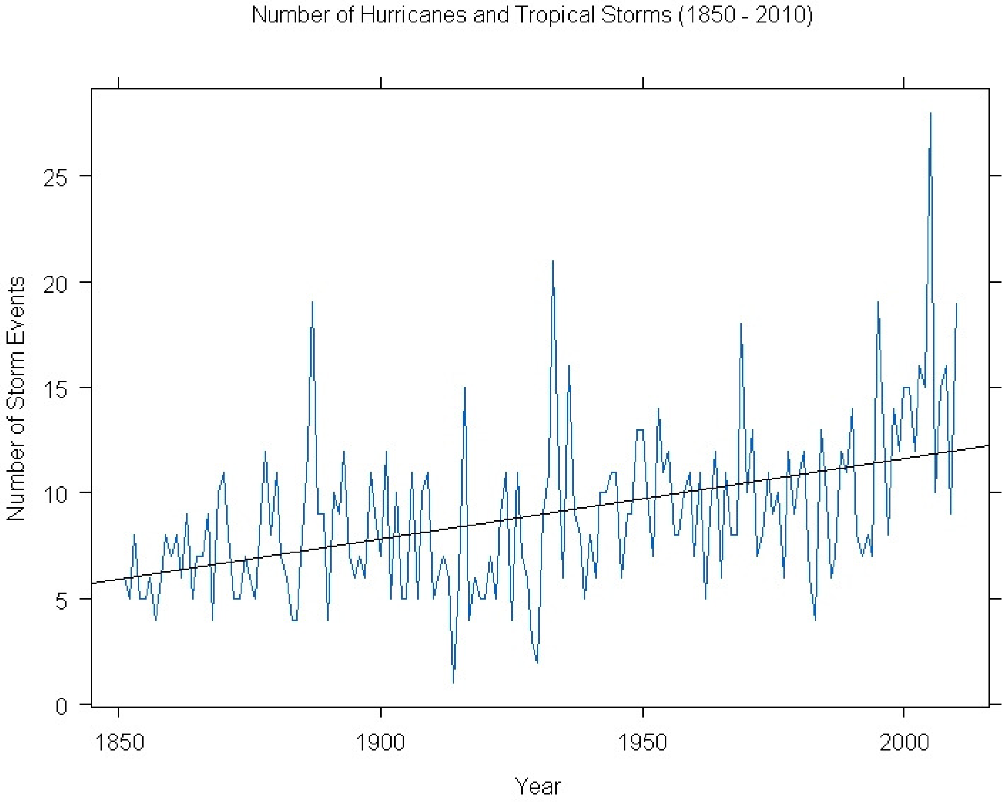


Figure 1. Hurricane and tropical storm frequency. Frequency of hurricanes and tropical storms in the Atlantic basin from 1850 – 2010.

STUDIES ALONG THE GULF OF MEXICO

A large number of North American coastal marsh studies have occurred in New England in a mesotidal environment (Bertness 1991a, Bertness and Leonard 1997, Crain et al. 2004, Donnelly and Bertness 2001). A long data record is partly responsible for this trend. Because of the large number of New England marsh studies it is tempting to extrapolate their findings of strong zonal patterns and well known biologic interactions to the Gulf Coast, this is however not necessarily advisable (Kunza and Pennings 2008). The East coast of the US has a predictable semidiurnal tidal regime that influences much of the marsh patterns observed whereas the Gulf Coast has a complicated mixed to diurnal tidal regime that is much less predictable, in the sheltered bays, leading to less pronounced, more overlapping zonation (White et al. 1985) and more interaction patterns most likely do to less frequent inundation. It is thus advisable to review current research regarding coastal marshes along the Gulf Coast.

Studies along the Gulf Coast of the US are generally focused on Coastal Louisiana and the Mississippi delta (Chabreck, Joanen and Paulus 1989, Draut et al. 2005, Gabrey and Afton 2001, Reed et al. 1997, Rogers 1988, Visser et al. 2000, Walker et al. 1987) but also extend to Alabama and Georgia as well (Kunza and Pennings 2008, Letzsch and Frey 1980, Roland and Douglass 2005). Chabreck began his studies of the marshes of Louisiana mapping wetland vegetation types in 1968 identifying four salinity zones; fresh, intermediate, brackish, and saline (Visser et al. 2000), these were some of the first vegetation classification maps for the Gulf Coast marshes. The classifications were revisited in 2000 by Visser et al. focusing on the marsh vegetation of the Chenier

Plain using helicopter surveys to create a comprehensive coast wide map. Visser et al. (2000) found seven vegetation classes along Chenier Plain expanding on Chabreck's original classification. Visser's seven vegetation classes include; Mesohaline Mixture, Mesohaline Wiregrass, Oligohaline Wiregrass, Oligohaline Paspalum, Fresh Maidencane, and Fresh Bultongure, and were created using species abundance data and TWINSPAN.

Research along the Gulf Coast has generally focused on the influence of subsidence and sea-level rise leading to coastal wetland loss (Rogers 1988, White, Morton and Holmes 2002, Walker et al. 1987). Many factors affect wetland loss along the Gulf Coast, but one of the most important is altered hydrology as a result of levees and dams (Rogers 1988, Walker et al. 1987). Along with altered hydrology, subsidence also leads to loss of wetlands and is a common phenomenon in the Gulf Coast (Morton, Bernier and Barras 2006). Subsidence has been very pronounced in the Gulf Coast, specifically in the Galveston Bay system, where fluid withdrawal has been shown to result in rapid land loss (White and Tremblay 1995). White et al. (2002) noted that nearly 2000 hectares of coastal marshes has been lost along the Texas coast between 1950 and 1980, most of this as a result of reduced sediment supply and subsidence. Of the 2000 hectares lost in Texas wetlands, this related to approximately 12 percent of the salt marshes in the Galveston Bay system (White et al. 1993). In an attempt to understand the causes of wetland loss in the Galveston Bay system, Ravens et al. (2009) investigated the causes of wetland loss finding that for approximately 94 percent of the studied marshes the primary cause of wetland loss was low sedimentation and accretion rates. This is in line with most of the findings in the Galveston Bay system and is likely the result of damming of the Trinity and Mississippi rivers (Ravens et al. 2009).

It is apparent from a review of the literature above that very few vegetation dynamics studies have been conducted along the Gulf Coast, more specifically along Galveston Bay. Much of the marsh literature related to vegetation dynamics has been conducted in New England and may not be applicable to the complex setting of the Gulf Coast; exceptions include Bhattacharjee et al. (2007 and 2009). Bhattacharjee et al (2007) investigated the effects of a muskrat eat-out at Anahuac NWR on the composition of marsh vegetation. Baseline vegetation was monitored in the years 1989-1991 prior to the disturbance and then for a decade 1992-2002 following the eat-out to determine its influence on the vegetation (Bhattacharjee et al. 2007). Using the same long term vegetation data from Anahuac NWR vegetation was monitored for fourteen years at five permanent transects to assess the importance of thirty eight biotic and abiotic factors on vegetation production (Bhattacharjee, Haukos and Neaville 2009). Bhattacharjee et al. (2009) found that biomass was the greatest when locations were inundated. Other studies in the Galveston Bay system have found that the ability of coastal marsh migration to occur along with sea level rise will depend on the economic rate of return of urban real estate in the area (Feagin et al. 2010). That is, if the value of property is greater than the value of ecosystem service provided by the marshes the urban landscape will be maintained and block the migration of marshes along with sea level rise, but if the opposite is true the urban landscape will be removed to allow for the migration of the coastal marshes and the maintaining of the provided services.

The literature review above illustrates many of the accepted theories on coastal marshes. With the respect to the Gulf Coast and the Galveston Bay system more research is needed to understand the important phenomenon that influences vegetation dynamics. Also, studies relating the interaction of climate change to vegetation process along the Gulf Coast are needed to understand more thoroughly the potential outcomes that may arise due to sea-level rise and more frequent intense storm events. The primary focus of this thesis will address the roles of both biotic and abiotic factors in structuring the coastal marshes along the East Bay of Galveston Bay and assess the implications of projected climate change both with regards to mean sea level rise as well as more frequent and severe storm events.

CHAPTER III

METHODS

STUDY SITE

The area of focus for this study is along the Gulf Coast of Texas in Chambers County. Galveston Bay is southeast of Houston and is the seventh largest bay-estuary-lagoon system in the United States (White and Tremblay 1995). Galveston Bay is protected from the rest of the Gulf of Mexico by a peninsula and barrier-island complex (White et al. 1985, White and Tremblay 1995) consisting of the Bolivar peninsula, Galveston Island and Follets Island, which provides protection from the open Gulf by reducing wave action, partially leading to the establishment of coastal marshes (Reed 1990). The marshes of the East Bay are part of the Chenier plain system that extends from south western Louisiana through south eastern Texas. The Chenier plain system is a series of stranded beaches composed of Mississippi river sediment that has been transported by longshore currents (Chabreck et al. 1989, Gosselink 1978, Visser et al. 2000).

The specific site for data collection will be along the landward side of the East Bay of Galveston Bay (94º 31’W 29º 37’ N) in Chambers County (Figure 2). The East Bay is primarily protected by the Bolivar peninsula and its waters vary in depth from about 1.2 to 2.4 meters (Lester 2002) and the bottom consists primarily of fine mud and shell (White et al. 1985). Tidal inflow occurs in East Bay via Rollover Pass and Bolivar Roads. Freshwater inputs come from the Trinity River in Trinity Bay and through bayou

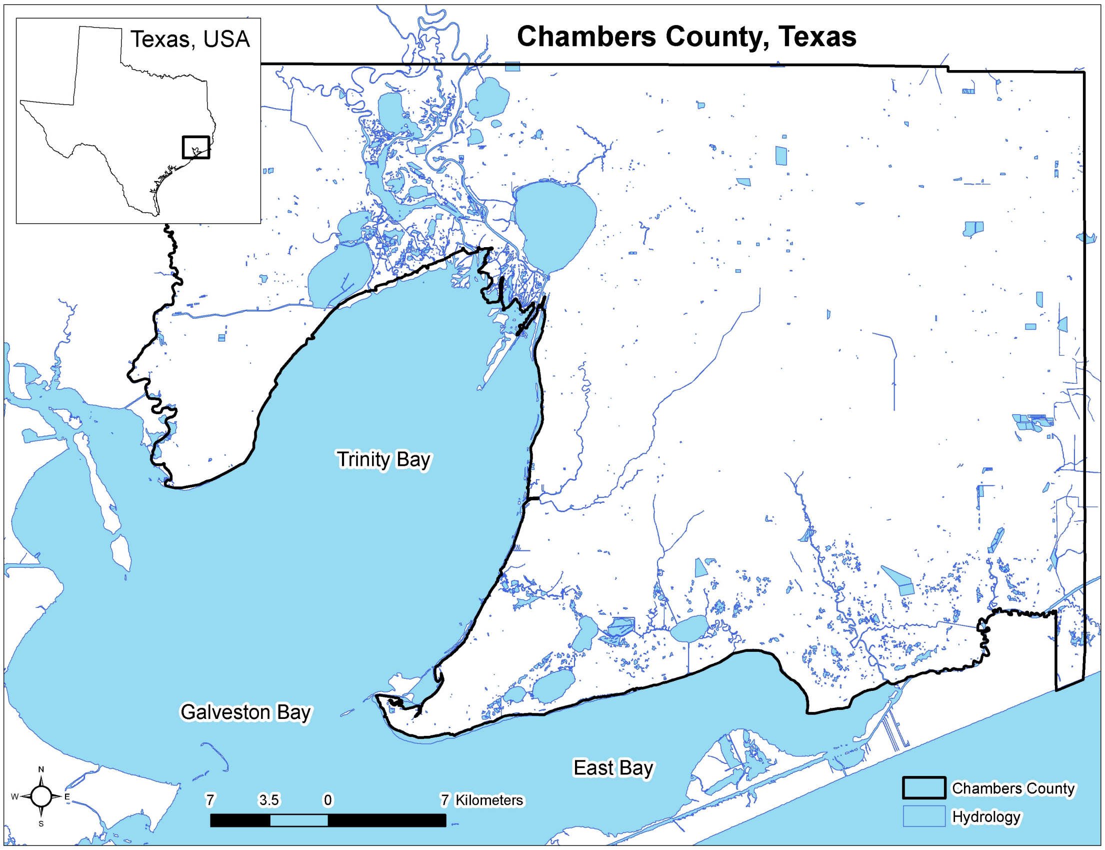


Figure 2. Chambers County, TX.

sources and precipitation. The salinity levels of the East Bay very based on freshwater input but range approximately from five to fifteen ppt (White et al. 1985).

The study's marshes extend from Smith Point to Anahuac NWR and extend from the shores of East Bay inland approximately 12 kilometers. The marshes along East Bay consist primarily of intermediate to brackish marshes with some transitional and tidal freshwater marshes intermixed throughout the study site. The soil structure along east bay consists primarily of alkaline and saline, clayey and loamy soils of the Harris-Veston-Ijam association (Crout 1976). Vegetation most common to the East Bay includes *Spartina patens* (Ait.) Muhl.*,* *Spartina spartineae* (Trin.) Merr. Ex Hitchc.*,* *Distichlis spicata (L.) Greene*, *Paspalum vaginatum* Sw., *Schoenoplectus americanus* (Pers.) Volkart ex Schinz & R. Keller, and *Schoenoplectus robustus* (Pursh) M.T. Strong. The study site consists of three levels of marsh vegetation: high marsh (intermediate to tidal fresh), mid marsh (intermediate to brackish), and low marsh (brackish to saline). Marsh types change as a function of salinity concentration that commonly is linked to changes in elevation. The four common marsh types found along the Gulf of Mexico are salt marsh, brackish marsh, intermediate marsh and fresh marsh (Stutzenbaker 1999, Chabreck et al. 1989).

Extensive anthropogenic modification may be seen at the study site including approximately four faults in the area created as a result of gas and oil extraction in the gulf, hydraulic modification, agriculture, grazing practices, and fragmentation of the landscape with ditches, canals, roads, and levees (Adam 2002, Gedan, Silliman and Bertness 2009, Ravens et al. 2009, White et al. 1985, White and Tremblay 1995). The study site's climate is characterized by humid sub-tropical conditions with annual rainfall in Chambers County reaching approximately 130.8cm a year with large variability in localized rain fall amounts, occurring due to hurricanes and tropical storms, and temperature ranging between 9ºC in the winter to 35ºC in the summer (Figure 3) (White et al. 1985). The predominant wind direction is south to southeast.

The tidal range of the Galveston Bay system is considered micro-tidal with the mean astronomical tidal range along the bay shore falling between 0.2m to 0.4m and onshore wave heights reaching 1.1 meters (White et al. 1985). Wind driven increases in bay waters appear to contribute much greater variability than does the diurnal tidal regime.

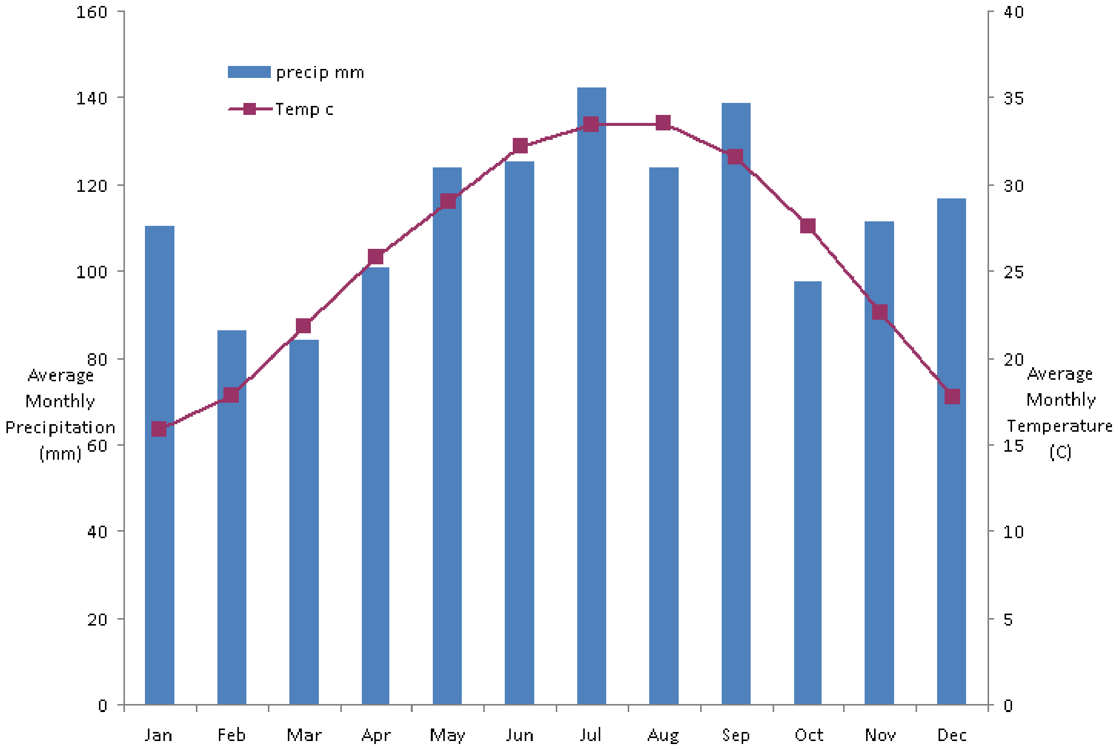


Figure 3. Chambers County Climograph.

Canada Ranch

Canada Ranch, owned and operated by Leroy Ezer, is a commercial cow-calf ranch established in 1929 in Chambers County, Texas (Figure 4). The ranch lies approximately 6 kilometers from the shores of east bay and 4 kilometers from Trinity Bay. Although the ranch is significantly inland from the two bays it is influenced by tidal waters from both via Gordy Marsh and Lone Oak Bayou, out of Trinity Bay, and, as a result of damage during hurricane Ike, through the Robinson Lake channel out of East Bay (Figure 4). The Canada Ranch is managed for cattle grazing primarily through burning and herbicidal application. The eastern portion of the ranch has not been grazed or managed since 2008 as a result of damage sustained to the access bridge crossing the Robinson Lake channel. This provided a unique setting to compare vegetation assemblages at the Canada Ranch that had been managed versus unmanaged.

Anahuac NWR

Anahuac NWR (Figure 5) consists of 34,000 acres of coastal marshes and prairies that are managed for the benefit of neo tropical migratory birds and waterfowl by the United States Fish and Wildlife Service (USFWS). The refuge was established in 1963 and is located in southeast portion of Chambers County, Texas, approximately 2 kilometers from the eastern boundary of the Canada Ranch.

Anahuac NWR is bordered on the south by the East Bay and is bisected through the middle by Oyster Bayou which empties into the bay. The refuge is surrounded by roads and levees that prevent the entry or exit of water on to the marsh. Anahuac NWR uses a variety of methods to manage its marshes including a controlled burning rotation, water level adjustment, and grazing. The refuge manages salinity targets through the use structural marsh management and aims to keep the water level approximately two inches above or below marsh elevation. Water will usually only be drained off if high salinity levels occur, due to disturbance, in order to reduce the total tonnage of suspended salt in the water column; this is, however, done with caution (Walther 2011). The agricultural units, primarily cereal grains, are planted in the northern units of Anahuac NWR and were not included as part of this study. The brackish and intermediate marshes found in the southern portion of the refuge were chosen for this study in order to remove the effects of grazing and agricultural food plots in the northern region.

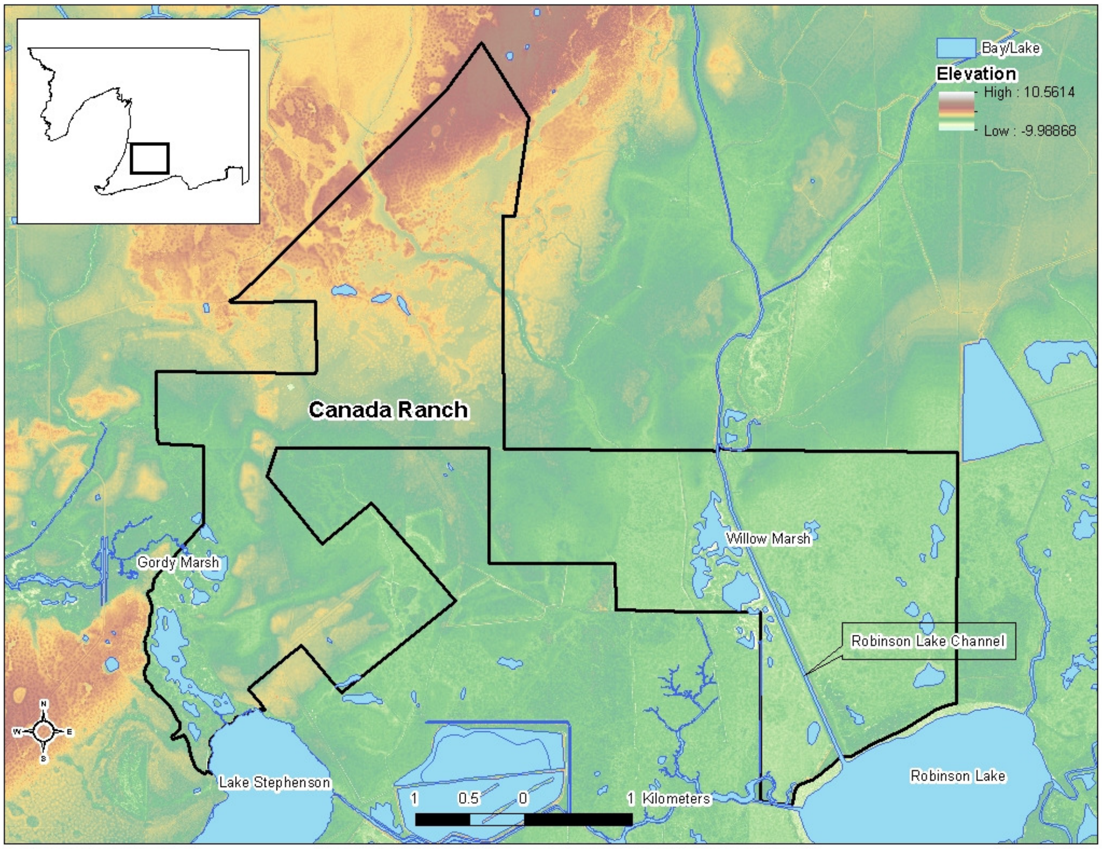


Figure 4. Canada Ranch.

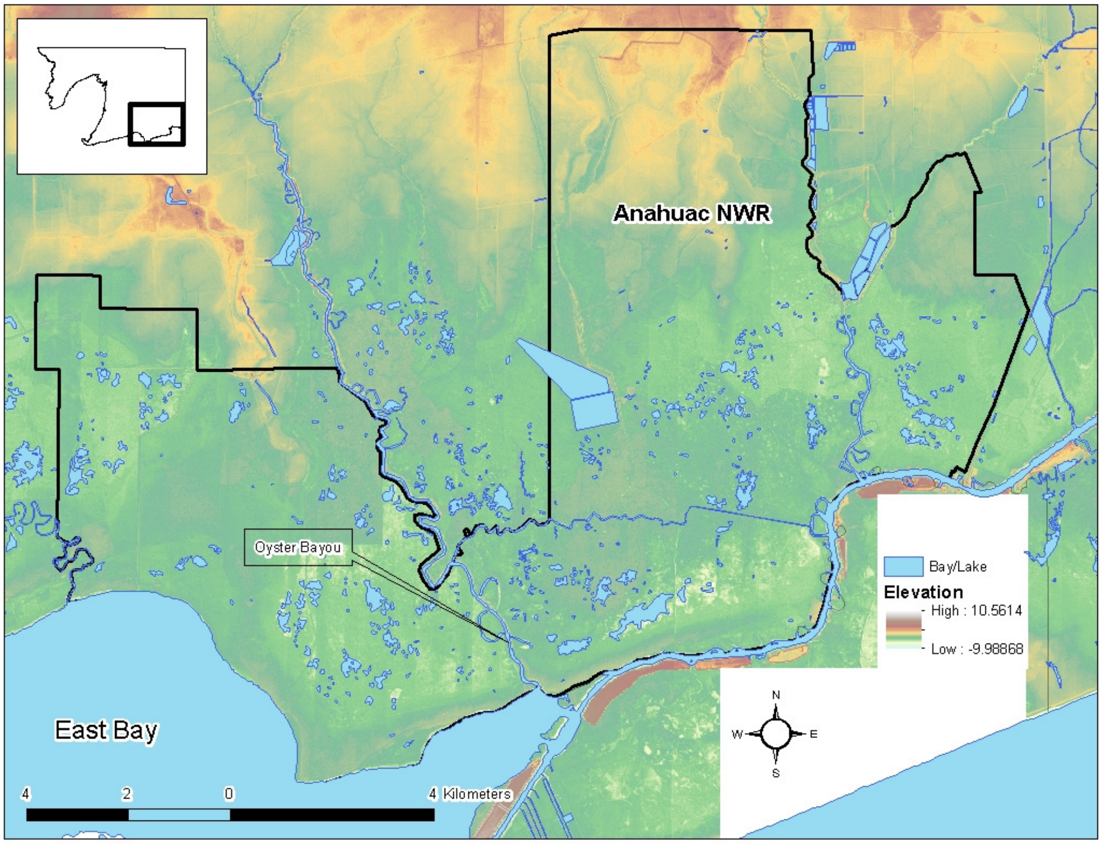


Figure 5. Anahuac NWR.

SAMPLE DESIGN

Sample sites were established to capture the variability of the marsh types typical along the Gulf of Mexico. Preliminary site visits provided geolocated photographs that were used to aid in the classification of a 2008 Landsat 5 TM scene (Path 25 Row 40) into the five marsh zones. Using ENVI (ITT Visual Information Solutions 2009) the Landsat scene was layer-staked using bands 5,4, and 3 then smoothed using a low pass convolution filter to reduce high frequency spectral information in the scene. Unsupervised classification was carried out using an ISODATA classifier which iteratively clusters pixels together based on the similarity of their spectral signature until the maximum grouping number is met (Jensen 2005) (Figure 6). The classification was parameterized to a maximum of 10 classes and a minimum of 5 and 50 clustering iterations were run. The output spectral classes were then grouped into information classes and assigned to each of the five vegetation zones (High, Mid, Low, Tallow, and Bare) using .5 meter high resolution ortho photos of Chambers county as a guide. The classified Landsat scene was then subset by the boundaries of the Canada Ranch and Anahuac NWR and sampled using a stratified, random proportional sampling scheme in ENVI (ITT Visual Information Solutions 2009, Boulder, Colorado) (Figure 7).

I established 185 sample plots at two study locations near the East Bay of Galveston bay. Sample sites were created to capture five different vegetation zones. High Marsh (60), Mid Marsh (100), Low Marsh (19), Tallow (3), and Bare Ground (3). The plots were accessible by foot, kayaking, and use of a United States Fish and Wildlife Service (USFWS) airboat.

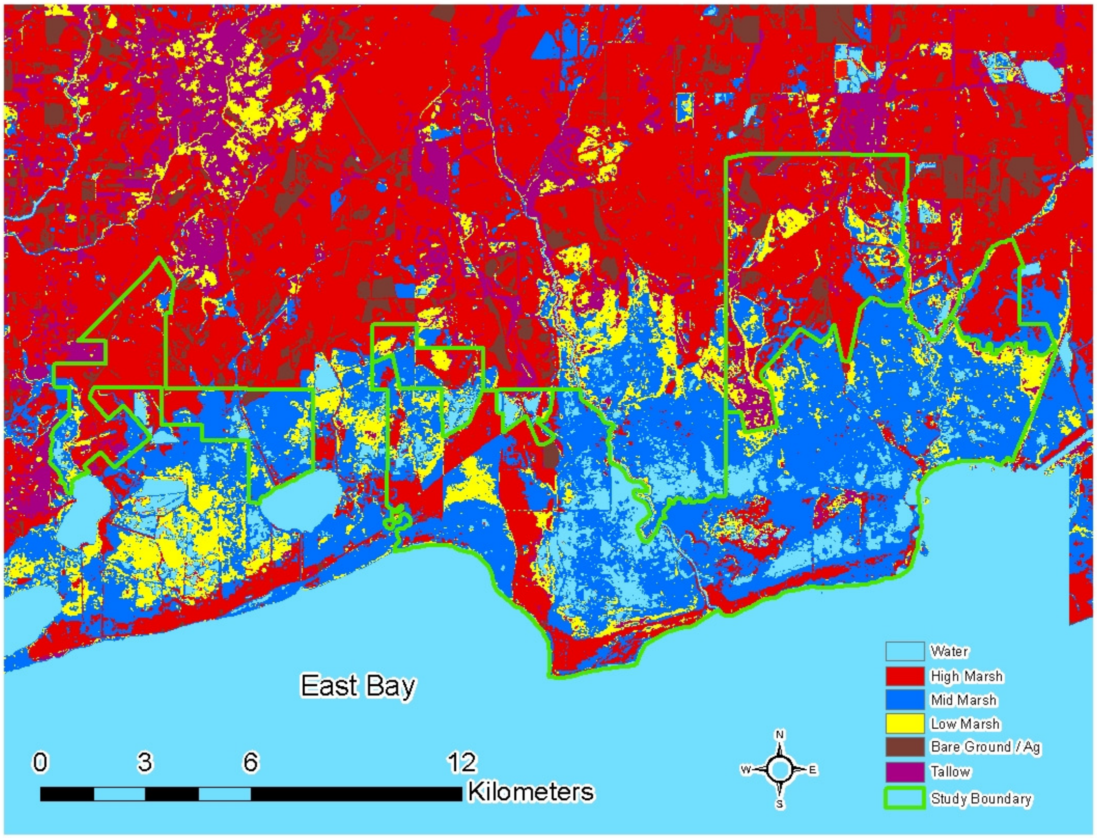


Figure 6. Marsh Classification. Landcover types used to create stratified, random proportional sampling scheme.

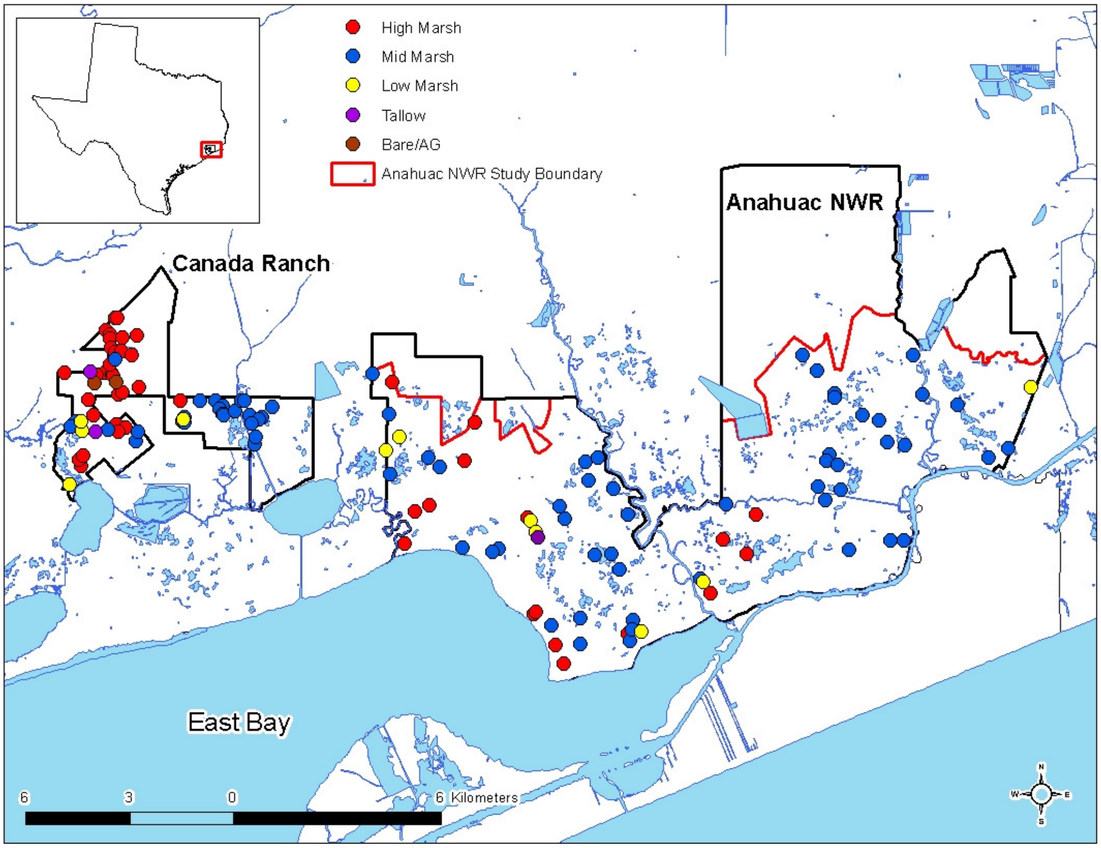


Figure 7. Plot distribution. Randomly selected plot locations at the study site. Plot colors correspond to marsh type classification in figure 6.

Each plot was sampled to record the presence of marsh species in 25, 20cm x 20cm, sub-units of a 1m x 1m quadrate sampling frame (Figure 8). If a species was present in a subunit it was recorded and the total of a given species in a sample ranged from 0 – 25 representing relative dominance of vegetation at a given plot. The latitude and longitude of each plot was recorded and a plot photograph was taken to document the phenological state of the vegetation and as a visual record of the plot. All plots were sampled between May 21st, 2010 and July 16th, 2010 to minimize variation in seasonal phenological changes in marsh vegetation. Samples of marsh species were collected and pressed for future identification and plot photographs were archived for plot validation. Due to access difficulties plots in dense marsh stands that were distant from roads were not all sampled. 63 plots were sampled at the Canada Ranch and 73 plots were sampled at Anahuac NWR resulting in 35 species represented (Table 1). Stutzenbaker's Aquatic and Wetland Plants of the Western Gulf Coast (Stutzenbaker 1999) and Godfrey and Wooten's two volume Aquatic and Wetland Plants of Southeastern United States (Godfrey and Wooten 1981a, Godfrey and Wooten 1981b) were selected as the floras.

The collected floristic data was organized in an ordered plot by species table that contained plots in rows and species in columns. Plots were named based on the landcover classification they were sampled from and numbered sequentially e.g. HM_01, if the sampled plot was at Anahuac NWR "A" was placed on the end and if the plot was included as an extra plot "B" was included e.g. LM_01_A or LM_02AB. The cells in the data table contained values in a range from 0 – 25 and was generally sparse, containing many zeros as is common in ecological data.

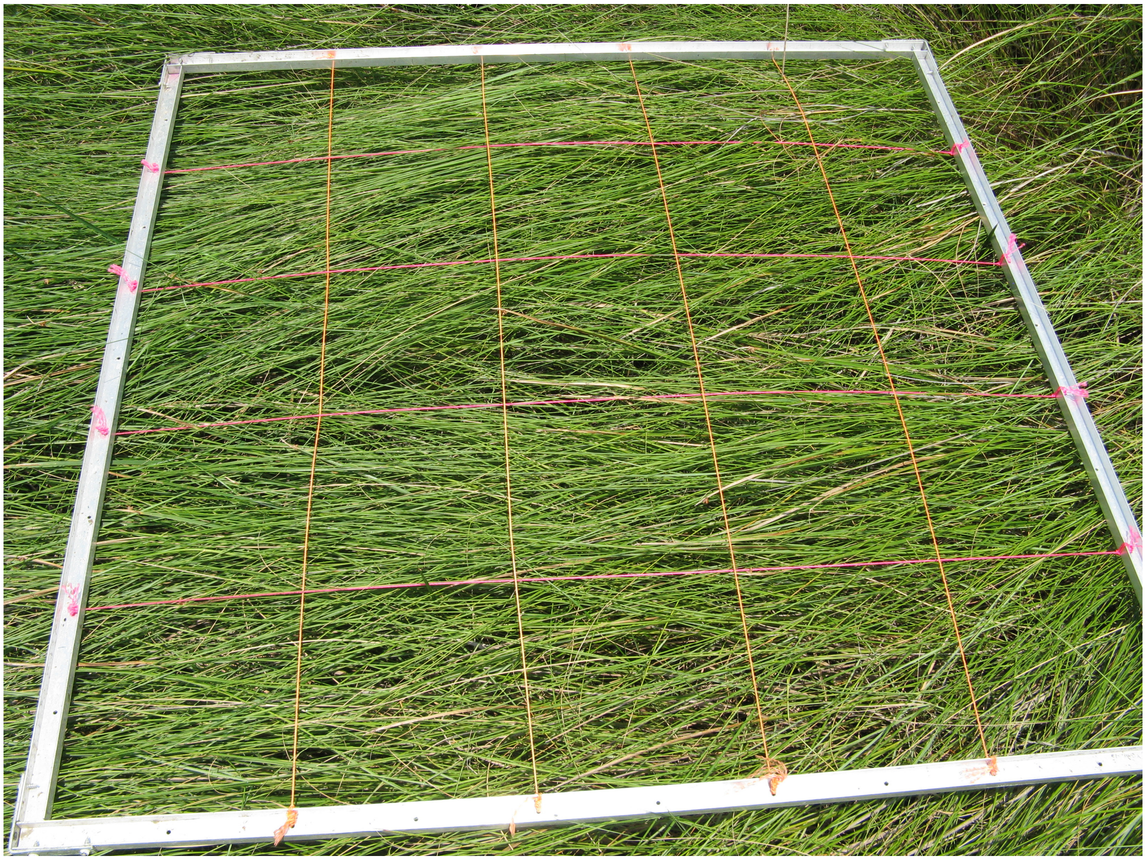


Figure 8. Typical *Spartina patens* marsh quadrat.

Table 1. Marsh species. Combined 35 plant species identified at both the Canada Ranch and Anahuac NWR.

Code	**USDA Plants Database Name**
Amaaus	*Amaranthus australis* (Gray) Sauer
Ambcum	*Ambrosia cumanensis* Kunth in H.B.K.
Bacmom	*Bacopa momieri* (L.) Wettst.
Bapbra	*Baptisia bracteata* Muhl. Ex Ell.
Borfru	*Borrichia frutescens* (L.) DC.
Croell	*Croton* sp.
Diovir	*Diodia teres* Walter
Disspi	*Distichlis spicata* (L.) Greene
Elemon	*Eleocharis montevidensis* Kunth
Iposag	*Ipomoea sagittata* Poir.
Ivaann	*Iva annua* L.
Junbra	*Juncus brachycarpus* Engelm.
Junint	*Juncus interior* Wieg.
Junroe	*Juncus roemerianus* Scheele
Lyccar	*Lycium carolinianum* Walt.
Lytliin	*Lythrum lineare* L.
Mimstr	*Mimosa strigillosa* Torr. & A. Gray
Pasvag	*Paspalum vaginatum Sw.*
Phraus	*Phragmites australis* (Cav.) Trin. *ex* Steud.
Rubspp	*Rubus spp*
Sabcom	*Sabatia campestris* Nutt.
Scioln	*Schoenoplectus americanus* (Pers.) Volkart ex Schinz & R. Keller
Scical	*Schoenoplectus californicus* (C.A. Mey.) Palla
Scrob	*Schoenoplectus robustus* (Pursh) M.T. Strong
Scipun	*Schoenoplectus pungens* (Vahl) Palla var. pungens
Salbig	*Salicornia bigelovii* Torr.
Setgen	*Setaria geniculata* (Lam.) Beauv.
Spapat	*Spartina patens* (Ait.) Muhl.
Spaspa	*Spartina spartineae* (Trin.) Merr. Ex Hitchc.
Sualin	*Suaeda linearis* (Ell.) Moq.
Typang	*Typha angustifolia* L.
SppOne	herb species
SppTwo	grass species
VigLut	*Vigna luteola* (Jacq.) Benth.

DATA ANALYSIS

Cluster Analysis

Vegetation composition is inherently complex and multivariate. Cluster analysis is a way to find groups in the data based on its underlying or latent structure (Gauch and Whittaker 1981). I used hierarchical cluster analysis to investigate the similarity of sampled plots. Cluster analysis was conducted using PC-ORD (McCune and Mefford 1999) with a Euclidian distance measure paired with Ward's linkage. In cluster analysis the first step is construction of a similarity matrix to quantify the similarity among plots. I chose Euclidian distance as the similarity measure (Equation 1); P = species, $a_{i,j}$=abundance of species j in sample unit i.(McCune and Grace 2002).

$$ED_{i,j} = \sqrt{\sum_{j=1}^{P} (a_{i,j} - a_{h,j})^2} \qquad \textbf{(1)}$$

Ward's method is used to merge and cluster plots into similar groups by searching for the minimum variance. This is done by minimizing the increase in the sum of squares distances from each sample to the centroid of the group to which it belongs (McCune and Grace 2002). Cluster analysis using Euclidean distance with Ward's linking is the recommended method because it is space conserving and avoids distortion (McCune and Grace 2002). The cluster analysis results in a dendrogram representing the grouping of entities at various levels of similarity. Cluster analysis is a useful technique because it forces the explicit scale of analysis (Little, Guntenspergen and Allen 2010) to be acknowledged before conclusions can be drawn from ecological data. In this study, the plant assemblage level was chosen as the explicit scale of analysis. Methods used to determine the optimal classification are discussed below.

Indicator Species Analysis

Indicator Species Analysis (ISA) is a quantitative tool used to test the faithfulness of a species to a specific group. Ecological data that are concerned with using individual species as a method of characterizing a predictive vegetation association must be able to identify the characteristic species that are most important in identifying different vegetative associations (Dufrene and Legendre 1997). A perfect indicator is always present in its indicated group and is absent from all other groups (Dufrene and Legendre 1997, McCune and Grace 2002). ISA is used with ecological data representing frequency and abundance of species (McCune and Grace 2002). The plot level data collected at the study site were run through ISA to quantitatively identify which grouping level would be used to run the multi-response permutation procedure and identify the optimal classification scheme. ISA produces an indicator value ranging from 0 – 100 where 0 signifies no indication and 100 is a perfect indicator (McCune and Grace 2002) and the significance of the indicator value is tested through the use of a Monte Carlo test run 5000 times. The resulting p values are then evaluated for statistical significance.

Multi-Response Permutation Procedure

Multi-Response Permutation Procedure (MRPP) is a method for determining if significant differences exist between two or more groups. The hypothesis of no difference between groups is tested and the procedure results in three statistics (P, A, and

T). The P value indicates the probability of finding a smaller or equal delta, the weighted mean within-group distance (McCune and Grace 2002). The agreement, A statistic, can be analyzed to understand the homogeneity within groups compared to a random pattern. The results range between -1 and 1, where 1 indicates complete homogeneity within groups, and -1 indicates no homogeneity within groups. In ecological data values greater than 0.3 are considered fairly high (McCune and Grace 2002). To test for the separation between groups the test statistic, T, is used. Values of T are negative; the more negative T is the more separation occurs between groups. MRPP is useful in ecological studies because it does not need to meet distribution assumptions such as multivariate normality (McCune and Grace 2002). Along with ISA, MRPP is used to quantitatively trim the classification dendrogram and determine the appropriate grouping level of the classified floristic data.

HYDROLOGICAL MODELING

Mike 21(DHI 2010), a wave and flow simulation model was used to interpolate surface water elevation across Galveston Bay so that a flood inundation model could be created to calculate flood frequency at sampled locations throughout the Canada Ranch and Anahuac NWR. Mike 21 interpolates a flow surface using a triangular irregular network (TIN). To create the TIN light detecting and ranging (LiDAR) data, flown in 2006, at 5 meter resolution was used for the terrestrial component of the landscape and National Oceanic and Atmospheric Association (NOAA) bathymetry data was used for the marine landscape. Both the LiDAR and bathymetry data were North America

Vertical Datum 1988 and North America Datum UTM Zone 15N. The wind and tide data that were extrapolated across the TIN was taken from Morgan's Point gauge station North West of Trinity and East Bays (Figure 9). This station was chosen because it represented the tide and wind data gauge that is most northerly of the Galveston Bay system and specifically the study sites. The model takes the known wind and tide data from the gauge station and interpolates it across the landscape so that water surface elevations can be modeled.

Inundation Frequency

Due to the resolution of the LiDAR data, modeling of the tidal regime was not feasible at the Canada Ranch and Anahuac NWR, and a second inundation model was constructed to predict flood frequency within the study area. A digital elevation model (DEM) can be constructed from bare ground LiDAR elevation points using an inverse distance weighting (IDW) interpolation method in ArcGIS. The LiDAR DEM was clipped to the study area surrounding the Canada Ranch and the hourly water surface elevation data that was modeled from Mike 21 was extracted from five locations. Based on visual interpretation of the location of a sampled plot and the connectivity of the hydrology one of the five modeled water surface elevation locations was chosen to represent inland water surface. The assumption was made that as long as the plot location was within the appropriate connected hydrological area it would be flooded based on the elevation of the water at a given hour. A python script was developed to iteratively extract the hourly water surface elevation and construct a binary raster image that was either inundated or non-inundated and then the hourly raster images were combined and inundation frequency was calculated.

Inundation frequency was calculated for all sample locations from water surface elevations modeled using Mike 21 and calculated based off of hourly observations for the year 2008 for each sampled plot at the Canada Ranch and Anahuac NWR. The assumption is made that there are no barriers to flow from either Trinity Bay via Gordy Marsh, or East Bay via the inlet at Lake Surprise or Oyster Bayou (Figure 4). If a plot has an elevation (derived from LiDAR) less than or equal to the modeled hourly surface water elevation then the location has the potential to be inundated and will be considered inundated for the observed hour, if the plot is higher than the threshold elevation it is not inundated. The binary hourly data (1 inundated, 0 non-inundated) are then summed (n) and divided by the total hours (T_r) to calculate inundation frequency (Equation 2).

$$\int = n / T_r \qquad \textbf{(2)}$$

Inundation occurs when modeled water surface elevation is greater then marsh elevation at a given location.

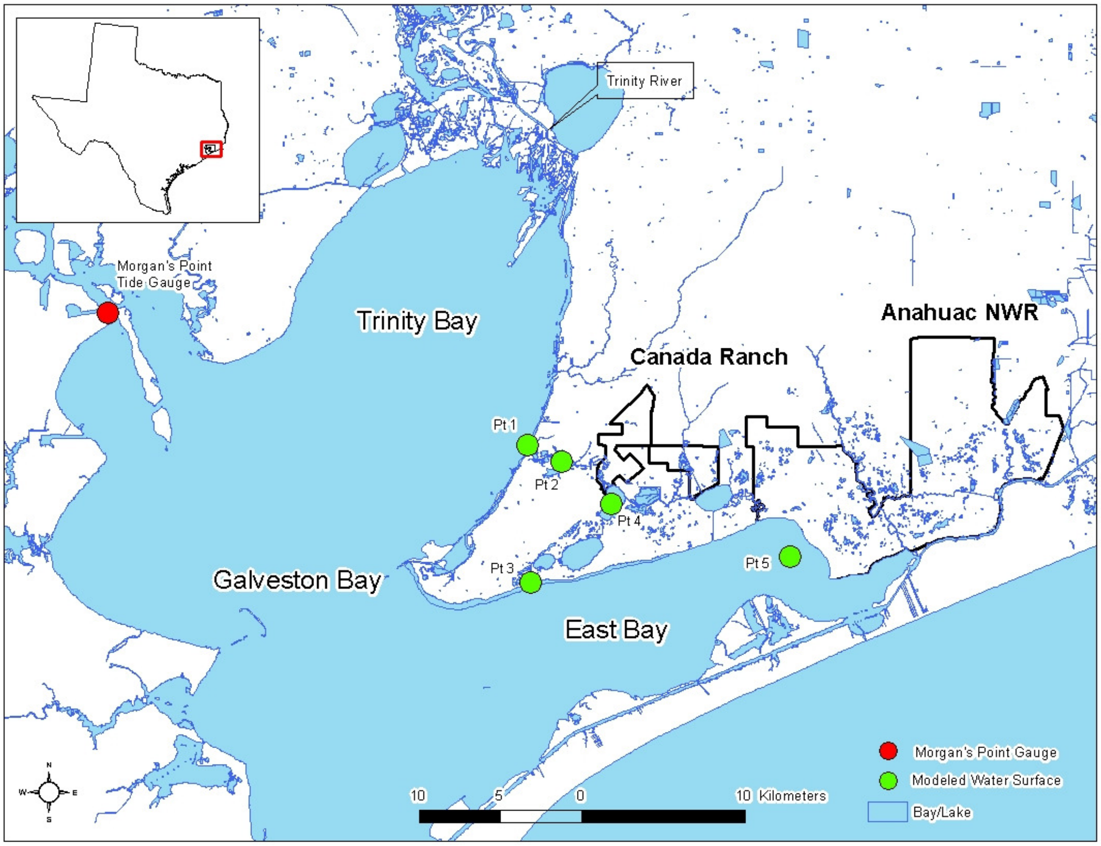


Figure 9. Morgan's Point gauge station. Selected water surface elevation points interpolated from the Morgan's Point gauge station using Mike 21 for inundation modeling.

SPECIES DIVERSITY

Species diversity is the distribution and abundance of vegetation in a landscape observed as species richness, or the total number of species that occur in a given sample (Whittaker 1972). It is, however, very difficult to accurately identify the factors that are important in contributing to species diversity (Huston 1979). Species richness (S) is easily interpreted, but gives no information on how evenly species are distributed or how dominant species are in a landscape. To answer the questions regarding evenness (E) and dominance alpha diversity must be calculated. Alpha diversity, the diversity occurring in individual plots (McCune and Grace 2002) is calculated using the Shannon-Wiener index (H) and, although the two may be correlated, Simpson's index (D) is also calculated as is recommended by McCune and Grace (2002). Simpson's index calculates the number of species i and the proportion of individuals belonging to species i (P_i^2) in a plot (Equation 3). Shannon's diversity calculates the number of species i and P_i is the proportion of individuals belonging to species i (Equation 4). Simpson's and Shannon-Wiener indices were used for alpha diversity in individual plots. Evenness was calculated by dividing Shannon's diversity by the average species richness (Equation 5).

$$D' = 1 - \sum_{i}^{S} P_i^2 \qquad \textbf{(3)}$$

$$\mathrm{H} = -\sum_{i=1}^{S} (P_i \log P_i) \qquad \textbf{(4)}$$

$$\mathrm{E} = \mathrm{H}/\log \mathrm{S} \qquad \textbf{(5)}$$

The diversity measures were computed for all plots as well as for clustered vegetation groupings in order to investigate which environmental and anthropogenic variables contribute to species diversity along the East Bay marshes.

PREDICTION MODELING

Species prediction modeling is a technique that allows species or community types to be determined as a function of predictor variables (Segurado and Araujo 2004) and assesses if groups differ from one another (McCune and Grace 2002).

CART

Classification and regression tree (CART) analysis is used to recursively partition the dataset into increasingly homogenous groups with a tree output (De'ath and Fabricius 2000, Pesch et al. 2011, Vayssiéres, Plant and Allen-Diaz 2000). One of the benefits of using CART is that the output is easy to interpret, as each branch leads to a node that is binary in nature. Through the recursive partitioning procedure a threshold value is identified, where values less then the threshold value are assigned to one branch and values greater than the threshold value are assigned to another (McCune and Grace 2002). The partitioning seeks to identify increasingly homogenous groups where the predictor variables show the highest statistical relationship with the target vegetation assemblage (Pesch et al. 2011).

CART is used to perform species prediction modeling using the RPART package (Therneau and Atkinson 1997) in S plus (SP2000 for Windows, Insightful, inc). RPART (recursive partitioning) is a package utility that allows for more precise control of the output tree and modeling over the standard TREE program in S plus. Vegetation assemblages, defined via cluster analysis, and diversity measures are used as the dependent variable and inundation frequency, elevation and burn regime are the predictor variables.

The output tree from the RPART program is pruned to maximize its explanatory power by plotting the complexity parameter from an RPART fit and identifying the appropriate tree size (Therneau and Atkinson 1997). The complexity parameter is calculated at each partition of the tree along with an estimate of homogeneity and misclassification (McCune and Grace 2002). The tree is pruned so that the smallest possible tree that minimizes relative error is chosen as the best tree.

The CART analysis will help identify which variables best define a vegetation assemblage and identify threshold values for diversity and vegetation assemblage at the study site. CART was chosen over other models as it is easier to interpret mixed data (e.g. categorical and numeric) (Cairns 2001) in a somewhat homogenous environment. With categorical data the accuracy of the CART model is assessed by dividing all misclassified cases by the total number of observations, this results in a risk assessment of the CART model (Pesch et al. 2011). Because burn data is only available at Anahuac NWR its data will also be treated separately from the full dataset.

Burn Frequency

Burn frequency was calculated for Anahuac NWR from burn maps provided by US Fish and Wildlife Service at Anahuac NWR. The number of years since a unit was last burned was extracted from digitized polygons delineating the boundary of burn units for the years 2003-2010 (Figure 10) and used as independent variables for species distribution modeling.

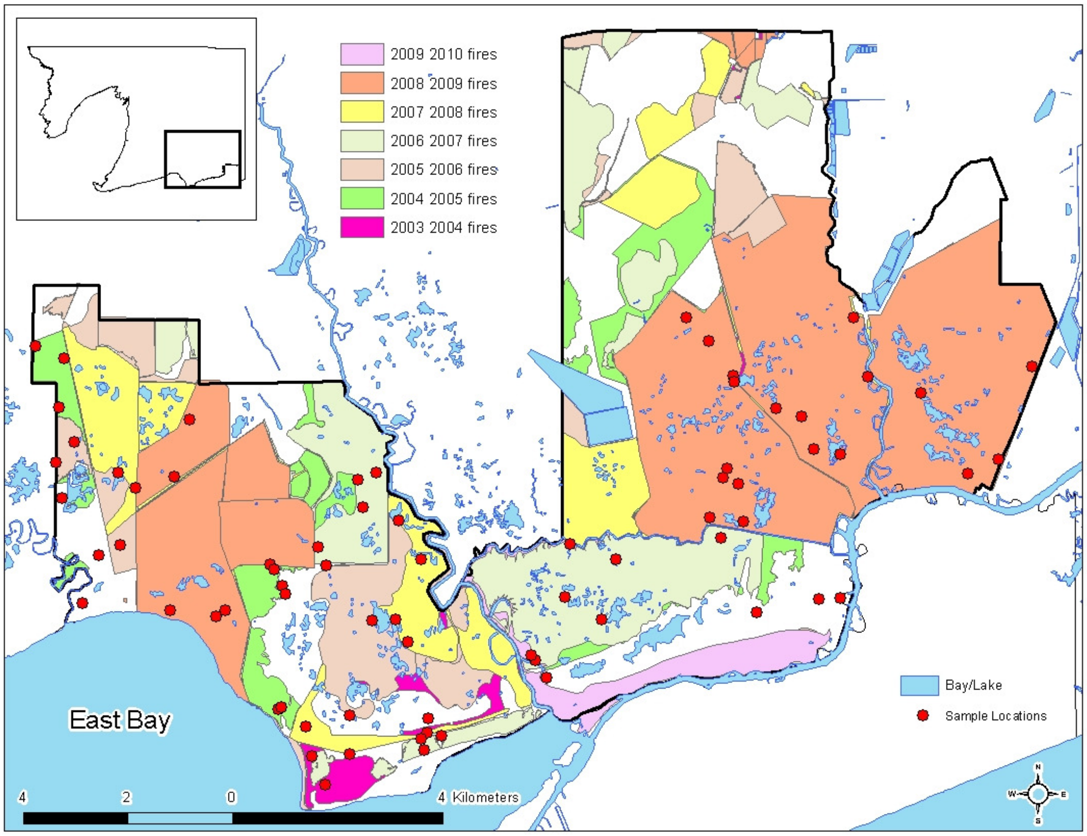


Figure 10. Anahuac NWR burn units. Units represent areas burned for the years 2003-2010 with plot locations.

CHAPTER IV

RESULTS

CLUSTER ANALYSIS

35 species were identified (Table 1) at the East Bay marshes and are present in at least one sampled plot. The species frequency data that was recorded for each plot in the field was transposed into a floristic data matrix in a plot by species format. The cluster analysis was conducted using PC-Ord (McCune and Mefford 1999) and a visual analysis of the dendrogram revealed good separation between the clustered groups. In order to determine the appropriate level at which to trim the dendrogram, ISA was run for cluster levels eighteen through two, and the average lowest p value was calculated (Figure 11). The starting cluster level of eighteen was chosen because at this level no groups were excluded from the analysis and I felt that explanatory power would be lost with much larger clusters. Cluster level four had the lowest average p value ($p = 0.30182$). A subjective trimming was also conducted, where the dendrogram was trimmed at variable locations to improve explanatory power. The subjective clustering further split the dendrogram into seven vegetation types. When MRPP was run for the subjective clustering configuration the p value was only slightly higher ($p = 0.329446$) than at grouping level four (Figure 12) but offered more explanatory power and was thus selected for continued analysis.

Pruning the dendrogram to seven assemblages MRPP identified strong homogeneity within groups ($A = 0.33601$) and strong separation between groups ($T = -53.053785$). McCune and Grace (2002) argue that an A statistic greater than 0.3 is high in community ecology. This grouping level was found to be statistically significant at a P value < 0.01. The clustering dendrogram was thus trimmed at variable locations (Figure 13), allowing approximately 70 percent of the original information to remain intact and creating ecologically significant vegetation groupings.

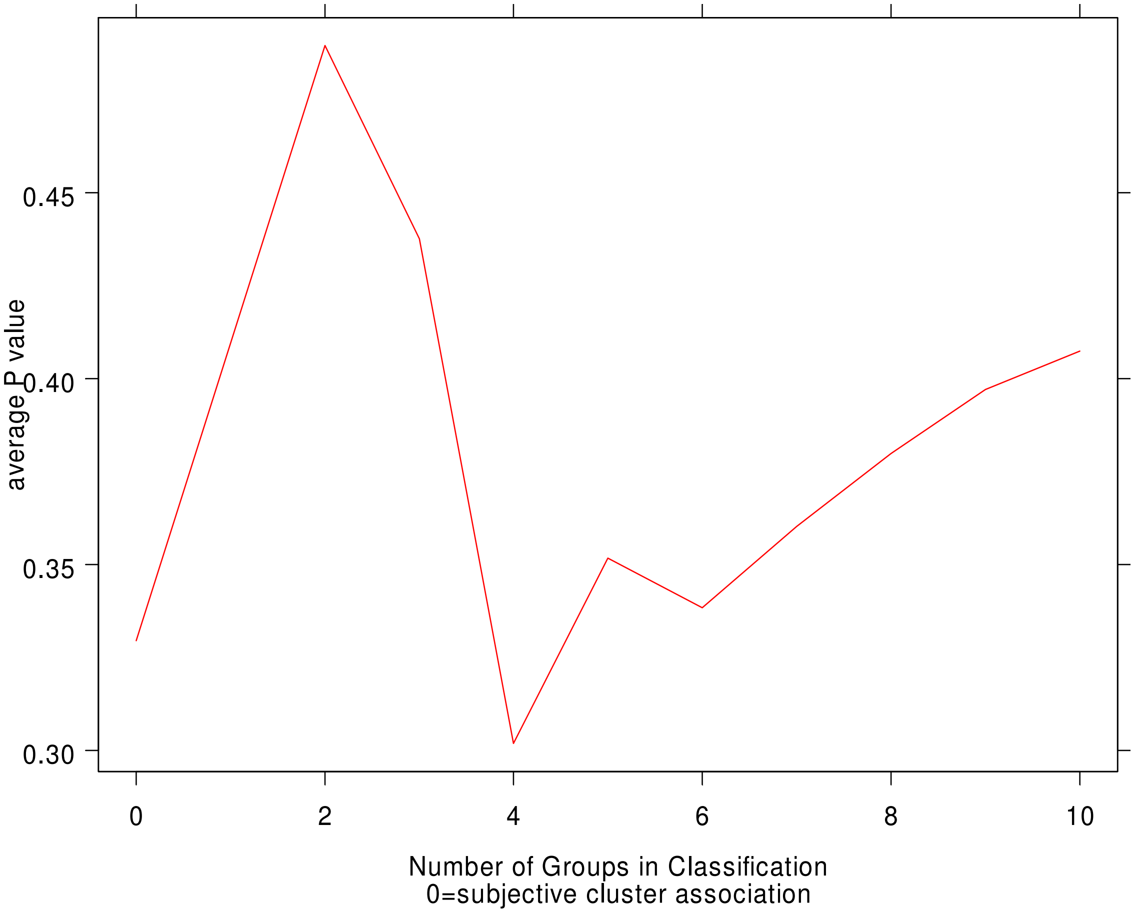


Figure 11. ISA lowest average P values. Group 4 had the lowest average P value and group 0 was the result of a subjective grouping procedure.

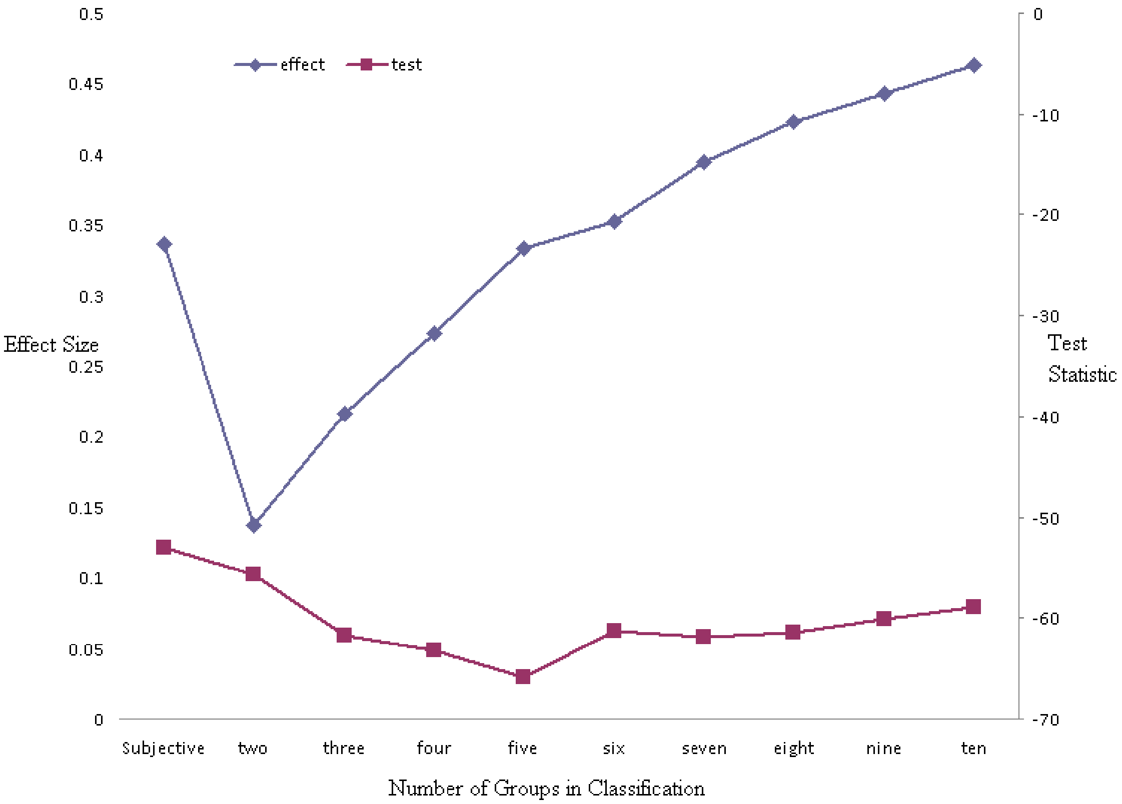


Figure 12. MRPP effect size and test statistic. Test Statistic shows separation between groups where the lower the value the greater the separation, and effect size indicates within group homogeneity where the closer the value is to 1 the more homogenous the group.

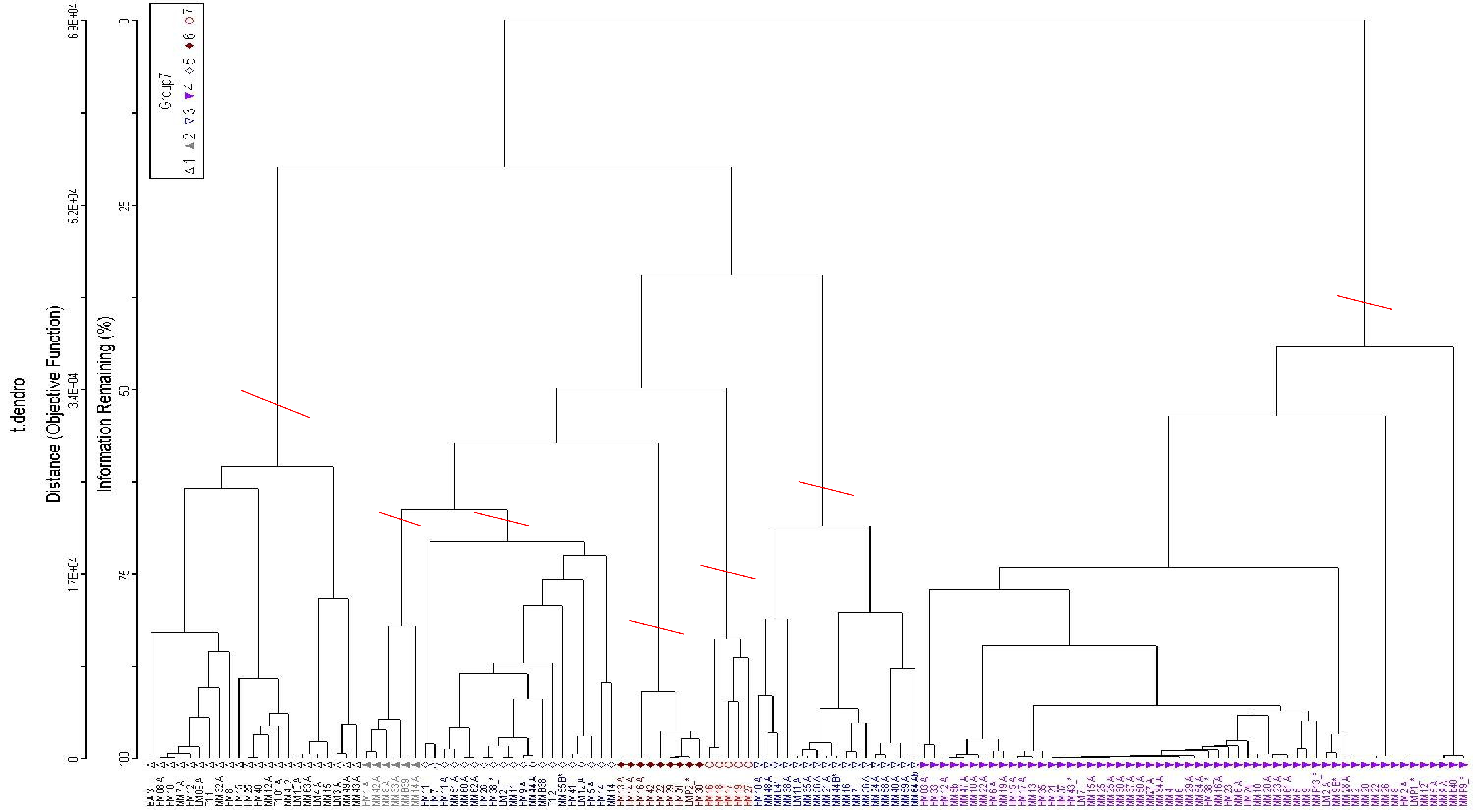


Figure 13. Cluster dendrogram. Output from hierarchical cluster analysis and pruning locations established through ISA, and MRPP illustrating the seven vegetation groups of the East Bay marshes. Groups were named based on the dominant vegetation that occurring in the clustered plots: Pasvag, Scioln, Mixed, Spaspa, Diovir, Disspi, and Spapat

Vegetation Assemblages

Group one consisted of 22 plots and was dominated by the species *Paspalum vaginatum*. Pasvag is a grass found in brackish to fresh marshes usually in wet soils with low salinity levels less than 3.5 (PPT) (Stutzenbaker 1999). Other species were present and the Pasvag group was distributed equally between the Canada Ranch (12 plots) and Anahuac NWR (10 plots). The plots were high marsh and bare ground at Canada Ranch but showed more variability at Anahuac NWR where the plots were classified as high, mid, and low marsh. At the Canada Ranch Pasvag plots occurred at elevations above 2 meters and were clustered near the North West extent of the ranch, while at Anahuac NWR the Pasvag plots were located at elevations less than 0.5 meters and were spread across the refuge. Pasvag is a desired grass for grazing purposes and is managed for at the Canada Ranch due to its high protein content for cattle.

Group two consisted of 6 plots dominated by *Schoenoplectus americanus* (formerly *Scirpus olneyi*, Scioln). Anahuac NWR contained 5 of the plots and all plots were inundated at the time of sampling. Canada Ranch contained 1 plot and the observed condition was wet soil, this plot occurred east of the Robinson lake channel where little management activity has occurred since the bridge was damaged during hurricane Ike. The plots consisted of nearly pure stands of *Sch. americanus* but there were some occurrence of *Sp. patens* and *Schoenoplectus robustus*. All plots occurred at elevations less than 1.00 meter.

Group three, mixed vegetation sites, consisted of 20 plots with no dominant species present. Plots contained mainly annuals and perennials that are adapted to withstand disturbance such as frequent burning, mowing, grazing, and in some instances elevated salinities found in salt pans in the case of *Salicornia bigelovii*. The distribution of plots shows a lot of variability with plots occurring in all marsh types, ranging in elevation from 0.2 – 2.9 meters, and observed conditions ranging from dry salt pans to inundated low marsh, and also grazed and burned conditions noted. Management strategies used between the two study areas can be seen in this group, particularly the presence of *Eleocharis montevidensis* which is adapted to withstand burning and grazing and *Ambrosia cumanensis* which is commonly found in grazed and disturbed sites (Stutzenbaker 1999).

Group four consisted of 9 plots dominated by *Spartina spartinae* (Spaspa). Spaspa, Gulf Cordgrass which is a marsh grass occurring at higher elevations in intermediate to saline marshes. Spaspa can tolerate frequent disturbances from saline conditions to burning and may be found further inland in salt pans (Stutzenbaker 1999). Spaspa dominated all plots in this group, nearly exclusively with very few other species present. Three Spaspa plots occurred at Anahuac NWR, all three along an elevated ridge, less than 0.29 km from East Bay at elevations of approximately 1.00 meter and classified as high marsh sites. At the Canada Ranch 6 Spaspa plots were sampled all occurring as high marsh sites except LM P2* which is a plot on an elevated ridge near the Gordy Marsh tidally influenced area of Canada Ranch. It was likely classified as low marsh due to the resolution of the landsat imagery used to create the initial classification.

Canada Ranch Spaspa plots range in elevation from 0.5 to 1.1 meters and were not found to be inundated at the time of data collection.

Group five consisted of 5 high marsh plots all clustered near the North West portion of the Canada Ranch. The group contained low growing herbs such as *Diodia teres* (Diovir), and shrub species including *Croton sp.*, *Borrichia frutescens* (Borfru) as well as the grasses *Sp. spartineae* and *Pa. vaginatum*. The plots were not inundated at the time of sampling and showed signs of grazing. The elevation ranged from 1.00 – 2.16 meters at this group level.

Group six consisted of 17 plots dominated by *Distichlis spicata*. Disspi is a dominant perennial grass of brackish to saline marshes that is capable of rapidly colonizing disturbed patches. In many cases Disspi was accompanied by Spapat and Scirob but the Disspi group contained 12 different species occurring in at least one plot. Disspi is a competitively inferior species and although it can rapidly dominant a disturbed site it is generally displaced by Spapat as condition s improve restricting Disspi to generally inhospitable locations (Emery et al. 2001). This group consisted almost exclusively of mid marsh plots with only two plots occurring outside of this type (HM 10 A, LM 11 A). HM 10 A at an elevation of 1.00 meters was found 0.3 Km from the East Bay on a ridge and most likely experienced high levels of salinity compared to some of the lower surrounding plots and LM 11 A is 0.03 Km from Oyster Bayou, the major tidal bayou splitting the East and West units at Anahuac NWR, indicating high salinity levels and a propensity towards Disspi. Based on qualitative comments made during field work all plots in the Disspi group were inundated to some degree and the three plots occurring at the Canada Ranch were east of the Robinson lake channel. Many of the plots were sampled by Air Boat curtsey of USFWS at Anahuac NWR and salinity levels, randomly sampled while collecting floristic data, were between 8 and 14 (PPT) and showed considerable variability between the two sampling days. Elevation ranged from -0.027 meters on the edge of a flooded pond, to 1.00 meter on the ridge at HM 10 A.

Group seven consisted of 46 plots dominated by *Spartina patens* (Spapat). Spapat, (Marsh Hay Cord Grass), is the dominant marsh grass found along the East Bay and the Texas coast in general (Stutzenbaker 1999). Spapat is typical in brackish marshes where one of its characteristics is growing in dense mat like stands (Brewer and Grace 1990). In this study Spapat has the highest presence occurring in 1855 subplots (Table 2) with nearly complete stands occurring in all plots of this group. The Spapat group ranged across the entire study area of both the Canada Ranch and Anahuac NWR (Figure 14) and was the dominant marsh species observed during field sampling. Conditions ranged from dry to deeply inundated and from low elevations, -0.40 meters in old lake beds, to high elevations, 1.42 meters near the north end of the Canada Ranch. Spapat can survive in all marsh types but is dominant in brackish marshes and can form dense stands of pure Spartina (Godfrey and Wooten 1981b, Stutzenbaker 1999), this was observed in many cases during field work (Figure 15). The distribution of vegetation assemblages can be seen in figure 14 and figure 16 illustrates the relative abundance of species in each clustered vegetation group.

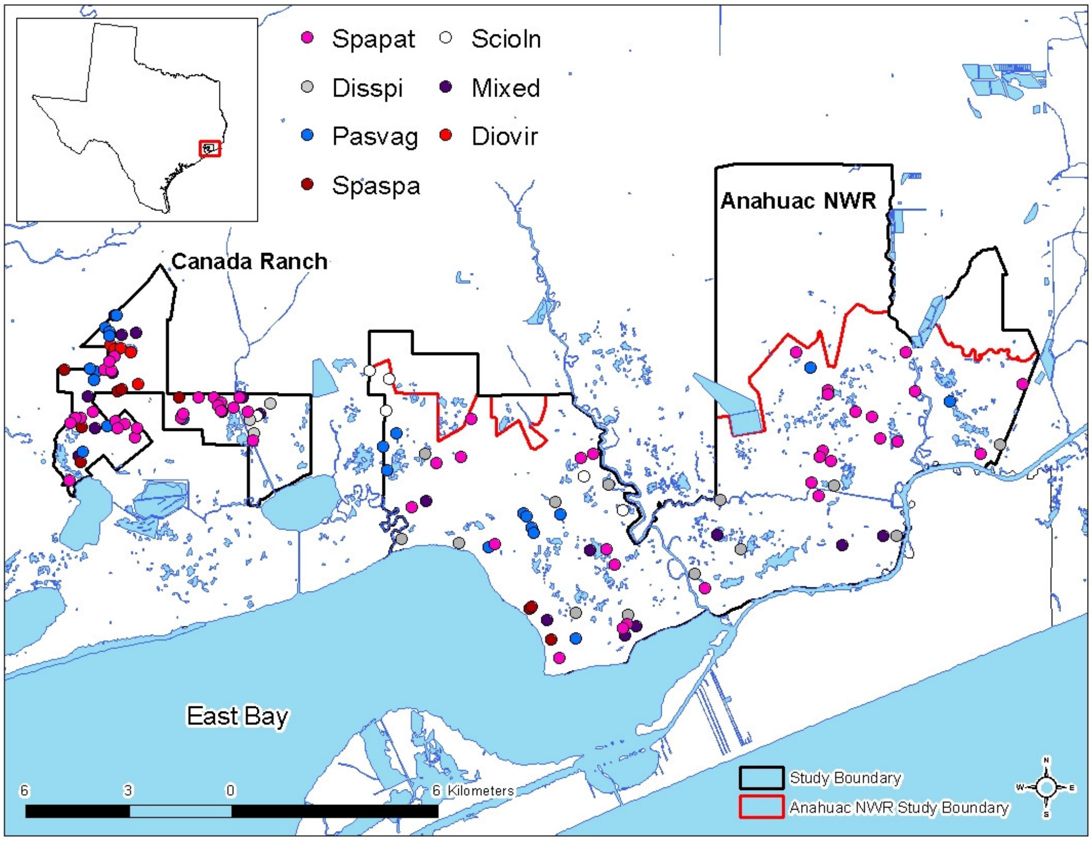


Figure 14. Spatial distribution of clustered vegetation assemblages. Vegetation assemblages overlaid on sampled plots at the East Bay study sites.

Figure 15. Typical *Sp. patens* meadow. A monospecific stand of *Sp. patens* at Anahuac NWR.

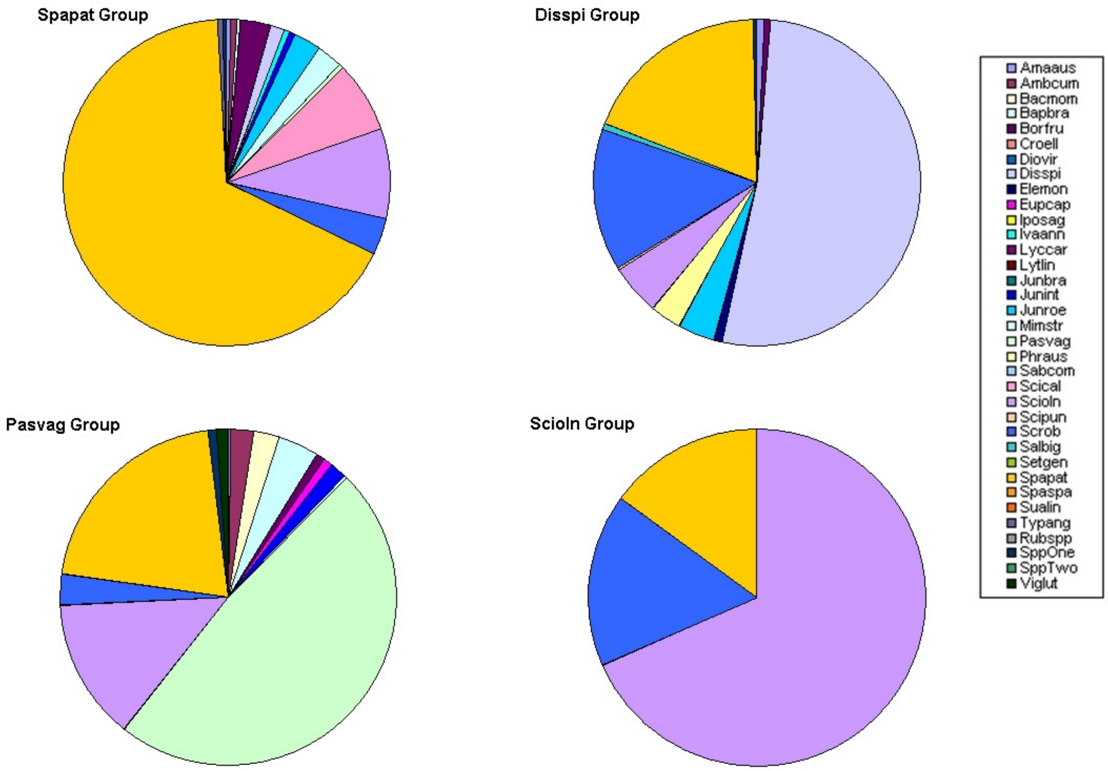
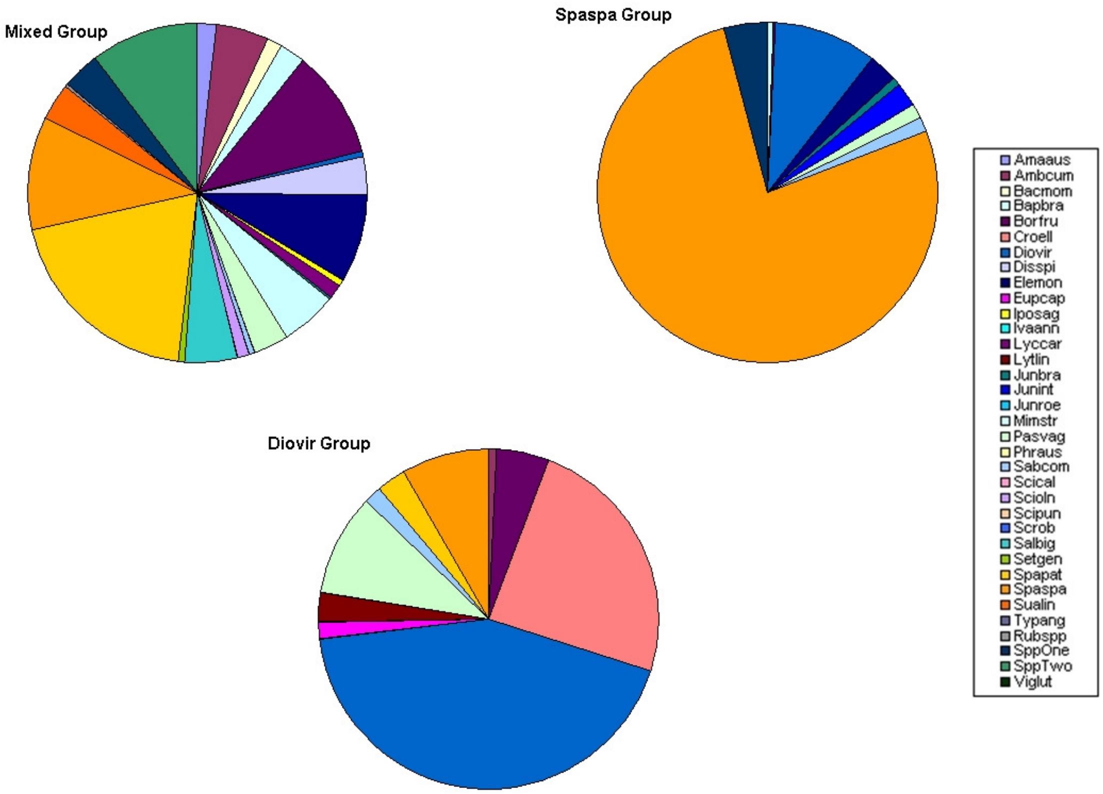


Figure 16. Species abundance. The relative abundance of individual species occurring in each of the seven vegetation assemblages created during cluster analysis. Spapat, Disspi, Pasvag, and Scioln seen above, and Mixed, Spaspa, and Diovir on opposite page.


Mixed Group

Spaspa Group

Diovir Group

Figure 16. Continued.

The dominance of individual species occurring at the Canada Ranch and Anahuac NWR is a function of the dominant process influencing the landscape as well as species life history traits. Spapat was the most dominant vegetation type, 42 percent of all sampled plots were classified as Spapat (Table 2). Also, *Sp. patens* was the dominant individual species at both the Canada Ranch and Anahuac NWR followed by *P. vaginatum, Sc. americanus,* and *D. spicata* (Table 3).

Table 2. Percentage of sampled plots in each vegetation assemblage.

Percentage of plots in classified vegetation types	
Pasvag	16%
Scioln	5%
Disspi	12%
Spapat	42%
Mixed	15%
Spaspa	7%
Diovir	3%

Table 3. Species counts. Identified vegetation species occurring in sampled plots at Canada Ranch and Anahuac NWR. Each count represents the occurrence of a species within one 20cm x 20cm subplot of the 1m x 1m sampling frame.

Species	Code	Count
Spartina patens	Spapat	1855
Paspalum vaginatum	Pasvag	566
Schoenoplectus americanus	Scioln	479
Distichlis spicata	Disspi	416
Spartina spartineae	Spaspa	244
Schoenoplectus robustus	Scrob	234
Borrichia frutescens	Borfru	142
Schoenoplectus californicus	Scical	139
Diodia teres	Diovir	129
Juncus roemerianus	Junroe	83
Mimosa strigillosa	Mimstr	80
Baptisia bracteata	Bapbra	63
Ambrosia cumanensis	Ambcum	62
Croton sp.	Croell	58
Eleocharis montevidensis	Elemon	55
herb sp.	SppTwo	53
grass sp.	SppOne	41
Juncus interior	Junint	36
Bacopa momieri	Bacmom	32
Amaranthus australis	Amaaus	29
Salicornia bigelovii	Salbig	28
Phragmites australis	Phraus	22
Suaeda linearis	Sualin	19
Typha angustifolia	Typang	16
Eupatorium capillifolium	Eupcap	14
Sabatia campestris	Sabcom	11
Vigna luteola	Viglut	11
Iva annua	Ivaann	8
Lycium carolinianum	Lyccar	7
Lythrum lineare	Lytlin	7
Juncus brachycarpus	Junbra	4
Ipomoea sagittata	Iposag	3
Setaria geniculata	Setgen	3
Schoenoplectus pungens	Scipun	1
Rubus sp.	Rubspp	1

INUNDATION FREQUENCY

Mike 21 interpolated hourly water surface elevations across the Galveston Bay system for the year 2008. Five locations were selected, based on their location to an observed tidal inlet, to extrapolate threshold values into the study sites in order to calculate inundation frequency at the sampled plots. As a first order approximation of accuracy a pressure transducer was placed at the Canada Ranch (Figure 17) near Gordy Marsh. The pressure transducer recorded water levels at 10 second resolution and showed approximately a 10cm daily tidal signature with a spike in water depth to 30cm with the storm surge from hurricane Alex, a hurricane that made landfall approximately 300 miles away (Figure 18). The modeled water surface elevation showed an approximately 0.3 m tidal signature (Figure 19).

Inundation frequency showed that three plots, all at Anahuac NWR, were inundated a significant portion of the time, greater than 70 percent of the year, and that six plots, split evenly between the two study sites, showed inundation frequencies of approximately 25 percent of the time. Twenty three plots showed at least a 10 percent inundation frequency, split evenly between the study sites, and were dominated by Spapat and Pasvag. The majority of plots, 112, were inundated less than 10 percent of the year and 11 plots showed zero inundation, even with the storm surge from hurricane Ike (Figure 20, Figure 21).

Although elevation and inundation frequency are highly correlated both variables introduce different processes to the composition and structure of the marsh. High elevations may experience less frequent inundation but may also experience higher levels of salinity, and lower elevations, experiencing more frequent inundation may have lower salinity levels but vegetation may experience a lower period of photosynthetic activity. It is for this reason that both variables are investigated through diversity measures and species prediction modeling.

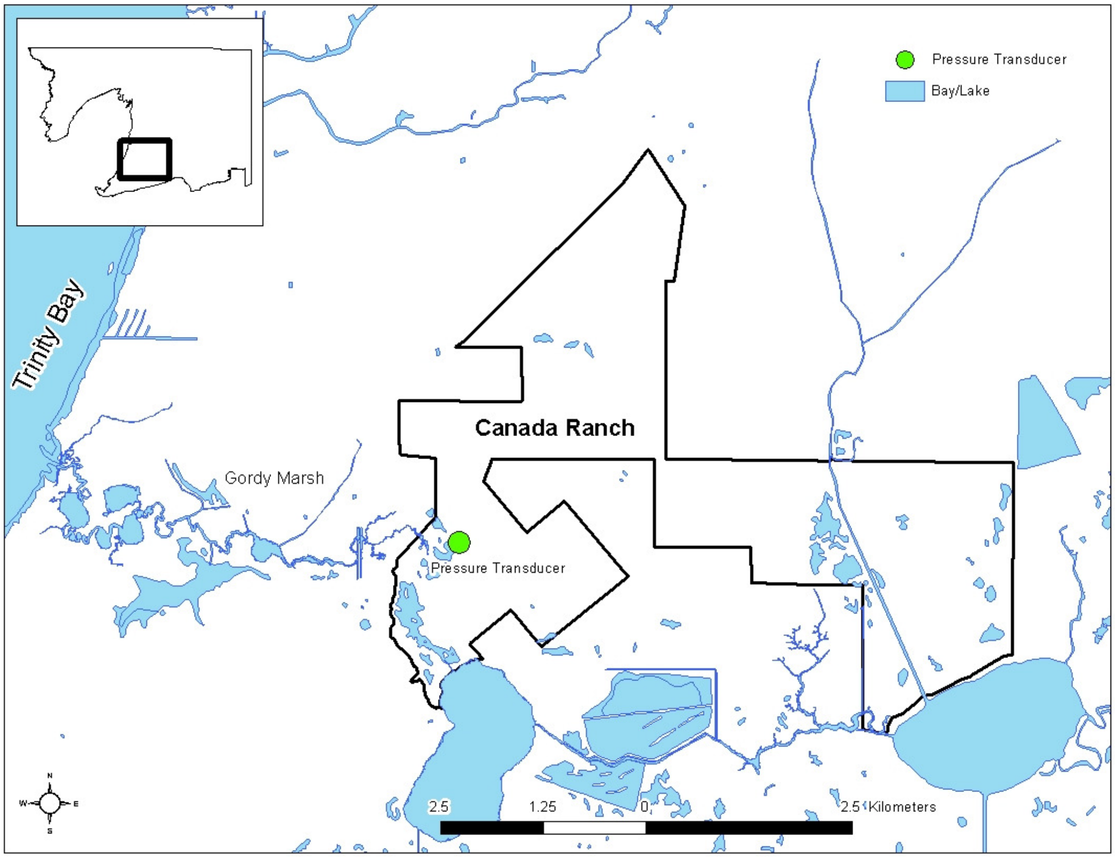


Figure 17. Pressure transducer. PT placed at the Canada Ranch from May 21, 2010 – July 29, 2010. 10 second observations of water depth were recorded and resampled to one minuet and one hour for comparison to the modeled water surface elevation.

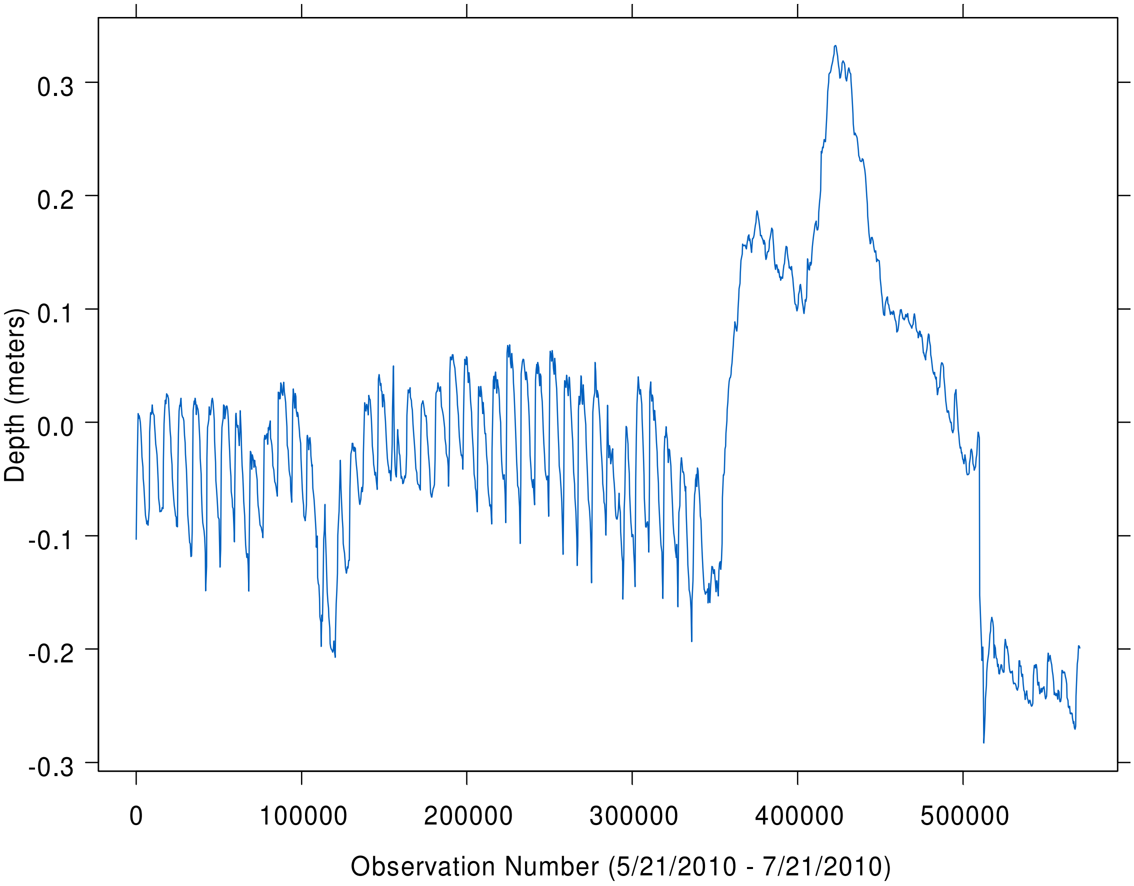


Figure 18. Observed water surface elevation at Canada Ranch. Observations are at one minute resolution, from May 21 – July 21, 2010.

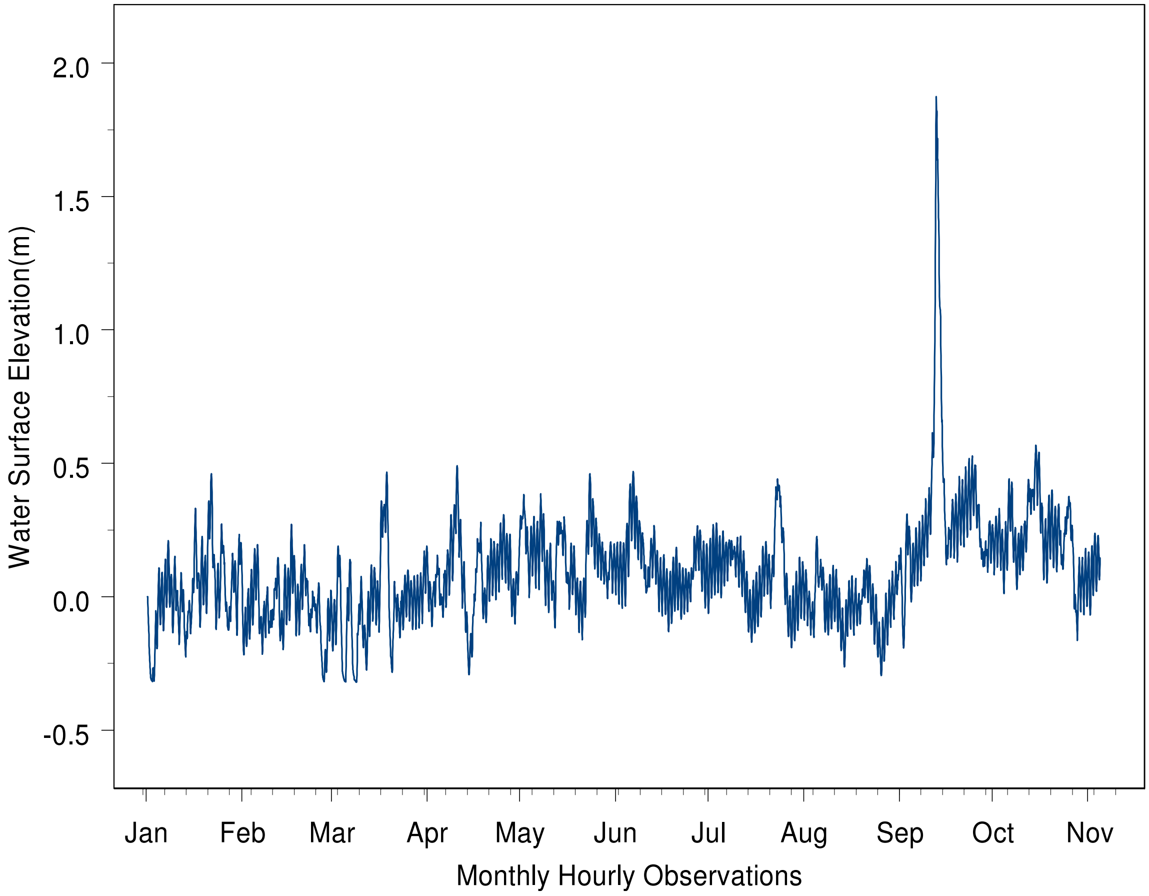


Figure 19. Modeled hourly water surface elevation at Canada Ranch. Water elevation is from Point one near the mouth of Gordy Marsh in Trinity Bay. Tide and wind data were taken from Morgan's Point gauge station, using 2008 data, and modeled using Mike 21. Tidal influence to the western portion of the Canada Ranch is facilitated through Gordy Marsh. The modeled tidal signature shows an approximately 0.3 meter tide.

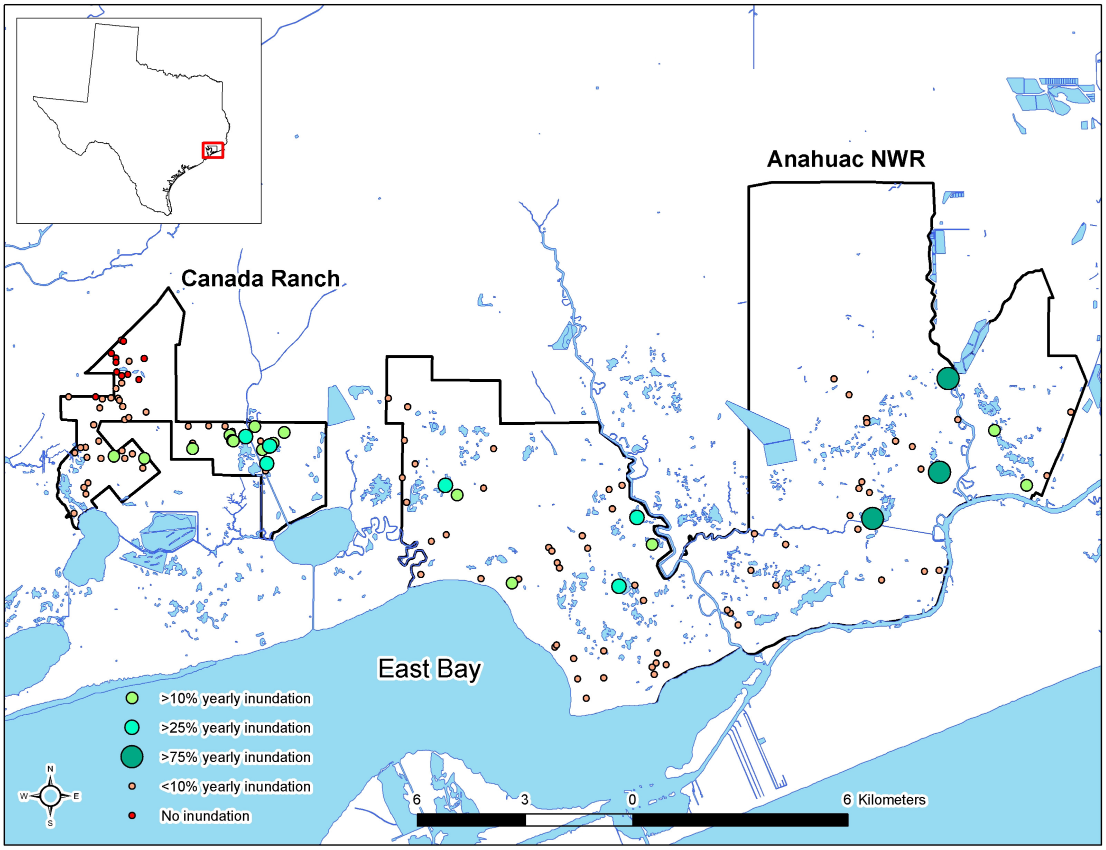


Figure 20. Hydrology of sampled plots. Three plots were inundated greater than 70 percent of the year, and that six plots showed inundation frequencies of approximately 25 percent of the time. Twenty three plots showed at least a 10 percent inundation frequency. The majority of plots, 112, were inundated less than 10 percent of the year and 11 plots showed zero inundation.

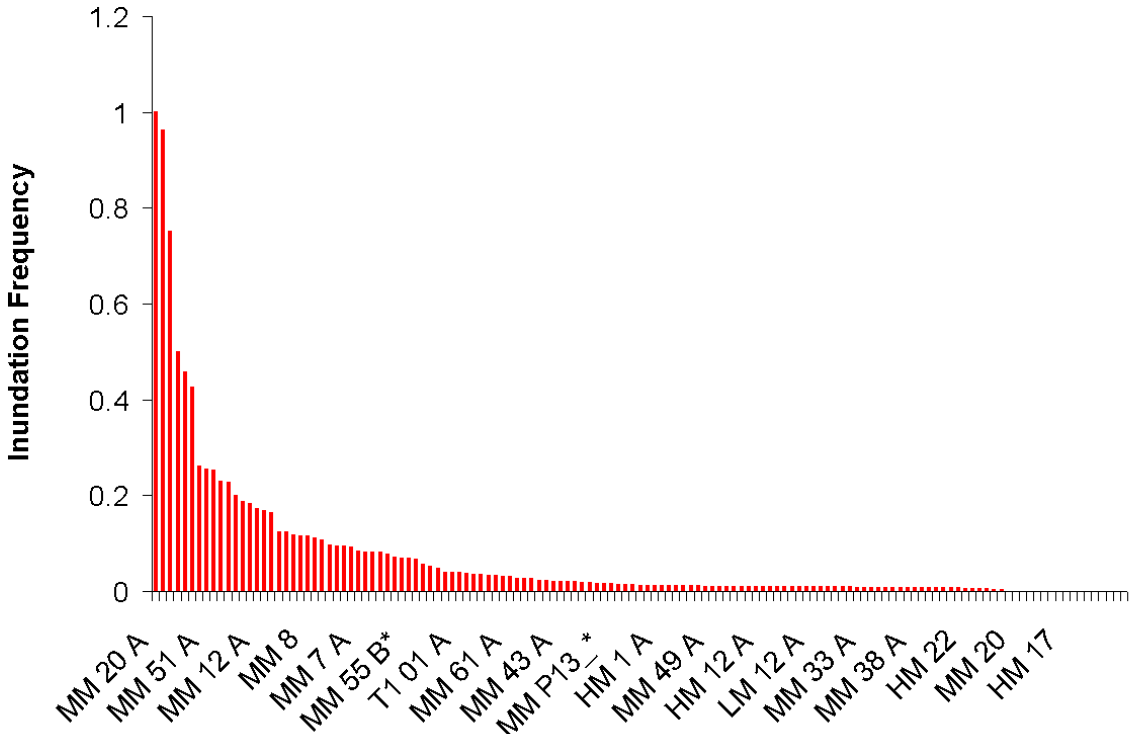


Figure 21. Inundation frequency distribution. 11 plots have inundation frequencies greater than 20 percent of the year.

DIVERSITY

Species richness, evenness, Shannon diversity, and Simpson's diversity are calculated for each vegetation assemblage (Table 4) and plot. Shannon's diversity was plotted as a function of elevation in order to understand how plot diversity changed with topographic variability (Figure 22). The results indicated that there is no statistical relationship between Shannon's diversity and elevation. However, there is a positive relationship between species richness and elevation ($p = 0.015$) (Figure 23). When species richness and Shannon's diversity were tested against inundation frequency there was no statistical linear relationship, but both diversity measures did show a negative trend with inundation frequency (Figure 24, Figure 25). Because frequent inundation leads to oxygen deficiencies in the soil, vegetation must be adapted to this type of stress or they will not persist (Mony et al. 2010). Though not significant, there is a trend that illustrates that higher species diversity and richness are found at less frequently inundated locations.

Diversity measures were also tested at the vegetation assemblage level where the average diversity measures, average elevation, and average inundation frequency were compared. Similar to plot level analysis, Shannon's diversity as a function of elevation and inundation frequency was not statistically significant (Figure 26), but group richness did show a statistical relationship to elevation ($p < 0.05$) (Figure 27). Although inundation frequency and group species richness were not significant there is a negative trend between richness and inundation (Figure 28).

At Anahuac NWR species diversity was plotted against burn frequency to investigate how management practices may be influencing the diversity of species

(Figure 29). Spaspa had the lowest average species richness at 1 but also the highest average years since last burned (6.333 years) (Figure 30, Table 5). Regression analysis showed no significant relationship between the number of years since an area was burned and its diversity. Group diversity showed similar results, with a moderately negative trend in diversity where more frequently burned locations had higher diversity; the results were not statistically significant.

Table 4. Diversity measures for vegetation assemblages. S = richness, E = evenness, H = Shannon's index, D'= Simpson's index, avg elev = average elevation, and avg inun = average inundation frequency.

group name	S	E	H	D'	avg elev	avg inun
Pasvag	2.80	0.792	0.283	0.505	0.838	0.036
Scioln	1.50	0.489	0.339	0.243	0.440	0.134
Disspi	2.90	0.810	0.835	0.508	0.449	0.155
Spapat	2.10	0.661	0.547	0.351	0.604	0.075
Mixed	3.00	0.704	0.758	0.436	0.848	0.057
Spaspa	2.30	0.379	0.465	0.250	0.831	0.008
Diovir	3.80	0.731	0.954	0.511	1.750	0.001

Table 5. Anahuac NWR vegetation assemblages, average inundation and burn frequency, and their corresponding diversity measures.

Group	Avg Inundation Frequency	Last Burned	S	E	H	D
Disspi	0.1541	4.9231	2.6154	0.8106	0.7740	0.4764
Spapat	0.0948	2.8276	2.0345	0.5897	0.4960	0.3141
Scioln	0.0614	5.0000	1.6000	0.5872	0.4068	0.2912
Mixed	0.0582	5.4444	2.5556	0.7228	0.7212	0.4352
Pasvag	0.0418	6.1667	2.5833	0.8216	0.7993	0.4962
Spaspa	0.0068	6.3333	1.0000	0.0000	0.0000	0.0000

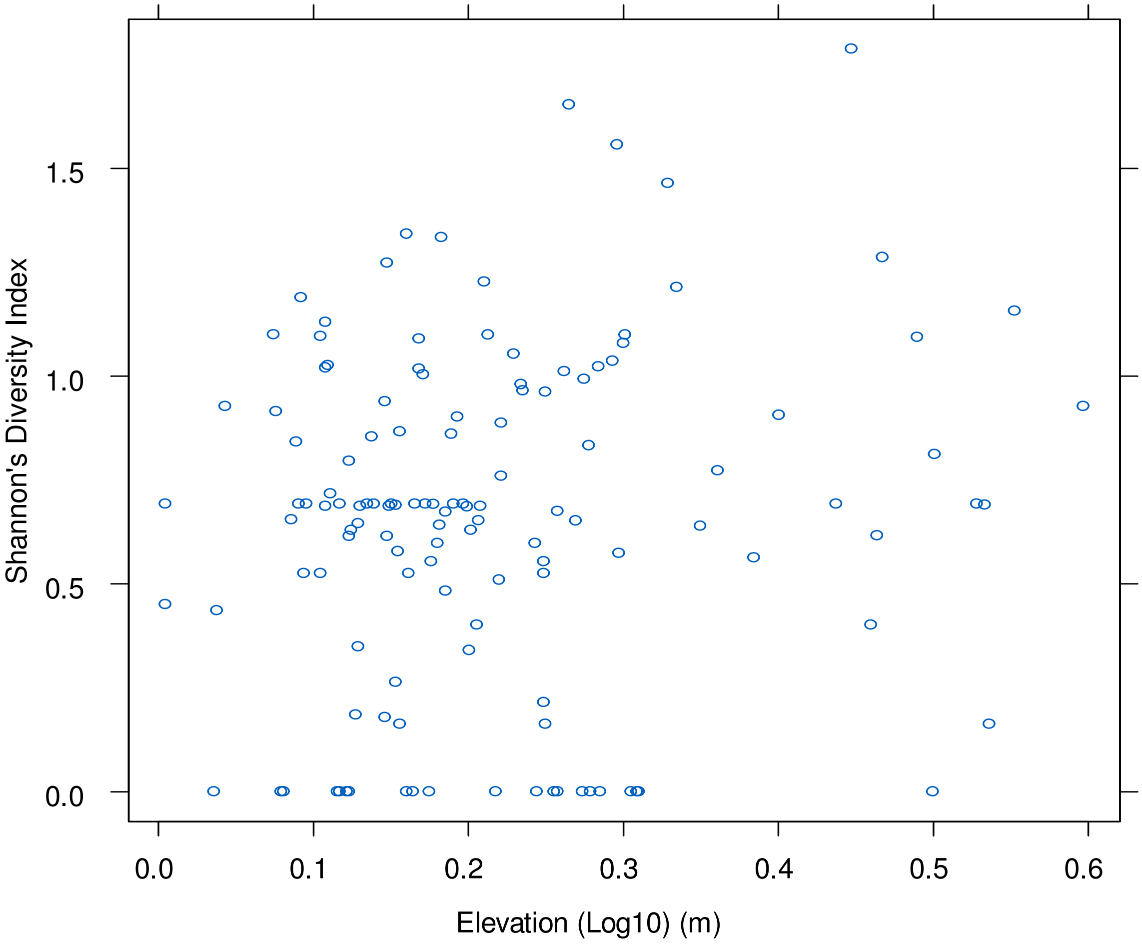


Figure 22. Plot diversity as a function of elevation (log10). No statistical relationship was found, p > 0.05. Strong scatter of plot diversity is noted at intermediate elevations.

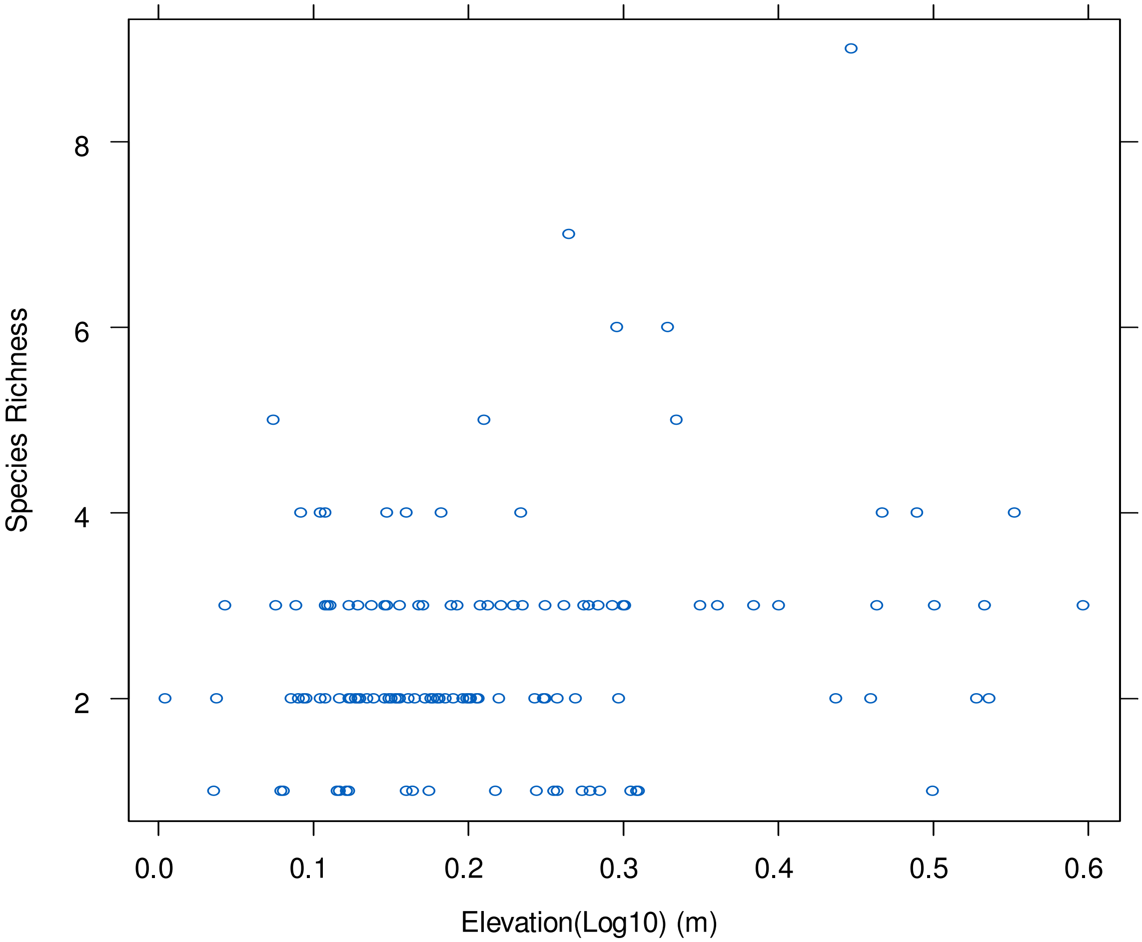


Figure 23. Plot richness as a function of elevation (log10). A statistically significant relationship was found, p = 0.015.

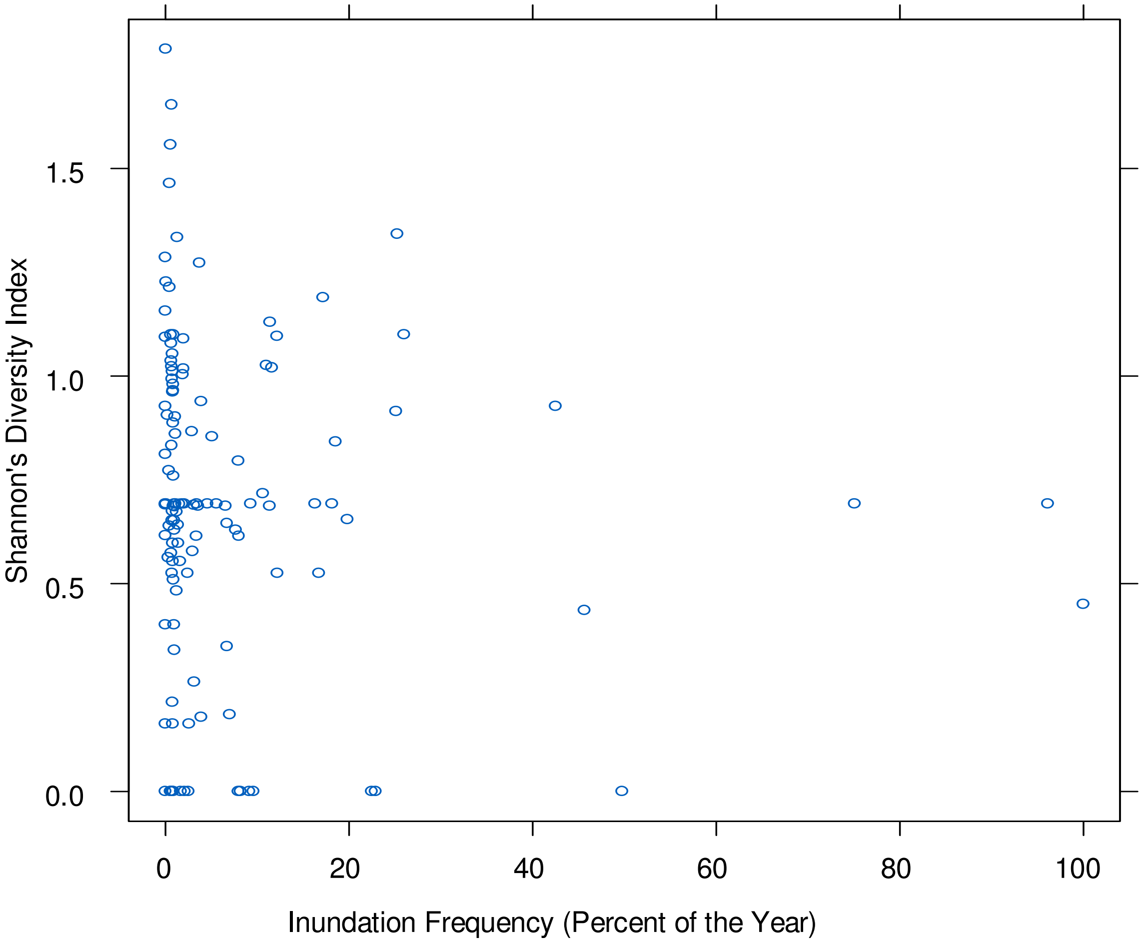


Figure 24. Plot diversity as a function of inundation frequency. Shannon's diversity was used to plot diversity as a function of modeled inundation frequency. Regression analysis found no statistical significance between diversity and inundation frequency.

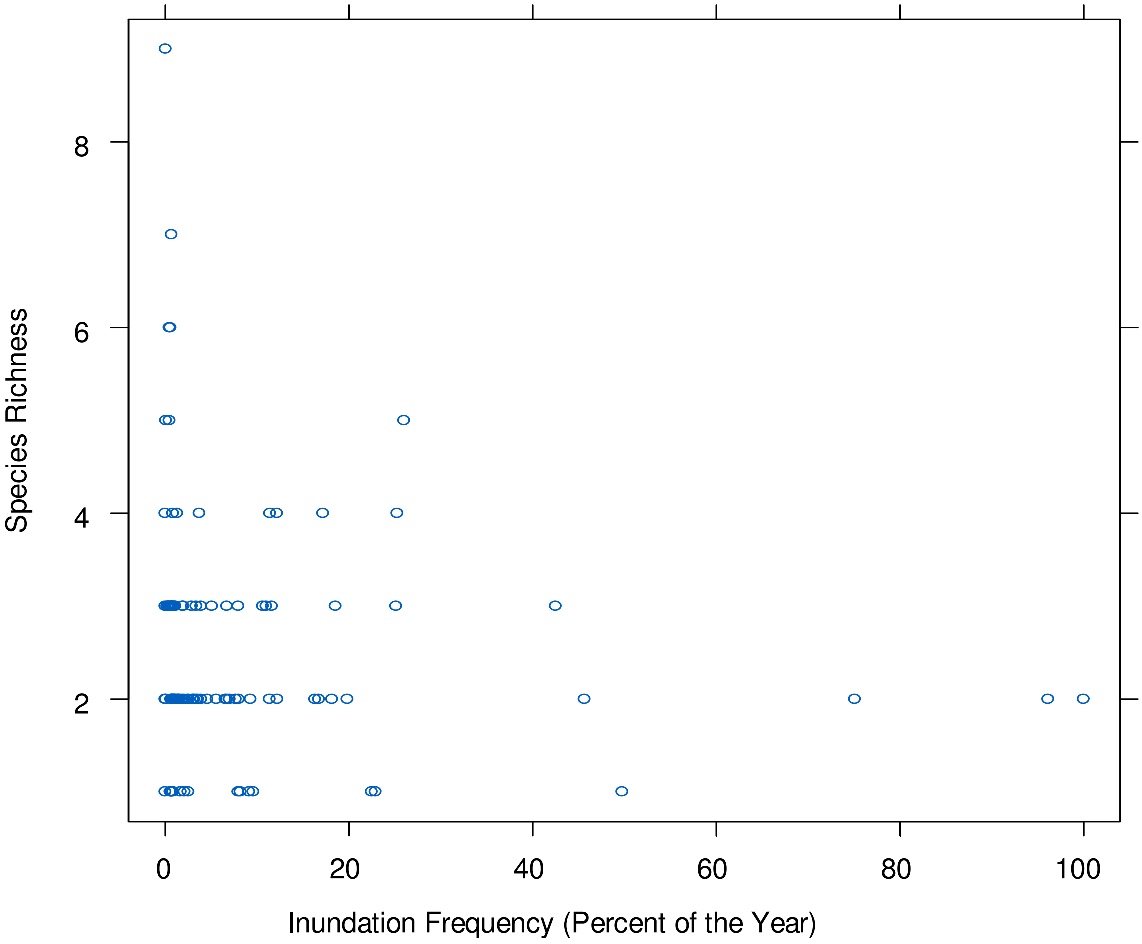


Figure 25. Plot richness as a function of inundation frequency. Regression analysis found no statistical significance between species richness and modeled inundation frequency.

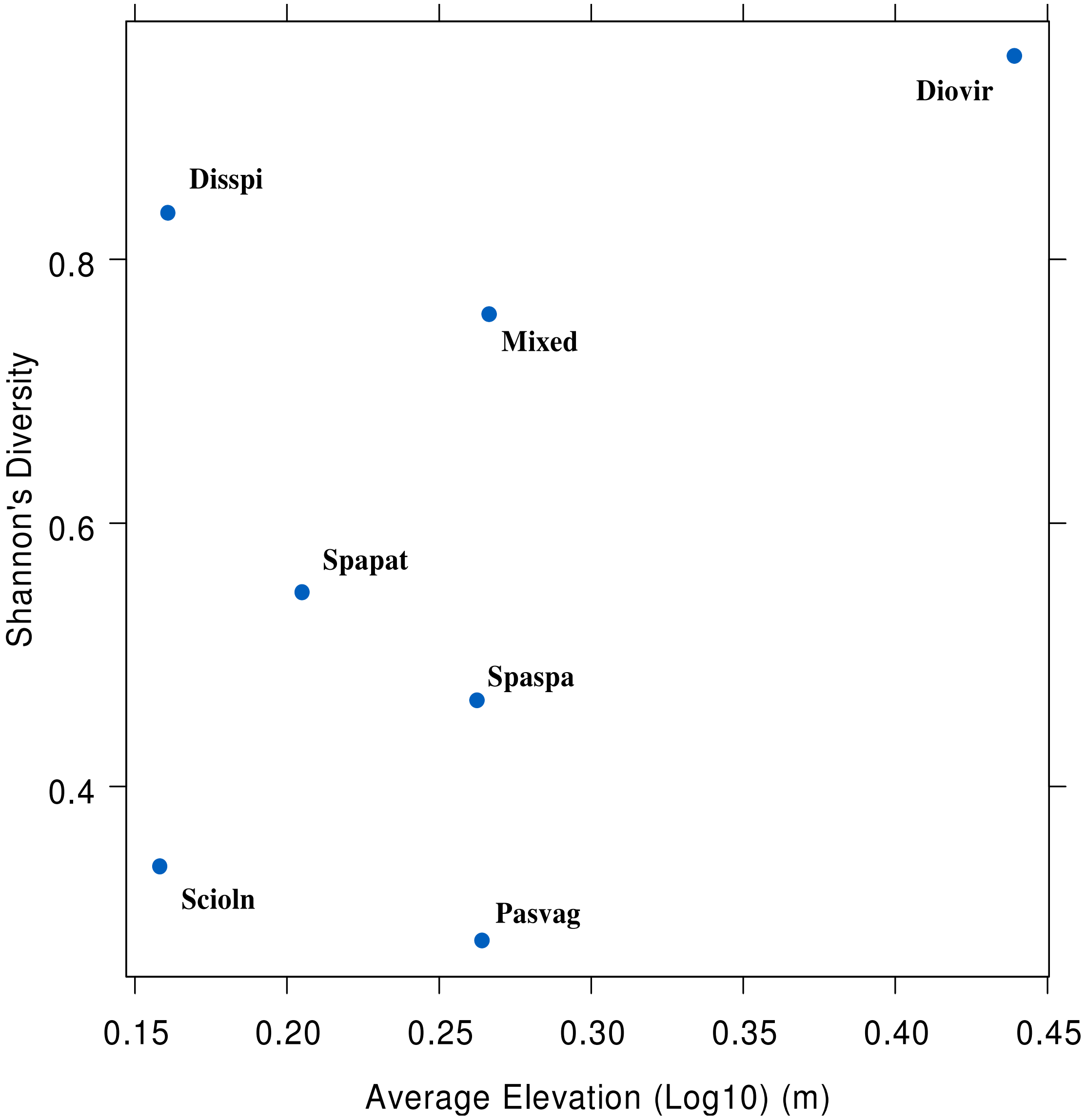


Figure 26. Diversity of vegetation assemblages as a function of elevation (m). Results indicate that there is no statistical relationship between elevation and diversity.

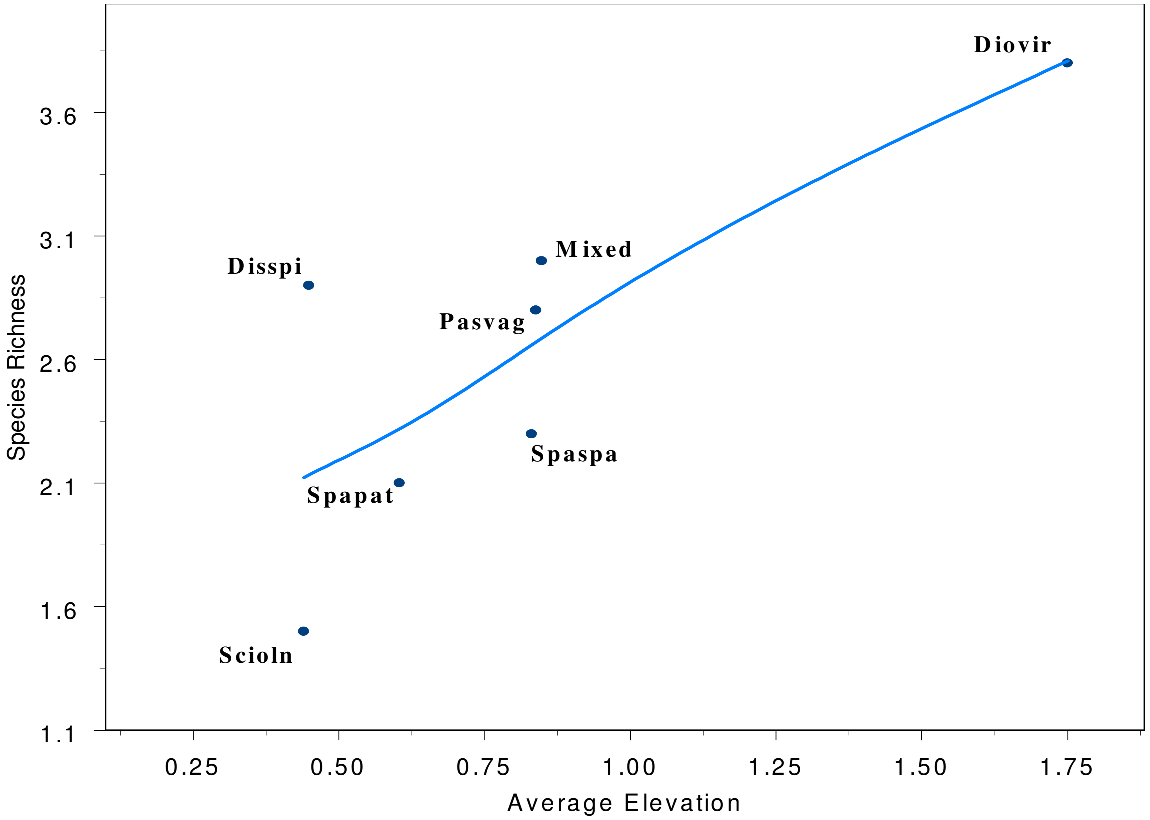


Figure 27. Richness of vegetation assemblages as a function of average group elevation (m). Species richness increases with increased elevation, except in the case of the Disspi group. Linear regression indicates that the relationship is statistically significant, $p<0.05$.

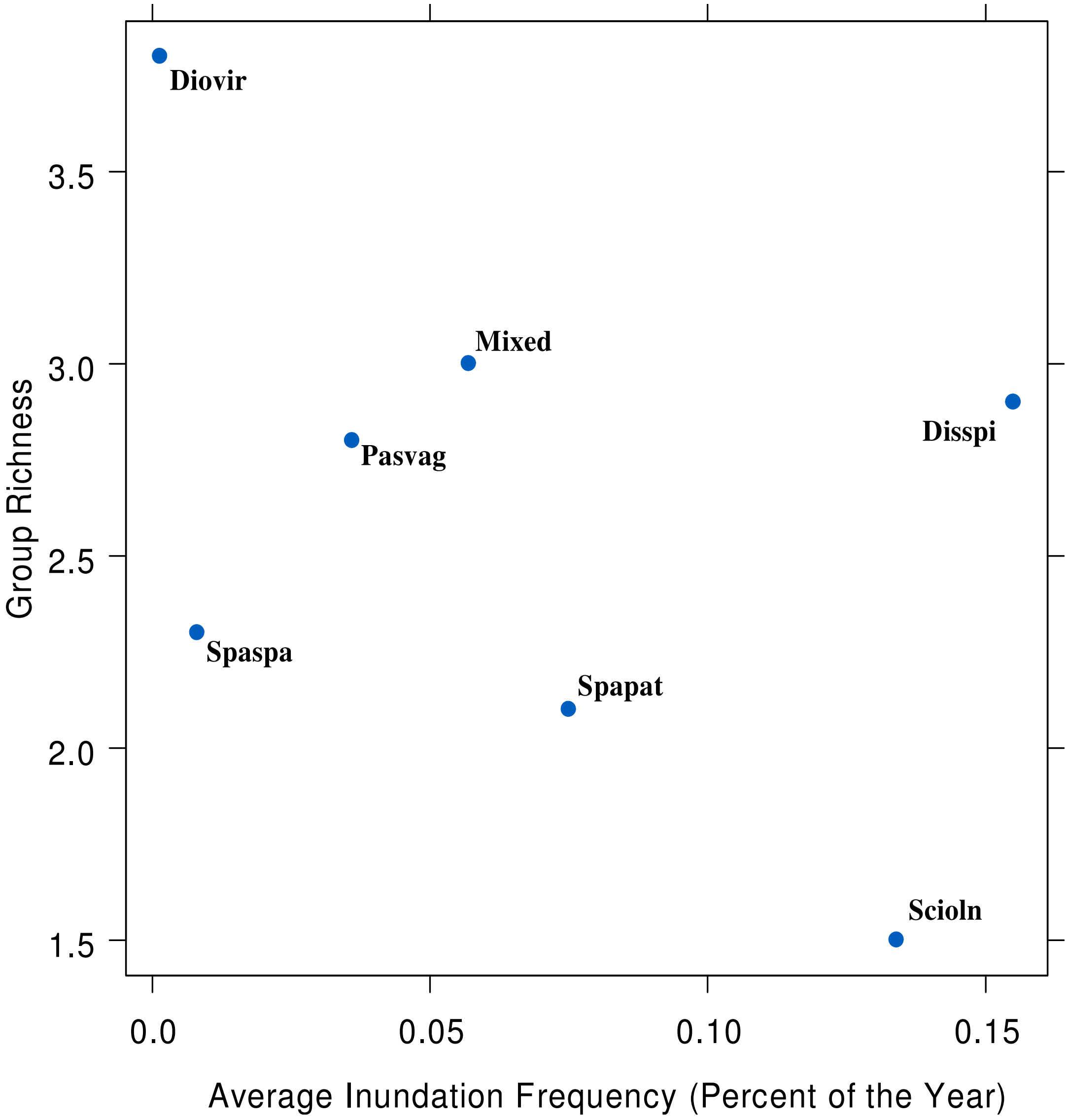


Figure 28. Richness of vegetation assemblages as a function of average inundation frequency. Results show decreasing species richness with increasing inundation frequency, the results are not statistically significant.

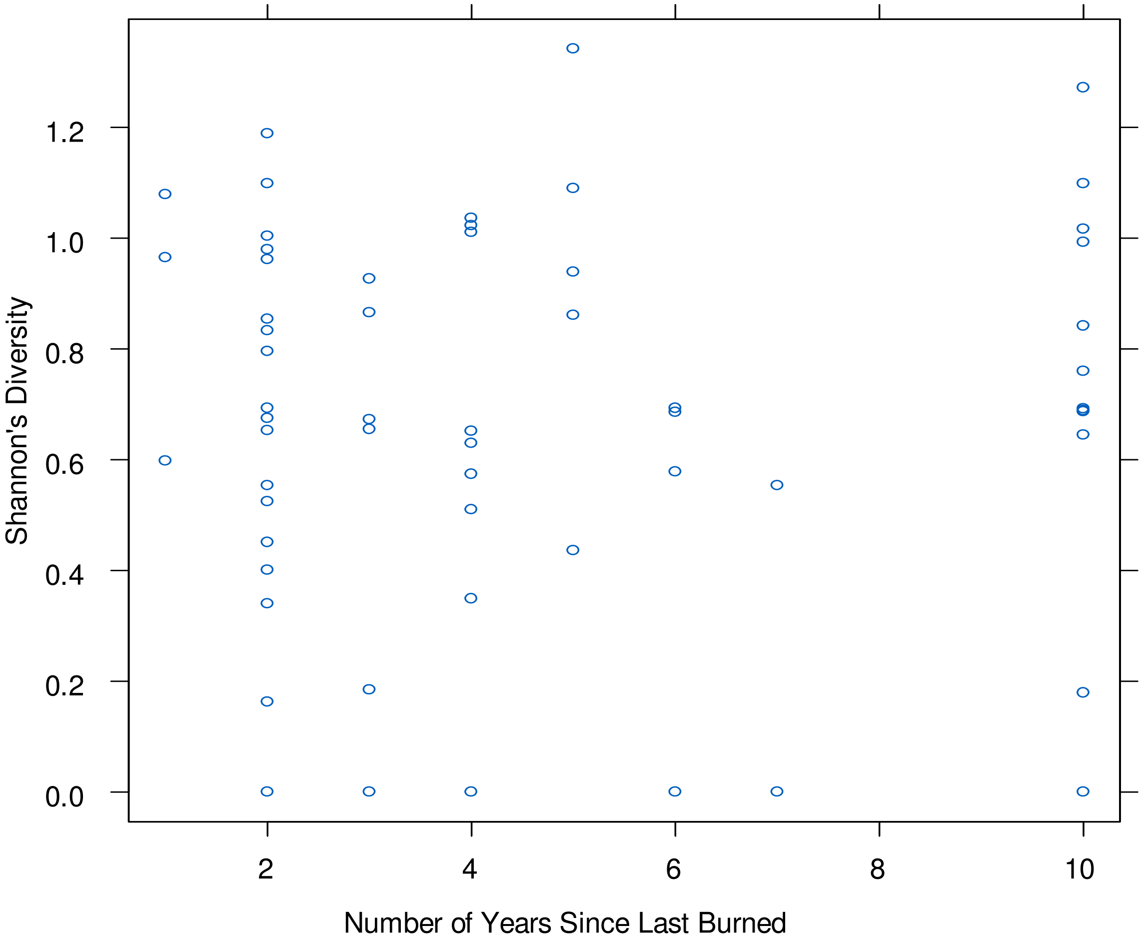


Figure 29. Diversity as a function of burn frequency at Anahuac NWR. Only modest increases in diversity are seen at less frequently burned locations.

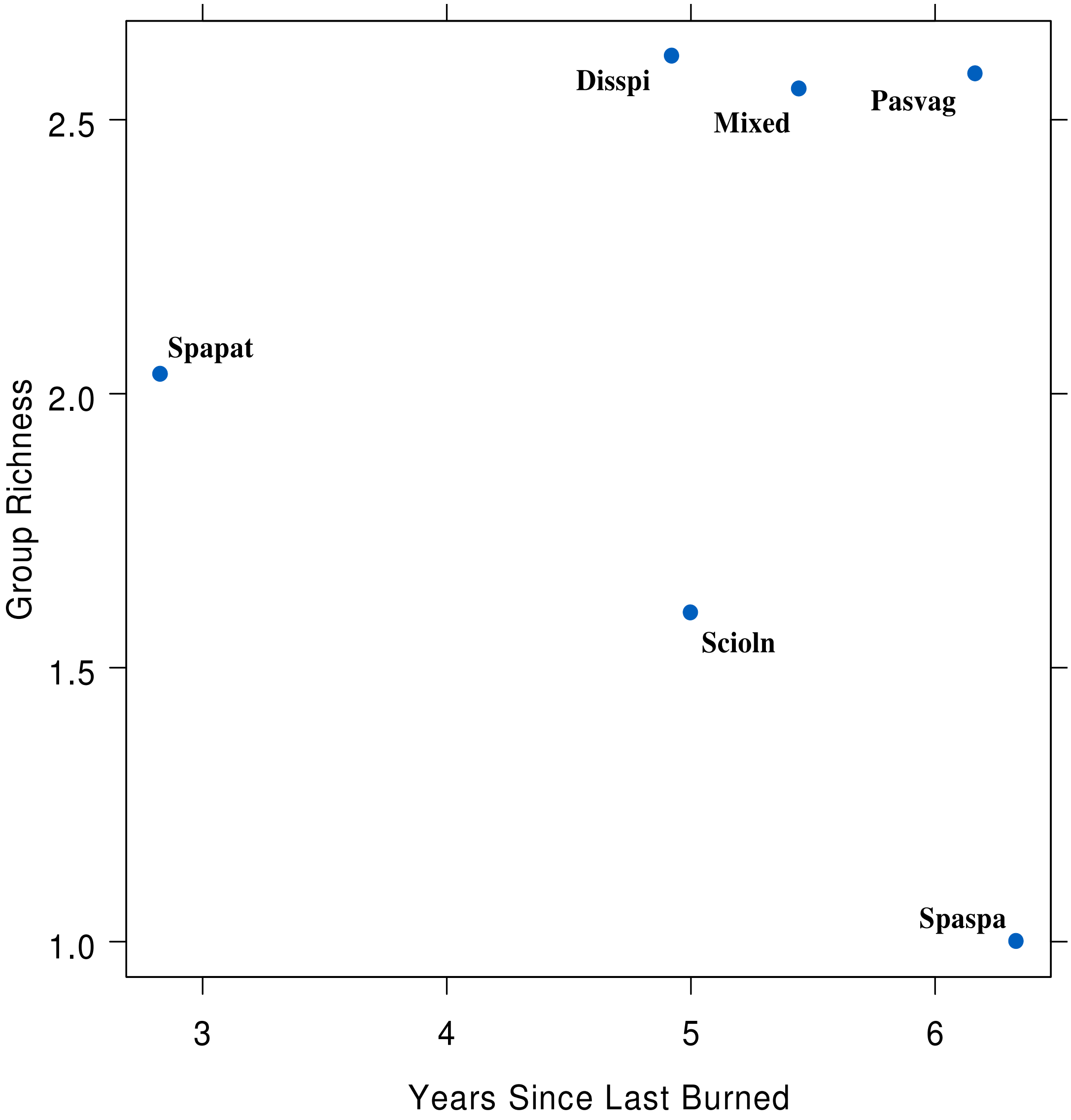


Figure 30. Richness of vegetation assemblages as a function of average number of years since the assemblage was last burned at Anahuac NWR. Results indicate there is not a statistical relationship between group richness and years since burned, but there is probably a component to diversity associated with burning and other management practices.

Canada Ranch has a species richness of 28 species where Anahuac NWR has only half as many species present, with a richness of 14 species (Table 6). The higher richness at the Canada Ranch may be a result of more frequent burning and heavier grazing, which I am unable to quantify but have observed in the field. The Canada Ranch also has a lower inundation frequency of 5.4 percent while Anahuac was inundated on average 8.6 percent of the time.

Table 6. Comparison of diversity measures and environmental variables between Anahuac NWR and the Canada Ranch.

		Site Comparison	
Location	Richness	Average Inundatior	Average Elevations
Canada Ranch	28	5.40%	0.90(m)
Anahuac NWR	14	8.60%	0.54(m)

PREDICTION MODELING

CART

One of the chief concerns of biogeography is how environmental processes influence the distribution, and diversity of vegetation. The classified coastal marshes represent a host of underlying environmental variables, but it is difficult to deduce, without extensive data collection, which environment variables best support the different vegetation assemblages. Classification and regression tree analysis was performed in order to identify thresholds for differentiating vegetation diversity requirements as well as for predicting vegetation assemblage. The goal was to apply CART to characterize the influence of flood frequency, elevation, and in the case of Anahuac NWR burn frequency, on marsh species composition and diversity. CART analysis was preformed separately on the floristic data collected at Anahuac NWR because the Canada Ranch did not have reliable burning records.

When investigating the species richness of all plots two predictor variables were chosen, elevation and inundation frequency. The CART model developed threshold values of the predictor variables that corresponded to specific values of species richness. The output regression tree (Figure 31) shows that both high elevations and high inundation frequencies relate to high levels of species richness at the plot level. This is worthy of note, because in general the two predictor variables are inversely related at high elevations and high inundation frequencies.

When vegetation assemblages are investigated using CART with species richness, elevation and inundation frequency as the predictor variables (Figure32), the initial

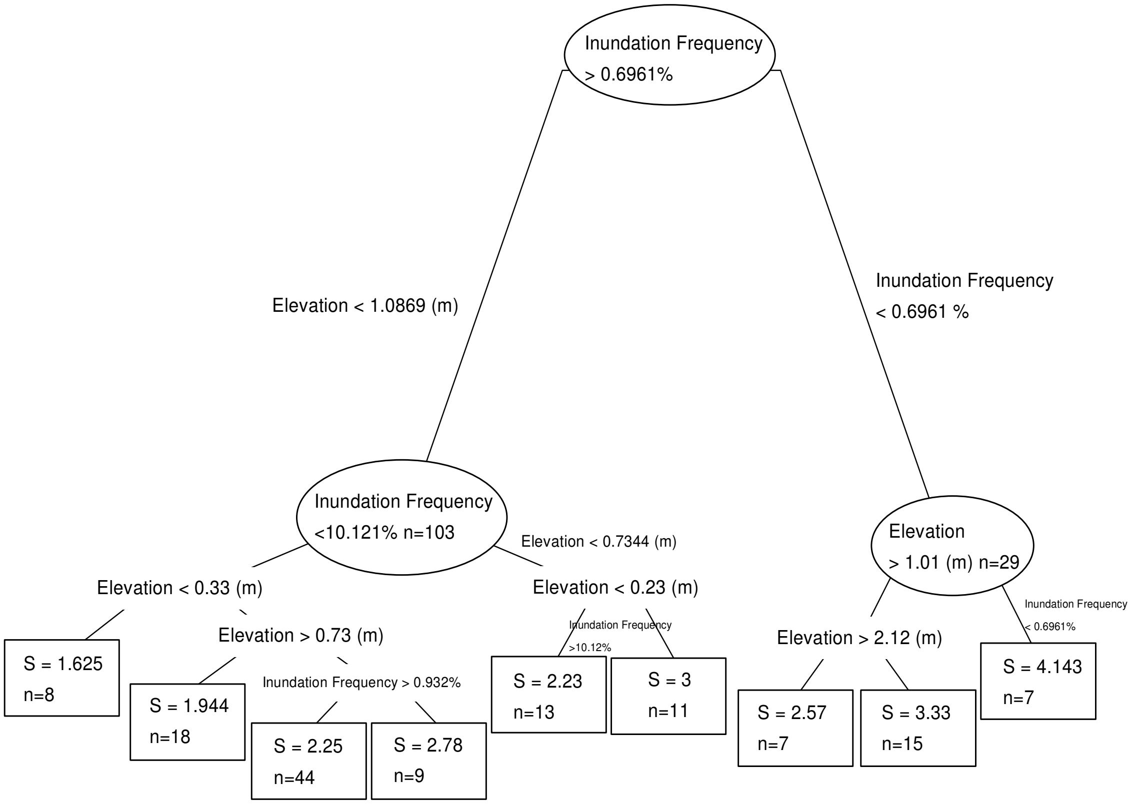


Figure 31. CART: Richness vs. elevation and inundation frequency. CART Tree using rpart to predict species richness as a function of two predictor variables (elevation and inundation frequency). High inundation frequencies (>10 percent) and high elevations (>1 m) predict the highest species richness and lower species richness values are predicted at moderate elevations with inundation frequencies less than 10 percent.

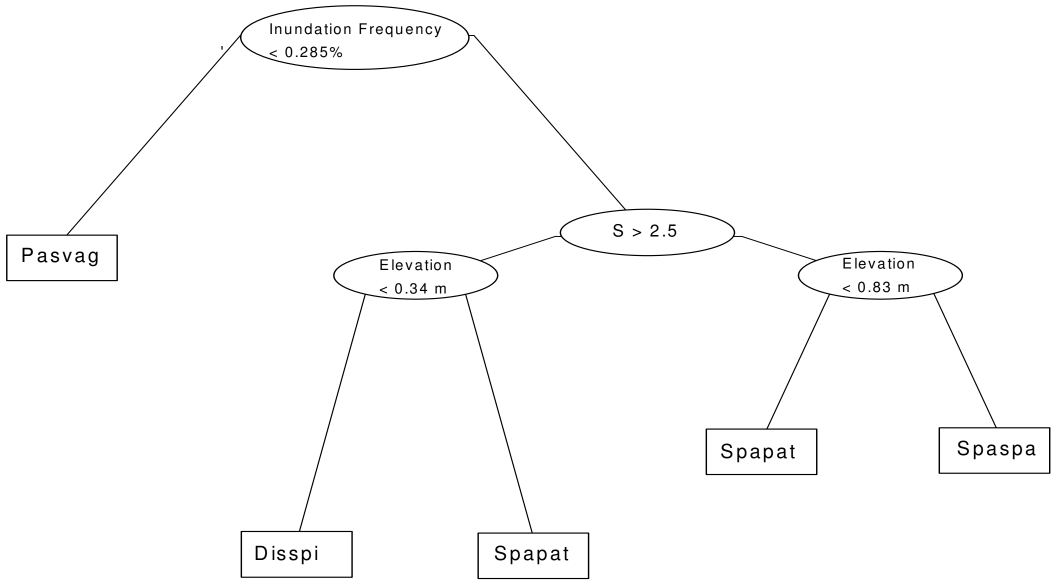


Figure 32. CART: Vegetation assemblage vs. richness, elevation and inundation frequency. Vegetation assemblages and their threshold predictor variables: species richness, elevation, and inundation frequency. Pasvag occurs at low inundation frequencies, Disspi occurs at low elevations, Spapat occurs between elevations of 0.3m-0.8m, and Spaspa occurs at higher elevations. Misclassification error = 47 percent.

environmental threshold is identified as inundation frequency of 0.285 percent of the year, this is equivalent to a location being flooded slightly more than one day a year. The second threshold relates to species richness of 2.5 species. If a location is flooded less than the primary threshold Pasvag is predicted. At more frequent inundation, elevation less than 0.83 meters, and species richness greater than 2.5, Spapat is predicted. Disspi is predicted at high species richness with the lowest elevation, less than 0.34 meters, and Spaspa is predicted with the lowest species richness and the highest elevation, greater than 0.83 meters. The misclassification error for the classification tree was 47 percent (62/132).

At Anahuac NWR the CART model showed that more frequent burning, less than 4.5 years between ignitions, resulted in Spapat assemblages exclusively. Burn histories greater than 4.5 years resulted in Spaspa and Pasvag (Figure 33). The misclassification error for the Anahuac NWR vegetation assemblage prediction was 44 percent (31/71).

A conceptual model was created to illustrate the distribution of vegetation assemblages at Anahuac NWR as a result of elevation and burn frequencies (Figure 34). The model uses threshold values determined via CART analysis as the boundaries for the three vegetation assemblages.

Additionally, species richness was investigated using elevation and burn frequency as predictor variables. Predicted diversity values were relatively equal across all conditions. The lowest richness values, 1.5 species, occur at locations with a moderate period between ignitions, between 5.5 and 8.5 years. The highest richness values, 2.58 occurred at locations burned less than once every 8.5 years (Figure 35).

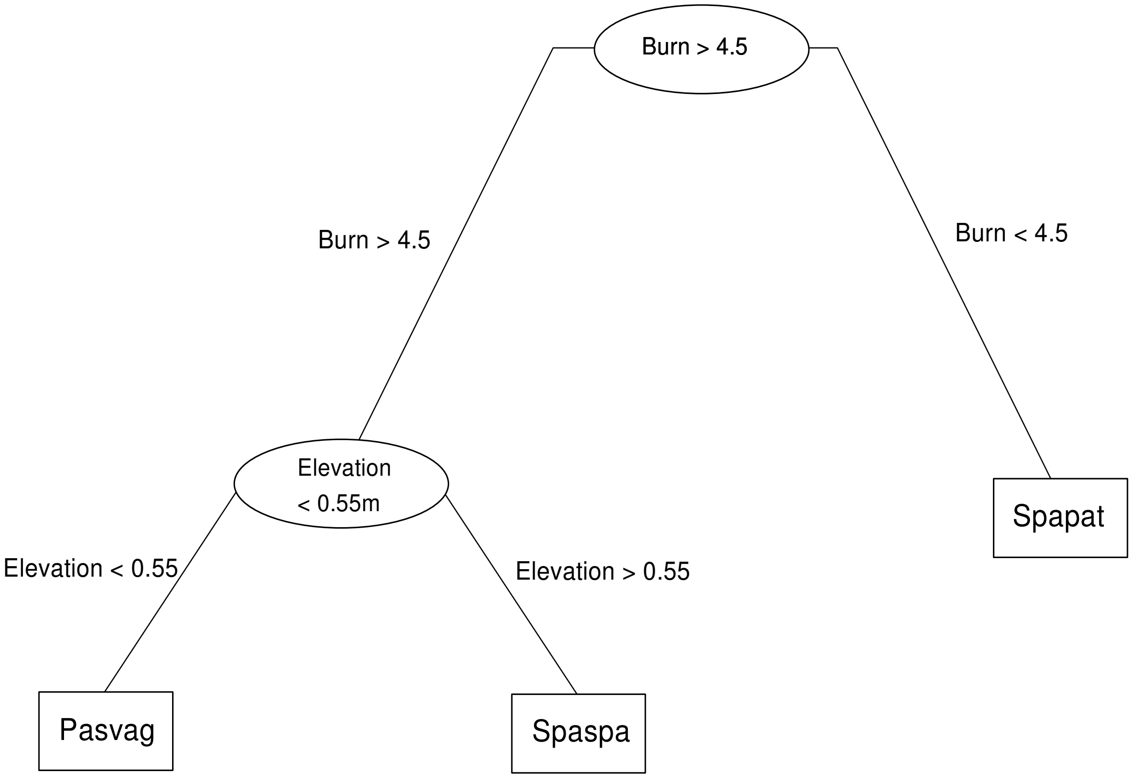


Figure 33. CART: Vegetation assemblages vs. elevation and burn at Anahuac NWR. Predictor variables were elevation and years since last burned. All variables are for Anahuac NWR. Misclassification error= 44 percent.

The average inundation frequency and burn history were also plotted against clustered vegetation assemblages at Anahuac in order to view trends in the two different processes. Disspi showed the highest average inundation frequency and an average of 4.9 years since last burned. Spapat had the next highest average inundation frequency but also was the most frequently burned at 2.8 years since last burned. The lowest average inundation frequency occurred for the Spaspa assemblage also with the longest period of being unburned at 6.3 years (Figure 36).

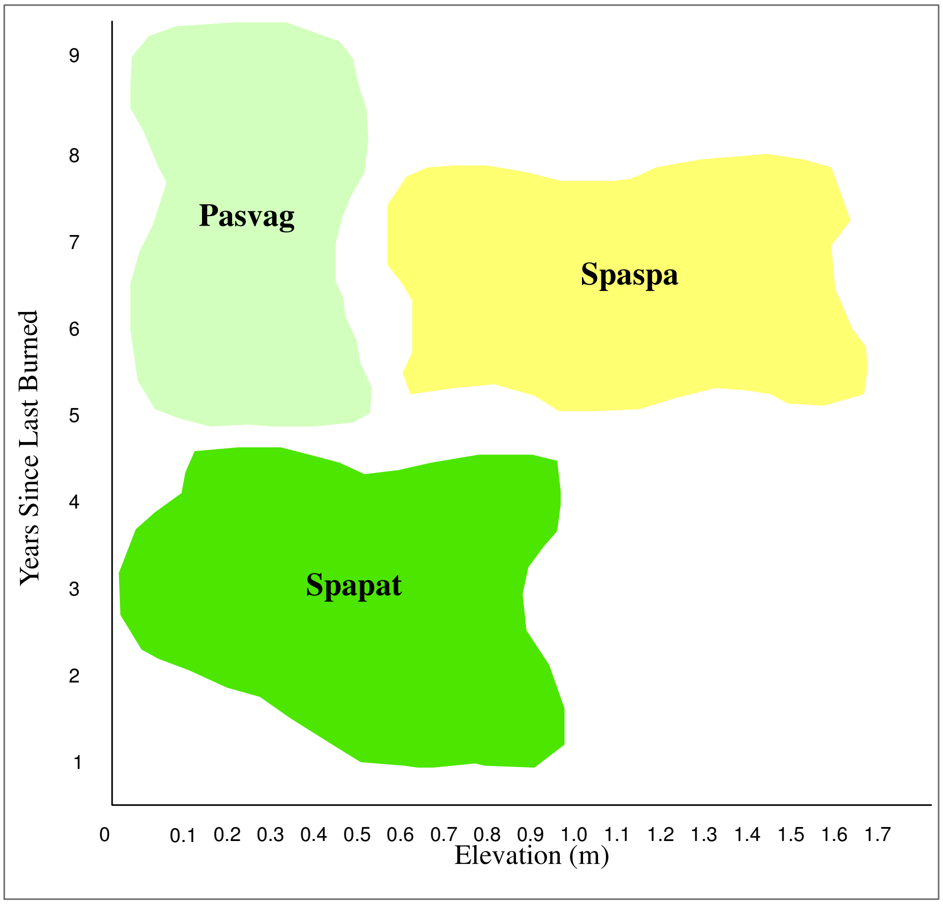


Figure 34. Conceptual model of Anahuac NWR vegetation assemblages. The location of the assemblages is based on the threshold values calculated using CART. Years since last burned is on the Y axis and Elevation in meters is on the X axis.

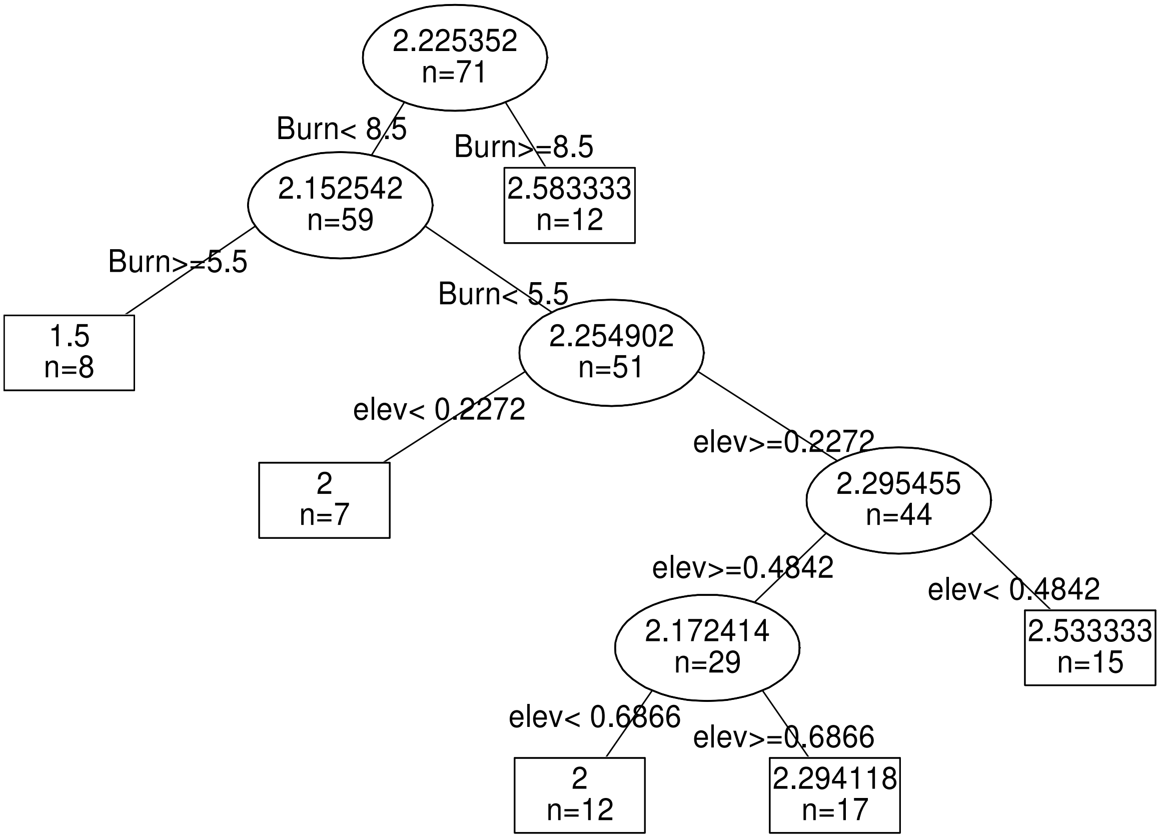


Figure 35. CART: Richness vs. elevation and burn at Anahuac NWR. Species richness values at Anahuac NWR predicted from elevation and burn frequency. Threshold values of elevation and burn frequency are calculated using CART. Variables: elev = elevation (m), burn = number of years since an area was last burned.

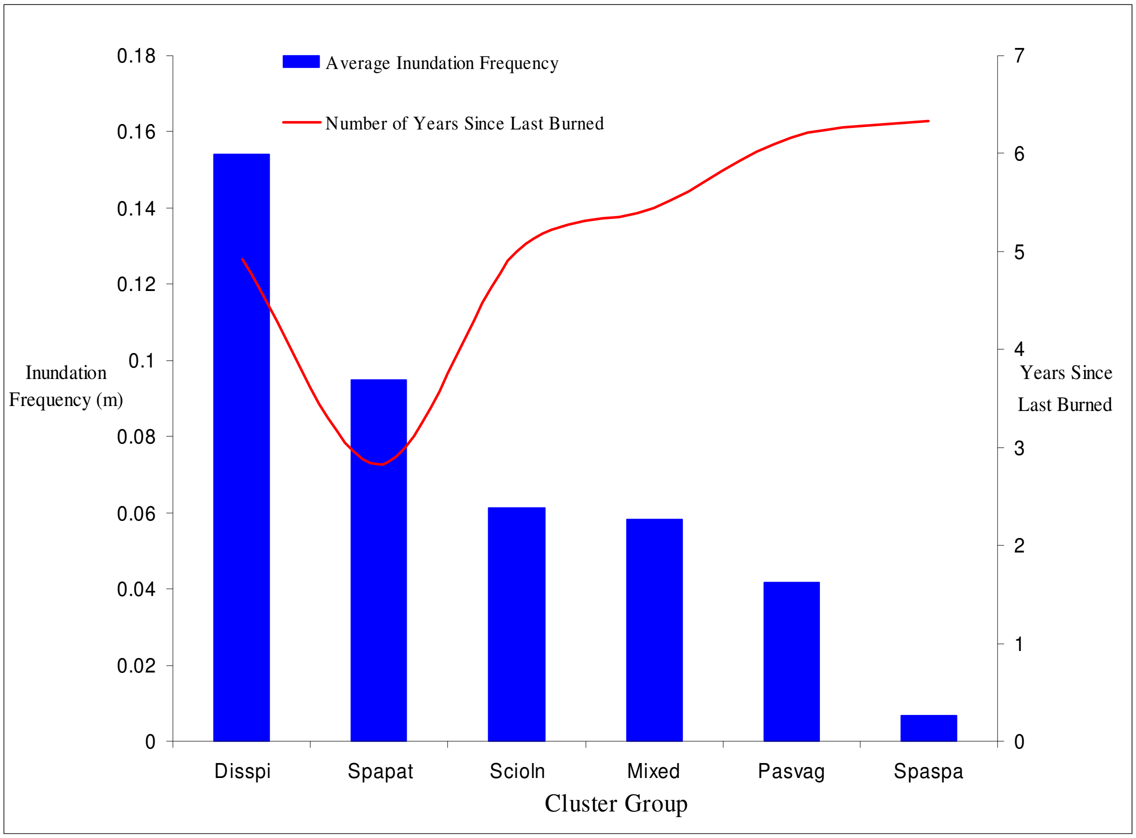


Figure 36. Inundation frequency and burn frequency by vegetation assemblage at Anahuac NWR.

CHAPTER V

DISCUSSION

This thesis investigated the relationships between vegetation associations, biotic and abiotic process, as well as management practices that influence them at two locations along the East Bay of Galveston Bay. Previous research has shown that elevation, inundation frequency, and competition are important in structuring coastal marshes (Adam 1990, Bertness 1991b, Emery et al. 2001, Mitsch and Gosselink 1986, Odum 1988, Redfield 1972). In addition to the aforementioned biotic and abiotic environmental variables management practices, such as burning, grazing, and other anthropogenic activities, have been identified as important factors in structuring coastal marshes (Adam 2002, Gabrey and Afton 2001, Mitsch and Gosselink 2000). The frequency of inundation has been found to be inversely related to species richness where less frequently inundated sites tend to have a greater number of species present (Casanova and Brock 2000). This pattern has been observed in many studies related to diversity of marsh species and inundation frequency (e.g. (Kunza and Pennings 2008). Although this study reinforces many aspects of the marsh literature, including the importance of stress gradients in structuring marsh vegetation, it also begs to ask many new questions related to the influence of irregular inundation frequency and management activities on marsh composition.

COMMUNITY/ ENVIRONMENT INTERACTION

Seven dominant vegetation assemblages were identified through cluster analysis: Pasvag, Scioln, Mixed, Spaspa, Diovir, Disspi, and Spapat. The composition of the classified vegetation groups was significantly different. The hierarchical cluster analysis should capture the underlying processes occurring in the marshes and thus reflect an accurate pattern of vegetation assemblages along the East Bay. Elevation and inundation frequency are the primary environmental gradients that were investigated in this study and likely are responsible for much of the variability in marsh structure along with vegetation competition (Adam 1990, Emery et al. 2001, Mitsch and Gosselink 1986, Redfield 1972). The study of coastal marshes and their related vegetation zones have focused nearly exclusively on marshes designated as “salt marshes”, where the limits of marsh vegetation are delimited by the mean high water line. Along the Chenier Plain few “salt marshes” actually exist because salinity levels rarely exceed 18 ppt (Visser et al. 2000). In this study the marshes are brackish (mesohaline) to intermediate (oligohaline) and likely involve more complex factors (Brewer and Grace 1990) determining the patterns of marsh zonation. Brackish marshes along the Gulf Coast are less influenced by mean high water but a combination of irregular tidal inundation, precipitation (Kunza and Pennings 2008), and the probable influence of wind driven sea level set up on the marshes. This phenomenon has received less attention in the literature and may have contributed to the weaker relationships between vegetation pattern and flooding processes in this study. I also acknowledge that there was a lack of data collected on environmental variables and that the statistical tests may be more robust with the inclusion of other variables, notably salinity level and soil moisture content.

The seven classified groups represented very different patterns of marsh vegetation in this study; Spapat, Disspi, Scioln, Pasvag, Spaspa, Diovir, and Mixed. When comparing the vegetation assemblages to previous studies (e.g. Visser et al. 2000) the Spapat, and Scioln groups corresponded with the Mesohaline Wiregrass group, Disspi corresponded to Mesohaline Mixture, and Pasvag corresponded with Oligohaline Paspalum. Visser et al. (2000) noted that over 51 percent of their classified marshes were oligohaline marshes dominated by *Sp. patens*; this correspondingly relates to the majority of the marshes in this study as well. Spapat was the dominant vegetation assemblage, 42 percent of the sampled plots were classified into the Spapat assemblage. *Sp. patens,* as the dominant species was found in 68 percent of all sampled plots. *Sp. patens,* found in brackish (Mesohaline) marshes, is generally located above the mean high water line because it is less able to efficiently oxygenate its rhizomes under frequently waterlogged and inundated conditions (Bertness 1991b). Because this study found such large monospecific stands of *Sp. patens* it can be assumed that the marshes of the East Bay are generally above mean high water and that inundation depth is low at tidally influenced locations, occurring generally during spring high tides or during storm events; this phenomenon was noted based on the low threshold values during inundation modeling. Broome et al. (1995) proposes that *Sp. patens* is able to tolerate a large range of environmental conditions, but Bertness (1991) found that despite its ability to tolerate this large range of conditions its distribution limits in the low marshes were constrained by physical conditions (e.g. frequent inundation by saline water and waterlogged soil). At higher elevations *Sp. patens* is a weaker competitor and is displaced by competitive dominants such as *Juncus* species (Emery et al. 2001).

Disspi was found in more frequently inundated locations, implying a more stressful environment (Emery et al. 2001), but showed higher species richness in contrast to Casanova and Brock (2000) who found high inundation frequency correlated to low species richness. The Mesohaline Mixture of Visser et al. (2000) was the only category containing *D. spicata* as a dominant with *Sp. patens* and matched up well with the Disspi group.

Pasvag was identified as falling into the Oligohaline Paspalum group of Visser et al. (2000) with the lowest occurrence in their study. I identified the Pasvag group occurring in 16 percent of the sampled marsh. Pasvag was dominated by *P. vaginatum* and co-dominated by *Sp. patens*.

The study area is on the western edge of the Chenier plains and is influenced by many of the same process as those in Visser et al. (2000). This study concentrates on a smaller area at the western edge of the Chenier plain, but also finds strong similarities to Visser et al's (2000) regional study.

It is interesting to note that in most coastal marshes along the Gulf of Mexico and the Atlantic coast, and salt marshes in particular, the species *Spartina alterniflora* is the dominant vegetation due to its ability to tolerate extended periods of inundation and its ability to oxygenate its rhizomes. It is, however, conspicuously absent from all plots sampled along the East Bay. This may be due in part to the irregular inundation regime experienced at the study site. Kunza and Pennings (2008) note that the lower marsh zones along the coast of Texas commonly consist of *Spartina alterniflora* and one or two other species. Bertness (1991) shows through experimental plot manipulation that under less frequent inundation *Sp. alterniflora* is competitively displaced by *Sp. patens*, this may explain its absence at the study site.

This study used hierarchical cluster analysis it identify vegetation assemblages common along the East Bay. Use of hierarchical cluster analysis has been shown to be successful in other biogeographic studies as well (Gauch and Whittaker 1981, Kim et al. 2010, Kim et al. 2011). Kim et al. (2011) used a similar method to predict vegetation assemblages in a backbarrier salt marsh in Denmark where a mixture of quantitative and graphical interpretation of the cluster dendrogram identified four significant vegetation groups.

HYDROLOGY AND VEGETATION

Because the LiDAR elevation data were too coarse to accurately model inundation frequency I devised a mixed method of interpolating water surface elevation from observed tide and wind data, via Mike 21, and incorporating the use of a GIS. Many assumptions must be considered when interpreting these data. This study assumes that there are no barriers blocking flow from either East or Trinity Bay, such as water control structures or impoundments, into the study sites. The flow from the Galveston Bay system to the study sites is contingent on the elevation of a given pixel and the interpolated hourly water surface elevation. This is essentially the probability that a given location will be inundated based on the observed and modeled conditions. It would be beneficial in the future to acquire higher resolution LiDAR (< 0.5 m resolution) that is more accurately able to capture the variability of surface elevation across the landscape. A possible explanation for the inability of Mike 21 to model inundation may stem from the difficulty of the LiDAR laser pulse to penetrate the dense marsh canopy and accurately capture a bare ground elevation (Wang et al. 2009). In an environment such as a coastal marsh with such a low elevation range (~ 1.5 m vertically), a topographic error of thirty centimeters would be enough to completely lose the tidal signature. A second assumption of this study is the return flow across the landscape. Because inundation potential was calculated hourly the landscape is reset every hour with a new potential to be inundated. For this reason flood duration was not calculated. This is undesirable because duration of inundation is an important component influencing vegetation composition. Under periods of extended inundation vascular plants may experience anaerobic conditions and these sites would most likely be inhabitant by hydrophitic vegetation with special adaptations to this type of stress (Bertness 1991b). Casanova and Brock (2000) found that frequency and depth had little influence on vegetation assemblages but that the duration of individual flooding events best correlated with a specific vegetation group.

In microtidal systems, such as the East Bay, the astronomical tidal regime may explain only a portion of the inundation experienced in the marsh. Wind driven sea level setup and overmarsh flooding may play a more important role in structuring marsh vegetation than does astronomical tide alone (Kim et al. 2011, Li et al. 2011, Reed 1989).

The relatively low frequencies of tidal inundation, 70 percent of plots were inundated less than 5 percent of the time, may indicate a lack of stress across the marsh. Costa et al. (2003) studied the effects of irregularly flooded salt marshes in Brazil to better understand the role of stress tolerance and biological interactions and determined that vegetation zonation and marsh structure may be more a component of competition and a “lottery mechanism” when strong tidal regimes are absent. Likewise, Kunza and Pennings (2008) found that irregular marsh flooding may first favor one species and then another leading to no single dominant over time and a weak pattern of zonation.

DIVERSITY

Many factors contribute to the diversity of a landscape, including nutrient availability, competitive interactions, and frequency of population reduction (e.g. hurricanes) (Huston 1979). Factors such as species pools (Ricklefs 1987) and competition (Grime 1977, Tilman 1985) have been suggested as important components in structuring diversity. Huston (1979) argues that diversity is not a component of competitive ability, but the expression of variable rates of competitive ability. The vegetation data collected in this study are an important resource to gain a better understanding of diversity along the Gulf Coast.

Previous studies along the Gulf Coast (Baldwin and Mendelssohn 1998, Bhattacharjee et al. 2009, Gough, Grace and Taylor 1994, Kunza and Pennings 2008) and elsewhere (Casanova and Brock 2000, Olff, Bakker and Fresco 1988, Silvestri et al. 2005) have shown that low species richness is found at lower elevations where frequency of inundation is greatest. Gough et al. (1994), in their study of species richness and community biomass along the Gulf Coast in Louisiana, showed that the strongest, linear, relationship with species richness was elevation.

This study found similar results, both at the vegetation assemblage level and at the plot level, where vegetation assemblages occurring at lower elevations, experiencing more frequent inundation and generally had lower species richness, this study notes that

Disspi showed an unusually high species richness and was one of the most frequently inundated vegetation group. Disspi diversity may be explained via Huston's (1979) hypothesis of diversity where Disspi, dominated by *D. spicata*, has a high growth rate and in areas of high population reduction diversity may actually increase. Similarly, Kunza and Pennings (2008) found high species richness at less frequently inundated locations and noted in their comparison of marsh diversity between Texas and Georgia salt marshes that Texas marshes had higher amplitude of species diversity than did Georgia, and this may be a result of less stressful conditions in Texas marshes due to irregular inundation regimes.

I propose that the stress gradient imposed by inundation is important to the vegetation structure of the marsh and that the weak relationship between elevation and species diversity, using Shannon's diversity index, may be a result of the irregular flooding regime that is experienced at the study location. Irregular flooding may allow vegetation assemblages to inhabit a wider range of locations and competitive processes may contribute to the variability in species diversity (Costa et al. 2003, Emery et al. 2001).

Along with inundation frequency, the influence of management practices, using burning at Anahuac NWR as a proxy, was investigated to understand its effects on diversity. The results indicated no significant relationship between the number of years since an area was burned and the species richness. Generally, slightly higher diversity was found at moderate frequencies of burning. The highest group species richness, Disspi (2.62 species), occurred at intermediate levels of burning (4.92 years), and lower group richness values occurred at both higher and lower burn frequencies. Species richness only increased modestly with the number of years since last burned, and at the longest period between burns (Spaspa at 6.3 years) the lowest species richness (1) was found. Gabrey and Afton (2001) found that winter burning of marshes along the Chenier Plain in Louisiana did not affect species richness or composition (Gabrey and Afton 2001). I argue that diversity and species richness in the coastal marshes are not the result of one or two factors but rather an array of different processes that have been captured in the cluster analysis. It is difficult to identify the significant processes influencing the diversity of the coastal marshes without first collecting data on more environmental variables such as soil characteristics, salinity levels of flooding waters, storm process, other microtopographic characteristics, herbivory, and extensive management variables including grazing loads, and herbicidal applications. Currently observed and modeled environmental characteristics may only contribute a portion of the variability in structuring the coastal marshes.

ENVIRONMENTAL THRESHOLDS

One way to understand environmental thresholds on the diversity of vegetation assemblages is through the use of CART models. CART models are an improvement over other ordination techniques because they are nonparametric (De'ath and Fabricius 2000), they can use both categorical and numeric data (Pesch et al. 2011), and are able to capture non-linear relationships that are difficult to quantify using linear models (McCune and Grace 2002).

The findings in this study show that high species richness was related to both high inundation frequencies (>10 percent) and high elevations (> 1m). This finding is interesting because the two predictor variables are inversely related; inundation frequency is strongly correlated with elevation. Huston (1979) hypothesized that high species richness would be related to both high frequencies of population reduction (e.g. stress imposed by inundation) and increased growth rates. At high elevations high growth rates may contribute to high species richness while at high inundation frequencies population reduction may be contributing to the high species richness. What is more difficult to explain are the lower species richness values at moderate elevations and inundation frequencies. According to the intermediate disturbance hypothesis, the highest diversity is maintained at intermediate disturbance frequencies (Connell 1978). Based on Connell’s intermediate disturbance hypothesis, moderate inundation frequencies would result in higher species diversity as a result of sufficient disturbance to disallow a single species from competitively excluding others, but allowing enough lag between disturbances for species other than those adapted to frequent stress to establish. This study did not find evidence of the intermediate disturbance hypothesis. One possible explanation may be that fewer species are both stress tolerators and good competitors. Many studies have argued that competitive exclusion will limit species richness (Grime 1977, Tilman 1982) and that highly stressful environments (e.g. frequently inundated marshes) should have low species richness (Kunza and Pennings 2008). One explanation for the low species richness at moderate inundation and elevation levels is the presence of *Sp. patens*. *Sp. patens* can tolerate a large range of salinity levels and is the dominant species in the brackish marshes of the Gulf Coast (Broome et al. 1995, Stutzenbaker 1999). *Sp. patens* grows in dense monospecific stands and at higher salinity levels and is generally a better competitor when greater resource availability is present (Emery et al.

2001). Because it is such a dominant species there is very low species richness in plots dominated by it.

Management practices, such as burning, were also investigated at Anahuac NWR. The CART model suggests that higher burn frequencies (< 2.5 years) and moderate inundation frequency (< 10 percent) will result in the Spapat vegetation assemblage exclusively. Moderate periods between burnings resulted in Disspi with Spapat present also. Locations that were burned infrequently, greater than 4.5 years and at low inundation frequencies (< 0.9 percent) resulted in the Spaspa assemblage and Pasvag and Mixed assemblages at more frequently inundated locations (>0.9 percent). According to Gabrey and Afton (2001) managers burn marsh vegetation to remove dominant species; along the Chenier Plain these are *Sp. patens* and *D. spicata*. In most cases this is done to open up patches for less competitive species that are desired as wildlife food including *Sc. americanus* and *Sc. robustus*. Gabrey and Afton (2001) also note that fire usually will temporarily decrease vegetation density but that this decrease is short lived, usually less than one year. They also found that *Sp. patens* biomass increased with more frequent burnings in unimpounded marshes. This has the potential to explain the monospecific stands of *Sp. patens* at the more frequently burned locations at Anahuac NWR. *Sp. patens*, a perennial, can spread via seed or through rhizomes and runners (Godfrey and Wooten 1981b), and because most marsh burning only removes above ground biomass it does not have any long term effects on species recovery (Gabrey and Afton 2001, Nyman and Chabreck 1995). Because fire does not appear to influence species richness to any significant extent this study agrees with Gabrey and Afton (2001) that many species in the coastal marshes appear to be fire adapted. Most coastal marsh species have evolved over a lightning induced burning regime caused by summer thunderstorms. The frequent lightning ignited fires lead to fire adaptability of the coastal vegetation (Nyman and Chabreck 1995). Season of fire was not investigated here, but may be important in influencing species response to burning. Fall and winter ignitions tend to favor species that have early season growth, such as *Sc. americanus*, but spring ignitions will remove *Sc. americanus* and *Sp. patens* dominated marshes will occur (Nyman and Chabreck 1995). Also, it would be desirable to compare different burn regimes between the Canada Ranch and Anahuac NWR so that the effects of different management strategies can be understood.

The threshold values identified through the use of CART are important indicators of tolerance levels for different species assemblages. This information can be useful for future studies wishing to perform species distribution modeling and for identifying specific management targets related to burning and structural marsh management.

The misclassification and error percentage was greater than 40 percent, and at first glance seems high, but other studies have found similar error rates (e.g. (Aho, Weaver and Regele 2011, Cairns 2001). Aho et al. (2011) explain that the high error rates may be attributable to unmeasured factors, and I agree that the high misclassification may well be a product of unknown environmental and anthropogenic processes. It is suggested by Aho et al. (2011) that to improve the predictability of the model additional data must be collected.

VEGETATION DYNAMICS

Most studies investigating the composition and distribution of marsh vegetation acknowledge that the relationship between elevation and inundation frequency is very important in predicting species distribution (Adam 1990, Mitsch and Gosselink 1986, Redfield 1972). Most of these studies do not consider irregularly flooded marshes, but see (Costa et al. 2003, Kim et al. 2011). The seven vegetation groups established from the clustering procedure capture the underlying variables that are important in structuring the vegetation assemblages and thus take into account the irregular flooding patterns that are typical in a mirotidal, diurnal environment that is also influenced by less predictable wind driven marsh inundation. CART analysis identified threshold values of elevation and inundation frequency, as well as the influence of burning at Anahuac NWR. Although we have not collected data on wind driven sea-level set up on the marshes it has been documented to occur along the Gulf Coast, specifically with strong winter cold fronts (Li et al. 2011, Reed 1989). As would be expected, the average elevation and inundation frequency of the clustered vegetation groups shows that the higher the elevation the less frequently that location will be inundated. There is also an inverse relationship between inundation frequency and species richness where locations that experience less stress from inundation have higher species richness as is the case with the Diovir group with 0.14 percent average inundation frequency, and average species richness of 3.6 species. An exception in this study is the Disspi group with the highest average inundation frequency of 15.6 percent, and a relatively high average species richness of 2.8 species. This finding is curious in some regards because the Disspi assemblage is dominated by *Distichlis spicata* which is usually restricted to stressful locations (e.g. frequently inundated or disturbed patches) (Emery et al. 2001). Not only does the relationship between elevation and inundation play an important role in structuring the marsh but also the presence of management activities.

This study indicates that patterns of vegetation zonation cannot be entirely explained by elevation and tidal inundation, although they play a critical role. Competition between species as well as irregular flooding events from winter storms, hurricanes and tropical storms have the ability to cause extended periods of inundation by saline water, introduce and redistribute large amounts of sediment, and also remove large areas of established marsh. The irregular flooding patterns typical of the Gulf Coast likely have led to the extended and overlapping range of most of the marsh vegetation.

GENERALIZATIONS

Although not explicitly investigated here, the impacts of increasing frequency, duration, and intensity of storm events will likely have an impact on the structure of the Gulf Coast marshes. If the CART model results are assumed to be accurate they can be used as critical threshold values for predicting vegetation assemblages and modeling shifts in patterns as a result of changes in individual values. If rising sea levels and reduced sediment importation cause vegetation assemblages to pass this critical threshold then it can be assumed that they will convert to the assemblage predicted above or below the critical threshold depending on the direction of the changes.

This research investigated the influence of modeled hydrology and measured elevation on the distribution of observed vegetation along the East Bay of Galveston Bay. The techniques utilized represent accepted methods of studying vegetation dynamics.

Future research would benefit by studying the influence of wind generated waves on the composition of marsh vegetation as well as investigating the influence of increasing storm events. Developing a predictive model of species distribution would allow the findings to be tested and the accuracy assessed in order to extrapolate the findings to other marshes influenced by similar processes. The floristic data are a good baseline for biogeographical studies along the Gulf Coast and future studies should be able to use this baseline to track changes in vegetation pattern as a result of shifts in biotic, abiotic, and anthropogenic conditions. Collection of additional environmental variables would also improve the understanding of the pattern process relationships in the marshes.

CHAPTER VI

CONCLUSIONS

SUMMARY OF FINDINGS

One hundred thirty-two plots were sampled along the East Bay of Galveston Bay and classified into seven statistically different vegetation assemblages using hierarchical clustering analysis so that vegetation dynamics could be studied. Using hydrological modeling and CART analysis threshold values were identified that best captured the relationship between pattern and process at the study site.

Modeled inundation frequency was only able to capture the probability that a given location would be flooded based on the modeled water surface elevation of the bay and the elevation of the marsh platform. Inundation frequency did not correlate with species richness or diversity in this study. However, because elevation did correlate with species richness I argue that inundation frequency does play an important role in structuring the marsh, along with other unmeasured environmental processes, and may be related to connectivity of the marsh.

The influence of marsh flooding events, other than daily tidal inundation, such as hurricanes, tropical storms, winter cold fronts, and wind tides has been shown to be of great importance to marsh vegetation composition (Costa et al. 2003, Howes et al. 2010, Kim et al. 2011, Kunza and Pennings 2008, Li et al. 2011, Michener et al. 1997). Irregular flooding can lead to less pronounced zonation of the marshes along the Gulf of Mexico. Studies have also shown that not only is the frequency of flooding events important, but the duration of individual flooding events (Casanova and Brock 2000).

It is also important to try and understand how management activities such as burning, grazing, structural marsh management and altered hydrology may be influencing the vegetation. Future studies must include quantification of these anthropogenic activities to truly understand the processes that are important in structuring the marsh.

This study found the main factor contributing to species richness, at both vegetation assemblage and plot levels, was elevation ($p<0.05$). Vegetation at lower elevations had lower species richness, sans the Disspi assemblage. Along the east bay inundation frequencies less than 0.70 percent and elevations greater than 1.0 meter had high diversity in general. Species assemblages were identified using CART analysis with moderate classification success and improvements in error reductions may be achieved by measuring additional environmental and management variables, including soil moisture, and salinity levels.

When burn frequencies were included in the CART model Spapat was predicted at less than 4.5 years between burns, and Pasvag and Spaspa were predicted at burn frequencies higher than 4.5 years. A conceptual model was created to illustrate the location of the predicted vegetation assemblages in two dimensional burn by elevation space.

In marshes, diversity has been shown to increase with decreasing inundation frequency and increasing elevation. This study did find that the highest elevations and lowest inundation frequencies supported the highest diversity of vegetation. However, high diversity was also found at the lowest elevation and the highest inundation frequency. This finding is in contrast to Connell’s (1978) intermediate disturbance hypothesis which suggests that the highest diversity should occur at the moderate elevations and inundation frequencies.

This study demonstrates that the processes that are important for creating the distinct salt marsh zones along the Atlantic coast may not be transferable to other geographic locations, such as the East Bay, if there are different underlying mechanisms contributing to the marsh structure. Stress gradients such as inundation frequency and elevation can only explain a portion of the vegetation variability observed and further research is need to understand the influence of wind tides, salinity levels, soil moisture and grazing on the vegetation assemblages.

This study demonstrated the usefulness of cluster analysis for identifying characteristic vegetation assemblages as well as using CART analysis to identify characteristic environmental variables contributing to their composition. These techniques are recommended when complex multivariate ecological data do not meet the assumptions of standard parametric procedures.

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APPENDIX

LIST OF EQUATIONS

EQUATION Page

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