Predicting Wetland Susceptibility to *Phragmites australis*: An Assessment of Environmental Conditions in Coastal Louisiana with Recommendations for Wetland Management

Master's Thesis Submitted to the Faculty of the Bard Center for Environmental Policy

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Abstract

Phragmites australis (common reed) has expanded rapidly in the United States over the past two centuries and come to be regarded by many as a noxious or invasive species – one that tends to spread prolifically in an undesirable or harmful manner. *Phragmites* has also been found to flourish in disturbed areas, which is an important consideration in Louisiana given the large potential for disturbance associated with wetland construction and restoration techniques; where rapid loss of coastal wetlands ensures that such activities will continue. It is in this context that the debate over the potential impacts of *Phragmites* expansion on the Gulf Coast has prompted the considerations of this thesis.

The goal of this thesis is to address the expansion of *Phragmites* in coastal Louisiana through an analysis of the environmental conditions that compose the wetlands in which *Phragmites* has already been identified. A model was developed to predict wetlands with conditions too extreme for the establishment of *Phragmites* using thresholds for water salinity, water level, and water temperature; however, it was unable to predict wetlands prone to establishment. The model identified a significant correlation between four additional abiotic variables (soil salinity, soil moisture, bulk density, and percent organic matter) and *Phragmites* establishment, growth, and productivity. Recommendations ensuing from this analysis include the conditions under which resource managers should consider the control of *Phragmites* and the areas of new research and data collection that are needed to better understand, predict, and make decisions regarding the expansion of *Phragmites* in coastal Louisiana.

Executive Summary

Coastal wetlands are ecosystems of vital importance both ecologically and commercially, especially in coastal Louisiana, which contains about 40% of the wetlands in the lower 48 states (Edwards and Proffit, 2003). Despite the importance of these ecosystems, they are very fragile. This is particularly true for Louisiana, which loses about 40 square miles of wetlands every year as a result of both natural and anthropogenic forces (Edwards and Proffit, 2003; Mitsch and Gosselink, 2000). Although wetland construction and restoration projects have the potential to make-up for lost wetland ecosystems, restoration sites serve as areas that are particularly prone to invasion by noxious species. Noxious plant species should be of concern because the specific vegetative communities that coastal wetlands contain can significantly impact the ecosystem services provided. *Phragmites australis* is an example of one of these noxious species and has historically demonstrated a significant ability to alter vegetation dynamics and subsequently is a threat to the functionality of wetland ecosystems.

Phragmites australis has aggressively invaded coastal marshes of North America over the past 200 years and has the potential to degrade the quality of these habitats by forming dense monocultures and displacing native vegetation. The aggressive behavior of this species is attributed to the introduction of a non-native Eurasian genotype and anthropogenic changes in the environment that have produced more suitable conditions for *Phragmites*. Although invasion and

expansion of *Phragmites australis* has substantially altered the landscape of the Northeastern United States, other areas of the US have only been mildly affected. However, in recent years attention has been drawn to the expansion of *Phragmites australis* in the south, particularly along the Gulf of Mexico. There are concerns that *Phragmites australis* will alter the landscape of Gulf Coast wetlands, in a manner similar to that of the Northeast, prompting recent research on *Phragmites australis* in the area. This concern serves as the motivation for this thesis.

This thesis examines current distributions of *Phragmites australis* in coastal Louisiana, analyzes the environmental conditions that promote its establishment and expansion, and identifies the factors that are most important in predicting the susceptibility of individual marshes to invasion by *Phragmites australis.* Given the rapid loss of wetland ecosystems in coastal Louisiana and subsequent need for wetland creation and restoration practices, this thesis voices concern for the conditions that can affect *Phragmites australis* establishment and expansion in restoration areas. Examining the invasion of *Phragmites australis* through the lens of coastal restoration is important because disturbance associated with such activities can expose bare substrate, disturb soils, and impact hydrology (Kirk, Berquist, and Priest, 2003; Burdick and Konisky, 2003). These changes can make restoration areas particularly susceptible to invasion. Insight into the environmental conditions that promote the growth and expansion of *Phragmites australis* will help resource managers and project planners identify high-risk areas and make informed decisions on how to address the situation.

Two models were developed to address the goals of this study. The first is a predictive model that predicts the presence of *Phragmites australis*. The model is based on tolerance ranges of environmental variables (inundation time, salinity, and temperature) derived from the literature. Environmental data (both abiotic and biotic) was compiled in state databases along 390 transects throughout the wetlands of coastal Louisiana and was compared to the established tolerance ranges. This model takes an if-then approach; if the value for a particular environmental parameter falls within a given range then that site has the potential to allow *Phragmites* establishment. This potential is described categorically as 'yes' or 'no'. Once if-then metrics are established for each site then the results are examined. The model predicts that if all environmental variable models were denoted with a yes, then *Phragmites australis* will be present at a given site. The efficiency by which the model makes its predictions was then cross checked by comparing the results to actual distributions of *Phragmites australis* along the transects that the environmental data was collected. Although this model can predict whether or not a *Phragmites australis* stand can exist at a given site, it provides no insight into how productive a given population will be. For this reason a correlation model was developed to further analyze environmental variables involved in this study.

The second predictive model, the correlation model, identifies the environmental variables that are most correlated with the presence of *Phragmites australis* and its productivity, which was estimated using two different proxies:

average height and percent cover. Multiple regressions were used to determine empirical relationships between metrics for *Phragmites* and environmental conditions at transects points throughout coastal Louisiana. After the results were collected, insignificant variables were identified, verified with a correlation matrix, and eliminated in a step-wise fashion. This process resulted in the elimination of all variables except for minimum salinity and bulk density, which were the only variables that remained individually significant when combined in a single model.

Results indicate that almost 20% of the wetlands examined in this study had established *Phragmites australis* populations in them. The predictive model correctly identified whether *Phragmites australis* was present or absent in nearly 75% of all examined sites; however, the model turned out to be much better at predicting which sites had environmental conditions that were too extreme for establishment by *Phragmites australis* rather than which sites were at high risk of establishment (i.e. there were fewer false negatives than false positives). It is likely that the results of this model could be improved by incorporating additional variables other than salinity, percent time flooded, and temperature. This model could also be improved if it were able to account for the stage of invasion, the likelihood of a site receiving genetic material from other *Phragmites australis* stands, or the form of *Phragmites australis* (haplotype) being analyzed.

The correlation model found that, out of the environmental variables observed, bulk density and minimum salinity were the most significantly

correlated with the presence, average height, and percent cover of *Phragmites australis*. Although the correlation model examined a large number of abiotic variables, data was not available for porewater sulfide concentration, which has been shown to be one of the primary limitations to the establishment and productivity of *Phragmites australis*. However, model results could indirectly reflect the effect of sulfide concentration through the incorporation of bulk density into correlation models. Bulk density could be a potential proxy for sulfide concentration because of the correlation between increased soil bulk density and decreased sulfide porewater concentrations seen in the literature (Schrift, Mendelssohn, and Materne, 2008).

This research concludes that the likelihood of establishment by *Phragmites australis* is dependent on a combination of different environmental variables and cannot be predicted using singular variables out of context. On the other hand, it seems that the areas prone to establishment by *Phragmites australis* can be predicted using a combination of a few variables: primarily salinity, inundation time, and soil bulk density. Based on results from models in this thesis, the current distribution of *Phragmites australis* in coastal Louisiana, and a review of the current literature, I make the following recommendations:

- States should invest in the additional collection of data regarding the location of current populations of *Phragmites australis*, as well as the rate and extent of their expansion. This data should be combined with research on hydrology, chemistry, soil properties, and disturbance and made publicly available.

- Further scientific studies are needed to increase genetic sampling of known populations of *Phragmites australis* populations and the impacts of different haplotypes of *Phragmites australis* on the functional capacity of coastal wetlands.
- Scientist should develop a consistent language to name and describe different haplotypes of *Phragmites australis*.
- In making decisions about the restoration of sites containing *Phragmites australis* or in its control, resource managers should weigh the potential structural benefits against the negative impacts that *Phragmites australis* can have on wetland ecosystems on a case-by-case basis.
- Resource managers should express particular concern in dealing with this species in areas subsidized by dredged material or in other areas where construction or restoration activities are taking place.

Chapter 1: Introduction

Tidal wetlands are ecosystems of vital importance characterized by high primary productivity and a range of ecosystem services (D'Alpaus et al., 2007). Ecosystem services provided by tidal wetlands include the dissipation of wave energy, water filtration, sediment accretion, and habitat creation (Callaway, 2005). The specific vegetative communities within these habitats are important because plant species composition and structure can significantly impact chemical, biological, and physical processes (Shafer et al., 2007). Despite their importance, the continued existence of coastal marshes is threatened by both natural and anthropogenic forces. Some of the major threats include land subsidence, sea-level rise, and coastal development all of which diminish or alter landscape properties (Chambers et al. 1999; Burdick and Konisky, 2003). Edwards and Proffit (2003) report that Louisiana, which contains about 40% of the wetlands in the lower 48 states, has incurred almost 80% of wetland loss in the US since the 1950's. This represents a total loss of almost 40 square miles of coastal wetland loss in Louisiana per year (Edwards and Proffit, 2003; Mitsch and Gosselink, 2000). This rapid loss and widespread acknowledgement of the ecological importance of coastal wetlands has created resolve to reverse the loss of wetland habitat in the United States. Wetland loss can be mitigated through preservation, restoration, and construction of wetland areas and has been promoted by major environmental regulations such as § 404 of the Clean Water Act and no-net-loss policies (Streever, 2000; Edwards and Proffit, 2003).

Wetland construction and restoration projects have the potential to make-up for lost wetland ecosystems; however, preventing the establishment of exotic or invasive species within restoration sites is often a problem due to high levels of initial disturbance associated with restoration activities (Callaway, 2005). The establishment of invasives with potential to outcompete native species (Callaway, 2005) within newly restored wetlands is important because the post-disturbance environment drives the structure and dynamics of many ecosystems (Schrift, Mendelssohn, and Materne, 2008). Although the term *invasive species* encompasses a large range of introduced, exotic, or nuisance plant and animal species, the term "invasive" more generally refers to species tend to spread prolifically in an undesirable or harmful manner. *Phragmites australis* (here after referred to as *Phragmites*) is an example of an invasive in this context. *Phragmites* has been characterized as an "aggressive colonizer of disturbed sites" that displaces more desirable species and may result in a net loss of ecosystem function for the wetlands that it colonizes (Kirk, Berquist, and Priest, 2003).

Phragmites is an "extremely flexible" species (Minchinton and Bertness, 2003) and can survive in most wet habitats (Kirk, Berquist, and Priest, 2003). It is a salt-tolerant glycophyte (Chambers, 1997) and has been shown to flourish within the range of salinity and flood gradients common to most U.S. tidal marshes (Burdick and Konisky, 2003). *Phragmites* has aggressively invaded coastal marshes of North America over the past century by forming monocultures and displacing native marsh plants (Chambers et al., 1999; Minchinton and Bertness, 2003; Tulbure and Johnston, 2010). Scientists attribute the increase in *Phragmites* over the past two centuries with the genetic divergence associated with the introduction of a non-native Eurasian genotype (Kirk Berquist and Priest, 2003; Tulbure and Johnston, 2010) and the production of suitable conditions for *Phragmites* establishment and expansion by anthropogenic activities (Chambers et al., 1999; Minchinton and Bertness, 2003; Burdick and Konisky, 2003).

The primary goal of this thesis is to explore the environmental conditions that support the establishment of invasive *Phragmites* and to determine which environmental factors are most strongly associated with its establishment in the tidal marshes of Coastal Louisiana. Ranges for water salinities, water levels, and inundation periods that support the establishment of *Phragmites* were identified from previously published literature on *Phragmites*. These variable ranges were then compared to actual conditions at various sites across the Louisiana coast to predict whether or not *Phragmites* was likely to be present or absence. The accuracy of these predictions was then determined by comparing them to vegetative data that records the actual distribution of *Phragmites* in the examined sites. The developed prediction model provides some insight into how water salinity, water level, and inundation time interact to affect the likelihood of *Phragmites* establishment, however the limited robustness of the tests suggests that there are other significant environmental variables affecting the likelihood of

Phragmites establishment that need to be incorporated into the model. For this reason, a correlation model was developed to determine which other environmental variables (percent time flooded, soil pH, soil salinity, soil moisture, bulk density, and percent organic matter) are significantly correlated with *Phragmites* establishment.

Although this study does not directly analyze how anthropogenic impacts or wetland construction activities might influence the favorability of a given habitat for *Phragmites* establishment, the information provided can help to make predictions about the impacts of such activities. For example, if a constructed wetland changes the elevation, that change could be interpreted as a decrease in water and inundation time. Estimated changes of these variables could then be run through the models to predict whether or not such changes are likely to effect the chance of *Phragmites* establishment.

From a management perspective, the goal of this thesis is consequential because knowing the ability of *Phragmites* to survive and grow across a range of environmental conditions will promote the identification of tidal wetlands that are susceptible to *Phragmites* invasion. Furthermore, the identification of ranges of environmental variables that influence *Phragmites* invasion will ideally help to inform resource managers in the development of control methods and decision to eradicate or limit the future spread of *Phragmites*. This thesis emphasizes the relationships between the construction and restoration of coastal wetlands with dredged material and the risk of establishment or expansion by *Phragmites* within such sites. This inquiry is important because such activities can create disturbance and promote the successful establishment and expansion of *Phragmites* populations.

The goals of this study and the questions that it addresses are important for two reasons. The first reason is that the rapid decline of wetlands in coastal Louisiana in combination with the increase in acceptance of their importance will lead to an increase in the need for wetland construction and restoration projects in the future. Secondly, the increased ability of invasive *Phragmites* to expand, propagate, and compete within disturbed tidal wetlands could impact the functional and/or structural capacity of constructed or restored wetlands. These two points should be considered in the context of a coastline that will increasingly bear the impacts of anthropogenic activities and thus an overall increase in the likelihood of *Phragmites* establishment.

Chapter 2: Literature Review

Section 2.1: Phragmites Characteristics and Background

Phragmites is a perennial grass (Burdick and Konisky, 2003) and is classified as a glycophyte that is tolerant to both flooding and salinity stresses (Saltonstall, 2002; Chambers, 1997). *Phragmites* exhibits high genetic variability (Hansen et al., 2006) and plasticity (White, Hauber, and Hood, 2004), which enables it to survive across a wide range of environmental conditions and thrive in most wet environments (Konisky and Burdick, 2004; Kirk, Berquist, and Priest, 2003). It is well documented that *Phragmites* forms large, monospecific stands associated with a decrease in wetland plant diversity (Chambers et al., 1999; Tulbure and Johnston, 2010; Minchinton and Bertness 2003; Meyerson, Lambert, and Saltonstall, 2010) and a decrease in ecosystem function (Tulbure and Johnston 2010; Minchinton and Bertness 2003).

The formation of monospecific stands and displacement of other wetland species by *Phragmites* can be partially attributed to competitive interactions between *Phragmites* and other wetland plants. Competition with matrix vegetation has the potential to limit *Phragmites* growth directly, by acting as a natural buffer to suppress the local spread of *Phragmites*, and indirectly, by reducing the availability of nutrients and other resources to *Phragmites* (Minchinton and Bertness, 2003). Despite the potential for competition to reduce *Phragmites* productivity and growth, the large size of *Phragmites* helps it to access resources and makes it a potentially dominant competitor both above and belowground (Burdick and Konisky, 2003). *Phragmites* grows taller and has a higher biomass than other marsh grasses; therefore, it suppresses many co-occurring species directly through shading and litter mat formation (Tulbure and Johnston, 2010; Kirk, Berquist, and Priest, 2003; Minchinton and Bertness, 2003). Burdick and Konisky (2003) note that organic litter from *Phragmites* could (a) produce wrack, capable of burying and killing shorter meadow grasses and thus providing space for *Phragmites* expansion or (b) fuel fires that would likely kill woody plants and recycle nutrients, but leave behind unharmed *Phragmites* rhizomes buried in wet sediment. The strength of *Phragmites* as a competitor is also related to its substantial belowground biomass and elaborate rhizome system (Hellings and Gallagher, 1992). These subterranean structures allow *Phragmites* to ameliorate physical and biological stresses by extending roots into deeper, less saline groundwater (Chambers, 1997) and accessing distant resources (Burdick and Konisky, 2003). Minchinton and Bertness (2003) have observed a tendency for *Phragmites* to shunt resources from senescing shoots to its rhizomes, which can then expand and give rise to vertical rhizomes just below the soil surface. The combination of these characteristics makes *Phragmites* a strong competitor and contributes to its ability to take advantage of favorable environmental conditions when they arise (Minchinton and Bertness, 2003).

2.1a Range

Invasion by *Phragmites* has become an increasingly common feature in many tidal marshes of the East and Gulf coasts of the United States (Chambers et al., 1999; Bart and Hartman, 2002). *Phragmites* has a cosmopolitan distribution and is abundant in marsh communities worldwide (Hansen et al., 2006; Saltonstall, 2002). Although fossil records indicate that *Phragmites* has been present in the United States for at least 40,000 years (Saltonstall, 2002), its relative abundance in North America has changed dramatically over the last 200 years (Chambers et al., 1999; Meyerson, Lambert, and Saltonstall, 2010). Today, *Phragmites* is widespread in New England, but expansion is also rapid along the southern Atlantic coast and in the Mississippi delta region of the Gulf of Mexico (Chambers et al., 1999; Hansen et al., 2006). The distribution and abundance of *Phragmites* has increased so rapidly that Meyerson, Lambert, and Saltonstall (2010) refer to the North American invasion by introduced *Phragmites* as "one of the most complete and dramatic biological invasions that has been documented," and the existence of *Phragmites* has been confirmed on the Gulf Coast as well.

2.1b Habitat and Zonation

Phragmites can survive in most wetland habitats (Kirk, Berquist, and Priest, 2003), and has been observed expanding in marshes with salinities ranging from oligohaline (0.5-5 ppt) to polyhaline (18-30 ppt) (Burdick and Konisky, 2003; Konisky and Burdick, 2004). *Phragmites* is generally considered a freshwater species that is disadvantaged by frequent inundation in saline areas. For this reason, *Phragmites* generally expands seaward along the upper border of salt marshes, which are less affected by saline inundation. However, in recent years, the expansion of *Phragmites* has been increasingly observed in areas of low, more physiologically stressful marsh (Minchinton and Bertness, 2003). This change in zonation is due to two factors: the introduction of a more salt-tolerant haplotype of *Phragmites* (Kirk Berquist and Priest, 2003) and an increase in freshwater, nutrient inputs, and disturbance associated with coastal development (Tulbure and Johnston, 2010). Despite this recent departure from higher, fresher marshes towards lower, more saline marshes, the zonation of *Phragmites* is still dependent on the combination of several factors: the availability of limiting resources, interspecific competition, and abiotic stressors (Minchinton and Bertness, 2003).

The upper limit of the vegetative zone occupied by *Phragmites* is generally set by the terrestrial (landward) border, where stands of *Phragmites* are limited by biotic stresses like competition with other species (Burdick and Konisky, 2003) or grazing (Hellings and Gallagher, 1992). The lower (seaward) limit is set by abiotic and/or physical stresses associated with nutrient availability (Hellings and Gallagher, 1992), salinity gradients (Tulbure and Johnston, 2010), anoxic soils (Chambers, 1997), and tidal flooding (Minchinton and Bertness, 2003). Despite these limitations, *Phragmites* seems well adapted to tolerate conditions in both mesohaline and polyhaline marshes – as is demonstrated by its ability to survive across a broad range of flood and salinity gradients (Konisky and Burdick, 2004).

2.1c Reproduction and expansion

Phragmites reproduces both sexually and asexually (Meyerson, Lambert, and Saltonstall, 2010). Seed production in *Phragmites* is rare (Bart and Hartman, 2002), and although seedlings are able to germinate on exposed substrates, they are unable to colonize substrates that are frequently submerged, densely vegetated (Tulbure and Johnston, 2010), or have high salinity (Bart and Hartman, 2002). Due to this poor seed viability, most stands establish or expand via rhizome spread and clonal growth (Chambers et al., 1999). Furthermore, stems derived from rhizomes have a much higher tolerance to salinity than juveniles derived from seeds (Bart and Hartman, 2002). Results from a study by Minchinton and Bertness (2003), suggest that rhizome viability could be the result of the tendency of *Phragmites* to shunt resources from its senescing shoots (above-ground biomass production) to its rhizomes, which can then extend to give rise to vertical rhizomes when conditions are favorable for expansion. *Phragmites* has even been observed expanding via horizontal rhizome growth at a rate of up to 2 m/yr (Tulbure and Johnston, 2010). Hansen et al. (2006) observed that if it is unable to invade wetlands directly via seed or rhizome propagation, *Phragmites* appears to invade wetlands via clonal growth, which also seems to be a primary factor influencing the distribution of *Phragmites* throughout Gulf Coast wetlands (Chambers et al., 1999).

Section 2.2: Genetic Variation, Distribution, and Hybridization

2.2a Genetic Variation

Fossil records indicate that *Phragmites australis* has been present in the southwestern United States for at least 40,000 years and on the Atlantic and Pacific coast for several thousand years (Saltonstall, 2002); however, with the introduction of non-native genotypes around the 19th century (Saltonstall, 2002), the relative abundance and spread of *Phragmites* has increased rapidly over the past two centuries (Figure 1) (Chambers et al., 1999; Meyerson, Lambert, and Saltonstall, 2010).

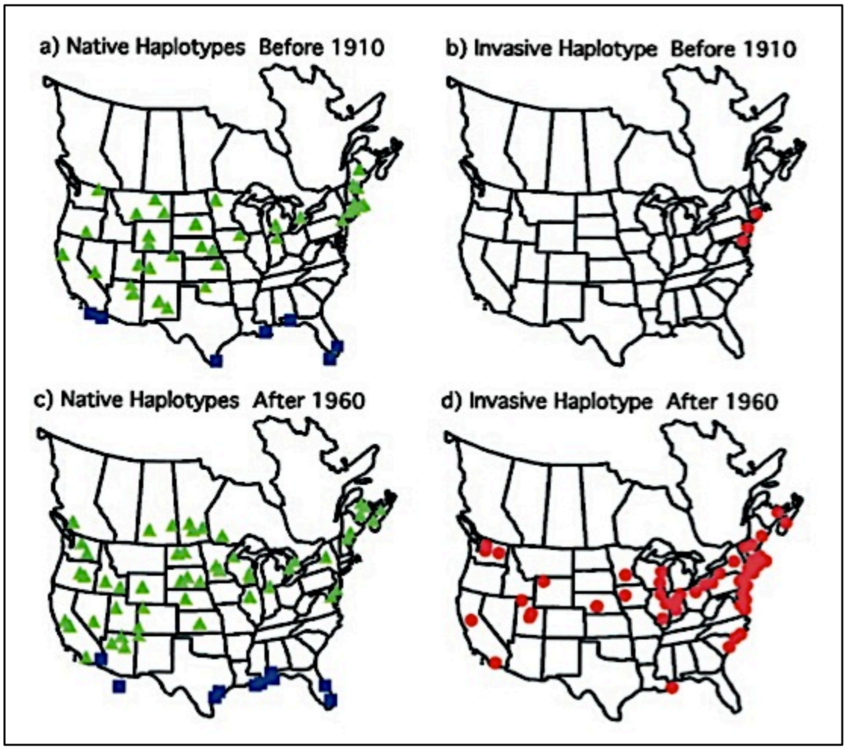

Figure 1: "Distribution of Phragmites *haplotypes in North America. Green triangles represent the 11 native haplotypes, blue squares represent haplotype I, and red circles represent the invasive haplotype M. (a and b) the distribution of haplotypes in the 62 herbarium samples collected before 1910. (c and d) The distribution of haplotypes in 195 samples collected after 1960" (Saltonstall, 2002; reproduced with permission).*

Saltonstall (2002) found that a total of 27 *Phragmites* haplotypes exist world-wide, out of which 11 are unique to North America and considered native to the continent (Saltonstall, 2003; Hansen et al., 2006; Peterson and Partyka, 2006) (Figure 2). Saltonstall (2002) labeled the 11 native haplotypes A-H and the invasive haplotype M. Haplotype M is the most common world wide as well as in North America (Figure 1) (Saltonstall, 2002). Saltonstall analyzed the distribution of different *Phragmites* haplotypes before 1910 and after 1960. From her analysis she found that, with the exception of a couple sites, almost all native haplotypes had been replaced with the invasive haplotype M, suggesting that haplotype M is the highly aggressive and competitive form of *Phragmites*. Tulbure and Johnston (2010) partially attributed the dominance of the M haplotype to its' increased ability to aerate its root system, compared to other haplotypes, and thus an increased ability to inhabit anoxic soils and thus tolerate more inundation with saltwater than native *Phragmites* haplotypes.

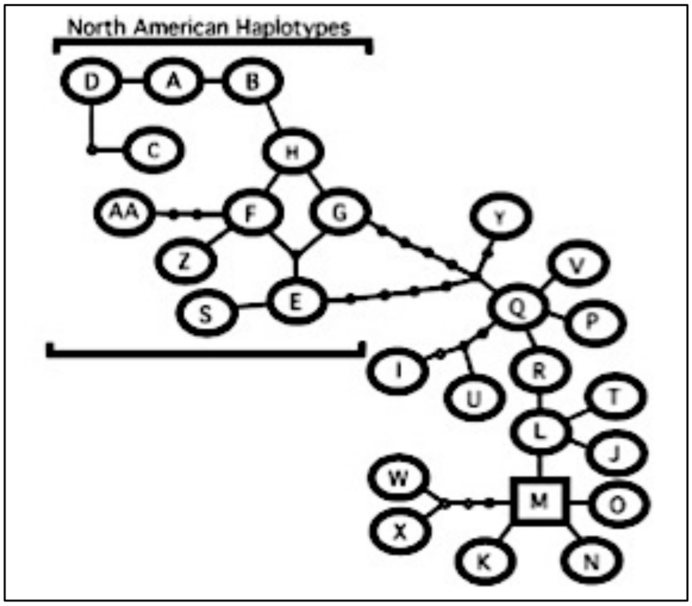

Figure 2: "Parsimony network of Phragmites *chloroplast haplotype diversity obtained from sampling 345 populations worldwide. Each link between haplotypes represents one mutational difference, following coding of indels as single characters. Unlabeled nodes indicate inferred steps not found in the sampled populations. Loops in the network are the result of homplasies in the number of repeats in some indels. The ancestral haplotype, or root of the network, is indicated by a square. Geographic distribution of haplotypes is as follows: North America = haplotypes A-H, S, Z, AA, I, and M; South America = I and Y; Europe – L-O, and T; Asia/Australia = I, J, L, M, O, P, Q, U, W, and X; Africa = K, M, R, and V" (Saltonstall, 2002; reproduced with permission).*

2.2b Phragmites *on the Gulf Coast*

The rapid expansion of *Phragmites* across North America has raised awareness and concern about the increased dominance and spread of *Phragmites* on the Gulf Coast, where three different lineages have been identified: Native, Introduced and Gulf Coast (Meyerson, Lambert, and Saltonstall, 2010). The Gulf Coast haplotype (haplotype I) is most closely related to an Asian Haplotype (Q) and was also found in South America where it is dominant (Figure 2) (Saltonstall, 2002). The Gulf Coast clone differs from other haplotypes present in North America because it has horizontal growth, stiff leaf blade tips, and closely positioned leaves (Hansen et al., 2007), as opposed to the vertical growth displayed by all other *Phragmites* haplotypes.

Despite its morphological differences, it is not known for certain whether Gulf Coast *Phragmites* is native or introduced to the region (Meyerson, Lambert, and Saltonstall, 2010; Shafer et al., 2007; Saltonstall 2002). Peterson and Partyka (2006) note that even if the Gulf Coast lineage is native, in wetlands altered by development, it has the potential to expand into large, monospecific stands and thus express patterns of establishment similar to invasive.

There are several other concerns regarding the presence of *Phragmites* in the Gulf Coast region. A study by Howard et al. (2007) showed that Gulf Coast *Phragmites* had lower rates of vegetative spread than introduced *Phragmites*, which illustrates the potential for introduced *Phragmites* to possibly outcompete and displace Gulf Coast *Phragmites* populations (Meyerson, Lambert, and

Saltonstall, 2010). Another concern has arisen from Gulf Coast *Phragmites* invasion into wetlands of the southwest (Texas to California) where it has reportedly expanded rapidly, displayed aggressive growth and dominance, and invaded previously unimpacted watercourses – suggesting that the Gulf Coast lineage is also acting invasively (Meyerson, Lambert, and Saltonstall, 2010). Despite increasing concerns, the expansion of Gulf Coast *Phragmites* and the impacts of introduced *Phragmites* in the Gulf region are not well understood (Meyerson, Lambert, and Saltonstall, 2010). Although haplotype diversity has shown decline *between* populations over the past decades, *within*-population variation has increased (Saltonstall, 2002), which could mean increased hybridization in the future – as was suggested by Meyerson, Lambert, and Saltonstall (2010).

2.2c Hybridization

Hybridization is the process by which organisms of different varieties or species reproduce to form a hybrid. In the case of *Phragmites*, hybridization would occur through reproduction between different haplotypes. Although Chambers et al. (1999) found hybridization to be low between the dominant delta clone and less-dominant one, more recent studies indicate that hybridization might be higher in the Gulf of Mexico than originally thought (Meyerson, Lambert, and Saltonstall, 2010; White, Hauber, and Hood, 2004). In an early study on the clonal differences between *Phragmites* populations of the Mississippi River Delta, White, Hauber, and Hood (2004) identified two dominant populations as “background” and “patchy”, but also found recombinant populations that were electrophoretically different: indicating a potential for hybridization in *Phragmites*.

Another study by Meyerson, Lambert, and Saltonstall (2010), suggested that hybridization between native and introduced *Phragmites* could also explain the convergence of three *Phragmites* lineages in the Gulf Coast and Southwest United States. Alternatively, genetic variation among populations from different regions could be the result of growing in environments with different climates (Hansen et al., 2006). White, Hauber, and Hood (2004) also used local environmental differences to explain morphological differences of *Phragmites* in three different subdeltas, which they attribute to the species’ plasticity. On the other hand, Hansen et al. (2006) found that significant morphological differences existed between different *Phragmites* populations and between different clones of the same population, irrespective of site conditions.

Studies indicate that *Phragmites* is a polymorphic species whose morphology can be affected by both the environment and/or genetic factors (White, Hauber, and Hood, 2004). Differences in local environmental differences at specific sites likely explain the morphological differences between different populations across the three subdeltas examined by White, Hauber, and Hood (2004). Similarly, Hansen et al. (2006) suggests that it is possible that genetic variation among different geographic populations is the result of growing in different climatic environments; however, the same authors also point out that significant morphological differences have been found between different clones within the same population irrespective of site conditions, which would suggest a more genetically derived difference in morphology. Regardless, natural selection that favors improved physiological tolerance in saline wetlands is probably a strong driver for genetic divergence (Burdick and Konisky, 2003).

Morphological differences between *Phragmites* species should be of concern because they could lead to changes in both behavior and physiological tolerances. Therefore morphological differences may favor non-native genotypes and allow them to proliferate and alter the genetic structure of the species (Saltonstall, 2002). This is logical given the role that natural selection has in driving genetic divergence by favoring those plants with improved physiological tolerance to tidal, saline conditions (Burdick and Konisky, 2003).

Section 2.3: Environmental Variables

The purpose of this section is to explore the interactive effects between *Phragmites* and some of the environmental variables that affect its viability, productivity, and distribution within tidal wetlands. Understanding environmental variables is important because they influence growth, survival, and competitive interactions of plants (Howard and Rafferty, 2006). Biotic variables that can limit the survival and growth of *Phragmites* include competition, predation (herbivory), disease, alleopathy, and parasitism (Burdick and Konisky, 2003). Competition is thought to be one of the most important determinants of salt marsh community structure (Burdick and Konisky, 2003). However, given the difficulty of quantifying biotic variables like competition, this study will focus on the relationship between *Phragmites* and abiotic variables. Important abiotic variables that I will discuss in this thesis include salinity, flooding, nutrients and soil characteristics. Combinations of different abiotic variables can significantly affect *Phragmites* growth and distribution. For example, *Phragmites* does not seem to thrive in wetlands that experience combinations of high salinity, extensive tidal flooding, and undesirable edaphic features like anaerobic soils (Chambers, 1997).

It must also be noted, however, that the manner in which *Phragmites* is affected by different environmental conditions depends on the stage of invasion that a particular population is in. Bart and Hartman (2002) point out four distinct stages of invasion: (1) dispersal of seeds or rhizome fragments, (2) initial emergence of new stands, (3) survival of newly emerged stems, and (4) post-establishment and spread of growth. Initial emergence seems more constrained by salinity and inundation while post-establishment spread and growth seem more affected by anoxia and sulfide concentrations (Bart and Hartman, 2002). If *Phragmites* invasion is viewed a process of events dependent on the stage of invasion then researchers can better determine the causes of invasion an increase the potential for intervention (Bart and Hartman, 2002).

2.3a Salinity

Previous studies (e.g. Chambers 1997; Bart and Hartman, 2002; Hellings and Gallagher, 1992; Burdick and Konisky, 2003; Tulbure and Johnston, 2010) have indicated a reduction in growth parameters of *Phragmites* under saline conditions. Hellings and Gallagher (1992) found that stem height, density, and biomass of *Phragmites* were all negatively affected by increasing salinity. Increased salinity leads to a reduction in *Phragmites* growth because it has been shown to inhibit nutrient uptake (Burdick and Konisky, 2003; Bart and Hartman, 2002). Increased salinity also causes *Phragmites* to divert energy (carbohydrates) away from active meristematic growth, towards the maintenance of osmotic balance (Hellings and Gallagher, 1992; Burdick and Konisky, 2003; Bart and Hartman, 2002). Bart and Hartman (2002) point out that even moderate saline concentrations can have a negative effect on the survival and performance of newly buried rhizomes and can limit root elongation from seeds. These observations support the fact that the seaward expansion of *Phragmites* is limited by salinity (Tulbure and Johnston, 2010; Hellings and Gallagher, 1992; Burdick and Konisky, 2003). On the other hand, although Bart and Hartman (2002) found salinity reduces rhizome and seed viability, they were unable to use salinity to predict areas to which *Phragmites* could spread clonally.

The ability of *Phragmites* clones to survive higher salinities could explain why *Phragmites* has been invading higher salinity marshes so successfully over the past hundred years. Some of the most rapid expansion rates of *Phragmites* have been observed in mesohaline marshes with salinities ranging between 5 and 18ppt; however, significant expansion rates were also observed in fresh (oligohaline) and salty (polyhaline) marshes (Burdick and Konisky, 2003). This observation supports results from Chambers et al. (1999) who was unable to find clear evidence that recent changes in *Phragmites* abundances differed significantly between ogliohaline and mesohaline tidal marshes and suggests that *Phragmites* is at least somewhat tolerant of the salinity ranges typical of most North American tidal marshes. Although Burdick and Konisky (2003) found a correlation between increased salinity and decreased *Phragmites* growth, Konisky and Burdick (2004) later noted that this correlation did not occur consistently, suggesting that salinity was not the only important influence of *Phragmites* growth. For example, Chambers (1997) points out that it is the combination of flooding and elevated salinity that affects plant vigor. It should also be noted that even under stressful conditions, anthropogenic impacts that increase freshwater inputs or nutrient loads, as discussed later, could help *Phragmites* overcome the negative effects of high salinity environments. Inconsistencies in these inputs could also lead to inconsistencies in the correlation between salinity and *Phragmites* growth or expansion.

2.3b Flooding

Hellings and Gallagher (1992) found that *Phragmites* growth parameters decrease with increased flooding level. Tulbure and Johnston (2010) also found water depth affected the degree of *Phragmites* cover. Burdick and Konisky (2003) proposed that a possible reason for the effect of water level on plant growth could be based on alteration to the soil substrate, where frequent flooding results in anoxic, low redox conditions. This finding is congruent with findings by Chambers (1997) who also found that increased flooding in combination with increased salinity levels could enhance pore water sulfide concentration, thereby reducing plant vigor. The frequency of flooding was also shown to effect organic matter accumulation with less frequent flooding leading to higher organic matter accumulation (Shafer et al., 2007).

2.3c Nutrients and Soil Characteristics

Tulbure and Johnston (2010) found that *Phragmites* cover was significantly higher on sandy as compared to organic and clay soils; however, they also note that this pattern of establishment could be due solely to the fact that *Phragmites* frequently invades newly exposed substrates, which are often characterized by sandy soils. Minchinton and Bertness (2003) found that *Phragmites* grows poorly under low nutrient conditions and excess nutrients seem to benefit *Phragmites*, making it a more efficient competitor for other limiting resources (Chambers et al., 1999). However, there does not appear to be any association between the spread of *Phragmites* and soil phosphorus concentration (Chambers, 1997).

In general, it seems that *Phragmites* is able to tolerate most soil conditions (Tulbure and Johnston, 2010), which suggests that soil characteristics are not a major limiting factor to *Phragmites* establishment or development. On the other hand, the evidence presented above suggests that *Phragmites* prefers disturbed, oxidized soils and is limited by anoxic soils or by those with high sulfide concentrations.

Anoxia results in decreased nutrient uptake by isolated rhizome fragments (Chambers, 1997) and can lead to inefficient respiration if the rhizosphere is not supplemented with pressure ventilation (a method of oxygenating roots) by larger clones; therefore, anoxia typically prevents initial establishment by rhizome fragments, but has limited effects on the expansion of clones, which are capable of aerating their roots (Bart and Hartman, 2002). Anoxia and sulfide concentration are closely related because anaerobic respiration reduces sulfate to sulfide (Chambers, 1997). High sulfide concentrations are likely to decrease ATP production and ammonium uptake by plants (Bart and Hartman, 2002). Therefore, elevated pore water sulfide concentrations can inhibit nitrogen cycling in the rhizosphere and inhibit nitrogen uptake and stunt growth in some *Phragmites* populations (Chambers, 1997).

High sulfide ion and salinity concentrations are toxic, reducing nutrient uptake and stressing osmoregulatory processes (Burdick and Konisky, 2003). This seems to limit growth in small isolated *Phragmites* clones, but does not seem to significantly limit rhizome propagation or productivity in larger *Phragmites* clones which can extend taproots to reach deeper, less saline water (Chambers, 1997). This, in combination with the ability of larger clones to ventilate their roots with atmospheric oxygen, is what allows *Phragmites* to tolerate a wide range of soil conditions (Tulbure and Johnston, 2010).

Since sulfide concentrations are one of the few factors shown to significantly inhibit *Phragmites* growth, bulk density is a soil feature that is also likely to affect *Phragmites*. High bulk density has been shown to decrease sulfide concentrations thus increasing nutrient availability and increasing plant productivity and recruitment (Schrift et al., 2008).

Section 2.4: Disturbance and Anthropogenic Alterations

Anthropogenic modifications of coastal marshes have produced favorable environmental conditions for the establishment, growth, and expansion of *Phragmites* and are a leading explanation of its rapid spread over the past two centuries (Minchinton and Bertness, 2003; Burdick and Konisky, 2003; Tulbure and Johnston, 2010). These modifications include increased nutrient concentrations, land use changes, exposed mineral soil, and changes in hydrology (Tulbure and Johnston, 2010). Activities that expose bare substrate and increase nutrient inputs create prime habitat for *Phragmites* (Chambers et al., 1999; Kirk Berquist and Priest, 2003). Unfortunately, even disturbance caused by restoration activities (discussed more thoroughly in section 2.6) can enhance the spread of *Phragmites* via movement of equipment and soil (Meyerson, Lambert, and Saltonstall, 2010). Similarly, development activities that disturb soils (especially those involving marsh filling or the construction of channels) and alter hydrology can increase the favorability of an area for *Phragmites* establishment (Burdick and Konisky, 2003). Furthermore, any activities that lower salinity at established sites (Bart and Hartman, 2002) or restrict tidal flushing (Chambers et al., 1999) can also increase the spread or chance of *Phragmites* establishment into otherwise saline areas (Bart and Hartman, 2002). These impacts are relevant in Coastal Louisiana because many Gulf Coast and Southwest wetlands are already under significant stress from hydraulic alterations, pollution, and development; subsequently, they have become affected by *Phragmites* invasions (Meyerson, Lambert, and Saltonstall, 2010).

Section 2.5: Potential Effects of *Phragmites* Establishment on Wetland Function

Wetland functional capacity is defined as the ability of a wetland to perform functions relative to the ability of reference standard wetlands to complete similar functions (Shafer et al., 2007). The impact of *Phragmites* establishment on the functional equivalency of tidal wetlands is controversial. Quantification of this impact depends on the condition of the wetland prior to *Phragmites* establishment and on varying opinions regarding what the intended function of a particular wetland should be. Results from Kirk, Berquist, and Priest (2003) suggest that *Phragmites* lacks the potential to enhance or maintain functional equivalency in comparison to other marsh species. However, Chambers, et al. (1999) argue that the perception that the conversion of regularly flooded tidal marshes to those dominated by *Phragmites* results in reduced functionality is not adequately supported to date by research. It is difficult to determine the impact of *Phragmites* on functional equivalency because it affects such a broad range of ecosystem services: water quality, biodiversity, trophic transfer, and sediment trapping/stabilization (Chambers et al., 1999).

There are some distinct disadvantages to *Phragmites* establishment. One of the most well documented disadvantages is the reduction of overall plant diversity associated with *Phragmites* dominance and formation of monotypic stands (Tulbure and Johnston, 2010; Chambers, 1997; Chambers et al., 1999, Minchinton and Bertness, 2003). Replacement of native vegetation with *Phragmites* propagules can lead to habitat conversion, reducing faunal richness and abundance – especially for migratory birds (Chambers et al., 1999; Minchinton and Bertness, 2003). Despite the drawbacks that *Phragmites* establishment can have on biodiversity, *Phragmites* has been associated with several environmental and economic benefits. For example, Minchinton and Bertness (2003) indicate that the total production of marsh plants actually increases. Furthermore, *Phragmites* has been shown to alter soil properties and nutrient pools (Tulbure and Johnston, 2010) and significantly increase the functional value of wetlands in terms of water quality through its ability to reduce excess nutrients and heavy metals from the wetlands that it occupies (Chambers et al., 1999). Historically, *Phragmites* has provided economic benefits including goods such as roofing materials and services such as water filtration (Meyerson, Lambert, and Saltonstall, 2010).

One of the reasons that the negative impact of *Phragmites* on functional capacity is debatable is because in spite of the problems it causes, *Phragmites*-induced ecosystem alterations can greatly benefit the wetland function of shoreline stabilization; *Phragmites* can increase sediment trapping and biomass production relative to other wetland species. *Phragmites'* elaborate rhizome system and substantial belowground biomass provides a high potential for sediment trapping (Hellings and Gallagher, 1992). This could lead to an increase in sediment accretion and substrate stabilization (Chambers et al., 1999). This could be seen as an advantage in areas experiencing rapid subsidence and/or sea-level rise – such as coastal Louisiana, which according to estimates by Edwards and Proffit (2003), could be losing up to about 40 square miles of wetland habitat every year. On the other hand, increased sediment accretion could decrease water circulation leading to habitat loss for estuarine species dependent on planktonic or nektonic life stages (Hellings and Gallagher, 1992).

Another debatable attribute of *Phragmites* is the production and accumulation of dead organic material. Although enhanced accumulation of organic material (accretion) leads to increases in wetland surface elevation, Burdick and Konisky (2003) showed that such buildup can promote fires, which can kill plants and alter nutrient cycling, or generate wrack that can smother shorter wetland grasses (like *Spartina* or *Juncus* species) and create space for *Phragmites* expansion.

The ways that *Phragmites* influences ecosystem function are debatable and some, such as nutrient exchange and trophic transfer, are either understudied or unclear (Chambers et al., 1999). Given these various effects that *Phragmites* can have on ecosystem services and wetland function, resource managers should weigh the potential costs and benefits of *Phragmites* establishment in consideration with the wetland functions desired on a case-by-case basis. It is for this reason that Hellings and Gallagher (1992) recommend the management goal of control – as opposed to eradication.

Section 2.6: Wetland Construction and Beneficial Use Practices

Disturbance in wetlands can occur naturally but can also result from anthropogenic impacts. Even attempts to restore or construct wetland areas can result in significant levels of site disturbance (Meyerson, Lambert, and Saltonstall, 2010). Beneficial use (BU) or the utilization of dredged sediments as a resource material is an example of a method that can be used for the creation or restoration of intertidal wetlands (Bolam and Whomersley, 2005). The U.S. Army Corps of Engineers (1986) defines beneficial use as: "all productive and positive uses of dredged material, which covers broad use categories ranging from fish and wildlife habitat development to human recreation, to industrial/commercial uses" (Streever, 2000). Different goals for BU also mean that BU projects are unique to the project area, will involve different methodologies, and will have various effects on the environment and environmental variable. The context of the discussion of BU in this thesis is restricted marsh construction or restoration practices; however, the results and impacts of this usage still vary based on individual project goals. General changes to the environment with the addition of dredged material additions can be viewed in table 1.

Table 1: Changes in environmental variables with dredged material additions and implications of such changes.

Changes in Environmental Variables with Dredged Material Additions			
Variable	**Typical Change**	**Effect**	**Citation**
Elevation	Increase	Affects nutrient availability and hydro period	Schrift, Mendelssohn, and Materne, 2008
Exposed Substrate	Increase	Provides opportunity for establishment	
Physical Heterogeneity	Decrease	Affects hydro period and vegetation distributions	Callaway, 2008; Streever, 2000
Marsh Edge	Decrease	Marsh edge is the most productive area of wetlands	Streever, 2000
Hydro period	Decrease	Increase the component of freshwater, invasive, or upland plant species	Shafer et al., 2007
Sulfides	Decrease	High sulfides limit nutrient uptake by plants and thus limit productivity	Schrift, Mendelssohn, and Materne, 2008
Bulk Density	Increase	High bulk density can be a proxy for soil mineral content and therefore generally increases plant productivity	Edwards and Proffit, 2003; Schrift, Mendelssohn, and Materne, 2008
Organic Matter	Increase		Edwards and Proffit, 2003

Due to high levels of initial disturbance associated with excavation and construction of wetland sites, invasion by exotic or unwanted opportunistic plant species are often a problem at restoration sites (Callaway, 2005; Kirk, Berquist, and Priest, 2003). A study by Minchinton and Bertness (2003) revealed that *Phragmites* typically outcompetes other plants in disturbed settings. They found that as the severity of disturbance increased, the aboveground biomass increased for *Phragmites* while decreasing the aboveground biomass of matrix vegetation. For this reason, the presence of *Phragmites* is generally considered an indicator of site disturbance or stress (Shafer and Schmidt, 2007).

Despite the advantages that site alterations with BU could have for *Phragmites* establishment, other characteristics could limit the capacity for *Phragmites* to settle such area. For example, alterations have been shown to reduce tidal flows or hydro period (Shafer et al, 2007), which is important because seldom flushed marshes can generate high substrate salt concentrations (Schrift, Mendelssohn, Materne, 2008) and limit the potential for *Phragmites* establishment. This decrease soil tidal flow can also lead to less anoxic soils and thus a decrease in soil sulfide concentration. In fact Schrift, Mendelssohn and Materne (2008) found soil sulfide concentrations, an attribute shown to limit *Phragmites* productivity, sharply decreased with the addition of sediment. Regardless of the means in which BU promotes *Phragmites*, the establishment of *Phragmites* in restoration sites has the potential to alter ecosystem function (Kirk, Berquist, and Priest, 2003) and should therefore be of concern for project or resource managers on a case-by-case basis.

Chapter 3: Methods and Models

Section 3.1: Data Description and Information

Two types of data were collected and analyzed for the purposes of this study. The first type, species-specific data, was obtained from a review of current scientific literature and used to develop ranges of environmental variables that are conducive to *Phragmites* establishment. The second, geo-referenced plot-level data, obtained through a regional database was used to analyze differences in environmental conditions at reference (natural) sites and at those invaded by *Phragmites.* Data acquired from scientific studies and state databases were assumed accurate unless noted otherwise. For example, if the database fails to identify the presence of *Phramites* for a particular site, then it is assumed that *Phragmites* is not actually present at that site.

Species-specific data was obtained through an exploration of current scientific literatures that discuss the relationships between *Phragmites* and environmental variables. Through this research, ranges of environmental conditions (salinity, water level, and percent time flooded) tolerated by *Phragmites* were compiled and used to construct the models displayed in the predictive model subsection of this chapter. Literature values or ranges were established for pH, salinity, sulfide concentration, and water level, and reflect the environmental conditions that scientific studies have identified as suitable for the establishment of *Phragmites*. The literature also identified porewater sulfide concentration as an important variable (Bart and Hartman, 2002; Burdick and Konisky, 2003; Chambers, 1997), but conclusive or approximate ranges were unavailable for this variable

The second type of data, plot-level data, serves as a baseline for the environmental conditions for all sites examined across the Louisiana coast. Ecosystem-level data was collected from transects and monitoring points within the Coastwide Reference Monitoring System (CRMS) network. The CRMS network classifies sites by the dominant vegetative zone. Vegetation classifications are determined by the dominant plant types, cover, and saline concentration and are classified as Saline, Intermediate, Brackish, Fresh, or Swamp (Figures 3a and 3b).

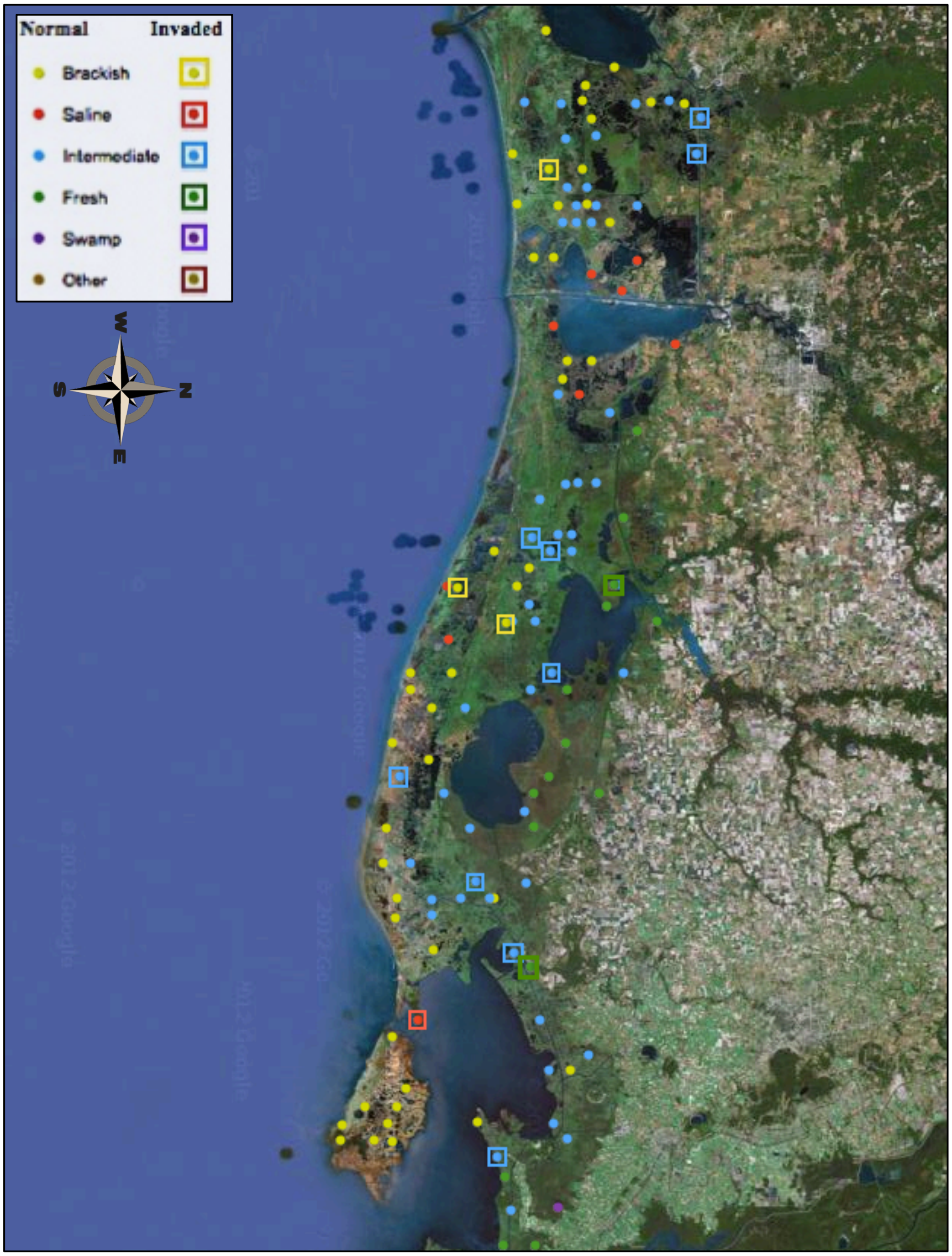

Figure 3a: West-Louisiana. The location of CRMS monitoring stations, the vegetative type at each station (brackish, saline, intermediate, fresh, or swamp), and whether or not Phragmites australis *has been observed.*

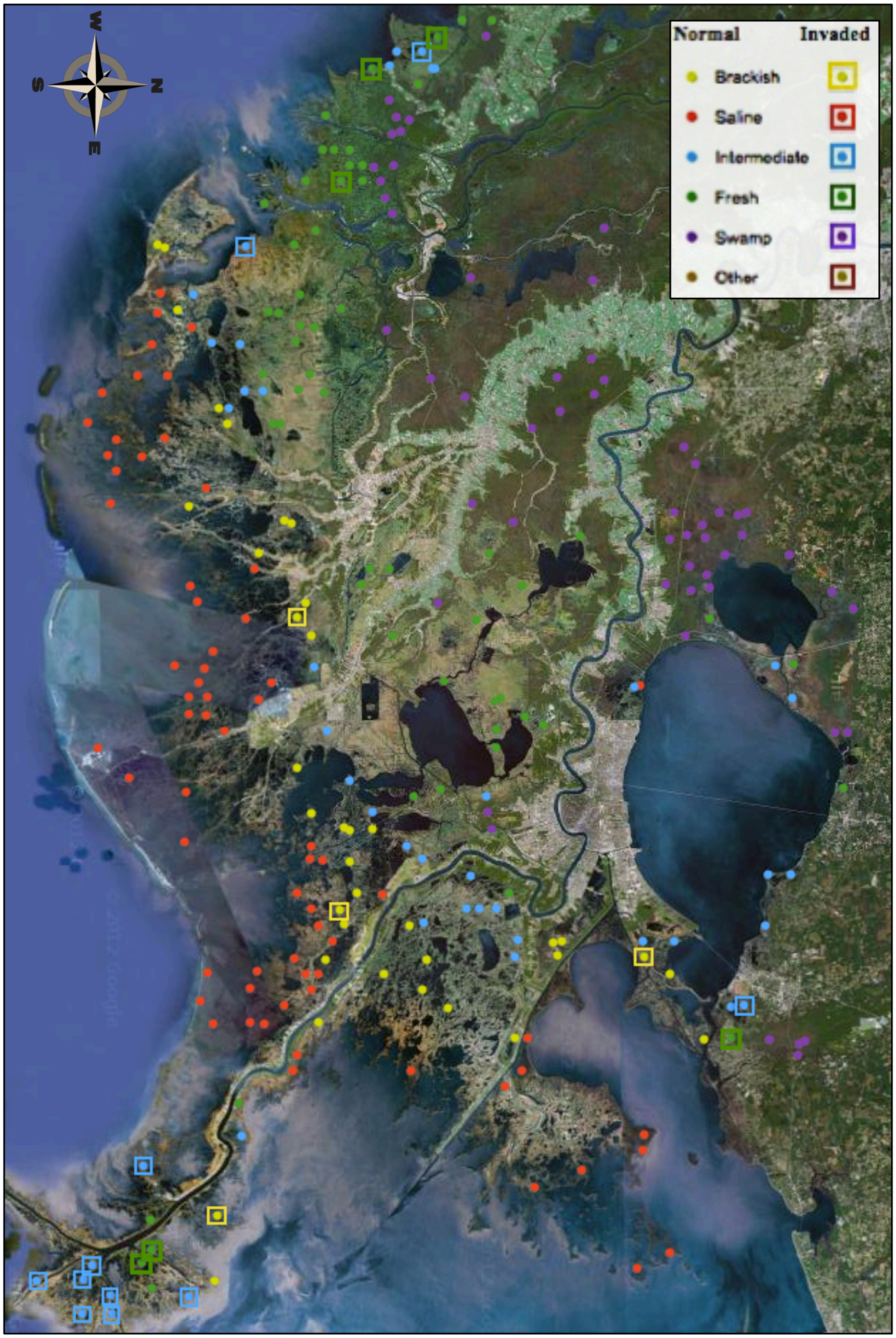

Figure *3b: East-Louisiana. The location of CRMS monitoring stations, vegetative types, and observed populations of* Phragmites australis.

The CRMS network contains 390 monitoring stations across the entire Louisiana coast. CRMS collects five different types of data: (1) hydrographic data, which is updated hourly from remote sensors and includes water level, water temperature, specific conductance, and salinity; (2) accretion data, updated every six to twelve months; (3) vegetation data, which is assessed annually via transects within sites and includes vegetation species, relative abundance and dominance of species in the area, and vegetative community type; (4) soil properties data, collected when the site is established, includes wet and dry soil pH, soil specific conductance, soil salinity, soil moisture content, bulk density, percent organic matter, and wet and dry volume; and (5) surface elevation data, collected every 6-36 months. All CRMS data is made publicly available through the Coastal Protection and Restoration Authority of Louisiana (CPRA) and can be downloaded on a site-by-site basis from the CRMS spatial viewer[1] or as meta-data files via CPRA's website[2].

The vegetative and soil properties data used in this analysis were downloaded directly from CPRA's website. Hydrographic data, specific to the project, were obtained through special request through the CRMS website and included daily data for all CRMS sites.

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[1] http://sonris-www.dnr.state.la.us/gis/agsweb/IE/JSViewer/index.html?TemplateID=21

[2] http://www.ocpr.louisiana.gov/crm/coastres/monitoring.asp

Section 3.2: Data Management

3.2a Hydrographic data

Daily hydrographic data for each site was obtained for salinity (ppt), water level (ft), and water temperature (^{o}C), each with a daily average, minimum, and maximum. From this data, extreme daily high (max_max) and low (min_min) metrics were created by averaging the 30 highest maximums and the 30 lowest minimums for each variable at each site. This was done in order to examine the impact that extremes had on *Phragmites* presence and growth parameters, in comparison to 'normal' ranges of variables. All variable metrics (average, minimum, maximum, min_min, and max_max) were averaged across the entire year leaving one set of hydrographic data for each CRMS site. Sites that were missing a significant amount of data (about 3 months) throughout the year were eliminated based on a data completeness level of 75%, which is the same metric used by the USGS in their analyses of CRMS data (personal communication Piazza 2012). After data compression, the final variable, percent time flooded (percentage of the year the site was flooded) was added for each site. Data for this final variable was not available on the CRMS website but was made available by data managers upon request.

3.2b: Vegetation Data

CRMS sites were classified by three different metrics: *Phragmites* presence (yes/no), average height, and percent cover. All sites containing *Phragmites* received a "yes" for *Phragmites* presence and values from the data table were given to the dependent metrics: average height and percent cover. Sites indicated by the CRMS data to be free from invasion by *Phragmites*, received a "no" for *Phragmites* presence, 0.00 for average height, and 0.00% for percent cover.

3.2c Soil Properties Data

The CRMS network collects soil data via a series of soil cores taken at each site; three soil cores are taken throughout the site and analyzed every 4 cm (up to a depth of 24 cm). The cores were analyzed for soil pH, specific conductance, soil salinity, soil moisture, bulk density, and organic matter. In order to compress this data, mean values for the 3 soil cores were calculated for each depth at each site. Since *Phragmites* has a substantial belowground biomass and elaborate rhizome system (Hellings and Gallagher, 1992), its roots are likely to extend with equal density well below 24 cm. Due to this fact, the values of examined variables are likely to be equally important in predicting *Phragmites* presence at each soil depth; therefore, values for each soil depth (0-24 cm) were averaged, similar to the methods of Chambers (1997). Stations lacking depth ranges were removed from the analysis.

Although data was available for specific conductance, specific conductivity was removed from the model because it is another measure of soil porewater ion concentration and therefore is a similar metric to soil salinity. This was confirmed by regressing soil salinity against specific conductance, which demonstrated significant tight, linear coupling between the two variables. Specific conductivity and soil salinity correlated almost perfectly with an R^2 value of 0.9990 and a significance of less than 0.0001 (Figure 4). Failure to remove this variable from the models would skew the model by disproportionally weighting the importance of both specific conductivity and soil salinity variables.

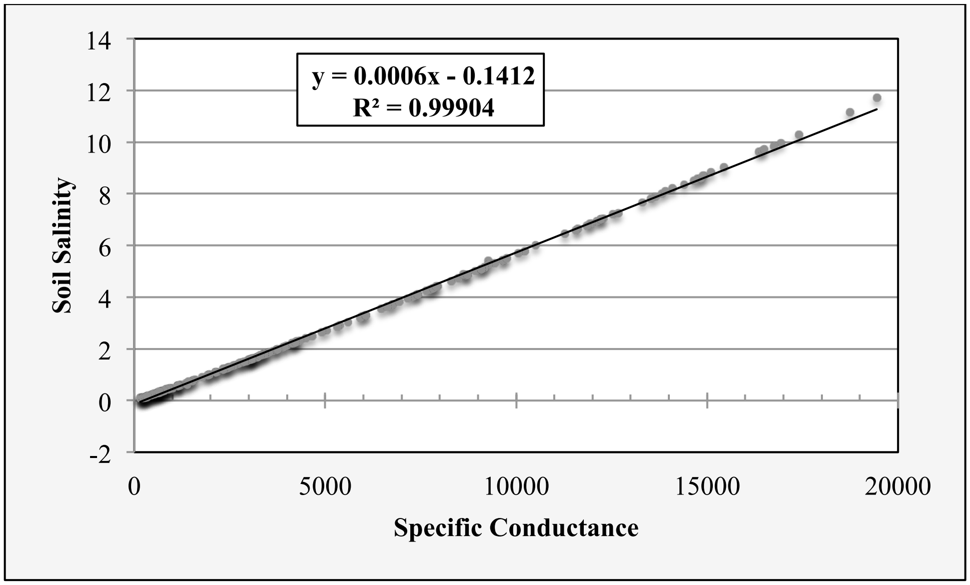

Figure 4: Correlation between specific conductance and soil salinity (R^2 = 0.999; P< 0.0001).

3.2d Master Data Set

Microsoft Excel was used to combine and manage all data sets. The master data set was compiled by organizing relevant hydrographic, vegetation, and soil property data for each site. After removing sites with insufficient data or data, 213 out of the original 390 sites (54.6%) remained: only 36 of these sites (16.9%) contained *Phragmites*.

Section 3.3: Predictive Model – Predicting the Presence of *Phragmites*

The predictive model was developed as a tool to predict whether or not *Phragmites* is likely to occur at a given site by comparing the ranges of species-specific data from the literature to plot-level data across each site. Variables examined in this model included salinity, water level, and temperature. The literature also identified sulfide concentrations and soil pH as limiting factors in *Phragmites* success; however, these variables were not included in this study. Sulfide concentration was not examined because plot-level data was not available for the sites examined. The variable pH was not examined because all CRMS sites fell within the preferred range of *Phragmites* indicated by the literature; therefore, including or restricting pH as a variable has no effect on the outcome of the predictive model.

The predictive model selects sites for which values for salinity, water level, and temperature fall within the ranges determined from the literature. Sites that met these criteria were determined suitable habitat for *Phragmites* and therefore a “yes” was given for *Phragmites* establishment at each site. These “yes” and “no” delineations were then compared to “actual” *Phragmites* distributions. Although the predictive model examines salinity, water level, and temperature, the model was simplified by breaking down these components into individual sub-models, which were then combined to yield results. Sub-models were constructed for each of the examined parameters using simple IF/THEN metrics in Microsoft Excel; for each site, if the ecosystem-level ranges for 'variable x' fall within the ranges for that variable outlined by the species-specific data, then the model generates a 1. *Phragmites* was predicted as 'present' in the cumulative model if all sub-models generated a 1 for a given site. The salinity sub-model uses a threshold of 21 ppt. If a given site exceeds 21 ppt then the model predicts that conditions were too harsh for *Phragmites* establishment, but predicts that *Phragmites* can establish in lower salinities. The water level sub-model uses a low threshold of -0.33 and a high threshold of 0.16 meters. If the typical water level for a given site falls within this range then *Phragmites* is predicted to be able to establish, but not if the range for water level and a given site is outside of this threshold. The inundation sub-model uses a low threshold of 25% time flooded and a high threshold of 67% time flooded. Any sites with ranges between these two values will predict that *Phragmites* will be able to establish. Other sites assume that conditions are two dry or two inundated for *Phragmites* establishment.

The robustness of the model – the degree to which predicted *Phragmites* distribution correlates with actual distribution – was determined by comparing the predicted results to the actual distribution of *Phragmites* indicated by the vegetation data. Correlation was determined by running an ANOVA in Stata 9 using a confidence level of 0.05.

Section 3.4: Correlation Model – Identifying the Environmental Variables Most Correlated with *Phragmites* Presence and Productivity

The goal of the second model was to identify variables that significantly affect the distribution or productivity of *Phragmites* within the CRMS network. Correlation between environmental variables and *Phragmites* distribution was determined through a logistic regression between environmental variables and *Phragmites* presence (yes/no). The presence or absence of *Phragmites* was used to determine significant differences in environmental variables between sites containing *Phragmites* and reference sites that did not.

The correlation between environmental variables and *Phragmites* productivity was conducted through an OLS regression of the independent environmental variables against the dependent variables (percent cover and average height), which serve as proxies for *Phragmites* productivity. The selection of these dependent variables is similar to those of a study by Chambers (1997), in which species presence and height were selected as the criteria to use to determine the influence of soil water chemistry on potential *Phragmites* spread. Percent cover demonstrates the amount of horizontal vegetative growth that *Phragmites* population's display. By comparing how percent cover changes between different sites, insight can be gained into how different combinations and ranges of environmental variables can promote or restrict vegetative growth by

Phragmites. Comparisons between the average heights of *Phragmites* populations at different sites can also provide insight into how environmental variables affect *Phragmites* productivity because average height is a proxy for primary productivity within individual *Phragmites* populations. For example, if a population has higher average height or higher percent cover, then it can be assumed that the ranges of environmental variables at that site are more conducive to *Phragmites* growth.

Statistically insignificant variables were eliminated in a step-wise fashion leaving only the variables that were most significantly correlated with the dependent variables – *Phragmites* productivity and distribution. Results of the step-wise regression were verified using a correlation matrix showing correlations of all variables (independent and dependent) with each other. All regressions in this model were conducted using STATA 9 or JMP statistical packages and a confidence level of 95% was used to assess all results for statistical significance.

Chapter 4: Results

CRMS data shows that *Phragmites* is present in Coastal Louisiana and has primarily invaded fresh to intermediate marshes, but is also capable of establishment in saline wetlands under certain conditions. Of the 213 CRMS sites examined, 36 sites (about 17%) contained established populations of *Phragmites* (Table 2). The majority of identified *Phragmites* populations occurred in intermediate wetlands, but there were also notable populations within fresh and brackish wetlands. Only one saline wetland within the CRMS network was found to support populations of *Phragmites* and no *Phragmites* populations were identified in swamps. Overall, *Phragmites* has invaded 34.48% of intermediate sites, 14.58% of brackish, 30.77% of fresh, and 2.00% of saline marshes (Table 2).

Table 2: Identification of the number of Phragmites *populations in each vegetative type. Reference wetlands are those transects free from invasion.*

	Saline	Intermediate	Brackish	Fresh	Swamp	All
Invaded	1	20	7	8	0	36
Reference	49	38	41	18	30	176*
Total	50	58	48	26	30	212*
* One of the 213 total sites was not classified into any of these categories.						

Section 4.1: Predictive Model

The predictive model successfully predicted *Phragmites* presence or absence in 74.18% of the CRMS sites. The model successfully predicted *Phragmites* presence in invaded sites 3.29% of the time, gave a false positive 12.21%, successfully predicted *Phragmites* absence in reference sites 70.89%, and gave a false negative 13.62% of the time (Table 3).

Although the model accurately predicted *Phragmites* presence or absence 74.18% of the time, when run independently, the components of the model (Salinity, % Time Flooded, and Water Level) varied in their ability to accurately predict *Phragmites* presence (Table 4). Water level is a more efficient predictor of *Phragmites* presence than salinity and percent time flooded (Table 4); however the results of the full predictive model are still more robust when all three variables are included, an increase in accuracy from 64.79% to 74.18% (Tables 3 and 4). This result implies that suitable environments for *Phragmites* establishment are defined by more than one abiotic parameter and suggest that increased incorporation of these variables into the model will lead to an increase in the robustness of the model.

Table 3: Predictions of Phragmites *presence by the full predictive model. n=213.*

Prediction Model		Total Accuracy = 74.18%		
	Yes	**False (+)**	**No**	**False (-)**
# Observed	7	26	151	29
Percentage	3.29%	12.21%	70.89%	13.62%

Table 4: Predictive model components (salinity, percent flooded, and water level) displaying the distribution of predictions by each model with correct predictions in the yes or no category and incorrect predictions displayed as false negatives or false positives. Cells display the number of sites predicted (percentage of sites predicted) where n=213.

Model Component	Yes	False (+)	No	False (-)	Component Accuracy
Salinity	36 (16.90%)	168 (78.87%)	9 (4.23%)	0 (0.00%)	21.13%
% Flooded	22 (10.33%)	122 (57.28%)	55 (25.82%)	14 (6.57%)	36.15%
Water level	11 (5.16%)	50 (23.47%)	127 (59.62%)	25 (11.74%)	64.79%

Section 4.2: Correlation Model

Thirteen of the 21 environmental variables examined were normally distributed and significantly correlated with the presence of *Phragmites*: average salinity, minimum salinity, min_min salinity, maximum salinity, average water level, maximum water level, average temperature, minimum temperature, maximum temperature, soil salinity, soil moisture, bulk density, and organic matter (Table 5). Other variables were neither normally distributed nor significantly correlated with *Phragmites* presence. Eighteen out of 21 variables were significantly correlated with *Phragmites* height. The only four not significantly correlated were max_max salinity, minimum water level, percent flooded, and soil pH (Table 6). Seventeen out of 21 variables were significantly correlated with *Phragmites* percent cover. Those not significantly correlated were the same as those for *Phragmites* height with the addition of min_min Water Level (Table 6).

Table 5: Results from correlation between Phragmites *presence and environmental variables. * indicates significance at alpha level of 0.05 and ** indicates significance at an alpha level of 0.01.*

Environmental Variable		**p-value**
Salinity:	Average	0.0018**
	Minimum	0.0016**
	MinMin	0.0024**
	Maximum	0.0034**
	MaxMax	0.1450
Water Level:	Average	0.0390*
	Minimum	0.3677
	MinMin	0.0940
	Maximum	0.0064**
	MaxMax	0.1728
Temperature:	Average	<.0001**
	Minimum	<.0001**
	MinMin	0.0558
	Maximum	0.0071**
	MaxMax	0.2461
% Flooded		0.9726
Soil pH		0.7049
Soil Salinity		0.0021**
Soil Moisture		0.0004**
Bulk Density		0.0002**
% Organic Matter		0.0049**

Table 6: Results from bivariate regression; correlation between environmental variables and the dependent variables Phragmites *height and percent cover. * indicates significance at alpha level of 0.05 and ** indicates significance at an alpha level of 0.01.*

		Average Height	**% Cover**
Environmental Variable		**p-value**	**p-value**
Salinity:	Average	0.0012**	0.0130*
	Minimum	0.0009**	0.0095**
	MinMin	0.0026**	0.0172*
	Maximum	0.0035**	0.0352*
	MaxMax	0.2192	0.7758
Water Level:	Average	0.0026**	0.0063**
	Minimum	0.1238	0.1111
	MinMin	0.0500*	0.0657
	Maximum	<.0001**	0.0007**
	MaxMax	0.0141*	0.0328*
Temperature:	Average	<.0001**	<.0001**
	Minimum	<.0001**	<.0001**
	MinMin	0.0103*	0.0023*
	Maximum	<.0001**	0.0003**
	MaxMax	0.0401*	0.1145
% Flooded		0.3146	0.3069
Soil pH		0.3853	0.4508
Soil Salinity		0.0019**	0.0094**
Soil Moisture		<.0001**	<.0001**
Bulk Density		<.0001**	<.0001**
% Organic Matter		0.0013**	0.0025**

Sites with and without *Phragmites* had significantly different abiotic conditions (Figures 5 and 6). The two variables most strongly correlated with *Phragmites* cover and average height were minimum salinity and soil bulk density (Tables 6-7). The coefficient for minimum salinity (-0.12) indicates a negative correlation with *Phragmites* presence. This correlation was significant with a p-value of 0.005 (Table 7a). Minimum salinity was also negatively correlated with the average height of *Phragmites*, with a coefficient of -3.46, and negatively correlated with percent cover, with a coefficient of -0.58 (Tables 7b-c). The coefficient for bulk density (2.81) was positively correlated with *Phragmites* presence and had a significant p-value of 0.002 (Table 7a). Bulk density was also positively correlated with the average height of *Phragmites*, with a coefficient of -156.67, and positively correlated with percent cover, with a coefficient of 32.89 (tables 7b-c).

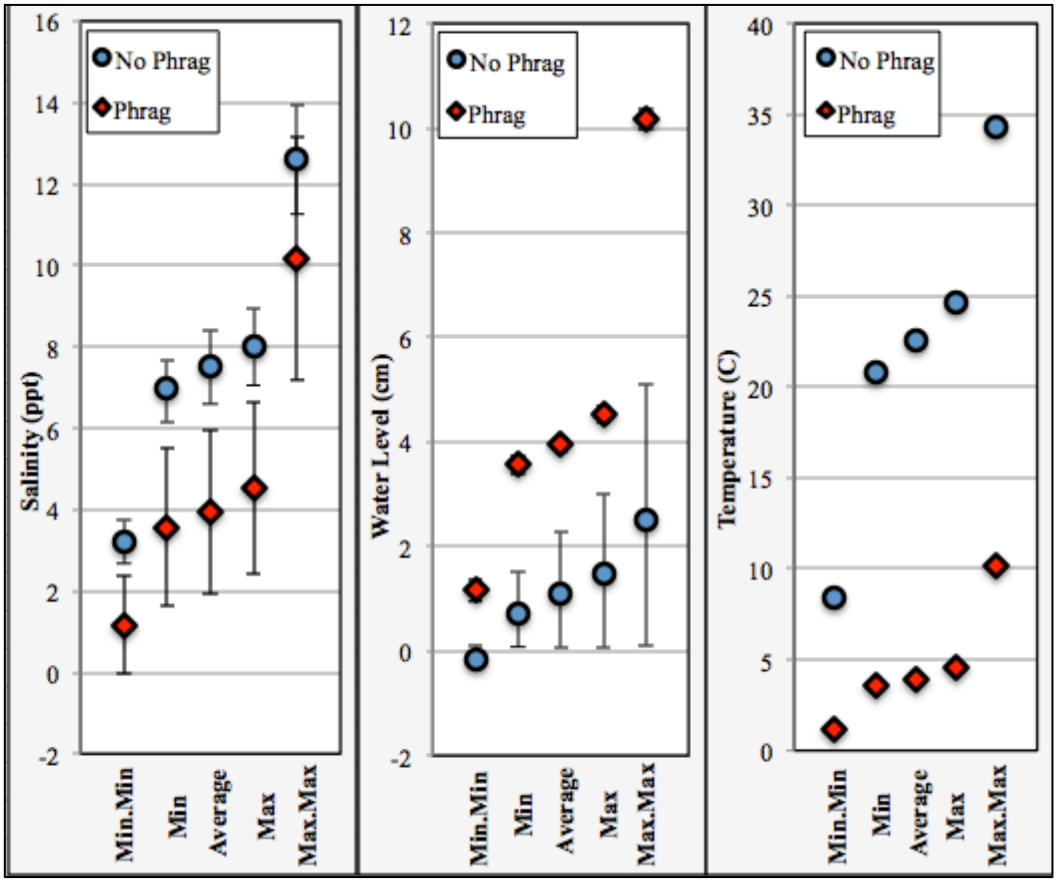

Figure 5: Salinity, water level, and temperature relationships with the presence of Phragmites. *Error bars represent 95% confidence intervals.*

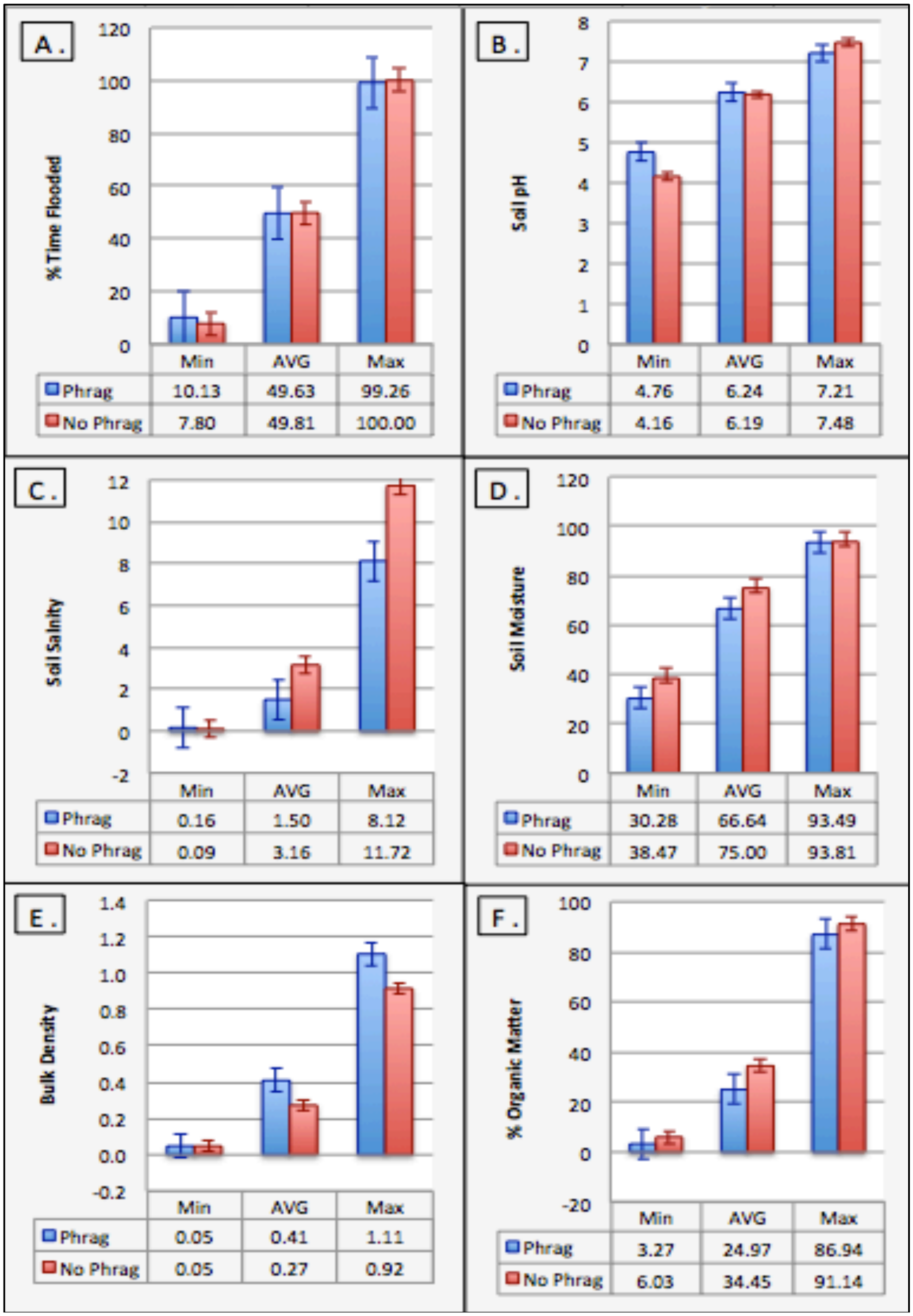

Figure 6: Comparison between environmental variables for sites invaded by Phragmites *(Phrag) and those without* Phragmites *(No Phrag). Differences are significant for Soil Salinity, Soil Moisture, Bulk Density, and Organic Matter (figures 3.C - 3.F). Error bars represent 95% confidence intervals.*

Tables 7a-c: Final regression models across all dependent variables (a) Phragmites *presence, (b) average height of* Phragmites*, and (c) % cover of* Phragmites*. The least significant variables were removed in a stepwise fashion leaving only minimum salinity and bulk density, the variables that were still individually significant when placed in the same model.*

(7a) Binary: Final Logistic Regression

Logistic Regression: Phrag. Binary				Number of Observations = 208		
Chi-squared = 21.73				Prob > chi-squared = 0.0000		
Log Likelihood = -81.7728				Pseudo R-squared = 0.1225		
	Coefficient	Std. Error	z	P>z	[95% Conf. Interval]	
Min.Salinity	-0.1184	0.0422	-2.81	0.005	-0.2054	-0.0402
BulkDensity	2.8123	0.8872	3.17	0.002	-1.1326	4.5037
_cons	-1.9338	0.4118	-4.70	0.000	-3.0420	1.0733

(7b) Average Height: Final Regression

Source	Sum of Squares	Degree of Freedom	Mean Square	Number of Observations = 208 F(2,205) = 19.22		
Model	286881.50	2	143440.7	Prob > F = 0.0000		
Residual	1530265.33	205	7454.7	R-squared = 0.1579		
Total	1817146.83	207	8778.5	Adjusted R-squared = 0.1497		
				Root MSE = 86.399		
	Coefficient	Std. Error	t	P > t	[95% Conf. Interval]	
Min.Salinity	-3.4552	0.9980	-3.46	0.001	-5.4229	-1.4874
BulkDensity	156.6677	30.5417	5.13	0.000	96.4516	216.8838
_cons	11.6522	12.6392	0.92	0.358	-13.2672	36.5716

(7c) Percent Cover: Final Regression

Source	Sum of Squares	Degree of Freedom	Mean Square	Number of Observations = 199 F(2,205) = 15.15		
Model	11041.2308	2	5520.6154	Prob > F = 0.0000		
Residual	71407.4172	196	364.3236	R-squared = 0.1339		
Total	82448.6480	198	416.4073	Adjusted R-squared = 0.1251		
				Root MSE = 19.087		
	Coefficient	Std. Error	t	P > t	[95% Conf. Interval]	
Min.Salinity	-0.5802	0.2232	-2.60	0.010	-1.0204	-0.1399
BulkDensity	32.8907	6.7995	4.84	0.000	19.4810	46.3003
_cons	0.6720	2.8591	0.24	0.814	-4.9665	6.3106

Chapter 5: Discussion

Section 5.1: Predictive Model

The predictive model only included salinity, water level and percent time flooded. Although several significant variables were left out, the predictive model should still be a strong predictor of *Phragmites* presence because inundation and salinity are the factors that strongly affect vegetative zonation within tidal wetlands (Hellings and Gallagher, 1992).

The fact that the predictive model correctly predicts sites without *Phragmites* 70.89% of the time but only correctly predicts sites that do have *Phragmites* 3.29% of the time implies that it is easier to predict wetlands with abiotic conditions that are too harsh for *Phragmites* than it is to predict which wetlands are susceptible to *Phragmites* establishment (Table 2). The ability for the model to predict wetlands without *Phragmites* better than it predicts wetlands with *Phragmites* could be the result of the large number of sites without *Phragmites* entered as binary inputs into the predictive model. However, it could also be related to the stage of invasion at a given site, the random probability of a site receiving viable seeds, rhizomes, or clones, and/or to genetic differences between different *Phragmites* populations examined in this study.

5.1a: Multi-Stage Invasion Complication

The inability of the model to accurately predict habitat that *Phragmites* can occupy is likely due to the fact that *Phragmites* invasion is a multi-stage process involving different combinations of clonal spread, rhizome establishment, vegetative growth, and seedling germination. Each of these stages has different tolerances to environmental variables and thus varies in their response to different conditions or events within the wetland watershed (Bart and Harman, 2002).

5.1b Genetic Material Opportunity Assumption

The model does not account for the likelihood of a site being exposed to *Phragmites* genetic material (seeds, clones, or rhizomes) and thus assumes that the risk of acquiring genetic material is equal across all sites; however, in actuality, the probability of a site acquiring genetic material would vary among sites and depend on a number of factors such as distance from the nearest population, the level of soil disturbance, the source of hydrological inputs, or the potential for severe weather patterns like hurricanes. Although the accuracy of the predictive model would increase if a probability metric for genetic material could be established, the events that promote the likelihood of a site receiving genetic material are too broad for such an analysis. However, the distance of a site from known *Phragmites* populations is a metric that could be easily established as a proxy and incorporated into future models.

5.1c Genetic Variation

The vegetative dataset did not include information on what *Phragmites* haplotypes were located in CRMS transects; therefore, it is likely that this model has indiscriminately examined populations of both haplotypes (Introduced and Gulf Coast). The lack of distinction between haplotypes could be a factor hindering accuracy in the predictive model. Given this uncertainty, all populations examined in this thesis were assumed to be the introduced Eurasian haplotype (haplotype M). Reasoning for this assumption is as follows; assuming that established *Phragmites* populations are the Gulf Coast haplotype will underestimate the potential for *Phragmites* establishment – given that the introduced Eurasian haplotype is more tolerant to a wider range of environmental conditions (Meyerson, Lambert, and Saltonstall, 2010) – and lead to more conservative estimates for the number of wetlands in which *Phragmites* could be established. For the same reason, if it is assumed that the *Phragmites* observed in this study is the more tolerant introduced haplotype, then the number of wetlands at risk to invasion will be overestimated. Future studies should try to incorporate haplotype identification[3] and thus avoid this problem.

Section 5.2: Correlation Model

Soil bulk density and minimum salinity were the two variables most correlated with *Phragmites* establishment and growth. In the final logistic models with minimum salinity and bulk density, minimum salinity showed a consistent

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[3] Swearingen, J. and K. Saltonstall. 2010. Phragmites Field Guide: Distinguishing Native and Exotic Forms of Common Reed (Phragmites australis) in the United States. Plant Conservation Alliance, Weeds Gone Wild. http://www.nps.gov/plants/alien/pubs/index.htm

negative correlation with all *Phragmites* presence and growth parameters. The coefficients for bulk density were positively correlated with all *Phragmites* presence and growth parameters; however, these coefficients are larger than the coefficients for minimum salinity, suggesting that bulk density has a greater effect on *Phragmites*, than minimum salinity.

The significant negative correlation between minimum salinity and bulk density supports evidence from the literature that salinity is one of the major factors controlling the zonation and limiting the growth potential of *Phragmites populations*. Soil bulk density could be significantly correlated with *Phragmites* presence for two reasons: (a) because greater soil bulk density increases the potential viability of *Phragmites* or (b) because the establishment of sites by *Phragmites* has led to significant increases in the soil's bulk density attributes via its ability to alter soil properties and nutrient pools(Tulbure and Johnston, 2010). The fact that bulk density is significantly correlated with *Phragmites* presence and growth parameters suggests that the mineral composition or the degree of compaction of the substrate influences the viability or productivity of *Phragmites* in Louisiana's tidal wetlands, or at least gives *Phragmites* an advantage over matrix vegetation. Another reason for this correlation could be that high bulk density is correlated with low sulfide concentrations, which is a limiting factor to *Phragmites* growth (Schrift et al., 2008). On the other hand, correlation between soil bulk density and *Phragmites* could be that the presence of *Phragmites* results in an increase in soil Bulk Density. This would be a logical hypothesis given that

Phragmites establishment has been shown to alter soil properties and nutrient pools (Tulbure and Johnston, 2010; Chambers, 1997).

Although coefficients for minimum salinity and bulk density were all highly significant, the model displayed low R^2 values (figure 7a-c). The low R^2 value could suggests that although the data is correlated, the correlation might not be linear and would perform better with a log transformation. A more likely possibility is that the low R^2 value is a result of the large number of zeros entered into the model to represent sites without *Phragmites*.

Chapter 6: Conclusions and Policy Recommendations

This thesis has shown that predictive models can be used to determine the vulnerability of wetlands to establishment by *Phragmites* if environmental data is available. This thesis has also confirmed, independently of existing literature on *Phragmites* establishment and productivity, that water salinity, water level, temperature, soil salinity, soil moisture, bulk density, and percent organic matter are all environmental metrics correlated with *Phragmites* presence and growth potential. These variables should be accounted for and incorporated into future predictive models to enhance the ability of resource managers to predict the vulnerability of wetlands to *Phragmites* in the future. These results are important given the potential for *Phragmites* to expand along the south coast and concerns that this expansion could indicate could indicate invasive behavior by the plant. These results could also help resource managers make better decisions about what the best way to approach the controversial issue of *Phragmites* on the Gulf Coast.

Phragmites is expected to continue expanding throughout the tidal wetlands of North America, especially into large areas of the Gulf Coast and Southeastern United States (Chambers et al., 1999). However, there is not a clear answer to address whether or not the expansion of *Phragmites* (either invasive or native acting invasively) is good or bad. Given the controversial nature of this issue, resource managers should weigh the potential loss of ecosystem function that would occur if a site was invaded by *Phragmites* against the potential benefits

(Kirk, Berquist, and Priest, 2003). Potential benefits include providing a buffer against wave damage, stabilizing estuarine banks, and providing refuge cover (Hellings and Gallagher, 1992). For example, Chambers et al. (1999) point out that *Phragmites*-dominant marshes may accrete sediment better than the marshes they replaced, which in some instances, could help maintain wetland habitats in spite of global sea level rise. Given such potential benefits, the management goal in many areas should emphasize control rather than eradication (Hellings and Gallagher, 1992). However, if eradication is deemed necessary for a particular area, recognition of the threat of *Phragmites* at early invasion stages is ideal because it provides opportunity for early action and rapid response (Meyerson, Lambert, and Saltonstall, 2010).

Resource managers should be particularly conservative in their decisions to eradicate *Phragmites* populations in coastal Louisiana given the rapid loss of coastal wetlands, which many have determined to be almost forty square miles per year. Areas experiencing rapid land-loss and subsidence might benefit from the structural benefits and buffering capacity of *Phragmites*. In this situation, although functional capacity is compromised, the existence of *Phragmites* might make a critical difference in whether or not the habitat continues to exist at all. On the other-hand, areas at low risk of subsidence and marsh loss due to sea-level rise would probably benefit from the control or eradication of *Phragmites* and preference the establishment of wetland species that will provide a higher functional capacity. Resource managers should heed particular caution towards

Phragmites invasion if sites prone to establishment are also sites that have, or will have, received dredged material as part of a restoration or construction practice. Particular caution should also be given to *Phragmites* populations and other wetland areas in Plaquemines parish, the area where the Mississippi River empties into the Gulf of Mexico. Land-loss in this area is not an issue of concern, given that this region is still being formed by sedimentation; however, given the large supply of nutrients and fresh water into these areas, *Phragmites* is likely to flourish. Transect data from CRMS sites confirms that this is likely the case given that many of these sites had nearly 100% cover for transects within identified *Phragmites* populations.

Decisions regarding the contexts in which *Phragmites* establishment and expansion is beneficial or problematic could be better informed if additional data on the distribution of *Phragmites* and the conditions in which it thrives was available. Data could be enhanced with additional scientific studies, better monitoring of environmental conditions, and detailed surveys of current *Phragmites* populations and their composition.

North America lacks a national database for invasive species (Meyerson, Lambert, and Saltonstall, 2010). Furthermore, according to Chambers et al. (1999) wetlands occupied by *Phragmites* have not been identified at the national level and most states or other regional areas that have identified them, have often not made the data readily available. Therefore, more data should be collected regarding the location, rate, and extent of *Phragmites* expansion and make sure to differentiate between different haplotypes. This data should be combined with research on hydrology, chemistry, and disturbance to determine which uninvaded Louisiana habitats are susceptible to *Phragmites* invasion in the future (Meyerson, Lambert, and Saltonstall, 2010). Such information should be compiled and made accessible on both a national and regional level. This would be fairly easy for many states, especially Louisiana, where such information could be easily incorporated into pre-established monitoring efforts and databases like CRMS.

There is a poor understanding of the impacts associated with invasion of Introduced *Phragmites* (Eurasian) and the invasive expansion of Gulf Coast *Phragmites* (Meyerson, Lambert, and Saltonstall, 2010). Therefore, further research is needed concerning the impacts of different *Phragmites* haplotypes on wetland functional capacity and ecosystem functions in tidal wetlands. Furthermore, genetic sampling and monitoring of different *Phragmites* populations should be increased, so that resource managers have a better idea of the environmental tolerances of present *Phragmites* populations. One problem with much of the literature discussing haplotypes and genetic variation is an inconsistent naming scheme applied to alternate haplotypes and recombinants. A consistent language for discussing and naming haplotypes should be developed and normalized to increase the transparency of results across different studies.

Based on a review of current literature and the conclusions developed in this study, this thesis makes the following recommendations. States should invest in the additional scientific studies and the collection of data regarding the location of current populations of *Phragmites australis*, as well as the rate and extent of their expansion. This data should be combined with research on hydrology, chemistry, soil properties, and disturbance and made publicly available. Genetic sampling of known *Phragmites* populations and additional research concerning the impacts of different haplotypes of on the functional capacity of coastal wetlands should be increased and a consistent language to name and describe different haplotypes of *Phragmites* should be developed.

Future studies should compare the tolerance ranges of different *Phragmites* haplotypes. This would allow scientists to better speculate how different strains will behave or survive in different conditions. Although field experimentation would allow scientists to gain better insight into how different haplotypes will behave in actual environments, field studies incorporate the intentional introduction of *Phragmites* clones or genetic material. Detailed in-vitro experiments in combination with studies on already established populations and genetic sampling will likely produce the most results without increasing the risk of inadvertent establishment of *Phragmites* populations into the environment.

The collection and increased availability of *Phragmites* and environmental data is important because it will help educate the decisions of resource managers for who this thesis makes the following recommendations. In making decisions about the restoration of sites containing *Phragmites australis* or in its control, resource managers should weigh the potential structural benefits against the negative impacts that *Phragmites australis* can have on wetland ecosystems on a case-by-case basis. Resource managers should express particular concern in dealing with this species in areas subsidized by dredged material, in areas where construction or restoration activities are taking place, or in areas supported by high nutrient and freshwater inputs.

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