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A Long-Term Control Project for an Invasive Plant: Assessment of Phragmites Australis Reduction and Redevelopment of Native Vegetation in Interdunal Swales of Sandy Neck Barrier Beach, Cape Cod, Massachusetts

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A LONG-TERM CONTROL PROJECT FOR AN INVASIVE PLANT: ASSESSMENT OF *PHRAGMITES AUSTRALIS* REDUCTION AND REDEVELOPMENT OF NATIVE VEGETATION IN INTERDUNAL SWALES OF SANDY NECK BARRIER BEACH, CAPE COD, MASSACHUSETTS

A Thesis Presented

by

DENA TOMASSI

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A LONG-TERM CONTROL PROJECT FOR AN INVASIVE PLANT: ASSESSMENT OF *PHRAGMITES AUSTRALIS* REDUCTION AND REDEVELOPMENT OF NATIVE VEGETATION IN INTERDUNAL SWALES OF SANDY NECK BEACH PARK, CAPE COD, MASSACHUSETTS

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ABSTRACT

A LONG-TERM CONTROL PROJECT FOR AN INVASIVE PLANT:

ASSESSMENT OF *PHRAGMITES AUSTRALIS* REDUCTION AND

REDEVELOPMENT OF NATIVE VEGETATION IN INTERDUNAL SWALES

OF SANDY NECK BEACH PARK, CAPE COD, MASSACHUSETTS

August 2011

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Phragmites australis is a perennial wetland grass that is native to North America. However, salt marshes, estuaries, and other wetlands throughout the northeast USA and Canada have witnessed a dramatic range expansion and population increase of the introduced genetic variant *Phragmites australis* haplotype M (Saltonstall 2002), with loss of native vegetation through competitive exclusion. Within the dune system of Sandy Neck Barrier Beach, freshwater wetland swales form in low elevation areas, which harbor a diverse wetland plant community dominated by shrubs, and sedges -- and including some rare and endangered species. To conserve and protect these wetland plant associations, annual herbicide applications were initiated in 2002 in a control

program targeting the expanding populations of *Phragmites* M in the interdunal swales. To determine whether herbicide applications have reduced *Phragmites* infestations, estimated density and abundance scores from 2002-2009 were analyzed using a linear mixed model regression. *Phragmites* presence/absence data from the same time period was analyzed through binary logistic regression to determine whether herbicide applications were eradicating *Phragmites* from swales. The number of herbicide applications has significantly reduced the number of *Phragmites* stems within invaded swales, but the plant persists in all but a few of the treated swales. Data from a vegetation survey of 28 swales in 2010 were analyzed through cluster and multidimensional scaling analysis to investigate whether the composition of the plant communities differs between *Phragmites*-invaded swales versus swales never invaded by *Phragmites*. The vegetation found in uninvaded swales is distinctly different than that found in invaded swales. Additionally, the analysis of the survey data was used to determine whether reducing *Phragmites* in treated swales produces a vegetational shift toward non-*Phragmites* community structure. The analysis does not show that swales with reduced *Phragmites* plants have had a redevelopment of swale vegetation, similar to that found in uninvaded swales. More time or more herbicide applications may be necessary before changes to the plant community become evident.

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This work is dedicated to my parents and Sam, who all deserve to say, "I told you so".

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CHAPTER 1

INTRODUCTION

Invasive Plant Species

Invasive plant species have had substantial detrimental effects on habitats around the world. Global transport over the last century and a half has played a central role in the introduction of non-native plant species to different bioregions where they otherwise would not be found. Propagules of hundreds of invasive plants species have successfully colonized and altered habitats of every kind on virtually every continent. According to Pinmental et al. (2005), at least 50,000 species of foreign plants and animals have been introduced in the United States.

Vectors of Transport

Several modes of transportation are potential pathways for the movement of invasive species (Hulme 2009). Historically, plant species have been traded and transported by humans; however, unintentional introduction of species has increased by magnitudes since the Industrial Revolution and particularly in the recent decades of globalization (Hulme 2009, Westphal et al. 2008). Ships using soil as ballast (later replaced by water) is a common source for propagules of potentially invasive plant

species. For example, the introduction of Brazil's *Alternanthera philoxeroides* (alligator weed) to Australia in the 1940s was determined to be from ship ballast water (Zedler & Kercher 2004). Automobiles and recreational boating can facilitate expansion through the movement of plant fragments, as is often the case for aquatic and wetland invaders (e.g., *Myriophyllum spp.* {water milfoil} and *Hydrilla verticillata* {hydrilla}).

Horticulture is a major source of intentionally introduced plant species. Many introduced horticulture species are non-invasive, fulfilling the purpose for which they were brought with little negative impact. However, Reichard et al. (2001), determined that 82% of 235 woody species originally introduced for use in landscaping, have colonized outside their intended area. Habitats have suffered serious environmental effects caused by nonindigenous landscape species, such as Japanese honeysuckle (*Lonicera japonica*), English ivy (*Hedera helix*), cape ivy (*Delaireia odorata*), and Chinese tallow (*Triadica sebifera*) (Niemiera & Von Holle 2009). Another example is Kentucky bluegrass (*Poa pratensis*), which was intentionally introduced from Europe and is widely used to cultivate lawns, grasslands, and pastures (DiTomaso et al. 2006).

Characteristics of Invasive Plants

The ecology of invasive plant species has been heavily studied in the USA in order to understand, recognize, and prevent the introduction and spread of additional species. Although traits among invasive plant species are quite variable, some research has found that many invasives have similar characteristics that allow them to successfully colonize and expand into native habitats. Typical features that invasive species often have

in common include: rapid reproduction both sexually and asexually, high dispersal rates, tolerance of varied environmental conditions, and phenotypic plasticity (Baker 1974, Kolar et al. 2001, Daehler et al. 2000). Combining these traits with a lack of natural enemies and high propagule pressure, invasives very often are more aggressive competitors than native species, which allows for quick and dramatic range expansion (Sakai et al. 2001, Radosevich et al. 2007).

Negative Impacts

Introduced plant species that do colonize and expand into native habitats can have many negative impacts. First, prolific expansion by an invasive can cause a decline in native species richness, evenness, and, diversity leads, ultimately, to the displacement of native species, which has direct effects on biodiversity (Meyerson etl al. 2000, Radosevich et al. 2007, Kolar et al. 2001). Purple loosestrife (*Lythrum salicaria*) and Kudzu (*Pueraria lobata*) are common invasive plants in the USA, populations of which have led to decreases or total displacements native species (Forseth & Innis 2004). Biodiversity loss is of particular concern when there are threats to rare and endangered species by invaders.

Second, competition and expansion from invasives also alters resource availability. High numbers of invasive plants in an ecosystem may utilize resources that will no longer be available to natives: limited access to light, water, space, minerals, and nutrients forces the decline of native species populations (Packett et al. 2006, Meyerson et al. 2009). For example, *Phragmites australis* is a tall wetland grass that forms dense,

monotypic stands in wetlands because the sheer number of *Phragmites* plants occupies more space than natives and shades shorter plants (Windham 2001).

Third, invasives pose a serious threat to agricultural land and food production. According to Pimental et al. (2005), annual economic costs resulting from invasive alien species in the United States is estimated to be $120 billion. Many of the plants referred to as weeds by agriculturists are non-native invasives, which through competition with crop plants, reduces overall yield (Radosevich et al. 2007). In meadows and pastures, weeds outcompete native forage species, allowing the spread of potentially toxic or inedible grasses for grazing farm animals. For example, leafy spurge (*Euphorbia esula*) was intentionally introduced to grasslands in the USA in the 1800s and today infests nearly 1.2 million hectares of land in North America (Williams & Hunt 2002). A good competitor, the plant displaces native foraging vegetation through shading and monopolizing water and nutrient resources (Williams & Hunt 2002). It is also toxic when ingested by grazing livestock, leading to agricultural and economic loss (Williams & Hunt 2002). The yellow star thistle (*Centaurea solstitialis*) was introduced from the Mediterranean in the 1800s that now occupies 15 million acres of California grassland (Wilson et al. 2003). The plant displaces native grazing vegetation and is not grazed by livestock because of thorny spines that surround the flower head.

Lastly, changes in hydrology and nutrient cycling result from habitat alteration due to invasive plant populations. Increasing number of plants can lead to more residual biomass and sedimentation that can change the topography of a habitat and subsequently alter the movement of water and nutrients throughout an ecosystem (Bertness et al. 2002, Meyerson et al. 2009, Burdick et al. 2003).

Phragmites australis ([Cav.] Trin. Ex Steud., common reed) is a wetland and marsh invader and will be the focus of this thesis. Non-native *Phragmites* has been widely recognized as a threat to the ecosystem function of wetlands in North America and its several detrimental effects to native species and habitats have been well researched and documented.

CHAPTER 2

PHRAGMITES AUSTRALIS

Introduction to *Phragmites australis* (Common Reed)

Phragmites australis is a large perennial grass with long, flat, broad leaves and a flower at its terminal end (Cross & Fleming 1989). It can grow several meters tall and is found in freshwater and brackish wetlands (Cross & Fleming 1989, Marks et al. 1993). This plant reproduces primarily through vegetative reproduction, which leads to dense, monotypic, genetically identical stands (Saltonstall 2002, Alvarez et al. 2005). It has both horizontal and vertical rhizomes, which can colonize new areas if broken into fragments (Marks et al 1993). The plant does flower and set seed, but seed dispersal and seed viability is low (Alvarez et al. 2005). *Phragmites* is generally considered a low salt tolerance plant, however, it has recently been shown to invade habitats with varying salinity (Chambers et. al 1999).

Introduction and description of the invasive genotype

Over the past 150 years, salt marshes, estuaries, and wetlands ecosystems throughout the northeast USA and Canada have witnessed a dramatic expansion and increase in *Phragmites australis* (hereafter referred to as *Phragmites*) populations.

Phragmites has been considered a North American native plant community member for at least 40,000 years (Saltonstall 2002); however, its recent dramatic range expansion is thought to be because of an introduced genetic variant (Saltonstall 2002).

Although debate continues regarding its origin and history, *Phragmites* is considered native to North America. Prior to its recent spread, it was regarded as a common member of wetland plant communities. Nonetheless, for over a century, its distribution and abundance have increased, invading disturbed habitats, as well as intact areas (Saltonstall 2003). It is believed that the invasive *Phragmites* arrived to North America from Asia through the ballast soil of a ship in the mid-late 19th century (Saltonstall 2002, Saltonstall 2003).

Saltonstall (2002) was one of the first to describe *Phragmites* genetically. Through DNA sequencing, 27 haplotypes were identified worldwide based on modern and herbarium specimens. Eleven of these haplotypes were unique to North America, with haplotype I representing the most common native strain in North America. It was also demonstrated that throughout the 20th century, haplotype I populations persisted in their typical range, while another – haplotype M -- showed an obvious pattern of expansion.

Haplotype M is highly competitive compared to native *Phragmites* strains. It produces more shoots, more stem & leaf biomass as well as having a higher growth rate (Saltonstall 2002, Lelong et al. 2007). It also displays wider tolerances for some environmental features (i.e. – salt tolerance), which may as well be an advantage over some native species (Bertness et al. 2002).

Today, haplotype M is the most common haplotype in North America, with populations of native strains diminishing or being replaced due to its expansion (Saltonstall 2002, Bertness et al. 2002). Chambers et al. (2008) suggest that by the 1960s, *Phragmites* populations of haplotype M were in almost every US state. Three native haplotypes seem to have disappeared (Saltonstall 2002). Haplotype *Phragmites* M has been a cryptic invader: an organism that cannot be easily identified or differentiated from a native (Saltonstall 2002). The introduced haplotype M has remarkable morphological similarity with the native strains; therefore, initial colonizing populations of the invasive went unrecognized (Saltonstall 2002). As a result, by the time haplotype M was identified, it had already invaded many habitats over a large spatial scale (Chambers et al. 1999).

Negative Impacts of *Phragmites* M

Colonization and expansion of *Phragmites* stands have negative effects on invaded ecosystems (Cross and Fleming 1989). Native plant species are most affected by *Phragmites* invasion. Significant decreases in native plant community diversity and abundance have been documented in *Phragmites*-dominated habitats (Marks et al. 1993, Ailstock et al. 2001, Norris et al. 2002, Silliman et al. 2004, Derr 2008). Native vegetation is most often excluded because *Phragmites* outcompetes these species for a variety of resources, including light, space, and nutrient availability (Ailstock et al. 2001). There have also been demonstrated negative effects to animal communities, most notably waterfowl (Cross and Fleming 1989, Ailstock et al. 2001). For example, Keller (2000) surveyed marshes in the Charles River watershed in Massachusetts and found that

marshes dominated by *Phragmites* had the lowest plant diversity. Additionally, Warren et al. (2001) found that *Phragmites*-dominated tidelands in the lower Connecticut River had significantly lower plant diversity compared to other surrounding habitats. Invasion by *Phragmites* is of most concern in areas that have rare and endangered species (Marks et al. 1993). For example, the state-threatened sedge Carex aquatilis in Ohio is considered vulnerable due to invasive *Phragmites* stands (Marks et al. 1993).

Habitat destruction and alteration by humans has been suggested to facilitate the spread of *Phragmites* (Marks et al. 1993). *Phragmites* is successful in disturbed areas, frequently associated with construction areas, roadway ditches and other shoreline or coastal developments, such as agriculture, housing, or golf courses (Lelong et al. 2006, Lelong et al. 2007). These activities result in changes in several environmental factors: space, nutrient enrichment or availability, soil salinity and water levels. All of these have been correlated with promoting *Phragmites* expansion (Lelong et al. 2006, Lelong et al. 2007, Bertness et al. 2002, Chambers et al. 2008, Packett & Chambers 2006, Silliman et al. 2004).

The detrimental effects resulting from *Phragmites* M invasion makes it vital for ecologists and land managers to understand the structure and function of wetland habitats and their species, in order to maintain biodiversity, protect rare and endangered species, ensure stability and function of wetland and beach resources and to guide policy and management decisions. The challenge to conservation biologists, ecologists, and resource managers is to develop and establish management plants that: 1) will ultimately conserve and protect native species and biodiversity, 2) utilizes a variety of methods to control

Phragmites infestations, and 3) prevents the introduction of additional invasive plant species.

CHAPTER 3

SANDY NECK BARRIER BEACH

Sandy Neck is a six-mile long depositional spit located on the north shore of Cape Cod. As public land owned and protected by the Town of Barnstable and its Department of Marine and Environmental Affairs, environmental regulations and jurisdictions concerning Sandy Neck barrier beach are enforced by multiple agencies, ranging from municipal to federal. It has been designated as an Area of Critical Environmental Concern (ACEC) by the Massachusetts Coastal Zone Management (MCZM). The area of Sandy Neck and the adjacent Great Marsh has been designated a biodiversity conservation core habitat by the Natural Heritage & Endangered Species Program because of “its size, natural communities, and excellent ecological condition” (BioMap & Living Waters: Guiding land conservation for biodiversity in MA, 2004). This designation recognizes Sandy Neck as critical to terrestrial and wetland biodiversity. Finally, Sandy Neck also has several wetland resources that fall under the jurisdiction of the Massachusetts Wetland Protection Act.

Sandy Neck encompasses several resource areas, each representing important habitats for numerous rare and endangered species.   Nine species in Sandy Neck, including Terrapins, and Piping plovers, are currently recognized as endangered, threatened, or of special concern by some governing bodies or statute (e.g., MassWildlife

and Natural Heritage & Endangered Species Program). Such species and their habitats are protected under the following federal land state laws: the Rare & Endangered Species Act, Massachusetts Endangered Species Act (MESA), and the U.S. Endangered Species Act (ESA). As required by these laws and organizations, long-term management plans take the ecology and biology of these species under careful consideration: "The continued integrity of Sandy Neck's natural communities represents one of the most important goals of the management plan" (Woods Hole Group 2003).

Development of the Sandy Neck spit, barrier beach, and dune system

The formation of the Sandy Neck spit began 3,000-4,000 years ago when sea levels rose drastically due to glacial melting (Oldale 2001). Longshore drift and longshore currents carried sand from the cliffs of glacial deposits. Sand was also deposited inland by onshore winds, beginning the foundation of the dune system. The Great Marsh grew in a northerly direction because of the rising sea level and laterally because of the growth of the spit (Oldale 2001).

Spits, barrier islands, and barrier beaches are ever changing, dynamic environments. Many environmental factors constantly exert altering forces upon the ecosystem. Winds, waves, and storms continue to move and redeposit sediments, constantly growing and shrinking the spit and reshaping sand dunes. Other stressors, such as fluctuating water levels, salt water and salt spray, and human disturbance can exacerbate these processes.

The Sandy Neck dune system is comprised mostly of linear dunes, but some parabolic (U-shaped) dunes are also present. The parabolic dunes form when the center of the dune is blown out because of the prevailing westerly winds along Cape Cod (Oldale 2001, Sherman et al. 1993). Blowout areas and other low elevation areas within dune systems become important freshwater resources for flora and fauna. Seasonal and tidal variations in water level can provide access to local aquifers or water tables; however freshwater accumulation primarily results from precipitation (Shumway 2001, Smith et al. 2008). The availability of freshwater in an arid, dry and nutrient-deficient environment is key to the growth and support of plant communities in dune systems.

Dune systems are generally difficult habitats for plants to occupy because of many environmental stressors. The coastal environment is arid and dry with characteristic high temperatures in the summer. Regular wind patterns cause abrasion to plants from wind-blown sand. Strong winds during storms cause erosion, which can lead to plant root exposure. Storms and tides can also cause saltwater intrusion. Large amounts of fresh or saltwater can lead to waterlogged soils. Finally, sand is unstable, nutrient-deficient and has poor water retention abilities.

Sandy Neck Interdunal Swales

Interdunal swales (referred to as swales hereafter) are wetland communities that develop in the low-elevation, water accessible, areas of the dune system. As described above, swales are subjected to several environmental stressors. As a result, swale plant communities that do persist in these difficult environments are distinct and unique.

Swales include varieties of endemic, and rare and endangered plants, and thus support a source of biodiversity in habitats that are otherwise uninhabited and barren (Odum and Harvey 1988, Shumway et al. 2001).

Swale soils are normally moist and damp, and can be inundated with water after storms. In addition, when the groundwater table rises seasonally (often in the spring), swales can have several inches of standing water (Shumway 1996). During these times, swales act as vernal pools, critical habitats for species of invertebrates, insects, and amphibians (Woods Hole Group 2003). For example, *Scaphiopus holbrookii* (Eastern spadefoot toad) was listed as a threatened species in 2004. This species has been recorded on Sandy Neck and it utilizes vernal pools for larval development. Vertebrates on Sandy Neck include several species of resident and migratory birds, rodents, and turtles. Other common animals are whitetail deer, red foxes, coyotes, and snakes.

Since *Phragmites* had invaded many of the interdunal wetland swales that are habitats for rare and endangered plant species, a *Phragmites* removal program was initiated in 2002 on the conserved land of Sandy Neck Barrier Beach. This study aims to examine the success of the control program.

Focus Questions

The objective of this thesis is to assess the effectiveness of the *Phragmites* control project by investigating the following questions:

- Do herbicide treatment applications eradicate or reduce *Phragmites* infestations in swales?

- Does the composition of the plant communities differ between invaded swales that have received herbicide treatment versus uninvaded swales?
- If the above are so, does reducing *Phragmites* in treated swales allow for a vegetational shift toward non-*Phragmites* community structure over time?

CHAPTER 4

METHODS

Study Site: Sandy Neck Barrier Beach

Sandy Neck Barrier Beach is located in Barnstable, on the north shore of Cape Cod, Massachusetts, between Cape Cod Bay and the Great Marsh at 41°43’ N.70°22’ W (Coleman 2003). The beach extends approx. 10 km (6 miles) from its mainland connection, and can vary in width from 0.5-1 km (0.3-0.6 mile). Despite its small size, the beach system contains a variety of habitats: migrating sand dunes, open beaches, interdunal swales, maritime forests, salt marsh, vernal pools, bogs, etc. (Woods Hole Group 2003, Coleman 2003).

Geology

Sandy Neck barrier beach was developed during sea level rise when deposits from the Wisconsin glacier eroded by waves and were carried parallel to the land via long shore drift (Dunford and O’Brien 1997). In his study of the adjacent Great Marsh, Redfield (1972) analyzed peat cores from Sandy Neck to determine the beach’s age: the

oldest section on the western side is 3,170 years old. Sandy Neck is characterized as being geologically young – yet relatively stable compared to other barrier beaches. Still, like other barrier beaches, Sandy Neck is a dynamic landform, with erosion rates at 0.25-0.5 ft per year and an eastern accretion rate of 1.5 ft per year (Redfield 1972, Woods Hole Group 2003). The majority of soil at Sandy Neck is comprised of Hooksan soils. Soils of this type include loose sand, which is highly permeable, well drained, and nutrient poor (Woods Hole Group 2003, Dunford and O'Brien 1997).

Hydrology

The hydrology of Sandy Neck is also quite dynamic – with substantial temporal variation of salinity. First, there are large fluctuations in sea level due to tidal action from the bay and the marsh. Mean tidal range is from 9-13 vertical feet during full and new moon periods. Second, salinity is often higher due to episodic salt-water inputs related to weather. For example, ocean waters can be displaced beyond the fore-dunes during storms, leaving salt water retained in the swales. Salt-water leaching can also contribute to fluctuating ionic concentrations from the Marsh.

Freshwater supply varies greatly throughout the year, depending upon season, evapotranspiration, and precipitation. In general, freshwater accumulation comes predominately from precipitation, although groundwater and aquifers are also sources of freshwater within the dune system (Smith et al. 2008, Shumway et al. 2001). For example, the peak of the freshwater table annual cycle is in the spring, leaving most swales with one to several inches of standing water. During these times when some swales retain

standing water for extended periods of time, they are characterized as temporary ephemeral ponds, also known as vernal pools. Vernal pools are crucial habitats for the reproduction and development of many species of amphibians, insects, and plants.

Rare and Endangered Species

Nine species (Table 1) in Sandy Neck are currently recognized as endangered, threatened, or of special concern by some governing bodies or statute (e.g., MassWildlife and Natural Heritage & Endangered Species Program).

Two animal species have long-term monitoring and management strategies in place on Sandy Neck. Annually, nests of *Charadrius melodus* (piping plover) and *Malaclemys terrapin* (diamondback terrapin) are identified, quantified, and protected to aid in the survival of young. Trails and beachfronts are closed for the hatching and early development stages of these animals to minimize human disturbance to nests and hatchlings.

Beach staff and conservationists are also interested in the rare wetland plant species *Sabatia kennedyana* (Plymouth gentian). It is a perennial herbaceous plant that is currently found in only two interdunal swales on Sandy Neck as of 2001 (Coleman 2003). Unfortunately, both swales contain invasive species, including *Phragmites australis* and *Lythrum salicaria* (purple loosestrife), another invasive wetland species. Competitively dominant and aggressive plant invaders like these contribute to decreasing *Sabatia* populations, so *Lythrum salicaria* and *Phragmites australis* individuals are treated annually.

Human activities

Historical

Native Americans first settled and utilized the resources of Sandy Neck – mostly exploiting the abundant shellfish and finfish, and occasionally hunting marsh birds. After English settlements in the 1600s salt hay was taken from the Great Marsh and marine activities (fishing, shell fishing, boating, etc.) became commonplace (Woods Hole Group 2003). Portions of maritime forest areas were cleared for small agriculture and farm animals. A whaling community developed late in the 17th century, and was eventually replaced by the fishing industry in the 1800s (Dunfred and O'Brien 1997).

Contemporary

Despite conservation regulations and environmental enforcement, Sandy Neck has significant human impact. Prior to any control efforts, Sandy Neck experienced disturbance from foot traffic as a result of recreational activities, such as camping, fishing, shell fishing, beach goers, and hikers. Vehicular disturbance was also significant from off-roading throughout the beach. Conservation efforts have restricted foot and vehicular traffic to the open beachfront and only on marked, sand trails through the dune system. Vehicular traffic is further reduced in the summer when the majority of the beachfront and trails are closed due to piping plover and diamond back terrapin nests. Although not nearly as frequent as vehicles, horseback riding is also permitted.

Most vehicle and pedestrian activity takes place at the gatehouse and beach parking lot area. Every visitor is stopped at the gatehouse at the entrance of the beach.

After the gatehouse, visitors must drive along Sandy Neck Rd. (paved) to a parking lot. The parking lot has beach access, restrooms, and a concession stand. Most recently, there are plans for construction and renovation of the existing bathhouse also located along the parking lot. Visitors may also use their off-road vehicle (ORV) or recreational vehicle (RV) to access the beachfront, the marsh, and the dune system via sand trails (Figure 1).

Along the southern side of the beach, adjacent to the Great Marsh, anthropogenic activity has also been substantial. One of the most active ORV trails on Sandy Neck is the Marsh trail, which travels along the ecotone between the Great Marsh and Sandy Neck beach. The Cape Cod Mosquito Control Commission (CCMCP) constructed and repaired ditches in 1915, 1930, 1973, and 1975 (Coleman 2003). Disturbances like run-off, ditching, and tidal effects in this area have prompted the invasion of several plant species, such as *Panicum* and *Lythrum salicaria* (Coleman 2003, Smith et al. 2008).

Structures

There are 85 man-made structures found on Sandy Neck. The majority of these structures are primitive cottages or cabins, which lack plumbing and electricity. They are mostly found along the marsh trail and are often only inhabited during the summer. However, the southeastern tip of Sandy Neck has had the most development. A private cottage community, which contains the majority of the 85 structures, is inhabited year round by some, and actively utilizes the waterways between the Great Marsh and Barnstable Harbor.

Sandy Neck *Phragmites australis* M control project

Prior to 2002, conservationists and staff members were concerned about the potential impacts invasive plants species can have on the Sandy Neck ecosystem (Lombard pers. comm. and Coleman pers. comm. 2011). There are several invasive plant species present on Sandy Neck, such as purple loosestrife (*Lythrum salicaria*), reed canary grass (*Phalaris arundinacea*), switchgrass (*Panicum virgatum*), and common reed grass (*Phragmites australis*). Staff members observed *Phragmites* infestations as increasing and spreading the most, and growing concern for the rare and endangered species prompted the initiation of a control project.

The *Phragmites* control project in the interdunal swales of Sandy Neck Barrier Beach formally began in 2002 in a cooperative effort by the Nature Conservancy and the Town of Barnstable. The goal of the project is to reduce *Phragmites australis* from interdunal swales to a low level, and ultimately, to eradicate the plant, and therefore protect and conserve biodiversity of the swales community.

Swale Survey and Initial Plant Assessments

Initially, 133 swales were surveyed using GPS in 2001 (Coleman 2003). In subsequent years, small teams of crewmembers added additional swales during surveys. Swales were documented both on a GPS device and a map, as well as assigned an ID number. Crewmembers visually assessed the conditions and characteristics of each swale and transcribed their observations onto an assessment form. On this form, general site conditions (crew member names, weather, date, time, location, etc.) were noted.

Crewmembers had to draw sketches of the swales, indicating their relation towards North, other landmarks, and zones of predominant vegetation. Predominant native vegetation (i.e. – cranberry, rushes, beach grass) and the presence of any invasive plant species were recorded and their general location indicated on the sketch. The presence or absence of *Phragmites* was recorded, as well as an estimation of its abundance and density when it was present. Density, defined as the total number of *Phragmites* stems per swale area, was given one of the following scores: None (0), light (1), moderate (2), or heavy (3). Abundance (estimated percent cover of *Phragmites* stems) was given a score from 0 to 4 based on how much area of the swale the stems occupied: 0 indicates *Phragmites* absent, 1 indicates coverage between 0% and 25%, 2 indicates between 25% and 50%, 2 indicates between 50% and 75%, and 4 indicates >75%.

Following the initial survey and vegetation assessment, 55 of the 133 assessed swales were characterized as being infested with *Phragmites* (Table 4). Of the 55 invaded swales, 15 were treated in 2002. Ideally, all infested swales in a given year would receive herbicide treatment; however, there are several factors that affect how many and which swales are treated during a treatment event. First, funding was available only from 1-2 awarded grants (waiting to hear from Karen which ones and how much), which supported all aspects of the project (e.g. – herbicide, crew salary, vehicle, etc.).

Second, herbicide application using the cut-and-drip method is most effective to *Phragmites* during later summer-early fall (Moreira et al. 1999). During this time in the plant's life cycle, resources are primarily being moved to the horizontal rhizomes as opposed to the vertical portion. Applying the chemical during this time makes it likely that it will be translocated into the underground rhizomes, and will therefore be the most

successful. The *Phragmites* treatment season ranged from seven-eight weeks from mid-august to mid-October, where crew members often were not able to treat all swales, particularly in the early years when there were many moderately or heavily infested swales to treat. Second, funding and housing limited the number of crewmembers (ranged from 2-4 over the years) that could be hired to do treatment in a season (Lombard pers. comm.).

Third, crews travel to different swales primarily with an ORV on the sand trails throughout the dune system (Figure 1). Once crewmembers cannot go further with the vehicle, they must hike to the swale, carrying all necessary equipment. Given the terrain and weather, it's possible that swales with easy accessibility to an ORV trail may be more likely to receive treatment. For example, the marsh trail runs from the gatehouse at the entrance of Sandy Neck, along the Great Marsh to the eastern end of the dune system (Figure 1). This trail lends relatively easy access to many swales and may play a role in which swales received treatment in a given year.

Finally, limited manpower may influence the amount of swales that receive treatment. As described above, the project had to operate within its monetary limitations, which includes how many crewmembers can be hired and paid. A typical crew was comprised of two people, whose goal was to treat all invaded swales using a labor-intensive method in a narrow time period. Of the seven possible treatment years, five did not treat every invaded swale (2003, 2004, 2006, 2007, and 2009). In other words, swales have varying treatment histories, which may play a role effectiveness of treatment and the overall reduction or eventual eradication of *Phragmites* from a particular swale.

In addition to variable patterns in treatment history, the total number of known swales within the Sandy Neck dune system also varies. In 2004, crewmembers located and added 19 previously unknown swales to the 133 swales located during the 2002 survey. Nine more swales were located in 2007, bringing to total number of swales to 162. By 2009, the total number of swales included in the *Phragmites* control project was 176.

Chemical Treatments

Every herbicide treatment was documented by crewmembers. A chemical treatment form required the following information: general conditions (date, weather, time, etc.), developmental stage of *Phragmites* plants present (adult, flowering, seedling, etc.), concentration of herbicide solution, and treatment method (cut and drip or spray). As required by town and state law, all crewmembers attained Massachusetts Pesticide Applicator Licenses before handling or using any chemicals.

A dilute 2% concentration solution of Rodeo © (glysophate , N-phosphonomethyl glycine) herbicide and Cide-Kick II © surfactant was used for treatment applications. Another herbicide, Aquamaster © was also used. A 2% concentration has been effective in treating *Phragmites* infestations elsewhere (Riemer 1976, Monteiro et al. 1999) and is considered nontoxic to terrestrial and aquatic wildlife. To minimize non-target negative effects, manual treatment methods were employed predominately. The most frequent treatment method used was cut-and-drip, where crewmembers used garden scissors to cut the stem of an individual *Phragmites* plant and then insert 2-3 drops into the stem from a

small bottle. The cut stems were collected and placed outside the swale, in an area of bare ground, to dry out.

A swiping method was also occasionally used, where a crewmember would swipe the herbicide on the plant with a glove. This method was only used when stems were too small for cut-and-drip, as it did not appear to be as effective as the cut-and-drip method. The cut-and-drip method is more successful because it treats not only the vertical stem but also allows the chemical to reach the subsurface, horizontal rhizomes where buds and new plants are formed.

When the infestation of a swale was deemed to be too large or dense for manual treatment, crewmembers used backpack sprayers to apply the herbicide. As stated previously, crewmembers were trained how to operate these sprayers properly and were used in a way that minimized effects on non-target organisms.

Collection and Analysis of Past Project Data

The Nature Conservancy (Boston, MA) has stored assessment forms, chemical treatment forms, and other relevant documentation of the control project since its inception. In the early summer of 2010, I was given access to project documents from the treatment years of 2002-2009. From these documents, I was able to gather and organize pertinent information in a spreadsheet, such as distance to marsh trail and area of swale. For each swale in each year, *Phragmites*-related information was counted and tabulated: *Phragmites* presence/absence, whether the swale received herbicide treatment or not, estimated density, and estimated abundance.

To determine whether herbicide application eradicates *Phragmites* infestations, binary logistic regressions were performed for 2003-2009 historical data in SPSS 18, using *Phragmites* presence/absence for swales of each year respectively as the dependent variable. The first explanatory variable was the number of treatment applications a swale had received. Although herbicide was first applied following the assessment and survey of 2002, any effect the chemical would have to the presence/absence of *Phragmites* (and whether a swale would require further treatment) would not be evident until the following treatment year, when the infestation of each swale is assessed again. Consequently, the number of treatments for 2003 is determined based on the 2002 data. Similarly, the number of treatments in 2004 includes treatment in 2002 and 2003, and so on for each year up to 2009.

Distance to marsh trail was included as an explanatory variable because this was the main ORV route utilized by crewmembers during treatments. The preferential use of this trail and a swales' relation to it, may have an effect on the number of treatments a swale has received in 2002-2009 interval. The area of the swale was also considered an important factor because a larger swale potentially means a larger, denser *Phragmites* infestation, which may require more time and treatment applications in order to significantly reduce or eradicate the infestation (and vice versa for smaller swales). Additionally, larger infested swales may have been treated preferentially in order to hinder expansion. Although an effort was made to treat "new" infestations first, treatment may have been more opportunistic than intended due to logistical challenges such as tides and vehicle access.

The final explanatory variable was dune category. Structure and species composition of vegetation in swales can often depend on age (Shumway 1996). Over time, swales develop through periods of succession, from being primarily composed of herbaceous and graminoid plants, to containing communities with shrub and tree species (Smith et al. 2008, Shumway 1996). Environmental stressors (e.g. – storm damage, hydrologic effects, wind) can often hinder or prevent the further development of swale vegetation, particularly during the earliest stages (Coleman 2003). However, the dune ridges that swales form near or in between may offer some "protection" for stressors and allow the swale to develop into a more stable, persistent swale community (Johnson 1997). Protection from some stressors may also reduce or limit the vulnerability of a swale to invasion by *Phragmites*. Using LIDAR imagery (1" = 100' scale maps with a 2' contour interval for use at a 1:1200 scale) obtained from the Town of Barnstable GIS Department, a dune variable was created for each swale based on the number of dune ridges between the beachfront and the swale.

Contingency tables were created for each year to evaluate the relationship between presence of *Phragmites* and the number of herbicide applications. For each year interval, only swales that were characterized as having *Phragmites* present in the previous year were considered. Thus, each table indicates whether a given swale had retained or lost its *Phragmites* during the previous year (columns) and how many pesticide applications it had received during the course of the project (rows). For example, for the 2006-2007 interval, the swales categorized as having *Phragmites* present in 2006 were separated by the number of treatments they had received and by the *Phragmites* present/absence data from 2007.

To determine whether *Phragmites* infestations have been reduced by herbicide application, even if not eradicated, linear mixed model regressions were performed for estimated density and estimated abundance. Mixed model regression takes into consideration the repeated measure (herbicide application) that occurs every year, which may have a significant effect on the estimated density and abundance of a *Phragmites* infestation.

Vegetation Survey and Analysis

To compare the vegetational composition of *Phragmites* swales vs. non-*Phragmites* swales, as well as to detect any shift in vegetation structure of Phragmites swales towards that of non-*Phragmites* swales, 28 swales were intensively surveyed from early July until mid-August in 2010. Variation in treatment history from 2002-2009 divides the swales into seven different treatment categories: 1, 2, 3 4, 5, or 6 years of herbicide application, and no herbicide application (because *Phragmites* was not present).

Four swales in each of the seven treatment categories were chosen using a random number table. During the survey, the center of each swale was found, where a random number table was used again to select three different degrees from a compass. One transect was done along each of the selected degrees. A 1 x 1 m quadrat was placed every other meter along a tape measure to the outer edge of the swale. Each species within the quadrat was identified and an estimation of percent cover was determined. Completing the survey for a "typical" swale required about 2-3 hours, with considerable

variation depending on the size of the swale. Data were analyzed by cluster analysis and multidimensional analysis using SPSS 18.

CHAPTER 5

RESULTS

Effect of Herbicide Treatment on Presence/Absence of *Phragmites*

To determine whether the herbicide applications were reducing *Phragmites* infestations, I reviewed how estimated *Phragmites* presence, estimated *Phragmites* density (total number of *Phragmites* stems per swale area), and estimated *Phragmites* abundance (per cent cover by *Phragmites*) scores changed over time for the 133 swales first described in 2002. Overall, the original 2002 swales show a slight decreasing trend in the proportion of swales with *Phragmites* present over time (Table 4, Figure 4) – with an anomalous minimum in 2005, after three years of pesticide treatments. Comparing 2002 (pre-treatment) to 2009 (last year of data) shows little change in the proportion of swales infected by *Phragmites* (41% versus 35%). However, *Phragmites* was steadily reduced in this group of swales over the seven years of the control project, in terms of both density and abundance (Figure 2 and Figure 3). The reductions appear most strongly at the high ends of both density and abundance scorings.

In 2002, before herbicide applications had begun, 15% of swales were scored at the highest level of *Phragmites* density (score = 3), indicating heavy infestation (Table 5, Figure 2); however, by 2009, only 1.5% of these swales were given the highest density

ranking. The number of swales in the moderately dense infestation category was falling at the same time: about 16% of were moderately dense swales in 2002, compared to 8% in 2009 (Table 5, Figure 2). During this treatment period, the proportion of swales described as having a light infestation or no infestation (density score 0 or 1) rose from 68% to 90%. (Table 5, Figure 2).

This pattern of *Phragmites* reduction over the course of the control project is also evident from the estimated abundance data (Table 6, Figure 3). In 2002, 16% of the swales were given an abundance score of 4, indicating heavy infestation -- while none of the swales were given this maximum score in 2008 and 2009 (Table 6, Figure 3). Similarly, the number of swales in the second highest abundance category fell from 7 % in 2002 to 0% in 2009 (Table 6, Figure 3). Finally, swales given an abundance ranking of 1 increased over time, from ~13% in 2002, to almost 30% in 2009 (Table 6, Figure 3). During the same seven-year period, the proportion of swales described as having a light infestation or no infestation (abundance score 0 or 1) increases from 71.5 % to 93.2 %. (Table 6, Figure 3).

In linear mixed model regressions (mixed model due to repeated measures occurring over time), year, and number of herbicide applications are both highly significant predictors of *Phragmites* abundance score and *Phragmites* density score: *Phragmites* was increasingly reduced with repeated herbicide treatments over the years of the program (Table 8). The parameter estimates of both independent variables are negative, indicating a decreasing relationship with the dependent variable. In other words, as time and the number of treatments increase, the estimated density and abundance scores decrease (Table 8).

To determine whether herbicide applications have removed *Phragmites* from infested swales, I performed binary logistic regressions on loss of *Phragmites* for each year of the project. Number of treatment applications, distance to marsh trail, swale area, and swale age category were independent variables – potential predictors of whether a swale would lose its *Phragmites* in a given year. For the six possible treatment years, number of treatments was never a negative predictor for retaining *Phragmites* (Table 7).

To investigate further whether herbicide treatments eradicate *Phragmites* from invaded swales, contingency tables were created for each year of the project, with *Phragmites* present/absence as columns and the number of treatments as rows (Table 3). The pattern observed in these tables further supports the results of the binary regressions: herbicide applications are not eradicating *Phragmites* from the majority of treated swales. Few treated swales that were characterized as having *Phragmites* at the start of a treatment interval were characterized as not having *Phragmites* at the end. In the 2003-2004 and 2006-2007 intervals, only three of the total treated swales were described as having *Phragmites* absent. In the 2004-2005 and 2008-2009 intervals, however, 16 and 15 treated swales respectively did not have any *Phragmites* plants after being treated. Between 2005 and 2006, no swales were described as *Phragmites* absent. Finally, the 2007-2008 interval yielded 9 swales with no *Phragmites*.

Community Composition: Response of Vegetation to *Phragmites* Reduction

Thirty-eight different plant species were found during the intensive surveys of 28 swales during the summer of 2010, with fifteen species in the most species-rich swale.

To investigate the effect of herbicide treatment on plant composition, estimated percent cover data of plant species observed during my vegetation surveys of twenty-eight swales was analyzed through hierarchal cluster analysis and multidimensional scaling.

Hierarchal cluster analysis uses a linkage criterion to merge or split observations into clusters based on similarities among them. The analysis of the 2010 survey data employed Euclidean distance as the (dis)similarity metric and the unweighted pair-group averaging (UPGMA or between-groups) method as the linkage criterion. The cluster analysis, as displayed in a dendrogram, shows that the native plant community compositions of non-*Phragmites* swales are distinctly different from those of treated *Phragmites* swales (Figure 5). The first branch of the dendrogram, at a dissimilarity level of 25, separates all the swales that were never invaded by *Phragmites* from all but three of the swales that have had *Phragmites* (Figure 5). The three invaded swales included in the non-*Phragmites* cluster are two swales that have been treated for 6 years, the maximum number of possible treatments, and one other swale that experienced a sharp reduction in *Phragmites* after just two years of treatment.

There is a weak tendency for invaded swales with many treatments to connect earlier with uninvaded swales, and for swales with similar treatment levels to cluster together. As described above, the other swales included in the non-*Phragmites* cluster have received six years of treatment, and the next branching from the non-*Phragmites* cluster, at a species dissimilarity level of 20, contains two swales that have had five years of treatment and one swale with six years of treatment – but also includes one swale that has had only one year of treatment. Clusters of swales with similar treatment levels can

be seen at a dissimilarity of about 7, where three of the four swales that have received one year of treatment are clustered very closely.

Overall, the depicted differences in vegetational composition among swales indicate clearly that the *Phragmites* invasion did change the vegetative community in the invaded swales. However, the cluster analysis suggests only weakly that treatment (and the subsequent reduction *Phragmites* plants) allows native vegetation to return to a vegetative composition similar to that found in non-*Phragmites* swales.

The marked difference between non-*Phragmites* swales and treated, *Phragmites* swales is further supported by the results of the multidimensional scaling (MDS) analysis. MDS attempts to find the structure in a set of distance measures between objects or cases by assigning observations to locations in a conceptual space (two-dimensional for this analysis), such that the distances between points in the space match the given dissimilarities as closely as possible. The distance matrix used for the analysis of the 2010-swale vegetation surveys was created by computing Euclidean distances for all pairs of swales.

The graphical result of the MDS analysis displays the dissimilarities among swales along two vegetation axes (Figure 6). The four non-*Phragmites* swales are close together, along with another swale that has received the maximum possible treatments (6 pesticide applications), again indicating the strong effect of *Phragmites* on native vegetation, but there is no general pattern indicating that treatment to reduce *Phragmites* pushes the associations of native plants closer to a non-*Phragmites* condition.

That treatments to reduce *Phragmites* have not produced a strong return of native plants to a pre-*Phragmites* community structure can be seen more clearly when the

Euclidean distance of each swale from each of the four non-*Phragmites* swales is plotted against the number of treatment applications (Figure 7). The lack of a treatment-related pattern in this plot reappears in a parallel plot using just the Euclidean distances computed with only the non-woody fraction of native plants that might be expected to respond more quickly to the successful reduction of *Phragmites* (Figure 10). Cluster and MDS analysis performed on the non-woody fraction of native plants also produce results that closely resemble that results for the complete native assemblages (compare Figure 8 and Figure 9 for non-woody native plants to Figure 5 and Figure 6 for all native plants).

CHAPTER 6

DISCUSSION

Effect of Herbicide Treatment on Presence/Absence of *Phragmites*

Analysis of the 2002-2009 *Phragmites* presence/absence data and estimated density and abundance scores has demonstrated the control project's success in reducing the number of *Phragmites* plants in interdunal swales of Sandy Neck; but the relationship of number of herbicide treatments to *Phragmites* presence/absence, its estimated density, or abundance is unclear due to the lack of any control swales. The effects of the control project would be seen more clearly if compared to at least one (but preferably more) swale with a Phragmites infestation that did not receive herbicide treatment.

Although control efforts have resulted in a significant decrease in *Phragmites* stems, the plant persists in all but a few treated swales. Using any method, complete eradication is a very high standard of control. Eradication through herbicide treatment can be difficult because of the many variables that can limit the power of the chemical. Timing of the herbicide application, for instance, can restrict its effectiveness. Glyphosate has been demonstrated to be the most effective when applied to *Phragmites* in the fall (Cross and Fleming 1989, Derr 2008, Moreira et al. 1999). At this time in the plant's life

cycle, *Phragmites* is preparing for dormancy and nutrients are being directed to the horizontal rhizomes (Haslam 1969, Norris et al. 2002). Herbicide during this period will potentially be transferred throughout the entire root system, and can result in a high mortality rate (Derr 2008). In more recent years, the Sandy Neck control project has shifted to beginning treatment in the fall; however, prior to about 2006, the widespread, dense, and numerous infestations that existed in the swales required that the small crew begin earlier in the summer, in order to have enough time to potentially treat all infested swales. Initiating treatments prior to the fall in some treatment years may have limited the effectiveness of the herbicide, which may be what allows *Phragmites* to re-emerge. Since many factors have an effect on the success of herbicide treatments, repeat herbicide applications are usually required to gain complete control and eventually eradicate expanding *Phragmites* stands (Havens et al. 1997, Marks et al. 1993, Warren et al. 2001), and this may be the case on Sandy Neck.

The cut and drip application method utilized by the Sandy Neck crewmembers may have also contributed to the reduction of *Phragmites* infestations. Although this method is both time and labor intensive, cut and drip has several advantages: minimizes non-target effects, requires a low concentration of herbicide, and requires a very little amount of chemical (i.e. – 2-3 drops per stem). In addition to minimizing non-target negative effects, the cut and drip method provides a high probability for the chemical to be translocated from the vertical portion of the plant to the belowground, horizontal root system (Norris et al. 2002). The horizontal root system is where new *Phragmites* plants begin development and is usually found several inches below the surface and may extend many meters in every direction (Haslam 1969). By utilizing cut and drip, crewmembers

have made it very likely that not only will new *Phragmites* individuals be killed before growth, but also that the chemical will impact the extensive belowground root system.

The effectiveness of herbicide in reducing *Phragmites* populations has been seen in control projects elsewhere, as well as through various experimental studies. For example, in 1991, at the Brigantine National Wildlife Refuge (New Jersey, USA), aerial applications to tasseling *Phragmites* populations resulted in a 90% mortality rate (Avers et al. 2007). Moreira et al. (1999) employed several, different herbicide application methods, all of which resulted in 2-3 years of control of dense *Phragmites* stands in drainage channels in Portugal. Warren et al. (2001) used experimental plots on the Connecticut River in the Long Island Sound to test the effectiveness of three control methods: mowing, herbicide, and the combination of mowing and herbicide. The researchers concluded that mowing alone was ineffective at controlling *Phragmites* and that herbicide greatly reduced the number of *Phragmites* stems, *Phragmites* stem height, and *Phragmites* cover. Further, a greater reduction in *Phragmites* was observed in experimental plot that received mowing and herbicide. Finally, in a two-year study of herbicide efficacy, Mozdzer et al. (2008) treated experimental *Phragmites* plots in Virginia at various intervals with two concentrations of glysophate. All experimental plots, regardless of concentration, significantly reduced *Phragmites* abundance (Mozdzer et al. 2008).

Successful reduction and control of other invasive plant species besides *Phragmites* has also been achieved through herbicide treatments. In the Hueston Woods State Nature Preserve in Ohio, applications of herbicide to the biennial *Alliaria petiolata* (garlic mustard) decreased germination in the next year's cohort (Carlson &

Gorchov 2004). Community differences in understory vegetation were also documented after the reduction of *Alliaria* (Carlson & Gorchov 2004). In farmlands of southern California, Allen et al. (2005) found a marked decrease in *Bromus tectorum* (cheatgrass) and increased richness of native annuals within experimental units as compared to controls.

Community Composition: Influence of *Phragmites* on Native Vegetation

The vegetational survey performed in 2010 between uninvaded swales and *Phragmites*-invaded, treated swales revealed that the composition of native plant in non-*Phragmites* swales was clearly different from the composition of native plants in *Phragmites* swales. It appears that stands of *Phragmites* in interdunal swales have altered the native plant associations, threatening not only rare and endangered species, but also the integrity of native plant composition throughout the habitat.

Without thorough swale vegetation data collected prior to the control project, interpreting the degree to which *Phragmites* has created differences in native plants is difficult. However, other studies have documented decreases in diversity of native plants and other vegetational changes associated with *Phragmites* expansion. Through literature review, Meyerson et al. (2000) found studies that demonstrated higher species diversity in *Phragmites*-free environments compared to *Phragmites* invaded environments. In Kampoosa Bog ("Bog" is a misnomer: Kampoosa Bog is a wetland) in western Massachusetts, Richburg et al. (2001) found that the composition and structure of graminoid fen communities with *Phragmites* differ from those without. In a survey of 22

salt marshes in Narragansett Bay, Rhode Island, the analysis of plant community composition by Silliman et al. (2004) revealed that *Phragmites* dominance resulted in a large decrease in plant species richness. Finally, *Phragmites* expansion facilitated by disturbance and nutrient enrichment displaced native vegetation in a study by Minchinton et al. (2003).

Community Composition: Response of Vegetation to *Phragmites* Reduction

Alteration of native plant associations due to invasion is a major concern for land managers and conservationists when dealing with a *Phragmites* infestation, because the plant often greatly reduces and excludes native vegetation (Chambers et al. 1999). Although swale vegetation data prior to the initiation of herbicide applications is not available, obvious differences in vegetative composition between swales without *Phragmites* and swales with *Phragmites* was found through the cluster and MDS analysis. What is not clear from this analysis is whether the reduction of *Phragmites* plants allows for the re-emergence of a typical native vegetation association, such as those that occur in swales without *Phragmites*. The absence of historical swale plant data for comparison to these contemporary findings is a major obstacle to the examination of potential native vegetation recovery. In addition, several factors could be involved in the lack of a return to the uninfested plant composition in swales where treatment has reduced *Phragmites*. Herbicide dispersed from a backpack sprayer can harm non-target plant species and to prevent some native species from growing back. In addition, trampling by project crewmembers could retard recovery by suppressing native swale plants, such as

Vaccinium macrocarpon (cranberry) and some grasses, could be suppressed by trampling from foot traffic. Alternatively, more time may simply be needed for the return of native vegetation to become discernible.

Despite factors that may interfere with the re-emergence of native vegetation in Sandy Neck swales, *Phragmites* control programs in other areas suggest that treated swales may recover the native plant association over time. The redevelopment of resident plant species associations after treatment has been observed in other studies of *Phragmites* control programs. In a review of studies investigating *Phragmites* in brackish and freshwater environments, Meyerson et al. (2000) found that plant diversity usually increased -- over time -- after *Phragmites* plants decreased. Data on native species composition and richness collected before, during, and after *Phragmites* removal at two sites in Connecticut by Farnsworth et al. (1999) showed that the richness, density, and evenness of native wetland vegetation increased following removal. While comparing the effectiveness of three control methods for *Phragmites* along the Connecticut River, Warren et al. (2001) reported higher frequencies of *Agrostis stolonifera*, *Spartina patens*, and *Juncus gerardii* after two growing seasons in experimental plots with reduced *Phragmites*.

The analysis of the seven years of control efforts in the interdunal swales of Sandy Neck has demonstrated the negative impact an uncontrolled *Phragmites* population has on native vegetation composition, and favors continued control efforts. The substantial reductions in *Phragmites* density in many swales suggests that control is likely to improve with continued treatment – that eradication may be achieved eventually in many or most of the swales on Sandy Neck. The slight tendency for the plant

associations in swales with reduced *Phragmites* to resemble plant associations in uninvaded swales in turn raises the hope that many swales on Sandy Neck may recover their native vegetation with the future improved control of *Phragmites*.

The need for continued, more detailed, long-term monitoring and data collection is also evident through this analysis. The redevelopment of native vegetation in invaded swales is not apparent, as of yet. However, monitoring of the vegetation into the future will allow investigation and analysis of recovery patterns, as well as other environmental and ecological changes that result from the reduction of *Phragmites*.

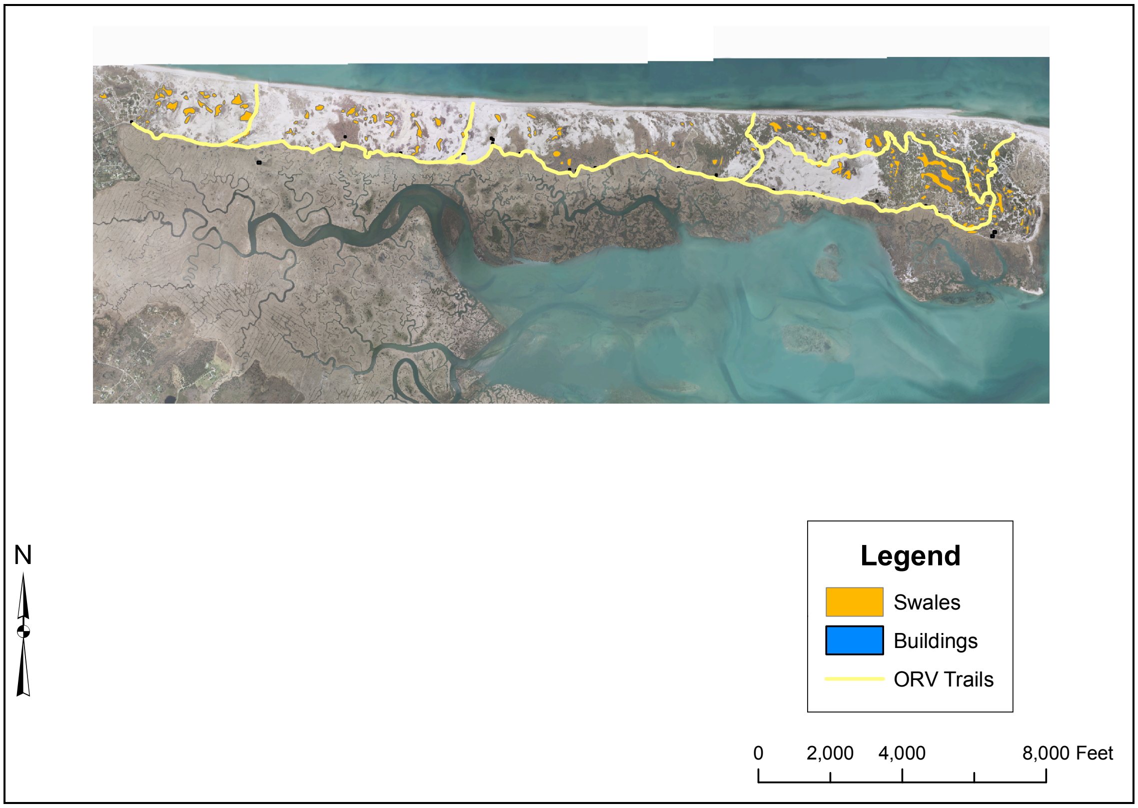

Figure 1: Sandy Neck Barrier Beach with swales, buildings, and ORV trails depicted (aerial photography provided by the Town of Barnstable Department of GIS; coordinate system is NAD 1983 State Plane Massachusetts Mainland FIPS 2001 Feet).

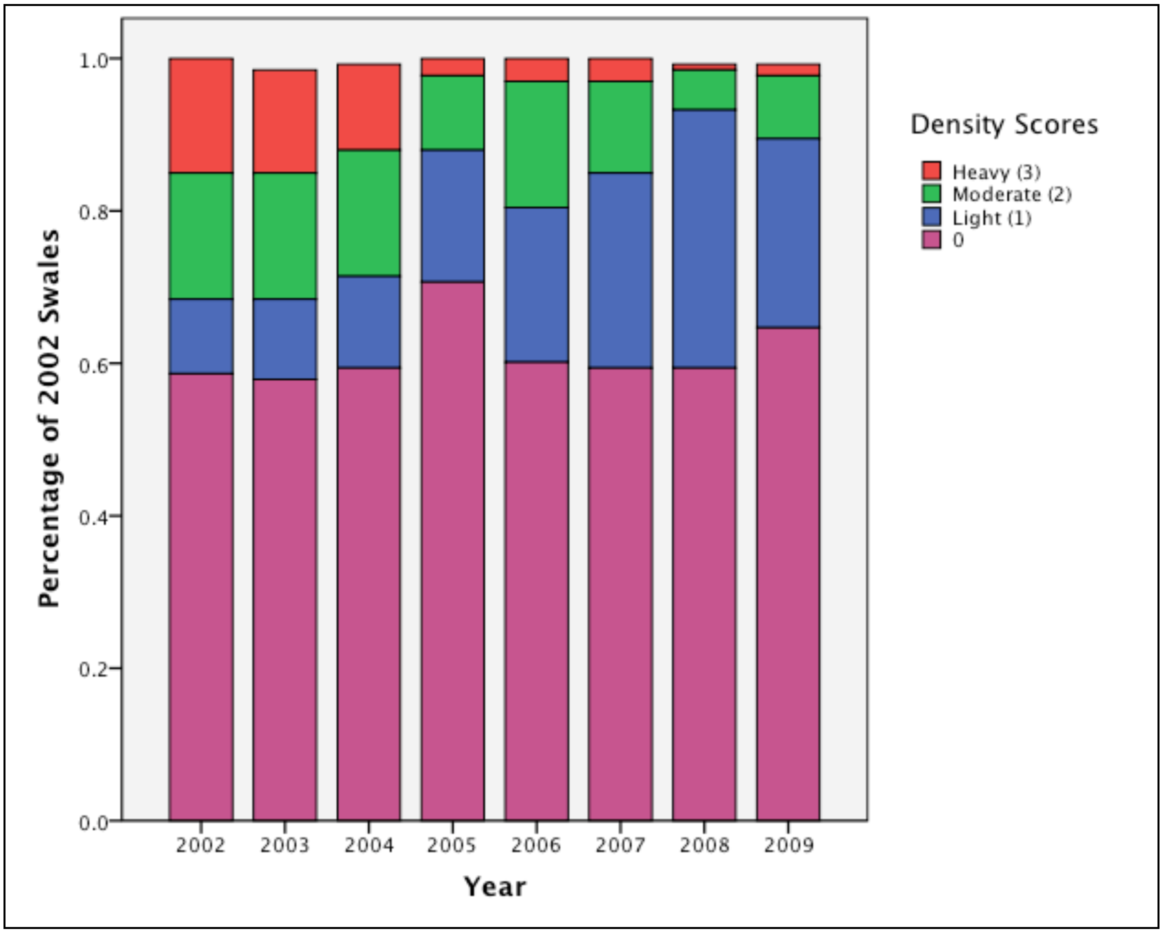

Figure 2: Estimated density (total number of stems per swales area: 0 = none, 1 = light, 2 = moderate, and 3 = heavy) scores from 2002-2009 of the original 2002 swales.

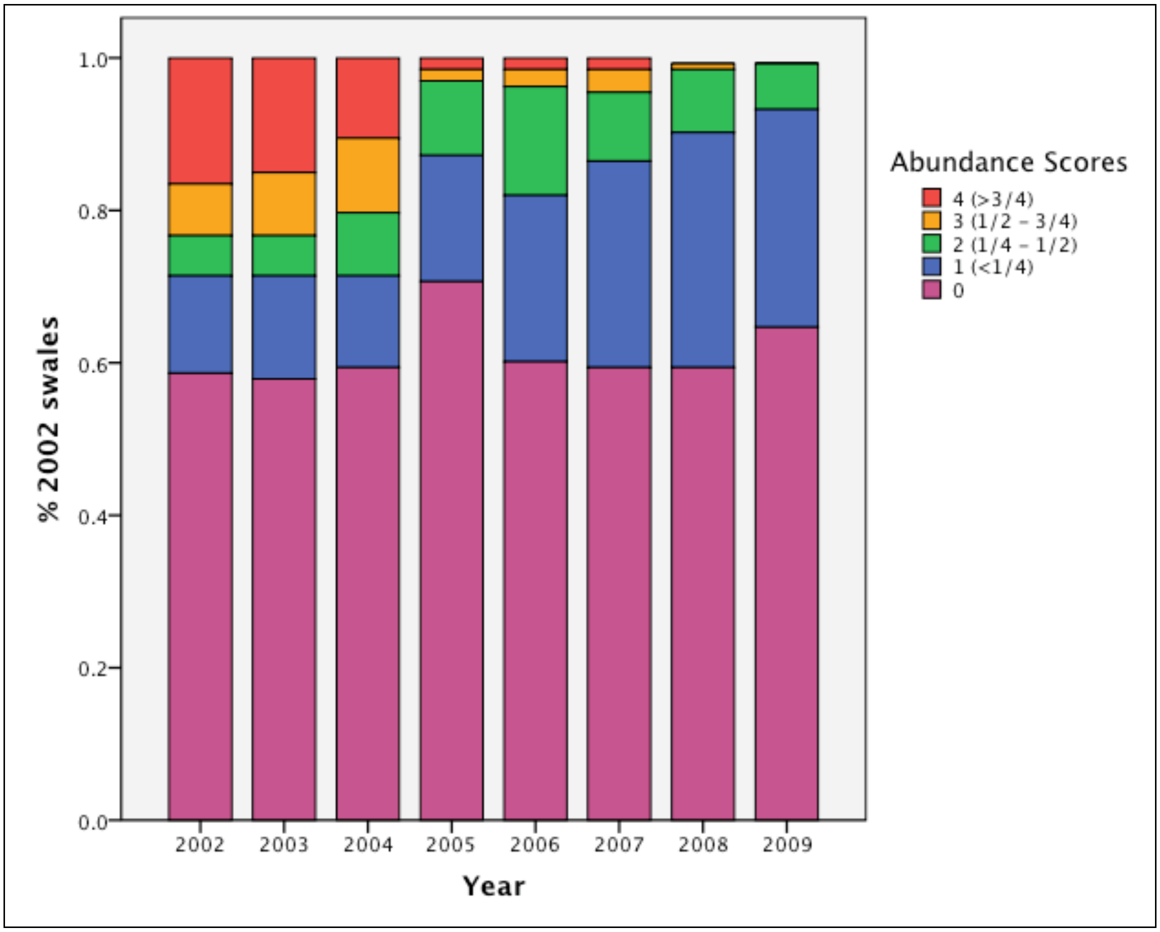

Figure 3: Estimated abundance scores (percent cover: 0 = 0%, 1 = 1-25%, 2 = 25% - 50%, 3 = 50% - 75%, 4 = 75% - 100%) from 2002-2009 of the original 2002 swales.

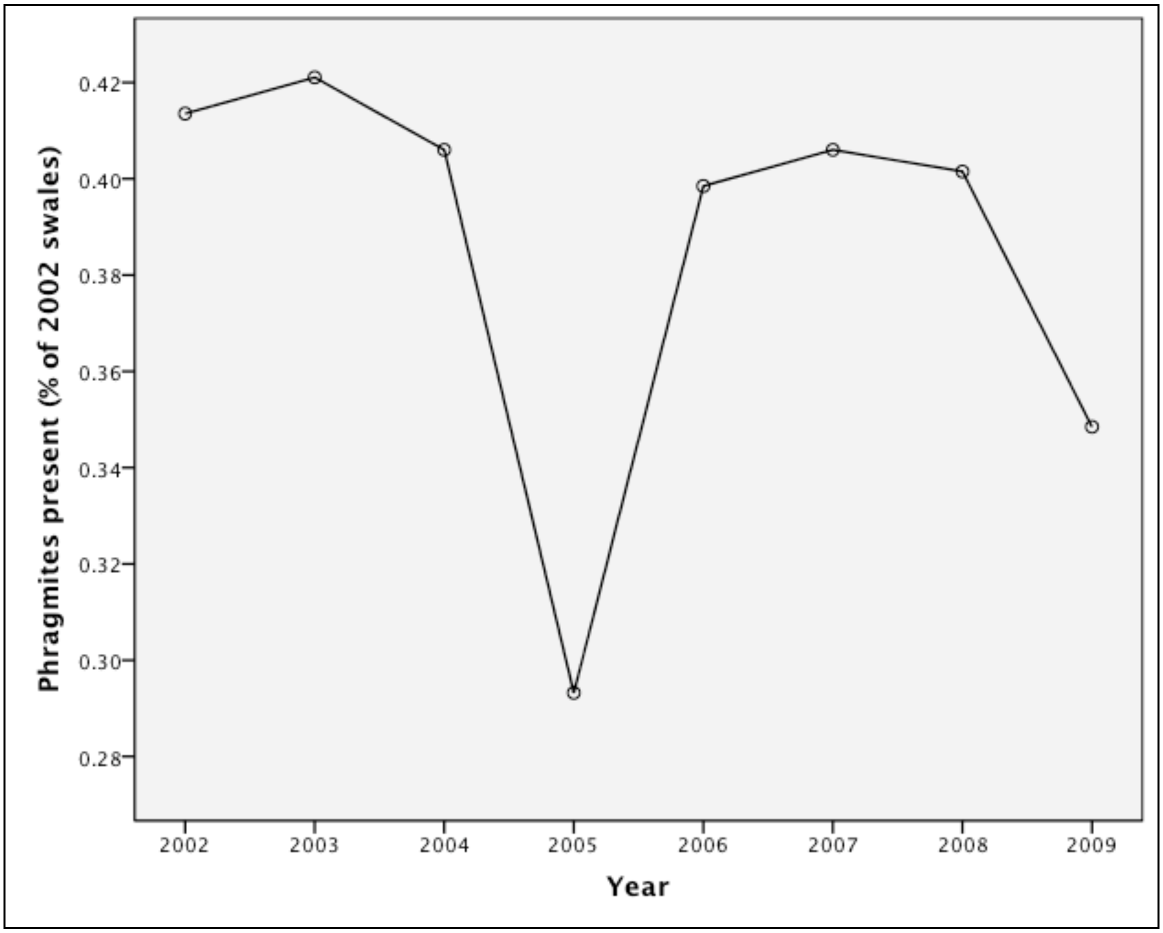

Figure 4: Percentage of 2002 swales that were categorized as having *Phragmites* present from 2002-2009.

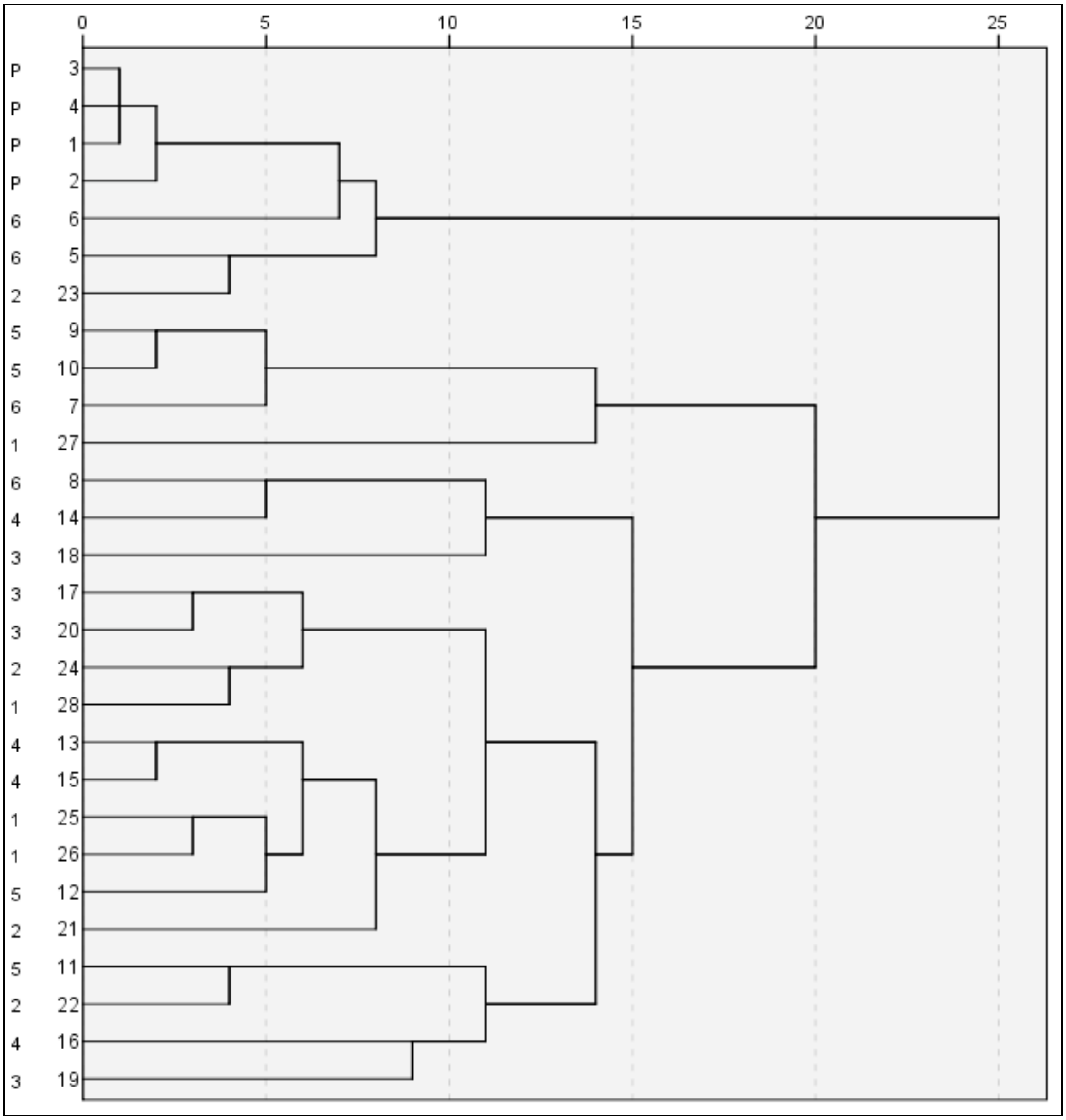

Figure 5: Dendrogram of the 28 surveyed swales produced from hierarchal cluster analysis. Left column indicates the number of treatments, where P represents uninvaded swales and the right column automatically generated during analysis.

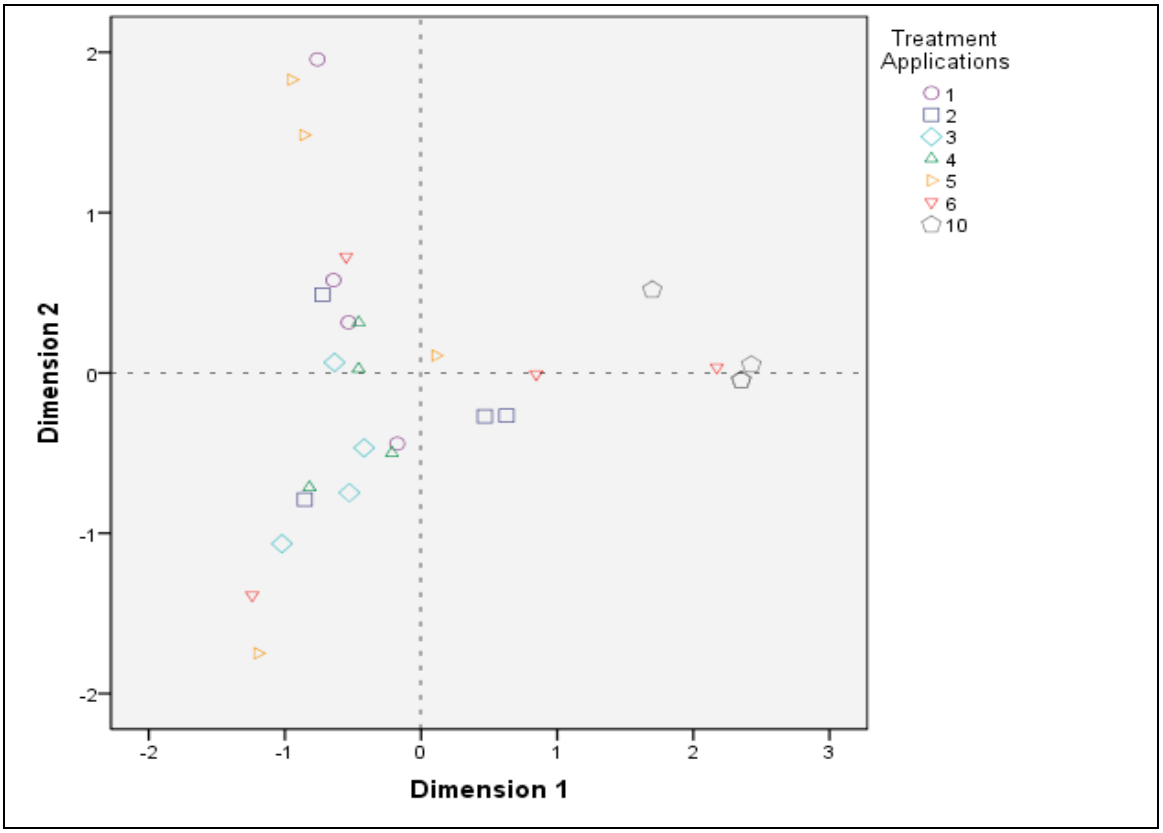

Figure 6: Graphical output generated by multidimensional scaling analysis, depicting the dissimilarities of surveyed swales along two vegetational dimensions.

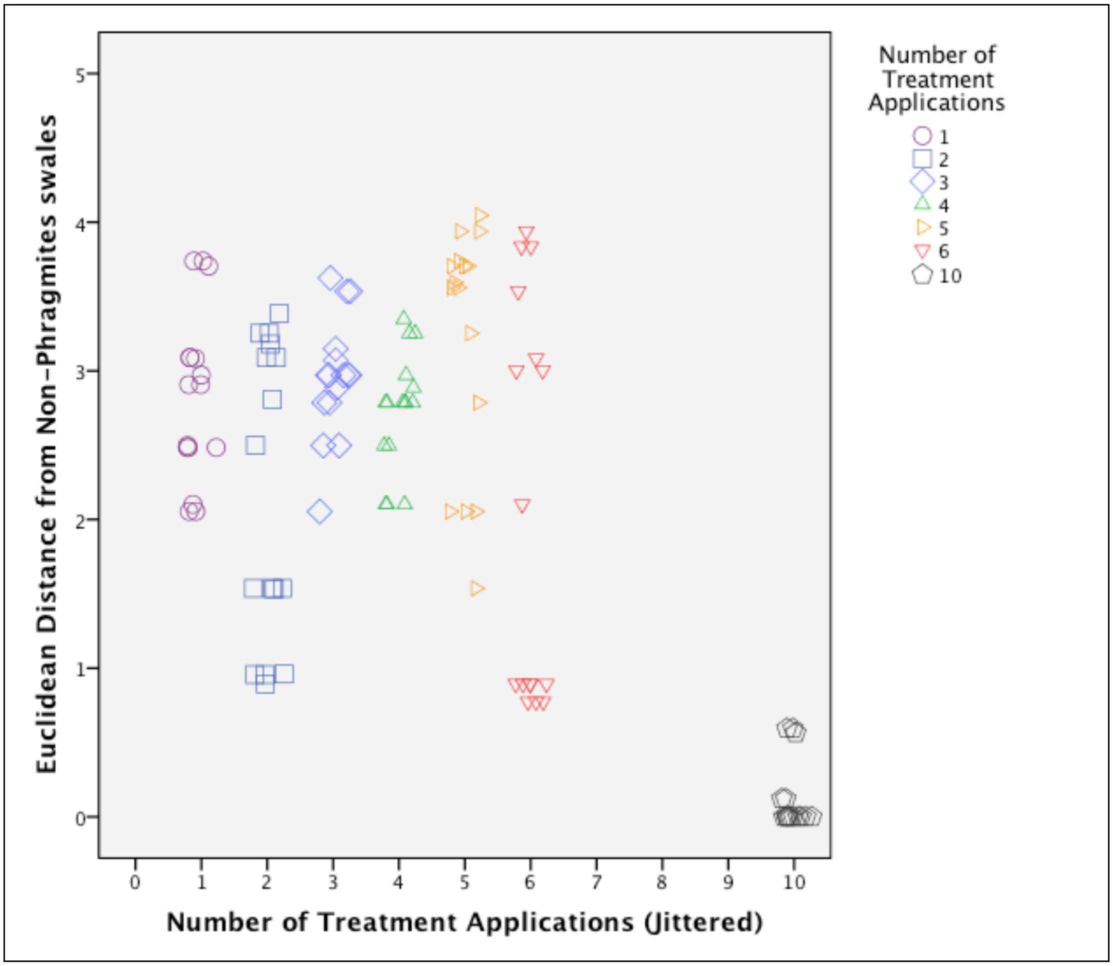

Figure 7: Euclidean distance of *Phragmites*-invaded surveyed swales from non-*Phragmites* surveyed swales. The number of treatment applications is jittered. 10 is an arbitrary label to represent surveyed swales that have never been invaded by *Phragmites*. 112 data points displayed.

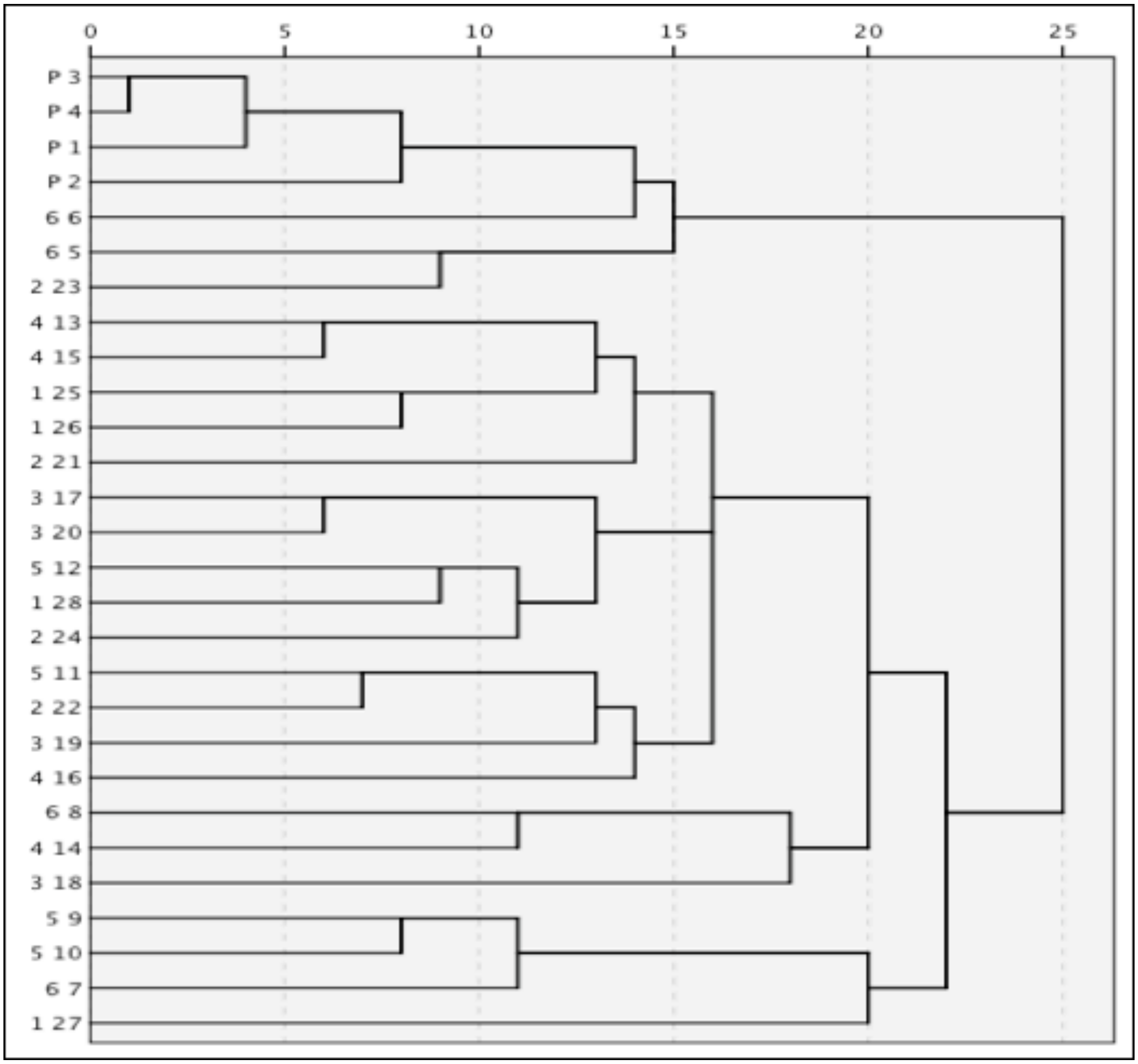

Figure 8: Dendrogram of 28 surveyed swales produced from hierarchal analysis excluding all woody species. Left column indicates the number of treatments, where P represents uninvaded swales and the right column automatically generated during analysis.

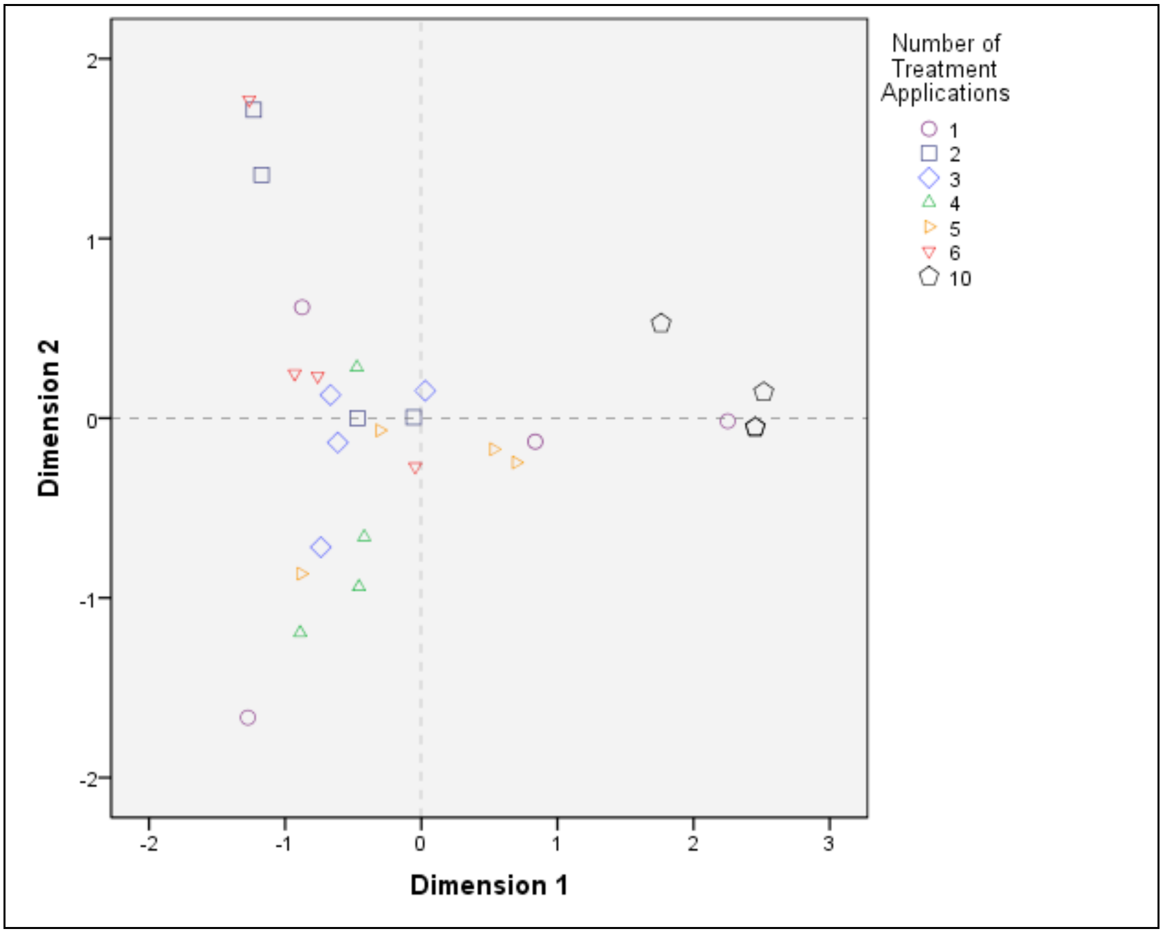

Figure 9: Graphical output generated by multidimensional analysis where all woody species were excluded, depicting the dissimilarities of surveyed swales along two vegetational dimensions.

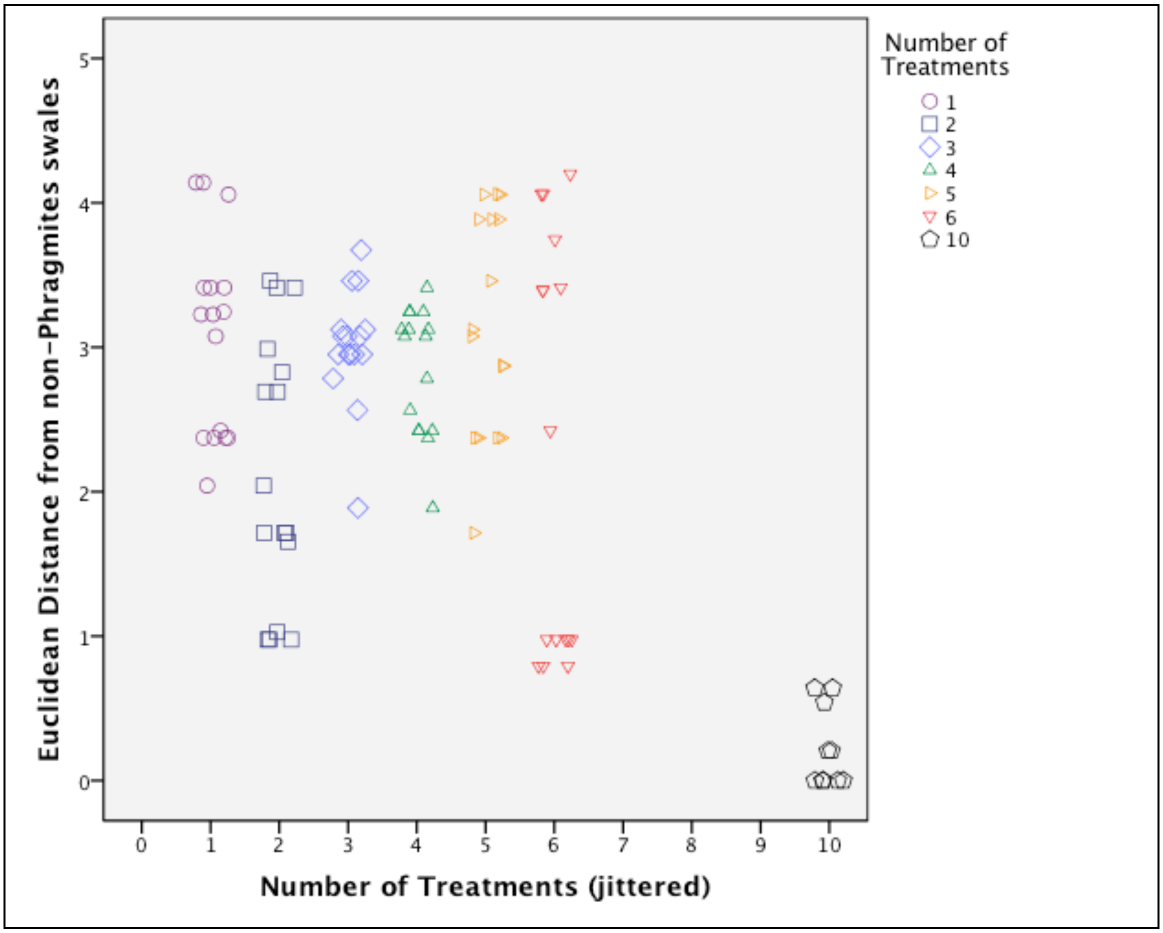

Figure 10: Euclidean distances of native plant communities of *Phragmites*-invaded swales from non-*Phragmites* swales excluding all woody species. The number of treatment applications is jittered. 10 is an arbitrary label representing surveyed swales that have never been invaded by *Phragmites*. 112 data points displayed.

Table 1: State listed rare and endangered species found on Sandy Neck Barrier Beach, Cape Cod, Massachusetts

Scientific Name	**Common Name**	**Life Form**	**Status**
Abagrotis crumbi benjamani	Coastal heathland cutworm	Moth	Special Concern
Charadrius melodus	Piping plover	Bird	Threatened
Drosera filiformis	Thread-leaved sundew	Plant	Special Concern
Malaclemys terrapin	Diamondback terrapin	Reptile	Threatened
Sabatia kennedyana	Plymouth Gentian	Plant	Special Concern
Scaphiopus holbrookii	Eastern spadefoot toad	Amphibian	Threatened
Setaria geniculata	Bristly foxtail	Plant	Special Concern
Sterna antillarum	Least tern	Bird	Special Concern
Sterna hirundo	Common tern	Bird	Special Concern

Table 2: List of plant species identified during 2010 survey of 28 interdunal swales

Scientific Name	**Common Name**
Agrostis hyemalis	Winter bentgrass
Ammophila breviligulata	Beach grass
Atriplex patula	Spear saltbush
Carex silicea	Beach sedge
Cladium mariscoides	Smooth sawgrass
Cyperus dentatus	Nut sedge
Drosera intermedia	Spatulate-leaved sundew
Hudsonia tomentosa	Beach heather
Juncus canadensis	Canadian rush
Juncus geradii	Saltmeadow rush
Juncus greenei	Greene's rush
Juncus pelocarpus	Mud rush
Juniperus virginiana	Eastern red cedar or juniper
Limonium carolinianum	Lavender thrift
Lycopodium inundatum	Club moss
Lycopus uniflorus	Northern bugleweed
Lythrum salicaria	Purple loosestrife
Myrica pensylvanica	Northern bayberry
Onoclea sensibilis	Sensitive fern
Phalaris arundinacea	Reed canary grass
Phragmites australis	Common reed
Pinus rigida	Pitch pine
Pluchea purpurascens	Sweetscent
Quercus coccinea	Scarlet oak
Salix cinerea	Gray willow
Schizachyrium scoparius	Little Bluestem
Scirpus americanus	Chairmaker's Bulrush
Scirpus cyperinus	Woolgrass
Smilax rotundifolia	Roundleaf Greenbrier
Solidago tenuifolia/ Euthamia tenuifolia	Slender fragrant goldenrod
Spartina spp.	Saltmarsh hay
Spiraea tomentosa	Steeplebush
Toxicodendron radicans	Poison ivy
Typha angustifolia	Narrowleaf cattail
Vaccinium macrocarpon	American cranberry
Xyris torta	Yellow-eyed grass

Table 3: Contingency tables of *Phragmites* presence/absence and number of treatments from 2003-2009 (+ indicates *Phragmites* present, - indicates *Phragmites* absent).

2003	Number of Treatments	*Phragmites* (-)	*Phragmites* (+)	SUM
	0	1	40	41
	1	0	14	14
	SUM	1	54	55
2004	Number of Treatments	*Phragmites* (-)	*Phragmites* (+)	SUM
	0	2	28	30
	1	1	12	13
	2	0	13	13
	SUM	3	53	56
2005	Number of Treatments	*Phragmites* (-)	*Phragmites* (+)	SUM
	0	13	3	16
	1	1	31	32
	2	1	12	13
	3	1	11	12
	SUM	16	57	73
2006	Number of Treatments	*Phragmites* (-)	*Phragmites* (+)	SUM
	0	--	--	0
	1	0	3	3
	2	0	31	31
	3	0	12	12
	4	0	11	11
	SUM	0	57	57
2007	Number of Treatments	*Phragmites* (-)	*Phragmites* (+)	SUM
	0	1	9	10
	1	0	13	13
	2	1	30	31
	3	0	15	15
	4	1	10	11
	5	0	0	0
	SUM	3	77	80

Table 3 (continued)

2008			
Number of Treatments	*Phragmites* (-)	*Phragmites* (+)	SUM
0	--	--	--
1	5	0	5
2	1	9	10
3	2	10	12
4	0	29	29
5	1	13	14
6	0	9	9
SUM	9	70	79
2009			
Number of Treatments	*Phragmites* (-)	*Phragmites* (+)	SUM
0	--	--	--
1	2	0	2
2	4	2	6
3	0	6	6
4	5	12	17
5	4	23	27
6	0	10	10
7	0	9	9
SUM	15	62	77

Table 4: Percentage of original 2002 swales categorized as having *Phragmites* (2002-2009)

Year	Percentage of original 2002 swales categorized as *Phragmites* present
2002	0.414
2003	0.42
2004	0.406
2005	0.293
2006	0.398
2007	0.406
2008	0.402
2009	0.348

Table 5: Average estimated *Phragmites* density scoring of the original 2002 swales from 2002-2009 (scores: 0 = none; 1 = light; 2 = moderate; 3 = heavy)

Year	0	1	2	3
2002	0.586	0.098	0.165	0.150
2003	0.579	0.105	0.165	0.135
2004	0.594	0.120	0.165	0.113
2005	0.707	0.173	0.098	0.023
2006	0.602	0.203	0.165	0.030
2007	0.594	0.256	0.120	0.030
2008	0.594	0.338	0.053	0.008
2009	0.647	0.248	0.083	0.015

Table 6: Average estimated *Phragmites* abundance scoring of the original 2002 swales from 2002-2009 (scores: 0 = none; 1 = <¼; 2 = ¼ - ½; 3 = ½ - ¾; 4 = >¾)

Year	0	1	2	3	4
2002	0.586	0.128	0.053	0.068	0.165
2003	0.579	0.135	0.053	0.083	0.150
2004	0.594	0.120	0.083	0.098	0.105
2005	0.707	0.165	0.098	0.015	0.015
2006	0.602	0.218	0.143	0.023	0.015
2007	0.594	0.271	0.090	0.030	0.015
2008	0.594	0.308	0.083	0.008	0.000
2009	0.647	0.286	0.060	0.000	0.000

Table 7: Binary logistic regressions for 2003-2009 *Phragmites* presence/absence (boldface values are significant; * indicates that binary logistic regression could not be performed)

Year	Variables	B	Exp(B)	df	Sig	Std. Error
2003	Number of Treatments	115.887	4.968×10^{-51}	1	0.988	7516.003
	Distance to Marsh Trail	226.542	2.432×10^{98}	1	0.988	14707.848
	Area	-18.283	1.148×10^{-8}	1	0.991	1586.337
	Age Category	-64.142	1.392×10^{-28}	1	0.992	6387.692
	Constant	98.783	7.963×10^{42}	1	0.990	7894.171
2004	Number of Treatments	0.489	1.630	1	0.591	0.908
	Distance to Marsh Trail	0.918	2.504	1	0.617	1.837
	Area	0.167	1.182	1	0.813	0.708
	Age Category	1.436	4.206	1	0.289	1.355
	Constant	1.274	3.574	1	0.343	1.344
2005	**Number of Treatments**	**1.602**	**4.965**	**1**	**0.007**	**0.598**
	Distance to Marsh Trail	**2.694**	**14.788**	**1**	**0.052**	**1.386**
	Area	0.155	1.168	1	0.779	0.553
	Age Category	0.629	1.876	1	0.474	0.879
	Constant	-1.881	0.152	1	0.087	1.098
*2006	Number of Treatments	--	--	--	--	--
	Distance to Marsh Trail	--	--	--	--	--
	Area	--	--	--	--	--
	Age Category	--	--	--	--	--
	Constant	--	--	--	--	--
2007	Number of Treatments	-0.421	0.656	1	0.612	0.831
	Distance to Marsh Trail	-0.196	0.822	1	0.922	1.992
	Area	-0.295	0.745	1	0.619	0.592
	Age Category	-18.263	1.171×10^{-8}	1	0.998	7242.907
	Constant	22.951	9.28×10^{-9}	1	0.997	7242.907

Table 7 (continued)

Year	Variables	B	Exp(B)	df	Sig	Std. Error
2008	**Number of Treatments**	**0.794**	**2.212**	**1**	**0.033**	**0.373**
	Distance to Marsh Trail	**-2.112**	**0.121**	**1**	**0.024**	**0.936**
	Area	0.165	1.180	1	0.587	0.304
	Age Category	0.627	1.873	1	0.454	0.838
	Constant	1.249	3.486	1	0.269	1.129
2009	Number of Treatments	0.424	1.528	1	0.063	0.227
	Distance to Marsh Trail	-1.250	0.287	1	0.076	0.703
	Area	0.127	1.135	1	0.490	0.184
	Age Category	-0.687	0.503	1	0.304	0.669
	Constant	0.985	2.678	1	0.345	1.043

Table 8: Linear mixed model regressions for estimated density and abundance scoring from 2002-2009 (boldface values are significant)

Density

Parameter	Estimate	Std. Error	df	t	p
Intercept	50.884	19.008	988.818	2.677	0.008
Number of Treatments	**-0.171**	**0.020**	**1059.072**	**-8.771**	**6.96×10^{-18}**
Year	**-0.025**	**0.009**	**988.850**	**-2.629**	**0.009**

Abundance

Parameter	Estimate	Std. Error	df	t	p
Intercept	94.811	23.152	997.975	4.095	4.56×10^{-5}
Number of Treatments	**-0.230**	**0.024**	**1070.933**	**-9.691**	**2.39×10^{-21}**
Year	**-0.047**	**0.012**	**998.018**	**-4.050**	**5.51×10^{-5}**

Illustration 1: Interdunal swale on Sandy Neck Barrier Beach (photo by D. Tomassi)

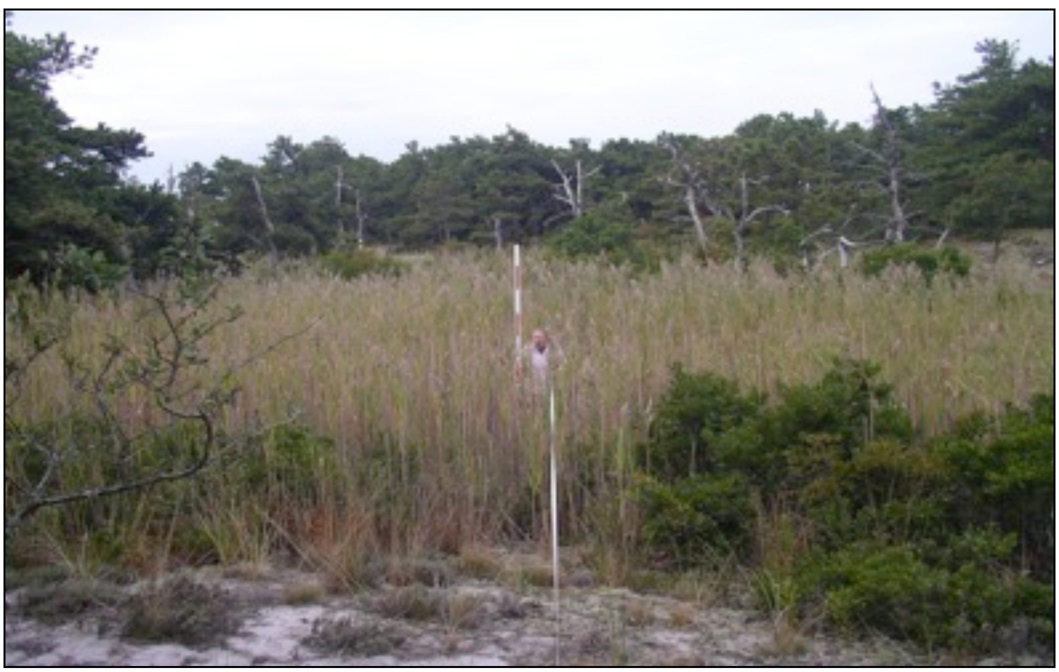

Illustration 2: *Phragmites* infested swale in 2004 (photo by The Nature Conservancy)

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