1-2014

Analysis of Herbicide Treatment Effectiveness on Common Reed (Phragmites australis) of Delaware Bay Salt Marshes

Laura Rosa Ruggeri
Montclair State University

MONTCLAIR STATE UNIVERSITY

Analysis of Herbicide Treatment Effectiveness on Common Reed (*Phragmites australis*) of Delaware Bay Salt Marshes

by

Laura Rosa Ruggeri

A Master's Thesis Submitted to the Faculty of

Montclair State University

In Partial Fulfillment of the Requirements

For the Degree of

Master of Science

January 2014

College of Science and Mathematics

Department of Biology and
Molecular Biology

Thesis Committee:

[redacted]

Dr. Meiyin S. Wu
Thesis Sponsor

[redacted]

Dr. Paul Bologna
Committee Member

[redacted]

Dr. Haiyan Su
Committee Member

Analysis of Herbicide Treatment Effectiveness on Common Reed (*Phragmites australis*) of Delaware Bay Salt Marshes

Abstract

Management of *Phragmites australis* (Cav.) Trin. ex Steud., or common reed, an invasive species within the Delaware Bay, U.S. has been ongoing since 1994 as part of the Estuary Enhancement Program (EEP) for Public Service Enterprise Group (PSEG). *Phragmites* is known to alter the habitat by creating a monoculture, increasing sediment trapping, and decreasing water circulation resulting in decreased biodiversity. Herbicide treatment at EEP *Phragmites*-dominated sites began as a means to mitigate for loss of nekton species resulting from operations of the Hope Creek-Salem Generating Station once-through cooling system. Using ArcGIS, effectiveness of herbicide treatment was compared at two of EEP's *Phragmites*-dominated sites in the Delaware Bay. The goal of this research was to assess effectiveness of aerial application of glyphosate-based herbicide by comparative analysis of mapped vegetation communities. Inundation frequency was incorporated into the analysis to assess if location on the marsh plain has an effect on treatment effectiveness. The results of this research demonstrated that vegetation cover changed significantly as a result of the herbicide treatment with more desirable (*Spartina* spp., etc.) and less undesirable (*Phragmites australis*) plants. Areas that did not receive any treatment, tended to produce an undesirable outcome (more *Phragmites*). No significant difference was observed among treatments of one, two or three applications during the study period. Unvegetated areas did not significantly differ throughout the various treatments over the study period. The results suggest that inundation did not significantly influence effectiveness of treatment. Any frequency of herbicide treatment used for restoration in a salt marsh will reduce *Phragmites* cover; however, depending on restoration goals and timeline the use of additional applications should be considered.

Keywords

Phragmites australis; wetland restoration; Estuary Enhancement Program; herbicide; glyphosate

ANALYSIS OF HERBICIDE TREATMENT EFFECTIVENESS ON COMMON REED (*PHRAGMITES AUSTRALIS*) OF DELAWARE BAY SALT MARSHES

A THESIS

Submitted in partial fulfillment of the requirements

For the degree of Master of Science

by

LAURA ROSA RUGGERI

Montclair State University

Montclair, NJ

2014

Acknowledgement

I would like to thank Drs. Meiyin Wu, Paul Bologna, Haiyan Su and Michael Weinstein for all their support, advice and guidance. I would also like to thank Mr. Ray Hinkle from URS Corporation for sharing his knowledge, *Phragmites* expertise and permitting my use of the data. I would not have been able to accomplish this project without your guidance. I would like to express my gratitude to PSEG's Estuary Enhancement Program for allowing use of data and providing me with years of experience at the restoration sites. I would also like to extend my appreciation to Bernabas Wolde for your help with statistical analysis and Taralyn Myers for your assistance with the GIS aspect of this project. Lastly, I would like to thank my loving husband and family for all your support and understanding along this journey.

TABLE OF CONTENTS

List of Figures — Pages

List of Tables — Pages

INTRODUCTION

Phragmites australis

Phragmites australis (Cav.) Trin. ex Steud., or common reed, (herein referred to as *Phragmites*) possesses an invasive genetic strain that has colonized numerous marshes along the eastern seaboard (Chambers et al. 1999) and is considered a noxious weed in many states (Uva et al. 1997). *Phragmites* is a perennial grass that produces seeds; however, they primarily colonize locally by producing sturdy rhizomes (Chambers et al. 1999). The stout rhizomes are usually 20-100 centimeters (cm) below the surface comprising of both vertical and horizontal rhizomes with vertical rhizomes growing rapidly and producing dense stands that grow up to 4-meter tall (Cross and Fleming 1989; Olson 2007). These dense belowground systems increase sediment trapping, leading to decreased water circulation and a reduction of planktonic and nektonic species throughout the ecosystem (Hellings and Gallagher 1992; Weinstein et al. 2009).

Phragmites distribution and abundance have increased throughout the continental United States over the past 150 years with new genetic lineages introduced increasing genetic diversity (Saltonstall 2003). Use of DNA sequence data defined the various haplotype populations throughout North America. Eleven haplotypes were found in North America and are considered to be native exhibiting strong genetic structure or similar pattern in the genetic makeup of the various populations between three geographic regions: Atlantic Coast, Midwest or West (Saltonstall 2003). The non-native/introduced haplotype (identified as M) dominates most of the Atlantic Coast and has apparently eliminated native lineages throughout the region (Saltonstall 2003). This non-native M haplotype is common in Europe and continental Asia and was identified as being introduced to North America in the late 1700's or early 1800's (Saltonstall 2003).

Phragmites Invasion

Human populations expanding to coastal areas and modifying wetlands facilitated the aggressive expansion of *Phragmites* throughout North America (Chambers et. al. 1999; Meyerson et al. 2000; Philipp 2005). As *Phragmites* becomes more prevalent in coastal areas, it becomes difficult to find natural tidal marshes dominated by native *Spartina alterniflora*, *S. cynosuroides*, and *S. patens* (Burdick and Konisky 2003; PSEG 2010). Native habitat throughout the Delaware Bay has been altered over the years by development along its shoreline (Philipp 2005). Changes in edaphic conditions, nutrient cycling, sediment deposition, flora and fauna diversity, and salinity levels allowed for *Phragmites* to expand throughout the region (Meyerson et al. 2000; Silliman and Bertness 2004). Additionally, disturbances often create well-drained features, which lower sulfide concentrations, making the site suitable for *Phragmites* invasion (Bart and Hartman 2000). *Phragmites* then continues to expand into more hostile areas through translocation from well-drained areas. However, Lathrop et al. (2003) found evidence that *Phragmites* establishment can occur at many landscape positions via various methods; *Phragmites* can spread within a marsh via colonization (new patches), linear clonal growth (along a preferred axis), or random circular clonal growth (non-directional).

For centuries, salt marshes in New Jersey were diked for commercial farming of salt hay and impounding for land reclamation for waterfowl and muskrat populations (Weinstein et al. 2000). In the later part of the 20th century, the non-native variety of *Phragmites* began appearing and colonizing those commercially diked areas (Teal and Peterson 2005; Philipp 2005; Hinkle and Mitsch 2005). Using field experiments, Burdick et al. (2003) studied the causes of *Phragmites* expansion and concluded that human impacts to habitat in conjunction with the plants' superior competitive abilities were key factors that explained its rapid spread throughout both tidal and freshwater wetlands.

Calculating rates of expansion is important to understand the rapid spread of *Phragmites*, given its monotypic nature and aggressive rhizomatous colonization. To assess *Phragmites* invasion aerial photography is often used. Numerous studies found that colonization rates decreased or stabilized with well-established colonies and had comparable results (Bailey 2007; Lathrop et al. 2003; Rice et al. 2000).

<u>Ecological Impacts</u>

The ecological implications of *Phragmites* dominance within an ecosystem can be seen at various levels from invertebrates to avian species and *Phragmites* has been recognized as a problematic, invasive plant. Many state and federal agencies including the U.S. Fish and Wildlife Service (USFWS), particularly in the Atlantic coastal and Great Lakes states, list *Phragmites* as invasive and/or nuisance (Kay 1995; Weinstein et al. 2009). While *Phragmites* does provide benefits to some wildlife species, such as marsh wren (*Cistothorus palustris*) and red-winged blackbird (*Agelaius phoeniceus*), it ultimately creates an impenetrable, monoculture with low diversity providing little ecological value to a wide variety of wildlife (Meyerson et al. 2000; Olson 2007). Wetlands composed primarily of *Phragmites* compared to wetlands dominated by cordgrass meadows (*Spartina* spp.) have lower species richness overall (Meyerson et al. 2000). *Phragmites* results in reduced animal mobility through the marsh ecosystem as a result of the plants' stem density and height. Avian species categorized as generalists, seek refuge in *Phragmites* stands and reduction of *Phragmites* coverage resulted in increased avian species' richness and abundance (Seigel et al. 2005). As *Phragmites* increases within the tidal marsh, it physically changes the structure of the vegetation and macroinvertebrate communities, replacing endemic species, affecting the ability for many bird species to forage, nest, and survive (Schaumburg et al. 2011). Additionally, *Phragmites* reduces the amount of resources that avian species can utilize and impedes several types of birds from foraging on the surface of the marsh (Seigel et al. 2005). One of the existing studies on salt marsh restoration (previously salt hay farm) demonstrated that as tidal flow returned and vegetation changed to smooth cordgrass (*Spartina alterniflora*), an increase in avian abundance, richness and frequency of occurrence was observed (Brawley et al. 1998).

Phragmites expansion also directly impacts fish biodiversity and abundance. Salt marsh fish (*Fundulus* spp.) populations were negatively impacted with increased amount of *Phragmites* (Hunter et al. 2006). Although little or no effect on larger fish and decapods crustaceans was observed, an overall negative effect of *Phragmites* on larval and small juvenile fish was evident (Able and Hagan 2000). As *Phragmites* invades a marsh and becomes the dominant species, there is an increase in aboveground biomass, stem density, and accumulated litter causing changes in elevation and drainage patterns, thus influencing flood dynamics and providing altered hydroperiods. As a result, marsh usage by *Fundulus* spp. and other taxa decreases resulting in increased rarity and average smaller sizes compared to fish species in a native *Spartina*-dominated marsh (Hunter et al. 2006). Overall *Phragmites'* negative impacts are more pronounced in early life stages of *Fundulus* ssp. and other species. Weinstein et al. (2000, 2005, 2009) reported fish from a *Phragmites*-dominated marsh have lower lipid contents, or otherwise lower energy reserves for survivability than fish from a *Spartina*-dominated marsh. Mummichogs (*Fundulus heteroclitus*) from a *Spartina*-dominated marsh were better equipped for reproduction and overwintering compared to those residing in *Phragmites*-dominated marsh (Weinstein et al. 2009).

Although some studies have suggested against complete eradication due to the plants' beneficial effects with stabilizing marsh banks, buffering storm surges and/or providing refuge for some wildlife (Hellings and Gallagher 1992; Cross and Fleming 1998), there is abundant information that suggests complete control of *Phragmites* results in increased species diversity and richness (Kay 1995; Meyerson et al. 2000; Seigel et al. 2005; Schaumburg et al. 2011).

Phragmites Management

There are many different methods to control an undesirable species ranging from mechanical to biological to chemical. Mechanical methods of control might include mowing, discing, bulldozing, crushing, or physical alterations consisting of shading, dredging, water level fluctuations, and burning (Cross and Fleming 1989). Mowing appears to be more effective in dry areas when implemented in the late summer for consistent years, while at flooded sites the use of a rotary ditch digger is effective in chopping up the rhizomes (Cross and Fleming 1989). Prescribed burns produce variable results with associated safety risks for humans, wildlife, and nearby communities (Fredrick 2000). Water-level manipulation is another effective mechanical control method for younger stands; however, well-established stands are likely to be unaffected by this method because *Phragmites*' runners are not able to anchor if the water level is greater than 30-cm, keeping the stand from expanding further. Increasing tidal exchange and therefore increasing salinity levels can be another method of physico-chemical control (Cross and Fleming 1989).

Biological control would require use of organisms (i.e. insects, rodents, birds and goats) to feed on or infect *Phragmites*, which is rarely practical and only cause incidental and localized damage to the plant (Cross and Fleming 1989). There are 26 herbivorous arthropods known to consume *Phragmites*, but only five are known to be native (Casagrande et al. 2003). Among them, *Rhizedra lutosa* is a non-native herbaceous arthropod recently introduced from Europe that is known to adversely impact *Phragmites*. However, this insect is known to feed on the rhizomes of the plant, which could potentially reduce *Phragmites'* colonization rates. *Rhizedra lutosa* is not having a significant impact on populations of *Phragmites* in North America due to low densities of the moth (Casagrande et al. 2003). Fredrick (2000) reported another European moth, *Archanara geminipuncta*, a potential biological control agent in Europe, has been observed to result in 96% damage to *Phragmites* shoots during outbreaks. However, this species is not present in North America and is not available as a treatment option.

In the United States, herbicide is commonly used to control *Phragmites* since neither a suitable biological predator nor safe or effective mechanical methods have yet been identified (Fredrick 2000). There have been a number of studies evaluating herbicides for control of *Phragmites*. Special attention was paid to the long-term effectiveness of any herbicide control to assess success and revise management plan in restoration (Back and Holomuzuki 2008). One of the more commonly used herbicides is a glyphosate-based herbicide that is commercially known as Rodeo® (Dow AgroSciences, Indiana), an aquatic form of Roundup®. Glyphosate is a broad-spectrum herbicide composed of three parts: the parent acid, salt, and proprietary components. The parent acid is the active ingredient, while the salt is used to stabilize the product. The proprietary component can be a surfactant or a defoamer, which is used to enhance foliar penetration of glyphosate and make the product more convenient to handle (Hartzler et al. 2006).

Riemer (1976) examined different application rates and evaluated the various effects of glyphosate application to *Phragmites*. Successive years of application were very effective with optimum rates measuring between 4 to 6 pounds acid equivalent per acre. Although Riemer's (1976) study only observed treatment effectiveness over a period of four years, the plots that received two consecutive years of herbicide applications were free of *Phragmites*. Similarly, Moreira et al. (1999) found that glyphosate application over 2-3 years when applied up to 1.62 kilograms per hectare (kg/ha) successfully managed *Phragmites*. Regardless of spray volume, type of sprayer, or time of treatment, control could be achieved with similar efficacies observed if cutting was incorporated into the herbicide application (Moreira et al. 1999). Higher rates of application produced only slightly better results; however, it will result in a greater financial burden and is not recommended for long-term management.

With each control method there are particular risks and benefits associated, which need to be considered prior to developing a *Phragmites* control plan. As discussed, mechanical control mechanisms either pose greater public risks (i.e. burning) or have variable results depending on site conditions (dry vs. flooded). Biological mechanisms appear to produce localized and incidental impacts to colonies for a relatively low cost, while chemical application was found to be most effective at a much higher cost. When considering glyphosate herbicide application it is important to know glyphosate is a nonselective herbicide targeting all grasses and broad-leaved emergents (Tiner 1995). Glyphosate will kill non-target plants growing within the spraying area. Yet, it degrades quickly into natural contents and is non-toxic to aquatic animals (Tiner 1995).

When selecting the appropriate control method, site-specific characteristics need to be included in the assessment prior to designing a management plan (Fredrick 2000). Whenever a control method is implemented, best management practices (BMPs) need to be incorporated including performing wildlife assessments, timing herbicide application appropriately, monitoring and performing follow-up treatments as necessary (OMNR 2011). It is important to including biodiversity as a project goal when using invasive species management as restoration means, particularly because some ecosystem functions respond positively to greater diversity (Zedler et al. 2001).

Estuary Enhancement Program

Public Service Electric and Gas Company (PSEG), now Public Service Enterprise Group – PSEG Power LLC, created the Estuary Enhancement Program (EEP) in 1994 in response to the New Jersey Pollutant Discharge Elimination System (NJPDES) permit required for the Hope Creek-Salem Generating Station. The once-through cooling system at the nuclear power plant requires obtaining cooling water from the Delaware River and results in a loss of nekton (Weinstein et al. 2001). The EEP was developed and implemented by a multidisciplinary team including ecologists, engineers, stakeholders, and state and federal agencies. The size of restoration site was quantified based on the area needed to restore annual fish biomass produced by Delaware Bay and annual fish biomass lost in the once-through cooling system. The model calculations originally suggested 981 hectares (ha) needed to be restored; however, to account for uncertainties in the reliability of the design a safety factor was applied (increasing the mitigation size by four), which resulted in a final permit stipulation of 4047 ha being restored; however, the final design resulted in a total of 5040 ha to be restored (Weinstein et al. 2001). For the restoration design of EEP, there were five landscape features that were determined to be desirable components of the restoration design and included tidal creek drainage characteristics, sub-tidal refugia for nekton in high order streams, sufficient wet/dry cycle, natural stream bank, and open water to vegetated ratio of 4:1.

Reference sites are vital for an ecological restoration study to compare natural changes to those being done deliberately as part of the restoration effort. The reference sites are needed for success criteria and tracking restoration trajectories and should be interspersed throughout the landscape to document natural functional changes that may provide insight to the restoration effort (Weinstein et al. 1997; Simenstad et al. 2006). Reference sites for EEP needed to be regionally specific and would span range of anticipated conditions. The standards for the reference sites were set to include time-trajectories and a range of marsh types that were representative of restoration end goals. Ultimately, nine restoration sites and five reference sites were selected (Weinstein et al. 2001).

The biological monitoring program included at EEP involved sampling in shallow waters, detrital production monitoring, fish production and food habits monitoring in restored marsh areas (Weinstein et al. 2001). Special permit conditions, project-specific rules imposed by the governing authority, included normal tidal inundation, restoration of degraded wetlands, and establishment of natural vegetation. The EEP performance criteria state that *Phragmites* coverage shall be under five percent of a site, no less than 95 percent vegetation mapped as desirable (*Spartina* spp.) and open water and associated intertidal flats will be less than 20 percent of the total marsh area. Performance criteria for *Phragmites* coverage were set to be ≤ 4 percent of the total marsh area (or ≤5% of the vegetated area of the marsh plain). Since there was considerable uncertainty in the measured values using photo interpretation at that time and ground truthing was not available, approximately 5% coverage was established as a reasonable 'target' value (Weinstein et al. 1997).

Restoration activities for *Phragmites*-dominated sites included broad application of herbicide treatment; however, other techniques were tested and included mowing, removal of relict dikes, and modification of micro-topography, all, which proved to be less effective, compared to herbicide application (Philipp 2005). Adaptive management was incorporated into EEP as a mean of meeting targeted goals, which allows for in-progress restoration evaluation and methods modified ensuring successful treatment (Weinstein et al. 2001). Adaptive management incorporates research into the design process with ecosystem development allowing for proper projections (Zedler 2005). Trial-and-error approaches are not predictable and often fail, while adaptive management leads to cause-effect relationships that allow the restoration goal to be accomplished. The goals implemented by EEP were aligned with ecological engineering principles for a self-sustaining restoration with the inclusion of adaptive management, realistic trajectories and by using both passive and active approaches to the project (Teal and Weinstein 2000; Simenstad et al. 2006).

The sites examined in EEP are located along the Delaware Bay in New Jersey and Delaware. The Delaware Bay once consisted of native salt marsh dominated by *S. alterniflora*, *S. patens*, *Juncus*, *Eliochoris*, *Typha* and *Scirpus* species (Turner and Warren 2003) and *S. cynosuroides* (PSEG 2009). Over the years this region has experienced extensive anthropogenic disturbance along its shoreline, resulting in significant alteration of the original habitat. Currently, there are three sites where *Phragmites* control continues to be implemented (Alloway Creek Watershed, The Rocks and Cedar Swamp) and there are two sites that serve as reference sites (Mad Horse Creek and Moores Beach) that are not actively being treated to minimize *Phragmites* (PSEG 2010) (Figure 1). Management of *Phragmites* will persist at the remaining EEP sites until the permit performance criteria are met, state agencies are satisfied with restoration efforts, and fish populations are stable and abundant.

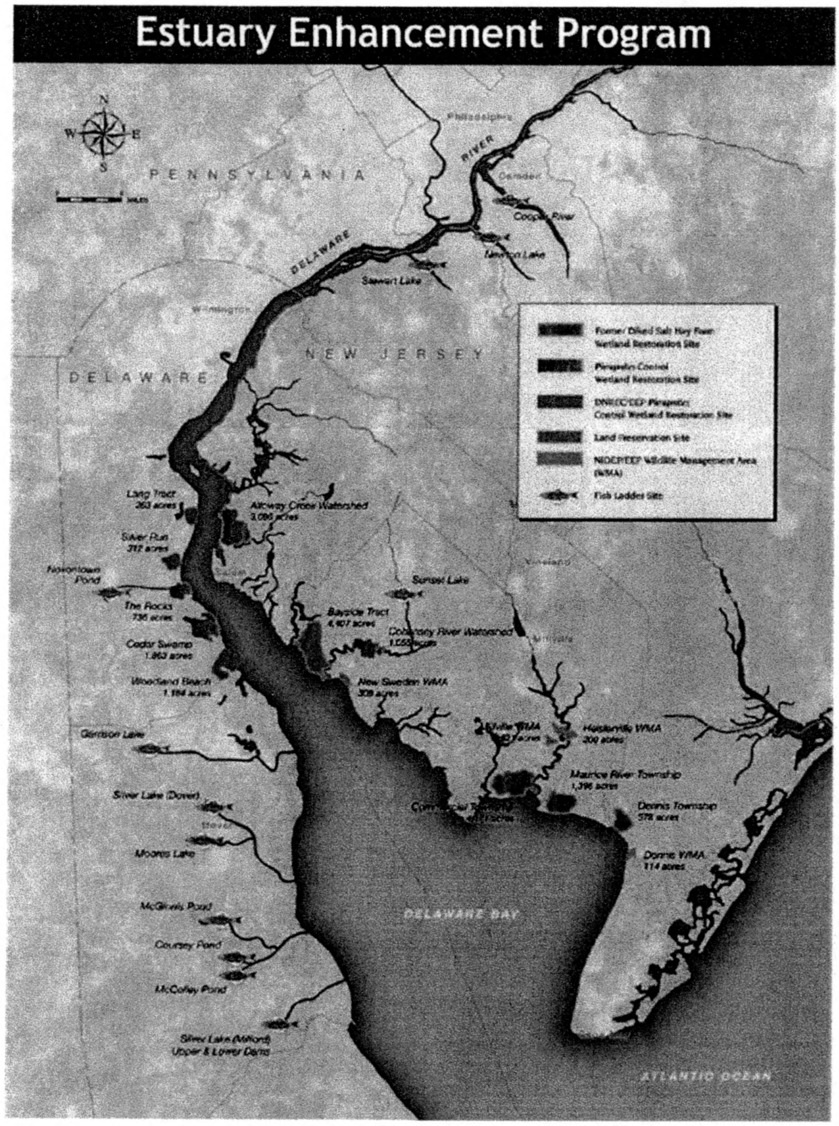

Figure 1. Estuary Enhancement Program Site Location Map (PSEG 2013). Including completed and ongoing restoration sites.

This research examined the effects of different frequencies of glyphosate treatment on plant communities in salt marshes along the Delaware Bay, specifically, the reduction of *Phragmites* and the increase of desirable plants. The project also evaluated impacts of inundation on treatment effectiveness. The objective of this study included to determine if one frequency was more effective and if there is a difference in treatment outcomes based on inundation frequency. The two study sites in the Delaware Bay are

Alloway Creek Watershed (ACW) in New Jersey and Cedar Swamp (CS) in Delaware. Spatial and temporal changes in vegetation communities were determined by interpreting aerial photography.

METHODOLOGY

Study Sites

The two EEP Restoration sites being examined are located along the upper Delaware Bay (Figure 2). The ACW Restoration site is located in Elsinboro and Lower Alloways Creek Townships in Salem County, New Jersey and encompasses 1138 ha. The CS Restoration site is located in the Town of Townsend, New Castle County, Delaware and encompasses 754 ha.

The sites designated by their overabundance of *Phragmites* are located in oligohaline regions, where mean salinities were 5 parts per thousand (ppt) and range from 0 to 20 ppt, depending on weather and hydrodynamics (Teal and Peterson 2005). The restoration efforts at ACW and CS began with a thorough investigation of historical uses of the sites to understand how to appropriately restore the marsh (Philipp 2005). A dike at ACW was constructed in 1848 to commercially farm the meadows behind the dike. Similarly, a dike and roadway were depicted on an 1850 map of CS indicating that the area behind the dike was also a farmed meadow. At ACW the dikes were abandoned, while at CS a natural storm event breached the barriers. Both sites demonstrated a change from open water/flats to dendritic channel drainage in an evolved marsh plain. As part of the 5040 ha (12454 acres) restoration, ACW and CS were selected as restoration sites for EEP and underwent herbicide treatment, prescribed burns and long-term control techniques because the dominant vegetation was *Phragmites* (Weinstein et al. 2001).

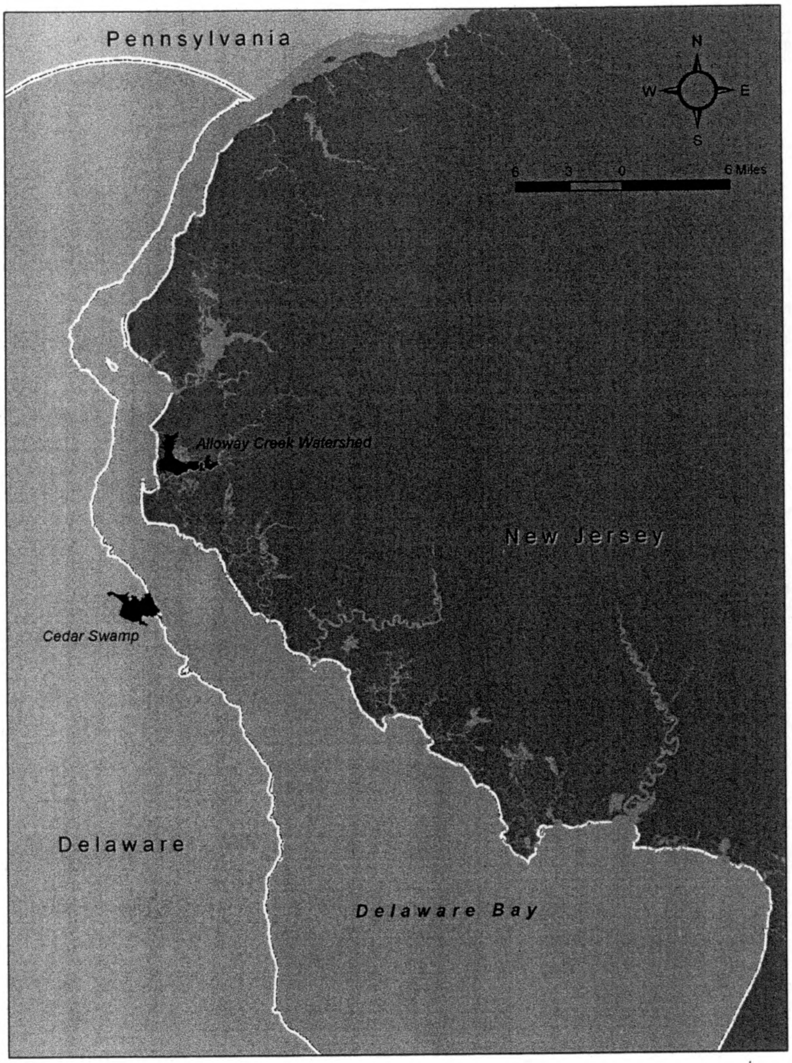

Figure 2. Alloway Creek Watershed and Cedar Swamp Restoration Sites
(Map Source: Site boundaries courtesy of URS Corporation; State Boundaries: PADEP 1996, DE OSPC 1999 and NJOIT OGIS 2010)

Glyphosate Treatment

During application of aerial herbicide of glyphosate (application rates varied and were unavailable) spray lines were recorded. These spray lines were ArcGIS compatible and were brought in as a shapefile to establish sampling plots for analysis. Study sites were reviewed, and determination of treatment frequencies was completed both on-screen and on hardcopies. To quantify and depict the treatment frequencies, polygon features were drawn using an editor session in ArcGIS around areas with treatment patterns (Figures 3 and 4). The analysis of spray lines from 2001 to 2010 resulted in four treatment frequencies: no treatment, one, two, or three spray events. At both sites, areas that did not have any recorded aerial herbicide treatment were designated as the reference (designated as 0). The different designations refer to different time intervals of treatments and are detailed in the below Table.

Ground treatment was completed as supplemental treatment; however, location of ground treatment was not recorded in the same manner and therefore omitted from this analysis. Additionally, ground treatment typically occurred in areas not aerially sprayed due to proximity to residential areas or forested upland areas.

Table 1. Details of Treatments: Number of Sample Plots, Years Sprayed and Total Area

Site	Treatments	Number of Plots	Years Herbicide Applied	Total Area of Treatment (ha) [% of Total Site]
ACW	Reference (0)	24	--	28.7 [4.4%]
	Two	19	2005 and 2007	21.8 [3.4%]
	Three (3c)	16	2002, 2004, 2006	22.3 [3.4%]
CS	Reference (0)	15	--	15.4 [2.04%]
	One	16	2004	21.0 [2.79%]
	Three (3a)	32	2004, 2006, 2008	43.3 [5.74%]
	Three (3b)	43	2004, 2005, 2007	53.8 [7.14%]

Sampling plots were randomly selected using ArcGIS Random Point Generator. Points were created within areas of each treatment frequency, and used as the center point for the plots and given a 120-feet radius using the Buffer tool, thus guaranteeing that all treatment plots had the same area: 0.42ha or 1.03 acres (ac). Each treatment plot was given an alphanumeric code; the first letter is capitalized and signifies what treatment followed by a number for the patch and lastly a lower case letter to identify the plot. Using the newly created plots in ArcGIS, previously mapped vegetation communities for each year in the study (2001 and 2010) were overlaid and re-drawn.

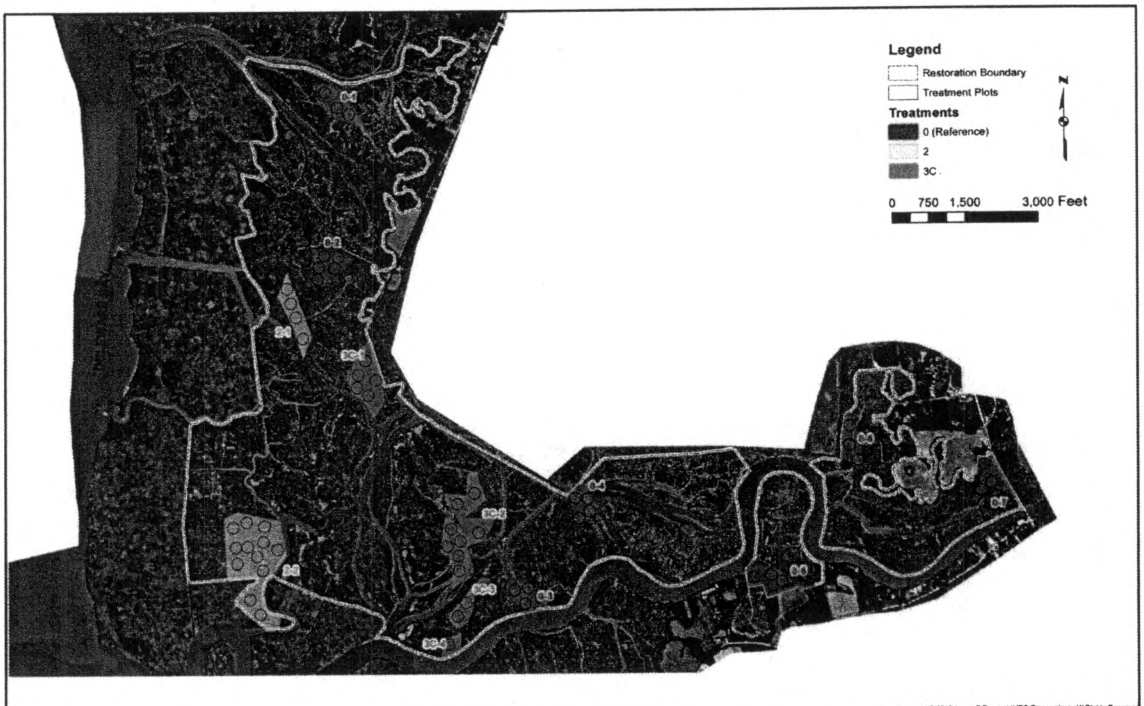

Figure 3. Alloway Creek Watershed Site Treatment Frequencies and Treatment Plots (Map Source: Herbicide data and Aerial Photography courtesy of URS Corporation; True color photography by BAE Systems, 2010)

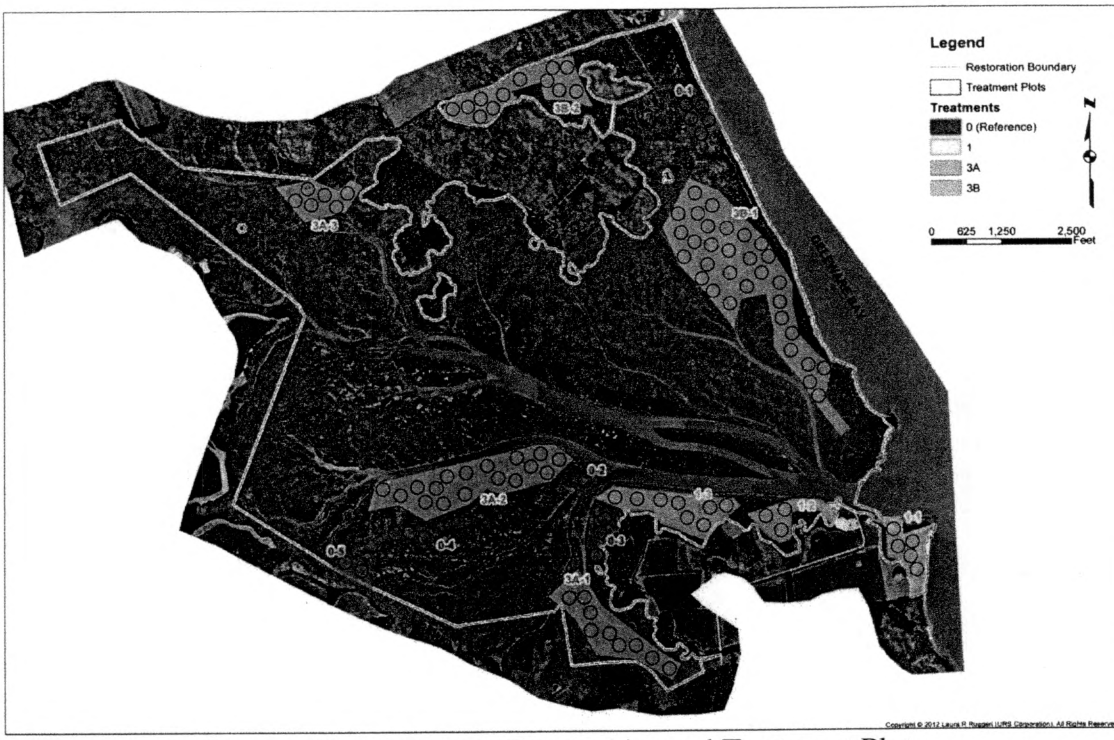

Figure 4. Cedar Swamp Site Treatment Frequencies and Treatment Plots
(Map Source: Herbicide data and Aerial Photography courtesy of URS Corporation; True color photography by BAE Systems, 2010)

Aerial Interpretation and Quantification

Mapping of marsh vegetation types on the wetland restoration and reference sites were completed each year utilizing annual color infrared (CIR) and true color aerial photography acquired for vector mapping and digital orthophotograph production (Hinkle and Mitsch 2005; PSEG 2010). Annually, a team of scientists familiar with the vegetation and physical features interpreted the CIR and true color aerial photography by identifying color/texture characteristics of the various cover types present. The various areas of species-dominated polygons or other site features (i.e. channels) identified on the aerial photography were delineated digitally while viewing the orthophotograph on the computer monitor. On-screen digitizing of cover type boundaries was performed using AutoCAD LT 2010™ (or earlier versions). Each polygon mapped was assigned an identifying code consisting of the dominant cover type. In order to be identified as a given cover type, it is necessary that the vegetative cover of the polygon exceed 30 percent, consistent with the approach utilized by the USFWS in the preparation of NWI maps (Tiner 1998). Therefore, if there is less than 30 percent of vegetation in a given plot it will be categorized as "Unvegetated".

As part of this study, previously mapped vegetation polygons were brought into ArcGIS as an AutoCAD (.dxf) file and then converted to a shapefile (.shp). The polygons created for the different treatment frequencies were overlaid on top of mapped vegetation for years 2001 and 2010. Vegetation communities were selected and then traced to create new polygon features within each treatment plot for the two study years. Each vegetation area was quantified using the calculate geometry function in the attribute tables. Area was then used for comparative analysis over the time frame of the study. Three vegetation categories were used in this study, modified from Hinkle and Mitsch (2005), and are detailed in the table below.

Table 2. Description of Vegetation Community Categories

Category	**Dominated Species/ Features Included**
Desirable Taxa	*Spartina alterniflora, S. cynosuroides, S. patens, Typha* sp., *Iva frutescens,* and *Baccharis hamlimifolia.*
Phragmites	Categorized by monotypic stands and *Phragmites*-dominated communities
Unvegetated	mud flat, wrack, channel, ponded or open water

For each treatment frequency, acres mapped within each vegetation community category were totaled using MS Excel formulas and pivot tables. Percent change in vegetation composition for each vegetation community category was calculated using the below formula and used to examine changes in the overall land cover taking into account for vegetation not present in 2001 (values of zero).

Percent change in vegetation composition was calculated by:

$$= (y2\text{-}y1/\text{Total Plot Area})*100$$

y1 = area of a vegetation community for start year of study (2001)
y2 = area of a vegetation community for end year of study (2010)

Inundation Analysis

A modified inundation frequency classification was incorporated into the analysis to account for distribution of treatment plots throughout the marsh plain. This analysis is to be considered a simplified attempt to categorize flow regime, inundation frequency and duration, soil redox and elevation for the treatment plots. Inundation designation was done using aerial orthophotographs at an on-screen scale of 1:18,000 for ACW and 1:15,000 for CS. Although the PSEG EEP annual analysis incorporates geomorphologic analysis as a means to quantify drainage density, this research used a modified approach influenced by Horton (1945), who emphasized topographic characteristics of the drainage area and utilizes an approach where the smaller streams have lower numbers and the central channel is assigned the highest number to determine the order of the drainage channels. Treatment plots were given an additional designation that included a number from one to three depending on its proximity to a drainage channel a proxy for inundation. Close proximity to the Delaware River (largest channel) would be considered high inundation (3), while a one represented smaller intertidal or subtidal channels with low inundation frequency.

Statistical Analysis

Percent change in vegetation composition

Statistical models were used to determine the effect of sites (ACW and CS), treatment frequencies (0, 1, 2 and 3), and inundation frequency (1-3) on percent vegetation change in area (mapped in acres). Two-way analysis of variances (ANOVA) was conducted and the Ryan-Einot-Gabriel-Welsch Q (REGWQ) method was used to do multiple comparisons for all combinations of treatment frequency analysis and vegetation analysis. The general linear model (GLM) procedure was used, which is the method of least squares to fit general linear models. The GLM model related one or several continuous dependent variables to one or several independent variables. Changes in vegetation communities between 2001 and 2010 were the main filter for analyzing the data; statistical analysis was conducted using SAS Software (SAS Institute 2012).

Two models were analyzed as part of this study to evaluate collected data, each focusing on different relationships. The first model assessed site and treatment as independent factors. The second model was a two-way ANOVA with treatment and inundation frequency as independent variables. Changes in vegetation communities were the dependent factors for all models.

RESULTS

Model One – Treatment

Vegetation mapping quantified areas as "*Phragmites*", "Desirable Taxa" or "Unvegetated" for both years 2001 and 2010. No significant differences between the two sites (ACW and CS) were observed for each of the mapped vegetation communities, Desirable Taxa (p= 0.1291), *Phragmites* (p=0.1758) and Unvegetated (p=0.8932) (Table 3, 4 and 5). Therefore data from the two study sites were pooled together to evaluate treatment effectiveness; model analysis was then modified to be a two-way ANOVA for the remaining analyses. Tables 3, 4 and 5 outline the ANOVA and the sum of squares analysis for each vegetation community.

Table 3. ANOVA Summary Table Comparing Percent Change for Desirable Taxa At Various Treatment Frequencies at Both Study Sites

Analysis of Variance:					
Source	**DF**	**Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	5	3.09654874	0.61930975	8.17	<.0001
Error	153	11.59679966	0.7579608		
Corrected Total	158	14.69334840			
Type III Sum of Squares Analysis:					
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr>F**
Site	1	0.17650074	0.17650074	2.33	0.1291
Treatment	3	2.99157604	0.99719201	13.16	<.0001
Site*Treatment	1	0.00006215	0.00006215	0.00	0.9772

Table 4. ANOVA Summary Table Comparing Percent Change for *Phragmites* at Various Treatment Frequencies at Both Study Sites

Analysis of Variance:					
Source	**DF**	**Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	5	3.47029470	0.69405894	8.47	<.0001
Error	152	12.45860459	0.08196450		
Corrected Total	157	15.92889928			
Type III Sum of Squares Analysis:					
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr>F**
Site	1	0.15164655	0.15164655	1.85	0.1758
Treatment	3	3.23880999	1.07960333	13.17	<.0001
Site*Treatment	1	0.12548993	0.12548993	1.53	0.2179

Table 5. ANOVA Summary Table Comparing Percent Change for Unvegetated at Various Treatment Frequencies at Both Study Sites

Analysis of Variance:					
Source	**DF**	**Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	5	0.52190320	0.10438064	1.51	0.1892
Error	153	10.56260821	0.6903665		
Corrected Total	158	11.08451141			
Type III Sum of Squares Analysis:					
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr>F**
Site	1	0.00124743	0.00124743	0.02	0.8932
Treatment	3	0.09332141	0.03110714	0.45	0.7172
Site*Treatment	1	0.24753344	0.24753344	3.59	0.0602

The results of the ANOVA and the REGWQ method demonstrated that any treatment (1, 2 or 3 applications) produced a significant increase in percent cover of Desirable Taxa ($p<0.001$) and a decrease in *Phragmites* ($p<0.001$) during the study period (Tables 3 and 4). No significant differences were found in percent cover changes of Unvegetated ($p=0.7172$) (Table 5). Percent cover of Desirable Taxa of reference (0 treatment) declined from 2001 and 2010 (-1%) while percent cover of *Phragmites* increased (8%). In contrast, any frequency of treatment (1-3 applications) demonstrated an increase of Desirable Taxa (ranging from 26-39%) and a decrease in *Phragmites* (ranging from -20 to-39%) from 2001 and 2010 (Table 6). However, the REGWQ method of analysis of treatments (1-3 applications excluding reference/0 treatment) did not demonstrate any significant differences in treatment frequencies. When assessing changes in Unvegetated areas, no significant differences existed among any of the treatments, including reference. Unvegetated areas essentially stayed the same throughout various treatments over the study period.

Due to the design of this study, each treatment had a different starting point in vegetation coverage (Table 6 and Figures 6-10). The starting and end averages for each treatment for Desirable Taxa and *Phragmites* were not uniform (Figures 9 and 10). Treatment One demonstrated the largest average increase in Desirable Taxa (39%) and the largest loss of *Phragmites* (-39%), while Treatments Two and Three averaged mid-twenties for each category.

Table 6. Average Area of each Vegetation Community by Treatment Frequency

	2001		2010		
Type	**Average Acres**	**% Cover**	**Average Acres**	**% Cover**	**% Change***
Treatment 0					
Desirable Taxa	0.80	77%	0.78	76%	-2.48
Phragmites	0.06	6%	0.14	14%	116.54
Unvegetated	0.17	17%	0.11	11%	-37.46
Treatment 1					
Desirable	0.40	38%	0.80	77%	101.28
Phragmites	0.61	59%	0.21	20%	-65.93
Unvegetated	0.03	3%	0.03	3%	-1.86
Treatment 2					
Desirable Taxa	0.25	24%	0.52	50%	107.09
Phragmites	0.74	72%	0.48	46%	-35.42
Unvegetated	0.04	4%	0.04	4%	-13.81
Treatment 3					
Desirable Taxa	0.67	65%	0.95	91%	40.90
Phragmites	0.25	25%	0.06	5%	-78.19
Unvegetated	0.11	11%	0.03	3%	-69.09

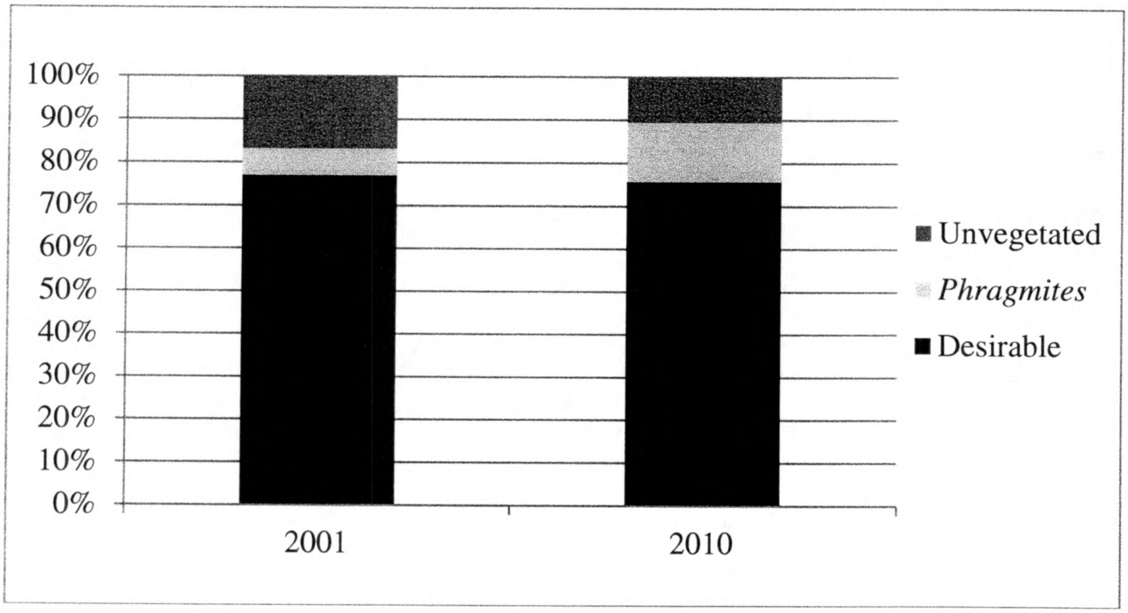

Figure 5. Average Percent Covers for 2001 and 2010 for Plots at Both Sites that received No Treatment (Reference) during the Study Period

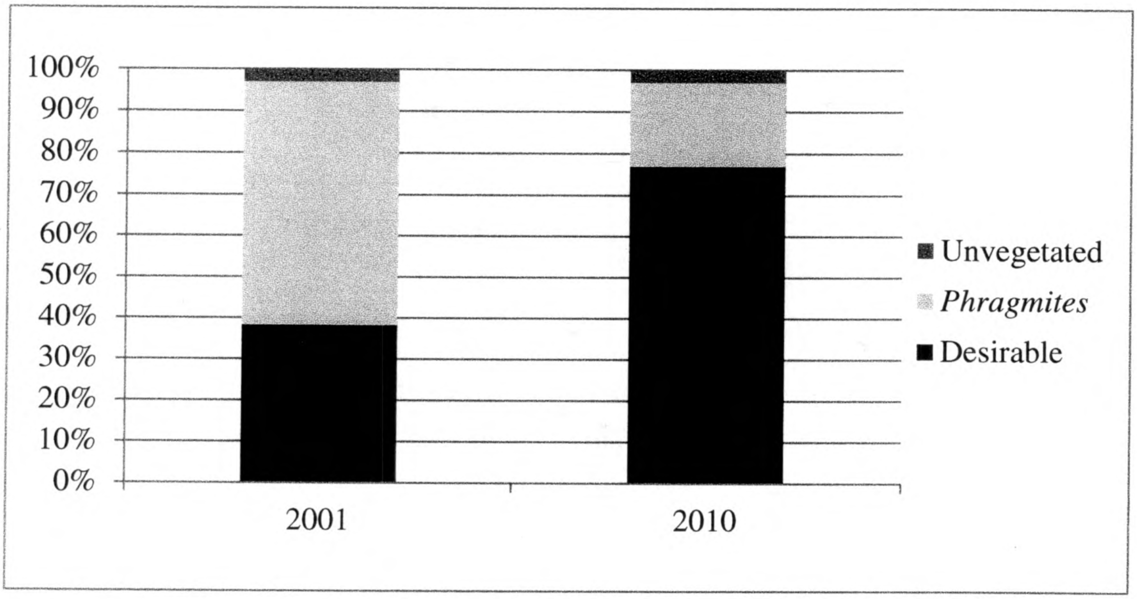

Figure 6. Average Percent Covers for 2001 and 2010 for Plots at Both Sites Treated Once during the Study Period

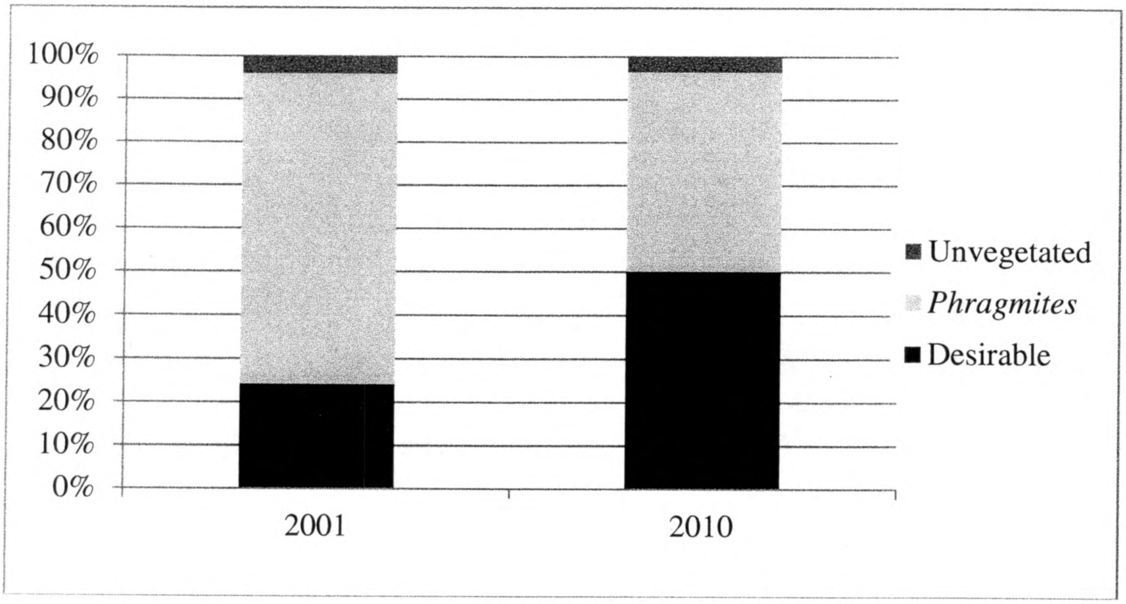

Figure 7.Average Percent Covers for 2001 and 2010 for Plots at Both Sites Treated Twice during the Study Period

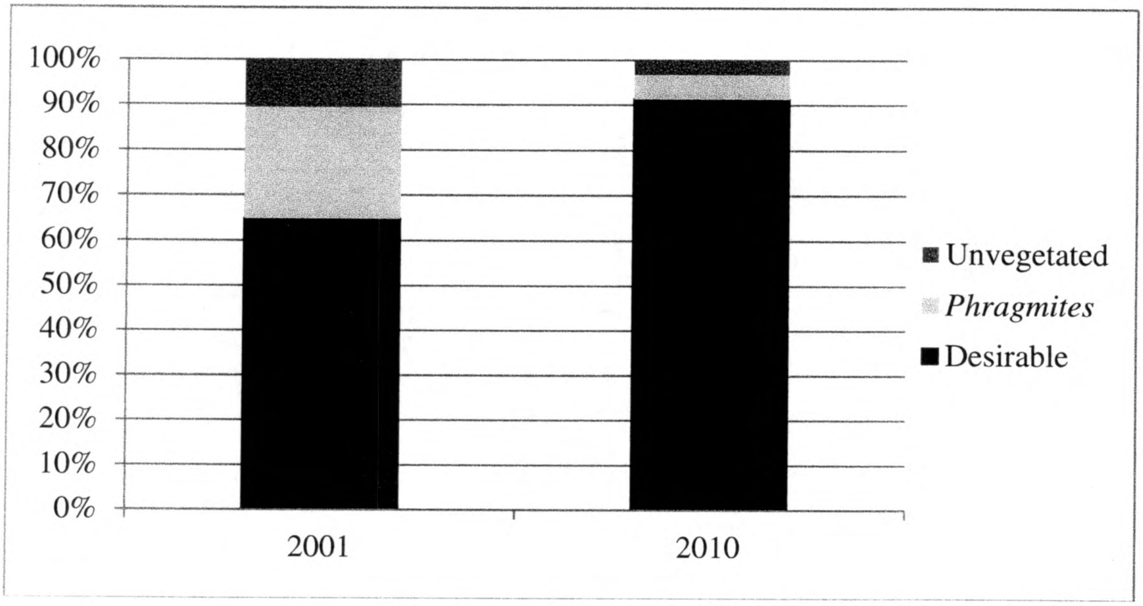

Figure 8.Average Percent Covers for 2001 and 2010 for Plots at Both Sites Treated Three Times during the Study Period

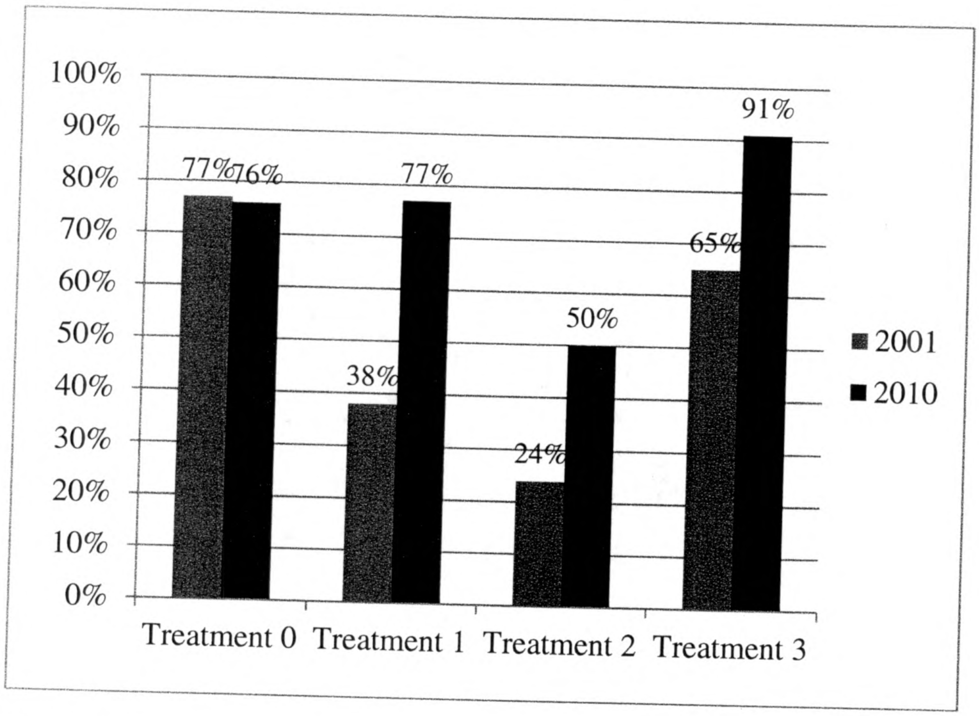

Figure 9. Average Percent Covers of Desirable Taxa for 2001 and 2010 for all Treatments at Both Sites (Treatment 0 = no applications/reference, Treatment 1 = 1 application, Treatment 2 = 2 applications and Treatment 3 = 3 applications).

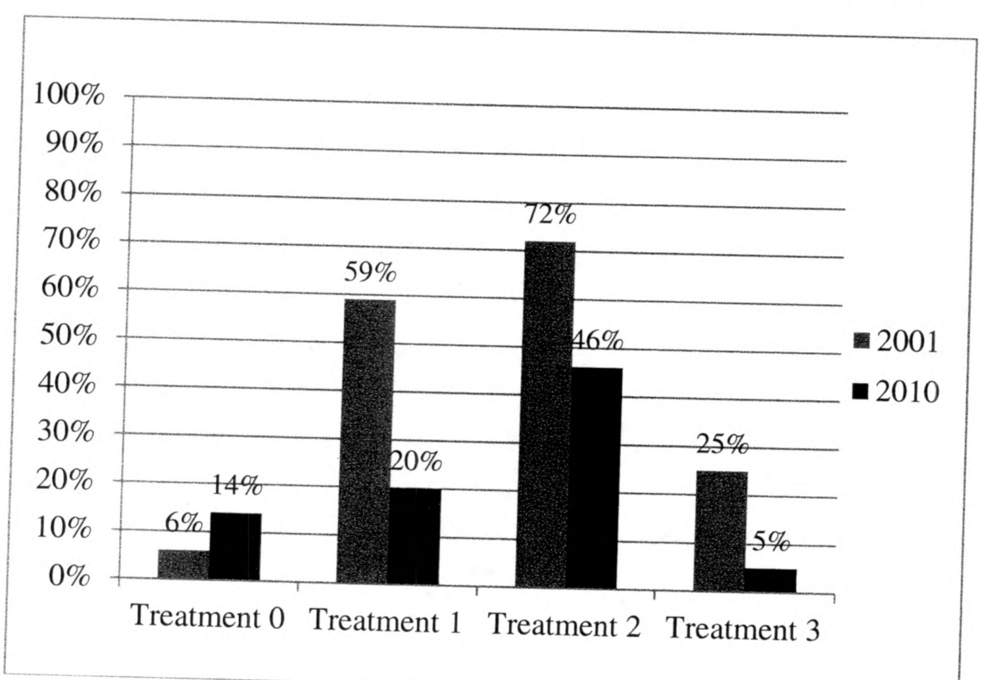

Figure 10.Average Percent Cover of *Phragmites* for 2001 and 2010 for all Treatments at Both Sites (Treatment 0 = no applications/reference, Treatment 1 = 1 application, Treatment 2 = 2 applications and Treatment 3 = 3 applications).

Model Two - Inundation

Since the treatment plots were located throughout the site, at varying distances from the Delaware River or other main channels, inundation analysis was incorporated to categorize variation caused by flow regime, inundation frequency and duration, soil redox and elevation among the treatment plots. Bart et al. (2006) found three patterns of invasion including from stands established on ditch- or creek-bank levees toward interior portions of high marshes. Understanding influence of inundation frequency of *Phragmites* invasion could provide insight for land managers as to where to focus efforts. Significant differences between inundation frequency designations were observed implying that location within the marsh plain can be assumed to affect treatments and/or *Phragmites* invasion. The data suggest that plots adjacent to smaller intertidal streams did not experience the same changes in vegetation communities under Desirable Taxa and *Phragmites*.

When examining changes under Desirable Taxa, significant differences were observed among treatments ($p= <0.001$) and inundation ($p=0.0075$); however, the interaction of the variables resulted in no significant differences ($p=0.6293$) (Table 7). Similarly under *Phragmites,* treatments ($p= <0.001$) and inundation ($p=0.0158$) were significant, but when looking at the interaction of the variables, no significant difference ($p=0.5856$) was observed. These results indicate that although the overall model had significant differences for inundation, the REGWQ multiple tests did not discriminate those differences when looking at interaction between treatment and inundation factors. Under Unvegetated, no significant differences were observed among treatments (p=

0.9411) and inundation (p=0.5012) or their interaction (p=0.5425). Tables 7, 8 and 9 outline the ANOVA and the sum of squares analysis for each vegetation community.

Significant differences observed under inundation for both Desirable Taxa and *Phragmites* signified that inundation classification or proximity to main channels impacts vegetation cover. However, the interaction between treatment and inundation did not result in a significant outcome for Desirable Taxa and *Phragmites*; therefore, treatment effectiveness cannot be connected to proximity to main channels. Inundation and treatment appear to separately impact vegetation cover.

Table 7. ANOVA Summary Table for Inundation and Treatments by Comparing Percent Changes of Desirable Taxa at Both Study Sites

Analysis of Variance:					
Source	**DF**	**Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	9	3.75014365	0.41668263	5.67	<.0001
Error	149	10.94320476	0.07344433		
Corrected Total	158	14.69334840			
Type III Sum of Squares Analysis:					
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr>F**
Treatment	3	2.35265945	0.78421982	10.68	<.0001
Inundation	2	0.74256872	0.37128436	5.06	0.0075
Treatment*Inundation	4	0.19030192	0.04757548	0.65	0.6293

Table 8. ANOVA Summary Table for Inundation and Treatments by Comparing Percent Changes of *Phragmites* at Both Study Sites

Analysis of Variance:					
Source	**DF**	**Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	9	4.0352441	0.44828049	5.58	<.0001
Error	148	11.89437487	0.08036740		
Corrected Total	157	15.92889928			
Type III Sum of Squares Analysis:					
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr>F**
Treatment	3	2.5127017	0.83757006	10.42	<.0001
Inundation	2	0.68519268	0.34259634	4.26	0.0158
Treatment*Inundation	4	0.22857860	0.05714465	0.71	0.5856

Table 9. ANOVA Summary Table for Inundation and Treatments by Comparing Percent Changes of Unvegetated at Both Study Sites

Analysis of Variance:					
Source	**DF**	**Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	9	0.72710297	0.08078922	1.16	0.3234
Error	149	10.35740844	0.06951281		
Corrected Total	158	11.08451141			
Type III Sum of Squares Analysis:					
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr>F**
Treatment	3	0.02747313	0.00915771	0.13	0.9411
Inundation	2	0.09649001	0.04824500	0.69	0.5012
Treatment*Inundation	4	0.21575278	0.05393820	0.78	0.5425

DISCUSSION

Although many studies have examined effectiveness of herbicide treatment for wetland restoration (Reimer 1976; Fredrick 2000; Mozder et al. 2008; Kay 1995; Rice et al. 2000; Derr 2008; Back and Holomuzuki 2008), this study specifically investigated herbicide effectiveness on a large-scale, long-term project. Wetland restoration as a science is young and success is relative, depending on the goals set for each project and the time interval between project completion and post-project evaluation (Whigham1999). Shortcomings surrounding wetland restoration include the need for standard indicators of ecosystem function, use of over simplified models to achieve diversity and ecosystem functions, and permit conditions not including future assessments (Zedler 2000). To have a successful project, restoration goals should be directed toward enhancement of specific biodiversity and function since restoration cannot be measured by only one attribute. Yet, there are many examples of failed restoration projects. Failures can be attributed to lack of monitoring, administrative failures (i.e. permitting conditions not including deadlines) (Turner et al. 2001), budget constraints, lack of connectivity to adjacent ecosystems, etc. (Whigham 1999).

Herbicide Effectiveness

This study analyzed the effectiveness of aerial herbicide application of glyphosate by examining vegetation community changes, seeking to find a recommended treatment frequency for managing *Phragmites* expansion using glyphosate. Similar to Moreira et al. (1999), regardless of spray application schedule (or treatment frequency), the results of this study showed a decrease of *Phragmites* could be achieved with glyphosate treatment. This study did not attempt to evaluate the success of *Phragmites* control, but rather to provide a snapshot on the status of an ongoing restoration project. All treatment frequencies except for the reference plots resulted in a decrease of *Phragmites* and an increase in desirable species. No statistical significance was found between the various treatment frequencies; therefore, any treatment is better than no treatment while managing *Phragmites*. Although the results suggests that one application produced a higher average reduction of *Phragmites* (-39%) compared to two (-26%) or three (-20%) applications, this result could be misleading. Treatment sites were selected due to its high land cover with *Phragmites*; the pre-treatment conditions were not the same. Although are treated with three times of glyphosate applications did not result in the highest increase in Desirable Taxa, in average, above 90% of the plots were covered by Desirable Taxa by 2010. Moreover, areas were treated with glyphosate prior to 2001. Our study only examined vegetation community at 2001 and 2010. Vegetation cover in 2001 might have already been influenced by previous herbicide applications, which was not included into the evaluation in this study. Additionally, areas in this study were treated at different time during the study period. The last spray event for selected study sites ranged from 2006-2008. Simply evaluation vegetation mapping at two time points, 2001 and 2010 might overlook the immediate effects of glyphosate application and variation in number of growing season post the last glyphosate treatment.

Although with limitation above, vegetation mapping from 2010 demonstrated that *Phragmites* remained less than 2001 data for all management sites regardless of treatment frequencies of one, two or three; herbicide application is effective in reducing *Phragmites* and should be included in management planning. Although, cost of glyphosate is relatively low, ranging from $6.00 - $18.00 per acre (these values are based on rate 22 ounces/acre for soybeans and may not include cost of applicator) (Sandell et al. 2008), restoration goals and project funding may influence the decision on frequency of herbicide applications. Generally, the cost for chemical control should be considered appropriately in restoration costs and should include pre and post restoration assessment to all project area.

To effectively reduce *Phragmites*, Back and Holomuzuki (2008) recommend at least two spraying events per growing season (within 30 days of initial application), while Reimer (1976) showed that consecutive years of glyphosate herbicide application resulted in increased effectiveness and prolonged control. The study area did not two treatments in one growing season or treatment in consecutive years. Instead, treatments were spread out with one or two years in between spray events. Additionally, Derr (2008) observed that *Phragmites* regrew in all treated plots and concluded that for successful treatments need to be repeated and frequent to eradicate the populations from the site.

<u>*Phragmites* and Restoration</u>

The difficulty of achieving complete control or eradication of *Phragmites* may be attributed to several factors including development/life span of the rhizomes (Derr 2008), spreading of unkilled/untreated individuals and/or delayed browning after treatment (Back and Holomuzuki 2008). At the EEP sites, development/life span of rhizomes and spreading of adjacent *Phragmites* patches are likely major inhibiting factors for reaching restoration success (Philipp 2005). Specifically at ACW, *Phragmites* persists throughout the area and has developed large monocultures immediately adjacent to the restoration site. Bart and Hartman (2002) demonstrated that *Phragmites* invasion is a multi-stage process, with poor drainage constraining expansion and survival controlled by lack of burial opportunities and salinity in the early stages. While in later stages of the invasion, *Phragmites* can spread into anoxic and high salinity areas, suggesting the process of invasion is facilitated by different human activities at different stages.

Phragmites stands at the EEP study sites have been dominating the region since the mid-20th century with rapid expansion over the last 50 years (Philipp 2005). Bart and Hartman (2003) found that larger rhizomes have a greater chance at establishing new clones than small rhizomes and larger rhizomes performed better in a variety of salinities. Currently the EEP performance criteria have not been met for these sites yet, and although aggressively treated, it is possible the well-developed rhizome root mat and dense long-lived stands of *Phragmites* could be hindering the success. Unfortunately, the program's performance criteria are set by jurisdictional agencies. Although the program has a potential to be an excellent study site for testing treatment effectiveness, it was not originally designed to be an experimental program. Although adaptive management efforts continue annually to improve treatment methods to reach the program's goals, perhaps the trajectory for restoration achievement may need to be re-evaluated and programs revised.

Since recently established *Phragmites* has a higher intrinsic rate of expansion, control mechanisms should be implemented on younger colonies to combat the expansion appropriately (Rice et al. 2000, Bailey 2007 and Lathrop et al. 2003). In Delaware, large established stands required up to five additional applications of herbicide compared to smaller stands (Rice at al. 2000). Due to its large area, this study did not incorporate patch size nor did it assess if various treatments were more effective on smaller patches versus larger. Although not explicitly identified in this study, perhaps a future experiment should analyze application rates in conjunction with *Phragmites* expansions rates to ultimately create an optimum guide for herbicide treatment that is site-specific.

Herbicide Selection and Application

Although glyphosate has been more commonly used over the years, another herbicide, imazapyr (Habitat®, BASF Corporation, North Carolina), has been found to have positive effects on the control of *Phragmites*. A 2008 study on comparing the efficacy of the two herbicides demonstrated that imazapyr was statistically superior in reducing *Phragmites* compared to glyphosate (Mozder et al. 2008). Imazapyr requires fewer applications and was found to be more effective than glyphosate (Mozder et al. 2008). With no surprise, both herbicides were found to be more effective if applied early in the growing season. Kay (1995) compared glyphosate and imazapyr application rates using 'wipe-on" methods, whereby a device or applicator is used to physically wipe-on or spread-on to the plant directly. The study used only one spray event in June, prior to flowering, and after two years of monitoring observed no significant differences between controls or any of the wipe-on treatments. Glyphosate herbicide application occurred late in the growing season at ACW and CS, which could be why the results vary from Kay (1995); whereby this study demonstrates a significant difference between reference and treatment frequencies.

Cross and Fleming (1989) mention that herbicide should be applied during the growing season, when sugars are being translocated from the leaves to the rhizomes. Conditions during spray events were not analyzed as part of this study; however, future studies could investigate if there was a significant difference in conditions and/or timing that may provide additional insight on effectiveness.

Inundation

In the Chesapeake Bay, *Phragmites* occurrence along the shoreline was not related exclusively to high salinity restrictions on plant distribution, but *Phragmites* occurrence was highest adjacent to cleared but undeveloped land (Chambers et al. 2008). The upper reaches and smaller intertidal areas at ACW and CS were adjacent to upland and agricultural areas, perhaps influencing *Phragmites* spread. Treatment effectiveness could be influenced by inundation due to flooding and/or flushing of vegetation recently sprayed. To better understand the relationship between treatment frequency and inundation frequency, further analysis is recommended with a more detailed geomorphologic analysis.

Unvegetated Areas

Although no significant differences were observed under the Unvegetated category and it is important to understand the value of this data. Perhaps it can be inferred that any herbicide application has little to no effect on Unvegetated areas in a marsh during the study period. Unvegetated areas are important to monitor during restoration activities for newly established *Phragmites*, which can demonstrate high intrinsic rates of increase as discussed by Rice et al. (2000), slowing down restoration efforts. Monitoring Unvegetated areas is important since the upper limit of *Phragmites* is set by the terrestrial border of the marsh (Minchinton and Bertness 2003); and *Phragmites* often are the first plant to colonize recently cleared environments, especially inhospitable and toxic soils (Rice et al. 2000). Since open water is not as vulnerable to *Phragmites* invasion compared to channel banks, mud flats, wrack areas (Bart and

Hartman 2002), perhaps modifying the Unvegetated category would had produced different results. To execute effective restoration activities it is recommended to monitor areas that are vulnerable to new colonization in conjunction with treating appropriate monotypic stands.

CONCLUSIONS

If the aggressive *Phragmites* genotype continues to expand and dominate Delaware Bay estuaries, it will replace a diverse tidal habitat with one that traps sediments, impedes fish passage, replaces endemic species, inhibits wildlife to forage and limits tidal exchange (Hellings and Gallagher 1992; Chambers et al. 1999; Meyerson et al. 2000; Siegel et al. 2005; Schaumburg et al. 2011). Restoration goals at EEP sites encompass biodiversity by intersecting large monocultures of *Phragmites* to smaller patches to facilitate species diversity. The results of this study indicate that that applying herbicide once can reduce *Phragmites* coverage by approximately 40 percent in a salt marsh. The results of this study demonstrated that a low frequency of herbicide application could still be effective in managing *Phragmites,* particularly when funding prohibits the repeat application of herbicide. When possible, adaptive management should be incorporated into all restoration projects as the need to adapt and evaluate conditions in real-time can prove to be helpful in meeting restoration goals.

References

Able, K.W. and S.M. Hagan. 2000. Effects of Common Reed (*Phragmites australis*) Invasion on Marsh Surface Macrofauna: Response of Fishes and Decapod Crustaceans. Estuaries. 23(5): 633-646.

Back, C.L. and J.R. Holomuzuki. 2008. Long-term Spread and Control of Invasive, Common Reed (*Phragmites australis*) in Sheldon Marsh, Lake Erie. The Ohio Journal of Science. 108(5): 108-112.

Bart, D., D. Burdick, R.M. Chambers and J.M. Hartman. 2006. Human facilitation of *Phragmites australis* invasions in tidal marshes: a review and synthesis. Wetlands Ecology and Management.14: 53–65.

Bart, D. and J.M. Hartman. 2003. The Role of Large Rhizome Dispersal and Low Salinity Windows in the Establishment of Common Reed, *Phragmites australis*, in Salt Marshes: New Links to Human Activities. Estuaries. 26(2B): 436-443.

Bart, D. and J.M. Hartman. 2000. Environmental determinant of *Phragmites australis* expansion in a New Jersey salt marsh: an experimental approach. Oikos. 89:59-69.

Brawley, A.H., R.S. Warren and R.A. Askins. 1998. Bird Use of Restoration and Reference Marshes Within the Barn Island Wildlife Management Area, Stonington, Connecticut, USA. Environmental Management. 22(4): 625-633.

Burdick, B. and R.A. Konisky. 2003. Determinants of Expansions for *Phragmites australis*, Common Reed, in Natural and Impacted Coastal Marshes. Estuaries. 26(2B): 407-416.

Casagrande, R.A., G. Balme and B. Blossey. *Rhizedra lutosa,* a Natural Enemy of *Phragmites australis* in North America. Estuaries. 26(2B): 602-606.

Chambers, R.M., L.A. Meyerson and K. Saltonstall. 1999. Expansion of *Phragmites australis* into tidal wetlands of North America. Aquatic Botany. 64: 261-273.

Chambers, R.M., D.T. Osgood and N. Kalapasev. 2002. Hydrologic and chemical control of *Phragmites* growth in tidal marshes of SW Connecticut, USA. Marine Ecology Progress Series, 239: 83-91.

Chambers, R.M., K.J. Kirk, S. Killeen and M. Berman. 2008. Common Reed *Phragmites australis* Occurrence and Adjacent Land Use Along Estuarine Shoreline in Chesapeake Bay. Wetlands. 28(4): 1097-1103.

Cross, D.H. and K.L. Fleming. 1989. Control of *Phragmites* or Common Reed. USFWS Waterfowl Management Handbook – University of Nebraska - Lincoln. 13: 4-12.

Derr, J.F. 2008. Common reed (*Phragmites australis*) response to mowing and herbicide application. Invasive Plant Science and Management. 1: 12-16.

Farnsworth, E.J. and L.A. Meyerson. 1999. Species composition and inter-annual dynamics of a freshwater tidal plant community following removal of invasive grass, *Phragmites australis*. Biological Invasions. 1: 115-127.

Fredrick, K. 2000. Need and Effectiveness of Control Measures on *Phragmites australis* in Restoration Situations. Restoration and Reclamation – Student On-line Journal. 6(2).

Hartzler, B., C. Boerboom, G. Nice and P. Sikkema. 2006. Understanding Glyphosate to Increase Performance. The Glyphosate, Weeds, and Crops Series. Purdue Extension. Available at: www.ces.purdue.edu/new.

Hellings, S.E. and J.L. Gallagher. 1992. The effects of salinity and flooding on *Phragmites australis*. Journal of Applied Ecology. 29: 41-49.

Horton, R.E. 1945. Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Reprinted from Geological Society of America Bulletin. 56: 275-370.

Hinkle, R.L. and W.J. Mitsch. 2005. Salt marsh vegetation recovery at salt hay farm wetland restoration sites on Delaware Bay. Ecological Engineering. 25: 240-251.

Hunter, K.L., D.A. Fox, L.M. Brown and K.W. Able. 2006. Responses of Resident Marsh Fishes to Stages of *Phragmites australis* Invasion in Three Mid Atlantic Estuaries. Estuaries and Coasts, 29(3): 487-498.

Kay, S. H. Efficacy of Wipe-On Applications of Glyphosate and Imazapyr on Common Reed in Aquatic Site. Journal of Aquatic Plant Management. 33: 25-26.

Lathrop, R.G., L. Windham and P. Montesano. 2003. Does *Phragmites* expansion alter the structure and function of marsh landscapes? Patterns and processes revisited. Estuaries. 26: 423-435.

Ludwig, D.F., T.J. Iannuzzi and A. N. Esposito. 2003. *Phragmites* and Environmental Management: A Question of Values. Estuaries. 26(2B): 624-630.

Meyerson, L.A., K. Saltonstall, L. Windham, E. Kiviat and S. Findlay. 2000. A comparison of *Phragmites australis* in freshwater and brackish marsh environments in North America. Wetlands Ecology and Management. 8: 89-103.

Minchinton, T.E. and M.D. Bertness. 2003. Disturbance-mediated competition and the spread of *Phragmites australis* in a coastal marsh. Ecological Applications. 13(5): 1400-1416.

Moreira, I., A. Monteiro, and E. Sousa. 1999. Chemical control of common reed (*Phragmites australis*) by foliar herbicides under different spray conditions. Hydrobiologia. 415: 299-304.

Mozder, T.J., C.J. Hutto, P.A. Clarke and D.P. Field.2008. Efficacy of Imazapyr and Glyphosate in the Control of Non-Native *Phragmites australis*. Restoration Ecology. 16(2): 221-224.

Olson, B. 2007. *Phragmites* Control Plan. USFWS Bear River Migratory Bird Refuge. Brigham City, Utah.

Ontario Ministry of Natural Resources (OMNR), Invasive *Phragmites* – Best Management Practices, Ontario Ministry of Natural Resources, Peterborough, Ontario. Version 2011. 15p.

Philipp, K.R. 2005. History of Delaware and New Jersey salt marsh restoration sites. Ecological Engineering. 25: 214-230.

Public Service Enterprise Group (PSEG). 2001-2010. Biological Monitoring Program 2001-2010 Annual Reports. Vols. 1 and 2, Newark, NJ.

PSEG, 2013. Estuary Enhancement Program Overview Map. Available on-line: http://www.pseg.com/info/environment/estuary.jsp (Accessed January 2013).

Riemer, D.N. 1976. Long-Term Effects of Glyphosate Applications to *Phragmites*. Journal of Aquatic Plant Management. 14: 39-43.

Rice, D., J. Rooth and J.C. Stevenson. 2000. Colonization and Expansion of *Phragmites australis* in Upper Chesapeake Bay Tidal Marshes. Wetlands. 20(2): 280-299.

Saltonstall, K. 2003. Genetic Variation among North American Populations of *Phragmites australis*: Implications for Management. Estuaries. 26(2B): 444-451.

Sandell, L., S. Knezevic and M. Bernards. 2008. Implications of commodity and input prices on soybean herbicide programs. Weed Science. Online: http://weedscience.unl.edu/pdfarticles/SoyET08.pdf

Schaumburg, K., W.M. Giuliano, and G.A. Langellotto. 2011. Avian-habitat relationships in urban and suburban tidal marshes of Connecticut. Urban Habitats. http://www.urbanhabitats.org/v06n01/avian_full.html

Seigel A., C. Hatfield and J.M. Hartman. 2005. Avian response to restoration of urban tidal marshes in the Hackensack Meadowlands, New Jersey. Urban Habitats. 3: 87-116.

Simenstad, C., D. Reed and M. Ford. 2006. When is restoration not? Incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration. Ecological Engineering. 26: 27-39.

Teal, J. M. and S.B. Peterson. 2005. Introduction to Delaware Bay salt marsh restoration. Ecological Engineering. 25: 199-203.

Tiner, R. 1995. Controlling the All-Too-Common Common Reed. Massachusetts Wetlands Restoration and Banking Program. http://www.massaudubon.org/saltmarsh/restoration.php. (Accessed 6/12/13).

Turner, R.E. and R.S. Warren. 2003. Evaluation of Continuous and Intermittent *Phragmites* Control. Estuaries. 26(2B): 618-623.

Uva, R.H., J.C. Neal and J.M. DiTomaso. 1997. *Weeds of the Northeast.* Cornell University Press. Ithaca, New York. 397pp. http://plants.usda.gov/java/invasiveOne?pubID=NEAST

Weinstein, M.P., J.H. Balletto, J.M. Teal and D.F. Ludwig.1997. Success criteria and adaptive management for a large scale wetland restoration. Wetlands Ecology and Management. 4(2): 111–127.

Weinstein, M.P., J.M. Teal, J.H. Balletto and K. Strait. 2001. Restoration principles emerging from one of the world's largest tidal marsh restoration project. Wetlands Ecology and Management. 9: 387-407.

Weinstein, M.P., S.Y. Litvinand V.G. Guida. 2009. Essential Fish Habitat and Wetland Restoration Success: A Tier III Approach to the Biochemical Condition of Common Mummichog *Fundulus heteroclitus* in Common Red *Phragmites australis*-and Smooth Cordgrass *Spartina alterniflora*-Dominate Salt Marshes. Estuaries and Coasts. 32.5(2009): 1011-1022.

Weishar L.L., J.M. Teal and R. Hinkle. 2005. Designing large-scale wetland restoration for Delaware Bay. Ecological Engineering. 25: 231-239.

Whigham, D. F. 1999. Ecological Issues Related to Wetland Preservation, Restoration, Creation and Assessment. The Science of the Total Environment. 240: 31-40.

Zedler, J.B. 2000. Progress in wetland restoration ecology. Trends in Ecology and Evolution. 15(10): 402-407.

Zedler, J.B., J. C. Callaway and G. Sullivan. 2001. Declining Biodiversity: Why Species Matter and How Their Functions Might Be Restored in Californian Tidal Marshes. BioScience. 51(12): 1005-1017.

Zedler, J.B. 2005. Resorting wetland plant diversity: a comparison of existing and adaptive approaches. Wetlands Ecology and Management. 13: 5-14.