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ORIGINAL PAPER

Response of *Phragmites* to environmental parameters associated with treatments

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Abstract This multi-year study evaluated the response of invasive *Phragmites australis* to changes in pore water geochemistry associated with tidal enhancement, alone or in combination with other prescribed management regimes used by the US Fish and Wildlife Service. A pilot study was conducted prior to the treatment experiment that showed a negative correlation between the growth of *Phragmites* and cation concentrations in a transitional vegetation zone. In the targeted 535-acre brackish-water impoundment (East Pool) where *Phragmites* dominated, the soil water chemistry was changed by introducing tidal salt water through water control structures in June of 1999. Soil profiles, pH, salinity and cation concentration data in addition to *Phragmites* height and density data were collected both before and after the treatments were imposed, where possible. It was generally observed that a soil water salinity above ~28 would be needed to maintain the reduction of *Phragmites* and to support its replacement by salt marsh species. In the tidal water manipulated experimental macroplots, the soil water salinity changed from 7.1 to 32 on average between 1999 and 2001. The reduction of the average height of *Phragmites* ranged from 25% to 84% for different treatment combinations, while untreated sites exhibited a slight increases in height. The reduction in average live density ranged from 51% to 87% for different treatment combinations. The greatest reduction of *Phragmites* density and height resulted when tidal enhancement was followed by a prescribed burn in the winter. Also, significant negative correlations were observed between *Phragmites* height and the main cations associated with tidal salt water including Mg^{2+}, Na^{+} and K^{+} and to a lesser extent Ca^{2+}. pH did not change drastically with the introduction of tidal water over the period of 1999–2001 and did not appear to play a significant role in changing the growth of *Phragmites*. A reduction of soil adhesiveness associated with the decay of *Phragmites* roots was observed after a two month period in 2001 when plants were

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submerged in standing water. This points to the need to maintain tidal exchange to promote a gradual transition from a *Phragmites*-dominated system to a *Spartina*-dominated system. Towards the end of the growing season in 2001, *Spartina patens* and *Distichlis spicata* had begun to ramify into the center of the island patches.

Keywords *Phragmites* · Salinity · Tidal enhancement · Cations · Glyphosate · Burn

Introduction

Phragmites australis is a cosmopolitan species occurring on every continent except Antarctica (Tucker 1990). The expansion of *Phragmites* in North American wetlands in the past 50 years is thought to be triggered by environmental disturbances (Chambers 1997), and possibly to more aggressive genotypes of the species (Neuhaus et al. 1993; Saltonstall 2002). The nearly impenetrable monotypic stands of *Phragmites* that form in these areas reduce habitat value for waterfowl and other wildlife (Roman et al. 1984), threaten plant biodiversity (Marks et al. 1994), alter the marsh soil properties through biomass accumulation (Windham and Lathrop 1999), and contribute to human concerns, like obstructed vistas (Tiner 1997). *Phragmites* has the potential for becoming invasive once established in altered environments (Windham and Lathrop 1999).

Efforts to control the growth of *Phragmites* have been made by management agencies and various researchers exploring biological control (Van der Toorn and Mook 1982; Tscharntke 1989), herbicide application (Riemer 1973, 1976; Cross and Fleming 1989; Kay 1995), burning, mowing and cutting (Thompson and Shay 1985, 1989; Kay 1995). As has been shown by other researchers, such treatments usually require intensive labor on an annual basis and do not have a lasting effect (Boone et al. 1987). In coastal wetlands, tidal enhancement was also imposed in some sites and shown to be somewhat effective in reducing *Phragmites* in degraded salt marshes (Tiner 1997; Roman et al. 1984). Certain aspects of pore water geochemistry, salinity and growth of *Phragmites* have been evaluated as well (Chambers 1997; Lissner and Schierup 1997; Hellings and Gallagher 1992; Vasquez et al. 2005). However, the extent to which *Phragmites* in the natural environment responds to the geochemical changes associated with tidal enhancement has not been explored. How effective is tidal enhancement alone, and in combination with other prescribed management approaches at suppressing *Phragmites* height and density? Clearly, answers to these questions are needed to identify the most cost effective and ecologically viable approach to manage this troublesome species.

The goals of the project were (1) to better understand the critical relationship between the growth of *Phragmites* in relation to changes in pore water geochemistry, and (2) to evaluate the response of *Phragmites* to different treatments in combination with tidal enhancement. The experiment was implemented in an impounded marsh where islands are trenched and the flow rate of tidal water can be controlled by tidal gates. By gradual alteration of the soil water chemistry from the edge of the trenches to the center of the island patches, the project expects to convert a *Phragmites*-dominated marsh to a system more closely resembling the tidal salt marsh that surrounds the impoundment. These data will offer insight on the growth of *Phragmites* as it relates to pore water geochemistry, soil and landscape change.

Pilot study in Stone harbor, New Jersey

A preliminary study on the relationship of pore water geochemistry and the growth of the *Phragmites* for the purpose of establishing a numerical correlation was conducted in the summer and fall of 1998. A hilly area where a gradual change of the *Spartina alterniflora* to *Phragmites* was selected on the premises of the Wetland Research Institute, Stone Harbor, New Jersey. The 20-m transect extended from the shoreline to the top of a sandy hill. The identification of plant species, measurement of plant height, water pH, salinity, and some selected cations were conducted.

A total of six monitoring wells were set up along the transect. The soil water samples were collected on a bi-weekly basis from the wells and adjacent open bay for a two-month period from

September to October, 1998. Soil water saturation decreased while the density of *Phragmites* increased from shore to the top of the sand hill. The height of *Phragmites* measured on the transect changed from 0.1 to 2.13 m from the shore to the sandy hill top. Along the same direction, the pore water salinities decreased from 31.4 to 16.7 on average. The Na concentration in the porewater decreased from 11,800 ppm to 5,535 ppm on average. The concentrations of Ca and Mg showed the same decreasing trend as well (Fig. 1). However, the Fe concentrations show a strong increase from 260 ppb to 1942.5 ppb (Fig. 2). This Fe concentration trend might reflect a change in pH because the acidity of the pore water usually increases as the salinity decreases in a natural setting (Ponnampuruma 1979; Langmuir 1997). It was also observed that *Spartina alterniflora* was replaced by *Phragmites* at a Na concentration of around 9,070 ppm, an Fe concentration of around 367.5 ppb, and as the salinity changed from 31–36 to 22–24 along the transect (Fig. 3). This preliminary study suggested that *Phragmites* reduction will require a sustained range of salinity above 28 in porewater salinity. Above 28, we observed a gradual change from *Spartina patens* to *Spartina alterniflora*. Other plant species at the study site include: *Iva frutescens* and *Distichlis spicata*.

The strong correlation between *Phragmites australis* growth characteristics and the subsurface porewater concentration (salinity, concentration of Na, Ca, Mg, and Fe) implies that by manipulating the geochemical condition of the pore water, one can, therefore, control the growth of *Phragmites* (Tiner 1997; Lissner and Schierup 1997). Also, the data indicates that a sustained salinity level of 28 may be the minimum level needed for a permanent reduction of *Phragmites*.

Fig. 1 Relationship of salinity, cation concentrations and height of *Phragmites*. Data was collected on 10/9/1998

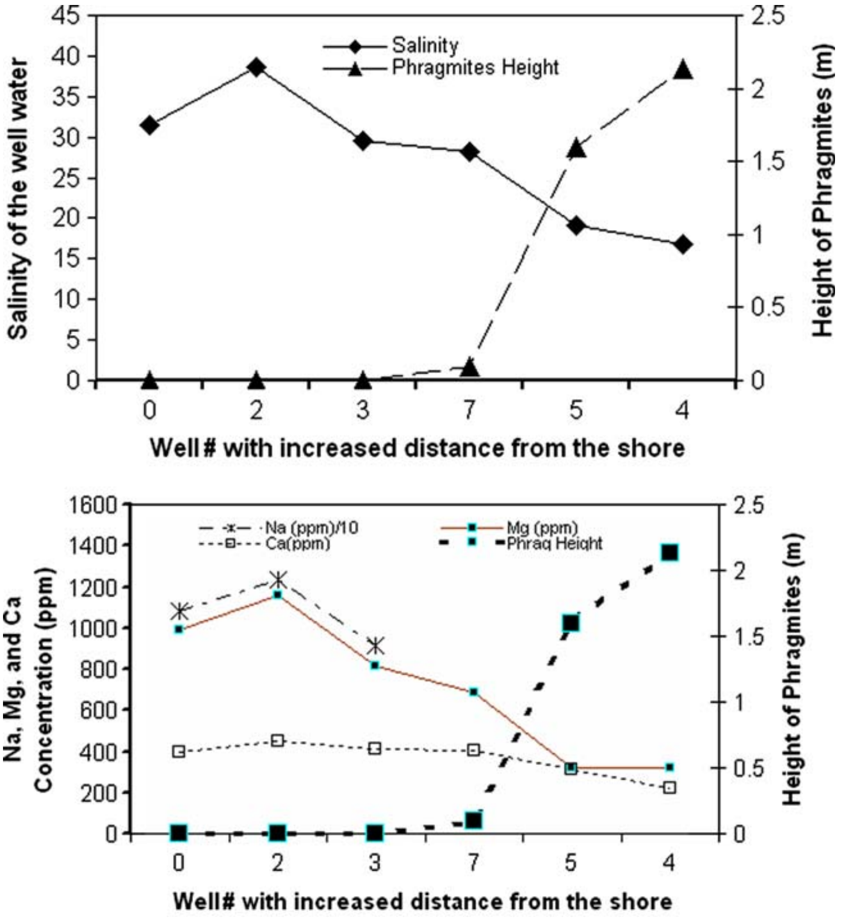
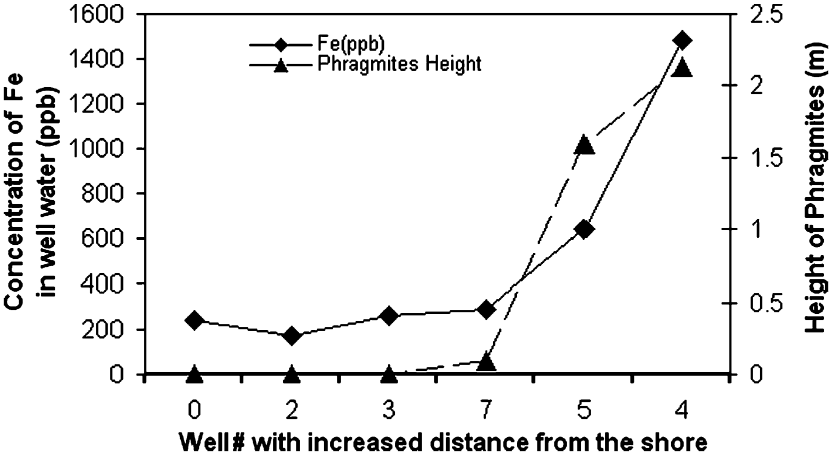


Fig. 2 Relationship of Fe concentration and height of *Phragmites*. Data was collected on 10/9/1998



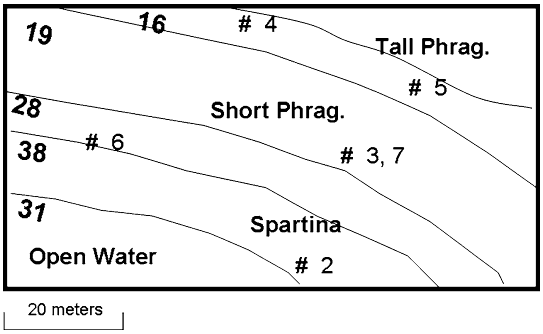


Fig. 3 Contours of *Phragmites* height and salinity. Bold numbers on the map are the salinity level while the normal numbers besides the # are the well numbers. # indicates the well locations

Experiment at EBF Refuge

Edwin B. Forsythe National Wildlife Refuge in Oceanville, New Jersey (hereafter referred to as EBF Refuge) encompasses the site of our experimental plots. EBF Refuge's fresh- and brackish water impoundments were constructed within a tidal salt marsh habitat during the 1950's to attract a greater diversity of migrating and resident waterfowl (Fig. 4). The impoundments include the East Pool (216 ha), the Southwest Pool (~120 ha) and the Northwest Pool (~243 ha). For many years, *Phragmites* was controlled via glyphosate applications, controlled burns, flooding, and mowing. This has resulted in few multiyear benefits as demonstrated by the progressive advancement of *Phragmites* in the EBF Refuge each year, where it seems to favor in particular the brackish conditions of the East Pool.

The tidal enhancement treatment was expected to suppress the growth of *Phragmites* by increasing the salinity of the pore water of the island patches in the East Pool where *Phragmites* dominates. The flux of saline tidal water in and out of the impoundment was regulated by the water control structures that the EBF Refuge had installed around the East Pool (Fig. 4). The water circulates around the island patches only in trenches, and therefore, creates a gradual soil water chemical change from the edge to the center of island patches (Fig. 5). It was anticipated that the change of pore water chemistry would reduce and eventually limit the monotypic growth of the *Phragmites* and encourage its replacement by a diversity of native vegetation more typical of the tidal salt marsh. This approach also appeared to be the most cost effective approach to *Phragmites* control in the East Pool. The freshwater impoundment of the Northwest Pool, which supports large patches of *Phragmites*, was our primary control site for comparison.

Macroplot design

Macroplots were assigned to eight different locations in the wetland complex (Fig. 4). The researchers coordinated with EBF Refuge staff to locate macroplots allowing the following treatments: Macroplot (1) tidal enhancement alone (TE Only); Macroplot (2) glyphosate application + controlled burn + tidal enhancement (G + B + TE); Macroplot (3) tidal enhancement alone (TE Only) and tidal enhancement followed by a controlled burn

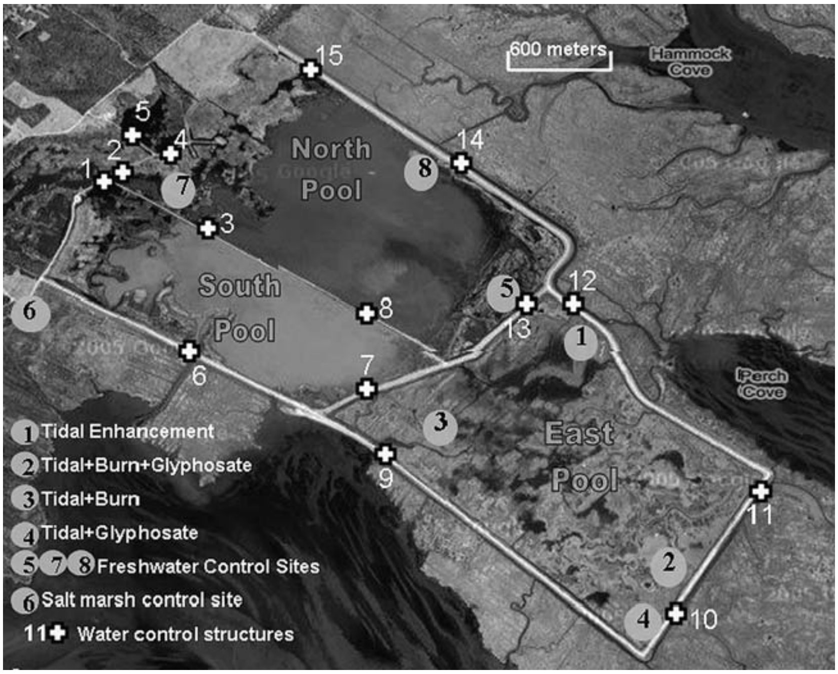


Fig. 4 Location of the impoundments at the Edwin B. Forsythe National Wildlife Refuge (EBF Refuge) near Oceanville, New Jersey. Circled numbers on the map mark the locations of the macroplots. Crosses on the map mark the water control structures. Base map is from the Google Map site

(TE + B); (4) Glyphosate application + tidal enhancement (G + TE). Macroplots (5), (7), and (8) served as untreated freshwater impoundments (Control); and Macroplot (6) served as an untreated salt marsh. Each macroplot consisted of up to seven subunits. Each subunit consisted of a vegetation patch generally dominated by *Phragmites*. Subunits were monumented with t-stakes and GPS location data.

Implementation of treatment protocols

Tidal enhancement

Prior to tidal introduction, the salinity of the channels and pore water in the East Pool averaged 7.1 in all four plots that were sampled in January and February of 1999. Continuous tidal water with a tidal range of approximately 2 m was introduced in July 1999 into the East Pool through the four tidal water control structures (gates) #9–12 after the freshwater gates #7 and 13 were closed. The gate at #10 was set to a full open position. The exterior tidal gates of the box culvert at #11 (approximately 6 feet wide) were lifted by cables to allow continuous tidal exchange with the estuary. The tidal gates of #9 and #12 were trap gate sets to allow only influx to the East Pool when water pressure from rising tides forced gates open. Staff gauges at gates #9, #10 and #12 allowed water levels to be recorded (Fig. 6). Island patches were generally not flooded except in June and July of 2001 when the cable of gate #11 broke accidentally during a spring tide and water became trapped. Because of rotten water boards in gate #11, flow along gate #11 was impaired during early 2001. These boards were removed late that year. The tidal water circulated along the island patches through channels and the salinity was introduced into the roots of *Phragmites* islands by pore water flow and diffusion processes. The tidal water salinity along the channels varied around 30 from 2000 to 2002 (Fig. 7) and average pore water salinity in East Pool was 27 in 2000 and 32 in 2001.

Fig. 5 *Phragmites* patches and water channels in 2002 (upper panel) and 2005 (lower panel). Establishment of green *Spartina alterniflora* (tall green) and *Spartina patens* (short green) along the edges of island patches shown on the lower panel while tidal enhancement continued

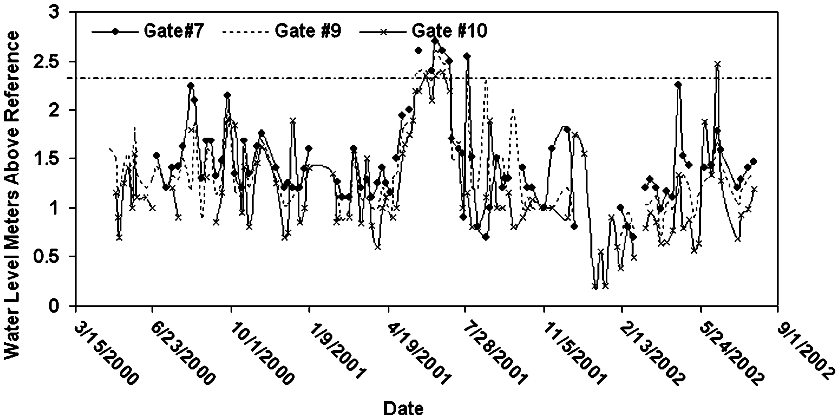


Fig. 6 Water levels at the three tidal gates in East Pool. The horizontal dashed line shows the approximate elevation of island patches relative to the water level

Prescribed burning

Burning was conducted in four subunits of Macroplot 2 in winter 1999 prior to tidal enhancement, and two subunits of Macroplot 3 in February/March of 2000 once tidal enhancement had commenced. New Jersey state law limits the burning season to October 1 through March 31. The purpose of the burning was mainly to reduce the dead standing biomass of *Phragmites*. *Phragmites* patches in Marcroplots 2 and 3 were torched and stems were generally burned down (Fig. 8).

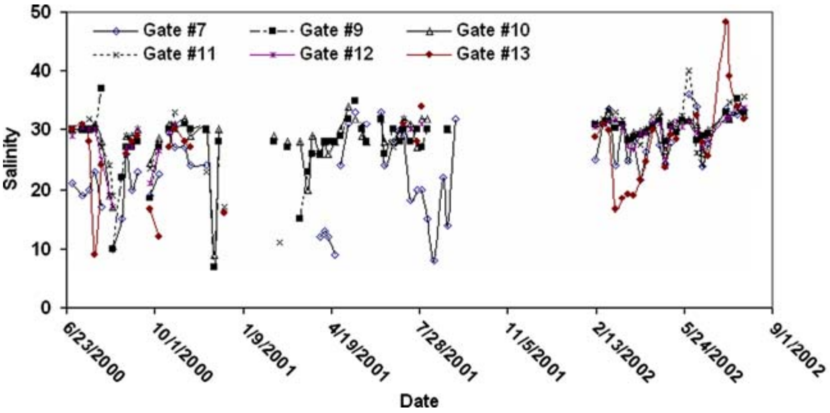


Fig. 7 Salinity levels at the six tidal gates in the East Pool

Fig. 8 A 0.5 × 1 m vegetation frame over a burned area. Photo taken in summer 2001

Because the burned islands were isolated from other islands, the burning area was easy to control.

Glyphosate application

Macroplots 2 and 4 were treated by aerial applications of glyphosate at four pints per acre in September 1998 prior to introduction of tidal flow. September applications allowed improved translocation to root masses after the tasseling stage when the plant redirects nutrients to the root zone.

Field data collection

Four field surveys were conducted beginning in 1999. The pretreatment vegetation, soil, and pore water chemistry survey was conducted in the winter of 1998–99 (12/29/98 to 3/17/99). A first year post treatment survey was conducted in winter of 2000 (1/14/00 to 2/12/00). Another first year post treatment survey (focusing on vegetation changes) was conducted in summer/early fall of 2000 (8/4/00 to 10/10/00). The second year post treatment survey was conducted during summer of 2001 (8/3/01 to 8/29/01).

Density and height of *Phragmites*

Power tests were performed to identify sample size and minimum detectable difference in plant density and height needed to conclude whether there was a significant change in growth within each treated area following the practice by Elzinga et al. (1998) and Zar (1984). Culm densities were measured in each subunit patch of *Phragmites* using a minimum of eight—0.5 m × 1 m (0.5 m^2) quadrat measurements. The quadrat was poised at a known starting point and was then moved successively across the center axis of the *Phragmites* subunit forming a belt transect. *Phragmites* total density (# culms per 0.5 m^2) was estimated in all macroplots (except M 6 Leeds—no *Phragmites*) on the four different sampling dates. All dead standing biomass was included (burned stubs were ignored). During the summer 2000 and summer 2001 sampling periods, we additionally measured live density (# live culms per 0.5 m^2). A minimum of three random height measurements per quadrat were made (for a minimum of 24 individual height values per subunit). Plants were measured from the base of the culm to the tip of the inflorescence through summer 2000. In August 2001, inflorescences were notably absent in the East Pool *Phragmites* patches, so we measured to the tip of the vegetative shoot.

Hydrogeochemical and soil conditions

Approximately seven freshwater soil cores each around 6.4 cm wide × 3.5 m deep were drilled with manual soil augers in the East Pool (Macroplot 2) in the years of 1999 and 2000. The soil cores of 2001 were less than 2 m. They are relatively shorter than those of the two previous years. Several additional cores were sampled in the Northwest Pool (Macroplot 5) and in the *Spartina* marsh (Leeds-Macroplot 6) both before and after treatment. Porewater salinity and pH was measured in situ in shallow (6'' deep) soil bore holes ($n = 3$) in the Macroplots using a hand-held refractometer and portable pH meter. In addition, several measurements were made in the channels surrounding the East and West pools and the *Spartina* marsh. Porewater samples were collected and returned to the lab for the quantitative analysis of cations in solution using an inductively coupled argon plasmometer (Baird ICP 2070).

Results of the EBF Refuge experiment

Pre- and post-treatment change of hydrology and pore water geochemistry

Salinity and pH

The averaged bore hole water salinity in the tidal enhanced East Pool changed from 7.1 in 1999 winter to 26.8 in winter of 2000 (Table 1). The average bore hole salinity of 32 in summer of 2001 is about 4 times greater than the salinity level in 1999. The bore hole water salinity in the controlled freshwater Northwest Pool and edges of the tidal marsh where we collected our water samples, all decreased by 10% to 43%. The decreases of salinity in those sampled areas may be the result of the increased freshwater seepage.

The average bore hole pH level in the East Pool decreased by about 6% and 12% in 2000 (pH = 4.8) and 2001 (pH = 4.5), respectively compared with the pH level in the winter of 1999 (pH = 5.1) (Table 1). The average pH of summer 2001 in both the control site and salt marsh showed a similar percentage (~10%) of decrease from that of 1999. The average pH was 3.9 in the control site and was 6.4 in the salt marsh in summer of 2001. Variations of salinity and pH in different treatment sites exist. However, it is unlikely that different treatment methods resulted in significant differences in pH.

Cations

The cations that were selected for measurement here are the major salt cations: Na$^+$, Mg^{2+}, K$^+$ and Ca^{2+}. The concentration changes of those major cations in the soil water were very significant in the East Pool (Table 1). The concentration of magnesium (Mg^{2+}) increased 106% in 2000 winter and increased 188% in 2001 summer from the initial concentration level of Mg^{2+} in 1999 winter. The concentration of potassium (K$^+$) increased 256% in 2000 and 470% in 2001 from the base levels in 1999. However, the concentration of calcium (Ca^{2+}) both in 2000 and 2001

Table 1 Pre- and post-treatment changes of salinity, pH, K$^+$, Ca^{2+} and Mg^{2+} values

	1999			2000			2001		
	East Pool	Control site	Salt marsh	East Pool	Control site	Salt marsh	East Pool	Control site	Salt marsh
Salinity	7.1 ± 2.6	9 ± 1	27 ± 4.5	26.8 ± 2.9	5.3 ±1.2	24 ± 3.6	32.3± 1.4	5.3 ± 6.7	15 ± 1.8
pH	5.1 ± 0.1	4.7 ± 0.4	7.6 ± 0.3	4.8 ± 0.2	4.3 ± 0.2	6.9 ± 0.2	4.5 ± 0.1	3.9 ± 0.03	6.4 ± 0.3
K$^+$ (ppm)	73 ± 10.6	40 ± 4	271 ± 83.1	260 ± 11.9	14 ± 48	226 ± 28.7	416 ± 12.9	105 ± 27.5	267 ± 59.3
Ca^{2+} (ppm)	413 ± 54.9	155 ± 39.5	NA	390 ± 30.9	84 ± 28.4	258 ± 13.7	372 ± 11.8	164 ± 46.5	231 ± 53.1
Mg^{2+} (ppm)	426 ± 74.9	139 ± 4	914 ± 219.7	876 ± 35.8	70 ± 33.2	766 ± 142.3	1226 ± 37.9	235 ± 40.3	723 ± 166.1

Values are expressed as means ±SE's. Number of sites range from 8 to 40

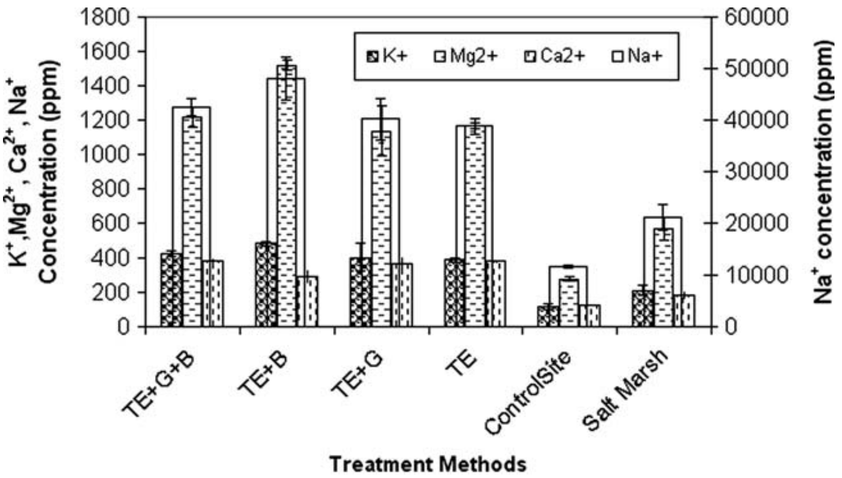


Fig. 9 Concentrations of K^+, Ca^{2+}, Mg^{2+} and Na^+ versus treatment methods 2001 summer data. Sample size: TE + G + B, 8; TE + B, 2; TE + G, 2; TE, 5; Control site: 2, Salt marsh: 3

shows a less than 10% decrease from the level in 1999. We think the level of calcium is related to the pH level in the water. Unless there is a sharp change in the pH levels, we would not expect to see a significant change in the calcium concentration. Because we did not have a good record of sodium in year 1999 and 2000, we did not do any comparisons of sodium with the data in 2001. The changes of cation concentration in both the control sites and salt marsh from year 1999 to 2001 were not as drastic as in the East Pool. Some variations in the concentrations of measured cations in different treatment sites in summer 2001 were observed (Fig. 9). The concentrations of Mg^{2+}, K^+, Ca^{2+}, Na^+ from TE+B sites show some apparent differences from concentrations of cations from the sites of other types of treatments.

There is one incident that needs to be mentioned. In May of 2001, tidal salt water was retained in the East Pool impoundment and almost all the island patches were completely inundated. This stacked high tidal water was eventually dried out in the impoundment. We believe that this event created an extended exposure of young plants to standing salt water and may have contributed to the dramatic reduction in live *Phragmites* in the East Pool, particularly inside the patches in 2001.

Change of density and height of *Phragmites*

In macroplots 1 and 3 where only tidal enhancement (TE only) was implemented, the average height of the *Phragmites* standing biomass was reduced from 179 cm in winter 2000 to 134 cm (Table 2) by summer 2001—a 25% reduction. The average live density changed from 66 to 32 plants per square meters, a 51% reduction in one year (Table 3). The total density (live and dead standing biomass) increased from 94 to 140 culms per square meter (Fig. 10). Of this, the final

Table 2 Changes in *Phragmites* height under different treatments in East Pool from 2000 to 2001

Treatment	Year	Mean ht. (cm)	Std. dv.	*n*	*t*	% reduction of Phrag height
TE ONLY	2000W	179.4	25.79	120	11.86	25%
	2001S	134.1	34.84			
TE + G	2000W	164.9	24.45	48	12.13	38%
	2001S	102.4	34.84			
TE + B	2000W	154.0	17.71	48	39.75	84%
	2001S	24.8	15.48			
TE + G + B	2000W	149.6	18.17	72	19.79	58%
	2001S	62.5	34.37			

n = number of height measurements per treatment

Table 3 Change of live density of *Phragmites* under different treatment in East Pool from 2000 to 2001

Treatment	Year	Mean live density/0.5 m^2	Std. dv	*n*	*t*	% reduction of live Phrag density
TE only	2000	32.5	15.21	40	7.06	51%
	2001	16.03	7.28			
TE + G	2000	38.31	29.3	13	4.30	76%
	2001	9.23	7.1			
TE + B	2000	19.19	11.59	16	5.30	82%
	2001	3.44	2.63			
TE + G + B	2000	67.1	21.54	32	13.54	87%
	2001	8.19	5.92			

n = number of density measurements per treatment

live density represented only 23% of the total density (Fig. 11).

In Macroplot 4 where a glyphosate application was followed by tidal enhancement (TE + G), the height of the standing biomass changed from 165 cm in winter 2000 to 102 cm by summer 2001, a reduction of 38% (Table 2). There was a 76% reduction in live culm density from summer 2000 to summer 2001, with an average of 20 plants per square meter remaining. However, including the dead biomass, total density increased by ~50%.

In Macroplot 3 where tidal enhancement was followed by a prescribed burn in winter 2000 (TE + B), the height of the standing biomass

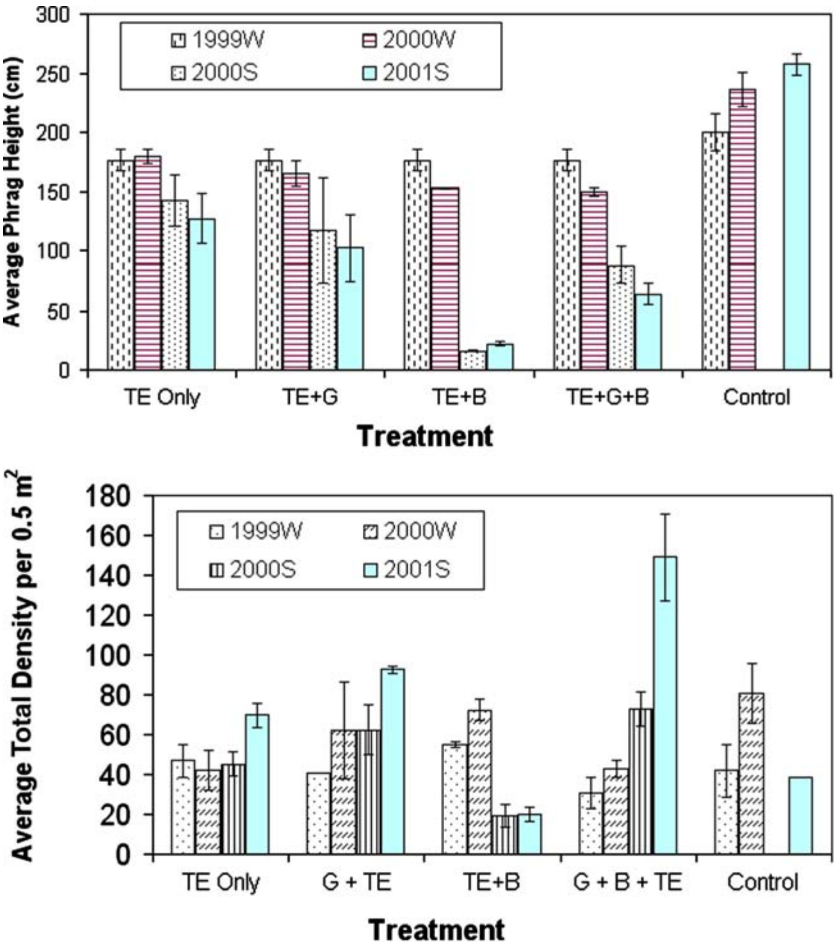


Fig. 10 Upper panel: height of standing *Phragmites* biomass versus treatment; low panel: total density of *Phragmites* versus treatment. Number of subunits used to calculate the average: control (n = 3, 6, 0, 2); TE Only (n = 6, 4, 4, 5); G + TE (n = 1, 2, 2, 2); G + B (n = 2, 2, 2, 2); and G + TE + B (n = 3, 3, 4, 4). Pre-treatment height values were averaged for all subunits measured (n = 7). Each subunit has 5 to 10 0.5 m^2 quadrats. values are expressed as means ± SE

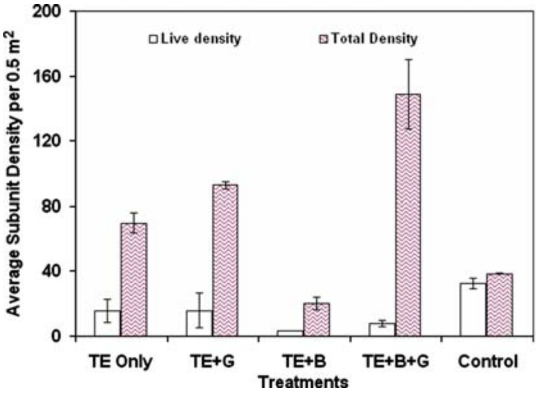


Fig. 11 Live versus total *Phragmites* density under different treatment combinations. Number of subunits: TE(5), G + TE(2), TE + B(2), G + TE + B(4), control(2). There were 5–10 quadrats per subunit

changed from 154 cm to 25 cm, a reduction of 84%, from winter 2000 to summer 2001. An 82% reduction in live density was observed between 2000 and 2001, with an average of eight plants per square meter remaining (Table 3). Total density (including dead biomass) decreased by 64%.

In Macroplot 2 where a glyphosate application was followed by a prescribed burn in winter 1999, then tidal enhancement (TE + G + B), the average height of the standing biomass changed from 150 cm to 63 cm, a reduction of 58%. Also, an 87% reduction in live density was observed from summer 2000 to summer 2001 with ~16 plants per square meter remaining. A geometric increase in total density was noted for this macroplot, culminating in ~300 plants per square meter by summer 2001. Of this standing biomass only 5% was living in contrast to the control Macroplot 8 where 84% of the total standing biomass was living (Fig. 11).

Because the original control macroplot had to be moved (Macroplots 5, 7, and 8 represent the three locations), year to year comparisons cannot be made to identify seasonal or phenological changes. However, treatment data may be compared to control data for any one year (Fig. 10). Live densities for the control site 2001S (66 per square meter) were more than double those of most treatments (except for TE + G + B in 2000, as noted above) (Fig. 11). For height, dramatic differences were noted between the control and treatment plots for 2001. Plants in the control plots had heights often exceeding 260 cm whereas plants in the treatment plots ranged from an average 23 cm in the TE + B treatment to 127 cm in the TE Only treatment in 2001.

Also, during the period of observation between August 3 and August 29, 2001, there were noted differences between the phenological patterns in plants found in the East Pool treatment macroplots and plants found in the North Pool control macroplot. The control plots displayed vigorous development of inflorescences. Very few, if any inflorescences were noted in the treatment plots. Inflorescences were beginning to appear in the TE + G macroplot towards the end of our field season, but were scant. A tetrazolium assay test was performed on seeds from those inflorescences in winter 1999 and they were shown to be non-viable.

Change in species composition and fauna associated with treatment in East Pool

In the field survey of August 2001, we noticed vigorous stands of *Spartina patens* and *Distichlis spicata* appeared to be replacing *Phragmites* in East Pool Macroplots 1, 3, and 4. In the East Pool Macroplot 2, *S. alterniflora* was becoming established in patches that ranged in size from 0.1 to 0.5 m^2. A noticeable expansion of *S. alterniflora* was observed in the tidally enhanced East Pool during a visit to the area in 2004 (H. Sun, personal observation). In the plots that were burned following tidal enhancement (TE + B), it did not appear as if *Phragmites* was being replaced by salt marsh species and these areas remained fairly barren as of 2001. Die-back of woody plants including *Baccharis halimifolia*, *Iva frutescens*, *Toxicodendron radicans* and *Juniperus virginiana* was evident particularly in low elevation islands exposed to greater flooding with salt water. Dead material seemed to be undergoing rapid decomposition, and old snags were providing refuge for birds (many egrets were seen using dead snags during sampling period). Fiddler crab activity was also noted in Macroplot 4.

Soil and geomorphic changes

The top two meters of the soil in the marsh were primarily organic mud interspersed with some sand lenses (Fig. 12). The most notable change

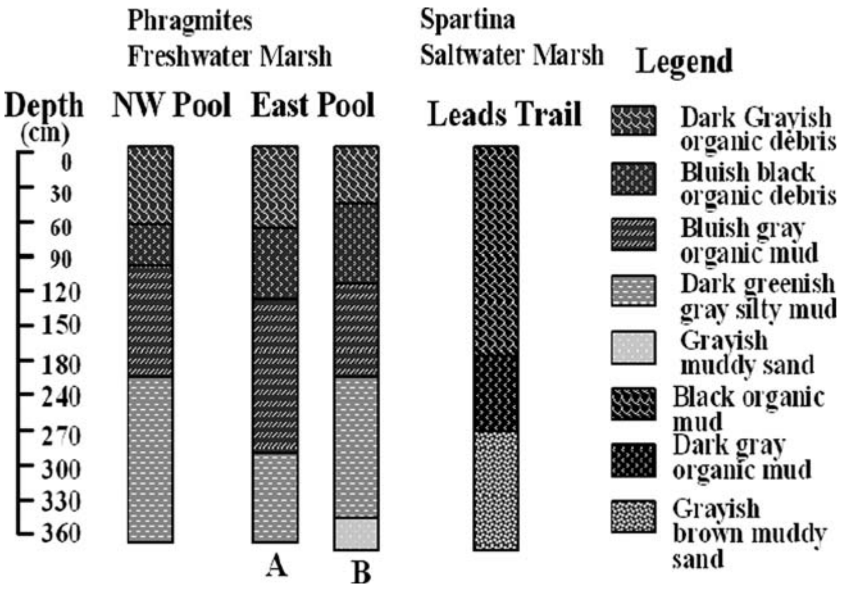


Fig. 12 Pre-treatment soil profiles in the experimental site

between pre- and post-treatment soil profiles was the significant decrease in soil adhesiveness. Many of the *Phragmites* roots had begun to decompose by August 2001. In the absence of a network of living roots to stabilize the soil, the potential for erosion of the island patches increases. It was observed by a former EBF manager during the summer of 2001 that *Spartina patens* had started to die back along the margins of the islands (Tracy Casselman, personal communication). This and other higher elevation salt marsh species cannot tolerate extended submersion in salt water. However, later on, he indicated that the *S. patens* was starting to recover (personal comm.). Furthermore, we did not observe obvious changes in the size of island patches during the August 2001 sampling period.

Discussion

Salinity and cation concentrations versus growth of *Phragmites*

Salinity is one of the important factors affecting the distribution of *Phragmites*, where the most vigorous growth is favored in brackish habitats at salinity levels less than 18 (Haslam 1971; Marks et al. 1994; Chambers et al. 1999). None-the-less, *Phragmites* stands in New York State have been observed growing in soils with salinity levels as high as 29, and on the Red Sea coast, levels as high as 40 have been reported (Hocking et al. 1983). The *Phragmites* population at EBF Refuge also appears to have a fairly high threshold of tolerance to salinity. In summer 2001, plants were observed growing in soils with salinities ranging from 6 (North Pool—Macroplot 8) to 41 (East Pool–Macroplot 3) for a short period, although we detected a significant decline in vigor as salinity levels increased. Based on the data from our pilot study, we expect that salinity levels above a threshold of 28 would suppress the growth of *Phragmites* and favor the growth of *Spartina* and other species (Sun et al. 1999). This is generally in line with the data we obtained from EBF Refuge, where a live *Phragmites* density reduction of 50% or more was achieved at salinity level of 30 in 1 year and a 25% reduction in height around a salinity level of 25. Hellings and Gallagher (1992) also noted a reduction of 50% or more in *Phragmites* density, height, and biomass when plants were inundated with salt water at salinity levels of 30. Our data suggests that the increase in Mg^{2+}, Na^+ , and K^+ concentrations may have contributed to the observed growth reduction in *Phragmites*. The correlation analysis suggests a significant negative relationship between Mg^{2+} and K^+, and plant height in *Phragmites* indicating that NaCl may not be the

Table 4 Non-parametric Spearman Rank Correlation of *Phragmites* height with the environmental parameters for the Stone Harbor October, 1998 Data, n = 6. Values were corrected for ties

	Salinity	Na	Mg	Ca	Fe
Correlation Coefficient	–0.941	–0.941	–0.941	–0.820	0.941
Z-value	–2.104	–2.104	–2.104	–1.833	2.108
p-value	0.035	0.035	0.035	0.067	0.035

Table 5 Non-parametric Spearman Rank Correlation of *Phragmites* height and density with the environmental parameters, for the Brigantine Refuge 1999–2001 data (n = 35), except Na which has only the 2001 data (n = 15)

	Salinity	pH	Na(2001)	Mg	Ca	K
Height vs.						
Correlation coefficient	–0.814	0.249	–0.636	–0.853	–0.423	–0.849
Z value	–4.749	1.454	–2.379	–4.974	–2.431	–4.952
p-value	< 0.0001	0.146	0.0174	< 0.0001	0.0151	< 0.0001
Total Density vs.						
Correlation coefficient	0.308	–0.093	0.193	0.299	0.215	0.392
Z value	1.796	–0.541	0.722	1.741	1.234	2.699
p-value	0.0726	0.589	0.4705	0.0817	0.2173	0.0894
Live Density (n = 15, 2001) vs.						
Correlation coefficient	–0.74	0.192	–0.458	–0.838	–0.283	–0.797
Z value	–2.769	0.718	–1.714	–3.137	–1.059	–2.983
p-value	0.0056	0.4726	0.0866	0.0017	0.2896	0.0029

only salt in tidal salt water responsible for growth suppression (Tables 4 and 5). The correlation of *Phragmites* growth with Mg^{2+} is also supported by our pilot study (Table 4). Further research is needed to test the hypothesis that magnesium and potassium salts independent of other salts can suppress growth in *Phragmites*. The cation data is useful for determining when and to what extent the pore water of the East Pool macroplots reaches dynamic equilibrium with the tidal salt water entering the impoundment. The average pore water Na^+ levels (9,177 ppm) measured in 2001 summer are less than levels reported for sea water (10,760 ppm). Pore water Mg^{2+} levels (1,226 ppm) in 2001 are also less than those for sea water (1,350 ppm). Pore water K^+ levels are slightly higher (416 ppm) than sea water (390 ppm), while Ca^{2+} levels (372 ppm) are lower than those for sea water (410 ppm). Dilution caused by fresh water discharge, precipitation, and exchange with plant roots will also influence the pore water cation concentration.

The explanation of the correlation of the cations with the growth of *Phragmites* can be complicated and the data we have from both our pilot and this experimental study are still not very conclusive. Is *Phragmites* growth negatively impacted by specific cations like magnesium? Further study is going to be needed on this point.

pH in the East Pool versus growth of *Phragmites*

It is surprising that the pore water pH (4–5) was still relatively low even two years following tidal enhancement (Table 1). Normally tidal inundation will cause the pH of acidic soils to increase asymptotically and stabilize around pH 6.7–7.2 (Ponnamparuma 1979). Low pH may be attributed to several factors. The contribution of fulvic and humic organic acids from the decay of the large amount of organic debris is one of the main factors (Armstrong et al. 1996; Armstrong and Armstrong 1999). The pH buffering ability at low pH by the reaction of aluminum with hydroxyl ions in soil may also play an important role (Brady and Weil 2004). Other factors may include the existence of low pH freshwater in the deep soil due to the slow drainage and seepage of groundwater in the marsh. Decomposition of organic matter by aerobic bacteria and the concomitant production of dissolved respiratory CO_2 can also depress pore water pH (Ponnamparuma

1979). Plant roots can compound conditions by removing cations in exchange for H^+ (Brady and Weil 2004). If clayey soil and plants selectively remove more cations (for example, Ca^{2+}, Mg^{2+}, K^+, and Na^+) than anions (for example, Cl^-, SO_4^{2-}, NO^{3-}, $H_2PO_4^-$), then the soil acidity increase. Though there have been anecdotal citings of *Phragmites* in highly acidic wetlands and mine tailings (Marks et al. 1994), it typically flourishes in environments where pH ranges from 5.5 to 7.5 (Haslam 1972).

Treatment methods versus growth of *Phragmites* in the East Pool

Tidal enhancement (TE Only) in the East Pool created the gradual increase of cations Mg^{2+}, K^+, and Na^+ in the pore water from the edge to the center of the island patches around macroplots. This change in return was related to a significant reduction of live *Phragmites* density and total *Phragmites* height, compared to the control and the pretreatment data. The number of live culms was reduced to nearly one third of the starting density in two and a half years. The most recent density estimate for the reference plots in the Northwest Pool was more than double the East Pool's TE Only treatment plots. Similarly, plants in the Northwest Pool control plots were more than two times as tall and averaged 260 cm. Hinkle and Mitch observed a marked decline in *Phragmites* cover following the return of normal daily tidal inundation in several coastal dikes of the Delaware Estuary (2005). In Fairfield, Connecticut, a diked marsh was restored to saltwater tidal action after a 30 meter section of dike was removed (Bongiorno et al. 1984). Over three years of time, plant height was reduced by about 100 cm. Plant density also showed a marked decline in one year from 11.3 to 3.3 plants per square meter (71%). Our density decline was slightly less over a two year span (66%) but the size of the impoundment and the timing of the treatment may have influenced the results. Height reduction has been comparable, however. The sharp decline in live *Phragmites* density and total height in 2001 may reflect the extended two month (May–June 2001) retention of salt water in the East Pool. While growth suppression of submerged young *Phragmites* shoots was no doubt enhanced, the colonization and growth of *Spartina patens* and *Distichlis spicata* may have been inhibited since these species can't tolerate extended periods of submergence. Accordingly, prolonged periods of tidal water retention could pose problems since island patches may begin to erode in the absence of rooting vegetation. The effects may be most severe in low elevation sites, burned plots, and island margins subjected to the greatest submergence.

The data suggests that the tidal enhancement + glyphosate (G + TE) treatment was only slightly better than the tidal enhancement alone (TE Only) treatment in the reduction of live culm density and height of *Phragmites* in the East Pool (Tables 2 and 3). This data is further substantiated by our observation that tall *Phragmites* stands still persisted in the higher elevation islands along the exterior margins of the East Pool—particularly along the southern edge where the pore water geochemistry change is weaker. These areas were targeted with aerial applications of glyphosate at four pints per acre in September 1998. It is possible that application drift or inadequate dosages influenced the results of our experiment. The combination of glyphosate, burning, and tidal enhancement (G + B + TE) resulted in a greater reduction in live density and height than either of the previously mentioned treatments. However, total density showed a greater increase over time compared to the other treatments. While glyphosate has a half life of 60 days, and is thought to have a minimum impact on surrounding vegetation and wildlife if applied correctly, there is mounting evidence that this herbicide may have deleterious effects on certain fish and aquatic plant species (Jiraungkoorskul et al. 2003; Marrs et al. 1993). Moreover, *Phragmites* may return once the glyphosate decays since below ground reserves are often unaffected. Tidal enhancement combined with a post TE burn (TE + B) seems to hold the greatest promise for the dramatic reduction in *Phragmites* density and height. All but the TE + B plots showed a significant increase in total standing biomass in comparison to the East Pool pretreatment data and to the Northwest pool control site data. If prescribed burns are deemed necessary, an end-of-the-season (late summer, early fall) burn may be preferable (Thompson and Shay 1989; Tiner 1997) although burning may not commence until October 1 by state regulation in New Jersey. However, the notable absence of colonizing salt marsh plants in the two post TE + B subunits (Macroplot 3) warrants careful evaluation of this treatment. Post TE burning may damage young colonizing salt marsh species, converting previously vegetated islands to barren salt flats. There may also be some advantages to not burning dead standing biomass. Dead biomass may encourage invertebrate populations that feed on the detritis (Weis and Weis 2003). We observed a number of fiddler crabs in August 2001 in the SE corner of the East Pool near macroplot 4. In addition to supporting the bird populations, the crabs dig burrows which, according to several studies (Bertness 1985, 1992) may help to aerate the soil, encouraging the colonization of *Spartina alterniflora*, and other salt marsh species. Stems of dead *Phragmites* may also help to pipe oxygen into the soils hastening the decomposition process and providing suitable conditions for colonization by desirable plant species (Gries et al. 1990). On the other hand, areas densely covered by dead standing biomass may not be as readily colonized by salt marsh species and could benefit from a prescribed burn. The timing of the burn is critical, depending on whether active *Phragmites* rhizomes are present in the proposed burn area. Where actively growing rhizomes are present, burning in the spring may actually stimulate growth of young *Phragmites* shoots, due to increased exposure to light and enrichment from the burn. This may explain the observed *Phragmites* growth spike in the summer 2001 TE + G + B plots.

The East Pool had begun to shift from a system supporting brackish marsh vegetation to one supporting vegetation more typical of the surrounding salt marsh near the edges of the island patches at the end of our sampling period in 2001. However, due to the prolonged retention of tidal water in 2001, the expected gradual change from a *Phragmites* dominated impoundment to a *Spartina* and *Phragmites* mixed marsh proceeded more quickly, and perhaps with some negative consequences. The dominant species of the brackish marsh system including *Phragmites australis*, *Iva frutescens*, *Baccharis halimifolia*, and *Toxicodendron radicans* are being replaced by *S. alterniflora*, *S. patens*, *Distichlis spicata*, and *Sesuvium maritimum* in some areas. Tidal enhancement continued in East Pool after our field survey. A noticeable expansion of *S. alterniflora* was observed in the East Pool during a visit to the area in 2004. Replacement of the vegetation is obvious in the 2005 field picture (Fig. 5) in which high *Phragmites* sites was treated by glyphosate again in 2004.

Summary and conclusions

This multiyear research showed a reduction of *Phragmites* height by 25% and density by 50% after 2 years (2000–2001) of restored tidal flow to an impounded marsh. A salinity of ~28 was required to sustain a long-term reduction of *Phragmites* at the site. The reduction of *Phragmites* was more strongly correlated with magnesium and potassium, than with sodium. pH is not significantly correlated with the growth of the *Phragmites* at the experiment plot. Prescribed burns appeared to accelerate the observed decline of *Phragmites* by as much as 83%, although the combustion of nutrient-rich detritus and potential damage to colonizing roots of salt marsh species warrant careful evaluation of this approach. Similarly, the benefits conferred by aerial applications of glyphosate are questionable, and may not be required in tidally enhanced sites. Finally, tidal exchange and optimum water levels must be maintained to avoid potential erosion.

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References

Armstrong J, Armstrong W (1999) *Phragmites* die-back: toxic effects of propionic, butyric, and caproic acids in relation to pH. New Phytol 142:201–208

Armstrong J, Afreen-Zobayed F, Armstrong W (1996) *Phragmites* die-back: sulphide- and acetic acid-induced bud and root death, lignifications, and blockages within aeration and vascular systems. New Phytol 134:601–614

Bertness MD (1985) Fiddler crab regulation of *Spartina alterniflora* production on a New England salt marsh. Ecology 66:1042–1055

Bertness MD (1992) The ecology of a New England salt marsh. Am Sci 80:260–268

Bongiorno SF, Trautman JR, Steinke TJ, Kawa-Raymond S, Warner D (1984) A study of restoration in Pine Creek Salt Marsh, Fairfield, Connecticut. In: Webb FJ (ed) Proceedings of the 11th annual conference in wetlands restoration and creation. Hillsborough Community College, Tampa, FL.Elzinga, C.L., Salzar, D.W.

Boone J, Furbish E, Turner K (1987) Control of *Phragmites communis*: results of burning, cutting, and covering with plastic in a North Carolina marsh. CPSU technical report 41, National Park Service, 15 pp

Brady NC, Weil RR (2004) The nature and properties of soils, 2nd edn. Prentice Hall, Upper Saddle River, New Jersey

Chambers RM (1997) Porewater chemistry associated with *Phragmites* and *Spartina* in a Connecticut tidal marsh. Wetlands: The J Soc Wetland Sci 17:360–367

Chambers RM, Meyerson LA, Saltonstall K (1999) Expansion of *Phragmites australis* into tidal wetlands of North America. Aq Bot 64:261–273

Cross DH, Fleming KL (1989) Control of *Phragmites* or common reed. USFWS Leaflet 13.4.12

Elzinga CL, Salzar DW, Willoughby JW (1998) Measuring and monitoring plant populations. BLM Tech Ref 1730–1731, 477 pp

Gries C, Kappen L, Losch R (1990) Mechanism of flood tolerance in reed, *Phragmites australis* (Cav.) Trin. ExSteudel. New Phytol 114:589–593

Haslam SM (1971) The development and establishment of young plants of *Phragmites* communis Trin. Ann Bot 35:1059–1072

Haslam SM (1972) *Phragmites communis* Trin. biological flora British Isles. J Ecol 60:585–610

Hellings SE, Gallagher JL (1992) The effects of salinity and flooding on *Phragmites australis*. J Appl Ecol 29:41–49

Hinkle RL, Mitch WJ (2005). Salt Marsh vegetation recovery at salt hay farm wetland restoration sites on Delaware Bay. Ecol Eng 25:240–251

Hocking PJ, Finlayson CM, Chick AJ (1983) The biology of Australian weeds. *Phragmites australis* (Cav.) Trin. ex Steud. J Aust Inst Agr Sci 12:123–132

Jiraungkoorskul W, Upatham ES, Kruatrachue M, Sahaphong S, Vichasri-Grams S, Pokethitiyook P (2003) Biochemical and histopathological effects of glyphosate herbicide on Nile tilapia (*Oreochromis niloticus*). Environ Toxicol 18:260–267

Kay S (1995) Efficacy of wipe-on applications of glyphosate and imazapyr on common reed in aquatic sites. J Aqua Manage 33:25–26

Langmuir D (1997) Aquatic environmental geochemistry. Prentice Hall, Inc., UK

Lissner J, Schierup H-H (1997) Effects of salinity on the growth of *Phragmites australis*. Aqua Bot 55:247–260

Marks M, Lapin B, Randall J (1994) *Phragmites australis* (P. communis): threats, management, and monitoring. Nat Areas J 14:285

Marrs RH, Frost AJ, Plant RA, Lunnis P (1993) Determination of buffer zones to protect seedlings of non-target plants from the of glyphosate spray drift. Agr Ecosyst Environ 45:283–293

Neuhaus D, Kuhl H, Kohl JG (1993) Investigation on the genetic diversity of *Phragmites* stands using genomic fingerprinting. Aqua Bot 45:357–364

Ponnamperuma FN (1979) The chemistry of submerged soils. Adv Agron 24:29–96

Riemer DN (1973) Effects of rate, spray volume, and surfactant on the control of *Phragmites* with glyphosate. Proc Annu Meet Northeastern Weed Sci Soc 27:101–104

Riemer DN (1976) Long-Term Effects of Glyphosate Applications to *Phragmites*. J Aqua Plant Manage 14:39–43

Roman CT, Niering WA, Warren RS (1984) Salt marsh vegetation change in response to tidal restriction. Environ Manage 8:141–150

Saltonstall K (2002) Cryptic invasion by a non-native genotype of the common reed, *Phragmites australis*, into North America. PNAS 99(4):2445–2449

Sun H, Browne KK, Husch J (1999) Pore water geochemistry in a transition zone of *Spartina* to *Phragmites* in a tidal marsh in Stone Harbor, New Jersey. Geol Soc Am Abst with Prog. 31:2

Thompson DJ, Shay JM (1985) The effects of fire on *Phragmites australis* in the Delta Marsh, Manitoba. Can J Bot 63:1864–1869

Thompson DJ, Shay JM (1989) First-year response of a *Phragmites* marsh community to seasonal burning. Can J Bot 67:1448–1455

Tiner R (1997) Managing common reed (*Phragmites australis*) in Massachusetts—an overview of the Species and Control Techniques. Mass. Wetlands Restoration and Banking Program. Executive Office of Environmental Affairs. 100 Cambridge St., Boston, MA 02202

Tscharntke T (1989) Attach by stem-boring moth increases susceptivility of *Phragmites australis* to gall-making by a midge: mechanisms and effects of midge population dynamics. Oikos 55:92–100

Tucker GC (1990) The genera of Arundinoideae (Gramineae) in the southeastern United States. J Arnold Arboretum 71:145–177

Van der Toorn J, Mook JH (1982) The influence of environmental factors and management on stands of *Phragmites australis*. I. Effect of burning, frost and insect damage on shoot density and shoot size. J Appl Ecol 19:477–500

Vasquez EA, Glenn EP, Brown JJ, Guntenspergen GR, Nelson SG (2005) Salt tolerance underlies the cryptic invasion of North American salt marshes by an introduced haplotype of the common reed *Phragmites australis* (Poaceae). Mar Ecol Prog Ser 298:1–8

Weis JS, Weis P (2003) Is the invasion of the common reed, *Phragmites australis*, into tidal marshes of the eastern US an ecological disaster? Mar Pollut Bull 46:816–820

Windham L, Lathrop RG Jr (1999) Effects of *Phragmites australis* (common reed) invasion on aboveground biomass and soil properties in a brackish tidal marsh of the Mullica River, New Jersey. Estuaries 22:927–935

Zar JH (1984) Biostatistical analysis. Prentice Hall, New Jersey