Predicting the Impact of Sea Level Rise on the Distribution of Phragmites Australis and Spartina Alterniflora and Changes in Community Compositions in Tidal Freshwater Marshes of James City County, Va

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Predicting the Impact of Sea Level Rise on the Distribution of Phragmites australis and Spartina alterniflora and Changes in Community Compositions in Tidal Freshwater Marshes of James City County, VA

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A Thesis presented to the Graduate Faculty of The College of William & Mary in Candidacy for the Degree of Master of Science

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Master of Science

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Approved by the Committee, June, 2017

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ABSTRACT

With ongoing sea level rise (SLR), tidal freshwater marshes (TFMs) eventually will be flooded with more brackish water. The impact of more water and salt on the plant community of TFMs, however, is unknown. With SLR, both the invasive reed *Phragmites australis* and the native salt marsh grass *Spartina alterniflora* could become dominant species in TFMs. I am looking at determining how increases in salinity and inundation caused by sea level rise will impact the relative distribution of *Phragmites* and *Spartina* in tidal freshwater marshes in Southeastern Virginia. Using GIS, I summarized past expansion patterns by mapping the current and historical distribution of *Phragmites* and *Spartina*. With soil samples collected from 6 TFMs in James City County with established *Phragmites* stand, I tested the effects of salinity and flooding on the germination of *Phragmites* and *Spartina* seeds and the subsequent effects of competition with these conditions. Inundation positively impacted the abundance of *Phragmites* and *Spartina*, while competition form *Phragmites* and *Spartina* decreased native species richness. Based on germination success and historical distributions, SLR-caused range shifts were predicted for *Phragmites* and *Spartina* and suggest *Phragmites* and *Spartina* will be more abundant in number within TFMs and in more TFMs in James City County. TFM area across James City County will diminish if accretion rates cannot keep pace with sea level rise and current TFMs will transition to oligohaline marshes, causing significant community changes.
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Introduction

Rapid decreases in global biodiversity stem from numerous environmental factors, notably climate change and the spread of invasive species (Center for Biological Diversity, 2015). Biodiversity is particularly vulnerable in tidal wetlands due to two main mechanisms, i.e., sea level rise driven by climate change and displacement or loss of native species caused by aggressive invaders. *Phragmites australis* is an aggressive, invasive plant species threatening native tidal marsh species in North America. Dense stands of *Phragmites* prevent light from reaching other species aboveground and reduce nutrient availability belowground (Medeiros et al. 2013).

Tidal freshwater marshes are estuarine systems found at the upper reaches of tidal influence, where in-coming freshwater from riverine systems and saline tidal waters meet (Perry et al 2009). Because the in-flux of freshwater from riverine systems overpowers the diluted saline tidal waters, these systems are fresh and, thereby, support a great diversity of species. As well as being a diverse ecosystem, tidal freshwater marshes sequester carbon, are proficient at nutrient and sediment assimilation, and provide valuable nurseries for many fish species (Odum et al. 1984; Nichols [date unknown]). Because tidal freshwater marshes are located on the upstream reaches of coastal estuaries (Perry et al 2009), they are threatened by sea level rise leading to increased salinity and inundation. Tidal freshwater marshes can migrate inland where possible, but human development is abundant along marsh borders preventing landward movement in many places. In addition, the upland slopes may be too steep to
allow inland migration. As a result, much of the existing tidal freshwater marsh area will either disappear or transition to oligohaline or mesohaline marsh. Within the existing marshes, significant community composition changes are expected with increases in salinity caused by sea level rise, as fewer wetland plant species are tolerant of salt.

Sea level rise causes saltwater to penetrate farther up estuarine river systems ([VA DCR] 2013), killing any native freshwater species intolerant of salt. This loss of native species opens space for aggressive invaders like *Phragmites*, a semi-salt tolerant species (Chambers et al 1998; Chambers et al 1999), to thrive. With rising salinity level, the influx of sea water also brings propagules of more salt-tolerant species like the native cordgrass *Spartina alterniflora*. The fundamental niche of *Spartina* contains most marsh habitats along the estuarine salinity gradient (Subudhi and Baisakh 2011). Salt marshes are considered the realized niche both because *Spartina* has been thought to be a poor interspecies competitor in low salinity and because so few other species are tolerant of high salinity (Sutter 2013). More recently however, *Spartina* has begun to occupy low marsh area in freshwater marshes transitioning to oligohaline marshes with sea level rise and salt intrusion (Field et al 2016). Together, these salt-tolerant species---the invasive *Phragmites* and native *Spartina*---threaten to replace the diverse community of native vegetation in tidal freshwater marshes exposed to sea level rise.

In a sample tidal freshwater marsh in Virginia, importance values (IV), or the level of impact a species has on the surrounding species and environment,
for both *Phragmites* and *Spartina* increased from 1974 to 2003 (Davies 2004). In 1974, neither species was in the top ten most important species for the marsh. However, by 2003 *Phragmites* was ranked 8th, having an annual mean IV of 1, while *Spartina* was ranked 9th with an annual mean IV of about 0.5. Although not natural competitors—*Spartina* prefers lower marsh elevations, whereas *Phragmites* prefers higher marsh elevations—*Phragmites* has historically impacted the species composition and nutrient availability of the surrounding environment more than *Spartina* (Davies 2004).

Germination will largely determine species composition and dynamics in new oligohaline marshes created by sea level rise (i.e. tidal freshwater marshes inundated by saline water). Seed banks play a critical role in the distribution of plant communities after disturbances, such as sea level rise, as seeds persist longer under stress than the standing vegetation (Wang 2008). In wetlands, seed banks may most accurately predict the future community distribution in the face of sea level rise (Deberry and Perry 2000). Of course, species first much reach the seed bank to germinate and the pathway to arrival in oligohaline marshes may differ. For example, *Spartina* seeds may be introduced via the influx of tidal brackish water, whereas *Phragmites* seeds may be carried in by the wind. The physical vectors of wind and water create opportunities for these species to spread into new wetland environments.

Once established in a wetland, *Phragmites* can expand clonally into adjacent marsh areas, but how seed dispersal and survival may affect the expansion of *Phragmites* into habitats with different abiotic conditions is
unknown. With sea level rise, the native *Spartina*, a salt marsh species, is expanding into more freshwater marshes (Sutter 2014) and may displace *Phragmites*. *Spartina* can withstand higher salinity levels of up to 35 parts per thousand (ppt) (Medeiros et al. 2013; [USDA] 2002) and sulfidic soil conditions (Chambers et al. 1998). Competition for resources has developed between *Spartina* and *Phragmites* in established stands of saltwater marshes (Medeiros et al. 2013). *Spartina* normally comes out ahead in nutrient competition and survivorship in water with higher salinity and sulfide levels (Chambers et al. 1998), while shading by *Phragmites* is still detrimental to *Spartina* in established stands. The outcome of plant competition often depends upon which species establishes first (RMC pers. comm. 2016).

*Phragmites* has highest seed germination success in unshaded freshwater tidal marshes, but germination rates also remain high in brackish water relative to salt-water (Gucker 2008; Kettenring and Whigham 2009). Lissner and Schierup (1997) found a negative correlation between *Phragmites* seedling growth and salinity, suggesting that salt penetration could decrease the current distribution of *Phragmites*. In less than 100 years, all existing *Phragmites* stands occurring in tidal freshwater marshes in James City County are projected to be inundated by brackish water ([CCRM] 2015). The delivery of saltwater and salt-tolerant, native species like *Spartina* could affect *Phragmites* expansion and lead to native species range shifts within coastal Southern Virginia.

How will increases in salinity and inundation because of sea level rise impacting the distribution of the invasive *Phragmites* and the native *Spartina* in
tidal freshwater marshes of James City County, Virginia? I determined the current distribution of *Phragmites* and *Spartina* in tidal freshwater marshes, the effects of two aspects of sea level rise (increased inundation and salinity) on *Phragmites* and *Spartina* germination and the predicted, future distributions of *Phragmites* and *Spartina* in tidal marshes of James City County.
Methods

Current and Past Distributions

Knowing the past and current distributions of *Phragmites* and *Spartina* will inform understanding of how their ranges will change with the influx of saltwater from sea level rise. Using data from the Center for Coastal Resources Management [CCRM] at the Virginia Institute of Marine Science, the current distributions of *Phragmites* and *Spartina* in tidal freshwater marshes of James City County were projected with current elevation, salinity, and land use data in ArcMap. The 2014 Tidal Marsh Inventory (TMI) includes percentage abundance of species within all tidal marshes and was selected for only James City County. The TMI, conducted by the CCRM, estimated percentage coverage of every plant species in tidal marshes of Virginia. The 2014 TMI data were collected between 2010 and 2014. The 1983 TMI data were collected between 1974 and 1988 for Virginia. Current elevation data were obtained from a Digital Elevation Model (DEM) downloaded through the USDA Geospatial Data Gateway and displayed for the county using a natural breaks classification. Salinity data were gathered in the field from collection sites during August 2016 using a YSI handheld salinity meter and classified by the specific value. County data were downloaded from the U.S. Census Bureau to establish the James City County border. Land use data were downloaded from the Department of Forestry and displayed only for James City County. Current distributions of *Phragmites* and *Spartina* were displayed by the categorical percent abundance within the marsh: trace, present or dominant. Trace abundance meant less than 1% of the marsh.
area was covered by the species. Present meant 1-50% of the marsh area was covered by the species, and dominant meant that more than 50% of the marsh area was covered by the species.

Using the paper-printed, 1983 tidal marsh inventory of James City County, the categorical amount (trace, present or dominant) of *Phragmites* was added to the attribute table of the appropriate marsh in the 1983 tidal marsh inventory feature class. The historical ranges for *Phragmites* and *Spartina* were displayed categorically by abundance in the marshes in time series maps, used to then visually analyze expansion patterns for *Spartina* and *Phragmites*.

**Effects of Salinity and Inundation on Germination**

To simulate the effects of sea level rise, the impact of salinity and inundation changes on *Phragmites* and *Spartina* germination were compared in a greenhouse setting. Soil samples were collected from six freshwater tidal marshes in James City County with *Phragmites* populations. Three of the sample sites had *Phragmites* populations less than 50% of the marsh area, while the other three sites had *Phragmites* populations greater than 50% (density information from Center for Coastal Resources Management) and were randomly selected from all *Phragmites*-containing tidal freshwater marshes of James City County. From these sites, soil was collected during March 2016 from the top 2-5 cm of the soil surface on the leading edge of a *Phragmites* stand in the marsh. After collection, the soil samples were stored at 3C until experimental set-up. The
first experimental set-up occurred within a week, whereas the samples remained at 3C for about six months prior to the second experimental set-up. These soil samples were used as putative seedbanks for *Phragmites*, *Spartina*, and other tidal marsh species and subjected to multiple salinity and inundation treatments, described below.

Figure 1. Map showing the location of James City County, the area of interest, within the state of Virginia. Virginia and James City County boundary files come from the U.S. Census Bureau and the topographic basemap comes from ArcGIS online.
The first experiment was set up in the middle of March 2016 using these soil samples with 3 replicates of the 4 treatments for each of the six sites. A small 15 cm diameter plastic nursery pot contained the soil sample set inside a larger 27 cm diameter plastic tank containing the appropriate water level for the treatment. 4 treatments consisted of exposed soil in freshwater, soil fully
inundated with freshwater, soil inundated with brackish water (a mix of salt and freshwater), and exposed soil in brackish water. Soil inundation was maintained by keeping the water level in the large tank at the soil surface of the inner nursery pot. Exposed soils were maintained by keeping the water level 3.75 cm below the soil surface of the inner tank, which was sufficient to keep the soils moist. Freshwater (0 parts per thousand [ppt] salinity) was applied to half the treatments to represent current conditions, while brackish water (5 ppt salinity) was used to represent the oligohaline conditions that sea level rise will create. Freshwater was collected from nearby spigots in the greenhouse. Brackish water was created by mixing 10 grams of Instant Ocean with 1 gallon of freshwater, and then tested using a YSI handheld salinity meter, ensuring a salinity level of 5 ppt in each brackish treatment. Freshwater was added to all treatment tanks approximately weekly to replace water lost to evapotranspiration. In the greenhouse, artificial lighting above the set-up was set on 12-hour periods. Temperatures were maintained at 23.8°C throughout the greenhouse experiment.

Each week for two months (March 2016-June 2016), the number of sprouted seeds in each pot were counted and the plant heights were measured. The seedlings and growth were monitored with a numbered grid and pictures. As the plants became identifiable in the last month of the study, the seedlings were matched with their species with the help of wetland botanists.

With the abundance and height results from the greenhouse experiment, an ANOSIM (analysis of similarity) was conducted to determine how similar the compositions of the “wetlands” created under each treatment were. Using Primer,
the final week’s data distribution was normalized using a square root transformation. Once normalized a similarity matrix was created. An ANOSIM was then run on that similarity matrix, testing similarity among plant “communities” produced by each treatment. A two-way crossed ANOSIM with replicates was used, blocking by site as there were significant differences in community type between sites.

A second germination study was conducted between September 2016 and January 2017, with 4 soil replicates of the same 4 inundation and salinity treatments for each of the six sites. In this second experiment, supplemental *Phragmites* and *Spartina* seeds were added to the soil that was collected in March to determine their specific germination responses to salinity and inundation. Ten *Spartina* seeds and a pinch of *Phragmites* seeds were scattered across the soil surface of each pot. The number of *Phragmites*, *Spartina*, and other germinating species were counted weekly using a numbered grid. Most species were the same ones that had appeared in the first study. For those new species, their number was collected in the grid and matched with their species as identified by a wetland botanist in the last month of the experiment.

In the greenhouse, natural fall daylight hours were used for growth. Ambient light left on for 12-hour periods from surrounding greenhouse bays may have filtered in, but no artificial lighting was purposely used. Temperatures were maintained at 23.8°C throughout the greenhouse experiment.

The similarity in community composition for each treatment type was analyzed using an ANOSIM. With the abundance from the greenhouse
experiment, an ANOSIM (analysis of similarity) was conducted to determine how similar the compositions of the “wetlands” created under each treatment were. The final week’s abundance of *Phragmites* and *Spartina* were measured with and without the other freshwater species’ abundances. Using Primer, the distributions of data were normalized using a square root transformation. Once normalized a similarity matrix was created. An ANOSIM was then run on that similarity matrix, testing similarity among plant “communities” produced by each treatment. Once again, a two-way crossed ANOSIM with replicates was used, blocking by site.

**Habitat Suitability Model**

With the increase in *Phragmites* and *Spartina* abundances under inundation found in the second germination study (see results), two distribution models were created to predict future distributions of *Phragmites* and *Spartina* in tidal marshes of James City County.

Sea level rise projections at 20-year intervals were modeled by the Center for Coastal Resources Management by simulating inundation in ArcGIS over topographic LIDAR data. The sea level rise scenario used, considered the high scenario as of September 2015, projected rates of increase of about 9 mm y^{-1} were used.

For the 50-year model (2060), future tidal freshwater marsh was identified by creating a 15 cm buffer around the 2014 tidal freshwater marsh data. The 15 cm buffer represents an average accretion rate of 3 mm y^{-1}. Accretion rates are
the rate of change in elevation of a marsh through depositional and removal processes (Neubauer et al. 2002). Accretion rates in tidal freshwater wetlands vary spatially and temporally, but on average are between about 1 mm y\(^{-1}\) and 20 mm y\(^{-1}\) along the Atlantic and Gulf Coasts of the U.S. (Neubauer 2008). 20% of tidal freshwater marsh accretion rates sampled in Neubauer et al’s (2008) study had accretion rates below the sea level rise rate of 3.8 mm y\(^{-1}\) and few of the sites sampled by Beckett et al (2016) had rates greater than 3.2 mm y\(^{-1}\). Therefore, 3 mm y\(^{-1}\) was chosen as an average representation, assuming most marshes are not doing better than sea level rise. Tidal marsh features in the buffer that would be underwater in 2060 were selected for by location. From this selection, features were erased from the buffer feature using the erase tool.

Land use data were selected by attribute for crop, barren and marsh land, which are open or cleared lands that would be suitable for quick conversion to tidal marsh. Land use data were also selected by attribute for mixed, hardwood and pine forests, which would be suitable for conversion by marsh depending on the resistance of the forest to sea level rise. Forest resilience rates vary depending on the community composition of the forest and the bordering marsh ecotone (Field et al 2016).

The tidal marsh buffer and land use were used to create potential tidal marsh areas under each sea level rise scenario. From that potential land, lower elevations were selected from the DEM for potential *Phragmites* and *Spartina* establishment, as the greenhouse results indicate both species will be more abundant in inundated marsh. As both species reproduce clonally as well by
seed, they are more likely to expand in greater numbers into adjacent marsh areas. That suitable land was then categorized based on the current distribution of *Phragmites* and *Spartina*.

The same habitat selection procedure was done for the 100-year model (2100), using a 30 cm buffer and the 2100 water level data.
Results

Current and Past Distributions

In 1983, *Phragmites* was only present in trace amounts in a few tidal freshwater marshes in James City County. Since then, *Phragmites* has grown significantly in population throughout James City County (Figures 1 & 2). Particularly, *Phragmites* is more widespread along the York River and lower portion of the county along the James River and is present in many more tidal freshwater marshes. *Phragmites* is heavily present along the York River, Jamestown Island and College Creek. In the southern portion of the county, *Phragmites* expanded outwards from marshes within which it previously established (Figure 2). However, *Phragmites* has also appeared in many marshes throughout the county not adjacent to the 1983 locations.

*Spartina* was already present in several tidal freshwater marshes in 1983, despite being a salt marsh species (Figures 3 & 4). While species count data suggest that *Spartina* is migrating into tidal freshwater marshes in Virginia (Sutter 2013), the area of tidal freshwater marshes containing *Spartina* has actually decreased since 1983. *Spartina* coverage along the York River and the southern tip of James City County has diminished dramatically in the past two decades, but has expanded greatly into College Creek and Skiffes Creek in the southern portion of the county.
Many of the native freshwater species currently persist in tidal freshwater marshes throughout the county, competing and surviving in many marshes with strong *Phragmites* presence (Figures 5-11).

Figures 3&4. The map on the left shows the distribution of *Phragmites* with three levels (dominant presence, presence, and trace presence) within the tidal freshwater marshes of the northern portion of James City County in 1983. The map on the right shows the current distribution of *Phragmites* with the same three levels within the tidal freshwater marshes of the northern portion of James City County in 2014.

Figures 5&6. The map on the left shows the distribution of *Phragmites* with three levels (dominant presence, presence, and trace presence) within the tidal freshwater marshes of the southern portion of James City County in 1983. The map on the right shows the current distribution of *Phragmites* with the same three levels within the tidal freshwater marshes of the southern portion of James City County in 2014.
Figures 7&8. The map on the left shows the distribution of *Spartina* with three levels (dominant presence, presence, and trace presence) within the tidal freshwater marshes of the northern portion of James City County in 1983. The map on the right shows the current distribution of *Spartina* with the same three levels within the tidal freshwater marshes of the northern portion of James City County in 2014.

Figures 9&10. The map on the left shows the distribution of *Spartina* with three levels (dominant presence, presence, and trace presence) within the tidal freshwater marshes of the southern portion of James City County in 1983. The map on the right shows the current distribution of *Spartina* with the same three levels within the tidal freshwater marshes of the southern portion of James City County in 2014.
Germination Study

Of the 72 pots in the first germination study, germinating plants were observed in 45. A total of 656 plants germinated with 637 surviving until the end of the study, representing 21 species. *Eleocharis acicularis* was numerically dominant and germinated in 20 of the pots. *Zizania aquatica* was found in 15 pots, and *Persicaria punctata* was found in 10. The rarest species were *Sagittaria subulata*, *Rumex verticillatus*, *Eupatorium perfoliatum*, *Hypericum mutilum*, *Chenopodium album* and *Amaranthus cannabinus*, occurring separately in just 1 pot each. No germination was observed from any of the 12 pots from one site, which was apparently due to a problem in the greenhouse space where the pots were located. As a result, these pots with no germination were not included in the analysis. An additional 15 pots across all the treatment types had no germination. To maintain a balanced sample design and reduce the analytical impact of pots with zero germination, I randomly selected 15 pots to remove from statistical analysis. This adjustment that yielded the same number of samples in each treatment group was repeated 10 times. No effect of salinity or inundation was found on the abundance or existence of species within the germination study.

Neither *Phragmites* nor *Spartina* seeds germinated during this first study. The most prominent freshwater species found in this study included *Persicaria punctata*, *Eleocharis acicularis* and *Zizania aquatica*. Five species were found only in the saline treatments, while another five species were found only in the fresh treatments. *Amaranthus cannabinus*, *Hypericum mutilum*, *Bidens laevis*, *Rumex verticillatus* and *Sagittaria subulata* were found only in saline treatments,
while *Chenopodium album*, *Carex stricta*, *Pluchea odorata*, *Eupatorium perfoliatum*, and *Sagittaria lancifolia* were only found in the fresh treatments (Figure 13).

Of the 96 pots in the second germination study, germinating plants were observed in all of them. However, surviving plants were found in only 90 by the end of the study. A total of 1853 germinating plants survived until the end of the study, representing 16 species.

The second germination study showed a greater number of *Phragmites* (R=0.077, P=0.022) and *Spartina* (R=0.18, P=0.001) in the flooded treatments compared to the non-flooded treatments, irrespective of salinity (see Figure 14). *Phragmites* survived in 78 out of 96 pots and germinated at some point in all but 5 pots. *Spartina* survived in 79 out of 96 pots and germinated at some point in all the pots. Relative to the first germination study, fewer species germinated in these soils seeded with *Phragmites* and *Spartina*. The species richness was 8 for all the treatments except for the flooded brackish, which had a richness of 6. The number of total individuals was again higher in the flooded treatments than the non-flooded treatments. Using the coefficient of community to calculate the degree of similarity in results from the two germination studies, I found a 58.8% similarity in seedbank species. *Persicaria punctata*, *Schoenoplectus robustus*, *Echinochloa walteri*, and *Juncus acuminatus* were found in all the treatments (Figure 16). *Peltandra virginica* and *Pluchea odorata* were only found in the non-flooded brackish treatment. *Amaranthus cannabinus* was only found in the non-flooded freshwater treatment, while in the first germination study it was only
found in the flooded brackish treatment. *Acer rubrum, Sagittaria subulata,* and *Carex albolutecens* were only found in the flooded freshwater treatment.

Figure 11. Graph showing results of greenhouse pilot study determining how differing levels of salinity and inundation affect germination success of freshwater tidal marsh plants. For each treatment, n=18. The green represents the species richness for each trial (the total richness is listed above the bar). The blue bar represents the total number of individuals of all species per treatment (the total number of individuals is listed above the bar).
Figure 12. Graph showing the abundance of each freshwater plant species per treatment during the first greenhouse study. The bottom graph shows total number of species, while the top graph is cut off at 40 to zoom in on the smaller abundances. NSNF is the freshwater non-flooded treatment. SNF is the brackish non-flooded treatment. NSF is the freshwater flooded treatment. SF is the brackish treatment.
Figure 13. Graph showing results of second greenhouse study determining how differing levels of salinity and inundation affect the germination success of *Phragmites* and *Spartina*. The number of *Phragmites* individuals is represented in green, while the number of *Spartina* individuals is represented in blue. The black bars represent the standard error. NSNF is the freshwater non-flooded treatment. SNF is the brackish non-flooded treatment. NSF is the freshwater flooded treatment. SF is the brackish treatment.
Figure 14. Graph showing results of second germination study determining how differing levels of salinity and inundation affect germination success of freshwater tidal marsh plants. For each treatment, \( n=24 \). The green represents the species richness for each trial (the total richness is listed above the bar). The blue bar represents the total number of individuals of all species per treatment (the total number of individuals is listed above the bar).
Figure 15. Graph showing number of other freshwater species found within the different treatments during the second greenhouse study after a cold dormancy period. NSNF is the freshwater non-flooded treatment. SNF is the brackish non-flooded treatment. NSF is the freshwater flooded treatment. SF is the brackish treatment.
Figure 16. Map showing the current distribution of various tidal freshwater marsh species from the 2014 tidal marsh inventory (CCRM). These species were found in the seedbanks sampled from six James City County marshes. They are mapped with the sea level rise projection in 20 year increments to show threat to these species’ habitat.
Figure 17. Map showing the distribution of *Schoenoplectus robustus*, a native freshwater species, in the northern portion of James City County found during the seed bank greenhouse experiment. This distribution is sourced from the 2014 tidal marsh inventory.

Figure 18. Map showing the distribution of four native freshwater species in the southern portion of James City County found during the seed bank greenhouse experiment: *Sagittaria lancifolia*, *Amaranthus cannabinus*, *Persicaria punctata* and *Schoenoplectus robustus*. *Sagittaria lancifolia*, *Amaranthus cannabinus*, *Persicaria punctata* were not present in tidal marshes of the northern portion of the county at the time of the 2014 tidal marsh inventory, where the distribution information comes from.
Figure 19. Map showing the distribution of *Peltandra virginica* in the northern portion of James City County from the 2014 tidal marsh inventory. *Peltandra virginica* was found in the seedbank of the first greenhouse experiment.

Figure 20. Map showing the distribution of *Peltandra virginica* in the southern portion of James City County from the 2014 tidal marsh inventory. *Peltandra virginica* was found in the seedbank of the first greenhouse experiment.
Figure 21. Map showing the distribution of *Rumex verticillatus* and *Zizania aquatica* in the northern portion of James City County from the 2014 tidal marsh inventory. *Rumex verticillatus* and *Zizania aquatica* were found in the seedbank greenhouse experiments.

Figure 22. Map showing the distribution of *Rumex verticillatus* and *Zizania aquatic* in the southern portion of James City County from the 2014 tidal marsh inventory. *Rumex verticillatus* and *Zizania aquatic* were found in the seedbank greenhouse experiments.
Habitat Suitability Model

The total area occupied by tidal freshwater marsh in James City County will diminish as sea level rise inundates a majority of the current marsh area. Marshes must keep pace with current sea level rise at 3.17 mm y\(^{-1}\) (NOAA 2016) or face inundation. Many existing marshes with low accretion rates will be lost. At 3 mm y\(^{-1}\), the marshes will persist, but tidal freshwater marshes with accretion rates less than 3 mm y\(^{-1}\) will not. Sea level rise rates have increased over the past couple decades and may continue to increase if actions are not taken to mediate climate change (NOAA 2016). Thus, tidal freshwater accretion rates will need to continue increasing at the same pace to sustain the wetlands.

As marsh coastlines disappear, tidal freshwater marshes will migrate landward, slowly converting uplands at lower elevations into marsh. However, grey infrastructure (i.e., buildings, roads, parking lots, etc.) prevents a lot of landward movement of the marshes. Marshes will only be able to convert existing barren land, meadows, agricultural field into marsh as rising waters move landward. Over a longer period of time, pine, hardwood, and mixed forests may be converted to tidal freshwater marsh as well.

With the high rate projections of sea level rise and lack of transformable land, there will likely be a loss of marsh area in James City County from 2,431.7 ha in 2014 to 429.95 ha in 2060 and then to 422.01 ha in 2100. From 1983, tidal freshwater marshes lost approximately 431 ha as the total land area decreased from 2,863.06 ha. Tidal marshes (tidal freshwater, tidal brackish and tidal salt marshes) represent 2,431.7 ha of 5,277.17 ha of wetlands in James City County.
(information obtained from the National Wetlands Inventory). The remainder are non-tidal wetlands. *Phragmites* alone, covered 735.88 ha in James City County, an increase of 682.13 ha from 53.75 ha in 1983. *Spartina* was found across 203.99 ha in James City County, a decrease of 242.6 ha from 446.6 ha.

*Phragmites* and *Spartina* will likely move landward with the marshes in which they are already dominant or present (Figures 17-20). They will become dominant in the existing locations because there will be increased inundation, which was found in the second germination study to increase their abundance. *Spartina* now shares 154.2 ha of marsh with *Phragmites* compared to 20.48 ha in 1983. As both species’ abundances increased under inundated conditions, it is likely that the total area of shared marshes will continue to increase under sea level rise.

Figures 5-11 show the distribution of freshwater marsh species in James City County that had germinated in the seedbank studies. As with most of the tidal freshwater marshes, these marshes face inundation by brackish water by 2100. They will expand inland as possible, but there will be less suitable area for them to occupy.
Figures 23&24. Map showing the areas projected to be suitable tidal freshwater marsh for Phragmites in 2060 with sea level rise. Areas that are currently forested are represented in shades of purple, while areas that are currently non-forested are represented in shades of red. Forested areas will take longer to convert to TFM, so they are not as likely to be heavily occupied by Phragmites in 2060. The 2014 Phragmites distribution comes from the 2014 tidal marsh inventory. The James City County boundary file comes from the U.S. Census Bureau and sea level rise data come from the Center for Coastal Resources Management.
Figures 25&26. Map showing the areas projected to be suitable tidal freshwater marsh for *Spartina* in 2060 with sea level rise. Areas that are currently forested are represented in shades of purple, while areas that are currently non-forested are represented in shades of red. Forested areas will take longer to convert to TFM, so they are not as likely to be heavily occupied by *Spartina* in 2060. The 2014 *Spartina* distribution comes from the 2014 tidal marsh inventory. The James City County boundary file comes from the U.S. Census Bureau and sea level rise data come from the Center for Coastal Resources Management.
Figures 27&28. Map showing the areas projected to be suitable tidal freshwater marsh for *Phragmites* in 2100 with sea level rise. Areas that are currently forested are represented in shades of purple, while areas that are currently non-forested are represented in shades of red. The 2014 *Phragmites* distribution comes from the 2014 tidal marsh inventory. The James City County boundary file comes from the U.S. Census Bureau and sea level rise data come from the Center for Coastal Resources Management.
Figures 29 & 30. Map showing the areas projected to be suitable tidal freshwater marsh for *Spartina* in 2100 with sea level rise. Areas that are currently forested are represented in shades of purple, while areas that are currently non-forested are represented in shades of red. The 2014 *Spartina* distribution comes from the 2014 tidal marsh inventory. The James City County boundary file comes from the U.S. Census Bureau and sea level rise data come from the Center for Coastal Resources Management.
Discussion

Rates of sea level rise have increased over the past few decades and may continue to increase if actions are not taken to mediate climate change (NOAA 2016). Tidal freshwater marsh accretion rates will need to match sea level rise to be sustainable. Without higher accretion rates, the area occupied by tidal freshwater marshes in James City County will shrink dramatically as sea level rises. With the decrease in tidal freshwater marsh area, increased salinity, and inundation in existing marsh area, plant community composition will change. Notably, *Phragmites*, *Spartina*, and more salt tolerant native species will become more abundant in marshes throughout the county.

Although the marsh area containing *Spartina* has decreased in James City County since 1983, species count data shows that *Spartina* is becoming more prominent in some freshwater marshes regionally (Sutter 2014). *Spartina* may be occurring less frequently in marshes, but its coverage marshes where it does occur may have increased. The decrease in *Spartina* along the York River (Figures 7-10) is likely due to shoreline erosion (Milligan et al. 2010). This leads to a loss of marsh area and, thus, *Spartina* coverage. The York River shoreline is more exposed to boat traffic and likely experiences more wave action and resulting erosion than the James River, which experienced less erosion over the past decade. The decline in *Spartina* presence along the James River may be due to changes in community dynamics and biological interactions, although the specific mechanisms contributing to the loss of *Spartina* in those marshes are unknown.
With the landward migration of tidal freshwater marshes where possible, however, an expansion of *Spartina* across the county in these new tidal freshwater marshes is possible and even likely. Tidal freshwater marshes develop in three stages over time, beginning mainly as low or inter-tidal marsh and ending mainly as high marsh, with the middle stage consisting of low and high marsh (Odum et al. 1984). These new tidal freshwater marsh areas created by sea level rise will be low marsh. Sporadic tidal flows of salt water during summer periods of low freshwater runoff may briefly increase the salinity levels in the marshes, which will bring *Spartina* propagules into the new tidal freshwater marshes. With seed delivery, opportunities exist for germination and establishment of *Spartina* at low marsh elevations, with ample space for *Spartina* to thrive under increased inundation levels (Figure 13). Existing freshwater marshes newly converted to oligohaline marshes will provide a transitioning state under increasing salinity for *Spartina* expansion.

A recent study found little support for the competition-stress theory that predicts *Spartina* expansion should be prevented in freshwater marshes (Sutter et al. 2013). *Spartina* interacted differently with each freshwater species in the study; freshwater grass, such as *Leersia* and *Phragmites* were competitors, whereas non-graminoid species such as *Peltandra* had no effect on *Spartina* success. Further, recent expansion of *Spartina* in freshwater marshes may be due to the unsuccessful growth of freshwater species under slight increases in salinity (Sutter et al. 2014).
The disturbance caused by increased salinity and inundation as stressors on tidal freshwater marshes will also allow *Phragmites* to expand into newly created freshwater marshes and newly converted oligohaline marshes. *Phragmites* has already expanded greatly in number and distribution in tidal freshwater marshes across the county since 1983. *Phragmites* will continue to expand into new tidal freshwater marshes retreating landward from sea level rise, especially those adjacent to marshes wherein it is already prominent due to clonal expansion. Because *Phragmites* persisted in greater numbers under inundated and brackish conditions in the greenhouse experiment (Figure 13), *Phragmites* is expected to become more dominant in the new brackish marshes as well.

Many freshwater wetland species will still germinate in the presence of *Phragmites*, based on the results from the germination studies conducted. Many will likely be able to continue moving with the marshes, but in areas where tidal freshwater marshes are not able to expand inland, they will suffer under increased salinity levels. Most of the species found in the seedbank studies are found in both fresh and brackish marshes (Tiner 2009), which supports the absence of any significant effect of salinity. Many of the native species are also found in low marsh areas or persist with periodic flooding and, so, would not be detrimentally affected by inundation. The increased inundation under sea level rise may actually dissipate the effects of salinity on freshwater species, which would explain the lack of any effect of treatment on native freshwater species during the germination study (Sutter et al 2014).
Eight of the species that germinated in the greenhouse studies are annuals, while *Phragmites* and *Spartina* are perennials. The seedbank is a large determinant of future species composition, so we expect marshes with *Phragmites* and *Spartina* to have greater abundances of these perennials. As expected, species composition similarity in marshes dominated by annuals is very low (Hopfensperger et al 2009). Some annual species will still germinate, but competition from more abundant perennial species may decrease the diversity even more and change the community composition towards perennials remaining dominant.

In the absence of *Phragmites* found in the first germination study, a wide diversity of species grew. With competition from *Phragmites*, species richness decreased from 21 to 14. As *Phragmites* proliferates under inundation caused by sea level rise, native species richness decreases.

Protecting native freshwater species is important for preserving the integrity of tidal freshwater marshes. Native species provide many functions and ecosystem services for their environment and human societies, such as filtration, organic matter for the base of food webs, nurseries for juvenile species, and protection against storms (O’Brien and Walton 2011). Native freshwater mixed communities have the highest diversity of wildlife and wildlife foods of the marsh community types (Moore 1980). To protect native species, prevention efforts should be increased in lower elevation areas threatened by increased *Phragmites* proliferation. *Phragmites* prevention efforts, i.e. prescribed burns,
spraying, cutting, etc. (Hazelton 2014) should be focused in the areas highlighted in figures 17 and 19.

*Phragmites*, however, may aid in marsh accretion through soil building and biomass production in juxtaposition to the negative impact of reduced native species diversity (Kiviat 2013). Similarly, *Spartina* raises the elevation of marshes through sediment trapping and assimilation of flood waters, which once established may aid in the persistence of tidal freshwater marshes (Moore 1980). Despite decreased diversity, with added elevation by *Phragmites* and *Spartina*, tidal freshwater marshes may be able to keep pace with sea level rise. Although the community compositions will change, tidal freshwater marshes may persist with sea level rise.

A trend towards more brackish mixed communities because of sea level rise in freshwater marshes can already be seen in a nearby local marsh with the increase in IV of two other salt-tolerant species, *Spartina cynosuroides* and *Carex hyalinolepis* (Perry 1999). If *Phragmites* and *Spartina alterniflora* continue to expand within existing and future marsh area, these communities will see an even greater change.

Tidal marsh area in James City County has already decreased in 30 years from 1983 to 2014 by 431 ha. As rates of sea level rise continue to increase, James City County tidal marsh area will decrease at an increasing rate. At accretion rates of 3 mm y$^{-1}$, 2001.75 ha of tidal marsh will be lost by 2060 and an additional 7.94 ha by 2100. The majority of tidal marsh loss will occur in the next 50 years because most existing marshland will drown during that period with low
accretion rates. However, accretion rates vary yearly and by marsh and there is potential that more tidal marsh may sustain itself under sea level rise. Tidal freshwater marsh is a small proportion of that total tidal marsh area, which also includes brackish and salt marsh. While tidal marsh area has the potential to sustain itself as brackish and salt marsh with increased elevation, it is unlikely that the elevation gain will be sufficient to save significant amounts of tidal freshwater marsh.

*Phragmites* expansion of 682.13 ha from 1983 will continue to increase as increased salinity and inundation stress existing marshes and newly formed marshes inland. While *Spartina* coverage decreased 242.6 ha since 1983, studies have shown there may still be an increase in abundance and importance within freshwater marshes. The increased salinity and inundation within existing marshes and the development of new marshes will provide more opportunity for establishment and growth. James City County tidal marshes will be comprised of more brackish and salt marshes with a greater abundance of salt tolerant species, such as *Spartina, Phragmites, Eleocharis, Persicaria, Juncus, Leersia, Schoenoplectus* and *Zizania*. 
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