Delaware Saltwater Intrusion Study

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Overview
Sea level rise and major storm events are significant catalysts for change in coastal marshes and adjacent freshwater forested wetlands (Brinson et al. 1995, Donnelly and Bertness 2001, Kirwan and Megonigal 2013). Rising sea levels and severe coastal storms increase flooding frequency and duration as well as the occurrence of saltwater intrusion, resulting in changes to sediments and plant communities. This is particularly true in the Mid-Atlantic region of the United States, which is a hotspot of sea level rise acceleration (Sallenger et al. 2012). Together, such processes can convert freshwater forested wetland to high marsh, high marsh to low marsh, and low marsh to subtidal habitat in a step-by-step fashion over time (Brinson et al. 1995, Donnelly and Bertness 2001, Kirwan and Megonigal 2013, Raabe and Stumpf 2016, Langston et al. 2017; Figure 1). However, there remains some uncertainty in how freshwater forested wetlands and marshes are actually responding to these stressors in the state of Delaware. For instance, are habitat transitions occurring in this step-by-step fashion (Figure 1), or are certain transition states being bypassed? And, how are invasive species, such as the common reed (*Phragmites australis*), affecting these habitat transitions?

One way that coastal wetland habitats may respond to saltwater intrusion and increased flooding is the stepwise transition from freshwater forested wetland to estuarine high marsh, high marsh to low marsh, and low marsh to open water. Saltwater intrusion kills salt-intolerant trees (Bianchette et al. 2009) and can prevent seedlings from growing to maturity (Williams et al. 1999, DeSantis et al. 2007). As trees die off and fail to regenerate, areas that trees once inhabited may be replaced by native estuarine shrub and herbaceous high marsh species, such as *Baccharis halimifolia*, *Iva frutescens*, *Spartina patens*, and *Distichlis spicata* (Brinson et al. 1995, Williams et al. 1999). Areas that were historically high marsh that experience increased inundation may shift to low marsh, where estuarine low marsh flood-tolerant species, such as *Spartina alterniflora*, may displace high marsh species that are less tolerant of flooding. If areas of

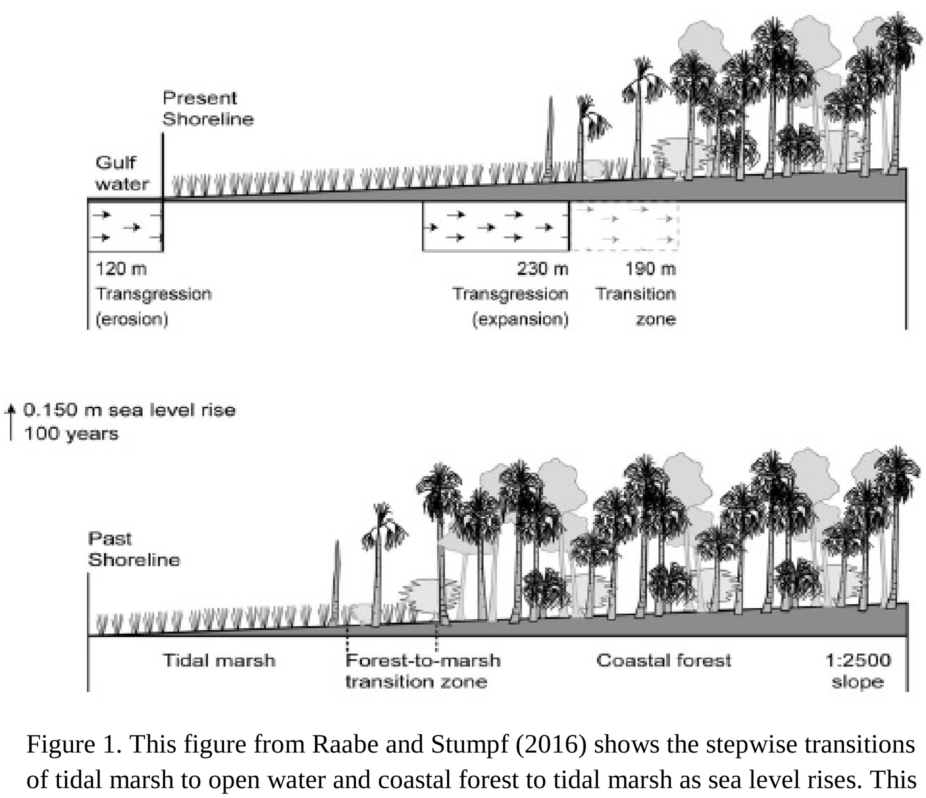

Figure 1. This figure from Raabe and Stumpf (2016) shows the stepwise transitions of tidal marsh to open water and coastal forest to tidal marsh as sea level rises. This process has been described in many marshes along the East Coast of the U.S.

low marsh become inundated too frequently, low marsh vegetation will begin to die and the area will convert to open water (Donnelly and Bertness 2001). Yet another possibility is that certain transition states are being by-passed. If sea-level rise is happening more quickly than anticipated, it could be that freshwater forested wetlands are converted directly to low marsh or open water, or that high marsh is converted directly to open water, by-passing intermediate transition states.

It could also be that freshwater forested wetland habitats are replaced by *P. australis* instead of native high marsh plants, particularly in areas experiencing brackish water intrusion with low salinity. Many saltmarsh plant species are outcompeted by freshwater plant species in freshwater or low-salinity brackish water environments, forcing them to grow in saltwater environments where they do not face competition from salt-intolerant species (Crain et al. 2004). *P. australis* is a strong competitor that can grow in fresh and brackish water (Chambers et al. 2003, Crain et al. 2004); thus, in areas where trees are dying from increased flooding and saltwater intrusion but salinity is not yet very high, *P. australis* can likely prevent native salt-tolerant species from colonizing. This phenomenon has already been seen along the coast of New Jersey, where the rate of salt marsh migration inland has lagged behind the rate of forest loss because of the invasion of *P. australis* following tree death (Smith 2013).

Because of this uncertainty, there is a need for field visits to areas that are experiencing increased flooding and salt water intrusion in order to describe habitat responses. This information would allow scientists and managers to better predict how coastal freshwater wetlands in Delaware will respond in the face of sea level rise and saltwater intrusion. The way in which habitats are changing could have important implications for various wetland functions, such as wildlife habitat, coastal storm protection, and carbon sequestration (Craft 2012).

Purpose

The purpose of this study was to describe physical and biological components of habitats that have likely experienced increased flooding and saltwater intrusion in Delaware due to sea level rise. Specifically, we wanted to see if freshwater forested wetland habitats adjacent to estuarine marshes are converting to high or low estuarine marshes with native vegetation, open water, or are being rapidly colonized by invasive species such as *P. australis.*

Study Design

Site Selection

As sea levels rise and push saltwater further inland, areas that are currently palustrine (i.e. freshwater), but that are right near the estuarine-palustrine boundary, are most likely to experience saltwater intrusion. Thus, we used 2007 Delaware wetland maps to see where saltwater changes to freshwater in Delaware waterbodies (i.e., the estuarine-palustrine boundary, or salt line), and we focused on these areas as our study sites. We further narrowed down our list of sites by focusing on those that were accessible, and prioritized accessible sites that were publicly owned for easier access due to time constraints. We also tried to ensure that most major rivers had at least one site associated with them to get a range of sites spread across the state (Figure 2). We selected 15 sites in total.

Point Selection

At each site, we carefully placed 4 points at which we collected data in the field. We placed points in areas where we were most confident that changes have occurred due to increased flooding and saltwater intrusion (Figure 3). Points were chosen using GIS after synthesizing information from mapped wetland changes over time, visible vegetative change over time, mapped soil types, and potential for marsh migration. Mapped wetland changes were examined by comparing Delaware state wetland maps from 1981 and 2007, with 2007 being the most recent layer available (Figure 3). Vegetative change was examined through visual inspection of aerial imagery from 1968, 1992, and 2012, with 2012 being the most recent layer available (Figure 3). Soil types were examined using Delaware state soil maps. Marsh migration potential was considered by isolating only highly suitable land for marsh migration from DNREC's marsh migration model.

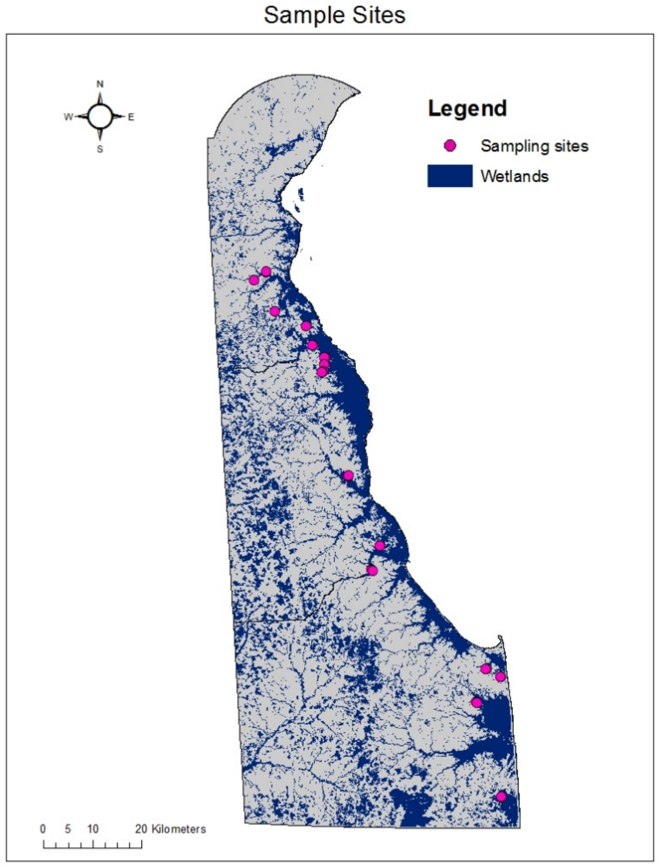

Figure 2. Locations of 15 sample sites along the coast of Delaware.

Points were placed along a habitat gradient, beginning in estuarine emergent marsh and moving toward palustrine forested wetlands. Point 1 was placed in habitat that was classified as estuarine on wetland maps from 1981 and 2007, and was classified as having a frequently flooded soil type on state soil maps. This was done to describe the habitat in the area that had been considered salt or brackish marsh for at least 26 years to see how Points 2-4 compared in terms of habitat components. One site was an exception, where Point 1 was emergent marsh in 1981 and was open water in 2007. Points 2 and 3 were placed in areas where changes were seen that suggest that saltwater intrusion and increased flooding have likely occurred; for example, in areas where wetlands were mapped as palustrine in 1981 and were then mapped as estuarine in 2007, in areas that were mapped as being irregularly flooded in 1981 and regularly flooded in 2007, or in areas of visible tree or shrub loss. Such areas were referred to as 'transitional marsh.' Point 4 was placed in palustrine forested wetlands that were adjacent to areas where habitat changes were seen at Points 2 and 3, as these forested wetlands are likely to also experience change. When possible, points were oriented toward forested wetland areas identified as being highly suitable for marsh migration, as these areas are likely to see saltwater intrusion and increased flooding as part of the process of estuarine wetlands moving inland with increasing sea levels.

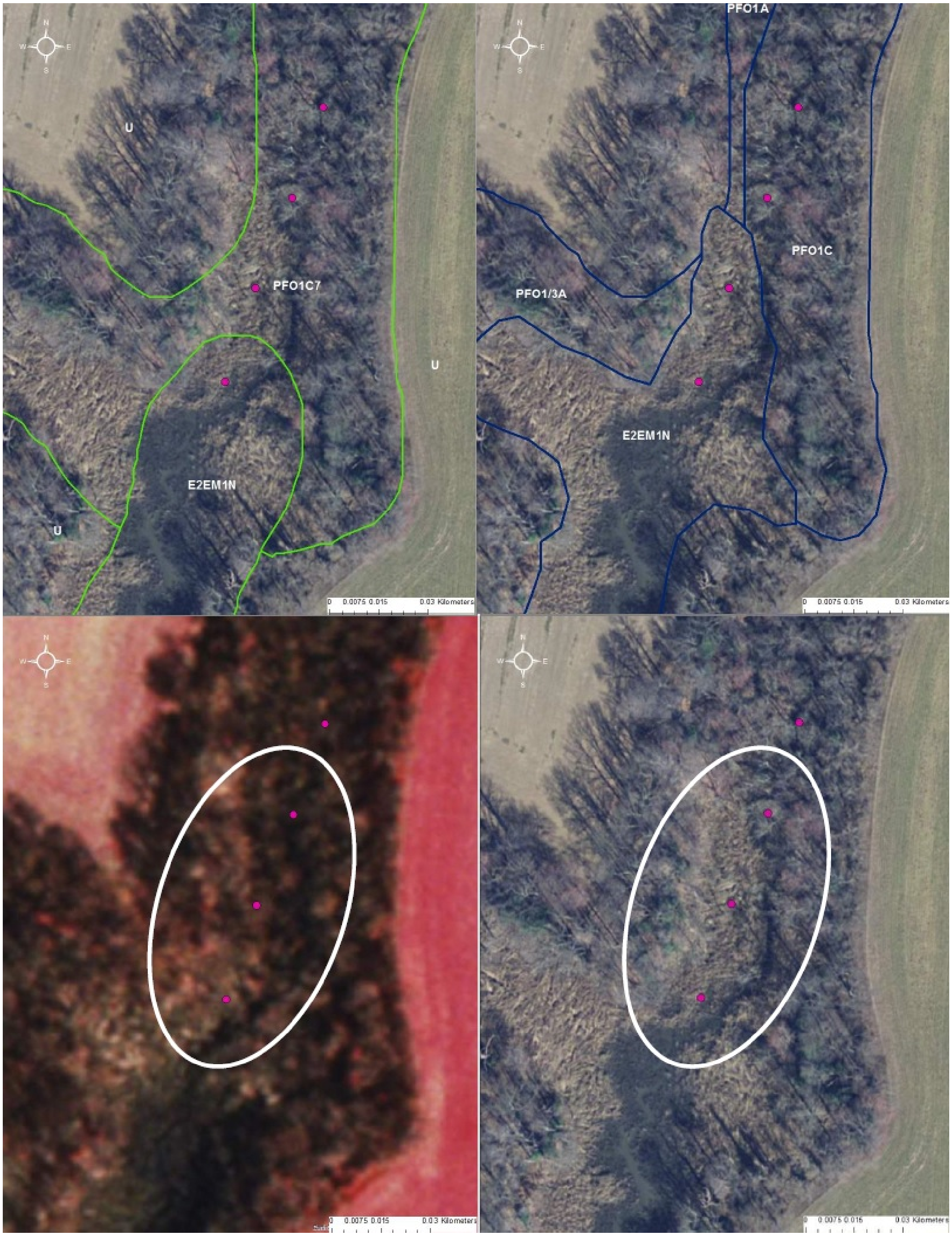

Figure 3. An example showing how points were placed based on wetland type changes and vegetative changes seen over time using Delaware state wetland maps and aerial photos. Pink dots show Points 1-4. *Top left*: green lines and associated white letter and number codes show mapped wetland lines in 1981, overlaid on a 2012 aerial image. *Top right*: blue lines and associated white letter and number codes show mapped wetland lines in 2007, overlaid on a 2012 aerial image; notice how the area where Point 2 is was palustrine in 1981, but changed to estuarine in 2007, suggesting that saltwater intrusion is occurring in this area. *Bottom left*: aerial image from 1992; notice how much of the area within the white circle is trees. *Bottom right*: aerial image from 2012; notice how much of the area within the white circle has experienced tree loss and expansion of *Phragmites australis*, further suggesting saltwater intrusion and increased flooding is occurring in this area.

When possible, the 4 sampling points were aligned in a linear fashion and were equidistant from each other for simplicity. However, sampling points at some sites were either nonlinear or were not equidistant in order to place points in target areas. The most direct path possible was taken to walk between points, and this walking path was referred to as the ‘transect’. We navigated to each point using a handheld GPS unit. Points were moved only if, upon visitation, they were not in the correct habitat area described above.

Plot placement

At each of the 4 points, a 3m-radius circular plot was established with meter tapes, using the point as center. Within the 3m-radius circular plot at each point, two 1 x 1m square subplots were placed along the meter tapes oriented in the direction of the transect. One was placed from 0 to 1m, and the other was placed from 5 to 6m (Figure 4). The larger circular plot and smaller square subplots were used to describe plant species, plant layers, soils, and plant percent cover (see below).

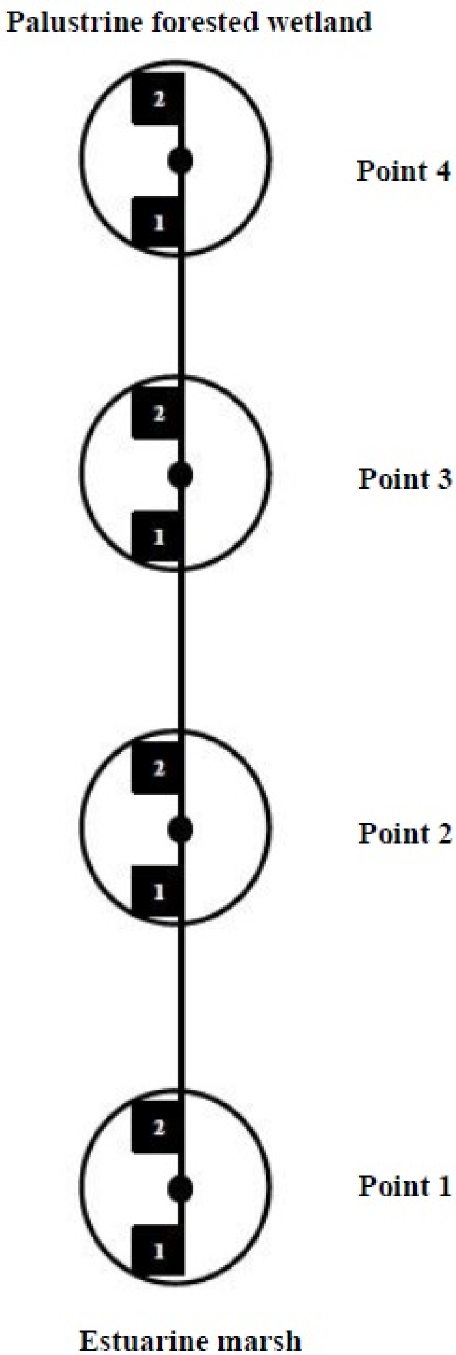

Figure 4. A schematic drawing of placement of the 3m-radius circular plot and the 1 x 1m subplots at each point. Drawing not to scale.

Methods and Metrics

Site characterization

Before assessing metrics, basic information about the site was recorded, including: tide stage; date and time; watershed; and GPS coordinates of the 4 sampling points. A site sketch of important features and plot locations was completed throughout each field visit. After all field visits were complete, a 30-day Standardized Precipitation Index (SPI) was determined for each site from the Office of the Delaware State Climatologist. The SPI indicates the extent to which precipitation conditions during a specified time period (here, 30 days) differ from normal historic conditions, where positive index values indicate conditions that were wetter than normal and negative values indicate conditions that were dryer than normal at a specified location (Office of the Delaware State Climatologist). Specifically, SPI values ≤ -0.5 indicate dryness, values between -0.5 and 0.5 indicate normal conditions, and values ≥ 0.5 indicate wetness.

Salinity and specific conductance

Salinity and specific conductance both measure the dissolved ion content in the water. At least one salinity and specific conductance reading was taken per site using a digital salinity meter (YSI instrument). When possible, readings were taken at multiple points per site (Points 1-4) to describe the salinity gradient. Salinity and specific conductance readings were taken where possible, either from tidal creeks, standing water on the surface of the marsh, or water that filled in a freshly dug soil pit. The manner in which the readings were taken was recorded for every reading.

Soils

Soil color and texture were described at each of the 4 points. These qualities of wetland soils can be informative in determining the hydrologic regime of an area. Soil pits were dug to about 30-40cm at each of the 4 points. Soil texture was described by feel, and colors of matrix and redox features were described using the Munsell soil color book. Presence or absence of organic matter, such as root material, was also noted. If too much standing water was present, soil profiles were not taken and soils were recorded as “standing water.”

Presence of standing dead trees, large downed wood, and coarse woody debris

Standing dead trees present either in current existing marshes or along edges of forests that border marshes can be signs that increased flooding and saltwater intrusion have occurred or are occurring and are causing forest retreat (Kirwan et al. 2007, Raabe and Stumpf 2016). Therefore, the number of standing dead trees were recorded by visually assessing the area along the transect. Large downed wood and coarse woody debris were also counted in the same manner, as these large pieces of wood could be remnants of old trees that have died. Standing dead trees were defined as snags ≥1.5m tall and ≥ 15cm DBH. Large downed wood was defined as wood lying horizontally on the ground that was ≥ 15cm DBH. Coarse woody debris was defined as wood lying horizontally on the ground that was ≥7.5cm DBH but < 15cm DBH. Any standing dead trees that were not directly along the transect, but were visible at the site from the transect, were not counted but were noted on the site sketch. Counts were then standardized for comparisons among sites by dividing counts by total transect lengths.

Additionally, statistical analyses were performed to determine if there were significant correlations between salinity or specific conductance and the standardized number of standing dead trees, large downed wood, or coarse woody debris. Spearman’s rank correlation tests were used because data were not normally distributed.

Plant layers

Several plant layers were counted at each of the 4 points to describe the vegetative structure of each area. Plant layers were recorded as present or absent from the 3m-radius circular plot, regardless of percent cover occupied by each layer. The following plant layers were recorded:

SAV, herb, shrub, sapling, tree, and vine.

Plant species

All plant species seen within the 3m-radius circle at each of the 4 points were recorded to get a detailed sense of the plant community living in each area. Species present were recorded regardless of percent cover. This was done to make general inferences about species richness at each point.

Percent cover

Percent cover of plant species was estimated within both subplots at each point to characterize the prevalence of different species. When present, percent cover of bare ground and standing water were also recorded. When multiple layers were present within a subplot (i.e. herbs, shrubs, and overhanging trees), percent cover often exceeded 100% within that subplot.

Sapling:Tree Indicator

We used an indicator (developed by Kirk Havens, VIMS, personal communication) that describes differences in mature tree and sapling plant communities within a site. Specifically, the indicator is a ratio based on total numbers of saplings and trees, numbers of each tree and sapling species, and the wetland indicator statuses of those species. Each wetland indicator status is assigned a different number from 1 to 5. The equation used to calculate the index is listed below:

$$\frac{\sum \text{\# sapling species x indicator status/\# Saplings}}{\sum \text{\# tree species x indicator status/\# Trees}}$$

Ratios < 1.0 show that the wetland is becoming wetter and shifting to a more water-tolerant community, while ratios > 1.0 show that the wetland is becoming drier and plants are shifting to a less water-tolerant community. The idea behind this is that if a habitat is getting wetter, regeneration of adult upland species will cease and will be replaced with growth of more flood-tolerant species. In this study, trees were defined as tree species with DBH ≥ 7.5cm, and saplings were defined as tree species with DBH < 7.5cm and with woody stems.

Changes in plant community salinity tolerance

We researched salinity tolerances of trees species to see if there was an overall shift in salinity tolerances of tree and sapling communities. We might expect to see a shift where saltwater intrusion is happening in which the sapling community is overall more salt-tolerant than the mature tree community. Plant salinity tolerance was defined generally as, “None”, “Low”, “Medium”, or “High”, as classified on the Plants Database by USDA and NRCS (2018).

Results

Site Characterization

We performed site visits from early August to early October 2017, and from late July to early September in 2018. Tide stages varied for site visits from low to high tide. Field sites encompassed many HUC10 watersheds, including the Smyrna, Leipsic, Appoquinimink, Mispillion, St. Jones, Delaware Bay, Delaware Inland Bays, and Little Assawoman watersheds. Based on SPI values, 5 sites (33.3%) had normal precipitation conditions, 3 sites (20.0%) had dryer than normal conditions, and 7 sites (46.7%) had wetter than normal conditions at the time of visitation.

Estuarine Marsh (Point 1)

Figure 5. A soil sample at a study site in a tidal estuarine marsh.

Point 1 was located in wetlands that were mapped as estuarine emergent marsh. Salinity and specific conductance readings were highly variable among sites. We were able to obtain readings at Point 1 for all but one site. Salinity ranged from 0.5 ppt to 17.5 ppt, and specific conductance ranged from 0.91 mS/cm to 28.5 mS/cm. These readings were collected opportunistically from different locations depending on the site, including from soil pits, standing surface water, and creeks. Salinity showed no relationship with standardized number of standing dead trees (ρ= -0.399; p=0.141), standardized amount of large downed wood (ρ= -0.481; p=0.069), or standardized amount of coarse woody debris (ρ= -0.095; p=0.737) along transects. Similarly, there was no relationship between specific conductance at Point 1 with standardized numbers of standing dead trees (ρ= -0.388; p=0.153), large downed wood (ρ= -0.456; p=0.088), or coarse woody debris (ρ= -0.046; p=0.873).

Soil samples were taken at Point 1 at most sites (80.0% of sites), and all resembled those of typical tidal marshes (Figure 5). All soils were wet and saturated, and most contained few to no sand particles and were dark gray-brown or black in color with no redox features. Soils were organic muck or mucky peat with some small roots present, were very soft and soupy when hollows were present, and often smelled sulfurous. Soil samples were not taken at 3 sites (20.0% of sites) at Point 1 because there was too much standing water present. Several sites (20.0%)

were composed of hummocks and hollows, where soils were extremely soft within unvegetated hollows.

Twelve of fifteen sites (80.0%) had an herbaceous plant layer at Point 1 with no other plant layers present. One site (6.7%) also had an SAV layer present, and one site (6.7%) also had a shrub layer. Another site (6.7%) did not have any plant layers present because although it was once an emergent wetland (as seen in aerial imagery), it is now open water. Sapling:tree indicator values could not be calculated for any sites at Point 1 because the indicator was undefined due to the lack of saplings and trees.

Species that were commonly found at Point 1 in estuarine marsh were *Spartina alterniflora, P. australis*, *Pluchea odorata*, *S. patens*, and *D. spicata.* In terms of percent cover, marsh areas at Point 1 were most often dominated by unvegetated areas of bare ground or water, and by *S.alterniflora* (46.7% of sites). Despite all of these points being mapped as estuarine wetlands, a couple of sites (13.3%) that had low salinity readings ($\leq$ 2.0 ppt) were instead dominated by *Peltandra virginica* and bare ground, suggesting that those areas are actually tidal freshwater marshes upon field visitation. Again, one site had no plants present at Point 1 because it had converted from emergent marsh to open water.

Transitional marsh (Points 2 and 3)

Points 2 and 3 were located in transitional marsh, where Point 2 was adjacent to estuarine marsh and Point 3 was adjacent to palustrine forested wetland. We collected salinity and specific conductance readings at 12 of 15 sites (80.0%) at Point 2, with salinity ranging widely from 0.0 ppt to 15.7 ppt and specific conductance from 0.0 mS/cm to 25.56 mS/cm. These readings were collected opportunistically from either soil pits or standing surface water. At Point 3, we obtained readings from 10 of 15 sites (66.7%), with salinity ranging from 0.0ppt to 10.8ppt, and specific conductance ranging from 0.0 mS/cm to 18.44 mS/cm. These were collected from either soil pits or standing surface water.

Soil samples were taken at most sites at Point 2 (80.0% of sites). All samples resembled those of typical tidal marshes and were similar to soils observed at Point 1. These soils were dark brown, dark gray-brown, or blackish in color and had no redox features. Soils were organic muck or mucky peat, were composed of little to no sand, and were wet and saturated, often smelling of sulfur. Similar to Point 1, soil samples were not taken at 3 sites (20.0%) at Point 2 because there was too much standing water present.

Soils were slightly more variable in composition at Point 3, closer to the current forest edge, at study sites where samples were taken (86.7% of sites). Many soils were a uniform dark brown, dark gray, or black (46.7% of sites) and were largely organic, while others were lighter gray or brown and were composed mostly of clay and some organic material under a darker organic top layer (40.0%). A few sites (20.0%) had some redox features present beneath the top organic layer. All soils had roots and rhizomes and were wet and saturated. The fact that these soils all had relatively thick organic top layers, or were composed mostly of organic material throughout, shows that these areas are very wet. As soils become wetter, organic matter can begin to build up over older soils. Thus, it is possible that forested wetlands that once extended farther out used to have soils that contained redox features, and those soils are now accumulating organic material as they get wetter. The soil at one site even had a layer of tree leaves about 16cm below the surface that were not decayed, suggesting that trees might have grown there at one point but no longer do, and decomposition is slow because of increasingly wet, anaerobic soil conditions.

All sites had an herbaceous layer at Point 2, and many sites (53.3%) had only this layer. No sites had any SAV or saplings at Point 2, while 20.0% had shrubs, 26.7% had vines, and 6.7% had trees. All sites had an herbaceous layer at Point 3, and no sites had SAV. One-third (33.3%) of sites had shrubs at Point 3, 20.0% had saplings, 40.0% had trees, and 53.3% had vines.

Point 2 was slightly more diverse than Point 1 at most sites and was usually located in a higher marsh zone than Point 1. Species that were commonly found included *P. australis, P. odorata, Persicaria punctata,* and *Hydrocotyle prolifera.* Native estuarine high marsh species that are common in Delaware such as *S. patens, D. spicata, I. frutescens, B. halimifolia,* or *Symphyotrichum subulatum* were present at some of these sites, but only one site was dominated by a native high marsh species (*S.patens*). Instead, these areas were most often dominated by *P.australis* and bare ground/standing water (53.3% of sites). Some other dominant communities at Point 2 included *H.prolifera-Typha angustifolia* and *P.virginica*-bare ground/standing water. Sapling:tree indicator values could not be calculated for any sites at Point 2 because the indicator was undefined due to the lack of saplings and trees.

At Point 3, closer to forested wetland, species that were often present were *P. australis, Toxicodendron radicans, H. prolifera, Acer rubrum,* and *Smilax rotundifolia* (Table 1). The most common dominant community in terms of percent cover was *P.australis*-bare ground/standing water (46.7% of sites; Table 1). One site (Site 10) was unusual in that it was dominated by *S.patens* at Points 1 and 2 closer to a tidal creek, while the dominant herbaceous layer at Point 3 farther inland was *S.alterniflora* (Table 1). This site also had unvegetated pools of water between Points 2 and 3, and the marsh surface was an unstable floating mat, perhaps suggesting marsh deterioration. Trees that were present at study sites were either lone trees that were still partially alive but surrounded by marsh, or trees along the forest edge that hung over the subplots. Similar to what was seen at Point 2, none of these areas were dominated by species that are traditionally

Table 1. Most dominant species at each site in transitional marsh habitats based on percent cover in subplots at Point 3. Bare ground is also included as a cover type in the herb/ground layer because it was prominent at all sites. Species listed first in each category had the highest percent cover in subplots, and the species listed second had the second highest percent cover. Species are only listed in this table if they represented ≥ 10% cover in subplots.

Site Number	Herb/Vine/Ground Layer	Shrub Layer	Canopy Layer
1	bare ground, *Cicuta maculata*	------	*Acer rubrum, Quercus alba*
2	*Phragmites australis*, bare ground	------	------
3	*Phragmites australis* (dead sprayed), bare ground	------	------
4	*Juncus effusus, Hydrocotyle prolifera*	------	------
5	*Phragmites australis*, bare ground	------	------
6	*Phragmites australis*, bare ground	------	------
7	*Phragmites australis*, bare ground	------	------
8	Bare ground, *Phragmites australis*	------	*Acer rubrum*
9	*Phragmites australis*, bare ground	------	*Nyssa sylvatica, Acer rubrum*
10	bare ground, *Spartina alterniflora*	*Toxicodendron radicans, Morella cerifera*	------
11	bare ground, *Mikania scandens*	------	------
12	*Phragmites australis*	------	------
13	Bare ground, *Phragmites australis*	------	*Acer rubrum*
14	*Phragmites australis*, bare ground	*Morella cerifera*	------
15	*Smilax rotundifolia*, bare ground	*Viburnum dentatum*	*Acer rubrum, Carya cordiformis*

found in high marsh zones in estuarine marshes, such as *S. patens, D. spicata, P. odorata, I. frutescens, B. halimifolia* or *S. subulatum.* An indicator value was calculated for 2 sites (13.3%) at Point 3 that had both trees and saplings present. Both of those sites had indicator values greater than 1.0. These formula values specify that these habitats are getting drier.

Most sites (86.7%) had some standing dead trees present along the transect, which were usually located around Points 2 and 3 in transitional marsh (Figure 6). Standing dead trees were sometimes located well in front of the current forest edge and were surrounded by marsh, and were other times located right along the current forest edge. Most sites also had large downed wood and coarse woody debris (93.3%), which were also usually located around Points 2 and 3 along transects.

Figure 6. Standing dead trees at a study site along the transition area between a forested wetland and a brackish estuarine marsh.

Palustrine forested wetland (Point 4)

Point 4 was located in palustrine forested wetlands that were adjacent to current marsh areas where changes over time were evident. At Point 4, we acquired salinity and specific conductance readings at 7 of 15 sites (46.7%) from either creeks or standing surface water. Salinity ranged from 0.0 ppt to 8.8 ppt and specific conductance ranged from 0.0 mS/cm to 15.3 mS/cm. Most sites showed a general gradient from estuarine marsh to forested wetland, with water in the estuarine marsh being more saline and gradually becoming fresher moving from transitional marsh to forested wetland.

Soils at Point 4 at study sites varied, with some being largely dark brown and organic and some being lighter gray or gray-brown and mineral. Mineral soils were composed either of clay or a mix of clay and sand. Wetter soils did not have any redox features, while relatively dry soils contained redox concentrations. Such observations suggest that these forested freshwater wetlands varied in hydrologic regime; wet, dark, and largely organic soils indicate more continuous saturation, while lighter and dryer mineral soils with redox concentrations indicate less continuous saturation with a fluctuating water table.

Table 2. Most dominant species at each site in forested freshwater wetland habitats based on percent cover in subplots at Point 4. Bare ground is also included as a cover type in the herb/ground layer because it was prominent at all sites. Species listed first in each category had the highest percent cover in subplots, and the species listed second had the second highest percent cover. Species are only listed in this table if they represented ≥ 10% cover in subplots.

Site Number	Herb/Ground Layer	Shrub Layer	Canopy Layer
1	*Persicaria punctata*, bare ground	*Ilex verticillata*	*Acer rubrum*
2	bare ground, *Microstegium vimineum*	*Elaeagnus umbellata*	*Acer rubrum*
3	bare ground, *Leersia oryzoides*	-------	*A. rubrum, L. styraciflua*
4	*Phragmites australis*, bare ground	-------	*L. styraciflua*
5	bare ground	-------	*L. styraciflua, Q. michauxii*
6	bare ground, *Carex* sp.	*Viburnum dentatum*	*Liquidambar styraciflua, Nyssa sylvatica*
7	bare ground, *Carex* sp.	-------	*Quercus rubra, Asimina triloba*
8	bare ground	*Viburnum dentatum*	*Prunus serotina, Liriodendron tulipifera*
9	*Saururus cernuus*, bare ground	-------	*Ilex opaca, Nyssa sylvatica*
10	bare ground, *Lonicera japonica*	*Clethra alnifolia*	*Acer rubrum, Nyssa sylvatica*
11	bare ground, *Phragmites australis*	*Cornus* sp.	*Carya cordiformis*
12	bare ground, *Hydrocotyle prolifera*	*Morella cerifera*	*Acer rubrum, Magnolia virginiana*
13	bare ground, *Phragmites australis*	-------	*Acer rubrum, Magnolia virginiana*
14	bare ground, *Hydrocotyle prolifera, Leersia oryzoides*	*Morella cerifera*	*Acer rubrum, Magnolia virginiana*
15	bare ground, *Dioscorea villosa*	*Lindera benzoin*	*Acer rubrum, Fraxinus pennsylvanica*

All sites at Point 4 in forested freshwater wetlands had herbaceous plants and trees, while none had SAV. In addition, 80.0% of sites had shrubs, 86.7% had saplings, and 73.3% had vines. In general, the number of plant layers steadily increased from Point 1 in estuarine marsh to Point 4 in forested freshwater wetland, and most sites had the highest level of diversity at Point 4. Species often seen at Point 4 in forested freshwater wetlands were *P. australis, Liquidambar styraciflua, Nyssa sylvatica, A. rubrum, Viburnum dentatum, Lonicera japonica, Magnolia virginiana* (Table 2). Notably, all of these sites had tree cover over subplots, but all of them had a lot of bare ground with relatively little understory growth (Table 2). Many sites (53.3%) had *P.australis* starting to grow into the forest, even under the cover of the tree canopy. For some sites, *P.australis* was actually one of the dominant herbaceous plants under the trees (Table 2).

Sapling:tree indicator values were calculated for 13 of 15 sites (86.7%) at Point 4. Two sites did not have any saplings present and therefore had no indicator value. The sapling:tree indicator at Point 4 varied among sites. Four sites (26.7%) had values < 1.0 and were shifting wetter, 3 sites (20.0%) had values equal to 1.0 and were remaining the same, and 6 sites (40.0%) had values > 1.0 and were shifting drier, according to the formula. At 5 sites (33.3%), salinity tolerance of tree species was found to be increasing, where sapling species that were present had higher overall tolerance to salinity than mature tree species present. In contrast, at 3 sites (20.0%), salinity tolerance of tree species was found to be decreasing. At such sites, sapling species that were present had no tolerance for salinity, while tree species that were present were a mix of species with no tolerance or a medium tolerance for salinity. At 5 other sites (33.3%), there was no apparent change in salinity tolerance, as tree and sapling species that were present were both a mix of species with no tolerance or medium tolerance.

Discussion

Habitat Changes and Implications

There were many differences among our study sites, such as in salinity regimes or specific plant communities. Some of these differences were likely due to their positions relative to the Delaware Bay and the Atlantic Ocean, which influences tidal flow. Differences may also be attributed to the extent that freshwater influxes affect each site. However, some common patterns among sites were discerned from this study. Habitat transitions likely caused by sea level rise appeared to be occurring in a stepwise fashion. Evidence in the field showed that edges of forested freshwater wetlands have changed to high marsh, and one site showed obvious signs that low marsh has converted to open water. There was little evidence of any habitat states being bypassed, such as forested wetland forest converting to low marsh or open water. In most cases, where forest retreat has occurred, trees are not be replaced by native high marsh plant species, and are instead being replaced largely by invasive *P. australis*.

Wetland sites are prone to invasion by non-native plant species when they experience disturbances such as increased flooding, salinity intrusion, or creation of a canopy gap (Zedler and Kercher 2004). The invasive common reed, *P. australis*, was found at most sites between native salt marsh vegetation and freshwater forested wetland vegetation. It was similarly found at the few tidal freshwater sites between tidal freshwater marsh and freshwater forested wetland. *P. australis* is a common invader in tidal wetlands that have low salinities (Chambers et al. 2003), making our study sites inherently prone to invasion. The plant usually colonizes in high marsh zones that are irregularly flooded (Chambers et al. 2003), so it is not surprising that we found stands of it located between the current low marsh and the current forest. As trees along forested wetland edges die, space and canopy gaps are created for *P. australis* to move in and displace native plant species. The common reed was also found beginning to grow under the cover of the trees in the forested wetlands at over half of our study sites, which may be a sign that these forested wetlands are starting to undergo changes that could convert more forest into marsh in the near future.

It is possible that if flooding and saltwater intrusion continue to increase, *P. australis* stands will begin to die off; however, adult stands can be very resilient to flooding frequency and salinity once established (Chambers et al. 2003), so substantial increases in flooding or salinity may be necessary before native saltmarsh plants can take over. If these habitats do not reach a threshold beyond which the common reed cannot survive, they will likely remain *P. australis* marshes and will prevent native high marsh species from moving inland. If adult stands are well-established, they could also delay native *S. alterniflora* from moving inland once flooding frequency is high enough. Based on results from this study, retreating forest in Delaware is most likely to be replaced by *P. australis* under a variety of salinity regimes, not by native high marsh species. This could translate into a loss of native high marsh habitat in coastal wetland areas affected by sea level rise, which would negatively affect obligate wetland wildlife that rely on native high marsh vegetation, such as nesting saltmarsh sparrows (*Ammodramus caudacutus;* Erwin et al. 2006). A similar pattern has already been documented in New Jersey, where the rate of native salt marsh migration inland has lagged behind the rate of forest loss because of the invasion of *Phragmites* following tree death (Smith 2013).

At a few sites, it was evident from salinity and specific conductance readings, as well as from the marsh plant communities, that the marshes adjacent to the forested wetland were tidal freshwater wetlands despite the fact that they were mapped as estuarine wetlands. In such areas, it can be reasonably concluded that forest retreat thus far has likely been the result of increased flooding, not yet from significant saltwater intrusion. However, that may change in the near future if water levels continue to rise and saltwater continues to move further inland. Most sites, on the other hand, had brackish marsh adjacent to forested wetlands, meaning that observed habitat changes are likely the result of both increased flooding and saltwater intrusion. The number of standing dead trees per meter of transect was not related to salinity or specific conductance, suggesting that forest retreat can occur under a range of salinity regimes where increased flooding is occurring.

One unusual study site showed potential signs of habitat transition states being by-passed. This site did not follow general patterns observed at many other sites; *P.australis* was much less prevalent compared with other sites, there were unvegetated pools within floating mats of native high marsh vegetation, and some *S.alterniflora* was starting to grow among shrubs farther inland than the high marsh vegetation. Taken together, these could be signs that high marsh is converting straight to open water rather than to low marsh at this site. One possible explanation for this is peat collapse, where increased flooding and saltwater intrusion can cause high marsh vegetation to die, resulting in organic marsh soil compaction, marsh pool formation, and inability of *S.alterniflora* to fully colonize (DeLaune et al. 1994). However, no other sites demonstrated signs of habitat transition states being by-passed in this manner.

Observations from this study show that marshes in Delaware are capable of migrating inland in response to sea level rise. Thus, at least in some places, tidal marshes may be able to keep pace with sea level rise and continue to provide important ecosystem services, such as storm and flood protection and carbon sequestration. However, tidal marshes may function differently if *P.australis* instead of native high marsh vegetation continues to replace retreating forests. The common reed can efficiently build marsh elevation through increased rates of sediment accretion (Rooth et al. 2003), which could make marshes more resilient to coastal storms and sea level rise. However, loss of native high marsh species and invasion of *P.australis* degrades habitat quality for many wildlife species, as many obligate marsh species rely on native vegetation (Erwin et al. 2006, Guntenspergen and Nordby 2006). As marshes migrate inland, palustrine forested wetland habitat is lost. If topography or human development restricts palustrine forested wetland habitat from also moving further inland as marshes do, then such habitat may continue to shrink in coastal areas in Delaware.

The sapling:tree indicator (developed by Kirk Havens, VIMS, personal communication) was designed to make inferences about changes in hydrology regimes. Indicator values at points in freshwater wetlands varied among sites in this study, with some suggesting that areas are getting wetter, and others suggesting the areas are getting drier. A drying habitat is not what we expected to see if increased flooding and saltwater intrusion were occurring at a site; thus, some of the calculated indicator values were unexpected. However, there may be some limitations to the conclusions that can be drawn from this indicator. For example, Kirwan et al. (2007) found that loblolly pine seedlings would grow in abundance initially at sites that were experiencing increased flooding, but would then die off before maturity, resulting in a lack of recruitment into the adult population. Along these lines, it is possible that some of the young saplings that we saw at our sites could die off before reaching maturity. If that occurred, then the community would not truly be shifting towards trees that grow in drier conditions, as they would not be able to reproduce. Therefore, the presence of saplings at the time of our site visits may lead to spurious conclusions about drying habitats based on the structure of this indicator.

Additionally, all of the sites that had an index value > 1.0 at Point 4 showed some evidence of increased flooding or saltwater intrusion. Tree loss was visible over time in aerial imagery at all of these sites, and this was field-verified by the presence of standing dead trees. For instance, one site had a sapling:tree indicator of 1.13 at Point 4. However, substantial tree loss in the area was visible in aerial imagery (Figure 7), and a lot of standing dead trees, large downed wood, and coarse woody debris observed in the field further show that the forest edge has retreated. The habitat area between current forested wetland and *S. alterniflora-D.spicata* marsh at the site was dominated by *P.australis* and was inhabited by few live shrubs and very few living trees, also suggesting that the area is gradually getting too wet to support trees and shrubs. There were numerous pools of open water containing no vegetation in the area. The soil in the forested wetland at this site was wet, dark, and contained a lot of organic material, and *P. australis* was beginning to grow into the edge of the forest, all indications that the habitat is already wet and is likely getting wetter, not drier. Similar observations were made at all other sites that had indicator values above 1.0.

It is also possible that conditions are not yet wet enough at sites with index values ≥ 1.0 for flood-related changes to be occurring in the tree and sapling communities. If flooding has not yet increased enough to affect change, flood-intolerant species may still be able to regenerate in these wetland forests, which may have led to index values ≥ 1.0. For example, some of these sites had grayish mineral soils with redox concentrations and limited organic material, suggesting that the current hydrologic conditions are that of a fluctuating seasonal water table rather than continuous saturation or inundation. Such hydrologic conditions may not prevent flood-intolerant species from growing. This could change as sea levels continue to rise, especially because other signs of increased flooding have been noted at these sites.

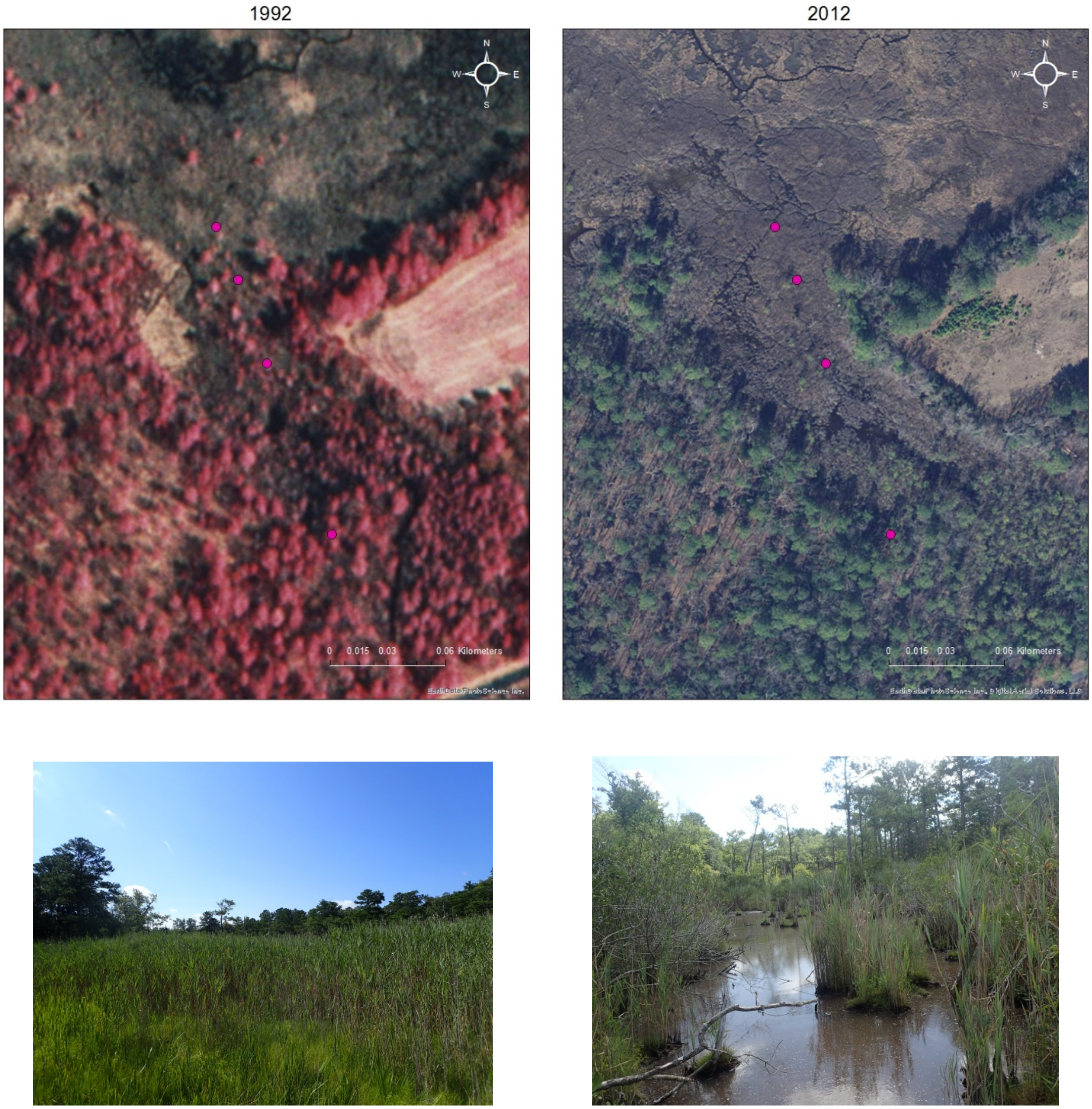

Figure 7. *Top right, left*: visible tree loss between 1992 and 2012 at a study site, respectively. *Bottom left*: *P.australis* dominated marsh between *S.alterniflora-D.spicata* marsh and current forested wetland. *Bottom right*: areas of open water with no vegetation were numerous from low marsh through the *P.australis* high marsh. All of these factors together suggest that this site is getting wetter.

Study Limitations and Future Directions

By nature, increased flooding and saltwater intrusion that are caused by sea level rise are phenomena that happen over time. Ideally, then, studies that explore these topics should also occur over several years to best capture what is occurring in nature. However, time and funding may realistically restrict research possibilities. This study was designed to describe physical and biological parameters of areas that have probably experienced, and will likely continue to experience, increased flooding and saltwater intrusion in Delaware. The study was not designed to be experimental; thus, there were no control or treatment sites. Each site was only visited once, representing a snapshot in time. Thus, past conditions had to be estimated from aerial imagery, and all future conditions at sites must be hypothesized by future marsh migration models and possible trajectories based on current conditions. To better characterize what has occurred, what is currently occurring, and what is most likely to occur in the future, these wetland habitats should be consistently monitored over a much longer period of time.

In this study, salinity and specific conductance readings were taken at points along transects in tidal creeks, from standing water, or from water filling soil pits. Such readings were taken opportunistically because each site was only visited one time. While that provided a rough idea of the salinity regime at each site, long-term monitoring would be much more accurate and informative, as readings can have temporal variation based on precipitation, storm events, and tides. This is particularly true because many sites were visited when conditions were wetter or drier than normal, which can affect dissolved ion content in water. Readings can also vary widely depending on the source of the reading (i.e. surface water or pore water); thus, long-term monitoring would best be conducted from a consistent source.

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