



Original Articles

Trends in vegetation and height of the topographic surface in a tidal freshwater swamp experiencing rooting zone saltwater intrusion

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ABSTRACT

A decrease in the ground surface height of coastal wetlands is of worldwide concern because of its relationship to peat loss, coastal carbon, and biodiversity in freshwater wetlands. We asked if it is possible to determine indicators of impending transitions of freshwater swamps to other coastal types by examining long-term changes in the environment and vegetation. In a tidal *Taxodium distichum* swamp in Hickory Point State Forest, Maryland, the topographic surface height (ground surface height) decreased by as much as 25.6 ± 2.2 to 50.8 ± 3.8 cm at two Surface Elevation Tables from 2015 to 2021 following salinity intrusion events related to hurricanes and offshore storms (e.g., Hurricane Melissa). In 2019, rooting zone salinity exceeded 5 ppt for >24.9 % of the time, with a maximum salinity level of 12.5 ppt. Tree growth of *T. distichum* trees declined and 60 % of these trees died along a 4 m wide \times 125 m transect in 2014–2016. Root biomass and ground surface height decreased roughly in conjunction with a salinity pulse in the rooting zone during Hurricane Melissa in 2019. Saplings survived but *T. distichum* seedlings were uncommon and did not survive in the study area. *Typha* \times *glauca* increased in cover (0.2 to 5.6 % cover plot⁻¹) from 2014 to 2016 so a vegetation shift toward *T.* \times *glauca* was apparent by 2021. This work captures a multi-year trend of decreasing ground surface height, tree growth and health, and freshwater status in the rooting zone that may be an indicator of impending vegetation transition.

1. Introduction

Peat building is essential to promote the resilience of coastal wetlands to salinity intrusion from sea-level rise, hurricanes (Chambers et al., 2019), and freshwater over-usage (Middleton and Souter, 2016). The process is facilitated by the active contribution of plant materials through root production (DeLaune et al., 1994; Middleton and McKee, 2001; Krauss et al., 2014; Wilson et al., 2018; Chambers et al., 2019) and slow rates of decomposition, particularly of wood in tidal swamps (Middleton, 2020). However, saltwater intrusion in tidal freshwater marshes may cause a biogeochemical switch to sulfate reduction by microbes along with rapid decomposition, loss of carbon, and permanent inundation (Weston et al., 2011). In such situations, tracking the health of coastal freshwater systems can alert scientists and managers of potential peat collapse (Chambers et al., 2019).

While decomposition may increase in freshwater tidal marshes (Weston et al., 2011), production decreases in tidal swamps at higher salinity levels (Middleton, 2020) could precede a decline in local ground surface height. As the sea-levels rise, these coastal freshwater wetlands

are subjected to increased salinity exposure from surface and groundwater sources (Wilson et al., 2011; Herbert et al., 2015). At the same time, even moderate or distant coastal storms (several hundred kilometers away; Wilson et al., 2011) can drive salinity into the groundwater, creeks, and aquifers of coastal wetlands, a situation made more dynamic with climate change (Intergovernmental Panel on Climate Change (IPCC), 2014). Ultimately, shifts in vegetation zonation patterns may occur on the coast as salinity rises because of the susceptibility of tidal freshwater species to these environments (Moffett et al., 2012; Powell et al., 2016).

To further contribute to coastal salinity increase, salt-tolerant species may pull salinity from saline groundwater into the rooting zone via evapotranspiration (Jiang et al., 2015; DeAngelis, 2012; Sternberg et al., 2007). Freshwater species are therefore at a disadvantage because most species stop evapotranspiration to cope with increased salinity in the rooting zone (Sternberg et al., 2007). *Taxodium distichum* trees have several ways of coping with elevated salinity (Krauss and Duberstein, 2010) including accessing freshwater in pockets underground (Krauss and Duberstein, 2010) and by using the roots emanating from knees to

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search for freshwater below the ground (Stahle et al., 2012). Also, salinity-affected trees may transport saline water to the outer layers of the xylem but both sap flow and the ability of the canopy to respond to water deficit is reduced in this situation (Krauss and Duberstein, 2010).

Elevated salinity can take a toll on tree health and ultimately drive peat collapse if roots and vegetation die and associated soil strength declines (Chambers et al., 2019). After that, the peat may become more compacted, and root channels may collapse as the peat decomposes (Chambers et al., 2019). Eventually, elevated salinity can cause tidal swamps to transition over decades to other types of wetlands such as marshes (>2 ppt or ~ 2 g/L) (Krauss and Duberstein, 2010).

Salinity surges contribute to vegetation tipping points (the critical point after which transition becomes inevitable) toward a regime shift (sudden change in vegetation or ecosystem function driven by a major external impact; Scheffer, 2009), depending on the type of local vegetation, precipitation, and freshwater input from riverine and overland flow (Jiang et al., 2015). The process leading to regime shift is rarely captured in field studies because monitoring studies are seldom in place to document long-term changes in salinity, vegetation health, and ground surface height (height-TSLVD or the height of the topographic surface established using a local vertical datum tied to NAVD 88). The datum is the fixed point represented by the SET monument.

We asked if it is possible to detect indicators of impending transition in freshwater swamps to other coastal types through long-term observations of vegetation health in response to rooting zone salinity spikes. The objective of our work was to examine how salinity intrusion in the rooting zone might affect the height-TSLVD, freshwater tree mortality, and vegetation dominance in a tidal *T. distichum* swamp at Hickory Point State Forest, Pocomoke River, Maryland from 2013 to 2021.

2. Materials and methods

2.1. Site description

Hurricanes and other severe storms can lead to saltwater intrusion events in the Chesapeake Bay region (Dennison et al., 2012; Middleton 2016a, b). Tidal freshwater swamps in Hickory Point State Forest along a tributary of the Chesapeake Bay experienced a salinity surge during the wrap-around event that pushed saltwater upstream in the lower Pocomoke River (Fig. 1) during Hurricane Sandy (October 29, 2012) (NOAA (National Oceanic and Atmospheric Administration), 2013; Middleton, 2016a). Salinity intrusion in the Chesapeake Bay watershed was thought to have been relatively low during Hurricane Sandy because of the high amounts of rain during this storm (Dennison et al., 2012). However, water and salinity surges were severe on the lower Pocomoke River near Hickory Point during that event. Wind from Hurricane Sandy traveled down the Potomac River, crossed the Chesapeake Bay, and pushed water into its eastern shore near the mouth of the Pocomoke River in a “wrap-around” event. This event severely flooded Crisfield, Maryland, which is near Hickory Point (Fincham, 2014; Middleton, 2016b). An earlier study of Hickory Point established plots and SETs at the site (HPB301-305 and HPBSET84-85, called SET 84 and SET 85 in this paper), respectively; Fig. 1 (Middleton 2016a). Freshwater tree mortality was linked to high salinity at Hickory Point following Hurricane Sandy (maximum soil salinity levels one year after storm = 3.5 ppt; Middleton, 2016a). Further evidence of the salinity surge from Hurricane Sandy was related to salinity levels measured in channel gages of the Pocomoke River at 13.1 and 18.6 ppt just upstream and downstream of the study site (Nassawango Creek and Shelltown gages, respectively; Maryland Department of Natural Resources 2012 as reported by Middleton, 2016a).

Forests of these tidal swamps were dominated by freshwater tree species such as *T. distichum*, *Acer rubrum*, *Liquidambar styraciflua*, and *Pinus taeda* (Middleton, 2016a,b). Soils are mapped as Puckum Series (poorly drained freshwater swamp) abutting Transquaking Series

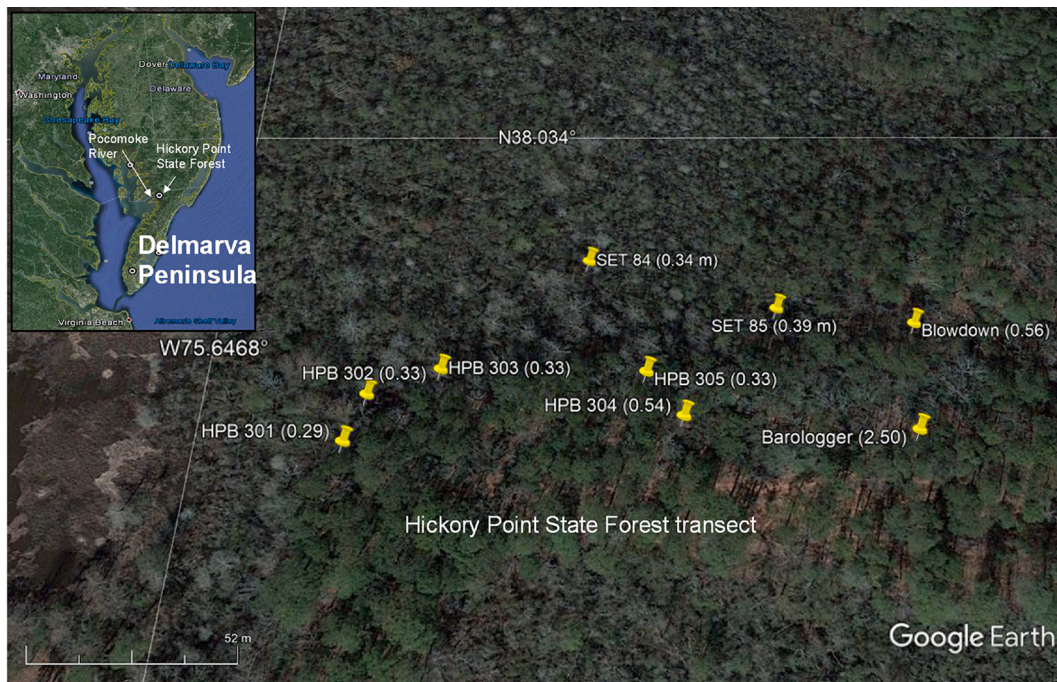


Fig. 1. Location of Hickory Point State Forest adjacent to the Pocomoke River, Maryland. The study transect was approximately 125 m in length with study plots located randomly within 25 m intervals (HPB301-305). The elevation (m) relative to NAVD 88 of each plot or other location of interest is in parentheses following the map label. Herbaceous vegetation and seedlings were measured in 1 m² plots placed to the south of each plot marker. A separate sapling plot was sampled in a 100 m² plot along the transect and to the south of HPB301 and HPB302 (10 m wide × 10 m long plot). An additional woody transect was observed in four transect sections (only in November 2021; 20 m wide × 175 m long). Surface Elevation Tables were located just north of the transect and referenced to NAVD 88.

(brackish marsh; USDA, NRCS (United States Department of Agriculture, Natural Resources Conservation Service), 2021a). Puckum types are very poorly drained and acidic at Hickory Point. Soils of the Puckum Series are comprised mostly of the organic matter contributed by woody species (<200 cm) overlaying mineral sand over bedrock (USDA, NRCS (United States Department of Agriculture, Natural Resources Conservation Service), 2021a). Note that gravel was observed underlying the SET areas; at a tree tip-up on the edge of the swamp, 25 cm of organic matter was observed over sand (B. Middleton, U.S. Geological Survey, personal observation).

2.2. Network description

Hickory Point State Forest is part of a larger network of study sites in the North American Baldcypress Swamp Network, all with identical sampling designs (Middleton et al., 2015). Hickory Point has five permanent plots marked with a stake and placed at stratified random positions along a 125 m transect (HPB301-305; Fig. 1). HPB301 is 85 m from the nearest open water of a tidal creek and 780 m to the channel of the Pocomoke River. Plots were marked with permanent plot stakes and the sampling area varied in size for each survey type as described below. See Table S1 for dates of site visits from 2013 to 2021.

2.3. Change in environment

2.3.1. Height-TSLVD

Changes in height-TSLVD were established using a local vertical datum and observed using Surface Elevation Tables (SET) (Cahoon et al., 2002) at Hickory Point State Forest, Pocomoke River, Maryland. SET techniques were originally developed for the purpose of establishing surveying monuments in wetlands, so that accurate changes in ground surface height could be made. In recent decades, Rod SETs or RSETs are the most commonly used, and the monument is fixed atop deeply set immovable rods (Cahoon et al., 2002). In 2014, two RSETs (called SETs in this paper) were established by driving rods to the point of refusal (sand, gravel, and bedrock), which was 2.5 to 3 m below the surface of the peat in the tidal freshwater swamp at Hickory Point State Forest, Maryland (Fig. 1).

These SETs were placed on the eastern end of the 125 m transect on March 28, 2014, so that SET 84 and SET 85 were positioned 16 and 45 m east of Plot HPB305, respectively. The locations of the two SETs were 29.0 vs 28.7 m apart, respectively as measured with Google Earth Pro (2022) and Turnbull (2019) (Fig. 1). The SETs were inserted in positions relatively free of knees to allow proper insertion of the rods, markers, and platforms (Location of SET 84 and 85: 38.03321°N, 75.64519°W vs 38.03333°N, 75.64490°W, respectively). Small woody roots interfering with platform placement were sawed beneath the ground. If large roots were detected beneath a monument (stationary point of measurement), the monument was moved to minimize long-term disruption to either the swamp ground surface height or the monument. Measurements of height-TSLVD began in 2015 after mud and vegetation had resettled.

Each year, height-TSLVD (Z) was measured with a leveled measuring arm attached to the fixed SET monument utilizing nine pins set in four directions (position) (Cahoon et al., 2002; Wagner et al., 2006) from 7/26/2015 (Day “0”) to 4/24/2021. The short pins used in 2015–2018 were replaced with longer pins in 2019–2021 (76 vs 183 cm) to accommodate the decrease in height-TSLVD because the short pins eventually dropped all the way through the SET arm.

Note that the usage of height-TSLVD or geometric height is unusual in ecology studies, but used in this paper instead of elevation following Meyer (2020; 2021). The geometric height is defined as the separation between the ground and an object, for example, the linear distance between the ground and an airplane (Meyer, 2020; 2021). The concept is used in this paper to measure the distance between the ground surface and the leveled SET arm (minus the offset from the SET monument to the arm; Fig. S1) by subtracting the “reading” of the pin length above the

SET arm from the total pin length. The advantage of this approach is that the distance measurement of the ground surface to the leveled SET arm is not affected by a change in pin length. Height-TSLVD was referenced to NAVD88 using a Trimble R10 Global Navigation Satellite System dual-frequency instrument via KeyNet and a hotspot phone connection using continuous three-minute occupations during the leaf-off period on November 11, 2021, and March 4, 2022.

Ecologists might consider height-TSLVD instead of elevation, because height-TSLVD is a direct measurement of the distance from the ground surface height to the monument (SET arm minus distance to the receiver; Fig. S1). Elevation based on mean sea level is more common, but it is a concept difficult for ecologists to employ in SET studies because of the highly specialized training required to determine mean sea level correctly (Tom Meyer, University of Connecticut, written communication, June 8, 2022). Problematic for most ecologists is that the orthometric correction to calculate elevation requires observations of the magnitude of Earth’s gravity field at the SETs (Tom Meyer, University of Connecticut, written communication, June 30, 2022). These orthometric corrections need to be calculated to account for the non-parallelism of the equipotential surfaces through which the plumb line passes and must remain perpendicular during measurement. Therefore, to estimate changes in ground surface height over time we used direct measurement of the distance from the ground surface to the SET arm or height-TSLVD, which is the height of the topographic surface established using a local vertical datum (datum = SET monument or the SET arm minus an offset based on the distance from the receiver to the level SET arm; Fig. S1) tied to NAVD 88. All height-TSLVD data are available from Middleton and David (2022a;b).

2.3.2. Environmental measurements

At each plot marker, day-of-site visit measurements of water quality and depth (with a meter stick) were sampled from 2013 to 2021 (Table S1). Porewater salinity and pH were measured with a temperature-compensated meter (room temperature; Oakton Salinity 6) after the collected water was transported to the lab. A CTD Diver salinity probe was deployed at 48 cm below the topographic surface (soil surface) in a well near SET 84 and the probe continuously recorded conductivity (EC), temperature, and water level changes from November 13, 2018, to November 11, 2021, with some data loss during 2020 due to equipment failure. Day-of-visit water depths at plots and SETs were matched to the continuously recorded water depths at SET 84 and can be used to estimate daily changes in water depths, extrapolating from water changes at SET 84 to SET 85 and Plots HPB301-305 based on the connection of the water sheet across the site (i.e., Leopold Method: Leopold et al., 1992, Middleton, 2020). Salinity levels of river water at positions upstream and downstream of Hickory Point during storms were obtained from published sources (Maryland Department of Natural Resources 2021).

Measurements of conductivity (EC) in S/m were temperature compensated and converted to ppt using CTD Diver software (2021), which is based on a temperature compensation equation reported in the U.S. Geological Survey (USGS; Wagner et al., 2006) standards for continuous water-quality monitors (Eric Coulombe, Van Essen Instruments, written communication, February 11, 2022). Similarly, continuous water depth changes were calculated from pressure estimates recorded at 15-minute intervals by the CTD Diver probe and compensated using air pressure data from hourly barometer estimates from Wallops Flight Facility (NASA). The air pressure is subtracted from the water pressure measured by the CTD Diver software to report changes in continuous water depth over time (Jonathan Evans, Van Essen Instruments, oral communication, February 3, 2022). All environment data are available from Middleton and David (2022c).

2.4. Vegetation

2.4.1. Root ingrowth

Annual root production over time was measured by examining root ingrowth into a mesh root bag filled with root-free substrate inserted into the ground within 0.25 m to the north of each of the five permanent plots. A soil core (7 cm diameter \times 30 cm depth) was filled with an implanted root bag of a similar size (root ingrowth core; Lund et al. 1970) and inserted each year during the summer field survey into the ground adjacent to each of the five plot markers after the previous year's core had been removed (2013 to 2021; Table S1). After removal, cores were divided into three sections (0–10, 10–20, and 20–30 cm depth) and washed through a sieve to separate soil from roots. Collected roots were dried until reaching a constant mass at 70 °C and weighed. One-time-per-year ingrowth bag removal allowed many months for the regrowth of roots into the core (Hertel and Leuschner, 2002; Vogt et al., 1998). All root data are available from Middleton and David (2022d).

2.4.2. Ground vegetation

Herbaceous species and woody seedlings were assessed in a single 1-m² quadrat within each of the five plots to the south of a linear transect (transect length = 125 m) during the growing seasons from 2013 through 2021. For each species, percent cover was visually assessed within the quadrat as follows: 1, 1%; 2, 1–5%; 3, 5–15%; 4, 15–25%; 5, 25–50%; 6, 50–75%; 7, 75–95%; 8, 95–100%, recording mid-points of cover classes (Daubenmire, 1959). In addition, *T. distichum* seedlings were counted along a 3 m wide transect between HPB301-305 from 2013 to 2021. All ground vegetation data are available from Middleton and David (2022e).

2.4.3. Woody vegetation

Annual sapling survey. To assess sapling regeneration, the number and height (cm) of all sapling individuals were recorded in one 100-m² plot (0.01 ha) between HPB301 and HPB302 from 2013 to 2021 (Table S1) following the methodology used in the network (Middleton et al., 2015).

Woody species survey. On November 11, 2021, the number and height of live trees, dead trees, and saplings along a 20 m wide \times 175 m long transect on either side of HPB301 to SET 85 (Fig. 1) were recorded between each of the plot posts to SET 85. Total number and mean height for each species were recorded along this 20 m wide \times 175 m long transect (Fig. 1; HPB301-302, HPB302-303, HPB303-304, HPB304-305, and HPB305-SET 85). The mean number and height of each species per m² were determined for each of four transect sections with the length of the sections measured with Google Earth Pro: HPB301-302, HPB302-303, HPB303-304, HPB304 to SET 85; 15.7, 22.5, 70.7, 17.5, and 46.3 m, respectively: total length of transect = 172.7 m. All woody species data are available from Middleton and David (2022f).

2.4.4. *Taxodium distichum* tree growth and mortality

In 2013, the nearest *T. distichum* tree to each of the five permanent plots along the transect was fitted with a dendrometer band ($n = 5$) (Anemaet and Middleton, 2013). These trees were widely spaced, and each selected tree fully emerged into the upper canopy. Tree bands were placed at breast height (~1.5 m height), noting that these trees had little fluting and no buttressing. Circumference growth increment was measured each year from 2014 to 2021 unless the tree had died (Middleton et al., 2015). Tree growth was analyzed by comparing the ratio of year-to-year growth for each tree (circumference ratios = the year's circumference (year₁) divided by the previous year's circumference (year_{t-1})) from 2014 to 2021 (Middleton et al., 2015). All tree growth data are available from Middleton and David (2022g).

2.5. Statistical analyses

2.5.1. Change in height of the topographic surface, 2015–2021

Procedures for determining height-TSLVD were established using a local vertical datum for each time step following Lynch et al. (2015) with certain modifications (Fig. S1). Instead of using the “reading” (height of pin above the surface of a SET arm or reading), the height of the pin from the soil surface to the SET arm surface was calculated as a functional measurement of height-TSLVD (instead of elevation) at a time step (reading – pin length; Fig. S1). A change in pin length during the study (2015–2018 vs 2019–2021: pin length = 76 vs 183 cm, respectively) was necessitated by the large drop in height-TSLVD. See Fig. S1 for a full explanation of the approach for using height-TSLVD.

The height-TSLVD was determined for each pin on the day of measurement (see Table S1, “summer” column) as the number of days since Day 0 (July 26, 2015) for each of the nine pins in each of four bearing directions (nine pin reps, four bearing reps per SET). The height-TSLVD on Day 0 was set as “0” for all pins at each SET (Kamrath et al., 2019). A SET arm of a different style was used in 2014 so these data were not used in the analysis.

We ran a regression analysis on height-TSLVD by time in days since the beginning of the study (Day 0) to compare the slopes of pins along each of the four bearings for each SET. The height-TSLVD by bearing did not differ for either SET 84 or SET 85 ($p > 0.05$), so the slopes of the pins were averaged by direction (following Kamrath et al., 2019). Model residuals were checked for homogeneity and normality. All comparisons were done using PROC GLM in SAS 9.4 (SAS 2002–2012). Bonferroni analysis was used to test differences in the slopes (Sokal and Rohlf, 1981) of the change in height-TSLVD from 2015 to 2021 for each bearing.

2.5.2. Root ingrowth

Root weight in each of the three depths of the core (0–10, 10–20, and 20–30 cm depth) did not differ ($p > 0.05$) based on ANOVA with plot nested within depth and year so that these values were summed across the three depths, and calculated on a $\text{g m}^{-3} \text{y}^{-1}$ basis for subsequent analyses. Using ANOVA, differences in annual root production were tested by nesting plot and year and the main effect of year. Means of interest were compared using one-degree-of-freedom contrasts of root weight $\text{g m}^{-3} \text{y}^{-1}$ by year using JMP SAS (2022).

2.5.3. Non-metric Multidimensional Scaling: Ground vegetation change and environment

Because of the inter-correlated nature of the variables, relationships of variables and plant species cover were explored using two Non-metric Multidimensional Scaling (NMDS) and Canonical Correspondence Analysis (CCA) models within the Vegan Package in R (Oksanen, 2012; R Core Team, 2022) using a starting number of 8468, which produced a stress value of 0.2145553. Variables were selected initially for subsequent NMDS and CCA using a p-value threshold of 0.15 using forward and backward stepwise regression procedures (Oksanen, 2012; R Core Team, 2020). Variables included year (2013–2021), salinity (ppt), log salinity, pH, and day-of-visit water depth. Percent covers of plant species in plots were arcsine square-root transformed (McCune and Grace, 2002). Only dominant species were used for analysis and these were defined as species with a cover of $> 0.3\%$. Significant variables were determined as those with $|t| > 1.96$ or $p < 0.05$ in the final regression and these variables were used in the NMDS and CCA. Salinity, log salinity, and day-of-visit water depth did not meet the selection criteria so were excluded from further analysis.

3. Results

3.1. Height of the topographic surface

Mean height-TSLVD decreased over time (n_{days} = number of days)

at both SET 84 and SET 85 from 2015 to 2021 (slope of mean height-TSLVD at SET 84 and SET 85: -0.020 vs -0.012 , respectively; Table 1; Fig. 2; Middleton and David, 2022a;b). The rate of the loss of height-TSLVD was higher at SET 84 than at SET 85 ($p < 0.0001$). By day 2,096 (April 24, 2021), mean height-TSLVD decreased 50.4 % faster at SET 84 than SET 85 (mean height-TSLVD loss in SET 84 and SET 85: -50.8 ± 3.8 vs -25.6 ± 2.2 cm, respectively), but did not vary by bearing direction within a SET plot ($p > 0.05$; Table 1). The measured height was adjusted to NAVD 88 (height-TSLVD) to estimate the height of SETs and plots along the transect (0.31 – 0.44 m; Fig. 1 and Table S2).

3.2. Environment

Salinity in the root zone well (1 m depth) was above 5 ppt for 24.9 % of 2019. Water depths above the soil surface at SET 84 in 2019 were: mean \pm S.E., minimum, maximum water depth: 22.3, 10.1, and 50.3 cm, respectively; Fig. 3). Salinity levels in the Pocomoke River upstream and downstream of the Hickory Point study site often increased at the time of the storms (Maryland Department of Natural Resources) (Table 2). pH values were lower at HPB301 and HPB302 than at HPB303-305 across all years (mean pH: 5.6 ± 0.2 vs 5.9 ± 0.1 ; $p < 0.0001$; Table S2). Day-of-visit water depths ranged from 0.1 to 4.3 cm. The mean day-of-visit pore water salinity at the plots along the transect was 1.1 ± 0.7 ppt (Fig. S2).

3.3. Vegetation

3.3.1. Root ingrowth

Total root ingrowth m^{-3} differed by year ($F = 13.6$, $p < 0.0001$) and was higher in 2017–2018 vs 2014–2016 and 2019–2020 (1280.1 ± 169.1 vs 285.9 ± 52.7 $g\ m^{-3}\ y^{-1}$, respectively; one-degree-of-freedom contrast: $t = -8.0$, $p < 0.0001$; Fig. 4), representing a 22.3 % decrease in root production by the end of the study.

Table 1

Regression analysis of height-TSLVD (~surface elevation) change over time (ndays since Day "0": 7/26/2015 to 4/21/2021) at two Surface Elevation Tables (SET 84 and SET 85) in a tidal *Taxodium distichum* swamp, Hickory Point State Forest, Pocomoke River, Maryland. The equations for the linear fits of the lines for the SETs had negative slopes (slope of mean height-TSLVD = -0.020 vs -0.012 , respectively). SET number \times ndays interactions are given in Fig. 2. Accumulated annual mean loss of height-TSLVD \pm S.E. is given in cm.

Variable	df	F	p	Annual mean loss of height-TSLVD \pm S.E.
SET Number	2	131.3	<0.0001	
SET 84				-18.0 ± 1.6 cm
SET 85				-11.0 ± 0.8 cm
Ndays \times Bearing	7	2.7	0.0192	
Ndays \times SET	1	246.8	0.0002	
Ndays \times SET 84;				
days (date)				
0 (7-26-2015)				0 ± 0 cm
355 (7-15-2016)				-0.4 ± 1.3 cm
746 (8-10-2017)				2.0 ± 0.5 cm
1056 (6-16-2018)				-8.4 ± 2.3 cm
1406 (6-1-2019)				-32.6 ± 3.2 cm
1834 (8-2-2020)				-35.9 ± 3.3 cm
2096 (4-24-2021)				-50.8 ± 3.8 cm
Ndays \times SET 85;				
days (date)				
0 (7-26-2015)				0 ± 0 cm
355 (7-15-2016)				0.4 ± 0.4 cm
746 (8-10-2017)				2.4 ± 0.5 cm
1056 (6-16-2018)				-9.5 ± 1.1 cm
1406 (6-1-2019)				-21.6 ± 1.3 cm
1834 (8-2-2020)				-23.1 ± 1.2 cm
2096 (4-24-2021)				-25.6 ± 2.2 cm

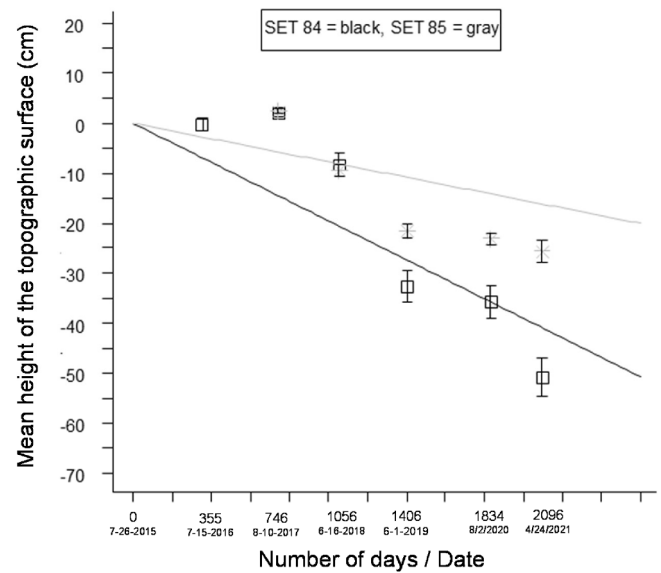


Fig. 2. Mean height-TSLVD or height of the topographic surface established with a local vertical datum and referenced to NAVD 88 (Z) was measured at Surface Elevation Tables (SET 84 and 85) in a tidal *T. distichum* swamp in Hickory Point State Forest, Pocomoke River, Maryland. Surface Elevation Tables were inserted into the swamps on March 13, 2014. Mean values height-TSLVD are given for SET 84 and 85 in number of days (ndays) since the beginning of the experiment, which was conducted from 2015 to 2021. The SETs were read by observing the pin length of nine pins above the SET arm and read in four directions (~N, S, E, W) and then subtracting the pin length from the reading (height-TSLVD in cm). The slope of change height-TSLVD (Z) over the number of days (ndays) since the beginning of the study (X) differed at SET 84 vs SET 85 (-0.020 vs -0.012 , respectively; $p < 0.0001$).

3.3.2. Ground vegetation

A total of 41 species were sampled at the site, with a plot richness of 4.3 ± 0.4 species $plot^{-1}$ from 2013 to 2021. Dominant species had a cover of > 0.3 % cover including *Boehmeria cylindrica*, *Calamagrostis canadensis*, *Hydrocotyle verticillata*, *Leersia oryzoides*, *Liquidambar styraciflua* (seedlings), *Osmunda cinnamomea*, *Onoclea sensibilis*, *Pluchea camphora*, *Polygonum sagittatum*, *Sagittaria latifolia*, *Sium suave*, *Thelypteris palustris*, *Typha \times glauca*, and minor grouping of species (total cover cover $plot^{-1}$: 1.2–8.9 % cover; Table S3). *Taxodium distichum* seedlings were found only in 2015, with a mean of 0.2 % cover, which did not survive. Seedlings of other woody species were found in plots from 2013 to 2017 including *Acer rubrum*, *Ilex glabra*, *Liquidambar styraciflua*, and *Morella cerifera*, but not after 2018 (total seedling cover: 0.1 – 0.9 % cover $plot^{-1}$). The mean percent cover of *Typha \times glauca* in the plots was low (0 to 1 % cover $plot^{-1}$) from 2013 to 2017, but in 2018 the cover increased to 4.5 %, and by 2021 the cover had increased to 6.2 % cover $plot^{-1}$. Note that *Phragmites australis* was found between HPB303 and HPB305, but was not sampled in the herbaceous and seedling plots (See Table S3).

Similarly, the CCA ordination graph shows an increase of *Typha \times glauca* and *Calamagrostis canadensis* in later years of the study (especially in HPB303-305 in 2016–2021; Fig. 5; Table S3, Table S4, and Table S5). pH became more neutral in the plots, *Calamagrostis canadensis* % cover $plot^{-1}$ increased, and *Pluchea foetida* cover increased in more acidic plots (Fig. 5; Table S2; maximum vs minimum pH values = 5.0 to 6.4). While not related to the model ($p > 0.05$), day-of-visit pore water salinity and water depth varied during the study (salinity: 0.2 to 2.3 ppt; water depth: 0.1 to 10 cm).

3.3.3. *Taxodium distichum* growth and mortality

The mean growth (circumference ratio) of *T. distichum* trees from 2013 to 2021 was 1.00291 ± 0.00081 . The growth of dendro-banded

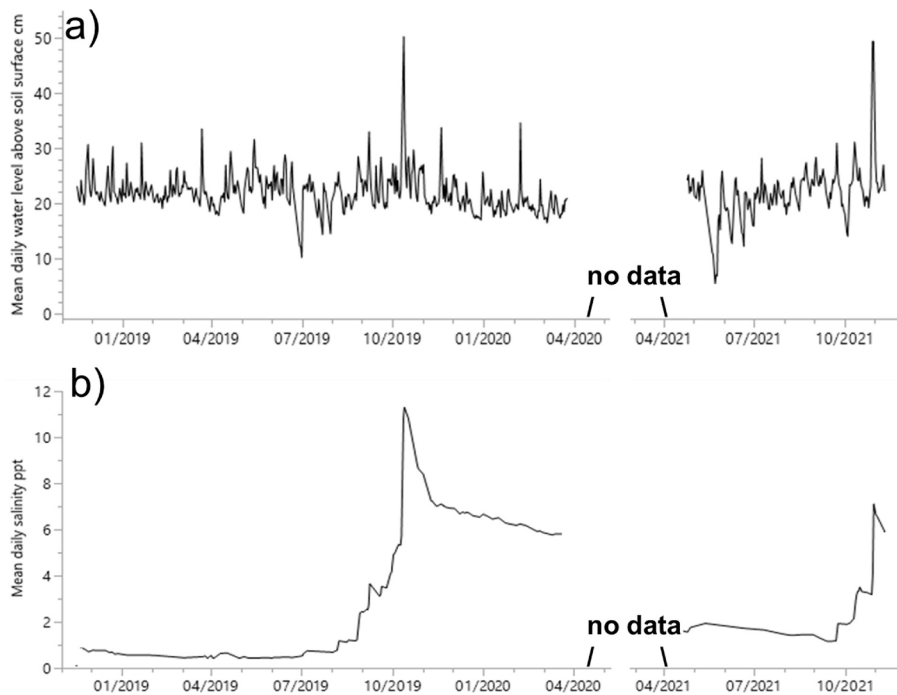


Fig. 3. Mean daily a) water level above the ground surface (cm) and b) salinity ppt near SET 84 at Hickory Point State Forest near Pocomoke City, Maryland using a CTD Diver to measure rooting zone water and salinity dynamics 42 cm below ground level. Note that peaks in both water level and salinity on October 11–14, 2019 (Tropical Storm Melissa), and October 29–30, 2021 (offshore storm) occurred at the same time as coastal storms and high tide flooding (Berg 2019, Wood 2019, NOAA, 2022).

Table 2

Salinity levels before and during various storms including Hurricane Sandy, Tropical Storm Melissa, and an unnamed off-shore storm: October 29–30, 2012, October 11–14, 2019, October 29–30, 2021, respectively, at monitoring stations in the Pocomoke River. All available data from 2012 were used from both the Pocomoke City (upstream) and Pocomoke Sound (downstream) stations of Hickory Point State Forest (n = 204 and 216, respectively) near Pocomoke City, MD. Data are from the Maryland Department of Natural Resources (2021).

Hurricane Sandy (October 29–30, 2012)				hurricane salinity			before-storm salinity		
Station	distance from Hickory Point km	latitude	longitude	max	min	mean	max	min	mean
Pocomoke City (ET10.1)	15.4 km upstream	38.084	75.566	13.1	<0.1	4.3	3.2	<0.1	0.2
Shelltown	10.8 km downstream	37.972	75.646	18.6	7.5	14.8	15.6	0.2	8.0
Pocomoke Bay (EE3.3, 3.4, or 3.5)	13.4 km downstream	37.963	75.649	n.a.	n.a.	n.a.	17.0	n.a.	17.7
Tropical Storm Melissa (October 11–14, 2019)				hurricane salinity			before-storm salinity		
Station	distance from Hickory Point km	latitude	longitude	max	min	mean	max	min	mean
Pocomoke City (ET10.1)	15.4 km upstream	38.084	75.566	n.a.	n.a.	10.7	n.a.	n.a.	0
Pocomoke Bay (EE3.3, 3.4, or 3.5)	13.4 km downstream	37.963	75.649	n.a.	n.a.	19.4	n.a.	n.a.	20.8
Offshore storm (October 29–30, 2021)				hurricane salinity			before-storm salinity		
Station	distance from Hickory Point km	latitude	longitude	max	min	mean	max	min	mean
Pocomoke City (ET 10.1)	15.4 km upstream	38.084	75.566	n.a.	n.a.	n.a.	n.a.	n.a.	0
Pocomoke Bay (EE3.3, 3.4, or 3.5)	13.4 km downstream	37.963	75.649	n.a.	n.a.	n.a.	n.a.	n.a.	16.4

trees near HPB301 and HPB302 was very slow by 2021 (1.0007), while those near HPB303-305 died between 2014 and 2016 (Fig. 6).

3.3.4. Woody vegetation (live/dead) height and density

In the annual sapling survey from 2017 to 2021, *Taxodium distichum* saplings had a density of 2.0 saplings per 100 m² and a mean height of 200 cm, noting that the random location of the single 10 m² sapling plot was between HPB301 and HPB302.

In the woody species survey along the 20 m wide × 175 m long transect in 2021, *T. distichum* trees were the tallest species at the site (mean height per transect length: 15–30 m; Table S6). *Myrica cerifera* had the highest mean density per m transect length at the site (0 – 0.6 individuals m⁻¹; Table S6). The highest species richness of live trees was found at the western end of the transect near SET 85 (species richness =

5; Table S6). Dead standing and downed *T. distichum* and *Nyssa biflora* were found along the transect, and these were more numerous on the eastern end of the transect (Table S6). Saplings along the transect were not numerous although some *Pinus* saplings were found between HPB303-304, and *T. distichum* and *Liquidambar styraciflua* were present at the eastern end of the transect (HPB305-SET 85; Table S6). Emergent species (*Typha × glauca* and *Phragmites australis*) were common immediately east of HPB301-302 (Table S6; emergent density: 0.2–14.3 individuals m⁻¹ transect).

4. Discussion

Coastal freshwater vegetation is dying where sea-level rise and/or storm activity have pushed too much salinity inland via ground and

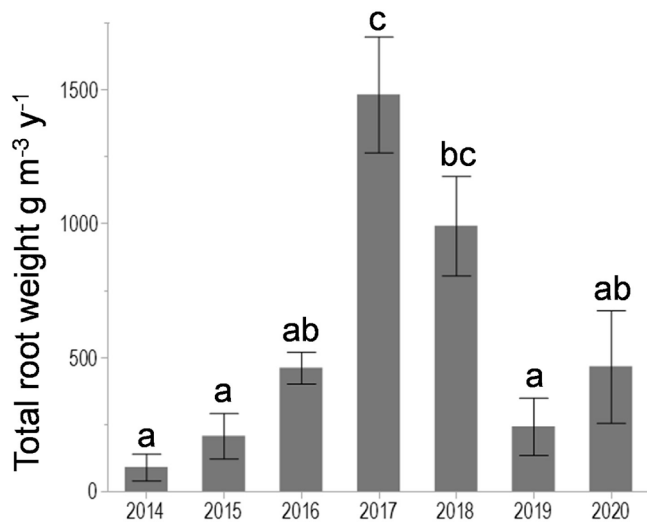


Fig. 4. Annual total root weight $\text{g m}^{-3}(-\text{y})^{-1}$ by year measured using root ingrowth cores, Hickory Point State Forest, Maryland. Significant comparisons ($p < 0.05$) of means of interest were conducted using one-degree-of-freedom contrasts and are indicated by different letters.

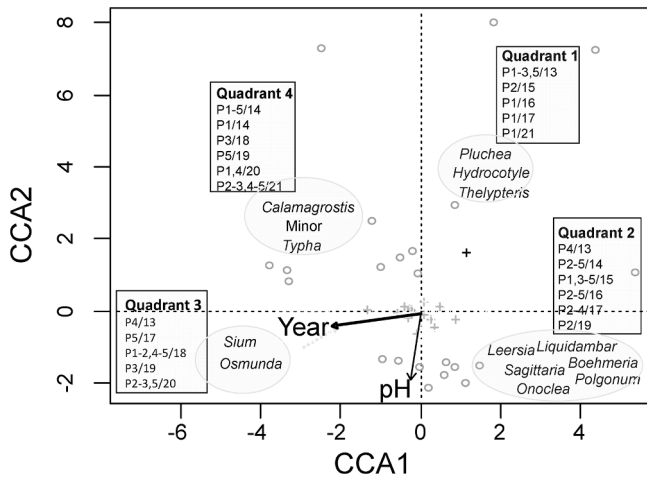


Fig. 5. Non-metric Multidimensional Scaling graphs of ground species exceeding a mean percent cover of $0.3 \% \text{ m}^{-2}$ from 2013 to 2021 (Year), Hickory Point State Forest, Maryland. The ordination was run using arcsine square root transformations of species' percent cover for values recorded by year along the transect of plots (HPB301-305). The location of each species on the ordination graph is indicated by 'o'. The position of the species on CCA1 vs CCA2 axis in Quadrant 1-4 can be: ++, +-, -, +-, respectively depending on the relationship of the species to the environment represented by each axis. Abbreviations include the plot's name (HPB301-305: P1-5, respectively), followed by the year 2013-2021: 13-21, respectively). The scores for species and plots are given in Table S4 and Table S5, respectively). Abbreviations for dominant species include *Boehmeria* (*Boehmeria cylindrica*), *Calamagrostis* (*Calamagrostis canadensis*), *Leersia* (*Leersia oryzoides*), *Liquidambar* (*Liquidambar styraciflua*), *Hydrocotyle* (*Hydrocotyle verticillata*), *Onoclea* (*Onoclea sensibilis*), *Osmunda* (*Osmunda cinnamomea*), *Pluchea* (*Pluchea foetida*), *Polygonum* (*Polygonum sagittatum*), *Sagittaria* (*Sagittaria latifolia*), *Sium* (*Sium suave*), *Thelypteris* (*Thelypteris palustris*), *Typha* (*Typha x glauca*), and minor species (total of non-dominant species). For a complete list of species see Table S3.

surface water (Wilson et al., 2011; Kirwan and Gedan, 2019; Taillie et al., 2019; Ury et al., 2021; Anderson et al., 2022), and/or where freshwater is depleted by extreme drought (Intergovernmental Panel on Climate Change (IPCC), 2014), over-usage, or drainage canals (Herbert et al., 2015; Middleton and Souter, 2016). Indicators of impending

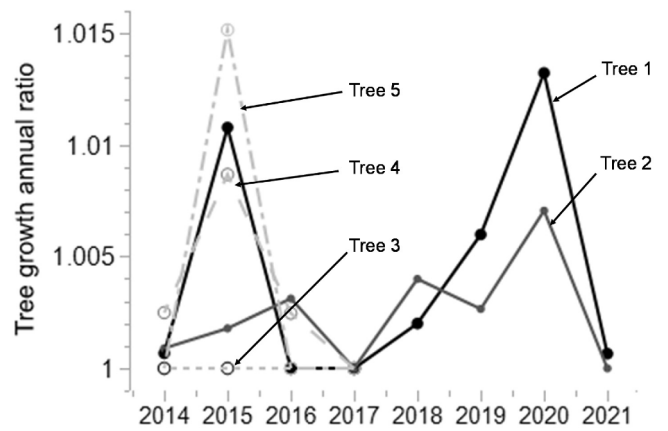


Fig. 6. *Taxodium distichum* trunk growth annual ratio (ratio of the increment of tree circumference in a year_t divided by the increment in year_{t-1} (mm)) for each of five trees fitted with dendro-bands. Trees 1 and 2 (solid lines) increased in circumference most years from 2013 to 2021; Trees 3, 4, and 5 stopped growing and died between 2014 and 2016 (i.e., 60 % mortality along the 4 m wide, 125 m transect by 2017; broken lines). Selected trees were those nearest to permanent plots positioned at stratified random positions along a transect at Hickory Point State Forest, Pocomoke River, Maryland.

regime shifts in coastal freshwater ecosystems include decreases in vegetation health, ground surface height, and rooting zone freshwater. This case history captured salinity changes in surface and root zone water with subsequent loss of height-TSLVD (~elevation), tree mortality, and vegetation change in a tidal freshwater *T. distichum* swamp in Maryland (Fig. 7).

The *T. distichum* swamp at Hickory Point was subjected to over-wash from a salinity surge during Hurricane Sandy in October 2012 (Middleton, 2016a) followed by subsequent hurricanes and offshore storms associated with rooting zone salinity spikes (Fig. 7). Eventually, 60 % of the *T. distichum* trees died along the 4 m wide \times 125 m transect (Fig. 6). Subsequently, a 5.5-month episode of elevated salinity occurred in the rooting zone from October 10, 2019, to March 27, 2020, during a tidal surge in the Chesapeake Bay produced by Tropical Storm Melissa (October 11-14, 2019; Berg, 2019; Wood, 2019). Despite the short period of record, other storm-related salinity spikes occurred in the rooting zone at Hickory Point during this study. There was evidence that pore water salinity near the soil surface increased along the transect over time but was never above 2.2 ppt during the study and was not related to the CCA model (Fig. 5). However, high levels of salinity in the rooting zone coincided with the vegetation shift and decline in ground surface height (Fig. 7).

Healthy *T. distichum* trees may be effective peat builders if the production of root and wood materials is high; the half-life of decomposing *T. distichum* wood can be longer than 300 years (Middleton, 2020). By 2017-2018, the Hickory Point study site was losing height-TSLVD at both SET 84 and SET 85 (Fig. 2). The sudden drop in the height-TSLVD was perhaps consistent with a newly formed hollow (Kroes et al., 2007), but visual observation suggests widespread development of unconsolidated peat in this swamp. At this site, more stable peat is comprised of plant roots, with unconsolidated organic matter in deeper holes (B. Middleton, U.S. Geological Survey, personal observation). The trees were dying mostly on the eastern end of the transect and in the vicinity of a large linear tip-up area perpendicular to the river impacted by a tidal surge event during Hurricane Sandy (blowdown in Fig. 1; Middleton, 2016b). Therefore, peat building and decline differences across Hickory Point may have been partly related to microtopography, which is known to influence salinity and is common in other coastal ecotones (e.g., mangrove and freshwater hammock) (Sternberg et al., 2007).

The length and intensity of salinity exposure were important in vegetation response in our study. In a model of the lower Waccamaw

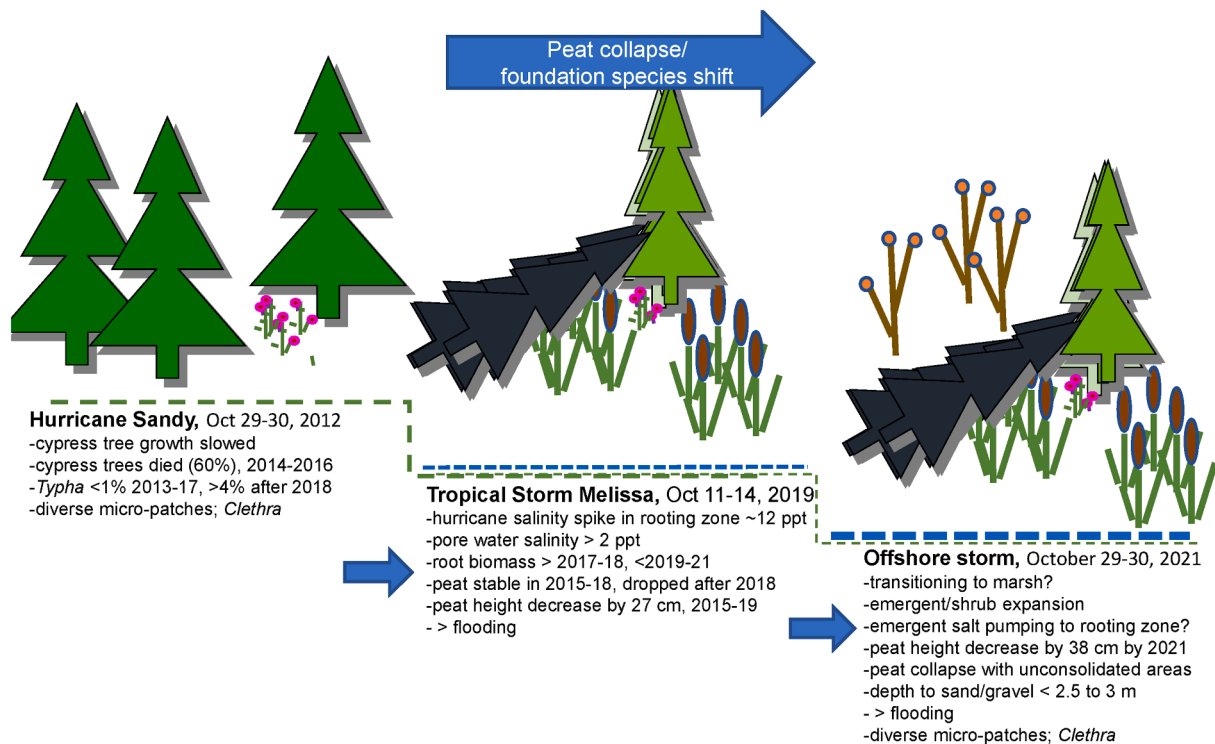


Fig. 7. Conceptual model depicting the shift in tidal swamp vegetation at Hickory Point State Forest, Maryland from 2012 to 2021 following elevated salinity in the rooting zone related to storm events.

River, pore water salinity exceeding 5 psu (~5 ppt) 57.5 % of the time drove tidal *T. distichum* swamp to brackish marsh (Wang et al. 2020). At Hickory Point, rooting zone salinity exceeded the long-term range of tolerance at times during the study. Even low levels of salinity (1 ppt) can reduce the growth of seedlings (Middleton, 2016) and saplings (Powell et al., 2016). The maximum salinity recorded in the rooting zone in 2019 was 12.5 ppt, and above 5 ppt for 24.9 % of that year (Fig. 3). After Hurricane Katrina in Louisiana, salinity was elevated in the tidal freshwater portions of estuaries and did not freshen for six months (Piazza and La Peyre, 2009). A better understanding is needed of the potential of freshwater to reduce soil salinity following storms, heavy rainfall, river floods, and freshwater mixing of groundwater (Wang et al., 2020). Ultimately, the combination of reduced freshwater and sea-level rise may cause the loss of tidal freshwater wetlands (Neubauer and Craft, 2007), which has been implicated in the loss of coastal elevation after major hurricanes (DeLaune and White, 2012, this study).

Many saline coastal marshes have thousands of years of peat accumulated from tidal freshwater species suggesting that these systems have weathered climate shifts in the past (Swarth et al., 2013). Sediment-poor systems in the northeastern United States are less poised for high rates of sea-level rise than sediment-rich systems (Morris et al., 2002; Neubauer and Craft, 2009) such as these forested wetlands in the Pocomoke River Watershed (Cronin et al., 2004). Saltwater intrusion can cause the rapid loss of trees such as *T. distichum*, *Nyssa aquatica*, and *Fraxinus pennsylvanicum* (Neubauer and Craft, 2009), with subsequent loss of height-TSLVD following spikes of salinity during offshore storms. Loss of elevation of up to 11 mm per year was observed following mass mangrove mortality after Hurricane Mitch on the Bay Islands of Honduras (Cahoon et al., 2003), noting that the rate of peat loss in our study was much higher (Fig. 2). Saltwater intrusion has the potential to impact future peat accumulation and height-TSLVD in these systems depending on how well freshwater species fare following storm-related salinity pulses in the rooting zone.

Other studies of partial coastal freshwater forest mortality and relict forest formation following storm-driven saltwater pulsing are found in

the literature. Similar to the findings of our study at Hickory Point State Forest Maryland, in Louisiana, *T. distichum* mortality after saltwater intrusion at soil salinity of ~2–5 ppt was associated with up to 85 % tree mortality (Hoepfner et al., 2008). *Conocarpus erectus* had a 25–50 % mortality and little regeneration after Hurricane Donna in 1960 in Coot Bay Hammock in Florida (Teh et al., 2015). *Sabal palmetto* and *Juniperus virginiana* var. *silicicola* forests on the Florida Gulf Coast declined because of tree mortality and lack of regeneration in the face of the interactive effects of storms, drought, and hypersaline groundwater (Desantis et al., 2007; Williams et al., 1999, 2003). Tree mortality of *T. distichum* also occurred during the temporarily elevated salinity of the 2011–12 drought along the Neches River in Texas USA, and in *Eucalyptus* forests during the Millennium Drought along the Murray River in Australia (Middleton and Souter, 2016).

Changes in flooding and salinity regimes lowered biodiversity in the Waccamaw and Pee Dee River watershed (Neubauer, 2013). If salinity remains high, Hickory Point is likely to turn into a mesohaline wetland type with a lower diversity of herbaceous species, and this has already occurred in other regional tidal swamps (Baldwin, 2007). In tropical situations, halophytic mangroves have moved into coastal freshwater hammocks because of groundwater salinity intrusion from sea-level rise (Saha et al., 2011). The high biodiversity of Hickory Point may eventually decline if the spread of *T. × glauca* and *Phragmites australis* act to increase salinity and ground shade (Fig. 7).

From a biodiversity perspective, *T. × glauca* and to a lesser extent *P. australis* had spread at Hickory Point by 2021 in Plots 3–5 (Fig. 7; Table S3; Fig. S3), and both species may be at least somewhat salt-tolerant (Yang et al., 2015). *Typha × glauca* increased in cover after 2019, from < 1 % cover to > 4 % cover starting in 2019 (Fig. 5; Table S3). While certain herbaceous species decreased over time including *Thelypteris palustris*, *Boehmeria cylindrica*, and *Onoclea sensibilis*, others increased including *Sium suave*, *Osmunda cinnamomea*, and *Calamagrostis canadensis* (Fig. 5). The recent expansion of *P. australis* and the presence of the shrub *Ilex glabra* may suggest that the system is entering a transitional phase (following Anderson et al., 2022), yet salt

intolerant species contribute species richness to this wetland (e.g., *Clethra alnifolia*) (Anderson et al., 2022).

Some emergent species related to *T. × glauca* and *P. australis* play a role in increasing salinity levels pumping salinity from the lower to upper layers of the ground surface (Yang et al., 2015). Salt-tolerant mangroves can pull salinity from groundwater into the root zone in the evapotranspiration stream (DeAngelis, 2012). While *T. × glauca* may or may not be an ecological indicator of increasing salinity at Hickory Point, the spread of both *Typha* and *Phragmites* coincided with an increase in rooting zone salinity and the decline in health and root production in this *T. distichum* swamp. An important finding in this study is that the root biomass and ground surface height-TSLVD simultaneously decreased by 2019 (Fig. 4 and Fig. 2, respectively), and roughly corresponded to high salinity in the rooting zone near the time of Tropical Storm Melissa in 2019 (Fig. 3 and Fig. 7).

An important question for the conservation of these coastal forests is: how much rooting zone salinity can these forests withstand without damage to freshwater trees and biodiversity (Fig. 7; Teh et al., 2008, Teh et al., 2015; Wang et al., 2020)? For tidal *T. distichum* forests, the long-term range of tolerance to salinity is below 2 ppt (~2 psu; Wang et al., 2020) or lower (Middleton, 2016b), and the level for conversion to brackish marsh is above 5 ppt (Wang et al., 2020). The rooting zone of the Hickory Point tidal swamp routinely exceeded levels tolerated by *T. distichum* after certain storms. Even so, Hickory Point is currently a high-value conservation area and supports high species richness in a mosaic of elevated and fresh salinity microhabitats (Fig. 7; Table S3).

5. Conclusions

This study documents the response of height-TSLVD (~elevation) and vegetation to elevated salinity, as well as the likely onset of regime shift toward peat collapse event and freshwater vegetation transition. The chain of events precipitating partial freshwater vegetation collapse was related to salinity intrusion by Hurricane Sandy in 2012, followed by salinity spikes in the rooting zone related to additional storms in the following decade. Sixty percent of the old-growth *T. distichum* trees died by 2017, root production decreased, portions of the peat in the site collapsed, and *T. distichum* seedlings did not survive. From 2013 to 2021, more saltwater tolerant *Typha × glauca* increased in cover from 0.2 to 5.6 % cover. Rooting zone salinity exceeded 5 ppt for >24.9 % of 2019, with a maximum salinity level of 12.5 ppt. To conserve freshwater wetlands on coasts, a focus on the health of vegetation may decrease the vulnerability of the ecosystem to peat collapse perhaps through the application of freshwater remediation or the removal of salt-tolerant species that could be acting as salt pumps to the rooting zone.

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Data Availability Statement

Data for this study are available in Middleton and David, 2022a-g.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data are included with references to the archive

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2022.109637>.

References

- Anderson, S.M., Ury, E.A., Taillie, P.J., Ungberg, E.A., Moorman, C.E., Poulter, B., Ardón, M., Bernhardt, E.S., Wright, J.P., 2022. Salinity threshold for understory plants in coastal wetlands. *Plant Ecol.* 223, 323–337.
- Anemaet, E., Middleton, B.A., 2013. Dendrometer bands made easy: using modified cable ties to measure incremental growth of trees. *Appl. Plant Sci.* 1, 1300044.
- Baldwin, A.H., 2007. Vegetation and seed bank studies of salt-pulsed swamps of the Nanticoke River, Chesapeake Bay. Conner, W.H., Doyle, T.W., Krauss, K.W. (Eds), *Ecology of tidal freshwater forested wetlands of the southeastern United States*. The Netherlands: Springer, New York, pp. 139–160. https://link.springer.com/chapter/10.1007/978-1-4020-5095-4_6.
- Berg, R., 2019. National Hurricane Center Tropical Cyclone Report. Tropical Storm Melissa (AL1420190) 11–14, October 2019.
- Cahoon, D.R., Lynch, J.C., Hensel, P., Boumans, R., Perez, B.C., Segura, B., Day Jr., J.W., 2002. A device for high precision measurement of wetland sediment elevation: I. Recent improvements to the sedimentation-erosion table. *J. Sediment. Res.* 72, 730–733. <https://doi.org/10.1306/020702720730>.
- Cahoon, D.R., Hensel, P., Rybcyk, J., McKee, K.L., Proffitt, C.E., Perez, B.C., 2003. Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. *J. Ecol.* 91, 1093–1105.
- Chambers, L.G., Steinmuller, H.E., Breithaupt, J.L., 2019. Toward a mechanistic understanding of “peat collapse” and its potential to coastal wetland loss. *Ecology* 100, e02720.
- Cronin, T.M., Willard, D.A., Newell, W., Holmes, C., Halka, J., Robertson, M., 2004. Introduction to Pocomoke Sound sediments and hydrography. Cronin TM (ed) Introduction to Pocomoke Sound sediments and hydrography. U.S. Geological Survey, OFR-2004-1350, Reston, Virginia, pp. 3–22.
- Daubenmire, R., 1959. A canopy-coverage method of vegetational analysis. *Northwest Sci.* 33, 43–64.
- DeAngelis, D.L., 2012. Self-organizing processes in landscape pattern and resilience: a review. *Int. Scholar. Res. Network* 2012, 274510. <https://doi.org/10.5402/2012/274510>.
- DeLaune, R.D., Nyman, J.A., Patrick Jr., W.H., 1994. Peat collapse, ponding and wetland loss in a rapidly submerging coastal marsh. *J. Coastal Res.* 10, 1021–1030.
- Dennison, W.C., Saxby, T., Walsh, B.M. [Eds.], 2012. Responding to major storm impacts: Chesapeake Bay and the Delmarva Coastal Bays. https://dnr.maryland.gov/waters/bay/Documents/LSRWA/Responding-to-MajorStormImpacts_IAN-UMCES_2012.pdf [accessed 10 June 2022].
- DeLaune, R.D., White, J.R., 2012. Will coastal wetlands continue to sequester carbon in response to an increase in global sea level?: A case study of the rapidly subsiding Mississippi River deltaic plain. *Clim. Change* 110, 297–314.
- Desantis, L.R.G., Bhotika, S., Williams, K., Putz, F.E., 2007. Sea-level rise and drought interactions accelerate forest decline on the Gulf Coast of Florida, USA. *Global Change Biol.* 13, 2349–2360. <https://doi.org/10.1111/j.1365-2486.2007.01440.x>.
- Fincham, M.W., 2014. The storm over surges: When Sandy came to Crisfield [online]. Chesapeake Quarterly 12. Available at website <http://www.chesapeakequarterly.net/sealevel/main9/> [accessed 15 February 2021].
- Google Earth Pro. 2022. <https://earth.google.com/web/>.
- Herbert, E.R., Boon, P., Burgin, A.J., Neubauer, S.C., Franklin, R.B., Ardón, M., Hopfensperger, K.N., Lamers, L.P.M., Gell, P., 2015. A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. *Ecosphere* 6 (art206).
- Hertel, D., Leuschner, C., 2002. A comparison of four different fine root production estimates with ecosystem carbon balance data in a *Fagus-Quercus* mixed forest. *Plant Soil* 239, 237–251.
- Hoepfner, S.S., Shaffer, G.P., Perkins, T.E., 2008. Through droughts and hurricanes: tree mortality, forest structure and biomass production in a coastal swamp for restoration in the Mississippi River Deltaic Plain. *For. Ecol. Manag.* 256, 937–948. <https://doi.org/10.1016/j.foreco.2008.05.040>.
- Intergovernmental Panel on Climate Change (IPCC), 2014. Summary for Policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E.,

- et al. (Eds). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, USA, pp. 1–32.
- Jiang, J., Fuller, D.O., The, S.Y., Zhai, L., Koh, H.L., DeAngelis, D.L., da Silveira Lobo Sternberg, L., 2015. Bistability of mangrove forest and competition with freshwater plants. *Agric. Forest. Meteorol.* 213, 283–290. <https://doi.org/10.1016/j.agrformet.2014.10.004>.
- JMP SAS, 2022 Statistical Analysis System. V. 16.0.0. SAS, Cary, North Carolina.
- Kamrath, B.J.W., Burchell, M.R., Cormier, N., Krauss, K.W., Johnson, D.W., 2019. The potential resiliency of a created tidal marsh to sea level rise. *Trans. Am. Soc. Agric. Biol. Eng.* 62, 1567–1577.
- Kirwan, M.L., Gedan, K.B., 2019. Sea-level driven land conversion and the formation of ghost forests. *Nat. Clim. Change* 9, 450–457.
- Krauss, K.W., Duberstein, J.A., 2010. Sapflow and water use of freshwater wetland trees exposed to saltwater incursion in a tidally influenced South Carolina watershed. *Canadian J. For. Res.* 40 (3), 525–535. <https://doi.org/10.1139/x09-204>.
- Krauss, K.W., McKee, K.L., Lovelock, C.E., Cahoon, D.R., Saintilan, N., Reef, R., Chen, L., 2014. How mangrove forests adjust to rising sea level. *New Phytol.* 202, 19–34.
- Kroes, D.E., Hupp, C., Noe, G.B., Conner, W.H., 2007. Sediment, nutrient, and vegetation trends along the tidal, forested Pocomoke River, Maryland. In: Conner, W.H., Doyle, T.W., Krauss, K.W. (Eds.), *Ecology of tidal freshwater forested wetlands of the southeastern United States*. U.S. Geological Survey, Reston, VA, pp. 113–137.
- Leopold, L.B., Wolman, M.G., Miller, J.P., 1992. *Fluvial Processes in Geomorphology*. Dover Publications, New York, USA.
- Lund, Z.F., Pearson, R.W., Buchanan, G.A., 1970. An implanted soil mass technique study herbicide effects on root growth. *Weed Sci.* 18, 279–281.
- Lynch, J.C., Hensel, P., Cahoon, D.R., 2015. The surface elevation table and marker horizon technique. A protocol for monitoring wetland elevation dynamics. Natural Resource Report NPS/NCBN/NRR—2015/1078. U.S. Department of the Interior, National Park Service, Fort Collins, Colorado.
- McCune, B., Grace, J.B., 2002. *Analysis of Ecological Communities*. MjM Software, Gleneden Beach, Oregon, USA.
- Meyer, T., 2020. Computing planimetric areas and volume error statistics. *Land Inf. Sci.* 23–31.
- Meyer, T., 2021. Earth's shape, sea level, and the geoid. The Geographic Information Science & Technology Body of Knowledge (2nd Quarter 2021 Edition), John P. Wilson (ed.). DOI: 10.22224/gistbok/2021.2.8 (link is external).
- Middleton, B.A., 2016a. Differences in impacts of Hurricane Sandy on freshwater swamps on the Delmarva Peninsula, Mid-Atlantic Coast, USA. *Ecol. Eng.* 87, 62–70. <https://doi.org/10.1016/j.ecoleng.2015.11.035>.
- Middleton, B.A., 2016b. Effects of salinity and flooding on post-hurricane regeneration potential of coastal wetland vegetation. *Am. J. Bot.* 103, 1–16. <https://doi.org/10.3732/ajb.1600062>.
- Middleton, B.A., 2020. Trends of decomposition and soil organic matter stocks in *Taxodium distichum* swamps of the southeastern United States. *PLoS One* 15 (1), e0226998. <https://doi.org/10.1371/journal.pone.0226998>.
- Middleton, B.A. and David, J.L., 2022a. Data Release: Peat collapse and vegetation shift after storm-driven saltwater surge in a tidal freshwater swamp. U.S. Geological Survey data release, ScienceBase parent page. <https://www.sciencebase.gov/catalog/item/632b017ed34e71c6d67bc03a>.
- Middleton, B.A., David, J.L., 2022b. Data Release: Peat collapse and vegetation shift after storm-driven saltwater surge in a tidal freshwater swamps, SETs. U.S. Geological Survey data release, <https://doi.org/10.5066/P9O3U8A9>.
- Middleton, B.A., David, J.L., 2022c. Data Release: Peat collapse and vegetation shift after storm-driven saltwater surge in a tidal freshwater swamps, CTD Diver data. U.S. Geological Survey data release, <https://www.sciencebase.gov/catalog/item/634019c6d34e342aee0717e2>.
- Middleton, B.A. and David, J.L., 2022d. Data Release: Peat collapse and vegetation shift after storm-driven saltwater surge in a tidal freshwater swamp, roots. U.S. Geological Survey data release, <https://www.sciencebase.gov/catalog/item/632b017ed34e71c6d67bc03a>.
- Middleton, B.A., David, J.L., 2022e. Data Release: Peat collapse and vegetation shift after storm-driven saltwater surge in a tidal freshwater swamp, vegetation. U.S. Geological Survey data release, <https://doi.org/10.5066/P9O3U8A9>.
- Middleton, B.A., David, J.L., 2022f. Data Release: Peat collapse and vegetation shift after storm-driven saltwater surge in a tidal freshwater swamp, tree height and density. U.S. Geological Survey data release, <https://www.sciencebase.gov/catalog/item/634ec19cd34e47431c1544a8>.
- Middleton, B.A., David, J.L., 2022g. Data Release: Peat collapse and vegetation shift after storm-driven saltwater surge in a tidal freshwater swamp, *Taxodium distichum* growth. U.S. Geological Survey data. release, <https://www.sciencebase.gov/catalog/item/634ec19cd34e47431c1544a8>.
- Middleton, B.A., McKee, K.L., 2001. Degradation of mangrove tissues and implications for peat formation in Belizean island forests. *J. Ecol.* 8, 818–828.
- Middleton, B.A., Souter, N., 2016. Functional integrity of wetlands, hydrologic alteration, and freshwater availability. *Ecosyst. Health Sustainability* 2 (1), e01200. <https://doi.org/10.1002/ehs2.1200>.
- Middleton, B.A., Johnson, D., Roberts, B., 2015. Hydrologic remediation for the Deepwater Horizon Incident drove ancillary primary production increase in coastal swamps. *Ecology* 8, 838–850. <https://doi.org/10.1002/eco.1625>.
- Moffett, K.B., Gorelick, S.M., McLaren, R.G., Sudicky, E.A., 2012. Salt marsh ecohydrological zonation due to heterogeneous vegetation-groundwater-surface water interactions. *Water Resour. Res.* 48, W02516. <https://doi.org/10.1029/2011WR010874>.
- Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B., Cahoon, D.R., 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83, 2869–2877.
- National Oceanic and Atmospheric Administration (NOAA), 2022. October 29–30: Coastal storm brings major tidal flooding. NOAA; <https://www.weather.gov/phi/evreview20211029>.
- Neubauer, S.C., 2013. Ecosystem responses of a tidal freshwater marsh experiencing saltwater intrusion and altered hydrology. *Estuaries Coasts* 36, 491–507. <https://doi.org/10.1007/s12237-01109455.x>.
- Neubauer, S.C., Craft, C.B., 2007. Global change and tidal freshwater wetlands: scenario and impacts. In: Barendregt, A., Whigham, D., Baldwin, A. (Eds.), *Tidal Freshwater Wetlands*. Backhuys Publisher, Leiden, pp. 253–310.
- NOAA (National Oceanic and Atmospheric Administration), 2013. Service Assessment. Hurricane/Post-Tropical Cyclone Sandy. October 22–29, 2012. NOAA, www.nws.noaa.gov/os/assessments/pdfs/Sandy13.pdf (accessed 27.07.14).
- Oksanen, J., 2012. Multivariate analysis of ecological communities in R: Vegan tutorial, www.cc.oulu.fi/jarioksa/opetus/metodi/vegantutor.pdf.
- Piazza, B.P., La Peyre, M.K., 2009. The effect of Hurricane Katrina on nekton communities in the tidal freshwater marshes of Breton Sound, Louisiana, USA. *Estuarine Coastal Shelf Sci.* 83, 97–104.
- Powell, A.S., Jackson, L., Ardón, M., 2016. Disentangling the effects of drought, salinity, and sulfate on baldcypress growth in a coastal plain restored wetland. *Restor. Ecol.* 24, 548–557.
- R Core Team, 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.
- Saha, A.K., Saha, S., Saddle, J., Jiang, J., Ross, M.S., Price, R.M., Sternberg, L.S.L.O., Wendelberger, K.S., 2011. Sea level rise and South Florida coastal forests. *Clim. Change* 108, 81–108. <https://doi.org/10.1007/s10584-011-0082-0>.
- Scheffer, M., 2009. *Critical Transitions in Nature and Society*. Princeton University Press, Princeton, N.J.
- Sokal, R.R., Rohlf, F.J., 1981. *Biometry*. W.H. Freeman and Company, New York.
- Stahle, D.W., Burnette, D.J., Villanueva, J., Cerano, J., Fye, F.K., Griffin, R.D., Cleaveland, M.K., Stahle, D.K., Edmondson, J.R., Wolff, K.P., 2012. Tree-ring analysis of ancient baldcypress trees and subfossil wood. *Quart. Sci. Rev.* 34, 1–15. <https://doi.org/10.1016/j.quascirev.2011.11.005>.
- Sternberg, L.S.L., The, S.-Y., Ewe, S., Miralles-Wilhelm, F., DeAngelis, D.L., 2007. Competition of hardwood hammock and mangrove vegetation. *Ecosystems* 10, 648–660.
- Swarth, C.W., Delgado, P., Whigham, D.F., 2013. Vegetation dynamics in a tidal freshwater wetland: a long-term study at differing scales. *Estuaries Coasts* 35, 559–574. <https://doi.org/10.1007/s12237-012-9568.x>.
- Taillie, P.J., Moorman, C.E., Poulter, B., Ardón, M., Emanuel, R.E., 2019. Decadal-scale vegetation change driven by salinity at leading edge of rising sea level. *Ecosystems* 22, 1918–1930.
- Teh, S.Y., DeAngelis, D.L., Sternberg, L.S.L., Miralles-Wilhelm, F.R., Smith, T.J., Koh, H.-L., 2008. A simulation model for projecting changes in salinity concentrations and species dominance in the coastal margin habitats of the Everglades. *Ecol. Modell.* 213, 245–256.
- Teh, S.Y., Tutoram, M., DeAngelis, D.L., Jiang, J., Pearlstine, L., Smith III, T.J., Koh, L.L., 2015. Application of a coupled vegetation competition and groundwater simulation model to study effects of sea level rise and storm surges on coastal vegetation. *J. Mar. Sci. Eng.* 3, 1149–1177. <https://doi.org/10.3390/jmse3041149>.
- Turnbull, M., 2019. WGS-84 World Geodetic System Distance Calculator. <https://www.cqsr.org/tools/GCDistance/>.
- Ury, E., Yang, X., Wright, J.P., Bernhardt, S.E., 2021. Rapid deforestation of a coastal landscape by climate change. *Title. Ecol. Appl.* 31, e02339.
- USDA, NRCS (United States Department of Agriculture, Natural Resources Conservation Service), 2021a. Official soil series descriptions and series classification. https://soils.eries.sc.gov.usda.gov/OSD_Docs/T/TRANSQUAKING.html. Washington, D.C. USA.
- Vogt, K.A., Vogt, D.J., Bloomfield, J., 1998. Analysis of some direct and indirect methods for estimating root biomass and production of forests at an ecosystem level. *Plant Soil* 200, 71–89. <https://doi.org/10.1023/A:1004313515294>.
- Wagner, R.J., Boulger Jr, R.W., Oblinger, C.J., Smith, B.A., 2006. Guidelines and standard procedures for continuous water-quality monitors—Station operation, record computation, and data reporting: U.S. + 8 attachments; accessed February 12, 2022. Geological Survey Techniques and Methods 1–D3, 51 p. <http://pubs.water.usgs.gov/tm1d>.
- Wang, H., Krauss, K.W., Noe, G.B., Stagg, C.L., Swarzenski, C.M., Duberstein, J.A., Conner, W.H., DeAngelis, D.L., 2020. Modeling soil porewater salinity response to drought in tidal freshwater forested wetlands. *e2018JG004996 JGR Biogeosci.* 125. <https://doi.org/10.1029/2018JG004996>.
- Weston, N.B., Vile, M.A., Neubauer, S.C., Velinsky, D.J., 2011. Accelerated microbial organic matter mineralization following salt-water intrusion into tidal freshwater marsh soils. *Biogeochemistry* 102, 131–151.
- Williams, K., Ewel, K.C., Stumpf, R.P., Putz, F.E., Workman, T.W., 1999. Sea-level rise and coastal forest retreat on the west coast of Florida, USA. *Ecology* 80, 2045–2063. [https://doi.org/10.1890/0012-9658\(1999\)080\[2045:SLRACF\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1999)080[2045:SLRACF]2.0.CO;2).
- Williams, K., MacDonald, M., Sternberg, L.S.L., 2003. Interactions of storm, drought, and sea-level rise on coastal forest: a case study. *J. Coastal Res.* 19, 1116–1121. <https://www.jstor.org/stable/4299253>.
- Wilson, A.M., Moore, W.S., Joye, S.B., Anderson, J.L., Schutte, C.A., 2011. Storm-driven groundwater flow in a salt marsh. *Water Resour. Res.* 47, W02535. <https://doi.org/10.1029/2010WR009496>.
- Wilson, B.J., Servais, S., Charles, S.P., Davis, S.E., Gaiser, E.E., Kominoski, J.S., Richards, J.H., Troxler, T.G., 2018. Declines in plant productivity drive carbon loss

- from brackish coastal wetland mesocosms exposed to saltwater intrusion. *Estuaries and Coasts* 41, 2147–2158.
- Wood, P., 2019. Why all the coastal flooding in Maryland lately. Tropical storm Melissa is to blame, forecasters say. *Baltimore Sun*, October 12, 2019.
- Yang, Y.N., Sheng, Q., Zhang, L., Kang, H.Q., Liu, Y., 2015. Desalination of saline farmland drainage water through wetland plants. *Agric. Water Manage.* 156, 19–29. <https://doi.org/10.1016/j.agwat.2015.03.001>.

Further reading

- SAS Institute Inc., (2002-2012). SAS 9.3. Cary, NC: Statistical Analysis System.
- Teh, S.Y., Koh, H.L., DeAngelis, D.L., Voss, C.I., Sternberg, L.dS.L., 2019. Modeling $\delta^{18}\text{O}$ as an early indicator of regime shift arising from salinity stress in coastal vegetation. *Hydro. J.* 27, 1257–1276. <https://doi.org/10.1007/s10040-019-01930-3>.
- USDA, NRCS (United States Department of Agriculture, Natural Resources Conservation Service), 2021b. The PLANTS Database (<http://plants.usda.gov>, 1 February 2021). National Plant Data Team, Greensboro, NC 27401-4901 USA.
- Zhai, L., Jiang, J., DeAngelis, D.L., Sternberg, L.dS.L., 2016. Prediction of plant vulnerability to salinity increase in a coastal ecosystem by stable isotopic composition ($\delta^{18}\text{O}$) of plant stem water: a model study. *Ecosystems* 19, 32–49. <https://doi.org/10.1007/s10021-015-9916-3>.
- Zhai, L., Krauss, K.W., Liu, X., Duberstein, J.A., Conner, W.H.J., DeAngelis, D.L., Sternberg, L.dS.L., 2018. Growth stress response to sea level rise in species with contrasting functional traits: a case study in tidal freshwater forested wetlands. *Environ. Exp. Bot.* 155, 378–386. <https://doi.org/10.1016/j.envexpbot.2018.07.023>.