Ecological Engineering 87 (2016) 62–70

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Differences in impacts of Hurricane Sandy on freshwater swamps on the Delmarva Peninsula, Mid-Atlantic Coast, USA

Beth A. Middleton

United States Geological Survey, Wetlands and Aquatic Research Center, 700 Cajundome Boulevard, Lafayette, LA 70506, USA

ARTICLE INFO

Article history:
Received 23 May 2015
Received in revised form 21 October 2015
Accepted 18 November 2015

Keywords:
Biogeography
Freshwater wetland
Northern geographic boundary
Salinity intrusion
Structural damage
Taxodium distichum
Tidal baldcypress swamp
Ecosystem shift

ABSTRACT

Hurricane wind and saltwater surge may have different influences on the subsequent composition of forests. During Hurricane Sandy, while damaging winds were highest near landfall in New Jersey, inundation occurred along the entire eastern seaboard from Georgia to Maine. In this study, a comparison of damage from salinity intrusion vs. wind/surge was recorded in swamps of the Delmarva Peninsula along the Pocomoke (MD) and Nanticoke (DE) Rivers, south of the most intense wind damage. Hickory Point Cypress Swamp (Hickory) was closest to the Chesapeake Bay and may have been subjected to a salinity surge as evidenced by elevated salinity levels at a gage upstream of this swamp (storm salinity = 13.1 ppt at Nassawango Creek, Snow Hill, Maryland). After Hurricane Sandy, 8% of the standing trees died at Hickory including *Acer rubrum*, *Amelanchier laevis*, *Ilex* spp., and *Taxodium distichum*. In certain plots of Hickory, up to 25% of the standing trees were dead, corresponding with high soil salinity. The most important variables related to structural tree damage were soil salinity and proximity to the Atlantic coast as based on Stepwise Regression and NMDS procedures. Wind damage was mostly restricted to broken branches although tipped-up trees were found at Hickory, Whiton and Porter (species: *Liquidamabar styraciflua*, *Pinus taeda*, *Populus deltoides*, *Quercus pagoda* and *Ilex* spp.). These trees fell mostly in an east or east-southeast direction (88–107°) in keeping with the wind direction of Hurricane Sandy on the Delmarva Peninsula. Coastal restoration and management can be informed by the specific differences in hurricane damage to vegetation by salt vs. wind.

Published by Elsevier B.V.

1. Introduction

Hurricane impacts on coastal freshwater forests are related to both breakage from wind and mortality from salinity intrusion, but few studies have attempted to disentangle the relative impacts of these two disturbances. The components of disturbance by hurricanes, wind and saltwater surge have different effects on coastal freshwater systems (Gresham, 1993a) and subsequent vegetation dynamics (Middleton, 1999). While wind damage is usually emphasized in post-hurricane studies (Middleton, 2009a), saltwater surge may affect much larger areas of the coast (Conner, 1995; Stanturf et al., 2007).

Hurricane Sandy had the potential for both wind and saltwater surge with flooding from Georgia to Maine (0.5–9 m; NOAA, 2013). Other hurricanes including Isabel caused 1.5–2.0 m of flooding in Chesapeake Bay (Shen et al., 2006), and Katrina caused up to 10 m of flooding in coastal Mississippi (Fritz et al., 2007). While the force of the tidal waves from storms can cause physical damage to vegetation (Stanturf et al., 2007), even a low amount of salinity can have severe effects on freshwater vegetation (Williams, 1993; Conner, 1995; Stanturf et al., 2007; Piazza and La Peyre, 2009; Werner et al., 2013). After a salinity intrusion event associated with a hurricane in a coastal wetland, salinity levels in the surface water may stay elevated for months (Steyer et al., 2006), with freshening not occurring for as long as one year after a hurricane (Chabrek and Palmisano, 1973). The time required for the freshening of salinified wetlands depends on the amount of rainfall, and the salinity levels of the surface and groundwater (Kaplan et al., 2010), and the process can take longer if soil salinity levels have increased (Overton et al., 2006). This topic is of specific interest to managers because post-hurricane management may depend on whether a hurricane-impacted site was affected by salinity intrusion.

Salt water intrusion damages freshwater wetlands (Gresham, 1993b; Craft, 2012), by causing species composition changes, e.g., tidal fresh to saltmarsh (Crain et al., 2004), and *Salix* – to *Tamarix* – dominated forests (Salinas et al., 2000; Vandersande et al., 2001). Certain marsh species are slow to recover after salinity intrusion from hurricanes, e.g., *Panicum repens* and *Myriophyllum*

E-mail address: middletonb@usgs.gov

http://dx.doi.org/10.1016/j.ecoleng.2015.11.035
0925-8574/Published by Elsevier B.V.

spicatum (Chabrek and Palmisano, 1973). Freshwater palm forests subjected to higher salinity have smaller trees and higher dominance by saltwater tolerant species in the understory, e.g., mangrove fern (*Acrostichum aureum*; Feagin et al., 2013). In freshwater swamps, higher tree density and production occur in *Taxodium distichum* (baldcypress) freshwater nearest 0 ppt (Wicker et al., 1981; Middleton et al., 2015, respectively).

The effects of salinity on species vary depending on life history stage (Middleton, 1999). For example, elevated salinity levels affect *T. distichum* seedlings more than adults (Conner and Askew, 1992). Sensitivity of early life history stages to salinity is typical of many freshwater species (e.g., *Sabal palmetto*: Williams et al., 1999, respectively); older established individuals can survive longer by utilizing stored belowground resources (Sutter et al., 2014). Because salinity intrusion causes regeneration suppression in freshwater species, vegetation may recover slowly after storms (Barry et al., 1993; Gresham, 1993b; Conner, 1995; Allen et al., 1997; Williams et al., 1999), depending on storm frequency and intensity (Michener et al., 1997; Stanturf et al., 2007). In the absence of salinity, conspecific tree seedlings (Middleton, 2009b) or saplings may re-establish after storms (Uhl et al., 1988), depending on the nature of the post-hurricane environment with respect to flooding, chemical characteristics, shading and seed supply (Middleton, 1999, 2009b).

T. distichum (baldcypress) is an important component of southeastern swamps (Middleton, 2009a), which could have individuals that are resistant to salinity intrusion. Some studies have found higher salinity tolerance in certain populations of *T. distichum* (Allen et al., 1997). Nevertheless, recent genetic studies do not support this idea; the genetics of *T. distichum* individuals surviving and succumbing to high salinity were the same in Gulf Coastal populations of *T. distichum* (Kusumi et al., unpublished data).

Episodic disturbance due to hurricanes may become more frequent with future climate change (IPCC, 2014). At the same time, hurricane events may become a tipping point for permanent shifts in vegetation (Hayden et al., 1991), because salinity intrusion can produce long-term changes in freshwater vegetation composition (Williams, 1993; Conner, 1995; Stanturf et al., 2007; Hoeppner et al., 2008; Shields et al., 2011; Werner et al., 2013). For example, a severe 3 m saltwater surge occurred during Hurricane Hugo in Hobcaw Forest, South Carolina, even though wind damage was minimal (Gresham et al., 1991). During the two years after Hugo, 66% of the trees died including *T. distichum* (Hook et al., 1991). After Katrina and Rita, most of the mid-story trees died in Lake Maurepas, Louisiana due to flooding and high salinity (Shaffer et al., 2009). Natural regeneration may be poor after hurricanes because the post-hurricane window for freshwater tree regeneration may be limited. Pre-emption may curtail the regeneration of freshwater trees if fast-growing and salt tolerant macrophytes move into swamps after storms; three years after Hugo in Hobcaw Forest, macrophytes established (e.g., *Typha* sp., *Phragmites australis*, *Alternanthera philoxeroides*, and *Cladium jamaicense*; Conner, 1995). Beyond lingering salinity in the environment after a hurricane, the establishment of non-resident species also can slow the recovery of an ecosystem (Halpern, 1988).

The objectives of this study were to explore the nature of forested swamp damage by saltwater intrusion and/or wind and water surge from Hurricane Sandy on the Delmarva Peninsula of Maryland and Delaware. Environmental and geographical variables and their inter-relationships to any tree structural damage were also examined.

2. Materials and methods

2.1. Hurricane Sandy

Hurricane Sandy made landfall on October 29, 2012 with highest winds near Atlantic City, New Jersey, but with storm impacts

Fig. 1. (A) Location of tree damage study by Hurricane Sandy in *T. distichum* swamps of the Mid-Atlantic Coast on the Delmarva Peninsula. (B) Riverine freshwater swamps included Trussum Pond (Trussum) and Cypress Point (Cypress) along the James Branch, a tributary of the Nanticoke River (Delaware Department of Natural Resources), and Willards (Willard), Whiton's Crossing (Whiton), Porter's Crossing (Porter) and Hickory Point Cypress Swamp (Hickory; tidally affected) along the Pocomoke River (Maryland Department of Natural Resources; Google Earth, 2015). Water gage information came from near Snow Hill MD (Nassawango), and salinity information came from the Shelltown and Pocomoke City Drawbridge gages.

occurring along the Atlantic seaboard from Maine to Georgia (NOAA, 2013). Though south of the eye of the storm, the Delmarva Peninsula was impacted by heavy storm surge, intense rainfall and wind (Dennison et al., 2012), with peak wind speeds from 108 to 121 km h^{-1} (USGS, 2014; Fig. 1). Rainfall amounts during this storm were estimated at 180 mm in Salisbury, Maryland (Fig. 1A; NASA, 2013). Tidal surge inundation levels on the Delmarva Peninsula were as much as 1.2 meters (NOAA, 2012a), with storm surge and inundation at Bishop's Head of 0.9 and 0.7 m, respectively (Fig. 1A; Blake et al., 2013).

2.2. Study area

Six *T. distichum* swamps were selected for study in the Chesapeake Watershed of the Delmarva Peninsula (Fig. 1A). Four riverine swamps along the Pocomoke River, Maryland included Willards (Willard), Whiton's Crossing (Whiton), Porter's Crossing (Porter) and a tidally affected swamp, Hickory Point Cypress Swamp (Hickory; Maryland Department of Natural Resources; Fig. 1B). Two swamps were studied in Delaware including Trussum Pond and Cypress Point (Trussum and Cypress, respectively) on the James Branch, a tributary of the Nanticoke River (Delaware Department of Natural Resources). As the most tidally affected study swamp, Hickory was the nearest to the Chesapeake and about 43 km from Bishop's Head (Fig. 1B). All sites had a developed canopy with a mixture of adult *T. distichum*, *Acer rubrum*, *Liquidambar styraciflua*, *P. taeda*, and/or *Populus deltoides*.

To determine the timing of a tree fall area at Hickory, air photos were examined to observe when canopy trees fell during 2011–2013 (USDA, 2014). Storm reports relevant to observed tree damage in study plots (wind, tidal surge) were identified for the Delmarva Peninsula during the growing season prior to this hurricane (i.e., March–October, 2012; NOAA, 2012b).

2.3. Experimental design

To study forest structure and damage, one transect was established in each study swamp. Along each 125 m linear transect, five structural plots of 10 m × 10 m (0.01 ha) were designated using a randomization process within 25 m intervals in March 2013, following the methodology used in a long-term research network (North American Baldcypress Swamp Network; Middleton et al., 2015). Start points of the five plots were each marked with a small wooden post. Transects were aligned parallel to the river, except for Whiton, which had limited accessibility during flooded periods. Of the five plots along each transect, Plots #1, 3, 5 were randomly selected for sampling with some exceptions. At Hickory, Plots #1–5 were sampled; this swamp was closest to Chesapeake Bay and from the mouth of the Pocomoke River. Sampled plots were renumbered consecutively for the purposes of data entry (e.g., sampled Plots #1, 3, 5 were renumbered as Plots #1, 2, 3). At Cypress Point, only Plot #1 was sampled because after March 2013, a nearby dam had been reconstructed, which rendered portions of the structural plots too deep to access on foot.

To examine tree material damaged by salinity intrusion, wind and/or water surge, all living saplings and adult trees within structural plots were sampled to the right of the transect facing forward along consecutively numbered plots. Similarly, any dead material was categorized as "trunk" vs. "branch" in March 2013, and newly dead material including tree death was noted during seven surveys in spring, summer and fall from 2013 to 2015 (~March 24/September 2/November 14, April 1/June 25/November 23, and July 27 in 2013, 2014, and 2015, respectively). Care was taken to not sample any structural material more than one time. About 1.3 m from the ground (tree) or end of the branch, diameter at breast height (dbh) was measured using a dbh tape. Height, trunk, and branch lengths of trees, branches and shrubs were made using a Nikon Forestry Pro Laser Rangefinder or measuring tape. All woody material in each plot was categorized by trunk or branch as standing live, leaning/tipping (with obvious signs of recent soil movement or trunk cracking), down originating in the plot (i.e., rooted in plot), standing dead, or down dead originating outside of the plot (or of undetermined origin). Of these structural characteristics, salinity intrusion may have caused standing dead trees. Wind may have broken branches. Wind or possibly storm surge nearer the coast may have produced broken, leaning or tipped-up trees. Origin of tree or branch was based on visually matching the remaining parts of trees. Trunk or branch material that had fallen before vs. after the storm were distinguished based on the presence/absence of mature un-abscissed leaves (indicating felling during the growing season), level of tree deterioration, and freshness of soil disturbance in the root ball of the tipped-up tree. Trees tipped by the hurricane had bare soil surrounding the roots, which suggested that trees had tipped late in growing season and in the timeframe of Hurricane Sandy, because this freshly exposed soil had no newly germinated seedlings (Middleton, 2009a). Some of tipped trees were not completely dead and still had greenish leaves. Trees and branches snapped by the hurricane had freshly exposed wood. Direction of tree fall was measured with a compass.

As another estimate of structural tree damage, percent canopy coverage was estimated using photos of the tree canopy taken with a digital camera fitted with a fisheye lens (Nikon FC-E9 Fisheye, Nikon Coolpix 8700) near the start point of the 10 m × 10 m plot during the leaf-off period in either March 2013 or 2014. Gap Light Analyzer version 2.0 software (Frazer et al., 1999) was used to estimate the percent canopy cover from the digital photo.

To determine the timing of canopy tree fall at Hickory, air photos were examined during 2011–2013 (USDA, 2014). Storm reports relevant to observed tree damage in study plots (wind, tidal surge) were identified for the Delmarva Peninsula during the growing season prior to this hurricane (i.e., March–October, 2012; NOAA, 2012b).

2.4. Environmental and geographical variables

While the environmental and geographical variables could have inter-related effects on tree structural characteristics with respect to hurricane damage, the effects of each variable might be more related to either salinity intrusion or wind/surge damage. As an explanation for the set of variables selected for examination in the study, the role of salinity intrusion was explored by examining patterns of structural tree damage to environmental variables including soil salinity, pore water salinity, and water depth as well as geographical variables including distance to the mouth of a river. Similarly, wind damage was likely more related to peak wind gusts and maximum sustained wind during Hurricane Sandy, and distance to the Atlantic Coast. These variables have certain inherent inter-relationships. For example, along a riverine gradient, distance of swamp to the mouth of a river would likely be related to soil and/or pore water salinity level in the swamps.

Various environmental variables were explored with respect to Hurricane Sandy effects on structural tree damage including levels of water depth, and pore water and soil salinity at sites. To estimate water level patterns at Hickory during Hurricane Sandy (i.e., to detect a storm surge), nearly continuous water level data were obtained for the Nassawango Creek gage from January 1, 2011 through June 22, 2014 (USGS 01485500; via Wendy McPherson, U.S. Geological Survey, Maryland – Delaware – District of Columbia Water Science Center, Baltimore, MD 21228). This gage is 29.4 river km upstream of Hickory along a tributary of the Pocomoke River near Snow Hill, MD (Fig. 1). Mean maximum water levels for Hickory during Hurricane Sandy (October 29–30, 2012) were roughly interpolated by comparing water depth and elevation at the Nassawango Creek gage vs. Hickory plots. On March 30, 2015 (3:00 pm), relative elevations were estimated at Hickory plots using a Trimble DiNi Digital Level. These rough elevations were based on water and elevation comparisons on this day. Subsequently, these derived elevations were used to estimate water levels at Hickory during Hurricane Sandy (October 29–30, 2012) based on the elevation of the water surge recorded at the Nassawango gage. Water depths at all sites and plots were measured with a meter stick on each day of visit.

To measure pore water salinity, water was extracted with a pore water sipper device from a depth of 5 cm within 1 m of each of the five plots during survey visits in 2013–2015. Extracted water was transported in a portable freezer to the lab, and salinity measured with a YSI EC 300® probe. To detect a salinity intrusion event during Hurricane Sandy, salinity data for 2012 was downloaded from the Pocomoke City Drawbridge and Shelltown stations (MDNR, 2012; http://mddnr.chesapeakebay.net/eyesonthebay/index.cfm#map). Mean, maximum and minimum salinity levels were compared during Hurricane Sandy (October 29–30, 2012) vs. non-hurricane days using all available 2012 data from the Pocomoke City and Shelltown recorders (April 24–November 13, 2012; $n = 204$ and 216, respectively; Fig. 1).

Soil salinity was measured by collecting soil with a shovel from the top 5 cm of the soil surface on June 25, 2014. Soil samples from Hickory were taken within 1 m of each of the five permanent plots, and put into separate Ziploc® bags (5 samples). Soil samples from all other sites were taken within 1 m of Plot 1 and put into a separate Ziploc® bags (1 sample per site). All soil samples were stored in a portable cooler and transported to a walk-in cooler at 4 °C at the Wetlands and Aquatic Research Center, Lafayette, Louisiana until analysis (March 2015).

To determine soil salinity, a slurry was prepared using 5 g of dried and crushed soil with 25 ml of distilled water. The slurry was shaken for 3 min and then electrical conductivity of the solution was measured with a YSI EC 300® probe. Salinity level was determined by applying a conversion factor to the EC value, which for these freshwater soil types was 640 (i.e., EC/640; Gibbs, 2000).

To determine if geographical position on the Delmarva Peninsula was related to structural tree damage, distances in kilometers were determined from each study site to the Atlantic Coast and to river mouth (i.e., the distance from the entry of either the Pocomoke or Nanticoke River in the Chesapeake Bay in river kilometers; Maryland vs. Delaware sites, respectively) using a distance measurement tool (Google Earth, 2015). Peak wind gusts and maximum sustained wind during Hurricane Sandy were determined using wind data from the measurement station nearest the site as reported in the Hazards Data Distribution System (HDDS) Explorer (USGS, 2014).

2.5. *Data analyses*

Structural material was assessed as the unique live or dead material sampled during any of the seven field surveys in 2013–2015, i.e., no material was recorded more than one time. Total volume of live standing material included the sum of all live trees and shrubs rooted in each plot. Total dead material included the sums of leaning/tipping trees, trees/shrubs down, standing dead, and branches down in each plot. Volume was calculated for each tree or branch using the formula for the volume of a cone: $V = \pi r^2 x(h/3)$ where V = volume, $r = (dbh/2)$ and h = height or length (m; Spies et al., 1988). This method underestimates tree volume, but for woody debris and trees damaged by storms, a cone gives as uniform approximation of the shape of the material (Spies et al., 1988). Total volume of live and downed wood was summed by species within a plot, and also the total of all species per plot was expressed on a per hectare basis.

Structural tree variables were first expressed as total volumes per species for each plot sampled at each site (i.e., 1–5 samples per site), and then percentages of the total alive + dead material in each structural variable category including total % volumes of leaning, dead standing, downed branches, downed trees, total dead material, and live trees. All of the dead material was likely from wind/surge damage, except for the standing dead trees, which were recently killed, and most likely by salinity intrusion during the storm. Another structural tree variable, percent canopy coverage was assessed as a mean per site. Environmental variables including pore water salinity and water depth were assessed for each plot in each site as the maximum value during seven field visits (∼March 24/September 2/November 14, April 1/June 25/November 23, and July 27 in 2013, 2014, and 2015). Geographical and wind variables were assessed on a per site basis including distance to the mouth of the river and the Atlantic coast as well as peak wind gusts and maximum sustained wind during Hurricane Sandy (October 29–30, 2012).

Using Stepwise Regression (forward and backward), environmental/geographical variables were selected for further examination using a p-value threshold of 0.15 using the PROC GLMSELECT Procedure in SAS 9.3 (2002–2012). Species dominance was defined as species that were present in more than one study swamp, and with a total live/dead volume $>13\ \text{m}^3$ per hectare (*A. rubrum*, *L. styraciflua*, *T. distichum*); other species were grouped in a “not dominant” group. In the final regression, significant variables were those with $|t| > 1.96$ or $p < 0.05$. Using the variables selected by this Stepwise Regression procedure, linear and second order polynomial regression analyses were used to test the relationship of tree structural variables (% volumes of leaning, dead standing, downed branches, downed trees, total dead material, and live trees). Several variables did not meet the selection criteria and were eliminated from further consideration including dominant species, % canopy coverage, wind variables (peak wind gust and maximum sustained wind during Hurricane Sandy), and maximum water depth on day-of-site visit) (Table 1).

Non-metric Multidimensional Scaling (NMDS) was used to explore the relationship of structural tree variables to the environmental/geographical variables that met the selection criteria using the Vegan Package in R (Oksanen, 2012; R Foundation, 2012). This analysis approach was selected because of the inter-correlated nature of the variables. Multivariate analysis was performed using two-dimensional NMDS with Euclidean dissimilarity matrices (selected environmental/geographical variables: distance to the Atlantic coast and river mouth, and soil and maximum pore water salinity). A starting number was selected (9084), which produced the lowest stress value out of 50 runs (stress = 0.04097368). Data were centered and scaled, and the analysis was performed using R (Oksanen, 2012; R Foundation, 2012). As an additional test, linear regressions were used to compare to compare pore water salinity at plots with either % dead tree material or the swamp distance to the mouth of the river using JMP SAS (2012).

3. Results

3.1. *General patterns of environmental/geographical variables on Delmarva Peninsula*

Salinity patterns along the river gradient from Chesapeake Bay – To assess the potential of salinity intrusion during Hurricane Sandy that could have affected structural tree damage patterns along the Pocomoke River, salinity levels upstream and downstream of Hickory were examined. Hickory is the closest study swamp to the Chesapeake Bay (Hickory vs. other swamps: 12 km vs. 52–80 km, respectively; Appendix 1) and the only study swamp

Table 1
Stepwise regression variable selection for structural and environmental variables including the percentage of damaged tree volume vs. total tree volume (live + dead) including branch, dead standing, trunk down, dead total (branch + dead standing + trunk down), leaning and live tree volume. Linear and second order polynomial regression were used to test these structural variables with geographical position of the sites (distance to the Atlantic Coast and the mouth of the river), storm wind characteristics (peak wind gust and maximum sustained wind), environment (soil salinity, maximum water depth 2013–2014, maximum pore water salinity), dominant species, and site. Not applicable (NA) indicates that the stepwise regression did not identify any significant dependent variables and these were removed from further consideration (i.e., structural variables: percentage of leaning and live trees; storm wind characteristics: peak wind gust and maximum sustained wind; environment: maximum water depth).

Dependent variable	Variable	Regression coefficient	F ratio	p
Branch	Model	0.14	11.3	
	Distance Atlantic Coast^2			<0.05
Dead standing	Model	0.02	5.9	
	Soil salinity			<0.05
	Soil salinity^2			<0.05
	Distance mouth river			<0.05
	Distance mouth river^2			<0.05
	Pore water salinity			<0.05
Trunk down	Model	0.15	8.2	<
	Pore water salinity			<0.05
	Distance mouth river			<0.05
	Distance mouth river^2			<0.05
Dead total	Model	0.09	7.1	
	Soil salinity			<0.05
	Soil salinity^2			<0.05
	Distance Atlantic Coast			<0.05

between the Shelltown and Nassawango Creek gages (10.8 and 29.4 river km upstream and downstream of Hickory, respectively). Other Pocomoke River study swamps were upstream of the Nassawango gage. Nanticoke River study swamps were not serviced by appropriate gages. During Hurricane Sandy, salinity levels at these gages recorded elevated salinity (Pocomoke City vs. Shelltown: maximum salinity = 13.1 and 18.6 ppt, respectively; October 29–30, 2012; Table 2), but dropped to pre-hurricane levels by November 2, 2015 (0.08 ppt).

During Hurricane Sandy, water levels along the Nassawango Creek tributary upstream of Hickory were elevated (Fig. 2). Based on comparisons of water depths at the Nassawango Creek gage and elevations at Hickory, the surge was approximately 0.41–0.67 m in the plots during Hurricane Sandy (Fig. 2). Mean water depths on day-of-visit varied from 0.0 to 0.08 m (Appendix 1).

Water was fresh in these swamps (<0.1) except that Hickory had higher pore water salinity on days of visits than other sites (mean pore water salinity: 0.9 ± 0.2 vs. <0.1 ± <0.1, respectively; Appendix 1). Pore water salinity at Hickory was higher in 2013 than 2014 (1.03 vs. 0.44 ppt, respectively; Appendix 1), dropping by a mean of 0.5 ± <0.1 ppt from 2013 to 2014. Soil salinity levels in 2014 were higher at Hickory than in other swamps (mean soil salinity = 1.8 ± 0.7 vs. 0.3–0.8 ppt; Appendix 1), and a part of the Hickory site had higher levels of soil salinity than other parts (Plots 2 and 3: 2.7 and 3.5 ppt, respectively).

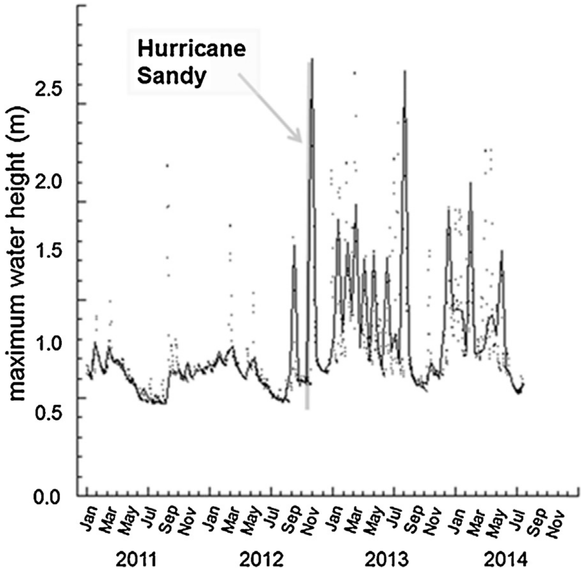

Fig. 2. (A) Mean maximum water levels at the Nassawango Creek gage (#01485500; 38°13′44.1″ N and 75°28′7.2″ W) during Hurricane Sandy (October 29–30, 2012) drawn using a regression with a smoothing spline fit. This gage is located on a tributary of the Pocomoke River in Worcester County near Snow Hill, MD and 29.4 river km upstream of Hickory. Gage data are via Wendy McPherson, U.S. Geological Survey, Maryland-Delaware-District of Columbia Water Science Center, Baltimore, Maryland 21228; http://md.water.usgs.gov. Surge depth was approximately 0.41–0.67 m at the Hickory plots during Hurricane Sandy.

Wind and geographical position during Hurricane Sandy – In these Delmarva swamps, peak gust winds ranged from 108 to 121 km per hour (Appendix 1) and sustained winds ranged from 83 to 94 km per hour during Hurricane Sandy (USGS, 2014). Distances from study swamps to the Atlantic Coast were 20–41 km (Appendix 1).

3.2. Structural tree characteristics and damage

Swamp tree composition on the Delmarva Peninsula – Overall, standing live trees had a mean volume of $315.7 \pm 61.4\ \mathrm{m^3\ ha^{-1}}$ (Appendix 1); sites did not differ and the variable was not selected as an important related to the pattern of structural tree characteristics in the Delmarva study swamps ($r^2 = 0.17$, $p = 0.20$). Similarly, the dominant species (*A. rubrum*, *L. styraciflua* and *T. distichum*) were not important variables contributing to the overall variation in structural tree characteristics within and among sites, i.e., the structural characteristics of each dominant species was not different than that of the “other” species ($r^2 = 0.34$, $p = 0.81$). Also, the percent (%) canopy cover after Hurricane Sandy was similar across swamps (mean % cover = 62.4 ± 1.6%; Appendix 1), so that this variable was not selected as an important variable by the Stepwise Regression procedure ($r^2 = 0.06$, $p = 0.25$).

Structural tree damage and salinity intrusion – Hickory had a higher percentage of recently dead standing trees than other sites (7.9 ± 4.6% vs. 3.3 ± 1.9%, respectively). Recently dead standing

Table 2
Salinity levels at continuous monitoring stations in the Pocomoke River during a Hurricane Sandy-related saltwater intrusion event (October 29–30, 2012) vs. non-hurricane periods before and after Hurricane Sandy. All available data from 2012 were used from both the Pocomoke City Drawbridge and Shelltown recorders ($n = 204$ and 216, respectively). These monitoring stations were upstream and downstream, respectively of the Hickory nearest Rehobeth, MD. Salinity data are from the Maryland Department of Natural Resources (2012).

Station	Distance from Hickory km	Latitude	Longitude	Hurricane salinity			Non-hurricane salinity		
				Max	Min	Mean	Max	Min	Mean
Pocomoke City	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

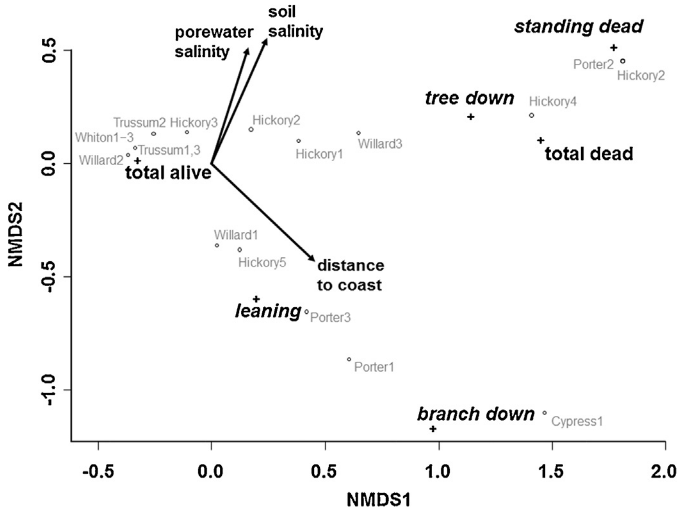

Fig. 3. NMDS graph of the structural components of tree damage across the Delmarva Peninsula along the Pocomoke and Nanticoke Rivers, Maryland and Delaware, respectively. Components included percentage of percentage of tree volume leaning, branch, dead standing, trunk down, dead total (branch + dead standing + trunk down), and live. Tree components were tested against significant variables identified in the Stepwise Regression (Table 1) including geographical position of the sites (distance Atlantic Coast, distance river mouth), environment (soil and pore water salinity). Site name abbreviation is followed by plot number (see Fig. 1 for key to abbreviations).

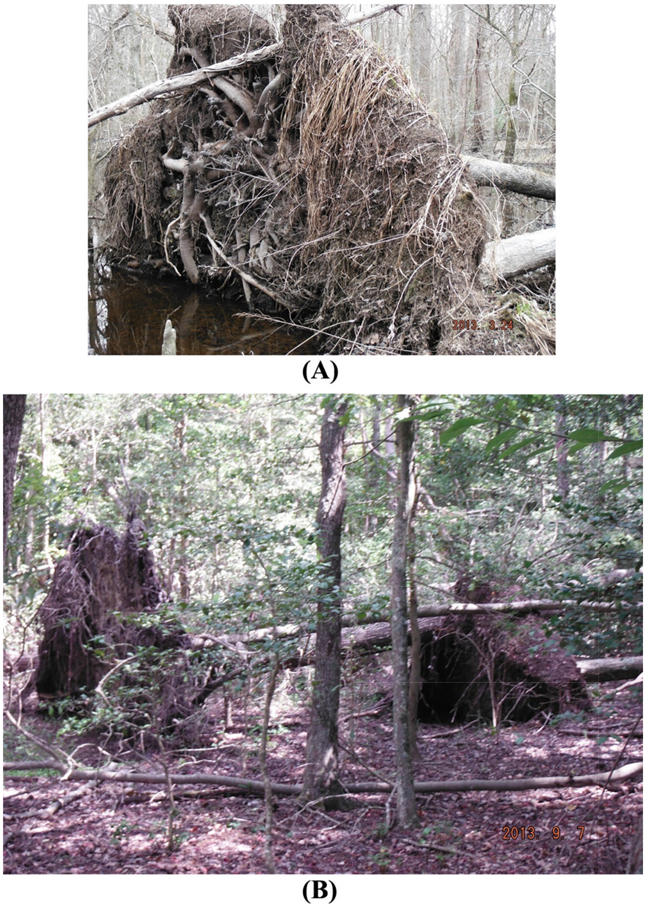

Fig. 4. (A) Tipped up tree along the Pocomoke River after Hurricane Sandy. (B) Windfall directions of downed trees after Hurricane Sandy were predominantly in an east to southeastward direction (88° to 107°) on the Delmarva Peninsula. Pictured are downed trees at Hickory Point Cypress Swamp near Pocomoke City, Maryland. Photos by Evelyn Anemaet, U.S. Geological Survey.

trees at Hickory were freshwater species including *A. rubrum*, *Amelanchier laevis*, *Ilex* spp., and *T. distichum* (volume dead standing trees = 0.4, 0.3, 0.3 and 33.0 m^3 ha^{-1}, respectively). Also at Hickory, percentage of standing dead trees was higher in plots with higher soil salinity levels (Plots 2 and 3: 25.0 and 11.1%, respectively). Soil salinity but not pore water salinity was related to structural tree characteristics (NMDS: $r^2 = 0.14$ and 0.11, respectively; $p = 0.05$ and 0.07, respectively) and soil salinity was positively related to both NMDS1 and NMDS2 (0.678 and 0.915, respectively; Fig. 3). Soil salinity levels in 2014 were higher at Hickory than at other sites (Appendix 1). Also, distance of the site to the river mouth into the Chesapeake was related to the pore water salinity level of these swamps ($R^2 = 0.72$, $p < 0.0001$), although neither of these variables were significant in the NMDS ($r^2 = 0.11$ and 0.11, respectively, $p = 0.11$ and 0.08, respectively).

Structural tree damage and wind/storm surge – Overall total structural tree damage was related to distance to the Atlantic Coast (NMDS1 and NMDS2; 0.725 and −0.689, respectively; $r^2 = 0.15$, $p < 0.05$; Fig. 3). Hickory, Willard and Porter had a number of downed branches; these sites lie along the "distance to Atlantic coast" vector line, increasing toward the center right of the ordination graph (Fig. 3). Wind and other geographical variables were not related to the NMDS model ($p > 0.11$). Total dead volumes of all structural types were higher at Hickory than in other swamps (total dead volume = 118.7 ± 81.7 vs. 9.1 ± 5.1 m^3 ha^{-1}; $t = 9.0$, respectively; $p < 0.00011$; Appendix 1). Hickory was the swamp closest to Chesapeake Bay, and had higher percent dead woody volume than elsewhere (mean percent % dead volume = 29.5 ± 18.7% vs. 1.8 ± 1.0%; Appendix 1). Swamps farther upriver from the Chesapeake (Cypress, Trussum, Willard, Whiton, Porter) had negligible structural tree damage (mean % dead volume: 2, <1, <1, 2.4 and 1.2%; Appendix 1). While the distance from the Chesapeake Bay and % dead volume were related in a linear regression ($r^2 = 0.81$, $p = 0.01$), Stepwise Regression did not identify the geographical variable as having explanatory value in the patterns of structural tree characteristics (NMDS model: $r^2 = 0.11$, $p = 0.11$).

At Hickory, *P. taeda*, *Quercus pagoda* and *Ilex* spp. trees tipped-up ($p < 0.02$; Fig. 1A and B) in an east or east-southeast direction (88–107°). Downed trees were sampled throughout Hickory, with a notable number of fallen trees on the northern end of the study site. Inspection of air photos (USDA, 2014) indicated that these canopy trees fell between 2011 and 2013 (USDA, 2014). In the other Delmarva swamps, large *P. deltoides* trees fell at Whiton in a southerly direction (180°). We observed fallen trees of *L. styraciflua* at Porters near the river channel, but no downed trees were sampled in this study. Overall, only a relatively small number of tipped trees were found at Whiton, Porter, and Willard (*P. deltoides* and *L. styraciflua*; Appendix 1) and there was minimal tree damage at Trussum and Cypress in Delaware (Appendix 1). Tree species with downed branches included *A. rubrum* and *L. styraciflua* (mean total volume = 0.02 and 1.96 m^3 ha^{-1}) (Fig. 4).

4. Discussion

4.1. Salinity impact of tidal surge

While wind impact is usually the focus of post-hurricane studies, salinity-intrusion can be even more important in driving coastal vegetation change (Conner, 1995). During Hurricane Sandy, tidal freshwater swamps closest to Chesapeake Bay were likely inundated with saline water. Salinity levels were elevated at gages along the Pocomoke River both up and downstream of Hickory near Pocomoke City, Maryland (salinity = 13.1 and 18.6, respectively; this study). After Hurricane Sandy, Hickory had dead standing tree volumes (up to 25%; this study) especially where local soil salinity levels were high (maximum soil salinity in 2014 = 3.5 ppt; this study). In Louisiana where saltwater intrusion events can be frequent and severe, freshwater tree mortality in swamps has reached up to 85% in soil salinities of 2–5 psu (~2–5 ppt; Hoeppner et al., 2008). Co-occurrence of soil salinity and death of standing trees at Hickory suggest that salinity intrusion occurred in that swamp during Hurricane Sandy.

The fate of salinity after a salinity intrusion event in freshwater swamps is not clear. In some cases, salinity may be high even 2.5 years after a storm intrusion event if soil chloride concentrations remain high (Gresham, 1993a). If salinity enters rooting zones in subsurface aquifers, long-term tree damage can occur (Werner et al., 2013), but it is unlikely that such a severe impact of saltwater intrusion occurred on the Delmarva Peninsula. There were such high amounts of rain during Hurricane Sandy, that salinity levels in Chesapeake waters were generally lower after Hurricane Sandy (Dennison et al., 2012), and at least pore water salinity levels at Hickory seemed fairly normal by 2014 (this study).

At Hickory some individuals of species intolerant of salinity were killed e.g., *A. rubrum*, *A. laevis*, *Ilex* spp., and *T. distichum*. While freshwater tree species are all susceptible to salt damage, the order of tree susceptibility of species (found in this study) from most to least susceptible: *A. rubrum*, *Magnolia virginiana*, *Q. pagoda*, *L. styraciflua*, *T. distichum*, and *P. taeda* (Barry et al., 1993). Standing dead trees were found of *A. rubrum*, *L. stryaciflua* and *T. distichum*. By August 2015, at least a few seedlings of *T. distichum* were observed at Hickory, indicating that freshening of the swamp may have been occurring (Middleton, personal observation).

4.2. Wind impacts to freshwater forests

In contrast, wind or tidal surge damage without salinity intrusion might have a very different vegetation trajectory than swamps damaged by salinity intrusion. Overall on the Delmarva Peninsula, there was relatively little tree breakage from the winds of Hurricane Sandy as compared to some other hurricanes. Tree breakage is roughly related to wind speed during hurricanes, but blowdown damage also depends on the amount of rainfall, because wet soils are less able to support tree roots (Valiela et al., 1996; Stanturf et al., 2007). Flood debris and water marks at Hickory were found intermingled with blowdown damage (personal observation), so that observed tip-ups may have been caused by a combination of soggy soil and wind. In this study, there was no relationship of peak wind speed tree structural damage e.g., downed branches, tip-ups and leaning trees. Nevertheless, there was a relationship of structural damage with proximity to the Atlantic Coast. The relationship of that geographical variable to structural tree damage is not clear and does not appear to be related to damage by either wind or salinity intrusion.

While wind damage from Hurricane Sandy was minimal, it is important to note that various tree species had little wind damage from Hurricane Sandy, which has also been the case in previous hurricanes (Gresham et al., 1991; Chapman et al., 2008; Middleton, 2009a; Conner et al., 2014). With respect to wind breakage, species in decreasing order of susceptibility include *A. rubrum*, *P. taeda*, *Q. pagoda*, *Magnolia virginiana*, *L. styraciflua*, and *T. distichum* (Barry et al., 1993). In order of decreasing order of susceptibility to uprooting species include *A. rubrum*, *P. taeda*, *Q. pagoda*, *L. styraciflua*, and *T. distichum* (Barry et al., 1993); bottomland forest species with shallower roots are most susceptible to blowdown (Hook et al., 1991). After Katrina where wind predominated along the Pearl River (MS), *T. distichum* was little damaged despite heavy damage to other freshwater tree species (Middleton, 2009a; Ramsey et al., 2009). After Hugo, *L. styraciflua* and *P. taeda* were more damaged than *T. distichum* in Hobcow Forest in South Carolina (Gresham et al., 1991). After Andrew in Louisiana, both *T. distichum* and *Nyssa aquatica* were less damaged than *L. styraciflua*, *A. rubrum*, *Celtis laevigata*, *Fraxinus pennsylvanica* and *Quercus* spp. (Conner et al., 2014) although both *T. distichum* and *N. aquatica* were very damaged in the Atchafalaya where wind-fields were especially high (Ramsey et al., 2001). Because of the selective removal of species, repeated hurricane disturbance can influence the trajectory of vegetation change in coastal forests (Greenberg and McNab, 1998; Middleton, 2009a). While wind damage to *T. distichum* during severe hurricanes usually is negligible (Middleton, 2009a), this study suggests that repeated salinity intrusion events could damage this species and shift species composition in these northern *T. distichum* swamps over time.

Interestingly at Hickory, fallen trees of certain shallow-rooted species (not *T. distichum*) were observed, which were likely toppled by Hurricane Sandy (east-southeast direction; 88–107°). These trees fell between 2011 and 2013 as based on the examination of available air photos (USDA, 2014). On the lower Delmarva Peninsula, the counterclockwise spin of hurricane winds on the left side of Sandy also were toward the east-southeast (NOAA, 2012c); trees tend to fall in the direction of the strongest wind in storms (Foster, 1988). The only other recent windstorm to affect the area occurred in June 2012, but the reports of tree damage were less extensive (Ohio Valley/Mid-Atlantic Derecho; NOAA, 2012b,d). The strongest winds of this derecho were in a north to northwest direction on the Delmarva Peninsula (NOAA, 2012d). In addition, debris deposited by flood water was common and was interspersed with toppled trees throughout Hickory. Therefore, it is likely that winds combined with wet soil and/or tidal surge uprooted these trees at Hickory during Sandy.

5. Conclusions and future implications

Disentangling the drivers of hurricane damage to coastal freshwater forests, namely wind, storm surge and salinity intrusion can give us better insights into potential approaches for remediation following hurricanes. For example, the success of revegetation after salinity intrusion may depend on our ability to remediate the site with freshwater, or to identify appropriate tree species to plant in post-hurricane salinity environments. As salinity intrusion increases as sea levels rise in coastal wetlands along the Chesapeake Bay (Najjar et al., 2010) and hurricane intensity increases (Michener et al., 1997), such insights into remediation for post-hurricane damage may be very useful to design future management strategies.

Post-storm ecosystem function is likely to differ if the forest has been disturbed by salinity intrusion vs. wind/surge damage. For example, coarse woody debris and related nutrient input may increase suddenly after windstorms (Spies et al., 1988). However, the production in *T. distichum* forests declines in higher levels of salinity (Shaffer et al., 2009; Kaplan et al., 2010), so that lower rates of woody debris input could occur after salinity intrusion. On the other hand, woody debris storage could be protracted after a salinity intrusion event because the rate of decomposition is slower in saline environments (Mendelssohn et al., 1999). Vegetation may change after hurricanes, and alter the quality of wetlands as animal habitat. Water flow is slowed according to the frictional characteristics of vegetation, so that changes in plant composition could alter the relative protection of the coast from tidal surge (Loder et al., 2009). Therefore, studies contrasting the storm effects of salinity intrusion vs. wind/surge may help in identifying potential changes in post-hurricane function as well as remediation approaches to regain the desired vegetation and function of these coastal wetlands.

Acknowledgements

For logistical support, we thank Mike Schofield and William Koth of the Maryland and Delaware Department of Natural Resources, respectively. This study was funded by the U.S. Geological Survey, GS2-5A, “Evaluating ecosystem resilience: assessing wetland ecosystem functions and processes in response to Hurricane Sandy impacts. Task 1. Hurricane Sandy Mitigation, Round 2.” Thanks to Darren Johnson (Wetlands and Aquatic Research Center) for statistical advice, Elijah Ramsey, and anonymous reviewers for comments on earlier versions of the manuscript. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix 1.

Percent damage based on the volume of dominant woody species at five sites on the Delmarva Peninsula including Hickory, Porter, Whiton and Willard on the Pocomoke (MD) and Trussum Pond (Trussum) on the Nanticoke River (DE) watershed using mean maximum salinity in 2013–2014 as a covariate. Soil salinity was measured from soil collected in June 2014. Dominant species had volumes >2 m^3 ha^{-1}. Mean total tree/shrub volume m^3 100 m^{-2} (0.01 ha) ± S.E. are given for woody structural classes including standing live, leaning/tipping (considered live volume), down tree/shrub originating in the plot, down branch, down originating from outside of plot (including branches of undetermined origin), total volume in plot (originating from inside the plot), and total live and dead volume (originating from inside the plot). Distances are given in kilometers from each study site to the Atlantic Coast and from the Chesapeake Bay entry of either the Pocomoke or Nanticoke River (in river kilometers; Maryland vs. Delaware sites, respectively). Means from a single sample plot are given for Cypress Point (Cypress) on the Nanticoke River (DE). Values for salinity are given in ppt.Hickory PocomokePorter Pocomoke-Whiton PocomokeWillard PocomokeCypress NanticokeTrussum Nanticoke**(a) Structural wood variable**[0,1-7]Live leaning tree Volume (m^3)14.4 ± 14.40.5 ± 0.50.0 ± 0.00.0 ± 0.00.00.0 ± 0.0[0,1-7]Dead down trees/shrub Volume (m^3)84.6 ± 83.50.0 ± 0.016.0 ± 16.00.0 ± 0.00.00.0 ± 0.0[0,1-7]Dead standing tree Volume (m^3)34.0 ± 33.67.2 ± 7.21.8 ± 1.80.0 ± 0.00.0<0.1 ± <0.1[0,1-7]Dead Branch down Volume (m^3)0.0 ± 0.011.1 ± 10.30.1 ± 0.10.1 ± 0.15.10.0 ± 0.0Total dead volume in plot (m^3)118.6 ± 81.718.3 ± 8.917.9 ± 17.90.1 ± 0.15.1<0.1 ± <0.1Total live + dead volume in plot (m^3)374.7 ± 56.0603.8 ± 203.7509.2 ± 83.6111.5 ± 51.1249.3167.9 ± 107.9Percent (%) dead volume29.5 ± 18.74.4 ± 2.72.7 ± 2.7<0.1 ± <0.12.0<0.1 ± 0.1[0,1-7]**(b) Environmental variable**Canopy cover (%)81.8 ± <0.188.4 ± <0.187.1 ± 0.296.0 ± 0.286.1 ± <0.190.9 ± 0.3Water depth (mean max; cm)0.8 ± 0.34.7 ± 2.98.3 ± 3.30.0 ± 0.00.0 ± 0.00.0 ± 0.0Pore water salinity (mean max ppt)0.9 ± 0.2<0.1 ± <0.1<0.1 ± <0.1<0.1 ± <0.1<0.1<0.1 ± <0.1Soil salinity (ppt)1.8 ± 0.7[a]0.80.30.30.50.5Gust wind speed (km per hr)113113108117122121Sustained wind speed (km per hr)888885929595[0,1-7]**(c) Geographical variable**Distance to Atlantic Coast (km)262022233641Distance to river mouth (km)125564805256[a] Soil salinity levels were higher in Plots 2 and 3 in 2014 (2.7 and 3.5 ppt, respectively).

References

Allen, J.A., Chambers, J.J., Pezeshki, S.R., 1997. Effects of salinity on baldcypress seedlings: physiological responses and their relation to salinity tolerance. Wetlands 17, 310–320.

Barry, P.J., Doggett, C., Anderson, R.L., Swain, K.M., 1993. How to evaluate and manage storm-damaged forest areas. Management Bulletin R8-MB-63, vol. 8. U.S. Dept. Agric. Forest Service Region, Atlanta, GA.

Blake, E.S., Kimberlain, T.B., Berg, R.J., Cangialosi, J.P., Beven I.I., J.L., 2013. Tropical cyclone report. In: Hurricane Sandy. NOAA, National Hurricane Center, www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf, 2013 (accessed 27.07.14).

Chabrek, R.H., Palmisano, A.W., 1973. The effects of Hurricane Camille on the marshes of the Mississippi River Delta. Ecology 54, 1118–1123.

Chapman, E.L., Chambers, J.Q., Ribbeck, K.F., Baker, D.B., Tobler, M.A., Zen, H., White, D.A., 2008. Hurricane Katrina impacts on forest trees of Louisiana's Pearl River basin. For. Ecol. Manage 256, 883–889.

Conner, W.H., 1995. Woody plant regeneration in three South Carolina *Taxodium/Nyssa* stands following Hurricane Hugo. Ecol. Eng. 4, 277–287.

Conner, W.H., Askew, G.R., 1992. Response of baldcypress and loblolly pine seedlings to short-term saltwater flooding. Wetlands 12, 230–233.

Conner, W.H., Duberstein, J.A., Day Jr., J.W., Hutchinson, S., 2014. Impacts of changing hydrology and hurricane on forest structure and growth along a flooding/elevation gradient in a South Louisiana forested wetland from 1986 to 2009. Wetlands 34, 803–814.

Craft, C.B., 2012. Tidal freshwater forest accretion does not keep pace with sea level rise. Global Change Biol. 18, 3615–3623.

Crain, C.M., Silliman, B.R., Bertness, S.L., Bertness, M.D., 2004. Physical and biotic drivers of plant distribution across estuarine salinity gradients. Ecology 85, 2539–2549.

Dennison, W.C., Saxby, T., Walsh, B.M. (Eds.), 2012. Responding to Major Storm Impacts: Chesapeake Bay and the Delmarva Coastal Bays. , www.mdcoastalbays.org/files/pdfs_pdf/Hurricane SandyAssessment-Final-1.pdf (accessed 27.07.14).

Feagin, R.A., Toledo-Rodriguez, F., Colón-Rivera, R.J., Smeins, F., Lopez, R., 2013. Species composition and differences in diversity among the *Pterocarpus officinalis* forested wetlands of Puerto Rico. Caribb. Nat. 1, 1–25.

Foster, D.R., 1988. Species and stand response to catastrophic wind in central New England, U.S.A. J. Ecol. 76, 135–151.

Frazer, G.W., Canham, C.D., Lertzman, K.P., 1999. Gap Light Analyzer (GLS), Version 2.0: Imaging Software to Extract Canopy Structure and Gap Light Transmission Indices from True-Colour Fisheye Photographs, User Manual and Program Documentation. Simon Fraser University, Burnaby, Canada.

Fritz, H.M., Blount, C., Sokoloski, R., Singleton, J., Fuggle, A., McAdoo, B.G., Moore, A., Grass, C., Tate, B., 2007. Hurricane Katrina storm surge distribution and field observation on the Mississippi Barrier Islands. Estuar. Coast. Shelf Sci. 74, 12–20.

Gibbs, S., 2000. How to texture soils and test for salinity. Salinity Notes 8: October 2000, Salt Action, New South Wales Agriculture, Government of Australia, vol. 1., pp. 325–444 www.dpi.nsw.gov.au/__data/assets/pdf_file/0008/168866/texture-salinity.pdf.

Google Earth, 2015. U.S. Department of State Geographer. kh.google.com (accessed 27.07.15).

Greenberg, C.H., McNab, W.H., 1998. Forest disturbance in hurricane-related downbursts in the Appalachian Mountains of North Carolina. For. Ecol. Manage. 104, 179–191.

Gresham, C.A., 1993a. Changes in baldcypress-swamp tupelo wetland soil chemistry caused by Hurricane Hugo induced saltwater inundation. In: Brissette, J.C. (Ed.), Proceedings of the Seventh Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SO-93. U.S. Dept. Agric. Forest Service Southern Forest Experiment Station, New Orleans, LA, USA, pp. 171–185.

Gresham, C.A., 1993b. Changes in baldcypress-swamp tupelo wetland soil chemistry caused by Hurricane Hugo induced saltwater inundation. In: Brissette, J.C. (Ed.), Proceedings of the Seventh Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SO-93. U.S. Dept. Agric. Forest Service Southern Forest Experiment Station, New Orleans, LA, USA, pp. 171–185.

Gresham, C.A., Williams, T.M., Lipscomb, D.J., 1991. Hurricane Hugo wind damage to southeastern U.S. coastal forest tree species. Biotropica 23, 420–426.

Halpern, C.B., 1988. Early successional pathways and the resistance and resilience of forest communities. Ecology 69, 1703–1715.

Hayden, B.P., Dueser, R.D., Callahan, J.T., Shugart, H.H., 1991. Long-term research at the Virginia Coast Reserve. Bioscience 41, 310–318.

Hoeppner, S.S., Shaffer, G.P., Perkins, T.E., 2008. Through droughts and hurricanes: tree mortality, forest structure and biomass production in a coastal swamp targeted for restoration in the Mississippi River Deltaic Plain. For. Ecol. Manage. 256, 937–948.

Hook, D.D., Buford, M.A., Williams, T.M., 1991. Impact of Hurricane Hugo on the South Carolina coastal plain forest. J. Coast. Res. SI8, 291–300.

IPCC (Intergovernmental Panel on Climate Change), 2014. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 1–33.

JMP SAS, 2012. JMP Software: Release 10.0.2. SAS Institute Inc., Cary, NC, USA.

Kaplan, D., Muñoz-Carpena, R., Wan, Y., Hedgepeth, M., Zheng, F., Roberts, R., Rossmanith, R., 2010. Linking river, floodplain, and vadose hydrology to improve restoration of a coastal river affected by saltwater intrusion. J. Environ. Qual. 39, 1570–1584.

Loder, N.M., Irish, J.L., Cialone, M.A., Wamsley, T.V., 2009. Sensitivity of hurricane surge to morphological parameters of coastal wetlands. Estuar. Coast. Shelf Sci. 84, 625–636.

MDNR (Maryland Department of Natural Resources), 2012. Chesapeake Bay Program, www.chesapeakebay.net/data/downloads/cbp_water_quality_database_1984_present; http://mddnr.chesapeakebay.net/newmontech/contmon/archived_results_quick_fullyear_graph2012.cfm?param=doc&tablename=pocomokecity2012&yea=2012&shortname=pocomokecity; http://mddnr.chesapeakebay.net/newmontech/contmon/archived_results_quick_fullyear_graph2012.cfm?param=doc&tablename=Shelltown2012&year=2012&shortname=Shelltown (accessed 27.07.14).

Mendelssohn, I.A., Sorrell, B.K., Brix, H., Schierup, H.–H., Lorenzen, B., Maltby, E., 1999. Controls on soil cellulose decomposition along a salinity gradient in a *Phragmites australis* wetland in Denmark. Aquat. Bot. 64, 381–398.

Michener, W.K., Blood, E.R., Bildstein, K.L., Brinson, M.M., Gardner, L.R., 1997. Climate change, hurricanes and tropical storms, and rising sea level in coastal wetlands. Ecol. Appl. 7, 770–801.

Middleton, B.A., 1999. Wetland Restoration, Flood Pulsing and Disturbance Dynamics. John Wiley and Sons, New York, pp. 320.

Middleton, B.A., 2009a. Effects of Hurricane Katrina on the Forest Structure of *Taxodium distichum* Swamps on the Gulf Coast. Wetlands, USA, pp. 80–87.

Middleton, B.A., 2009b. Effects of Hurricane Katrina on the tree regeneration in baldcypress swamps of the Gulf Coast. Wetlands 29, 135–141.

Middleton, B.A., Johnson, D., Roberts, B., 2015. Hydrologic remediation for the Deepwater Horizon Incident drove ancillary primary production increase in coastal swamps. Ecohydrology 8, 838–850.

Najjar, R.G., Pyke, C.R., Adams, M.B., Breitburg, D., Hershner, C., Kemp, M., Howarth, R., Mulholland, M.R., Paolisso, M., Secor, D., Sellner, K., Wardrop, D., Wood, R., 2010. Potential climate-change impacts on the Chesapeake Bay. Estuar. Coast. Shelf Sci. 86, 1–20.

NASA, 2013. Hurricane Sandy (Atlantic Ocean) October 28, 2013, www.nasa.gov/mission_pages/hurricanes/archives/2012/h2012_Sandy.html.

NOAA (National Oceanic and Atmospheric Administration), 2012a. Hurricane Sandy, www.nhc.noaa.gov/outreach/presentations/Sandy2012.pdf (accessed 27.07.14).

NOAA (National Oceanic and Atmospheric Administration), 2012b. National Climate Data Center. Storm Data. May–October 2012, vol. 54., pp. 5–10, www.ncdc.noaa.gov/stormevents/ (accessed 27.07.14).

NOAA (National Oceanic and Atmospheric Administration), 2012c. National Weather Service. Hurricane Sandy, www.weather.gov/okx/HurricaneSandy (accessed 27.07.14).

NOAA (National Oceanic and Atmospheric Administration), 2012d. JUNE 29, 2012 DERECHO. "The Ohio Valley/Mid-Atlantic Derecho of June 2012, www.spc.noaa.gov/misc/AbtDerechos/casepages/jun292012page.htm (accessed 27.07.14).

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.

Overton, I.C., Jolly, I.D., Slavich, P.G., Lewis, M.M., Walker, G.R., 2006. Modelling vegetation health from the interaction of saline groundwater and flooding on the Chowilla floodplain, South Australia. Austr. J. Bot. 54, 207–220.

Piazza, B.P., La Peyre, M.K., 2009. The effects of Hurricane Katrina on nekton communities in the tidal freshwater marshes of Breton Sound, Louisiana, USA. Estuar. Coast. Shelf Sci. 83, 97–104.

R Foundation, 2012. R. Version 2.15.1. The R Foundation for Statistical Computing, www.r-project.org.

Ramsey III, E.W., Hodgson, M.E., Sapkota, S.K., Nelson, G.E., 2001. Forest impact estimated with NOAA AVHRR and Landsat TM data related to an empirical hurricane wind-field distribution. Remote Sens. Environ. 77, 279–292.

Ramsey III, E., Rangoonwala, A., Middleton, B.A.Z., Lu, Z., 2009. Satellite optical and radar data used to track wetland forest impact and short-term recovery from Hurricane Katrina. Wetlands 29, 66–79.

Salinas, M.J., Blanca, G., Romero, A.T., 2000. Riparian vegetation and water chemistry in a basin under semiarid Mediterranean climate, Andarax River, Spain. Environ. Manage. 26, 539–552.

SAS Institute Inc., 2002–2012. SAS/GLMSELECT® 9.3: Reference. SAS, Cary, NC.

Shaffer, G.P., Wood, W.B., Hoeppner, S.S., Perkins, T.E., Zoller, J., Kandalepas, D., 2009. Degradation of baldcypress-water tupelo swamp to marsh and open water in southeastern Louisiana, USA: an irreversible trajectory? J. Coast. Res. 54, 152–165.

Shen, J., Wang, H., Sisson, M., Gong, W., 2006. Storm tide simulation in the Chesapeake Bay using an unstructured grid model. Estuar. Coast. Shelf Sci. 68, 1–16.

Shields, E.C., Moore, K.W., Parrish, D.B., 2011. Influences of salinity and light availability on abundance and distribution of tidal freshwater and oligohaline submersed aquatic vegetation. Estuar. Coasts 35, 515–526.

Spies, T.A., Franklin, J.F., Thomas, T.B., 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology 69, 1689–1702.

Stanturf, J.A., Goodrick, S.L., Outcalt, K.W., 2007. Disturbance and coastal forests: a strategic approach to forest management in hurricane impact zones. For. Ecol. Manage. 250, 119–135.

Steyer, G.D., Perez, B.C., Piazza, S., Suir, G., 2006. Potential consequences of saltwater intrusion associated with Hurricanes Katrina and Rita. In: Farris, G.S., Smith, G.J., Crane, M.P., Demas, C.R., Robbins, L.L., Lavoie, D.L. (Eds.), Science and the Storms – The USGS to Response to the Hurricanes of 2005, vol. 1306. U.S. Geological Survey Circular, Washington, DC, pp. 137–146.

Sutter, L.A., Perry, J.E., Chambers, R.M., 2014. Tidal freshwater marsh plant responses to low level salinity increases. Wetlands 34, 167–175.

Uhl, C., Clark, K., Dezzeo, N., Maquirino, P., 1988. Vegetation dynamics in Amazonian treefall gaps. Ecology 69, 751–763.

USDA (United States Department of Agriculture), 2014. Natural Resources Conservation Service GeoSpatial Data Gateway, Fort Worth, Texas, http://datagateway.nrcs.usda.gov/GDGOrder.aspx (accessed 01.07.14).

USGS (United States Geological Survey), 2014. Hazards Data Distribution System (HDDS) Explorer, https://hddsexplorer.usgs.gov/login/?RET_ADDR=https%3A%2F%2Fhddsexplorer.usgs.gov%2Fdata (accessed 27.07.14).

Valiela, I., Peckol, P., D'Avanzo, C., Lajtha, K., Kremer, J., Geyer, W.R., Foreman, K., Hersh, D., Seely, B., Isaji, T., Crawford, R., 1996. Hurricane Bob on Cape Cod. Am. Sci. 84, 154–165.

Vandersande, M.W., Glenn, E.P., Walworth, J.L., 2001. Tolerance of five riparian plants from the lower Colorado River to salinity, drought and inundation. J. Arid Environ. 49, 147–159.

Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T., Barry, D.A., 2013. Seawater intrusion processes, investigation and management: recent advances and future challenges. Adv. Water Resour. 51, 3–26.

Wicker, K.M., Davis, D., DeRouen, M., Roberts, D., 1981. Assessment of Extent and Impact of Saltwater Intrusion in the Wetlands of Tangipahoa Parish. Coastal Environments Inc., Baton Rouge, LA.

Williams, T.M., 1993. Saltwater movement within the water table aquifer following Hurricane Hugo. In: Brissette, J.C. (Ed.), Proceedings of the Seventh Biennial Southern Silvicultural Research Conference, Gen. Tech. Rep. SO-93. U.S. Dept. Agric. Forest Service Southern Forest Experiment Station, New Orleans, LA, pp. 177–184.

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.