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Processes Contributing to Resilience of Coastal Wetlands to Sea-Level Rise

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Abstract

The objectives of this study were to identify processes that contribute to resilience of coastal wetlands subject to rising sea levels and to determine whether the relative contribution of these processes varies across different wetland community types. We assessed the resilience of wetlands to sea-level rise along a transitional gradient from tidal freshwater forested wetland (TFFW) to marsh by measuring processes controlling wetland elevation. We found that, over 5 years of measurement, TFFWs were resilient, although some marginally, and oligohaline marshes exhibited robust resilience to sea-level rise. We identified fundamental differences in how resilience is maintained across wetland community types, which have important implications for management activities that aim to restore or conserve resilient systems. We showed that the relative importance of surface and subsurface processes in controlling wetland surface elevation change differed between TFFWs and oligohaline marshes. The marshes had significantly higher rates of surface accretion than the TFFWs, and in the marshes, surface accretion was the primary contributor to elevation change. In contrast, elevation change in TFFWs was more heavily influenced by subsurface processes, such as root zone expansion or compaction, which played an important role in determining resilience of TFFWs to rising sea level. When root zone contributions were removed statistically from comparisons between relative sea-level rise and surface elevation change, sites that previously had elevation rate deficits showed a surplus. Therefore, assessments of wetland resilience that do not include subsurface processes will likely misjudge vulnerability to sea-level rise.

Key words: accretion; elevation change; oligohaline marsh; resilience; sea-level rise; tidal freshwater forested wetlands.

Introduction

In coastal wetlands, hydrology is a key environmental driver that influences ecosystem structure and function (Keddy 2011). Sea-level rise-induced changes in salinity and flood regime can significantly impact plant growth and community composition (McKee and Mendelssohn 1989; Broome and others 1995; Williams and others 1999), potentially interrupting self-sustaining feedback

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mechanisms between hydrological, ecological, and geomorphological processes (Marani and others 2007; Kirwan and Murray 2008). Therefore, maintaining elevation relative to sea level is critical to preserving wetland ecological function and services.

Wetland elevation is a primary driver of plant biomass and ultimately defines the transition from stable to unstable marsh (Morris and others 2002). To keep their position within the tidal frame, coastal wetlands respond to sea-level rise by gaining elevation through complex feedbacks between surface elevation (flooding), sediment accretion, and plant growth (Cahoon and others 2006; Fagherazzi and others 2012). Thus, wetland elevation change is an emergent ecosystem-level response, and it therefore embodies characteristics of resilience according to Holling (1973), who defines resilience as an emergent ecosystem property that determines the persistence of ecological interactions and is a measure of the system's ability to absorb perturbations to external drivers.

The objectives of this study were to identify processes that contribute to resilience in coastal wetlands subject to sea-level rise and determine whether the relative contribution of these processes changes as wetland habitats transition from tidal freshwater forested wetland (TFFW) to oligohaline marsh. We used space-for-time substitution to illustrate the habitat transition from TFFW to oligohaline marsh (Brinson and others 1995). In these systems, salt-water encroachment has led to a dramatic shift from a forest-dominated wetland system to an herbaceous marsh (Krauss and others 2009), which has substantially altered the ecological function (Cormier and others 2013), energy flow (Noe and others 2013), and ecosystem services (Krauss and Whitbeck 2012). We assessed resilience as the ability of the wetland to maintain its elevation relative to rates of sea-level rise. Further, we refined the scale of wetland elevation measurements to quantify processes such as surface accretion, root zone subsurface change, and shallow hydro-geologic subsurface change to determine how contributions to elevation change, or resilience, vary along the transition gradient from TFFW to oligohaline marsh.

To understand what processes contribute to resilience in different wetland habitats, we asked the following questions: (1) Are TFFWs resilient to sea-level rise? (2) Are oligohaline marshes resilient to sea-level rise? (3) What processes associated with elevation change contribute to resilience in each habitat? (4) Do processes contributing to resilience differ among habitats?

Materials and Methods

Study Site

The study was conducted along transitional landscape transects on the coastal reaches of the Waccamaw River, a blackwater river near Georgetown, South Carolina (33°33′18.81″ latitude, −79°5′23.8914″ longitude), and the Savannah River, an alluvial river near Port Wentworth, Georgia (32°14′18.996″ latitude, −81°9′22.1076″ longitude) (USA; Figure 1). The experimental design was a randomized complete block design that included two landscape transects, four sites along each transect and two stations within each site ($n = 16$). The two rivers were selected to represent replicate landscape transects. The landscape transects spanned a gradient from healthy TFFW to oligohaline marsh. Each transect included a freshwater forested wetland site (upper forest; porewater salinity average 0.1 ppt), a moderately salt-impacted forested wetland site (middle forest; porewater salinity average 1.5 ppt), a highly salt-impacted, degraded forested wetland site (lower forest; porewater salinity average 3.0 ppt), and an oligohaline marsh site (marsh; porewater salinity average 4.0 ppt). Each site included paired, 20 × 25-m (500 m^2) stations covering a total area of 1000 m^2, from which major structural and biogeochemical characteristics have been collected over the past decade.

All sites along both transects contained soils that were classified in the Typic Hydraquent family (SSURGO 2015). Finer classification into soil series illustrated that sites further upstream contained soils from the levy series, and transitioned to soils from the tidal marsh (fresh) series further downstream. Along the Savannah transect, the upper forest contained levy soils, and all other sites along the transect contained tidal marsh soils. On the Waccamaw River, both the upper and middle forest contained levy soils, and the lower forest and marsh contained tidal marsh soils (SSURGO 2015). The vegetation composition, aboveground productivity, flooding, and nutrient biogeochemistry of these forest stands and a characterization of both rivers have been reported previously (Krauss and others 2009; Cormier and others 2013; Noe and others 2013).

TFFWs occupy the coastal reaches of tidally influenced rivers and cover at least 200,000 ha along the coast of the Southeastern United States (Field and others 1991). The upper forest sites represented true TFFWs, with hummock and hollow microtopography (sensu Duberstein and Conner, 2009), and were established in areas having no

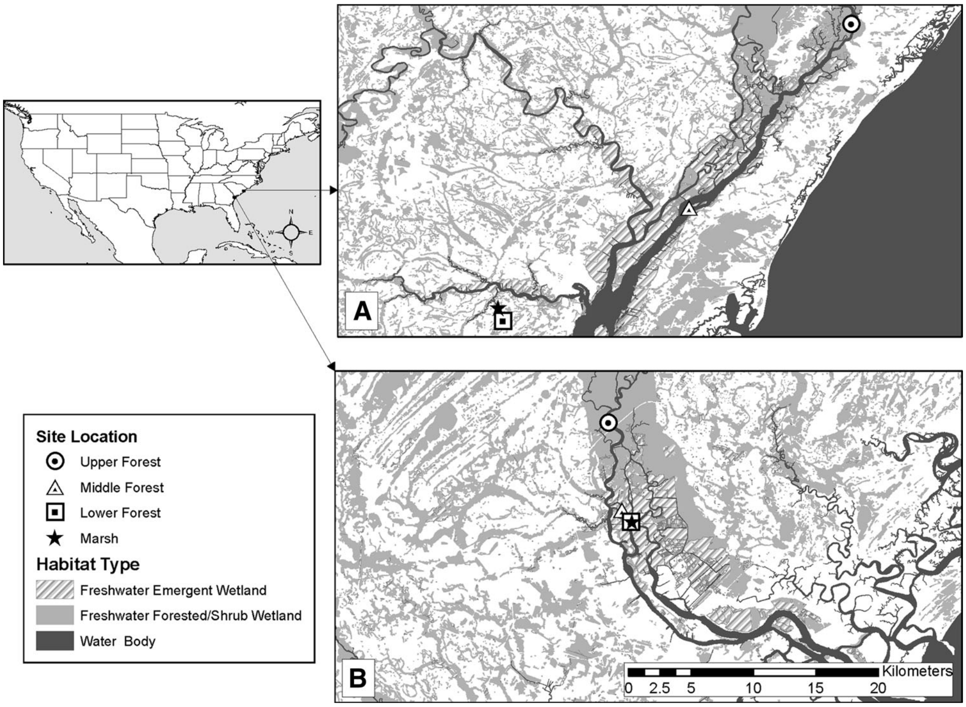

Figure 1. Location of upper forest, middle forest, lower forest, and marsh study sites along the landscape transects on the (**A**) Waccamaw River near Georgetown, South Carolina, USA and (**B**) Savannah River near Port Wentworth, GA, USA. Two deep and shallow RSET stations were located within each site along each transects.

obvious signs of salt-water encroachment. Overstory species included *Taxodium distichum*, *Nyssa aquatica*, *Nyssa biflora*, *Fraxinus* spp., and/or *Acer rubrum*. *Alnus serrulata* was present as a shrub on both the Waccamaw and Savannah River sites. The herbaceous community was dominated by *Polygonum hydropiperoides*, *Polygonum arifolium*, *Thelypteris* sp., *Carex* spp., *Commelina diffusa*, *Toxicodendron radicans*, and *Iris* sp. Middle forest sites exhibited early stages of salinity stress, including the presence of oligohaline marsh species. Overstory species were restricted to *T. distichum*, with a sparse mid-story of *N. biflora*. The herbaceous understory communities were composed of *Peltandra virginica*, *Sagittaria lancifolia*, *Lilaeopsis chinensis*, and some *Schoenoplectus robustus*. Lower forest sites were composed of a salt-stressed monoculture of *T. distichum* in the overstory, including many dead stems, with an understory of oligohaline marsh plants, including *Zizaniopsis mileacea*, *Spartina cynosuroides*, *S. robustus*, and *S. lancifolia* (Cormier and others 2013). Oligohaline marsh sites were composed entirely of herbaceous marsh species including *Z. mileacea*, *S. cynosuroides*, *S. robustus*, and *Typha latifolia* (Ensign and others 2014).

Mean temperatures during the study period for the Southeastern US Climate Region ranged from 19 to 20°C, and precipitation averaged between 900 and 1500 mm annually (U.S. Climate Divisional Database 2015). Tides along both rivers were semidiurnal with a mean range of 1.1 m for the Waccamaw River (NGS http://www.ngs.noaa.gov/Tidal_Elevation/diagram.jsp?PID=DD1392&EPOCH=1983-2001 accessed 03/11/2016) and 2.6 m for the Savannah River (NGS http://www.ngs.noaa.gov/Tidal_Elevation/diagram.jsp?PID=CK0427&EPOCH=1983-2001 accessed 03/11/2016). Flood frequency, flood duration, and mean water depth generally increased along the transect from TFFW to oligohaline marsh (Krauss and others 2009; Cormier and others 2013).

Surface Elevation and Accretion Measurements

Wetland site elevation was measured relative to the North American Vertical Datum of 1988 (NAVD88) with Global Positioning System (GPS) equipment, which provides 5-mm accuracy (Trimble 5700/5800 GPS Receiver). At each site, temporary benchmarks were established and the elevation relative to NAVD88 was determined using two consecutive static surveys of at least 2 h duration. The data were sent to OPUS (Online Positioning User Service, http://www.ngs.noaa.gov/OPUS/) for processing using Geoid12a. Processing occurred at a minimum 6 months after collection. The temporary benchmarks were tied to the wetland surface elevations at each of the replicate stations at all sites using a laser level device. Wetland surface elevations were averaged from a minimum of three locations within each station.

Surface elevation change was measured using the rod surface elevation table-marker horizon (RSET-MH) technique developed for wetland ecosystems (Cahoon and others 2002a, b; Webb and others 2013; Callaway and others 2013). Rod surface elevation tables (RSETs) measure the total elevation change of a wetland from the soil surface to the bottom depth of the benchmark (Figure 2). When used in conjunction with feldspar soil marker horizons (MH) that measure surface sediment accumulation, subsurface elevation change can be estimated between the MH and the bottom of the benchmark. Two types of RSETs were used for this study to measure both shallow and deep subsurface process influences on elevation change (Cahoon and others 2002b, Figure 2). One deep RSET and one shallow RSET were installed in accordance with NGS standards (Floyd 1978; Callaway and others 2013) in each station for a total of two deep and two shallow RSET benchmarks at each site. Deep RSETs were installed to refusal at a maximum depth of 17.1 m in the Savannah middle forest site and at a minimum refusal depth of 3.7 m in the Waccamaw lower forest site. The average installation depth of the deep RSETs was 11.4 m. The aluminum legs (that is, benchmark) of the shallow

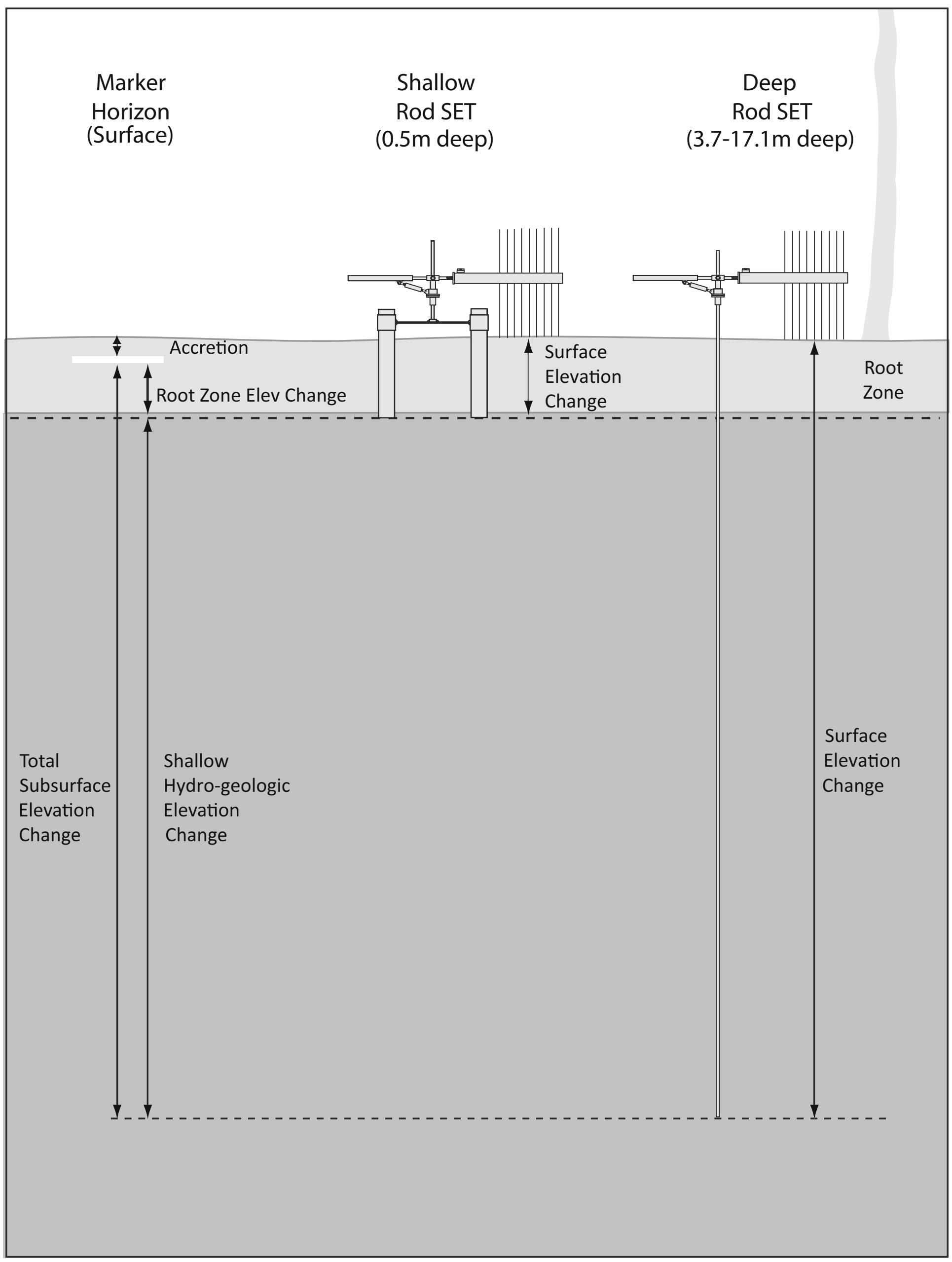

Figure 2. Illustration of different processes contributing to elevation change measured using the deep RSET, shallow RSET, and feldspar marker horizon.

RSET were installed to a depth of 0.5 m, which was equal to the plant rooting zone determined by soil auger test cores. Deep and shallow RSETs were installed at each of the sites in September 2009 and measurements were initiated in December 2009. Elevation measurements of nine pins in each direction were made for four to eight directions on each of the deep and shallow RSET benchmarks.

Vertical accretion was determined by measuring the depth of sediment deposited above a feldspar MH (Cahoon and others 2002a, b). Three feldspar MH plots were installed at each station in December 2009, at the time of the first RSET reading, and measured with all subsequent RSET readings. Three replicate cores, and three readings from each core, were taken from each MH plot during each sampling event using a miniature Russian peat corer. All RSET-MH plots were measured quarterly for the first year, bi-annually for the second year, and annually for the third, fourth, and fifth year through December 2014.

To incorporate the microtopographic variation observed at the upper forest sites, elevation change was measured both on hummocks and in hollows. Instead of four position readings on the deep and shallow RSET benchmarks, eight direction readings were made (double the other sites) representing approximately half hummock and half hollow environments. Similarly, instead of three feldspar MH plots, six feldspar MH plots were established at each RSET-MH station: three hummock and three hollow MH plots associated with each RSET benchmark. The averages of hummock and hollow data were used in all statistical analyses.

Experimental Design and Analyses

The experimental design was a randomized complete block design with sampling (Freund and Wilson 2003), where the rivers, or landscape transects, represented block-level error and the sites represented treatment-level error. Each site contained two subreplicates or ''stations,'' which represented sampling error. Linear regressions of average pin height over time were conducted to estimate a rate of elevation change for each direction on each benchmark, resulting in four to eight rate estimates per benchmark. Linear models explained between 44 and 94% of the variance in the elevation data. Similarly, linear regressions of accumulated sediment over time were conducted to estimate a rate of accretion for each plot, resulting in three to six rate estimates per plot. Linear models explained between 60 and 95% of the variance in the accretion data. After elevation change and accretion rates were estimated, we used a mixed model ANOVA, where river was the random factor, and site along transect and benchmark type were fixed factors, to test differences of elevation change and accretion rates between river, site, benchmark type, and subsequent interactions. Post-analysis comparisons were conducted using t-tests. Analyses were performed using SAS software, version 9.3 (SAS Institute Inc.).

Calculations

In addition to trends of surface elevation change and surface accretion, SET and MH data are used to calculate subsurface process influences on surface elevation, which collectively were termed shallow subsidence by Cahoon and others (1995). Shallow subsidence is calculated by subtracting elevation from accretion (Shallow Subsidence = Accretion − Surface Elevation Change) (Cahoon and others 1995). When accretion is greater than elevation change, shallow subsidence has occurred, and when elevation change is greater than accretion (for example, Cahoon and others 1995, 2006), shallow expansion has occurred (McKee and others 2007; Krauss and others 2014; Cahoon 2015). In this paper, we calculate total subsurface elevation change (that is, shallow subsidence or shallow expansion) by subtracting accretion from elevation (Total Subsurface Elevation Change = Surface Elevation Change − Accretion), where shallow subsidence is expressed as a negative value and shallow expansion as a positive value (McKee 2011). Total subsurface elevation change is equal to the difference between surface elevation change measured by the deep RSET and accretion (Total Subsurface = Deep RSET − Accretion). Root zone elevation change is equal to the difference between surface elevation change measured by the shallow RSET and accretion (Root Zone Elevation Change = Shallow RSET − Accretion) and incorporates both biological processes such as root production (Langley and others 2009) and physical processes such as compaction of soil pore space (Ewing and Vepraskas 2006). Shallow hydro-geologic subsurface elevation change is the difference between total subsurface and root zone elevation change (Shallow Hydro-Geologic = Total Subsurface − Root Zone) and incorporates both hydrologic processes such as soil dilation (Whelan and others 2005) and geologic processes such as compaction (French 2006) (Figure 2). The terms Total Subsurface Elevation Change and Surface Elevation Change are equivalent to VLM_s and VLM_w, respectively, in Cahoon (2015).

Relative contributions of individual processes were estimated as the percent of total vertical change, which was equal to the sum of surface and subsurface elevation change rates. Resilience, estimated as the change in sea level relative to the wetland surface, or wetland relative sea-level rise ($RSLR_{wet}$, Cahoon 2015), was quantified by comparing 5-year records of elevation change rates to long-term and short-term rates of relative sea-level rise (RSLR). $RSLR_{wet}$ was calculated by subtracting the wetland surface elevation change rate from tide gauge RSLR. When the rate of wetland surface elevation change is greater than the rate of RSLR, $RSLR_{wet}$ is negative, and sea level is declining relative to the wetland surface. Cahoon (2015) provides a detailed overview of appropriate techniques and assumptions of RSLR calculations versus surface elevation change data from coastal wetlands, which we follow here. We used the regional rate of RSLR (tide gauge) of 0.31 cm y^{-1} from the long-term 93-year record and 0.58 cm y^{-1} from the short-term 5-year record in Charleston, SC to assess resilience of the Savannah and Waccamaw River sites (NOAA, http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8665530 accessed 02/18/2015).

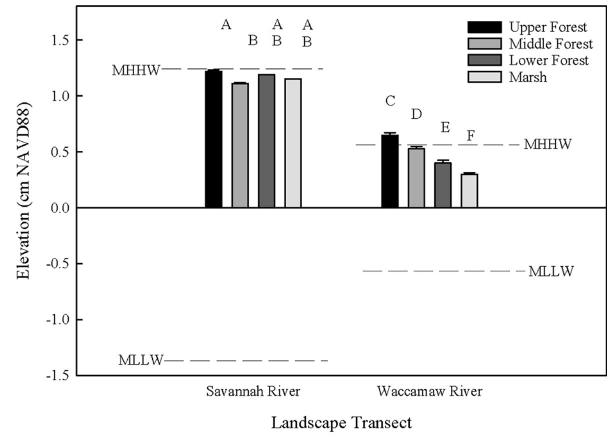

Figure 3. Wetland surface elevation and tidal datums relative to NAVD88 for sites along the Savannah and Waccamaw River transects. *Error bars* represent standard errors, *letters* represent significant differences determined by LSD ($p < 0.05$) post hoc comparisons.

Results

Site Elevation

Site elevation of the wetland surface relative to NAVD88 differed significantly between the two rivers. In general, the Savannah River was significantly higher in elevation than the Waccamaw River, and the patterns of elevation along the landscape transect were different between rivers ($p < 0.0001$, F 14.98, df 3; Figure 3). On the Waccamaw River, elevation relative to NAVD88 decreased with increasing salinity along the transect. Therefore, MHHW and MLLW, generated from a tide gauge located near the middle forest site, are likely too high relative to the wetland elevation for the lower forest and marsh sites on the Waccamaw River transect (Figure 3). Differences among site elevations along the Savannah River were not as dramatic as those on the Waccamaw River.

Surface Elevation Change

Surface elevation trajectories varied significantly across sites with increasing salinity, and patterns along the landscape transect were different between the two replicate rivers ($p < 0.0001$, F 19.09, df 3; Figure 4A, B). Along the Savannah River transect, all sites gained elevation over time; however, the lower forest and marsh gained elevation at a rate that was significantly greater ($p < 0.0001$, t −6.87, df 15; $p = 0.0005$, t −4.39, df 15, respectively) than the upper and middle forests (Figure 4A). In contrast, on the Waccamaw River, the upper and middle forests gained elevation at the same rate as the marsh ($p = 0.53$, t −0.65, df 15; p 0.4912, t −0.71, df 15, respectively), whereas the lower forest lost elevation over time ($p = 0.0071$, $t = -3.12$, df 15).

Wetland Resilience

Comparisons of surface elevation change to regional rates of long-term (93 years) RSLR demonstrated resilience (or lack thereof) of each site along the transition gradient (Figure 5A, B). Along the Savannah River, surface elevation change in the upper and middle forests was equivalent to both long- and short-term RSLR, and in the lower forest and marsh, elevation gain was nearly an order of magnitude greater than both long- and short-term RSLR, illustrating resilience in all sites along the Savannah River landscape transect (Figure 5A). However, given the relatively low rate of elevation gain, and its position within the tidal frame (Figure 3), the Savannah upper forest could be considered marginally resilient. For example, when surface elevation change rates were compared to the short-term rate of RSLR (0.58 cm y^{-1}) observed during the study period (2009-2014), there was a significant ($p < 0.1$) elevation rate deficit in the Savannah upper forest (Table 1). In contrast, surface elevation change in the Savannah middle

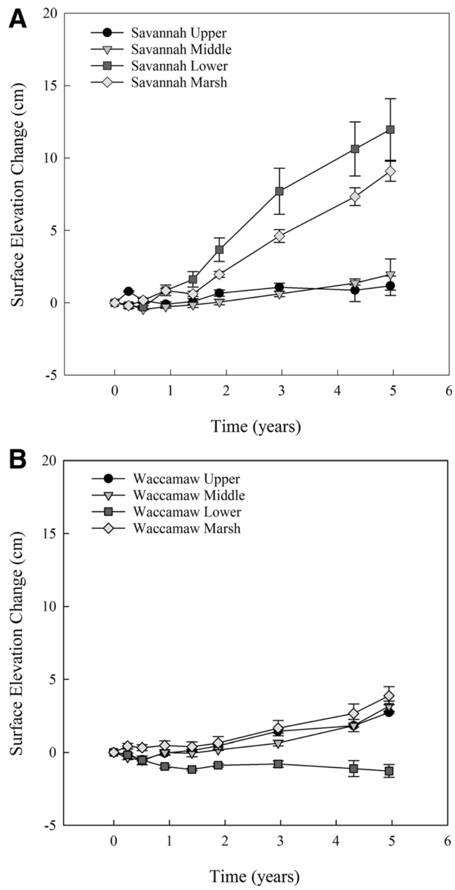

Figure 4. Surface elevation change over time in upper forest, middle forest, lower forest, and marsh sites along the (**A**) Savannah River landscape transect and (**B**) Waccamaw River landscape transect. *Error bars* represent standard errors.

forest was not significantly different from either long- or short-term rates of RSLR (Figure 5A), and the lower forest and marsh had $RSLR_{wet}$ values that were significantly less than zero for both short- and long-term RSLR comparisons (that is, $RSLR_{wet}$ is negative and sea level is becoming lower relative to the wetland surface) (Table 1).

Along the Waccamaw River, surface elevation change matched both long- and short-term RSLR in the upper and middle forests. Elevation change in the marsh exceeded long-term RSLR and was equivalent to short-term RLSR (Figure 5B). The only site that was not resilient to RSLR was the lower forest, which exhibited a significant elevation rate deficit for both long- and short-term RSLR (Table 1). Therefore, all sites on the Waccamaw River, with the exception of the lower forest, exhibited $RSLR_{wet}$ values less than or equal to zero (Table 1), indicating resilience to sea-level rise.

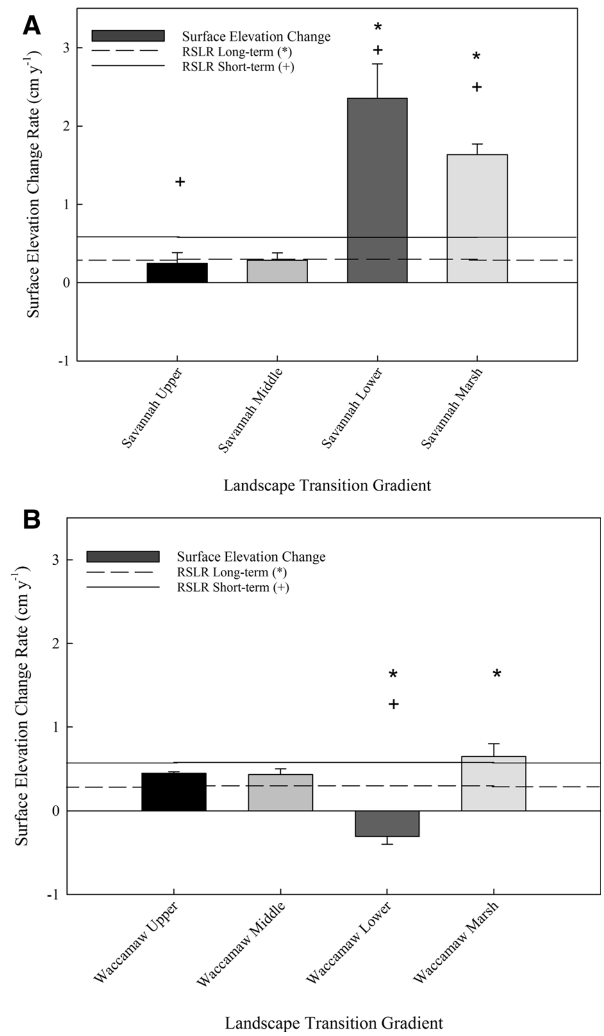

Figure 5. Wetland surface elevation change rate relative to regional long-term and short-term rates of relative sea-level rise (RSLR) along the (**A**) Savannah River and (**B**) Waccamaw River. Long-term (93 years) RSLR is represented by the dashed line. Short-term (5 years) RLSR is represented by the solid line. Data are from the NOAA record in Charleston, SC (Station ID 86553). Significant results ($p < 0.05$) of *t* tests represented by * and + for the comparison between surface elevation change and long-term RSLR and short-term RSLR, respectively.

Processes Contributing to Elevation Change

Surface Accretion

Accretion trajectories varied by river and site (Table 2). Along the Savannah River, accretion trajectories tracked surface elevation change at all sites that gained elevation, and increases in accretion reflect increases in elevation over time (Figure 6A). On the Waccamaw River, accretion rates were equivalent to surface elevation change rates,

Table 1. Wetland RSLR ($RSLR_{wet}$) Estimates for Sites Along the Savannah River and Waccamaw River Landscape Transects

Site	$RSLR_{wet}^{1,2}$		$RSLR_{wet}^{3}$	
	With Root Zone Contribution	No Root Zone Contribution	With Root Zone Contribution	No Root Zone Contribution
Savannah Upper	0.07^{ns}	-0.30^{ns}	0.35*	0.23*
Savannah Middle	0.03^{ns}	-0.18^{ns}	0.30^{ns}	0.528**
Savannah Lower	−2.04****	−2.31***	−1.77****	0.26*
Savannah Marsh	−1.32****	−1.18**	−1.05****	0.74***
Waccamaw Upper	-0.13^{ns}	-0.13^{ns}	0.13^{ns}	0.21*
Waccamaw Middle	-0.12^{ns}	-0.54^{ns}	0.15^{ns}	0.45**
Waccamaw Lower	0.63***	-0.30^{ns}	0.89***	0.17^{ns}
Waccamaw Marsh	−0.33*	−0.82**	-0.07^{ns}	0.36**

*Results of difference of least squared means analysis to test if $RSLR_{wet}$ is different from zero for each site represented as *$p < 0.1$, **$p < 0.05$; ***$p < 0.001$; ****$p < 0.001$. ns not significant, df 7. $RSLR_{wet}$ values significantly less than zero represent declining sea level relative to wetland surface, or an elevation rate surplus.*
[1]$RSLR_{wet}$ = Relative sea-level rise minus Surface elevation change.
[2]Denotes comparisons to long-term RSLR = 0.31 cm y^{-1}.
[3]Denotes comparisons to short-term RSLR = 0.58 cm y^{-1}. Values are the mean; all units are cm y^{-1}.

with the exception of the Waccamaw lower forest, where accretion significantly exceeded elevation change rates (Figure 6B; $p = 0.0069$, t 2.78, df 70).

Subsurface Elevation Change

Total Subsurface Elevation Change Total subsurface elevation change varied significantly among sites (Table 2), which was driven by the subsurface expansion occurring at the Waccamaw upper forest (Figure 7B). Otherwise, there was a negative total subsurface elevation change rate (that is, shallow subsidence) in all sites (Figure 7A, B).

Root Zone Subsurface Elevation Change Root zone subsurface elevation change was generally negative (that is, shallow subsidence occurred) across the landscape salinity gradient (Figure 7A, B), with the exception of root zone expansion occurring in the Waccamaw upper forest (Figure 7B).

Shallow Hydro-Geologic Zone Subsurface Elevation Change Subsurface elevation change in the shallow hydro-geologic zone varied significantly among sites (Table 2), and this pattern was consistent between both rivers (Figure 7A, B). Subsurface expansion in the shallow hydro-geologic zone occurred in the upper and lower forests on both rivers, whereas shallow hydro-geologic subsidence occurred in the middle forest and marsh. In all cases where shallow hydro-geologic uplift was occurring in conjunction with root zone subsidence, the root zone processes overpowered the shallow hydro-geologic processes, resulting in net negative subsurface elevation change (that is, shallow subsidence). Again, the Waccamaw upper forest was the exception, where both root zone expansion and shallow hydro-geologic expansion contributed to a net positive subsurface elevation change (Figure 7B).

Relative Contributions

Relative contributions of surface and subsurface processes varied significantly among rivers and sites along the transects ($p = 0.0008$, F 5.9, df 6). Along both landscape transects, surface accretion was the greatest contributor to elevation gain (35–88%) (Figure 8A, B), and in the middle forest and marsh, surface accretion was the sole process contributing to elevation gain. Contributions from the shallow hydro-geologic zone and root zone were not significant, and subsurface processes at all sites were overwhelmed by the contribution of surface accretion to elevation gain.

Processes resulting in elevation loss, which included root zone compaction and shallow hydro-geologic subsidence, accounted for 3–59% of total elevation change across all sites. Root zone compaction significantly contributed to elevation loss in the upper ($p < 0.0001$, t −5.02, df 23) and middle forests ($p = 0.001$, t −3.72, df 23) on the Savannah River and all sites along the Waccamaw River ($p \leq 0.01$, $t \leq -2.8$, df 23), except the upper forest (Figure 8A, B). In both marsh sites, subsurface

Table 2. Summary of Comparisons of Surface Elevation Change and Contributing Processes from Sites along the Savannah River and Waccamaw River Landscape Transects

Site	Accretion	Deep Surface Elevation Change	Shallow Surface Elevation Change	Mean Surface Elevation Change	Total Subsurface Elevation Change[1]	Root Zone Elevation Change[2]	Shallow Hydro-geologic Elevation Change[3]
Sav Upper	0.54 (0.1)	0.27 (0.3)	0.22 (0.2)	0.24 (0.1)	−0.29 (0.2)	−0.34 (0.1)	0.04 (0.1)
Sav Middle	0.75 (0.1)	0.16 (0.1)	0.42 (0.04)	0.29 (0.9)	−0.59 (0.08)	−0.33 (0.1)	−0.26 (0.2)
Sav Lower	2.6 (0.3)	2.4 (0.8)	2.3 (0.7)	2.35 (0.4)	−0.25 (0.07)	−0.26 (0.01)	0.01 (0.09)
Sav Marsh	2.0 (0.1)	1.4 (0.1)	1.9 (0.0)	1.6 (0.1)	−0.56 (0.0)	−0.09 (0.05)	−0.5 (0.05)
Wac Upper	0.38 (0.03)	0.48 (0.0)	0.42 (0.02)	0.45 (0.02)	0.09 (0.04)	0.034 (0.06)	0.06 (0.01)
Wac Middle	1.0 (0.2)	0.34 (0.03)	0.52 (0.1)	0.43 (0.07)	−0.68 (0.3)	−0.50 (0.39)	−0.18 (0.07)
Wac Lower	0.51 (0.1)	−0.26 (0.1)	−0.36 (0.2)	−0.3 (0.9)	−0.76 (0.2)	−0.9 (0.2)	0.1 (0.01)
Wac Marsh	1.2 (0.1)	0.61 (0.2)	0.7 (0.3)	0.65 (0.2)	−0.61 (0.1)	−0.52 (0.2)	-0.089 (0.1)
ANOVA							
River	58.57***	11.08*	18.58*	28.8***	0.35^{ns}	2.7^{ns}	4.2^{ns}
Site	45.14***	3.4^{ns}	4.67*	7.63*	4.82*	1.89^{ns}	6.4*
River x Site	35.16***	8.61*	10.74*	19.09***	2.74^{ns}	2.82^{ns}	1.41^{ns}

[1] *Total subsurface elevation change was calculated as the difference between elevation change measured by the deep RSET and accretion to indicate subsidence (−) or expansion (+).*
[2] *Root zone subsurface elevation change was calculated as the difference between elevation change measured by the shallow RSET and accretion to indicate subsidence (−) or expansion (+) within the root zone.*
[3] *Shallow hydro-geologic subsurface elevation change was calculated as the difference between total subsurface elevation change and root zone subsurface elevation change. Values are the mean .(±SE); all units are cm y^{-1}. Results of within-column mixed model ANOVA comparisons are indicated by F-ratios; significance is indicated by *$p < 0.05$, **$p < 0.001$; *** $p < 0.0001$; ns not significant. Degrees of freedom for the treatments River, Site, and River × Site are 1, 3, and 3, respectively.*

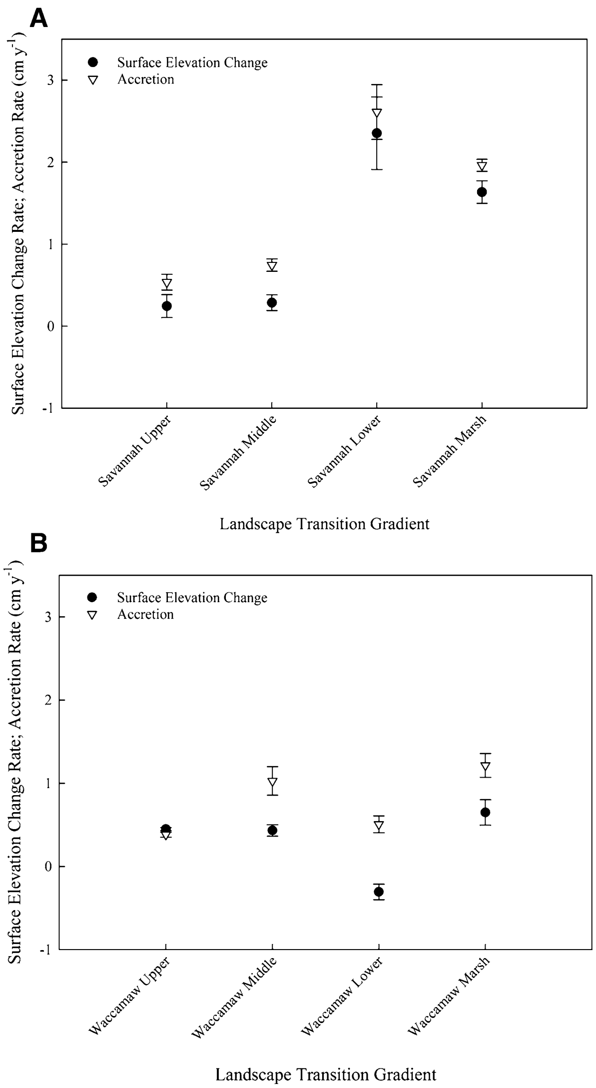

Figure 6. Surface elevation change and accretion rates along the landscape transition gradient on the (**A**) Savannah River and (**B**) Waccamaw River. *Error bars* represent standard errors.

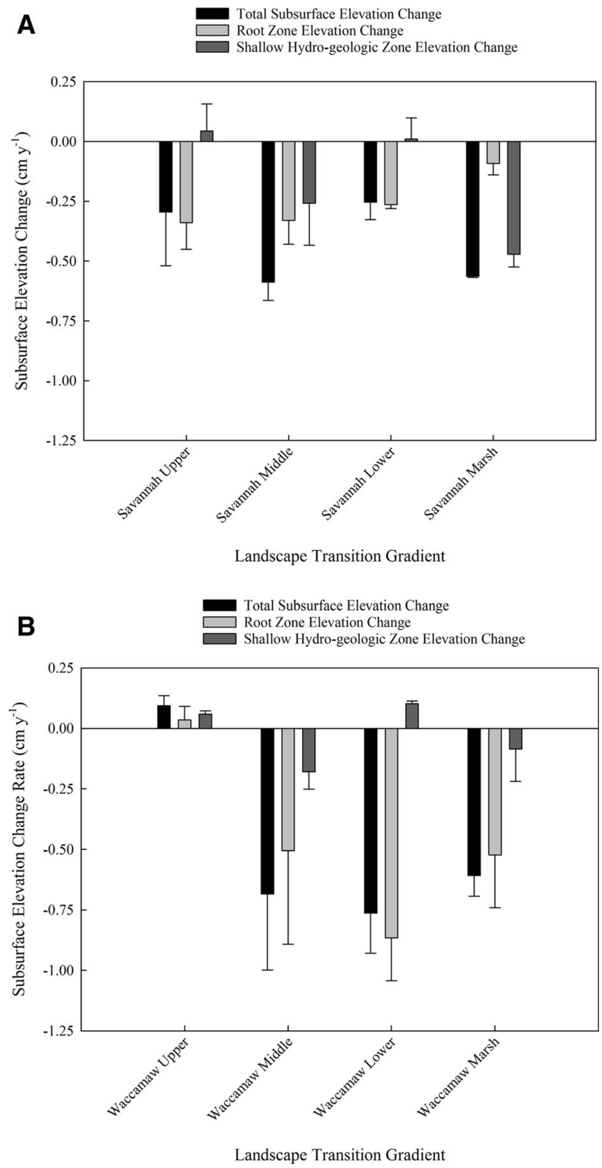

Figure 7. Subsurface processes along the landscape transition gradient on the (**A**) Savannah River and (**B**) Waccamaw River. *Error bars* represent standard errors.

elevation loss occurred. Shallow hydro-geologic subsidence was significant in the Savannah marsh ($p = 0.01$, t −2.8, df 23), and root zone compaction was significant in the Waccamaw marsh ($p = 0.0004$, t −4.16, df 23); however, surface accretion exceeded subsurface losses, resulting in a net elevation gain in both marshes (Figure 8A, B).

Discussion

Resilience is the propensity of a system to accommodate change and yet maintain equivalent ecological structure, function, and services (Holling 1973). To retain equivalent ecological function over time, coastal wetlands must adjust to gradual increases in sea level by maintaining a net gain in elevation that generally tracks sea-level rise (Reed 1995). Therefore, wetland resilience can be assessed by measuring elevation change relative to sea level change, and quantified as $RSLR_{wet}$, or the change in sea level relative to the wetland surface (Cahoon 2015).

Elevation maintenance in wetlands incorporates multiple processes and feedbacks between environmental and biological parameters (Cherry and others 2009; Krauss and others 2014). Wetland elevation change is influenced not only by surficial processes such as sediment accretion, but also subsurface properties including root zone expansion and compaction and shallow and deep geologic expansion and compaction (Cahoon and others 1995). To our knowledge, this is the first study to measure elevation change at a scale that separates surface and subsurface elevation processes in TFFW, and compares these measurements along the transitional gradient from TFFW to marsh.

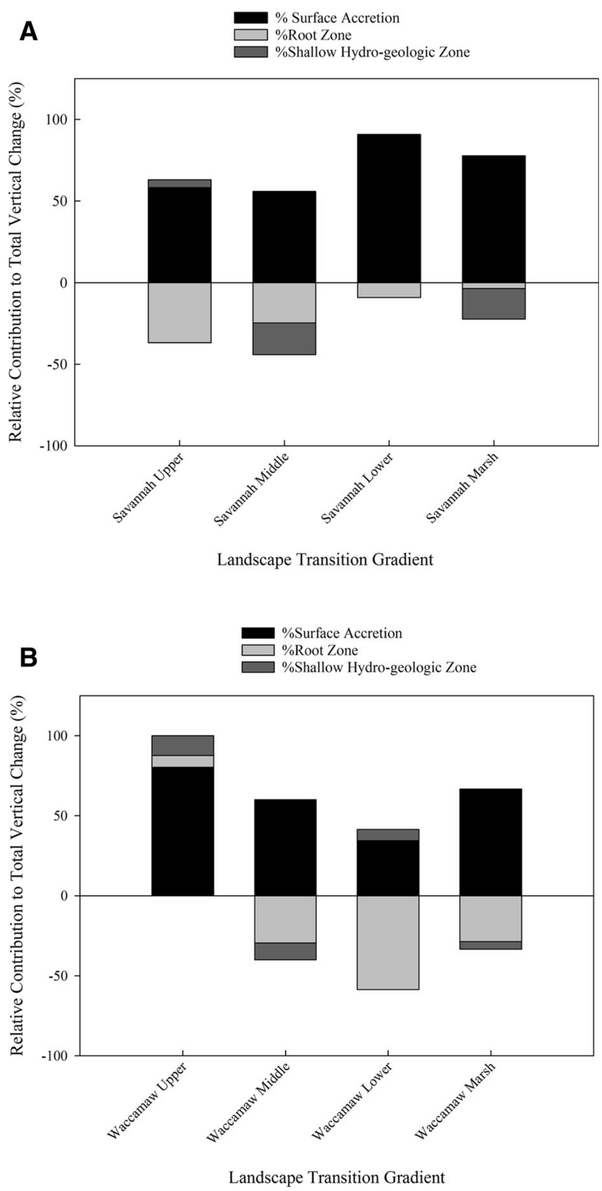

Figure 8. Relative contribution of surface and subsurface processes to total elevation change at each site along the landscape transition gradient on the (**A**) Savannah River and (**B**) Waccamaw River. Positive values represent contributions to elevation gain, whereas negative values represent contributions to elevation loss.

Processes Contributing to Resilience in the TFFW

By comparing trajectories of elevation change to rates of RSLR (Cahoon 2015), we determined that during this study period, TFFW are keeping pace with sea-level rise, although some may be considered marginally resilient. This result contrasts to previous work using Cs-137 techniques from Atlantic coastal TFFW that conclude consistent surface elevation deficits for TFFW (Craft 2012). Our results illustrate that accretion measurements alone (for example, feldspar MHs) are not sufficient to assess submergence vulnerability, because they do not account for processes that occur under the marker depth for feldspar and isotopic dating techniques, and therefore do not capture complex ecogeomorphic responses to increasing sea level (Kirwan and others 2016). Both TFFWs in this study had considerable positive shallow hydro-geologic zone influence on surface elevation change only discernable using the SET—MH method (Figure 7). All of this influence occurred below a depth of 50 cm in our study sites. The significant influence of the shallow hydro-geologic zone was also documented along riverine mangrove wetlands in the Everglades, Florida, USA (Whelan and others 2005), and this zone should be included for more accurate sea-level vulnerability assessments (Cahoon 2015).

Our data suggest that differences in resilience between the two rivers are attributed to local and regional variation in controls on subsurface processes (Kirwan and Gutenspergen 2012). Resilience in the TFFW was principally determined by processes occurring in the root zone. Although surface accretion is clearly important in contributing to elevation maintenance (Kirwan and others 2010), our analyses show that the primary difference between TFFW on Savannah (marginally resilient) and Waccamaw (resilient) Rivers is the relative contribution of root zone subsurface change to overall elevation. Root zone expansion is a significant contributor to elevation gain in Caribbean mangroves (McKee and others 2007) and potentially in other systems that have low rates of mineral sediment accretion (Langley and others 2009), such as the TFFWs in this study (Ensign and others 2014). However, more research is needed to quantify the contribution of root zone influences to wetland elevation maintenance in other systems.

Root zone expansion can occur through biological processes such as plant production of root biomass (Langley and others 2009) and/or physical processes such as dilation water storage or ''swelling'' (Cahoon and others 2011). In contrast, compaction in the root zone can lead to overall elevation loss (Whelan and others 2005) and is also influenced by both biological and physical processes such as decomposition (McKee and others 2007) and compression (French 2006), respectively. Soils of alluvial rivers (Savannah) have greater cellulose and lignin decomposition than soils of blackwater rivers (Waccamaw) (Entry 2000), which may contribute to greater rates of subsurface root zone compaction observed in the Savannah River TFFW. Subsurface elevation loss may also occur through structural failure following significant vegetation/root mortality (Cahoon and others 2003; Lang'at and others 2014). Salinity-induced mortality in the Waccamaw lower forest (Cormier and others 2013) may have contributed to the observed subsurface elevation loss. At the on-set of salinization, either through chronic exposure or acute pulses, root growth in even the most salt-tolerant TFFW tree species (baldcypress) is sensitive to low levels of salinity (Allen and others 1997), which may restrict root volume expansion depending on exposure concentration and duration.

Controls on the processes influencing root zone expansion and compaction can vary at both the local and regional scale. For example, nutrient availability, a central parameter influencing organic matter production (Deegan and others 2012) and decomposition (Ramirez and others 2012), varied at both the local (site) and regional (river) scale (Cormier and others 2013; Noe and others 2013). Differences in phosphorus mineralization were attributed to the distinct geologic characteristics of alluvial versus blackwater rivers, whereas nitrogen mineralization varied at the site scale along with changes in vegetation community (Noe and others 2013). Variation in these critical parameters may lead to differences in root zone contributions to elevation (Graham and Mendelssohn 2014) and ultimately to potential differences in resilience such as observed between the Savannah and Waccamaw River TFFW.

In addition to controls on biological processes, the differences in soil properties and geomorphic settings of blackwater versus alluvial rivers may impact physical processes contributing to elevation change in the root zone and shallow hydro-geologic zone. Changes in soil water storage from river stage (Whelan and others 2005), tidal (Nuttle and others 1990), rainfall (Cahoon and Lynch 1997), and drought (Rogers and others 2005; Cahoon and others 2011) events can cause a shrink-swell response in wetland surface elevation. Blackwater rivers, like the Waccamaw, generally have more organic soils compared to the mineral soils of alluvial rivers (Stanturf and Schoenholtz 1998), and water retention increases with organic matter content (Rawls and others 2003). Thus, differences in the soil properties and the nature of the hydrologic event may affect the duration and magnitude of elevation change and consequently result in differential patterns of resilience between rivers.

The strong influence of root zone compaction on elevation maintenance, or resilience, is evidenced by the residual effect of removing root zone contributions from rate deficit and surplus calculations (Table 1). When root zone contributions are removed from comparisons between RSLR and surface elevation change, sites that previously lagged behind sea-level rise now are keeping pace (McKee 2011). Specifically, if resilience assessments were based solely on accretion rates, the lower forest on the Waccamaw would be considered resilient, although surface elevation trajectories are significantly less than rates of RSLR. Therefore, when subsurface processes are omitted from elevation measurements, comparisons to sea-level rise will not be complete and may result in an incorrect assessment of resilience (Cahoon and others 2006; French 2006; Webb and others 2013).

It is also important to consider the implications of temporal variation between the tide gauge record and surface elevation change records. The comparison between 5-year surface elevation records and the 93-year tide gauge record, used in this study, requires the assumption that the historic rate of RSLR measured by the tide gauge occurred during the 5-year study period (Cahoon 2015). An alternative option is to assess resilience using the temporally co-occurring, or short-term, rate of RSLR (0.58 cm y^{-1}, 2009–2014). When we used short-term rates of RSLR in resilience assessments, the Savannah upper forest had an elevation rate deficit, whereas elevation change rates were equivalent to long-term RSLR. Thus, comparisons to the current short-term record illustrated the borderline resilience of the Savannah upper forest. On the other hand, the Waccamaw upper and middle forests and marshes on both rivers easily kept pace with RSLR given either the long-term rate (0.31 cm y^{-1}) or the current short-term rate (0.58 cm y^{-1}).

Although using historic RSLR trends can overestimate resilience in the upper forested wetlands, the long-term trend is less susceptible to anomalous changes in sea level. In contrast, the short-term record gives a more accurate description of current sea-level change and may capture acceleration of

SLR (Church and White 2006); however, short-term oscillations may also obscure real trends. Furthermore, elevation change rates measured in habitats that are lower in elevation and more frequently flooded, such as the lower forest and oligohaline marsh, represent a comprehensive response to future accelerated rates of SLR (Kirwan and others 2016). Therefore, our point-based comparisons of elevation change to long-term RSLR in the lower forest and oligohaline marsh, while limited to 5 years of elevation change data, may provide a more accurate assessment of resilience to future SLR conditions compared to assessments higher in the tidal frame (upper and middle forests). Thus, it is ideal to have long-term records for both surface elevation change and sea-level change across the entire tidal frame, which emphasizes the need for co-located measurements of long duration (McIvor and others 2013) and also the importance of considering the influence of temporal and spatial variation on submergence vulnerability assessments (Kirwan and others 2010; Kirwan and others 2016).

Processes Contributing to Resilience in the Marsh

The marshes on both rivers had an elevation surplus, indicating that both marshes were resilient to sea-level rise (Kirwan and others 2010). Other researchers have identified characteristics of resilience in oligohaline marshes with some capacity to recover from or persist through (Visser and others 2000) disturbances such as hurricane sediment deposition and salt spray (Guntenspergen and others 1995) and combinations of salinity pulsing, elevated flooding (Webb and Mendlessohn 1996; Howard and Mendelssohn 2000), and disturbance (Baldwin and Mendelssohn 1998).

Sediment accretion is the primary process contributing to elevation maintenance in marshes of this study. Kirwan and others (2010) demonstrated the importance of surface accretion in maintaining marsh elevations. In the present study, accretion rates are high enough to exceed subsurface elevation losses, resulting in net elevation gain that is sufficient to keep the marsh surface above increasing sea level. This was also observed by Graham and Mendelssohn (2014) who found that surface accretion exceeded subsurface subsidence in oligohaline marshes. Additionally, accretion is significantly greater in the marsh compared to both the stable and unstable TFFW, resulting in more elevation capital in the oligohaline marsh compared to the TFFW (Craft 2012).

Increased rates of mineral sedimentation in the marshes may reflect a feedback between herbaceous production and mineral sedimentation (Morris and others 2002) that is not necessarily present in the TFFW (Ensign and others 2014). The transition from TFFW to oligohaline marsh may result in greater herbaceous production and altered structure (for example, stems and litter) that may indirectly enhance sediment deposition by increasing surface roughness (Leonard 1997; Morris and others 2002; Rooth and others 2003). Ensign and others (2014) also suggest that closer proximity to the estuarine turbidity maximum may have resulted in higher rates of suspended sediment concentrations, with concomitant accretion, in the oligohaline marsh (Meade 1969).

This study illustrates how the balance between opposing forces of elevation gain and elevation loss are important in determining the overall resilience of a wetland system. Given that the TFFW have relatively low rates of surface accretion, the influence of subsurface processes become important to elevation maintenance. In the marsh, surface accretion is the dominant process and overshadows the importance of subsurface processes on elevation maintenance and system resilience.

We have shown that processes influencing resilience do differ between wetland community types, thus emphasizing the importance of measuring elevation processes at multiple scales to comprehensively assess and understand controls on resilience (Webb and others 2013) and long-term wetland sustainability. Furthermore, management activities to augment resilience in transitioning habitats must take account of the different parameters that influence those processes. If the goal of management is to maintain system resilience in the face of external pressure, it is first necessary to identify the critical parameters that, if altered, can cause significant changes in the processes and feedbacks that maintain resilience. Identification of critical parameters requires a mechanistic understanding of the effects and feedbacks between changing environmental parameters and ecological function (Folke and others 2004; deYoung and others 2008).

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