Global Change Biology

Global Change Biology (2012) **18**, 3615–3623, doi: 10.1111/gcb.12009

Tidal freshwater forest accretion does not keep pace with sea level rise

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Abstract

Soil properties, accretion, and accumulation were measured in tidal freshwater forests (tidal forests) of the Ogeechee, Altamaha, and Satilla rivers of the South Atlantic (Georgia USA) coast to characterize carbon (C) sequestration and nutrient (nitrogen-N, phosphorus-P) accumulation in these understudied, uncommon, and ecologically sensitive wetlands. Carbon sequestration and N and P accumulation also were measured in a tidal forest (South Newport River) that experiences saltwater intrusion to evaluate the effects of sea level rise (SLR) and saltwater intrusion on C, N and P accumulation. Finally, soil accretion and accumulation of tidal forests were compared with tidal fresh, brackish and salt marsh vegetation downstream to gauge how tidal forests may respond to SLR. Soil accretion determined using ^{137}C and ^{210}Pb averaged 1.3 and 2.2 mm yr^{-1}, respectively, and was substantially lower than the recent rate of SLR along the Georgia coast (3.0 mm yr^{-1}). Healthy tidal forest soils sequestered C (49–82 g m^{-2} yr^{-1}), accumulated N (3.2–5.3 g m^{-2} yr^{-1}) and P (0.29–0.56 g m^{-2} yr^{-1}) and trapped mineral sediment (340–650 g m^{-2} yr^{-1}). There was no difference in long-term accretion, C sequestration, and nutrient accumulation between healthy tidal forests and tidal forests of the South Newport River that experience saltwater intrusion. Accelerated SLR is likely to lead to decline of tidal forests and expansion of oligohaline and brackish marshes where soil accretion exceeds the current rate of SLR. Conversion of tidal forest to marshes will lead to an increase in the delivery of some ecosystem services such as C sequestration and sediment trapping, but at the expense of other services (e.g. denitrification, migratory songbird habitat). As sea level rises in response to global warming, tidal forests and their delivery of ecosystem services face a tenuous future unless they can migrate upriver, and that is unlikely in most areas because of topographic constraints and increasing urbanization of the coastal zone.

Keywords: carbon sequestration, N&P accumulation, saltwater intrusion, sea level rise, soil accretion, tidal freshwater forests

Received 29 March 2012; revised version received 8 August 2012 and accepted 10 August 2012

Introduction

Tidal forests occupy 200,000 ha of coastal land of the southeastern United States (Doyle *et al.*, 2007), mostly at the head of river-dominated estuaries (Craft *et al.*, 2009). They are sentinels of rising sea level, especially saltwater intrusion during drought and low flow conditions that stress forested vegetation (Day *et al.*, 2007; Anderson & Lockaby, 2011), increase tree mortality and sometimes convert forest to oligohaline or brackish marsh (DeLaune *et al.*, 1987; Hackney *et al.*, 1990; Krauss *et al.*, 2007). They are relatively uncommon and understudied primarily because most were drained or filled in the United States, Europe, and elsewhere since the tidal fresh zone typically represented the furthest point upriver that ships could transit and, therefore, cities were built there (Barendregt *et al.*, 2009). For these reasons, little is known about the ability of tidal forests to keep pace with SLR through soil accretion and even less is known about their contributions to carbon (C) sequestration and nutrient (N, P) accumulation relative to other tidal wetlands (Craft *et al.*, 2009; Loomis & Craft, 2010).

Sea level rise (SLR) is a persistent problem facing estuaries and coastal wetlands (Fitzgerald *et al.*, 2008; Neubauer & Craft, 2009; Dahl, 2011). It contributes to wetland loss through inundation and submergence (Day *et al.*, 2008) and habitat conversion through saltwater intrusion (Hackney *et al.*, 2007; Day *et al.*, 2008; Craft *et al.*, 2009). Saltwater intrusion also alters soil C, N, and P cycles by increasing C mineralization fueled by sulfate reduction (Weston *et al.*, 2006), releasing NH_4-N from cation exchange sites (Seitzinger *et al.*, 1991; Weston *et al.*, 2010; Jun *et al.*, 2012), mineralizing soil organic N (Canavan *et al.*, 2007; Jun *et al.*, 2012), and reducing denitrification (Craft *et al.*, 2009; Aelion & Warttinger, 2010; Giblin *et al.*, 2010; Larson *et al.*, 2010; Ensign *et al.*, 2012; Marton *et al.*, 2012). Phosphorus cycling responds in differing ways to SLR. Phosphorus sorption, for example, increases with saltwater intrusion (Jun *et al.*, 2012), but declines with increasing inundation (Reddy & Delaune, 2008; Jun *et al.*, 2012).

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Soil properties, vertical accretion, and accumulation were measured in three healthy (i.e., they do not experience saltwater intrusion) tidal forests of the Georgia (USA) coast and in a tidal forest that currently experiences saltwater intrusion to determine whether or not they are keeping pace with recent rates of SLR and to characterize the following ecosystem services, soil C sequestration, N, and P accumulation and mineral sediment deposition. Furthermore, soil accretion and accumulation of tidal forests were compared with tidal fresh, brackish and salt marshes downstream to predict how conversion of tidal forest to marsh will affect the resilience to SLR and the delivery of these services. In addition to soil-based ecosystem services, tidal forests contribute to N removal through denitrification (Ensign *et al*., 2012; Marton *et al*., 2012) and support biodiversity by providing habitat for migratory songbirds (Brittain & Craft, 2012) so it is critical to understand how these sentinels of SLR will respond to increased inundation and saltwater intrusion as the earth warms.

Materials and methods

Site description

Soils were collected from tidal freshwater floodplain forests (tidal forests) of the Ogeechee, Altamaha, and Satilla Rivers of the Georgia coast (USA) (Fig. 1). The Altamaha River (catchment size 35,112 km^2) is the third largest river on the east coast, the largest river in Georgia and originates in the Piedmont region (The Nature Conservancy, http://www.nature.org). The Satilla River (7,348 km^2) is a blackwater river whose catchment lies entirely within the coastal plain. Its waters contain low pH and high concentrations of humic substances relative to the Altamaha River (Marton *et al*., 2012). The Ogeechee

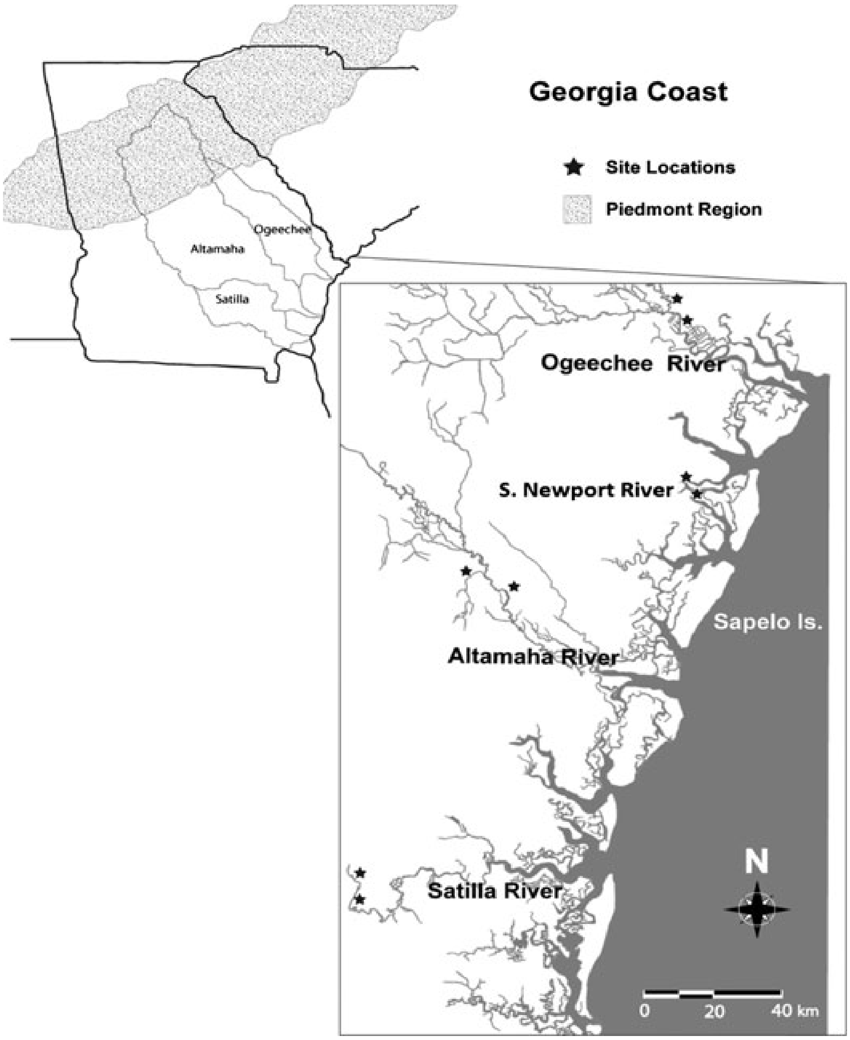

Fig. 1 Site map showing the locations of tidal forest sampling locations along the Altamaha, Ogeechee, Satilla, and South Newport rivers, Georgia, USA.

River (8,415 km^2) originates in the Piedmont, but drains mostly in the coastal plain. Discharge ranges from 34 m^3 s^{-1} in the Satilla River to 250 m^3 s^{-1} in the Altamaha River (Loomis & Craft, 2010). The three rivers comprise 92% of the tidal forest in Georgia (Jun *et al.*, 2012). Vegetation is dominated by bald cypress (*Taxodium distichum* [L] Rich.), tupelo gum (*Nyssa aquatic* L), and Ogeechee gum (*Nyssa ogeche* Bartram ex Marsh.). Swamp tupelo (*Nyssa biflora* Walt.), red maple (*Acer rubrum* L.), sweetgum (*Liquidambar styraciflua* L.), and water oak (*Quercus nigra* L.) also are present. Soils are classified as aquic Ultisols along the Ogeechee River and as fluvaquents along the Altamaha and Satilla Rivers (Natural Resources Conservation Service (NRCS), 2010). Tidal forests of the three rivers experience twice daily tidal pulsing, but inundation usually is shallow (0–10 cm), except during river-driven flood events.

Soils also were collected from tidal forests on the South Newport River (catchment size 492 km^2, 1.78 km^2 of tidal forest) where the forest is experiencing dieback as a result of saltwater intrusion. During regional droughts driven by La Nina climate cycles (DeSantis *et al.*, 2007), fresh discharge in the river is zero (C.B. Craft, personal observation). As a result, the tidal forests experience episodic saltwater intrusion caused by natural (coastal storms) and anthropogenic (construction of canals) factors that push saltwater into them during spring tides. At the time I collected soil samples, surface water salinity in the river was five. Vegetation of South Newport tidal forests is similar to the tidal forest on the other three rivers. However, a vigorous herbaceous layer of brackish marsh vegetation dominated by black needlerush (*Juncus roemerianus*, Scheele) had established as the trees die and sunlight reaches the forest floor. Soils of the South Newport River are classified as aquic Ultisols (Bayboro series, U.S. Department of Agriculture (USDA), 1982), similar to the Ogeechee River soils.

Soil accretion, C sequestration, and N and P accumulation

Two tidal forests were selected from each river for sampling in 2008 at which time two soil cores, 8.5 cm diameter by 60 cm deep were collected from each tidal forest. Within each forest, one core was collected from the levee and one from the interior floodplain. Cores were sectioned in the field into 2 cm increments for the top 30 cm and into 5 cm increments for the 30–60 cm depths.

Increments were air dried, weighed for bulk density, ground, sieved through a 2 mm mesh screen and analyzed for organic carbon, total N, and total P. Bulk density was calculated from the dry weight per unit volume for each depth increment (Blake & Hartge, 1986) after correcting for moisture content of an air dried sub-sample that was dried at 105 °C. Organic C and N were determined using a Perkin Elmer 2400 CHN analyzer (Perkin-Elmer, Norwalk, CT, USA). Analysis of an internal marsh soil standard (5.51 ± 0.6% C, 0.35 ± 0.03% N; n = 25) yielded recovery rates of 101% for C and 99% for N. Total P was determined by colorimetric analysis after digestion in nitric-perchloric acid (Sommers and Nelson, 1972). Analysis of NIST standard (#1646a) Estuarine Sediment (270 μg g^{-1} P, n = 19) yielded a recovery rate of 96% for P. Soil texture (0–10 cm) was measured by the hydrometer method (Gee & Balder, 1986). pH (0–10 cm) was measured on field moist soils using a 1 : 10 soil : solution ratio.

Ground and sieved soil was packed into 50 mm diameter by 9 mm deep petri dishes and analyzed for ^{137}Cs and ^{210}Pb to determine vertical accretion. ^{137}Cs was measured using gamma analysis of the 661.62 keV photopeak (Craft *et al.*, 2003) to estimate accretion since 1964, the year of maximum deposition of atmospheric Cs-137 from aboveground nuclear weapons tests. Total Pb-210 was measured using gamma analysis of the 46.5 keV photopeak (Craft *et al.*, 2003). Excess ^{210}Pb was calculated as the difference between total and background ^{210}Pb, determined from constant ^{210}Pb activities in the deeper (below 30 cm) part of the core (see Fig. 2b as an example). Pb-210 accretion rates were calculated using the constant activity model (Oldfield & Appleby, 1984). Rates of C sequestration and N & P accumulation were calculated using ^{137}Cs- and ^{210}Pb-derived vertical accretion rates and bulk density, C, N, and P concentrations down to and including the increment of maximum ^{137}Cs activity or extent of excess ^{210}Pb. Accumulation of mineral sediment was calculated in the same manner by subtracting the mass of soil organic matter, assuming that organic matter contains 50% organic C. Only those cores containing interpretable ^{137}Cs and ^{210}Pb profiles, such as those shown in Fig. 2, were used in the analysis.

Statistical analyses

Two-way analysis of variance (ANOVA) was used to test for differences in bulk soil properties, accretion and accumulation among tidal forests on the four rivers and among levee vs. interior floodplain sampling locations. ANOVA also was used to test for differences in ^{137}Cs vs. ^{210}Pb accretion and accumulation. Differences among tidal wetlands (tidal forest, tidal fresh, brackish, and salt marsh from Loomis & Craft, 2010) also were tested using ANOVA. Main effects means were separated using the Ryan-Einot-Gabriel-Welsh multiple range test [SAS (Statistics Analysis System) (2002) SAS User's Guide. Cary, NC]. All tests of significance were conducted at $P \le 0.05$.

Results

Soil properties

Tidal forest soils (0–30 cm) of the Altamaha and Ogeechee rivers contained high organic C, N, and P and low bulk density relative to the blackwater Satilla River and the South Newport River (Table 1). Bulk density ranged from 0.26 g cm^{-3} in the Altamaha River to 0.84 g cm^{-3} in the Satilla River and it was significantly lower in the Altamaha and Ogeechee Rivers than in the other two rivers. Organic C and N also were greater in Altamaha River soils (15.5% C, 0.90% N) than in Satilla (2.9% C, 0.18% N) and South Newport River soils (5.5% C, 0.35% N). Total P ranged from 160 μg g^{-1} (Satilla River) to 750 μg g^{-1} (Ogeechee River) and differed among all rivers. Soil pH (0–10 cm) also differed among all rivers,

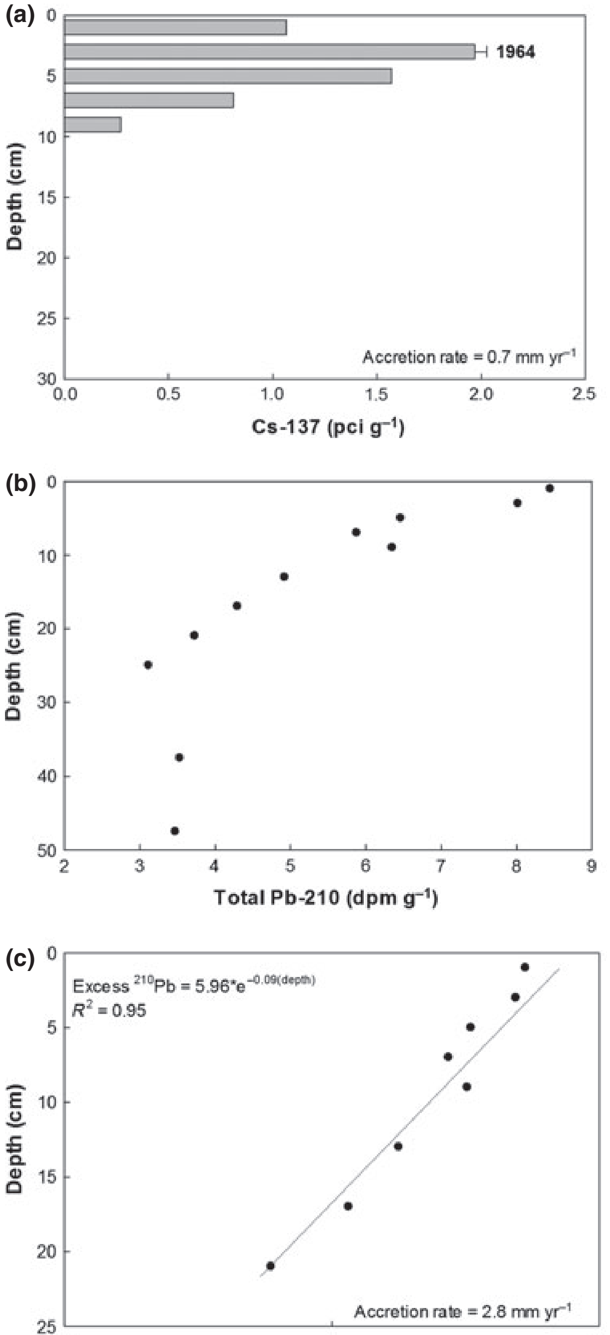

Fig. 2 Representative (a) ^{137}Cs, (b) total ^{210}Pb and (c) excess ^{210}Pb profiles with depth in a soil core collected from the floodplain of a tidal forest (site 2) of the Altamaha River.

being highest in the Altamaha River (5.6) and lowest (3.9) in the Satilla River. Tidal forest soils (0–10 cm) were dominated by sand-size particles (51%–84%) with the highest sand content in the Satilla River that originates in and drains the coastal plain (Table 1). Silt content ranged from 4% to 8% with no difference among rivers. Clay content was low (<3%) and it was higher in the Ogeechee than in the Satilla River (Table 1). There was no difference in soil properties among levee and interior floodplain locations (Table 1).

Soil cores generally exhibited a trend of increasing bulk density and decreasing C, N, and P concentrations with depth (data not shown). In soils of the Ogeechee, Satilla, and South Newport Rivers, bulk density was lowest in the surface and increased with depth. Conversely, organic C and total N and P were highest in the surface and decreased with depth down to 60 cm (data not shown). Soils of the Altamaha River had relatively uniform bulk density and organic C, N, and P concentrations with depth.

^{137}Cs and ^{210}Pb accretion

All 16 soil cores contained distinct ^{137}Cs maxima (Fig. 2a) and 11 cores exhibited interpretable ^{210}Pb profiles similar to the ones shown in Fig. 2b and 2c. Only one core from the Satilla River contained an interpretable ^{210}Pb profile. The goodness of fit (r^2) of regressions of excess ^{210}Pb vs. depth for the 11 cores ranged from 0.80 to 0.99.

^{137}Cs accretion ranged from 0.7 to 1.9 mm yr^{-1} and was significantly less in the Satilla River than in the Ogeechee River (Fig. 3). ^{210}Pb accretion ranged from 1.9 to 2.5 mm yr^{-1} and did not differ among rivers. There was no difference in soil accretion among levee (^{137}Cs = 1.2 ± 0.3 mm yr^{-1}, ^{210}Pb = 2.1 ± 0.2 mm yr^{-1}) and interior floodplain locations (^{137}Cs = 1.4 ± 0.2 mm yr^{-1}, ^{210}Pb = 2.5 ± 0.3 mm yr^{-1}). When averaged across all rivers, ^{210}Pb-based accretion was significantly greater than ^{137}Cs accretion (Fig. 3). Our ^{137}Cs and ^{210}Pb measurements of tidal forest soil accretion are less than the recent rate of SLR along the Georgia coast, 3.0 mm yr^{-1}) (http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8670870). Across all sites, there was no correlation between ^{137}Cs and ^{210}Pb accretion ($r = 0.07$, $P = 0.85$).

Carbon sequestration, N, and P accumulation and mineral sediment deposition

Carbon sequestration and N accumulation determined by ^{137}Cs ranged from 22 to 75 g m^{-2} yr^{-1} and 1.4–4.9 g m^{-2} yr^{-1}, respectively. It was greater in the Ogeechee River than in the Altamaha and Satilla rivers (Table 2) and was attributed to greater accretion in the Ogeechee River (Fig. 3). Phosphorus accumulation also was greater in the Ogeechee River (0.47 g m^{-2} yr^{-1}) than in the Satilla River (0.12 g m^{-2} yr^{-1}). Tidal forests of the South Newport River that experience saltwater

Table 1 Mean bulk density, organic C, N, P (0–30 cm), and particle size composition and pH (0–10 cm) ± 1 SE of healthy tidal forest soils of the Altamaha, Ogeechee, and Satilla rivers, Georgia, and the South Newport River that experience saltwater intrusion

River	Bulk density (g cm^{-3})	Organic C (%)	Total N (%)	Total P (μg g^{-1})	Sand (%)	Silt (%)	Clay (%)	pH
Altamaha	0.26 + 0.09^{b}	15.5 + 5.4^{a}	0.90 + 0.23^{a}	590 + 120^{b}	51 + 7^{b}	8 + 1	1 + 1^{a,b}	5.6 + 0.1^{a}
Ogeechee	0.41 + 0.12^{b}	10.4 + 3.5^{ab}	0.64 + 0.15^{ab}	750 + 40^{a}	65 + 5^{ab}	4 + 1	3 + 1^{a}	5.1 + 0.2^{b}
Satilla	0.84 + 0.04^{a}	2.9 + 0.7^{b}	0.18 + 0.04^{c}	160 + 50^{d}	84 + 4^{a}	8 + 2	<1^{b}	3.9 + 0.1^{c}
S. Newport	0.70 + 0.01^{a}	5.5 ± 0.5^{b}	0.35 ± 0.02^{bc}	360 ± 50^{c}	74 ± 3^{ab}	5 ± 1	1 ± 0^{a,b}	4.7 + 0.1^{b}
Levee	0.59 ± 0.10	8.6 ± 2.6	0.51 ± 0.31	470 ± 90	68 ± 5	7 ± 1	1 ± 0.3	-
Floodplain	0.52 ± 0.09	8.5 ± 1.9	0.51 ± 10	460 ± 90	68 ± 6	6 ± 1	1 ± 0.5	-

Means separated by the same letter are not significantly different (P = 0.05) according to the Ryan-Einot-Gabriel-Welsch multiple range test. pH was measured in the floodplain locations only.

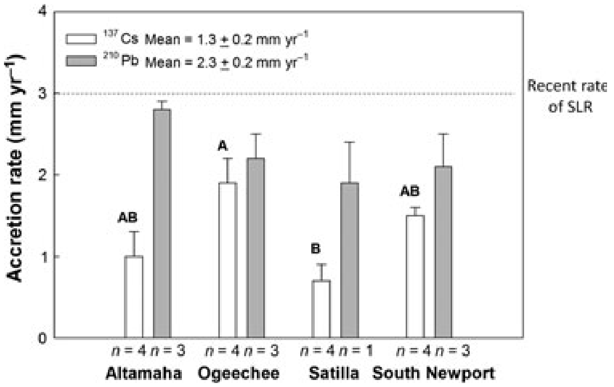

Fig. 3 Mean rates of ^{137}Cs and ^{210}Pb accretion in tidal forests of the Altamaha, Ogeechee, Satilla, and South Newport rivers.

intrusion had intermediate rates of C sequestration and N and P accumulation relative to tidal forests of the three healthy rivers. There was no difference in ^{137}Cs accumulation of mineral sediment among tidal forests of the four rivers. There also was no difference in ^{210}Pb-based nutrient and sediment accumulation among the four rivers (Table 2), nor was there a difference among levee vs. interior floodplain locations. As with soil accretion, ^{210}Pb-derived C sequestration, N, and P accumulation and sediment deposition was nearly double that of ^{137}Cs (Table 2). Except for P (r = 0.69, P = 0.02), there was no correlation between ^{137}Cs- and ^{210}Pb-based accumulation of materials.

Discussion

There are few studies of soil properties of tidal freshwater floodplain forests and no published studies of soil processes such as accretion that is required to maintain surface elevation as sea level rises, as well as C sequestration and nutrient (N, P) accumulation. Anderson & Lockaby (2007) compiled soil properties of 12 tidal

Table 2 Mean ^{137}Cs and ^{210}Pb-based rates of organic C, total N, total P and mineral sediment accumulation (g m^{-2} yr^{-1}) of tidal forest soils

	Organic C	Nitrogen	Phosphorus	Sediment
^{137}Cs				
Altamaha (n = 4)	42 ± 10^{bc}	2.7 ± 0.8^{bc}	0.23 ± 0.14^{ab}	180 ± 130
Ogeechee (n = 4)	75 ± 7^{a}	4.9 ± 0.1^{a}	0.47 ± 0.10^{a}	385 ± 85
Satilla (n = 4)	22 ± 12^{c}	1.4 ± 0.7^{c}	0.12 ± 0.06^{b}	340 ± 75
S. Newport (n = 4)	59 ± 5^{ab}	3.9 ± 0.1^{ab}	0.35 ± 0.05^{ab}	450 ± 110
^{210}Pb				
Altamaha (n = 4)	90 ± 10	5.6 ± 1	0.42 ± 0.23	480 ± 220
Ogeechee (n = 3)	83 ± 5	5.3 ± 0.7	0.62 ± 0.22	630 ± 350
Satilla (n = 1)	57	3.8	0.38	1510
S. Newport (n = 3)	88 ± 18	5.8 ± 1.6	0.65 + 0.29	400 ± 60
Mean ^{137}Cs	49 ± 6 A	3.2 ± 0.4 A	0.29 ± 0.05 A	340 ± 45 A
Mean ^{210}Pb	82 ± 6 B	5.3 ± 0.6 B	0.56 ± 0.09 B	650 ± 135 B

Means within the same column separated by the same letter are not significantly different (P < 0.05) according to the Ryan-Einot-Gabriel-Welsch multiple range test.

forests of alluvial (red water) and blackwater rivers of the southeastern United States and observed no consistent difference in soil pH (4.8–6.4) between the two forest types. Soil organic matter ranged from 9% to 77% with no clear pattern between alluvial and blackwater rivers. Nor was there a consistent difference in particle size composition between the two forest sites. Some tidal forest soils contained mostly sand and others such as the Apalachicola River (FL) soils contained mostly clay (Coultas, 1984). These findings contrast with Wharton *et al.* (1982), who found that, in non-tidal floodplain forest soils upriver, blackwater soils contained more sand than alluvial soils, similar to what I observed in tidal forest soils of the blackwater Satilla River vs. the alluvial Altamaha River. Detailed studies by Coultas (1984) and Anderson & Lockaby (2011) of tidal forest soils of the Apalachicola River, an alluvial river that drains mostly in the Piedmont region, revealed pH (5.4–6.0) and concentrations of organic C (7.5–18%) and N (0.45–0.89%) that were comparable to values measured in Altamaha and Ogeechee River soils (Table 1), and higher than those in the Satilla and S. Newport Rivers. Soil properties of our tidal forests soils generally fall within the wide ranges for organic matter, pH, and N compiled for alluvial and blackwater tidal forest soils of the southeastern Atlantic and Gulf coasts (Anderson & Lockaby, 2007).

In this study, and in studies of non-tidal alluvial floodplain forests of the southeastern United States (Craft & Casey, 2000), ^{210}Pb-derived soil accretion and accumulation were greater than measurements using ^{137}Cs. The ^{210}Pb method integrates accretion and accumulation over a longer time scale (100–125 years) than ^{137}Cs (since 1964, about 50 years). Craft & Casey (2000) attributed greater ^{210}Pb accretion and accumulation relative to ^{137}Cs to extensive land clearing and row crop agriculture in the southeast US Piedmont and coastal plain during the late 1800s and early 1900s that declined during the second half of the 20th century as agriculture declined in the region and forests re-established.

Tidal forests are sentinels of SLR because they are extremely vulnerable to saltwater intrusion. Saltwater intrusion at low salinities (e.g., 3) reduces water use, growth, height, and basal area of bald cypress and tupelo gum (Pezeshki *et al.*, 1990; Krauss *et al.*, 2009), two of the dominant species in tidal forests. Over time, saltwater intrusion can lead to forest death and replacement by brackish marsh vegetation or open water (DeLaune *et al.*, 1987; Hackney *et al.*, 1990; Conner *et al.*, 2007a; Krauss *et al.*, 2007; Krauss & Duberstein, 2010). Measured rates of ^{137}Cs and ^{210}Pb soil accretion in tidal forests are less than the current rate of SLR along the Georgia coast (Fig. 3), suggesting that these wetlands will convert to marshes or open water under current and projected future rates of SLR (Craft *et al.*, 2009).

There was no difference in soil properties, accretion, and accumulation between healthy tidal forests and a tidal forest (South Newport River) experiencing saltwater intrusion and where brackish marsh is replacing the forest (Tables 1 and 2, Fig. 3). There may be several reasons for this: (1) At the South Newport River, the conversion of forest to marsh is a relatively recent phenomenon, as seen by standing dead snags and unhealthy, but still standing live trees (Fig. 4). Soil properties, accretion, and accumulation, on the other hand, were measured over time scales of 40 (^{137}Cs) to 100 (^{210}Pb) years, which probably reflects conditions prior to saltwater intrusion at the site. (2) Unlike tidal forests of the Ogeechee, Altamaha, and Satilla rivers, the tidal forest of the South Newport River receives water and sediment from a much smaller catchment (492 km^2) than tidal forests on the other three rivers whose catchments are much larger, 7,348–35,112 km^2. Here, the newly forming brackish marsh does not receive the sediment load to increase soil accretion to rates found in brackish marshes of the healthy rivers and that will be needed to compensate for SLR in the future. Thus, the newly forming brackish marsh of the South Newport River is unlikely to keep up with SLR in the future and may, in fact, convert to open water.

Although soil accretion of tidal forests is less than the recent rate of SLR, measurements of accretion in marshes downstream on the Ogeechee, Altamaha, and Satilla rivers (Loomis & Craft, 2010) suggest that conversion of tidal forest to tidal fresh or brackish marsh will be accompanied by an increase in accretion that exceeds the current rate of SLR (Fig. 5). Tidal fresh and brackish marsh soils also

Fig. 4 Photograph showing the conversion of tidal forest to brackish marsh on the South Newport River. Note the sparse canopy cover, unhealthy live trees, and standing dead snags atop the developing brackish marsh vegetation.

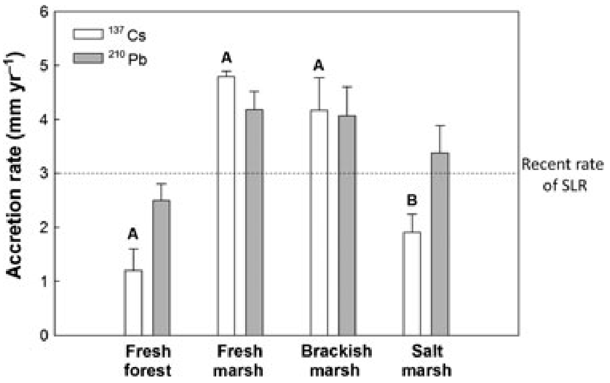

Fig. 5 Mean ^{137}Cs and ^{210}Pb soil accretion of tidal forest and marshes along the Ogeechee, Altamaha and Satilla rivers, Georgia, USA. The ^{137}Cs marsh data are from Loomis & Craft (2010). The ^{210}Pb marsh data are from C.B. Craft (unpublished). Means separated by the same letter are not significantly different ($P \leq 0.05$) according to the Ryan-Einot-Gabriel-Welsch multiple range test.

exhibit much greater C sequestration, N, and P accumulation and mineral sediment deposition than the tidal forests upstream (Table 3). Such high rates of accretion and accumulation are caused by greater inputs of sediment to the marsh surface (Table 3), driven by salinity that promotes flocculation and settling of particles (Loomis & Craft, 2010) and by the high density of emergent macrophyte stems that slow the velocity of tidal floodwaters and facilitate particle settling (Gleason *et al.*, 1979). Depth and duration of inundation also play a role as tidal fresh and brackish marshes are lower in elevation (1.17 and 1.07 m NAVD88, respectively) and inundated longer and deeper (10–30 cm) than those in tidal forests (1.41 m NAVD88, 0–10 cm) (C. Craft unpublished LiDAR elevation data for the Georgia coast and personal observation of inundation). Salt marshes, located at the marine end of the estuarine continuum, accrete and accumulate materials at rates comparable to tidal forests (Table 3). These marshes are lower in elevation (0.67 m NAVD88) than marshes and forests upstream, but are downstream of the estuarine turbidity maximum that is located in the area of the brackish marshes (Loomis & Craft, 2010).

Tidal fresh and brackish marshes will be better able to withstand increases in water level and salinity than tidal forests because, as sea level rises, they will sequester more C and trap more sediment than their forested counterparts. They also will accumulate more N and P in soils than tidal forests (Table 3).

On the other hand, saltwater intrusion-driven conversion of tidal forest to oligohaline and brackish marsh is likely to lead to a decline in N processing, at least initially, as NH_4-N is desorbed from cation exchange sites and mineralized during decomposition of soil organic matter (Weston *et al.*, 2006; Jun *et al.*, 2012). Denitrification also will decline (Aelion & Warttinger, 2010; Giblin *et al.*, 2010; Larson *et al.*, 2010; Ensign *et al.*, 2012; Marton *et al.*, 2012), offsetting the increased accumulation of N in soil (Table 3). Furthermore, tidal forests provide habitat for wading birds such as the wood stork (*Mycteria americana*) and neotropical migratory birds (Craft *et al.*, 2009; Brittain & Craft, 2012) that will be lost unless these wetlands are able to migrate upriver. In many watersheds, upstream migration is restricted by topographic limitations and/or watershed development (Neubauer & Craft, 2009). There is also the possibility that tidal forest habitat will convert directly to open water (Conner *et al.*, 2007b), in which case the ecosystem services of both forest and marsh habitat will be lost.

Table 3 Carbon sequestration, N and P accumulation, and mineral sediment deposition (g m^{-2} yr^{-1}) in tidal wetland soils. Tidal forest data are from the Ogeechee, Altamaha, and Satilla rivers (This study). ^{137}Cs marsh data are from the same three rivers as in Loomis & Craft (2010). ^{210}Pb data are from C.B. Craft (unpublished).

	Organic C	Nitrogen	Phosphorus	Sediment
^{137}Cs				
Tidal forest (n = 12)	46 ± 15^{b}	3.0 ± 1^{b}	0.27 ± 0.10^{b}	300 ± 60^{c}
Tidal fresh marsh (n = 12)	122 ± 11^{a}	8.1 ± 0.5^{a}	0.69 ± 0.01^{a}	860 ± 50^{ab}
Brackish marsh (n = 12)	99 ± 26^{a}	6.8 ± 1.4^{a}	0.99 ± 0.21^{a}	1240 ± 80^{a}
Salt marsh (n = 10)	39 ± 6^{b}	2.4 ± 0.4^{b}	0.29 ± 0.04^{b}	540 ± 90^{bc}
^{210}Pb				
Tidal forest (n = 8)	93 ± 5	6.2 ± 0.2	0.70 ± 0.08^{ab}	900 ± 220
Tidal fresh marsh (n = 9)	109 ± 5	7.2 ± 0.7	0.48 ± 0.07^{b}	670 ± 170
Brackish marsh (n = 8)	95 ± 15	6.3 ± 0.8	0.95 ± 0.21^{a}	1260 ± 320
Salt marsh (n = 8)	72 ± 10	4.4 ± 0.5	0.41 ± 0.06^{b}	1020 ± 110

Means separated by the same letter are not significantly different (P = 0.05) according to the Ryan-Einot-Gabriel-Welsch multiple range test.

Tidal forests cover 313 km^2 of the Georgia coast, of which 71% (223 km^2) are on the Altamaha (123 km^2), Ogeechee (29 km^2), and Satilla Rivers (71 km^2) (C. Craft unpublished data), and more than 2,000 km^2 along the southeastern and Gulf coasts (Doyle *et al.*, 2007). Along the Georgia coast, sea level is predicted to rise by 52–82 cm by 2100 according to the Intergovernmental Panel on Climate Change (IPCC), leading to a 20% decline (63 km^2) in tidal forest habitat through upriver migration of tidal fresh and brackish water marsh (Craft *et al.*, 2009). As marsh replaces forest, it is likely that rate of soil accretion will increase, buffering the newly developing marshes against the impacts of increased inundation and salinity. Although some ecosystem services (e.g., C sequestration in soil) will be enhanced as forest converts to marsh, other services (avian habitat, N processing) may decline. Regardless, tidal forests, with their accretion rates that are considerably less than the current rate of SLR, and their intolerance to low levels of salinity, serve as sentinels of global warming-driven accelerated SLR along the southeastern US coast and elsewhere.

Acknowledgements

I thank Ross Brittain, Mihee Jun, John Marton, Nate Knowles, and Anya Hopple for help with sample collection and laboratory analyses. Thanks to Scott Neubauer and two anonymous reviewers for providing thorough and constructive reviews of an earlier draft of the manuscript. This research was supported by the U.S. Department of Energy through grant TUL-563-07/08 and the National Science Foundation grant OCE-9982133 to the Georgia Coastal Ecosystems Long Term Ecological Research Program. This is contribution number 1019 from the University of Georgia Marine Institute.

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