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Wetland Soils

Carbon Sequestration and Nutrient (Nitrogen, Phosphorus) Accumulation in River-Dominated Tidal Marshes, Georgia, USA

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Soil organic C, N, and P were measured in salt, brackish, and tidal freshwater marshes in river-dominated estuaries (Ogeechee, Altamaha, and Satilla) of the Georgia coast to evaluate the effects of salinity on C, N, and P storage and accumulation. Tidal freshwater marshes had greater concentrations of organic C (10.81% w/w) and N (0.71% w/w) than brackish (7.71% C, 0.50% N) or salt (5.95% C, 0.35% N) marshes. Soil accretion rates of ^{137}Cs were greater in tidal freshwater (4.78 mm yr^{-1}) and brackish marshes (4.41 mm yr^{-1}) than in salt marshes (1.91 mm yr^{-1}). Consequently, organic C and N accumulation was greater in tidal freshwater (124 and 8.2 g m^{-2} yr^{-1}) and brackish (93 and 6.5 g m^{-2} yr^{-1}) marshes than salt marshes (40 and 2.4 g m^{-2} yr^{-1}). Phosphorus accumulation was greater in the brackish marshes. Lower salinity tidal freshwater and brackish marshes remove more C, N, and P; however, salt marshes dominate the spatial extent of the study area (60%) vs. brackish (33%) and tidal freshwater marshes (7%). Combining measurements of C, N, and P accumulation with tidal marsh area, we estimated that tidal freshwater, brackish, and salt marshes stored or removed the equivalent of 2 to 20% of watershed N inputs entering the estuaries from the terrestrial landscape. After accounting for N_2 fixation and denitrification, tidal marshes collectively removed the equivalent of 13 to 32% of the N entering estuaries. Tidal marshes, especially tidal freshwater and brackish marshes, are important for improving water quality and decreasing the impacts of N eutrophication of estuarine ecosystems.

Abbreviations: psu, practical salinity units.

Tidal marsh soils are hotspots of biogeochemical activity in estuarine and coastal landscapes. They sequester organic C and nutrients (N and P) (Craft et al., 1988), support anaerobic pathways of microbial metabolism (Capone and Kiene, 1988), and contribute to long-term marsh stability through organic matter accumulation and mineral sediment deposition (DeLaune et al., 1983; Hatton et al., 1983; Nyman et al., 1990, 1993; Craft et al., 1993; Morris et al., 2002).

Several studies have shown that tidal marshes play an important role in N and P processing of allochthonous nutrient loads to estuaries. Tidal marshes sequester nutrients through the deposition of sediment-bound P (Wolaver and Spurrier, 1988) and the transformation of soluble inorganic N into organic N that is buried over time (Bowden, 1987; Bowden et al., 1991). Marsh vegetation has relatively high primary production, which is exported at low rates due to burial and preservation under the anaerobic conditions of wetland soils (Odum et al., 1984). These conditions allow C and N to accumulate at high rates in marsh soils (Hussein and Rabenhorst, 2002; Bowden, 1987). Wolaver et al. (1983) showed that tidal marshes were a net sink for N and P from the adjacent estuary, with the largest fraction being sequestered in particulate form.

Other studies have suggested that tidal marshes have a less significant capacity to process nutrients. Bowden et al. (1991) suggested that marsh and river N cycles operate more or less separate from each other; dissolved N from riverine

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sources passes through the estuary, while within the marsh, N is recycled within the system between vegetation, microbes, and soil. Many studies suggest that tidal marshes act as transformers of nutrients, assimilating inorganic forms of N and P from the water column and transforming them into organic forms that are sequestered in soil (Valiela and Teal, 1979; Craft et al., 1988) or exported by tides (Nixon, 1980; Craft et al., 1989).

Other studies of tidal freshwater, brackish, and salt marshes indicate that higher C and N concentrations are linked to differences in salinity, tidal inundation, marsh age (Craft et al., 2003, 2007), and other factors such as soil drainage and redox potential that affect decomposition and net primary production (Blum, 1993; Nyman et al., 1993). Similarly, others suggest that the considerable variability in riverine N input processing in tidal marshes is best explained by differences in local sedimentation rates (Bowden et al., 1991; Morris and Bowden, 1986). In a comparative analysis of 61 published studies regarding soil properties of tidal marshes of the conterminous United States, Craft (2007) showed that tidal freshwater and brackish marsh soils had significantly higher C and N concentrations than salt marshes. In the same study, Craft (2007) found no difference in organic C and N accumulation among tidal freshwater, brackish, and salt marshes.

We measured concentrations and accumulation of organic C, total N, and total P in salt, brackish, and tidal freshwater marshes of three river-dominated estuaries of the Georgia coast to characterize nutrient storage and accumulation along the salinity gradient. Rates of accretion were measured using ^{137}Cs radiometric analysis. Measured rates of soil N accumulation were extrapolated to the landscape level for each marsh type to estimate the percentage of watershed N sequestered by tidal marshes in each river system. Loading rates were adjusted using three N removal scenarios to show how N_2 fixation and denitrification rates influence N accumulation.

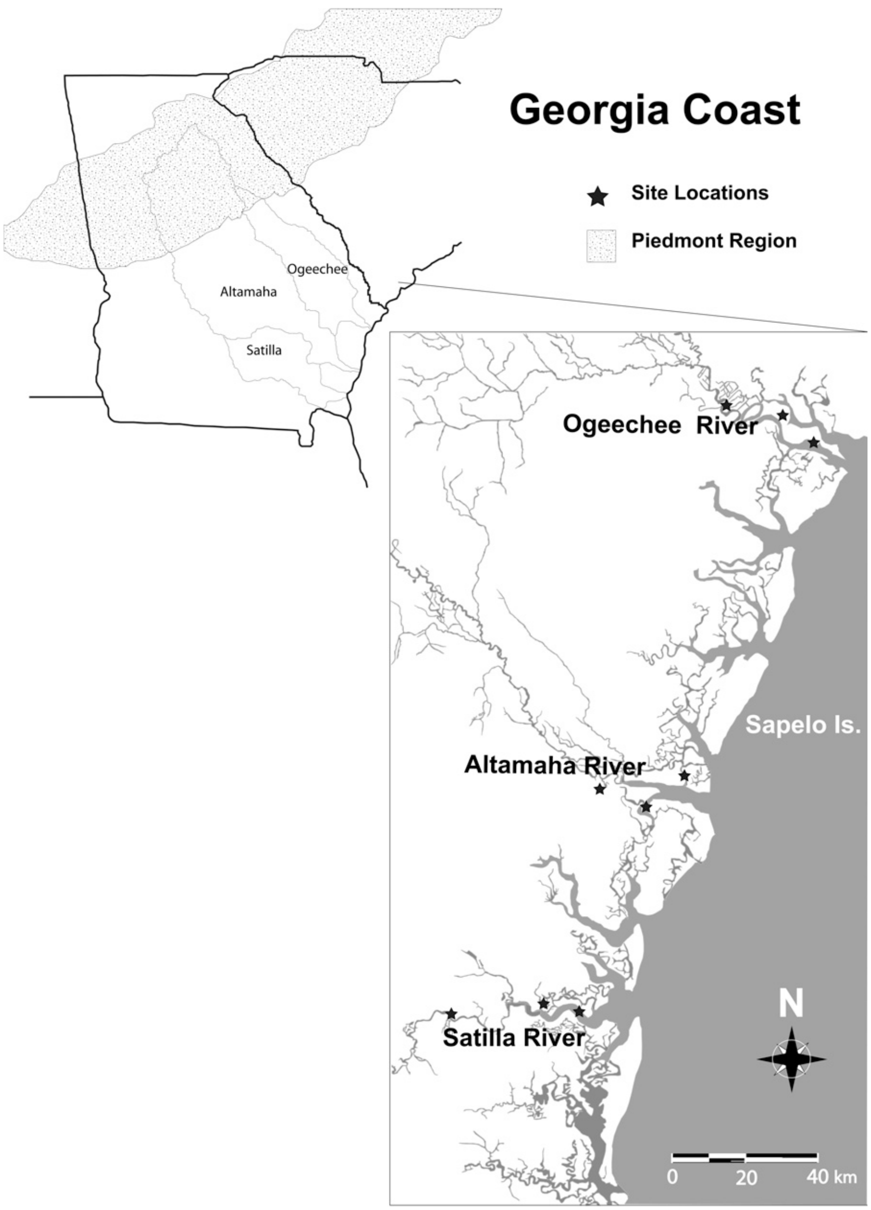

Fig. 1. Georgia coast study area identifying the locations of each watershed within Georgia and the Piedmont, with site locations along the Ogeechee, Altamaha, and Satilla Rivers.

MATERIALS AND METHODS

Site Description

Two salt marshes, two brackish marshes, and two tidal freshwater marshes were selected from three river systems on the Georgia coast (Fig. 1). The Altamaha River is the largest river in the study by both flow and drainage area (Table 1). Its upper reaches drain the foothills of the Appalachian range and its waters are laden with silt and clay from the Piedmont; the river proper resides in the upper Coastal Plain. The Satilla River drains only the Coastal Plain and the surrounding cypress–gum swamps. The Ogeechee River drains portions of the Piedmont and Georgia's Coastal Plain.

Tidal freshwater marshes were defined as having long-term salinity <0.5 practical salinity units (psu), brackish marshes with salinity between 0.5 and 15 psu, and salt marshes with salinity >15 psu based on measurements made in the adjacent estuary. Vegetation is dominated by smooth cordgrass (*Spartina alterniflora* Loisel.) in the salt marshes, giant cordgrass [*S. cynosuroides* (L.) Roth] (levee) and *Juncus roemerianus* Scheele (floodplain) in brackish marshes, and giant cutgrass [*Zizaniopsis milaceae* (Michx.) Döll & Asch.] and several other species in the tidal freshwater marshes (Table 1). Tidal marsh sites were located near the main estuary. On each river, wetland types were located in similar geomorphic settings. For a given habitat type (e.g., tidal freshwater marsh), the salinity of the estuarine surface waters differed among the three rivers during the summer of 2006, when measurements were made. For example, tidal marshes of the Altamaha River had much lower salinity than the Ogeechee and Satilla rivers (Table 1). Our sites, however, are representative of tidal freshwater, brackish, and salt marshes along each river.

Salt and brackish marsh soils of the Ogeechee, Altamaha, and Satilla rivers are mapped as Bohicket and Tidal marsh—fine, mixed, nonacid, thermic Typic Sulfaquents (Soil Conservation Service, 1980). Tidal freshwater marshes of the Ogeechee are mapped as Tfr marsh—fine, mixed, acid, thermic Typic Hydraquents, with the Altamaha tidal freshwater marshes mapped as Swamp—fine, mixed, acid, thermic Typic Fluvaquents (NRCS, 2008). Tidal freshwater marshes of the Satilla River are mapped as Tfr marsh—fine loamy, mixed, acid, thermic Thaptohistic Fluvaquents (Soil Conservation Service, 1980).

Soil Sampling and Analysis

In July of 2005, soil cores, 8.5 cm diameter by 60 cm deep, were collected from salt, brackish, and tidal freshwater marshes on each of the three rivers. There were two sites for each marsh type, and at each site we collected two cores (one levee and one marsh plain) for a total of 36 cores. Cores were sectioned in the field into 2-cm increments for the top 30 cm and into 5-cm increments for 30 to 60 cm. Because of the sample size ($n = 2$) at each site, levee and marsh plain cores were analyzed separately for soil properties; the data from those analyses were then combined for statistical analysis using an unweighted average.

Increments were air dried at 70°C, weighed for bulk density, ground, and sieved through a 2-mm mesh screen, then analyzed for organic C, total N, and total P. Bulk density was calculated from the dry weight per unit volume for each depth increment (Blake and Hartge 1986) after correcting for moisture content of an air-dried subsample that was dried at 105°C.

Organic C and N were determined using a PerkinElmer 2400 CHN analyzer (PerkinElmer Corp., Waltham, MA). Analysis of an internal marsh soils standard (mean ± SE: 5.51 ± 0.6% C, 0.35 ± 0.03% N) yielded recovery rates of 100% (w/w) for C and 95% (w/w) for N. Total P was determined by colorimetric analysis after digestion in HNO_3–$HClO_4$ (Sommers and Nelson, 1972). Analysis of NIST standard (no. 1646a) estuarine sediment yielded a recovery rate of 85% (w/w) for P.

Ground and sieved soil was packed into 50-mm-diameter by 9-mm-deep petri dishes and analyzed for ^{137}Cs to determine vertical accretion. The ^{137}Cs was measured by γ analysis of the 661.62 keV photopeak (Craft et al., 2003). Cesium-137 maxima had well-defined peaks, which represents the location of the soil surface in 1964, the year of peak deposition of atmospheric ^{137}Cs from aboveground weapons testing of thermonuclear weapons of mass destruction. Accumulation of organic C, N, and P was calculated using the ^{137}Cs vertical accretion rate and bulk density, and nutrient (C, N, and P) concentrations down to and including the increment of peak ^{137}Cs activity.

Statistical Analysis

Differences in soil properties, accretion, and accumulation among marsh types were evaluated using a two-way ANOVA, based on marsh type (salt, brackish, and tidal freshwater) and river system (Altamaha, Ogeechee, and Satilla rivers) followed by post-hoc comparison using the Ryan–Elinot–Gabriel–Welsch multiple range test (SAS Institute, 1996). All tests of significance were made at α (∂) = 0.05. Correlations between salinity and nutrient levels were calculated for each marsh type using Pearson's correlation test (SAS Institute, 1996).

Landscape Storage Using a Geographic Information System

Landscape accumulation of soil organic C, N, and P of tidal marshes was estimated using the mean nutrient accumulation rates for each marsh type multiplied by the spatial extent of each marsh type. Spatial extents for each marsh type by river were generated using geographic information system data from the National Wetland Inventory maps (U.S. Fish and Wildlife Service, 2005). We weighted our accumulation rates to account for differences in area and nutrient accumulation of levee

Table 1. Watershed size, discharge, flushing time, marsh type, and dominant plant community structure of the nine study marshes along the Ogeechee, Altamaha, and Satilla river systems.

River	Watershed†	Median discharge‡	Median flushing time‡	Suspended sediment§	Marsh type	Salinity	Plant species
	km^2	$m^3\ s^{-1}$	d	$mg\ L^{-1}$		psu ¶	
Ogeechee	8,415	61	20.7	9	salt	29	*Spartina alterniflora*
					brackish	23	*Spartina cynosuroides*#, *Juncus roemerianus*††
					tidal freshwater	12	*Scirpus validus* Vahl, *Scirpus americanus* Pers., *Scirpus robustus* Pursh, *Sagitteria lancifolia* L.
Altamaha	35,112	250	5.8	38	salt	17	*Spartina alterniflora*
					brackish	4.5	*Spartina cynosuroides*#, *Juncus roemerianus*††
					tidal freshwater	0.1	*Zizaniopsis miliacea*
Satilla	7,348	34	66.8	17	salt	31	*Spartina alterniflora*
					brackish	24	*Spartina cynosuroides*#, *Juncus roemerianus*††
					tidal freshwater	7	*Zizaniopsis miliacea*

† Schaefer and Alber (2007).

‡ Median discharge and flushing times during a 30-yr period (1968–1997) (Alber and Sheldon, 1999).

§ Alber and Flory (2002).

¶ Practical salinity units (Więski et al., 2010).

Species found in the streamside levee.

†† Species found in the floodplain.

Table 2. Bulk soil characteristics (bulk density, organic C and N concentration, and total P) for the top 30 cm of each set of cores. Values represent means ± standard error.

Marsh type	River	Bulk density	Organic C	Nitrogen	Phosphorus
		g cm^{-3}	% (w/w)	% (w/w)	mg kg^{-1}
Tidal freshwater	Ogeechee	0.27 ± 0.04	11.90 ± 0.9	0.71 ± 0.06	541 ± 62
	Altamaha	0.23 ± 0.04	11.58 ± 2.5	0.75 ± 0.14	610 ± 63
	Satilla	0.28 ± 0.04	8.98 ± 0.4	0.65 ± 0.03	495 ± 19
Brackish	Ogeechee†	0.46 ± 0.05	4.24 ± 0.4	0.31 ± 0.04	635 ± 92
	Altamaha	0.25 ± 0.04	11.38 ± 1.8	0.70 ± 0.07	611 ± 43
	Satilla	0.35 ± 0.04	6.65 ± 1.1	0.44 ± 0.04	588 ± 52
Salt	Ogeechee	0.37 ± 0.03	6.10 ± 0.3	0.35 ± 0.02	243 ± 29
	Altamaha	0.37 ± 0.03	5.42 ± 0.9	0.35 ± 0.05	549 ± 33
	Satilla	0.30 ± 0.02	7.57 ± 1.2	0.41 ± 0.06	282 ± 30
Mean tidal freshwater	(n = 12)	0.26 ± 0.02 a‡	10.81 ± 0.89 a	0.71 ± 0.05 a	548 ± 31 a
Mean brackish	(n = 11)	0.34 ± 0.03 ab	7.71 ± 1.17 b	0.50 ± 0.06 b	609 ± 32 a
Mean salt	(n = 12)	0.39 ± 0.05 b	5.95 ± 0.68 b	0.35 ± 0.03 c	369 ± 42 b

† Cores removed.

‡ Marsh means followed by the same letter are not significantly different ($\alpha < 0.05$) according to Ryan–Einot–Gabriel–Welsch multiple range test.

(10% of marsh area) vs. plain (90%) habitats present in our study sites (C. Craft, personal observation, 2009) and differences in accumulation.

The nutrient loading model of Schaefer and Alber (2007) was used to estimate the export of N into the estuary from the watershed based on land use in each watershed. Nitrogen loading rates based on watershed land use and land-use-specific N yields were extrapolated across the total acreage of that land use type present in each watershed (Schaefer and Alber 2007), yielding the estimated quantity of N exported from each watershed into each estuary. We used the estimates of Schaefer and Alber (2007) for N loading to the Ogeechee (2381 Mg), Altamaha (9586 Mg), and Satilla rivers (2682 Mg) based on land use and N yields in each watershed. We adjusted our N loading rates by taking into account ecosystem-level inputs (N_2 fixation) and outputs (denitrification). The N_2 fixation in tidal freshwater marshes (6.1 g m^{-2} yr^{-1}) and salt marshes (2.5 g m^{-2} yr^{-1}) were based on literature reviews by Neubauer et al. (2005) and Howarth et al. (1988a), respectively. The N_2 fixation of brackish marshes was interpolated between the two. Ambient and potential denitrification was measured directly using incubations of soil cores collected from each marsh on each river (Craft et al., 2009). Three scenarios were investigated: (i) N removal unadjusted for N_2 fixation and denitrification (baseline); (ii) N removal after subtracting inputs to soil from N_2 fixation and losses from ambient denitrification (low estimate); and (iii) N removal after accounting for inputs from N_2 fixation and losses from potential denitrification (high estimate).

RESULTS

Soil Properties, Accretion, and Accumulation

Tidal marsh soil properties consistently varied along the salinity gradient of the three rivers. Tidal freshwater marshes had lower bulk density than salt marshes (Table 2). Tidal freshwater marshes also contained higher organic C concentrations than either brackish or salt marshes. The N concentration also varied along the salinity gradient, as tidal freshwater marshes had higher N concentrations than brackish marshes, which were higher than salt marshes (Table 2). Total P was greater in tidal freshwater marshes and brackish marshes than in salt marshes.

Thirty-four of the 36 soil cores contained interpretable ^{137}Cs profiles. Representative ^{137}Cs profiles for each of the three marshes (tidal freshwater, brackish, and salt) in the Satilla River are shown in Fig. 2. Across all rivers, tidal freshwater (4.78 ± 0.37 mm yr^{-1}) and

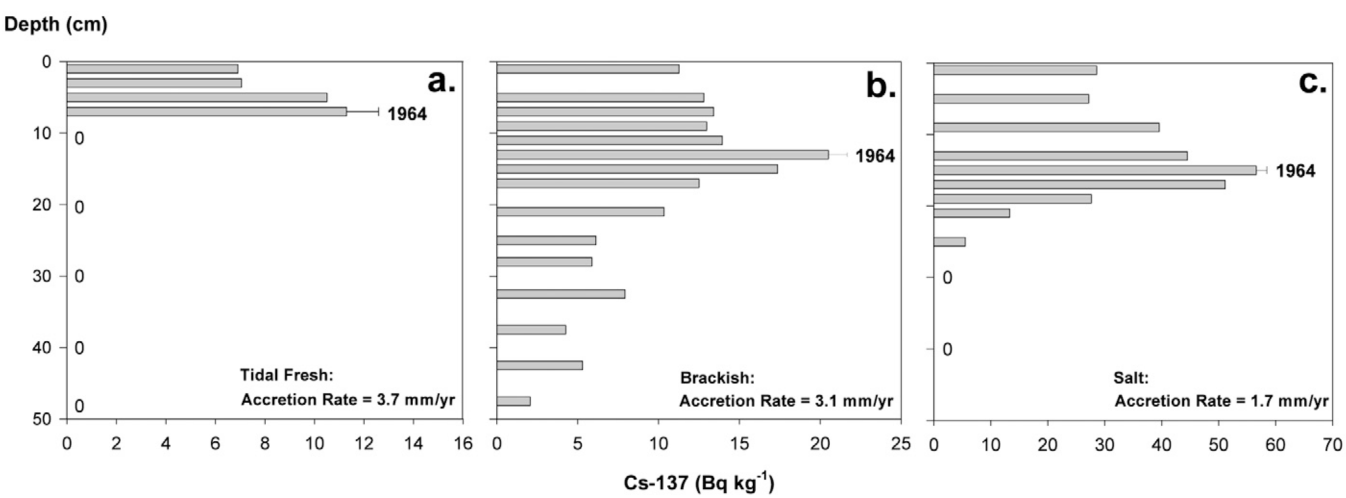

Fig. 2. Representative ^{137}Cs profiles with depth for (a) tidal freshwater, (b) brackish, (c) salt marshes of the Satilla River. Note that, excepting depths immediately above and below the ^{137}Cs peak, ^{137}Cs was measured in alternating depth increments down to the 50-cm depth for all cores; zeros denote where ^{137}Cs was no longer detected. Cesium-137 axis values differ between graphs.

brackish (4.41 ± 0.67 mm yr^{-1}) marshes had significantly higher accretion rates than salt marshes (1.91 ± 0.34 mm yr^{-1}) (Fig. 3).

Similar to accretion, organic C and N accumulation was greater in tidal freshwater (124 ± 10 g C m^{-2} yr^{-1}, 8.2 ± 0.63 g N m^{-2} yr^{-1}) and brackish marshes (93 ± 17 g C m^{-2} yr^{-1}, 6.5 ± 1.17 g N m^{-2} yr^{-1}) relative to salt marshes (40 ± 7 g C m^{-2} yr^{-1}, 2.4 ± 0.44 g N m^{-2} yr^{-1}) (Fig. 4a and 4b). In contrast to C and N accumulation, which decreased along the salinity gradient, P accumulation was significantly greater in brackish marshes (1.0 ± 0.21 g P m^{-2} yr^{-1}) than in either tidal freshwater (0.7 ± 0.09 g P m^{-2} yr^{-1}) or salt marshes (0.3 ± 0.07 g P m^{-2} yr^{-1}) (Fig. 4c). Although not significant, accumulation of mineral sediment also was greater in brackish marshes (1191 ± 256 g m^{-2} yr^{-1}) relative to tidal freshwater (856 ± 105 g m^{-2} yr^{-1}) and salt marshes (537 ± 103 g m^{-2} yr^{-1}) (Fig. 4d).

Variability among marsh types was greater than among river systems, although the brackish marshes of the Altamaha River had somewhat lower bulk densities and higher organic C and N concentrations than the brackish marshes of the other rivers (Table 2). Accumulation of C and N was also greater in the brackish marshes of the Altamaha River than in the brackish marshes of the Ogeechee and Satilla rivers (Fig. 4).

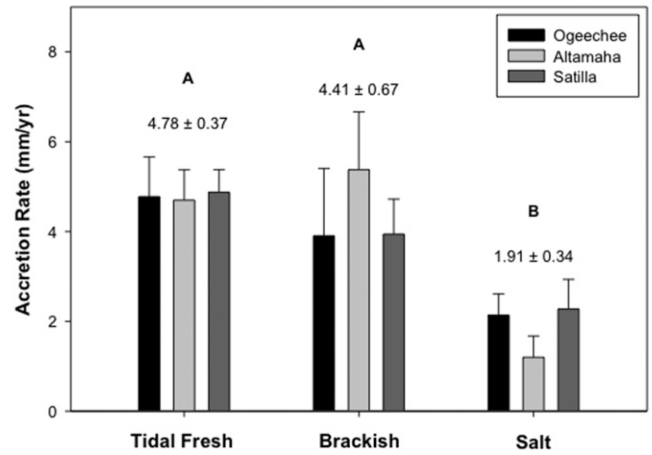

Fig. 3. Mean ^{137}Cs accretion rates for tidal freshwater, brackish, and salt marshes of three Georgia rivers. Letters denote statistical differences ($\alpha = 0.05$) from two-way ANOVA and post-hoc comparison using the Ryan–Elinot–Gabriel–Welsch multiple range test.

When averaged across all marshes and rivers, there was no difference in bulk soil properties, bulk density, C and N concentrations, and total P between levee and plain cores (Student's t-test, $P < 0.05$) (SAS Institute, 1996); however, vertical accretion and C, N, P, and

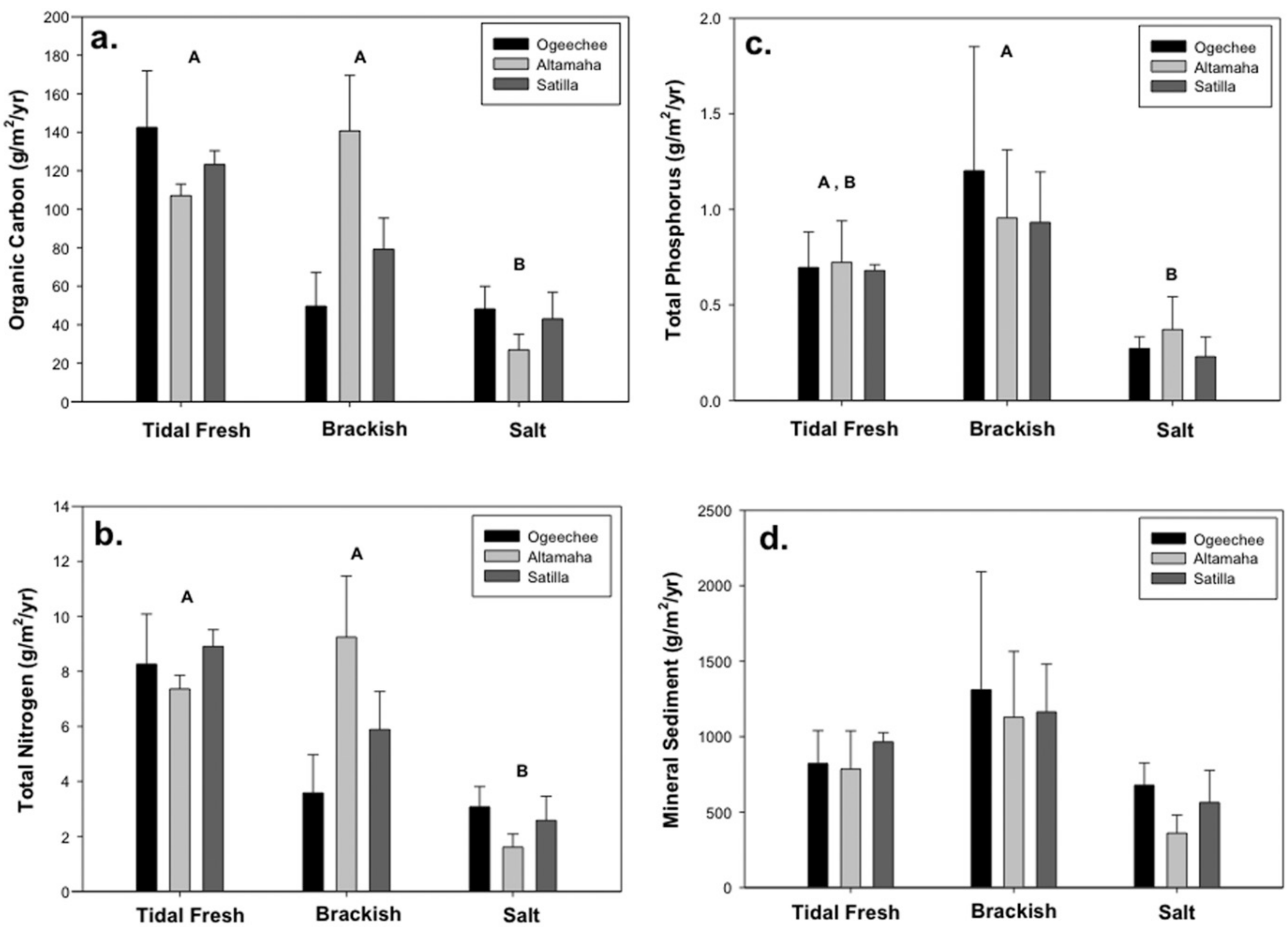

Fig. 4. Mean (a) organic C, (b) N, (c) P, and (d) sediment accumulation for tidal freshwater, brackish, and salt marshes of three Georgia rivers. Letters denote statistical differences ($\alpha = 0.05$) from two-way ANOVA and post-hoc comparison using the Ryan–Elinot–Gabriel–Welsch multiple range test. No statistical differences were detected for mineral sediment accumulation.

sediment accumulation generally were two times greater on the levee (3.75 ± 0.45 mm yr^{-1}, 85 ± 13 g C m^{-2} yr^{-1}, 5.8 ± 0.85 g N m^{-2} yr^{-1}, 0.6 ± 0.13 g P m^{-2} yr^{-1}, and 9081 ± 59 g sediment m^{-2} yr^{-1}) than on the plain (1.78 ± 0.45 mm yr^{-1}, 44 ± 11 g C m^{-2} yr^{-1}, 2.8 ± 0.75 g N m^{-2} yr^{-1}, 0.3 ± 0.07 g P m^{-2} yr^{-1}, and 379 ± 85 g sediment m^{-2} yr^{-1}). Many studies have documented enhanced accretion and accumulation on the levee of tidal marshes that have been attributed to greater depth and duration of inundation and close proximity to the sediment-rich waters of the estuary (Richard, 1978; Hatton et al., 1983; Craft et al., 1993; Morris et al., 2002).

Landscape-Scale Carbon Sequestration and Nitrogen and Phosphorus Accumulation

Among the three rivers, salt marshes occupy 53 to 64% of the tidal marshes in the study area, brackish marshes account for 29 to 40%, and tidal freshwater marshes account for 2 to 11%. Using marsh area (Table 3) and rates of nutrient accumulation (Fig. 4), we estimate that tidal marshes in the Altamaha River store 19,395 Mg C yr^{-1}, while the Ogeechee and Satilla river marshes store 10,160 and 10,119 Mg C yr^{-1}, respectively (Table 3). With respect to N, tidal marshes of the Altamaha River store 1245 Mg N yr^{-1}, whereas the Ogeechee and Satilla river marshes store 686 and 849 Mg N yr^{-1}, respectively. For P, the Altamaha River marshes store 158 Mg P yr^{-1}, whereas the Ogeechee and Satilla river marshes store less—160 and 108 Mg P yr^{-1}, respectively (Table 3).

DISCUSSION

Our study of tidal marshes within three river systems in Georgia supports the idea that variation in salinity leads to differences in soil properties among tidal freshwater, brackish, and salt marshes (Craft, 2007; Hatton et al., 1983; Sundareshwar and Morris, 1999). Soil bulk density was positively correlated ($r = 0.47$) and organic C and N concentrations were negatively correlated with salinity ($r = -0.61$ and -0.74, respectively). Soil accretion ($r = -0.49$), C accumulation ($r = -0.59$), and N accumulation ($r = -0.57$) also were negatively correlated with salinity (Table 1). Tidal freshwater marshes had low bulk density and high organic C and N relative to brackish and salt marshes (Table 2). Other factors such as soil drainage and redox potential may also influence soil C and N concentrations through net primary production and decomposition rates (Blum, 1993; Nyman et al., 1993).

In our study, we attributed decreasing soil organic C and N concentrations with increasing salinity to greater decomposition of organic matter. Craft (2007) observed that in situ decomposition of roots increased with increasing salinity from tidal freshwater to brackish to salt marshes. In that study, increasing decomposition along the salinity gradient was attributed to greater SO_4^{2-} reduction or bioturbation by fiddler crabs (*Uca* sp.), both of which increase with increasing salinity.

Soil P concentration was greater in tidal freshwater and brackish marshes than in salt marshes (Table 2) and also is attributed to reduced salinity, which increases the positive charge of metal hydroxides and facilitates P sorption (Barrow et al., 1980; Stumm and Morgan, 1981, p. 625–640; Sundareshwar and Morris, 1999). Furthermore, as salinity increases, the ability of P to sorb to sediments decreases because of the increase in Cl^- and SO_4^{2-} that compete with hydroxide-bound P for sorption sites (Stumm and Morgan, 1981, p. 625–640; Sundareshwar and Morris, 1999).

In our study of three river systems, soil accretion and C and N accumulation also were greater in tidal freshwater and brackish marshes than in salt marshes (Fig. 4a and 4b). Other studies report higher soil accretion in upstream portions of the estuary, closer to where freshwater and sediment inputs originate, relative to downstream areas where salinity is higher (Kearney and Ward, 1986; Craft, 2007; Sundareshwar and Morris, 1999).

Our results are consistent with published studies of organic C and nutrient accumulation along tidal marshes of the southeast United States. Craft (2007) reported ranges of organic C, N, and P accumulation of 20 to 150, 1.5 to 8, and 0.8 to 1.3 g m^{-2} yr^{-1}, respectively, in the tidal marshes of Georgia and the Southeast. In our study, C sequestration and nutrient (N and P) accumulation ranged from 27 to 142, 1.6 to 9.3, and 0.2 to 1.2 g m^{-2} yr^{-1}, respectively.

In our study, higher rates of accretion in tidal freshwater and brackish marshes was the result of both greater sedimentation and soil organic C concentrations, which add considerable volume to the soil (Craft et al., 1993).

Table 3. Size of each marsh by watershed and the associated rates of C, N, P, and sediment accumulation. Accumulation rates were extrapolated over the area of each marsh using a weighted average (levee = 10%, plain = 90%) by river system to calculate total marsh accumulation rates.

Watershed	Marsh area	Marsh accumulation C	N	P	Sediment
	km^2	Mg yr^{-1}			
Ogeechee River					
Tidal freshwater marsh	7	750	42.6	3.2	4,309
Brackish marsh	91	4,440	322.0	127.3	136,009
Salt marsh	176	4,971	321.9	29.5	75,445
Total	274	10,160	686	160	215,763
Altamaha River					
Tidal freshwater marsh	37	3,986	264.2	16.7	16,676
Brackish marsh	99	10,682	679.8	54.2	65,828
Salt marsh	211	4,728	301.5	87.6	72,429
Total	347	19,395	1245	158	154,933
Satilla River					
Tidal freshwater marsh	17	1,984	139.9	11.3	15,179
Brackish marsh	87	5,161	531.5	84.7	105,694
Salt marsh	115	2,974	177.1	12.4	32,834
Total	219	10,119	849	108	153,708

Sediment (and P) accumulation was greatest in the brackish marshes along the middle reaches of the estuaries (Fig. 4c and 4d), which probably corresponds to the estuarine turbidity maximum where freshwater and sea water mix and sediments flocculate (Sundareshwar and Morris, 1999).

Our study suggests that variation in tidal marsh soil properties is strongly associated with variation in salinity along the estuarine continuum; however, there is some variation in soil properties among the three rivers, which differed in watershed size, discharge, and origin. The Altamaha River is the largest of the rivers, both in watershed area and discharge (Table 1). Its tributaries originate in the rolling landscape of the Piedmont, but the river proper resides in the Coastal Plain (Sheldon and Alber, 2002). Its waters are high in suspended sediment relative to the Ogeechee and Satilla rivers (Alber and Flory, 2002). The Satilla River is the smallest of the rivers in terms of watershed area and discharge (Table 1). It originates in the low-relief landscape and sandier soils of the Coastal Plain. The Satilla River is a "blackwater" river that is high in tannins and dissolved organic matter and low in suspended sediment (Alber and Flory, 2002; Alberts and Takacs, 1999; Wharton et al., 1982). The Ogeechee River is intermediate in watershed area and discharge. Although it originates in the Piedmont, it drains areas of both Piedmont and Coastal Plain.

Comparison of tidal marshes among the three rivers revealed that variation in soil properties was strongly associated with freshwater discharge and sediment supply. Tidal freshwater marsh soils of the Altamaha and Ogeechee rivers, whose discharge is two and seven times higher, respectively, than the Satilla River (Table 1), contained greater organic C and N concentrations than soils of the Satilla River (Table 2). Soils of the Altamaha River tidal marshes also had lower bulk density than those of the Satilla River. Brackish marshes of the Altamaha River had lower bulk density and higher soil organic C and N concentrations than brackish marshes of the Satilla and Ogeechee rivers (Table 2), and accumulation of organic C and N was greater in Altamaha River brackish marshes (Fig. 4), where discharge was four and seven times greater than in the Ogeechee and Satilla rivers, respectively. Previous studies have documented the importance of freshwater to (increasing) soil organic C and N pools and accumulation in the tidal marshes of Georgia and elsewhere (Craft, 2007).

Legacies associated with anthropogenic activities (i.e., rice [*Oryza sativa* L.] cultivation that requires freshwater input) in the past also may have contributed to the high organic C and N concentrations in the brackish marsh soils of the Altamaha River. Compound specific analysis of soil organic matter in one of the Altamaha River brackish marshes revealed the presence of cycloartenol, a compound produced by rice (R. Jaffe, personal communication, 2003).

Tidal freshwater and salt marsh soils of the Altamaha River also contained more P than marshes of the Satilla and Ogeechee rivers (Table 2). In addition to greater freshwater discharge, the Altamaha River also had a higher suspended sediment concentration and load (Table 1), which may explain the higher soil P concentrations in these marshes. Salt marsh soils of the Altamaha River contain more clay (16%) than comparable marshes of the Ogeechee and Satilla rivers (3 and 1%, respectively) (C. Craft, unpublished data, 2009). Sorption and deposition of P has been shown to be strongly associated with clay size particles (Sundareshwar and Morris, 1999). There was no difference in soil P in the brackish marshes of the three rivers, which may be related to the proximity of these marshes to the estuarine turbidity maximum where sediment deposition and P accumulation are maximized (Fig. 4). Thus, in addition to freshwater input, sediment supply is an important determinant of soil properties, especially P, of tidal marshes in river-dominated estuaries of Georgia.

Our mass balance approach, based on watershed N loads and using landscape N sequestration rates unadjusted for N_2 fixation and denitrification (i.e., baseline), indicates that tidal marshes in the three rivers removed from 13 to 32% of the N exported from the watershed to the estuaries (Table 4). Tidal freshwater marshes sequestered 2 to 5% of the watershed N load, brackish marshes sequestered 7 to 20%, and salt marshes stored 3 to 14% of the watershed N load (Table 4). The removal of N was less in the Altamaha River, probably because of its high loading rate (9586 vs. 2381 and 2682 Mg yr^{-1} for the Ogeechee and Satilla rivers, respectively; Shaefer and Alber, 2007) relative to the tidal marsh area (Table 3). Within the marsh, N is removed by the processes of soil accumulation and denitrification. If we consider the high and low estimates of N removal and also account for inputs from N_2 fixation and loss from denitrification (ambient or potential), then tidal marshes remove as little as −8% and as much as 34%

Table 4. Tidal marsh N removal (soil accumulation plus denitrification) of watershed N from the three river systems. The baseline removal percentage does not account for N_2 fixation or denitrification. The low estimate is corrected for inputs from N_2 fixation and removal by ambient denitrification. The high estimate is corrected for inputs from N_2 fixation and removal via potential denitrification.

Watershed	Marsh area	Area by river	N removal		
			Baseline	Low estimate	High estimate
	km^2	%	%		
Ogeechee River					
Tidal freshwater marsh	7	2	1.8	0.0	1.7
Brackish marsh	91	33	13.5	−2.9	12.4
Salt marsh	176	64	13.5	−5.0	19.4
Total	274		28.8	−7.9	33.4
Altamaha River					
Tidal freshwater marsh	37	11	2.8	0.4	2.6
Brackish marsh	99	29	7.1	2.7	6.8
Salt marsh	211	61	3.1	−2.4	4.9
Total	347		13.0	0.7	14.2
Satilla River					
Tidal freshwater marsh	17	8	5.2	1.4	4.9
Brackish marsh	87	40	19.8	5.9	18.8
Salt marsh	115	53	6.6	−4.1	10.0
Total	219		31.6	3.2	33.8

of the N exported from the three watersheds (Table 4). Negative values occur when N_2 fixation is greater than soil N accumulation. The best estimates of landscape-scale N removal may be represented by our N sequestration rates unadjusted for N_2 fixation and denitrification (Table 4), which are assumed to balance each other (Valiela and Teal, 1979).

Based on this scenario, we estimate that tidal marshes of the three rivers remove or store the equivalent of 13 to 32% of the N exported from the watersheds.

Our approach to estimate landscape sequestration of C and nutrient (N and P) storage is constrained by the limited number of cores (one each from the levee and plain) and habitat-specific wetland sites ($n = 2$) on each river. At each site, we used a weighted average to account for differences in area and accumulation on the levee (10% of the total marsh area) vs. the marsh plain (90%); however, sampling two habitat-specific wetland sites per river may not capture the spatial variability of a given (freshwater, brackish, or salt) tidal marsh habitat. Furthermore, hydrologic connectivity, plant species composition, and other factors may vary within a given wetland type, which can affect soil properties and accretion rates. Despite these limitations, our landscape analysis provides important insight into the dynamics and magnitude of C sequestration and nutrient accumulation in riverine and estuarine tidal marshes of the region.

Anthropogenic coastal eutrophication caused by N is increasing throughout the United States as urbanization and land clearing have created greater overall discharge and concentration of nutrients in coastal watersheds (Rabalais et al., 1996; Howarth, 1998). Landscape sources of N that contributed the most to these watersheds were from agricultural activities, mainly fertilizers and livestock (Schaefer and Alber, 2007). Many estuaries are N limited (Howarth et al., 1988b) and, in response to greater N loading, are experiencing greater eutrophication (Howarth, 1998). Tidal marshes help to ameliorate N eutrophication in estuaries by slowing estuarine flushing rates (Sheldon and Alber, 2002), allowing greater N processing via denitrification, N_2 fixation, and soil sequestration, as reported in this study.

Eutrophic conditions are projected to develop more severely and worsen by 2020 in all three of the watersheds in our study domain and in other estuaries worldwide (Bricker et al., 1999). Current primary management efforts focus on limiting nutrient exports associated with agricultural, deforested, and urban land uses. Greater efforts are needed, however, to protect and restore tidal marshes along the Georgia coast and elsewhere. Specific focus should be placed on tidal freshwater and brackish marshes that occupy relatively small areas but possess higher rates (per unit area) of N accumulation than salt marshes. These marshes are providing valuable functions in helping to ameliorate N eutrophication of estuaries and coastal waters.

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