Available online at www.sciencedirect.com

ScienceDirect

Estuarine, Coastal and Shelf Science 78 (2008) 78–88

ESTUARINE COASTAL AND SHELF SCIENCE

www.elsevier.com/locate/ecss

Contributions of mineral and organic components to tidal freshwater marsh accretion

Scott C. Neubauer

Baruch Marine Field Laboratory, University of South Carolina, PO Box 1630, Georgetown, SC 29442, USA

Received 19 August 2007; accepted 20 November 2007
Available online 28 November 2007

Abstract

Vertical accretion in tidal marshes is necessary to prevent submergence due to rising sea levels. Mineral materials may be more important in driving vertical accretion in tidal freshwater marshes, which are found near the heads of estuaries, than has been reported for salt marshes. Accretion rates for tidal freshwater marshes in North America and Europe ($n = 76$ data points) were compiled from the literature. Simple and multiple linear regression analyses revealed that both organic and mineral accumulations played a role in driving tidal freshwater marsh vertical accretion rates, although a unit mass of organic material contributed ∼4 times more to marsh volume than the same mass input of mineral material. Despite the higher mineral content of tidal freshwater marsh soils, this ability of organic matter to effectively hold water and air in interstitial spaces suggests that organic matter is responsible for 62% of marsh accretion, with the remaining 38% from mineral contributions. The organic material that helps to build marsh elevation is likely a combination of in situ production and organic materials that are deposited in association with mineral sediment particles. Regional differences between tidal freshwater marshes in the importance of organic vs. mineral contributions may reflect differences in sediment availability, climate, tidal range, rates of sea level rise, and local-scale factors such as site elevation and distance to tidal creeks. Differences in the importance of organic and mineral accumulations between tidal freshwater and salt marshes are likely due to a combination of factors, including sediment availability (e.g., proximity to upland sources and estuarine turbidity maxima) and the lability of freshwater vs. salt marsh plant production.

Keywords: sedimentation; accumulation; soils; wetlands; coastal marshes; sea level changes; United States; Europe

1. Introduction

Tidal freshwater marsh stability and persistence are dependent on the net balance between material inputs (allochthonous particulate matter and in situ production) and material removal (via erosion and organic matter decomposition), which can allow these systems to grow vertically as sea levels increase. Over decades to centuries, rates of vertical marsh growth typically approximate or exceed rates of sea level rise (e.g., Orson et al., 1990; Neubauer et al., 2002; Köster et al., 2007). Because the zonation of plants within tidal marshes is largely a function of the hydroperiod (Odum et al., 1984; Mitsch and Gosselink, 1993), any imbalances between rates of marsh accretion and sea level rise may lead to changes in plant community composition or a shift from tidal marsh to open water habitats. Plants can influence marsh accretion through the production of refractory organic material (e.g., Orson et al., 1990) and can impact soil organic content and short-term (seasonal) rates of sedimentation (Pasternack and Brush, 2001). Further, there can be differences in long-term (decadal) marsh accretion or organic accumulation between different plant zones within the same marsh (e.g., Khan and Brush, 1994; Merrill and Cornwell, 2000). Differences in sediment availability can also impact sedimentation and accretion in tidal freshwater marshes. Darke and Megonigal (2003) reported up to an order of magnitude difference in short-term deposition rates between a pair of tidal freshwater marshes within the same river system; this dramatic between-marsh variability was attributed to proximity to the estuarine turbidity maximum.

E-mail address: scott@belle.baruch.sc.edu

0272-7714/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2007.11.011

Vertical accretion rates are also sensitive to sediment availability, with both Orson et al. (1990) and Khan and Brush (1994) reporting increases in historical marsh accretion rates following land-clearing activities in surrounding watersheds.

There have been no comprehensive studies to determine if mineral or organic inputs are more important to accretion in tidal freshwater marshes. This contrasts with tidal salt marshes, where the relative contributions of mineral and organic materials to vertical accretion have been well-studied (e.g., McCaffrey and Thomson, 1980; Nyman et al., 1993, 2006; Callaway et al., 1997; Turner et al., 2000; Chmura and Hung, 2004). Future environmental and anthropogenic changes to watersheds and near-coastal waters could significantly alter the dynamics of both sedimentary materials and organic matter production in the tidal freshwater zone. For example, (sub)urbanization, dam construction, and deforestation/reforestation are likely to influence inputs of particulate materials to the tidal freshwater zone and therefore could affect sedimentation onto the marsh surface. Similarly, plant productivity and community composition in tidal freshwater marshes may be altered due to sea level rise, nutrient enrichment, and salt water intrusion (e.g., Pearlstine et al., 1993; Morris et al., 2002; Crain, 2007).

The objective of this study was to determine the relative contributions of mineral and organic accumulations to vertical accretion in tidal freshwater marshes. Here, I use *accretion* to refer to a vertical increase in marsh elevation. *Mineral* and *organic accumulations* represent the mass of mineral (i.e., inorganic) or organic matter deposited on the marsh surface during tidal flooding via sedimentation (defined below) or produced in situ (e.g., belowground root production). *Sedimentation* is the deposition of water column particulate matter (both mineral sediments and organic material) onto the marsh surface. Each of these terms can be expressed as a rate by normalizing accretion, accumulation, or sedimentation to a relevant time scale. Because tidal freshwater marshes are located closer to upland sediment sources, I hypothesized that mineral accumulation would be more significant in tidal freshwater marshes than has been reported for saline marshes (e.g., Turner et al., 2000). Further, I expected that the importance of organic accumulation to marsh accretion would be greater in the northeastern U.S.A. (due to cooler temperatures limiting decomposition) and Louisiana (due to sedimentation onto natural levees and water control structures that limit sediment delivery to interior marshes) than in sediment-rich Southeast U.S.A. tidal freshwater marshes.

2. Materials and methods

Tidal freshwater marsh accretion rates and soil properties (organic content and bulk density) were compiled from the literature. Data were located for marshes distributed along the Atlantic coast of the U.S.A. (from Maine to Georgia), for several locations in coastal Louisiana, and for a single tidal freshwater marsh in Belgium (Table 1). Between one and three cores were taken from most marshes. No non-tidal sites were included. Only measured accretion rates are included in this compilation; thus the accretion rates of 0.13–0.36 cm y^{-1} derived from a mechanistic model for a Massachusetts, U.S.A. tidal freshwater marsh were not included (Morris and Bowden, 1986; Bowden et al., 1991). Soil properties are reported only for sites where accretion rates were measured; additional tidal freshwater marsh soils data can be found elsewhere (e.g., Appendix 1 in Craft, 2007).

2.1. Analytical methods

The majority of the accretion rates analyzed in this study were determined using ^{210}Pb ($n = 46$ samples) or ^{137}Cs ($n = 24$) geochronological dating techniques. The remaining accretion rates were calculated using pollen microfossils ($n = 3$), identifiable plant detritus (i.e., macrofossils; $n = 2$), or a sand layer that was deposited at a known date ($n = 1$) (Table 1). For ^{137}Cs, only accretion rates based on the 1963/64 ^{137}Cs peak are analyzed herein, although several sources also calculated rates using the 1954 date of first appearance (Orson et al., 1990, 1992; Neubauer et al., 2002). Khan and Brush (1994) calculated ‘‘instantaneous’’ accretion rates for selected 1 cm increments; this analysis reports only the average rate since the 1964–1966 layer (i.e., that closest to the 1963/64 ^{137}Cs peak). Plant macrofossils combined with aerial photographs that documented plant species changes were used to calculate accretion rates since 1958 in a tidal freshwater marsh in the Scheldt estuary, Belgium (Temmerman et al., 2003). Orson et al. (1990) measured sediment deposition above a 2 mm thick sand layer that was deposited on the marsh in 1965/66 during installation of a pipeline across the marsh.

The ^{210}Pb and ^{137}Cs dating approaches are most applicable over different time scales and therefore could provide different estimates of vertical accretion within a single site if compaction and decomposition differed in importance between shallower and deeper soils or if accretion rates have changed over time. However, when ^{210}Pb and ^{137}Cs were analyzed on the same marsh core, accretion rates from the two techniques were generally comparable (e.g., Orson et al., 1990, 1992; Church et al., 2006), but occasionally differed by $\sim$0.5 cm y^{-1} (Church et al., 2006). In some cases, an accretion rate could be calculated using one radioisotope but not the other (Köster et al., 2007). Working with a database of salt marsh and mangrove samples, Turner et al. (2006) determined that the ratio of accretion rates from the ^{137}Cs and ^{210}Pb approaches (that is, $\text{Sed}_{137}/\text{Sed}_{210}$) varied non-linearly as a function of soil bulk density. Applying the Turner et al. relationship to the bulk densities for the ^{210}Pb-dated cores analyzed herein resulted in a median $\text{Sed}_{137}/\text{Sed}_{210}$ ratio of 1.06 (10th and 90th percentiles of 0.93 and 1.59, respectively). Given the similarity of the calculated $\text{Sed}_{137}/\text{Sed}_{210}$ ratio to 1.0, no correction was made to adjust the ^{210}Pb-based accretion rates to the common time frame shared by the ^{137}Cs-based rates and the other dating methods used in this study.

Soil parameters (e.g., dry bulk density and soil organic content) were often reported along with accretion rates. Where these data were available, I extracted depth-specific information from figures and tables and calculated average soil

Table 1
Data sources used in this analysis; n = number of accretion rate data points, which is generally equivalent to the number of cores analyzed. Species lists reflect high diversity and co-dominance within single marshes, as well as spatial variability between marshes within the same river system

Location	n	Method	Dominant plant species[a]	Data source(s)
Abagadasset River, ME	1	^{210}Pb	ZizAqu	Köster et al. (2007)
Hudson River, NY	6	^{210}Pb	NupAdv, TraNat	Merrill (1999)
Delaware River, NJ	11[b]	^{210}Pb	BidLae, ImpCap, NupAdv, PelVir,	Orson et al. (1990, 1992), Sommerfield and Madsen (2003),
	10[c]	^{137}Cs	PolSpp, SagLat, ZizAqu	Church et al. (2006)
	1	Pollen		Orson et al. (1990)
	1	Sand layer		Orson et al. (1990)
Otter Point Creek, MD	3	^{210}Pb	AcoCal, LeeOry, PelVir, TypAng	Merrill (1999)
Patuxent River, MD	25	^{210}Pb	HibMos, NupAdv, PelVir, PolSpp, PonCor,	Merrill (1999)
	2	Pollen	SciAme, SpaCyn, TypAng, TypLat, ZizAqu	Khan and Brush (1994)
Pamunkey River, VA	3[d]	^{137}Cs	CarStr, LeeOry, PelVir, PhrAus, PonCor, SpaCyn	Campana (1998), Neubauer et al. (2002)
Altamaha River, GA	4	^{137}Cs	ZizMil	Craft (2007)
Gulf of Mexico, LA	7[d]	^{137}Cs	EleSpp, PanHem, SagLan	Hatton et al. (1983), Smith et al. (1983),
				DeLaune et al. (1986), Nyman et al. (1990, 2006)
Scheldt River, Belgium	2	Macrofossils	PhrAus, SalSpp	Temmerman et al. (2003)
All sites	76[e]	Various		

[a] Plant species abbreviations (first three letters of genus, followed by first three letters of species): AcoCal = *Acorus calamus*; BidLae = *Bidens laevis*; CarStr = *Carex stricta*; EleSpp = *Eleocharis* spp.; HibMos = *Hibiscus moscheutos*; ImpCap = *Impatiens capensis*; LeeOry = *Leersia oryzoides*; NupAdv = *Nuphar advena*; PanHem = *Panicum hemitomon*; PelVir = *Peltandra virginica*; PhrAus = *Phragmites australis*; PolSpp = *Polygonum* spp.; PonCor = *Pontederia cordata*; SagLan = *Sagittaria lancifolia*; SagLat = *Sagittaria latifolia*; SalSpp = *Salix* spp.; SciAme = *Scirpus americanus*; SpaCyn = *Spartina cynosuroides*; TraNat = *Trapa natans*; TypAng = *Typha angustifolia*; TypLat = *Typha latifolia*; ZizAqu = *Zizania aquatica*; ZizMil = *Zizaniopsis miliacea*.

[b] Six cores analyzed for bulk density, organic content, and accumulation rates.

[c] Three cores analyzed for bulk density, organic content, and accumulation rates.

[d] The two data points from Campana (1998) were each the average of two or three individual cores. The data point from Nyman et al. (1990) is the average of seven cores across three sites.

[e] Sixty-four cores analyzed for mineral and organic content and accumulation rates.

characteristics to the core section containing the 1963/64 ^{137}Cs peak (typically the top 15–30 cm). Depth$_{137}$ (that is, the depth to the ^{137}Cs peak, in cm) was calculated as $\text{Depth}_{137} = \text{Rate}_{\text{vert}}$ $(\text{Date}_{\text{core}} - 1963)$, where Rate$_{\text{vert}}$ is the vertical accretion rate (cm y^{-1}) and Date$_{\text{core}}$ is the calendar year each soil core was collected. Alternately, where depth-specific data were unavailable, I used average soil values as reported by the authors. In some cases, organic matter content was calculated from reported organic carbon values as % organic matter = 2 × % organic carbon.

2.2. Data analysis

The assembled data set was analyzed using individual core measurements (after Turner et al., 2000; Nyman et al., 2006) rather than marsh or site averages. This approach retains the variability in accretion rates and soil properties that has been reported between high vs. low marsh habitats, vegetation zones, or creekbank vs. interior locations within a single marsh (e.g., Khan and Brush, 1994; Merrill and Cornwell, 2000) and allows a robust determination of the relationships between accretion, accumulation, and soil properties across the range of conditions that can occur within and between individual tidal freshwater marshes. Bulk densities of organic and mineral matter (g cm^{-3}) were calculated from soil bulk density and the organic or mineral concentration (% dry weight) in the soil. Densities of 1.2 and 2.4 g cm^{-3} for organic and mineral material, respectively (Turner et al., 2000 and references therein), were used to convert calculated organic and mineral bulk densities to volumetric units (i.e., percent volume of soil that is organic or mineral matter). Accumulation rates of mineral and organic matter (g cm^{-2} y^{-1}) were calculated as the product of the vertical accretion rate (cm y^{-1}) and the mineral or organic bulk density of each individual core. Relationships between accretion rates and organic or mineral accumulations were determined using simple linear regression analyses for each river system and for the entire assembled data set. Additionally, stepwise regression analyses were used to develop models of accretion as a function of both organic and mineral accumulations. For the stepwise analyses, parameters were included in the model if $p \leq 0.10$. Residuals for the stepwise regression analyses were plotted and were not related to the predicted values. The accretion rate, soil bulk density, and organic content data were analyzed by region, where Northeast U.S.A. = NJ and points north, Southeast U.S.A. = DE to south FL, and Gulf coast U.S.A. = south FL to TX (regions defined following Craft, 2007). Data from the Scheldt River were not analyzed as a European region due to the low sample size ($n = 2$). Differences between regions were assessed using ANOVA, followed by Tukey's multiple comparison tests. All statistical analyses were conducted using JMP v. 5.0 (SAS Institute, Cary, North Carolina, U.S.A.).

The organic matter inventory, that is, the total mass of organic matter that has accumulated above a defined horizon (typically the 1963/64 ^{137}Cs peak), has previously been identified as a significant variable in salt marsh accretion studies (Nyman et al., 1993, 2006; Chmura and Hung, 2004). In this study, organic matter (and mineral) accumulation rates, rather than inventories, were presented and analyzed for two reasons. First, in several of the literature sources, it was not possible to determine exactly when cores were collected so inventories to the date of core collection could not be calculated. Second, core inventories (e.g., $\mathrm{Inv_{OM,\ core}}$) are directly and proportionally related to the accumulation rate (e.g. $\mathrm{Rate_{OM}}$) in studies when all cores are collected at the same time [i.e., $\mathrm{Inv_{OM,\ core}} = \mathrm{Rate_{OM}}\,(\mathrm{Date_{core}} - 1963)$ where $\mathrm{Date_{core}} - 1963$ is the elapsed time between the ^{137}Cs peak and the date of core collection]. When samples with a wide range of core collection dates are analyzed, as in this study (1987–2002), the apparent relationship between accretion and inventories (relative to the date of core collection) will change as a function of time, even if the underlying parameters (i.e., vertical accretion rate and organic matter bulk density) are constant. As an example, consider a hypothetical marsh with a constant vertical accretion rate of 1 cm $\mathrm{y^{-1}}$ and an organic accumulation rate of 0.05 g $\mathrm{cm^{-2}\,y^{-1}}$. If the marsh is sampled in 1973 (10 years after the 1963 ^{137}Cs peak), the organic matter inventory above the ^{137}Cs horizon is 0.5 g $\mathrm{cm^{-2}}$. If the same marsh is resampled in 2003 (40 years after the 1963 ^{137}Cs peak), the organic matter inventory increases to 2.0 g $\mathrm{cm^{-2}}$, illustrating that inventories will change depending on when samples are collected. In this case, soil inventories could be extrapolated to a common datum rather than to the (variable) core collection dates, but then, as above, the calculated inventory would be directly related to the accumulation rate. Therefore, there is no analytical benefit to report inventories instead of accumulation rates.

3. Results

3.1. Marsh accretion and accumulation rates

There was a wide range in reported tidal freshwater marsh accretion rates: 0.11–2.19 cm $\mathrm{y^{-1}}$, with an overall median rate of 0.76 cm $\mathrm{y^{-1}}$ (Fig. 1). Similarly, mineral (range: 0.003–0.748 g $\mathrm{cm^{-2}\,y^{-1}}$; median: 0.144 g $\mathrm{cm^{-2}\,y^{-1}}$) and organic accumulation rates (0.002–0.186 g $\mathrm{cm^{-2}\,y^{-1}}$; 0.037 g $\mathrm{cm^{-2}\,y^{-1}}$) were highly variable within and between individual river systems. The highest and lowest accretion and accumulation rates were all reported for marshes on the Patuxent River, Maryland. The lowest accretion and accumulation rates were measured near a *Scirpus* spp. (threesquare), *Spartina cynosuroides* (big cordgrass) transition zone, ~30 m from the river edge. The highest accretion and mineral accumulation rates were in a frequently flooded low marsh habitat dominated by *Nuphar advena* (spatterdock), whereas the highest organic matter accumulation rate was in a *S. cynosuroides* zone adjacent to a wide band of *N. advena* that occurred along the river edge (Merrill, 1999). For the entire data set, there were no

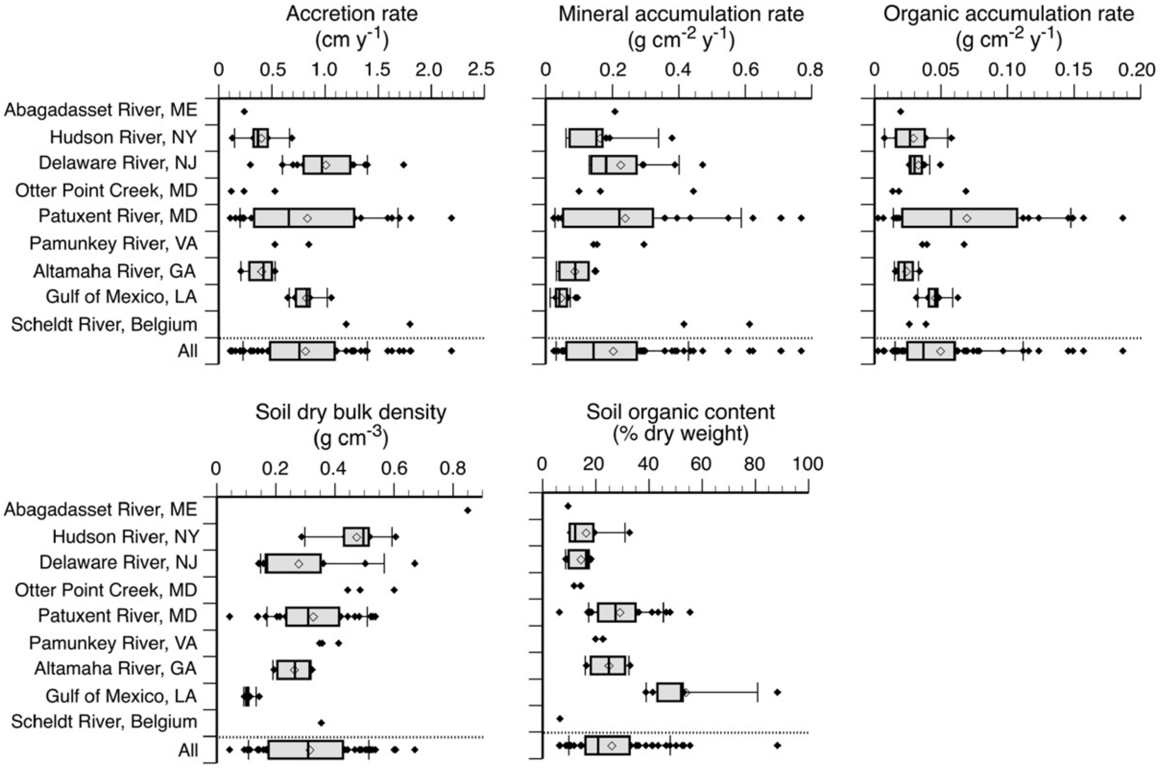

Fig. 1. Distributions of accretion rate, mineral and organic accumulation rates, soil bulk density, and soil organic content by river system. The ends of each box indicate the 25th and 75th percentiles of the data distribution, the vertical line within the box is the median, and the outlier bars mark the 10th and 90th percentiles. Open diamonds indicate the mean of each distribution. Solid dots show individual data points that lie beyond the ends of the box. No boxes are shown for rivers with three or fewer data points; *n* for the accretion and accumulation rates is shown in Table 1; *n* for the bulk density and percent organic data is the same as for the accumulation rates.

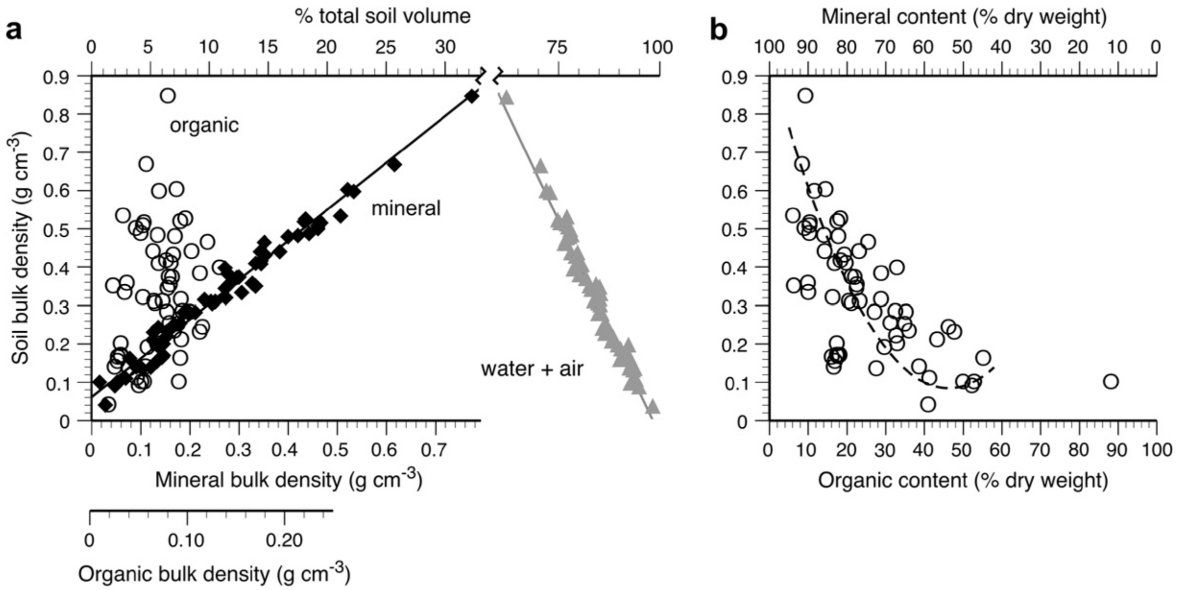

Fig. 2. (a): Relationships between soil bulk density and the percent of the soil volume occupied by organic and mineral matter, or air and water. Regression lines shown on panel (a) are: bulk density = 0.024(% mineral, vol.) + 0.061, $r^2 = 0.974$; bulk density = −0.022(% air + water, vol.) + 2.196, $r^2 = 0.976$; and bulk density = 0.954(mineral bulk density) − 0.051; $r^2 = 0.974$. (b): Relationship between soil bulk density and organic/mineral content as the percent of dry weight. The dashed line on panel (b) is the regression line calculated by Turner et al. (2000) for salt marsh soils: bulk density = 0.0004(% organic, dry wt.)^2 − 0.037(% organic, dry wt.) + 0.94.

differences in accretion rates by region ($p = 0.12$) although there was a general trend for lower accretion rates, on average, in the southeastern U.S.A. than in the other regions. Mineral and organic accumulation rates tended to be lower in the Gulf coast than elsewhere. There was not a relationship between the dating technique (e.g., ^{210}Pb, ^{137}Cs, pollen) and the calculated accretion rate ($p = 0.31$).

3.2. Soil properties

The median bulk density for all sites was 0.313 g cm^{-3}, with a range from 0.040 to 0.846 g cm^{-3} (Fig. 1). Bulk densities were similar in the Northeast and Southeast regions (averages of 0.372 and 0.336 g cm^{-3}, respectively), but significantly lower in the Gulf of Mexico marshes (0.106 g cm^{-3}). Of the material in the marsh soils, 5.8–87.9% was organic matter (overall median: 20.8%, mean: 25.3% by weight) (Fig. 1). There was a significant increase in the average soil organic content (weight basis) from northeastern (14.4%) to southeastern (26.3%) to Gulf coast marshes (53.5%). On a volumetric basis, organic matter occupied between 1.4 and 10.8% of the total soil volume, with a higher average amount in southeastern U.S.A. marshes (6.5%) than in northeastern or Gulf coast marshes (3.9–4.6% by volume, respectively). Mineral matter provided 0.5–32.0% of the soil volume, with the remaining 61.6–97.7% of the soil occupied by water and air-filled spaces. Mineral matter occupied only a small portion of the soil volume in Gulf coast tidal freshwater marshes (average: 2.1%) but averaged 10.7–13.5% of the volume in tidal freshwater marshes in the southeastern and northeastern U.S.A., respectively. The soil bulk density was highly correlated with the percent of soil volume occupied by mineral matter or air and water, but not with the volume of soil organic matter (Fig. 2a). Soil bulk densities were highest when the organic content (on a weight basis) was lowest, or conversely, bulk densities were high when the mineral content was high (Fig. 2b). There were no correlations between the vertical accretion rate and soil, mineral, or organic bulk density ($p = 0.53–0.76$), weight % organic matter ($p = 0.47$), or the volumetric mineral, organic, or air and water contents ($p = 0.51–0.75$).

3.3. Accretion–accumulation relationships

There were significant relationships between accretion rates and mineral/organic accumulation rates for the entire data set and for most individual rivers (Table 2, Fig. 3). For the entire data set, mineral and organic accumulations each individually explained slightly more than 50% of the variability in vertical accretion rates. Slope coefficients for accretion vs. mineral accumulation ranged from 1.15 to 4.64 cm^3 g^{-1} for individual rivers (2.04 cm^3 g^{-1} for the entire data set) and were greatest in the Gulf of Mexico region and Orson et al.'s (1990) Delaware River study. Slope coefficients for accretion vs. organic accumulation ranged from 10.71 to 24.20 cm^3 g^{-1} (9.21 cm^3 g^{-1} for all sites), suggesting that a unit input of organic matter resulted in a greater increase in volume than the same (mass) input of mineral material. With the exception of the two southernmost systems (Altamaha River and Louisiana), organic and mineral accumulation rates were positively correlated within individual rivers ($r^2 = 0.36–0.98$) and for the entire data set ($r^2 = 0.48$) (Table 2, Fig. 4).

Mineral and organic accumulations were both significant factors in the stepwise regression model for all tidal freshwater

Table 2
Simple regression statistics for relationships between vertical accretion (cm y^{-1}) and mineral and organic accumulation rates (g cm^{-2} y^{-1}). Units for the reported slope coefficients are cm^3 g^{-1} for accretion vs. accumulation, and g organic (g mineral)$^{-1}$ for organic vs. mineral accumulation; *, **, and *** indicate significance at $p \leq 0.10$, 0.05, and 0.01, respectively; n.s. = not significant (i.e., $p > 0.10$). Orson et al. (1990) and Church et al. (2006) data were analyzed separately since visual examination of the data suggested distinct relationships for these studies. The "All sites" regressions are shown on Figs. 3 and 4 and are for all data points, including the Abagadasset and Scheldt Rivers ($n = 1$ and 2, respectively), which were not analyzed separately

Location	n	Accretion vs. mineral accumulation		Accretion vs. organic accumulation		Organic vs. mineral accumulation	
		Slope (SE)	Adj. r^2	Slope (SE)	Adj. r^2	Slope (SE)	Adj. r^2
Hudson River, NY	6	1.53** (0.37)	0.761	9.60*** (1.57)	0.879	0.130* (0.054)	0.496
Delaware River, NJ – all	11	n.s.		23.46* (11.30)	0.248	0.041** (0.016)	0.359
Orson et al. (1990)	7	4.64** (1.26)	0.677	24.20** (8.33)	0.553	0.170*** (0.023)	0.903
Church et al. (2006)	4	n.s.		n.s.		0.109* (0.027)	0.838
Otter Point Creek, MD	3	1.15* (0.013)	0.975	n.s.		0.166* (0.017)	0.978
Patuxent River, MD	27	2.47*** (0.24)	0.796	10.91*** (0.68)	0.909	0.209*** (0.024)	0.735
Pamunkey River, VA	3	2.18** (0.14)	0.992	10.71* (1.06)	0.980	0.203** (0.007)	0.998
Altamaha River, GA	4	2.52* (0.71)	0.793	17.45* (4.38)	0.832	n.s.	
Gulf of Mexico, LA	7	4.45** (1.64)	0.516	n.s.		n.s.	
All sites	64	2.04*** (0.24)	0.525	9.21*** (0.11)	0.532	0.156*** (0.020)	0.482

marsh data points. In the model, which explained 62% of the variability in vertical accretion, an input of organic matter resulted in more than 4 times the leverage of the same mass input of mineral matter (5.50 vs. 1.18 cm^3 g^{-1}; Table 3). In the Northeast U.S.A., organic accumulation rates (but not mineral accumulation rates) were a significant predictor of vertical accretion, but the overall model had low predictive power ($r^2 = 0.22$). In the Southeast U.S.A., both mineral and organic accumulations were significant components of the model and together explained nearly 92% of the variability in vertical accretion rates. In contrast, only mineral accumulation rates were related to vertical accretion in Gulf coast tidal freshwater marshes. Further, the slope coefficient for mineral accumulation increased with increasing latitude (i.e., moving from the Gulf coast to the Southeast region), whereas the organic accumulation coefficient increased with decreasing latitude (i.e., Northeast vs. Southeast regions).

4. Discussion

This analysis of accretion rates and organic and mineral accumulation rates for tidal freshwater marshes along the Atlantic and Gulf of Mexico coasts of North America and on the Scheldt River in Europe demonstrated that both mineral and organic inputs are important in influencing vertical marsh growth (Fig. 3, Tables 2 and 3). On a weight basis, a unit input of organic matter contributes about 4 times more toward accretion than does the same input of mineral material. When extrapolated to the average soil composition of the studied tidal freshwater marshes (74% mineral, 26% organic by weight), organic accumulation accounts for 62% of vertical marsh growth with the remaining 38% due to mineral accumulation. This overall picture, however, obscures some large regional differences. In the Southeast U.S.A., as in the entire data set, stepwise and simple linear regressions indicated

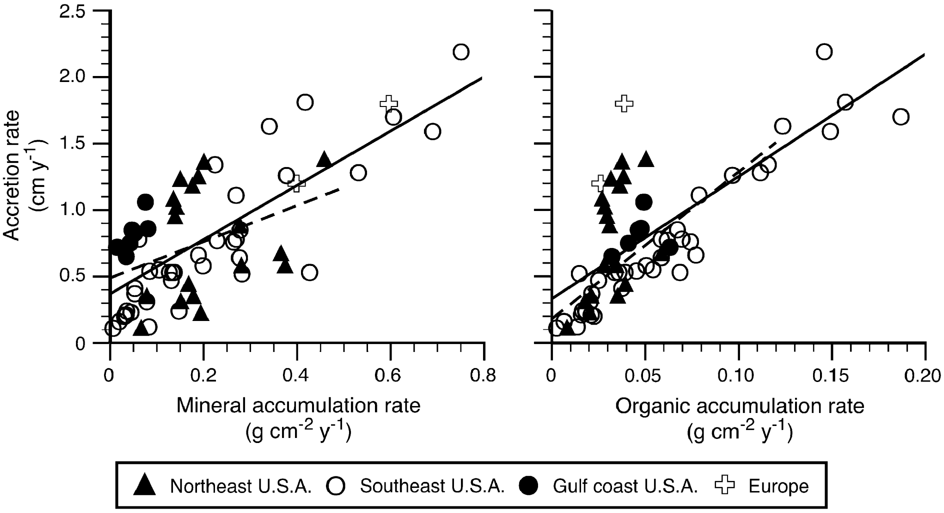

Fig. 3. Mineral and organic accumulation rates were strongly correlated with vertical accretion rates. Solid lines are fit to all data points and have equations of: accretion = 2.04(mineral accumulation) + 0.37, and accretion = 9.21(organic accumulation) + 0.33. Regression statistics are shown in Table 2. The dashed lines indicate the regression equations calculated by Turner et al. (2000) in an analysis of salt marsh accretion and accumulation: accretion = 1.36(mineral accumulation) + 0.49, and accretion = 11.06(organic accumulation) + 0.18. For presentation, data are grouped by region following Craft (2007).

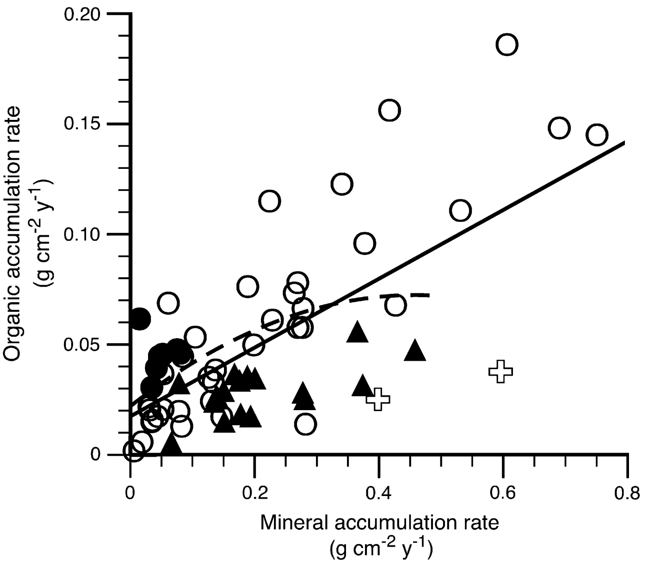

Fig. 4. Relationship between mineral and organic accumulation rates. The solid line is fit to the data points: organic accumulation = 0.156(mineral accumulation) + 0.017. Regression statistics are in Table 2. The dashed line is a polynomial fit from Turner et al.'s (2000) salt marsh analysis: organic accumulation = 0.022 + 0.22(mineral accumulation) − 0.24(mineral accumulation)^2. Symbols are as on Fig. 3.

that both mineral and organic accumulations drive rates of marsh accretion. In the Northeast U.S.A., vertical accretion was dependent on organic accumulation but not on mineral inputs. In contrast, only mineral inputs were significantly correlated with accretion in Louisiana marshes on the Gulf coast. For these regions, it remains to be determined if the trends identified in this analysis are real or instead are analytical artifacts due to high between-site variability (especially in the Northeast, see Table 2 and Fig. 1) or low sample sizes ($n = 7$ for the Gulf coast).

4.1. Tidal freshwater vs. salt marshes

A recent literature synthesis by Craft (2007) showed that vertical accretion rates were negatively correlated with salinity in tidal marshes of Georgia, with a similar (non-significant) trend for tidal marshes across the U.S.A. Accretion rates from the present study support this broad generalization: the median tidal freshwater marsh accretion rate of 0.76 cm y^{-1} is greater than the brackish and salt marsh averages reported by Craft (0.60 and 0.50 cm y^{-1}, respectively). This trend is driven, in part, by positive effects of freshwater on organic matter production and preservation (or conversely, positive effects of salt water on decomposition) (Craft, 2007). This suggests that sea level rise and salt water intrusion may have negative consequences for tidal freshwater marsh accretion, although modern accretion rates in marshes are generally greater than recent rates of sea level rise, regardless of salinity.

Table 3
Stepwise regression models for vertical accretion (cm y^{-1}) vs. mineral and organic accumulation rates (g cm^{-2} y^{-1}). Variables were added to the model if $p \leq 0.10$; *, **, and *** indicate significance at $p \leq 0.10$, 0.05, and 0.01, respectively; n.s. = not significant. Data are grouped by region following Craft (2007)

Region	n	Slope (cm^3 g^{-1})		Intercept (cm y^{-1})	Adj. r^2
		Mineral	Organic		
Northeast U.S.A.	18	n.s.	18.80**	0.22	0.220
Southeast U.S.A.	37	0.52*	8.99***	0.08	0.917
Gulf coast U.S.A.	7	4.45**	n.s.	0.63	0.516
All sites	64	1.18***	5.50***	0.27	0.618

Based on the analyses presented herein, vertical accretion in tidal freshwater marshes is a function of both mineral and organic matter accumulations, whereas accretion in tidal salt marshes is largely (or exclusively) driven by organic matter accumulation (e.g., Nyman et al., 1993, 2006; Callaway et al., 1997; Turner et al., 2000; Chmura and Hung, 2004) although, as discussed below, there is significant regional variability in the importance of mineral and organic inputs in salt marshes. This difference is consistent with the hypothesis that mineral inputs will be more significant in tidal freshwater marshes due to their proximity to upland sediment sources. Additionally, some tidal freshwater marshes can have high rates of sedimentation when located near the estuarine turbidity maximum (Darke and Megonigal, 2003), which is typically near the freshwater–oligohaline transition (Nichols and Biggs, 1985).

Another part of the difference between freshwater and saline tidal marshes is likely an artifact related to the geographic coverage of the individual data sets. With the exception of Chmura and Hung's (2004) study of Canadian marshes, the salt marsh analyses cited in the previous paragraph have been largely (122 of 141 data points; Turner et al., 2000) or exclusively based on data from wetlands along the Gulf of Mexico (Nyman et al., 1993, 2006; Callaway et al., 1997). Indeed, the slope coefficients for east coat U.S.A. tidal salt marshes (mineral: 1.15 cm^3 g^{-1}; organic: 5.82 cm^3 g^{-1}; from Turner et al., 2000) are similar to those for east coast tidal freshwater marshes (mineral: 1.00 cm^3 g^{-1}; organic: 6.34 cm^3 g^{-1}) and nearly identical to those for the entire tidal freshwater marsh data set (mineral: 1.18 cm^3 g^{-1}; organic: 5.50 cm^3 g^{-1}; Table 3). Therefore, it appears that tidal marshes along the U.S. Atlantic coast have similar depositional dynamics, regardless of salinity. In contrast, tidal freshwater and saline marshes along the Gulf of Mexico coast have different accretion vs. accumulation relationships, both between freshwater and saline marshes within this region as well as between the Gulf coast and other regions.

Vertical accretion in tidal freshwater marshes in Louisiana is correlated with mineral (but not organic) accumulation rates (Tables 2 and 3). In contrast, accretion in Gulf of Mexico salt marshes is significantly correlated to organic (but not mineral) accumulation rates or inventories (e.g., Nyman et al., 1993, 2006; Turner et al., 2000). If this is not an artifact due to low sample size ($n = 7$ for tidal freshwater marshes), it appears that accretion in tidal freshwater and salt marshes on the Gulf of Mexico is driven by different factors. This could be related to proximity to upland sediment sources, the estuarine turbidity maximum, or the high lability (and therefore lower preservation potential) of tidal freshwater marsh vegetation relative to salt marsh vegetation (e.g., Odum and Heywood, 1978; Webster and Benfield, 1986).

Despite differences between tidal freshwater and salt marshes in terms of the factors that influence vertical marsh growth, underlying soil parameters are governed by similar factors in all tidal marshes. The relationship between soil bulk density and mineral bulk density for tidal freshwater marshes is nearly identical to that of salt marshes (Fig. 2a; slope of 0.95 vs. 0.97 for salt marshes; Turner et al., 2000). Similarly, the correlation between bulk density and % organic matter reported by Turner et al. (2000) visually describes the tidal freshwater marsh data (Fig. 2b); bulk density decreases as organic content increases to about 40–50% and then remains fairly constant at higher organic matter concentrations. The similarities in mineral–organic–bulk density relationships indicate some common functional relationships between tidal freshwater and salt marshes, but differences in overall soil properties between these marsh types (e.g., bulk density, organic C, N, and P contents) suggest that seawater-derived salinity plays an important role in structuring the characteristics of tidal marsh soils (Craft, 2007).

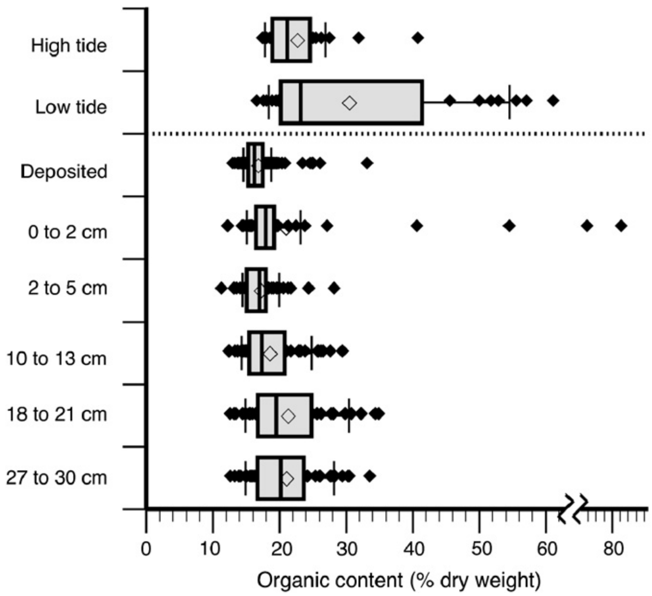

Fig. 5. Organic content of water column suspended solids, recently deposited sediments (“Deposited”), and marsh soils at various depths for Sweet Hall, a tidal freshwater marsh on the Pamunkey River, Virginia. High and low tide data are for ±1 h around the peak tide for a total of 10 tidal cycles in May, June, August, and November. Sediment and soil values are for multiple locations in the marsh and several sampling dates. Data presentation is as for Fig. 1; $n = 259$ for deposited material and 56–60 for soil depths. Water column data are from Anderson et al. (1998); deposited sediment and soil data are from Neubauer et al. (2002).

4.2. Organic matter sources

As documented in this study and multiple analyses of salt marshes (e.g., McCaffrey and Thomson, 1980; Bricker-Urso et al., 1989; Turner et al., 2000; Chmura and Hung, 2004; Nyman et al., 2006), organic matter can play an important role in driving vertical marsh growth. As discussed by Nyman et al. (2006), the source(s) of this organic matter have not been fully explored or explained. Most explanations have involved the sequestration of autochthonous plant production, including aboveground detritus (Craft et al., 1993), litter (Rooth et al., 2003), aquatic roots (Nyman et al., 2006), and subsurface roots and rhizomes (Wolaver et al., 1988). Together, the consensus that plants are primarily responsible for organic matter accumulation in tidal saline and brackish marshes is encapsulated in McCaffrey and Thomson’s (1980, p. 228) statement that “the vertical development of the high-marsh surface is governed by vegetative growth, not particle deposition.” Does this generalization based on salt marsh research apply to tidal freshwater marshes?

There are few data from tidal freshwater marshes regarding the sources of organic matter that contribute to vertical growth, but it is likely that both allochthonous and autochthonous organic matter sources will be important in some systems. At Sweet Hall marsh, a tidal freshwater marsh on the Pamunkey River, Virginia, water column particulate material is enriched in organic matter relative to recently deposited material and marsh soils (Fig. 5). Over a 16-month period, particulate matter deposited on the marsh surface averaged 16.5% organic (weight basis; Neubauer et al., 2002). Similarly, for a New Jersey tidal freshwater marsh, Orson et al. (1990) calculated that a significant fraction (30%) of the annual net particulate flux onto the marsh was as organic matter. Further, the nitrogen content of deposited sediments is correlated with the nitrogen content of marsh soils (Morse et al., 2004). With respect to marsh elemental budgets, inputs of carbon and nitrogen via sedimentation are significant. At Sweet Hall, 517 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ are deposited on the marsh surface (Neubauer et al., 2002), whereas an average of 307 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ are distributed between plant particulate inputs to the soil macro-organic matter pool, export from the marsh, and herbivory (Neubauer et al., 2000). Inputs of nitrogen via particle deposition (48 $\mathrm{g\,N\,m^{-2}\,y^{-1}}$) similarly exceed the retention of autochthonous production (27 $\mathrm{g\,N\,m^{-2}\,y^{-1}}$) (Neubauer et al., 2005a). A final line of evidence suggesting that the deposition of allochthonous material can be important is the correlation between organic and mineral accumulation rates for individual rivers and the entire tidal freshwater marsh data set (Fig. 4, Table 2) that may reflect the co-deposition of allochthonous organic and mineral materials. However, this correlation could also be due to the role that plants play in slowing water flow and promoting sediment deposition (i.e., higher autochthonous production promotes mineral deposition) (e.g., Leonard et al., 1995), or due to the positive influence of soil mineral content on plant productivity (i.e., higher mineral deposition promotes autochthonous production) (e.g., Bricker-Urso et al., 1989). These mechanisms are not mutually exclusive. Whether the organic matter associated with settling particles is ultimately buried and preserved long-term is unknown – it should be noted that up to 30% of deposited organic matter is mineralized within a month of deposition (Neubauer et al., 2002) and that rates of sediment-associated deposition of both carbon and nitrogen are more than double the long-term (^{137}Cs-based) burial rates of 224 g C m^{-2} y^{-1} and 18 g N m^{-2} y^{-1} (Neubauer et al., 2002, 2005a). It is likely that the importance of particle-associated organic matter will vary from system to system, but it is clear that sedimentation can provide considerable organic matter to some tidal freshwater marshes.

There is also a role for autochthonous production as a soil organic matter source in tidal freshwater marshes. At Sweet Hall, the organic content of marsh soils increased with increasing depth (to ∼21% below 18 cm; Fig. 5). The higher soil organic content in deeper soils is consistent with the belowground biomass distribution of *Peltandra virginica* (arrow arum) and *Pontederia cordata* (pickerelweed), the dominant plants at the study site. In a Patuxent River, Maryland, marsh with a similar plant community, the root and rhizome densities (g dm^{-3}) were 14–20 times greater in the 13–20 cm depth than in the top 8 cm of the soil (Neubauer et al., 2005b). Additionally, as speculated by Neubauer et al. (2002), high organic matter concentrations in surface soils (up to 80%, Fig. 5) may reflect localized detritus inputs or the presence of shallow adventitious roots. Together, these examples illustrate the potential importance of allochthonous organic matter sources (e.g., water column plankton and organics sorbed to mineral surfaces), in combination with autochthonous vegetative growth (e.g., roots, rhizomes, and detritus), in supporting vertical marsh growth.

4.3. Environmental factors driving marsh accretion and accumulation

The data sources used in this study did not allow for a robust testing of how accretion and accumulation in tidal freshwater marshes are related to factors such as tidal range, site elevation, rate of sea level rise, or climatic factors (e.g., similar to analyses by Chmura and Hung, 2004). The individual studies compiled for the analyses presented herein were designed for various purposes – comparing vegetation communities, assessing short-term vs. long-term accretion dynamics, or determining the developmental trajectory of a marsh, for example – and are often missing key data that would allow for ‘‘local’’ factors (e.g., site elevation and distance to nearest tidal creek) to be accounted for so that ‘‘regional-scale’’ factors (e.g., rate of sea level rise, climate, and tidal range) could be assessed. For example, Merrill (1999) reported accretion rates for 25 locations within the Patuxent River, Maryland; these sites contained both the lowest (0.11 cm y^{-1}) and highest (2.19 cm y^{-1}) accretion rates of the 76 measurements compiled for this entire tidal freshwater marsh analysis (Fig. 1). Factors such as climate and rates of sea level rise are going to be identical within this single river (within the resolution of available weather/tidal stations), indicating that factors such as site elevation and plant community need to be accounted for before other climatic and environmental variables can be assessed. Unfortunately, those data were not reported for most sites. Thus, a study designed to assess how environmental factors affect tidal freshwater marsh accretion and accumulation over large spatial scales would need to be designed to control for factors that can have a significant influence on small scales so that the effects of larger scale factors could be determined.

5. Conclusions

This first comprehensive analysis of accretion rates and organic and mineral accumulation rates for tidal freshwater marshes along the Atlantic and Gulf of Mexico coasts of North America and on the Scheldt River in Europe demonstrated that both mineral and organic inputs are important in influencing marsh accretion. This finding is in contrast to many salt marsh accretion studies, which have largely reported that organic (but not mineral) accumulation drives vertical accretion. There are, however, salt marshes where mineral accumulation is a significant factor (e.g., east coast U.S.A. marshes in Turner et al.’s, 2000 compilation). In part, real differences between freshwater and saline tidal marshes in terms of mineral sediment deposition and retention, and the preservation of autochthonous plant material affect the balance between organic and mineral accumulations. Regional variability in tidal freshwater marshes suggests that both mineral and organic components contribute significantly to accretion in the Southeast U.S.A. In contrast, only organic accumulation is significant in the Northeast U.S.A., while mineral accumulation appears to drive accretion in Gulf of Mexico tidal freshwater marshes. However, conclusions for the Northeast and Gulf coast regions are equivocal and would be strengthened with more data from these locations.

On a per unit mass basis, the average contribution of organic matter to marsh accretion is more than 4 times greater than the volumetric leverage of mineral matter. When the composition of the average tidal freshwater marsh soil is considered (74% mineral, 26% organic by weight), organic matter is responsible for 62% of vertical marsh accretion, with the remaining 38% from mineral contributions. The organic material that contributes to tidal freshwater marsh soil structure and vertical growth contains a combination of autochthonous production (both aboveground and belowground) as well as organic materials that are deposited on the marsh surface in association with mineral sediments.

Most tidal freshwater marshes are poised to grow vertically at rates that approximate or exceed current rates of sea level rise. Only 4% (three of 76 data points) of the compiled measurements had vertical accretion rates that were lower than the average 1.8 mm y^{-1} rate of global eustatic sea level rise since the 1960s (Gornitz et al., 1982). However, more than 20% of tidal freshwater marshes (16 of 76 samples) have decadal-scale accretion rates that are less the 3.8 mm y^{-1} forecast for 2090–2100 (based on the SRES A1B scenario of future population growth and greenhouse gas emissions; Meehl et al., 2007). An analysis of marsh accretion rates relative to recent rates of sea level rise would provide some predictive power to assess how tidal freshwater marshes in different regions will respond to increasing rates of sea level rise, as well as other changing environmental parameters. Such a study would need to be carefully designed so that potentially subtle regional-scale influences including sea level rise and tidal range could be separated from dominant local influences such as site elevation.

Acknowledgements

I thank Chris Craft and two anonymous reviewers for critical reviews of earlier versions of this manuscript. This work is contribution # 1468 of the University of South Carolina's Belle W. Baruch Institute for Marine and Coastal Sciences.

References

Anderson, I.C., Neubauer, S.C., Neikirk, B.B., Wetzel, R.L., 1998. Exchanges of Carbon and Nitrogen between Tidal Freshwater Wetlands and Adjacent Tributaries. Final Report for the Virginia Coastal Resources Management Program, Virginia Department of Environmental Quality.

Bowden, W.B., Vörösmarty, C.J., Morris, J.T., Peterson, B.J., Hobbie, J.E., Steudler, P.A., Moore, B., 1991. Transport and processing of nitrogen in a tidal fresh-water wetland. Water Resources Research 27, 389–408.

Bricker-Urso, S., Nixon, S.W., Cochran, J.K., Hirschberg, D.J., Hunt, C., 1989. Accretion rates and sediment accumulation in Rhode Island salt marshes. Estuaries 12, 300–317.

Callaway, J.C., DeLaune, R.D., Patrick Jr., W.H., 1997. Sediment accretion rates from four coastal wetlands along the Gulf of Mexico. Journal of Coastal Research 13, 181–191.

Campana, M.L., 1998. The Effect of *Phragmites australis* Invasion on Community Processes in a Tidal Freshwater Marsh. M.S. thesis, The College of William and Mary, Gloucester Point, Virginia.

Chmura, G.L., Hung, G.A., 2004. Controls on salt marsh accretion: a test in salt marshes of eastern Canada. Estuaries 27, 70–81.

Church, T.M., Sommerfield, C.K., Velinsky, D.J., Point, D., Benoit, C., Amouroux, D., Plaa, D., Donard, O.F.X., 2006. Marsh sediments as records of sedimentation, eutrophication and urban pollution in the urban Delaware Estuary. Marine Chemistry 102, 72–95.

Craft, C.B., 2007. Freshwater input structures soil properties, vertical accretion and nutrient accumulation of Georgia and United States (U.S.) tidal marshes. Limnology and Oceanography 52, 1220–1230.

Craft, C.B., Seneca, E.D., Broome, S.W., 1993. Vertical accretion in microtidal regularly and irregularly flooded estuarine marshes. Estuarine, Coastal and Shelf Science 37, 371–386.

Crain, C.M., 2007. Shifting nutrient limitation and eutrophication effects in marsh vegetation across salinity gradients. Estuaries and Coasts 30, 26–34.

Darke, A.K., Megonigal, J.P., 2003. Control of sediment deposition rates in two mid-Atlantic Coast tidal freshwater wetlands. Estuarine, Coastal and Shelf Science 57, 255–268.

DeLaune, R.D., Smith, C.J., Sarafyan, M.N., 1986. Nitrogen cycling in a freshwater marsh of *Panicum hemitomon* on the deltaic plain of the Mississippi River. Journal of Ecology 74, 249–256.

Gornitz, V.S., Lebedeff, S., Hansen, J.E., 1982. Global sea level trend in the past century. Science 215, 1611–1614.

Hatton, R.S., DeLaune, R.D., Patrick Jr., W.H., 1983. Sedimentation, accretion and subsidence in marshes of Barataria Basin, Louisiana. Limnology and Oceanography 28, 494–502.

Khan, H., Brush, G.S., 1994. Nutrient and metal accumulation in a freshwater tidal marsh. Estuaries 17, 345–360.

Köster, D., Lichter, J., Lea, P.D., Nurse, A., 2007. Historical eutrophication in a river–estuary complex in mid-coast Maine. Ecological Applications 17, 765–778.

Leonard, L.A., Hine, A.C., Luther, M.E., 1995. Surficial sediment transport and deposition processes in a *Juncus roemerianus* marsh, west-central Florida. Journal of Coastal Research 11, 322–336.

McCaffrey, R.J., Thomson, J., 1980. A record of the accumulation of sediment and trace metals in a Connecticut salt marsh. In: Saltzman, B. (Ed.), Advances in Geophysics, vol. 22. Academic, New York, NY, pp. 165–236.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.-C., 2007. Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 747–845.

Merrill, J.Z., 1999. Tidal Freshwater Marshes as Nutrient Sinks: Particulate Nutrient Burial and Denitrification. Ph.D. dissertation, University of Maryland, Cambridge, MD, USA.

Merrill, J.Z., Cornwell, J.C., 2000. The role of oligohaline marshes in estuarine nutrient cycling. In: Weinstein, M., Kreeger, D.A. (Eds.), Concepts and Controversies in Tidal Marsh Ecology. Kluwer Press, Dordrecht, pp. 425–441.

Mitsch, W.J., Gosselink, J.G., 1993. Wetlands, second ed. Van Nostrand Reinhold, New York, NY, USA.

Morris, J.T., Bowden, W.B., 1986. A mechanistic, numerical model of sedimentation, mineralization, and decomposition for marsh sediments. Soil Science Society of America Journal 50, 96–105.

Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B., Cahoon, D.R., 2002. Responses of coastal wetlands to rising sea level. Ecology 83, 2869–2877.

Morse, J.L., Megonigal, J.P., Walbridge, M.R., 2004. Sediment nutrient accumulation and nutrient availability in two tidal freshwater marshes along the Mattaponi River, Virginia, USA. Biogeochemistry 69, 175–206.

Neubauer, S.C., Anderson, I.C., Constantine, J.A., Kuehl, S.A., 2002. Sediment deposition and accretion in a mid-Atlantic (U.S.A.) tidal freshwater marsh. Estuarine, Coastal and Shelf Science 54, 713–727.

Neubauer, S.C., Anderson, I.C., Neikirk, B.B., 2005a. Nitrogen cycling and ecosystem exchanges in a Virginia tidal freshwater marsh. Estuaries 28, 909–922.

Neubauer, S.C., Givler, K., Valentine, S., Megonigal, J.P., 2005b. Seasonal patterns and plant-mediated controls of subsurface wetland biogeochemistry. Ecology 86, 3334–3344.

Neubauer, S.C., Miller, W.D., Anderson, I.C., 2000. Carbon cycling in a tidal freshwater marsh ecosystem: a carbon gas flux study. Marine Ecology Progress Series 199, 13–30.

Nichols, M.M., Biggs, R.B., 1985. Estuaries. In: Davis Jr., R.A. (Ed.), Coastal Sedimentary Environments. Springer-Verlag, New York, NY, pp. 77–185.

Nyman, J.A., DeLaune, R.D., Patrick Jr., W.H., 1990. Wetland soil formation in the rapidly subsiding Mississippi River deltaic plain: mineral and organic matter relationships. Estuarine, Coastal and Shelf Science 31, 57–69.

Nyman, J.A., DeLaune, R.D., Roberts, H.H., Patrick Jr., W.H., 1993. Relationship between vegetation and soil formation in a rapidly submerging coastal marsh. Marine Ecology Progress Series 96, 269–279.

Nyman, J.A., Walters, R.J., DeLaune, R.D., Patrick Jr., W.H., 2006. Marsh vertical accretion via vegetative growth. Estuarine, Coastal and Shelf Science 69, 370–380.

Odum, W.E., Heywood, M.A., 1978. Decomposition of intertidal freshwater marsh plants. In: Good, R.E., Whigham, D.F., Simpson, R.L. (Eds.), Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, pp. 89–98.

Odum, W.E., Smith III, T.J., Hoover, J.K., McIvor, C.C., 1984. The Ecology of Tidal Freshwater Marshes of the United States East Coast: a Community Profile. FWS/OBS-83/17. U.S. Fish and Wildlife Service, Washington, DC, USA.

Orson, R.A., Simpson, R.L., Good, R.E., 1990. Rates of sediment accumulation in a tidal freshwater marsh. Journal of Sedimentary Petrology 60, 859–869.

Orson, R.A., Simpson, R.L., Good, R.E., 1992. A mechanism for the accumulation and retention of heavy metals in tidal freshwater marshes of the upper Delaware River estuary. Estuarine, Coastal and Shelf Science 34, 171–186.

Pasternack, G.B., Brush, G.S., 2001. Seasonal variations in sedimentation and organic content in five plant associations on a Chesapeake Bay tidal freshwater delta. Estuarine, Coastal and Shelf Science 53, 93−106.

Pearlstine, L.G., Kitchens, W.M., Latham, P.J., Bartleson, R.D., 1993. Tide gate influences on a tidal marsh. Water Resources Bulletin 29, 1009−1019.

Rooth, J.E., Stevenson, J.C., Cornwell, J.C., 2003. Increased sediment accretion rates following invasion by *Phragmites australis*: the role of litter. Estuaries 26, 475−483.

Smith, C.J., DeLaune, R.D., Patrick Jr., W.H., 1983. Carbon dioxide emission and carbon accumulation in coastal wetlands. Estuarine, Coastal and Shelf Science 17, 21−29.

Sommerfield, C.K., Madsen, J.A., 2003. Sedimentological and Geophysical Survey of the Upper Delaware Estuary. Delaware Sea Grant #DEL-SG-04-04, Final Report to the Delaware River Basin Commission, West Trenton, New Jersey.

Temmerman, S., Govers, G., Meire, P., Wartel, S., 2003. Modelling long-term tidal marsh growth under changing conditions and suspended sediment concentrations, Scheldt estuary, Belgium. Marine Geology 193, 151−169.

Turner, R.E., Milan, C.S., Swenson, E.M., 2006. Recent volumetric changes in salt marsh soils. Estuarine, Coastal and Shelf Science 69, 352−359.

Turner, R.E., Swenson, E.M., Milan, C.S., 2000. Organic and inorganic contributions to vertical accretion in salt marsh sediments. In: Weinstein, M., Kreeger, D.A. (Eds.), Concepts and Controversies in Tidal Marsh Ecology. Kluwer Academic Publishing, Dordrecht, Netherlands, pp. 583−595.

Webster, J.R., Benfield, E.F., 1986. Vascular plant breakdown in freshwater ecosystems. Annual Review of Ecology and Systematics 17, 567−594.

Wolaver, T.G., Dame, R.F., Spurrier, J.D., Miller, A.B., 1988. Sediment exchange between a euhaline salt marsh in South Carolina and the adjacent tidal creek. Journal of Coastal Research 4, 17−26.